

PETROGENESIS OF SIERRAN PLUTONS:
A PETROLOGIC AND GEOCHEMICAL INVESTIGATION INTO THE
ORIGIN AND DIFFERENTIATION OF GRANODIORITIC PLUTONS
OF THE CENTRAL SIERRA NEVADA BATHOLITH, CALIFORNIA

by

Harold James Noyes

B.A., University of Minnesota
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SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF

DOCTOR OF PHILOSOPHY

at the

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HAROLD JAMES NOYES

SUBMITTED TO THE DEPARTMENT OF EARTH AND PLANETARY SCIENCES
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ABSTRACT

The Red Lake and Eagle Peak plutons in the central part of the Sierra Nevada batholith of California have radiometric ages of approximately 86 million years and range in mineralogical composition from granodiorite to granite. The Red Lake pluton is equigranular, has a locally greisenized marginal zone, and shows only minor mineralogic and chemical zoning, whereas the Eagle Peak pluton is mineralogically, chemically, and texturally zoned, with an equigranular margin and a porphyritic core. Modal and normative trends within each pluton are consistent with crystal fractionation of plagioclase and mafics leading to quartz and alkali feldspar enrichment in the residual liquid. Crystal settling is a dominant factor in producing the orderly zonation within the Eagle Peak pluton. Early loss of volatiles and a resulting increase in melt viscosity inhibited crystal settling within the Red Lake pluton and prevented the development of zoning. Aplites associated with both plutons formed from residual liquids of crystal fractionation. Biotite equilibria suggest internally buffered oxygen fugacity throughout most of the crystallization of the plutons. Comparison of mineralogic and whole rock data with experimental studies on natural and synthetic systems suggests a minimum intrusive temperature of $750 \pm 50^{\circ}\text{C}$. and a load pressure of 1.0 ± 0.5 kilobars. Late stage hydrothermal alteration within each pluton has produced minor kaolinite, sericite, and chlorite and appears to have reequilibrated feldspar compositions to subsolidus conditions.

REE distributions within the Red Lake and the Eagle Peak plutons are similar, although La/Yb is slightly greater and Eu/Eu* is slightly less in the Red Lake pluton. Compared to the Red Lake pluton the Eagle Peak pluton has higher abundances of Rb, Cs, U, Th, Sc, and Ta, lower Ba content, and lower Rb/Cs, K/Rb, K/Cs, and Th/U. Host rock normalized mineralogical trace element abundances are generally similar to phenocryst data from other areas and suggest magmatic conditions. The trace element data are consistent with the petrologic data indicating magmatic evolution by fractionation of early formed plagioclase, mafics, and accessories, producing a quartz-alkali feldspar enriched residual liquid with aplite generation as the final stage. Late stage hydrothermal alteration probably caused redistribution of some major and trace elements.

Quantitative modelling of crystal fractionation using major and trace element compositions of whole rocks and aplites indicates compositional variations within the Red Lake pluton can be accounted for by approximately 7% fractionation of plagioclase and mafics, whereas up to 20% fractionation of these phases may be required to produce the variations within the Eagle Peak pluton. The aplites can be generated by 6% to 84% fractionation of these phases from the most differentiated exposed host rocks.

Trace element variations among three members of an intrusive sequence, the Red Lake pluton, the Eagle Peak pluton, and the Mount Givens granodiorite, cannot be explained by crystal-liquid fractionation alone. Variations appear to result from partial melting of a vertically and laterally zoned source region near the lower crust-upper mantle interface, with plagioclase, hornblende, and possibly biotite as the dominant residual minerals.

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TABLE OF CONTENTS

ABSTRACT	2
ACKNOWLEDGEMENTS	4
TABLE OF CONTENTS	5
LIST OF ILLUSTRATIONS	11
LIST OF TABLES	15
CHAPTER I: COMPARATIVE PETROCHEMISTRY OF THE RED LAKE AND EAGLE PEAK PLUTONS, SIERRA NEVADA BATHOLITH	18
INTRODUCTION	18
LOCATION AND PREVIOUS WORK	23
METHODS OF STUDY	24
Modal Analysis	24
Major Element Analysis	24
Mineral Analysis	24
FIELD RELATIONS	30
Red Lake Pluton	30
Eagle Peak Pluton	33
Pegmatites and Aplites	37
Xenoliths	38
PETROGRAPHY	48
Red Lake Pluton	48
Plagioclase	48

Alkali feldspar	48
Myrmekite	48
Quartz	48
Hornblende	49
Biotite	49
Sphene	49
Magnetite	50
Chlorite	50
Allanite	50
Apatite	50
Zircon	50
Kaolinite, sericite, epidote, carbonate	50
Bear Butte Facies of the Red Lake Pluton	51
Eagle Peak Pluton	51
Aplites	53
Mineral Paragenesis	54
MINERAL CHEMISTRY	54
Alkali Feldspar	54
Plagioclase	63
Biotite	65
Chlorite	75
Hornblende	75
Magnetite	79
MODAL ANALYSES	86

MAJOR ELEMENT CHEMISTRY	98
CIPW Norms	107
Bear Butte Facies of the Red Lake Pluton	114
INTERPRETATION OF MODAL AND MAJOR ELEMENT DATA	122
CRYSTAL-LIQUID FRACTIONATION MECHANISMS	136
Convection and Gravitational Settling	136
Flow Differentiation	139
Additional Processes	141
INTERPRETATION OF MINERAL CHEMISTRY	142
Alkali Feldspars	142
Plagioclase	143
Aplite Feldspars	144
Feldspar Compositional Trend	145
Mafic Silicates and Oxides	145
Biotite	146
Hornblende	148
INTENSIVE PARAMETERS	149
Introduction	149
Aplites	149
Melting Data	152
Feldspar Geothermometer	152
Biotite Equilibria	155
DEVELOPMENT OF AKLALI FELDSPAR PHENOCRYSTS	162
APLITE FORMATION	165

SUMMARY	166
CHAPTER II: TRACE ELEMENT GEOCHEMISTRY OF SIERRAN PLUTONS	168
INTRODUCTION	168
SAMPLING, SAMPLE PREPARATION, AND ANALYTICAL METHOD	168
GRANITIC ROCKS	169
Rare Earth Elements (REE)	169
Sc, Hf, Ta, Th, U, Rb, Cs, and Ba	181
APLITES	184
MINERALS	189
Introduction	189
Feldspars	189
Biotite	208
Hornblende	209
Sphene	209
Mass Balances	210
INTERPRETATION OF WHOLE ROCK DATA	213
Introduction	213
Red Lake Pluton	213
Bear Butte Facies	215
Eagle Peak Pluton	217
Marginal sample E92	219
Aplites	221

INTERPRETATION OF MINERAL DATA	224
Feldspars	224
Feldspar Europium Anomalies	226
Cerium Anomalies	228
K-Rb Feldspar-Biotite Thermometer	229
Sc Biotite Thermometer	231
Hornblende Europium Anomalies	232
COMPARATIVE PETROGENESIS OF THE RED LAKE AND THE EAGLE	
PEAK PLUTONS	233
Biotites: Th, U, Rb, Cs, Ba	237
SUMMARY	238
CHAPTER III: CRYSTALLIZATION MODELS OF THE RED LAKE AND THE	
EAGLE PEAK PLUTONS	242
INTRODUCTION	242
PLUTON CRYSTALLIZATION MODELS	243
Red Lake Pluton	243
Eagle Peak Pluton: Major Element Models	247
Eagle Peak Pluton: Trace Element Models	253
Influence of Accessory Minerals	257
Summary.....	259
APLITE MODELS	262
Major Element Models	262
Trace Element Models	264
Summary of Aplite Models	265

CHAPTER IV: ORIGIN OF SIERRAN GRANITES	268
INTRODUCTION	268
STUDY AREA	271
DATA PRESENTATION	272
FRACTIONAL CRYSTALLIZATION MODELS	272
SOURCE REGION HETEROGENEITY	282
PARTIAL MELTING MODELS	289
IMPLICATIONS FOR THE ORIGIN OF THE SIERRA NEVADA	
BATHOLITH	305
REFERENCES	309
BIOGRAPHICAL NOTE	325

LIST OF ILLUSTRATIONS

Figure	Page
1. Index map of California showing study area	19
2. Granitic classification triangle showing modal compositions of samples from this study	21
3a. Sample locality and geological map of the Red Lake pluton	31
3b. Sample locality and geological map of the Eagle Peak pluton	34
4a. Attitudes of pegmatites and aplites of the Red Lake pluton	39
4b. Attitudes of pegmatites and aplites of the Eagle Peak pluton	41
5a. Pegmatite and aplite abundance, Red Lake pluton	43
5b. Pegmatite and aplite abundance, Eagle Peak pluton	45
6. Mineral paragenesis in the Red Lake and the Eagle Peak plutons	55
7. Classification of alkali feldspar structural state using X-ray diffraction data	59
8. MgO-FeO relationships in analyzed biotites	73
9. MgO-FeO-Fe ₂ O ₃ relationships in coexisting biotites and chlorites	77
10. MgO-FeO relationships in analyzed hornblendes	82

Figure		Page
11.	Exploded KPQM modal tetrahedron for the Red Lake pluton	87
12.	Exploded KPQM modal tetrahedron for the Eagle Peak pluton	92
13.	AFM diagram of whole rock data from the Red Lake and the Eagle Peak plutons	108
14.	MgO-FeO-Fe ₂ O ₃ relationships for whole rock samples of the Red Lake and the Eagle Peak plutons	110
15.	Alkali-mafic differentiation diagram for whole rock samples of the Red Lake and the Eagle Peak plutons	112
16.	Exploded normative granite tetrahedron showing CIPW normative compositions of the Red Lake and the Eagle Peak plutons	115
17.	Contoured modal analyses of the Red Lake pluton	123
18.	Contoured modal analyses of the Eagle Peak pluton	128
19.	Pressure-temperature water-saturated melting dia- gram of Sierra Nevada granodiorite	134
20.	Ab-Or-Q diagram showing pertinent experimental equilibria and Red Lake and Eagle Peak pluton aplites	150
21.	Temperature-fH ₂ O stability curves for Red Lake and Eagle Peak pluton biotites	157
22.	Temperature-fO ₂ stability curves for Red Lake and Eagle Peak pluton biotites	160

Figure		Page
23.	Average chondrite normalized REE abundances for the Red Lake and the Eagle Peak plutons	174
24.	Chondrite normalized REE abundances for the Red Lake pluton	176
25.	Chondrite normalized REE abundances for the Eagle Peak pluton	178
26.	Relative abundances of selected trace elements in the Red Lake and the Eagle Peak plutons	182
27.	Host rock normalized REE abundances for aplites from the Red Lake and the Eagle Peak plutons	185
28.	Selected host rock normalized trace element abun- dances for aplites from the Red Lake and the Eagle Peak plutons	187
29.	Host rock normalized REE abundances for mineral separates from Red Lake pluton sample CR29	193
30.	Host rock normalized REE abundances for mineral separates from Eagle Peak pluton equigran- ular sample E91	195
31.	Host rock normalized REE abundances for mineral separates from Eagle Peak pluton porphy- ritic core sample C1	197
32.	Host rock normalized REE abundances for alkali feldspar separates from the Red Lake and the Eagle Peak plutons	199

Figure		Page
33.	Host rock normalized REE abundances for plagioclase separates from the Red Lake and the Eagle Peak plutons	201
34.	Host rock normalized REE abundances for biotite separates from the Red Lake and the Eagle Peak plutons	203
35.	Distribution of REE between alkali feldspar and plagioclase from the Red Lake and the Eagle Peak plutons	205
36.	Trace element mass balances for whole rock samples of the Red Lake and the Eagle Peak plutons	211
37.	Average chondrite normalized REE abundances for three Sierra Nevada intrusives	277
38.	Geochemical variations among intrusives of the Boulder batholith	287
39.	Geochemical variations among three intrusives of the Sierra Nevada batholith	290
40.	Chondrite normalized REE abundances for partial melting models	300

LIST OF TABLES

Table	Page
1. Electron microprobe standards	26
2. Mössbauer parameters used in biotite analyses	28
3. Source and assignment of ferric/ferrous ratios for hornblendes and chlorites	29
4. X-ray diffraction parameters for alkali feldspars	58
5. Alkali feldspar analyses by electron microprobe	62
6. Plagioclase analyses by electron microprobe	64
7. Biotite analyses by electron microprobe	66
8. Averaged biotite analyses and structural formulas	70
9. Chlorite electron microprobe analyses and structural formulas	76
10. Hornblende electron microprobe analyses and structural formulas	80
11. Magnetite electron microprobe analyses	84
12. Summary of modal analyses of granitic rocks of this study	97
13a. Modal analyses of chemically analyzed granitic rocks of this study	99
13b. Supplementary modal analyses of the Eagle Peak pluton	101
14. Chemical analyses and CIPW norms of granitic rocks of this study	102

Table	Page
15. Average chemical compositions of the Red Lake and the Eagle Peak plutons	106
16. Representative analyses of three Sierran plutons	138
17. Feldspar thermometer temperature estimates	153
18. Accuracy and precision of trace element abundance determinations	170
19. Precision and uncertainty of trace element abundance determinations	171
20. Trace element abundances of granitic rocks of this study	172
21. Trace element abundances of mineral separates of this study	190
22. Purity of mineral fractions used in this study	192
23. Biotite: alkali feldspar Rb/K thermometry	230
24. Compositions of minerals used in modelling studies	245
25. Red Lake pluton crystallization models	246
26. Eagle Peak pluton crystallization models	249
27. Distribution coefficients used in crystallization models	255
28. Trace element solutions to pluton crystallization models	256
29. Aplite crystallization models	263

Table	Page
30. Trace element solutions to aplite crystallization	
models	266
31a. Mount Givens granodiorite REE concentrations	273
31b. Trace element abundances and ratios in Sierran	
granitic rocks	274
31c. Mount Givens granodiorite major element analyses	276
32. Distribution coefficients used in partial melting	
models	280
33. Compositional differences between altered and	
unaltered ocean floor basalts	284
34. Chemical compositions of components used in	
modelling studies	293
35. Calculated mode for COMPOSITE parent	294
36. Partial melting model results: residue	
composition	291
37. Modal abundances determined in partial melting	
models	297
38. Partial melting model results: trace element	
models	298

CHAPTER I

COMPARATIVE PETROCHEMISTRY OF THE RED LAKE
AND EAGLE PEAK PLUTONS, SIERRA NEVADA BATHOLITH

INTRODUCTION

Many Sierra Nevada batholith plutons are mineralogically, texturally, and chemically zoned (Bateman and others, 1963; Moore, 1963). Some plutons have well developed concentric zoning, whereas others exhibit only minor internal variations. In an effort to understand this zoning and the associated magmatic processes detailed field, petrologic, and geochemical studies have been made of the petrologically similar Red Lake and Eagle Peak plutons from the Huntington Lake Quadrangle in the central part of the batholith (Figure 1). Preliminary studies by Bateman and Wones (1972a;1972b) indicate these plutons are similar in age, size, and mineralogy. Mineralogical zoning is well developed in the Eagle Peak pluton but weak in the Red Lake pluton. This study considers the field relations, major element chemistry, and petrology of the two plutons.

These plutons are among the youngest plutons in the area and are possibly less subject to mineralogical or geochemical changes caused by subsequent intrusions. Extensive comparison of the data for these two plutons aids a better understanding of the magmatic processes responsible for their characteristics. Comparison to other Sierran plutons demonstrates that these two plutons are representative of similar plutons in the batholith.

Mapping in this study was conducted during the summer of 1972 using topographic sheets and stereo pairs with a scale of 1:62,500.

Figure 1: Index map showing location of study area and the region of Sierra Nevada intrusives.

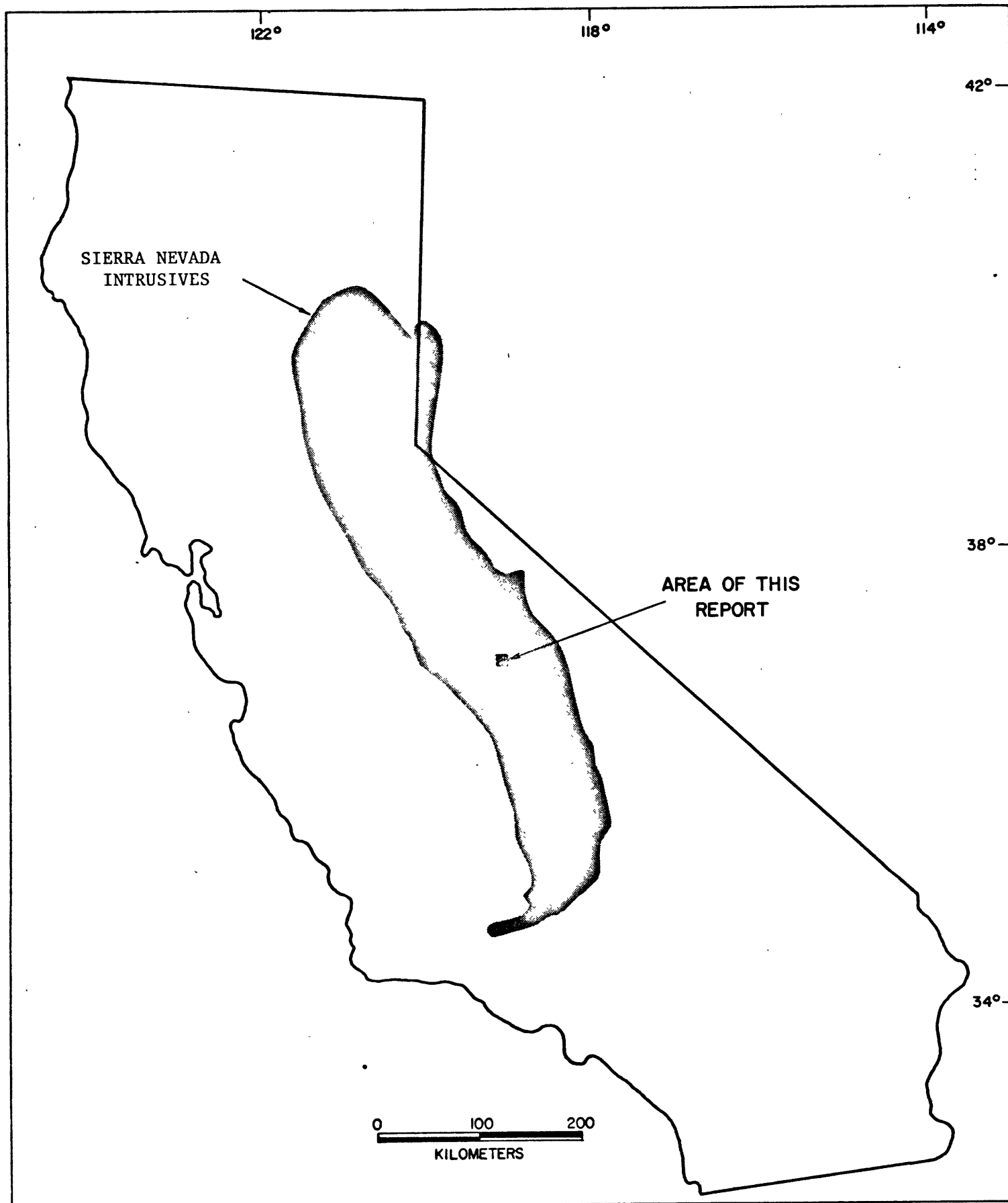


Figure 1

Figure 2: Granitic classification triangle showing modal compositions of samples from this study. Data from stained slab modal analyses, normalized to three components: alkali feldspar (A), plagioclase (P), and quartz (Q). Classification after Streckeisen (1967).

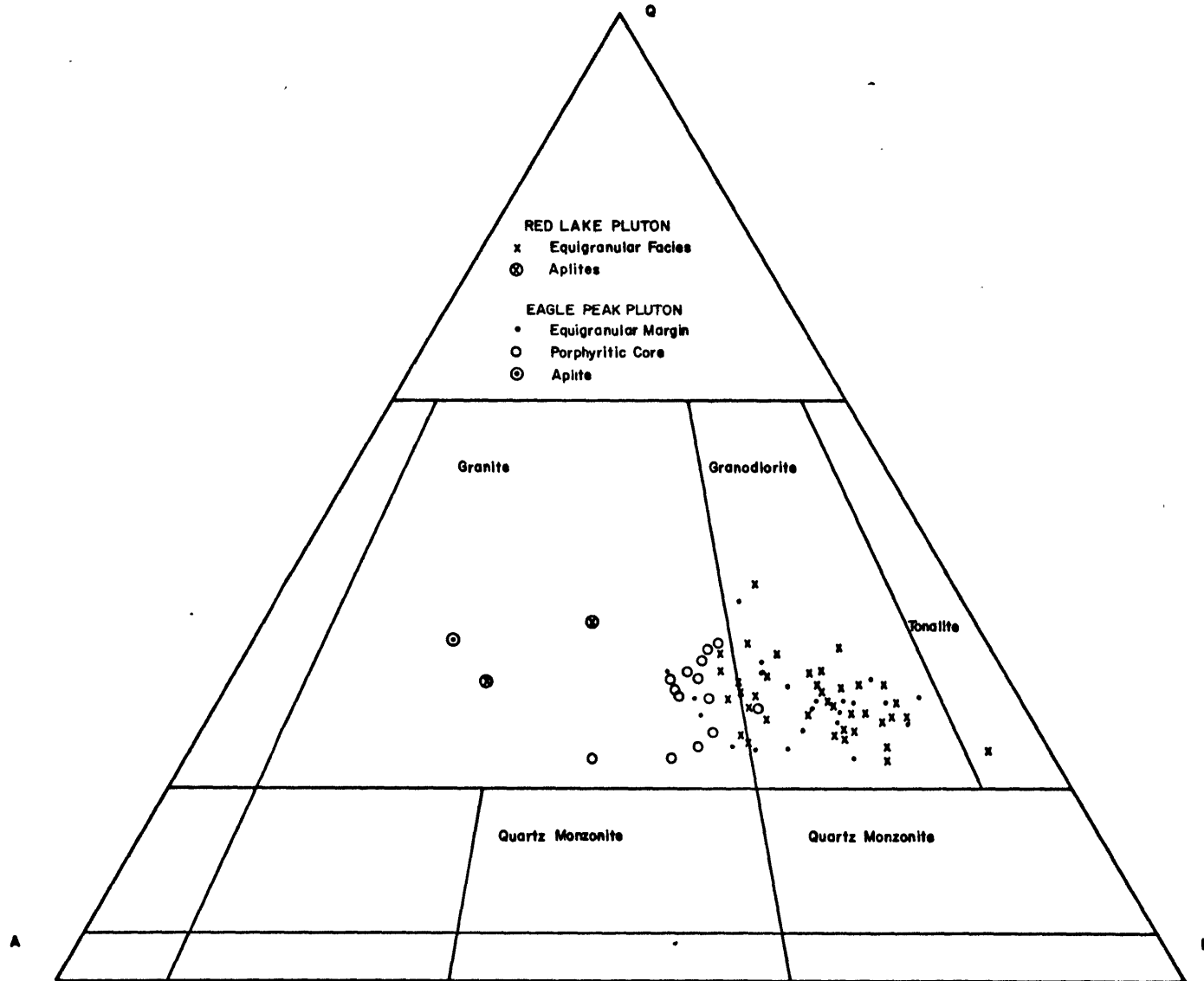


Figure 2

Locations were determined using triangulation and a pocket altimeter. Excellent exposures over large parts of the plutons provide exceptional control for detailed study.

A summary of the modal data obtained in this study, Figure 2, indicates that according to IUGS classification (Streckeisen, 1967) these plutons range from granodiorite to granite in mineralogical composition.

LOCATION AND PREVIOUS WORK

The Red Lake and Eagle Peak plutons are located about 90 kilometers northeast of Fresno, California. Approximate pluton centers are at $37^{\circ}9'N$, $119^{\circ}8'W$ and $37^{\circ}6'N$, $119^{\circ}1'W$, respectively. Both plutons lie on the western slope of the Sierra Nevada block within the region extensively studied by the USGS (Bateman and others, 1963). The Red Lake pluton is exposed between the altitudes of 2200 meters and 3000 meters, entirely within the Huntington Lake Quadrangle. Exposures of the Eagle Peak pluton lie between the altitudes of 2400 meters and 3000 meters within the Huntington Lake and the Blackcap Mountain Quadrangles.

Portions of the area were originally mapped and described by Hamilton (1956). More detailed studies by Bateman and Wones (1972a; 1972b) delineated contacts, defined age relations, and presented extensive petrologic and geochemical data. They determined the Red Lake pluton is a fine-grained, relatively homogeneous, equigranular granodiorite, whereas the Eagle Peak pluton is texturally zoned with a g r a n i t i c porphyritic core and a granodioritic equigranular margin (Figure 2). Both plutons occupy approximately 52 square

kilometers. In plan the Red Lake pluton is broadly crescentic and the Eagle Peak pluton is elliptical. Radiometric ages determined for the plutons are 85 million years for the Red Lake pluton and 87 million years for the Eagle Peak pluton (Bateman and Wones, 1972a). Contact relations and radiometric ages assign these plutons to the Yosemite intrusive series, the youngest series recognized in the batholith (Evernden and Kistler, 1969).

METHODS OF STUDY

Modal Analysis

Of the approximately 100 samples collected during mapping 28 were selected for stained slab modal analysis (Laniz and others, 1964). Modes were counted on surfaces of six or more square inches in which both feldspars had been stained. Thin section modes were performed on 15 samples by counting 1200 or more points on 25 x 75 mm slides across the entire slide on a rectangular grid.

Major Element Analysis

The samples selected for major element and microprobe analysis are representative of the least weathered outcrops of the major textural and mineralogical varieties observed during mapping.

Major element analyses were performed on splits from hand specimens chosen to be at least ten times the volume of the maximum heterogeneity observed in the outcrop.

Mineral Analysis

Mineral analyses were performed on carbon coated polished thin sections of rock samples using the MIT automated electron microprobe

at an accelerating potential of 15 kilovolts and a sample current of 0.03 microamperes. With this system a complete analysis is obtained by occupying a point only once. Beam size ranged from 2 to 5 microns for most analyses.

Various counting times and standards were used to obtain optimum analytical results. Standards used are listed in Table 1. Standards were as similar as possible in composition and structure to the minerals analyzed.

Only those feldspar analyses with oxide totals within the range 98.5 to 101.5 weight per cent were used to form the averages reported here. Reported biotite and hornblende analyses have oxide totals in the range 95 to 97 weight per cent and 97 to 99 weight per cent, respectively, consistent with inferred contents of unreported constituents (discussed later). Only a limited number of chlorite analyses were made and all are reported.

One standard deviation for analyzed elements is given for biotite samples CR29-6 and E92-1 in Table 7. These indicate the relative homogeneity of those two grains. Similar homogeneity was found from widely spaced analyses of other grains and thus the tabulated values are considered representative for the remainder of the analyses. Consequently, fewer analyses were considered necessary to characterize several of the other grains. Single standard deviation for grain averages from CR29 and from E92 are given in Table 8 and indicate the relatively minor variation in composition of biotite from any one rock. Similar results are shown for chlorite and hornblende analyses in Tables 9 and 10.

TABLE 1

Standards used in electron microprobe analysis*

Mineral	Si	Al	Ca	Na	K	Fe	Mg	Ti	Mn	V
Alkali feldspar	ORTH	DJ35	DJ35	DJ35	ORTH	--	--	--	--	--
Plagioclase	DJ35	DJ35	AN60	AN60	ORTH	--	--	--	--	--
Biotite	BIOT	BIOT	DJ35	DJ35	BIOT	BIOT	BIOT	BIOT	MNILM	--
Chlorite	BIOT	BIOT	DJ35	DJ35	BIOT	BIOT	BIOT	BIOT	MNILM	--
Hornblende	BIOT	BIOT	DJ35	DJ35	BIOT	BIOT	BIOT	BIOT	MNILM	--
Opaque	DJ35	DJ35	RHO	--	--	MNILM	MNILM	MNILM	MNILM	VAND

*All standards and compositions (except BIOT) provided by the MIT electron microprobe facility.

Abbreviations:

ORTH: Orthoclase glass

DJ35: Diopside (0.65) - jadeite (0.35) glass

AN60: Anorthite (0.60) - albite (0.40) glass

MNILM: Manganese ilmenite

RHO: Rhodonite

VAND: Vanadium metal

BIOT: Biotite standard, Table 1, Czamanske and Wones(1973)

Alkali feldspar separates were obtained from the 60-100 mesh size fraction of rock powder by heavy liquid techniques. A smear mount on a glass slide was made for each sample and three X-ray diffraction traverses were run for each between 15 and 57 degrees 2θ using CaF_2 (calcined at $800^\circ\text{C}.$) as an internal standard, a chart speed of $1/2''$ per minute, a goniometer speed of $1/2^\circ$ per minute, and filtered $\text{Cu K}\alpha$ radiation.

Ferrous/ferric ratios were determined by Mossbauer spectroscopy for biotites CR5 and C1 and were assumed for all other biotites, hornblendes, and chlorites. The value obtained for biotite CR5 was applied to all other Red Lake pluton biotites and that for biotite C1 was applied to all Eagle Peak pluton biotites. Bancroft and Brown (1975) have reported success using this technique, with the correction factor near one for chemical:Mossbauer $\text{Fe}^{+2}/\text{Fe}^{+3}$ ratios. Mossbauer parameters are given in Table 2. Hornblende and chlorite ferrous/ferric ratios are based on values for Sierran rocks similar to those studied here. Specimens were selected as similar in composition to the minerals of this study as possible. Ratios and references are shown in Table 3. It will be seen that the samples discussed here are typical of the Sierra Nevada batholith, and that this procedure is adequate for this study.

Structural formulas for biotite, hornblende, and chlorite were calculated according to the method discussed by Borg (1967) as water and fluorine analyses are not available for the samples of this study. Thus, the number of oxygen atoms per unit cell was assumed to be 23

TABLE 2

Mossbauer parameters for Sierran biotites

Sample	2 X	+2 Fe Absorptions						+2 Fe Absorptions						+3 Fe	
		M2			M1			M1			M2			+2	+3
		C.S.	Q.S.	H.W.	C.S.	Q.S.	H.W.	C.S.	Q.S.	H.W.	C.S.	Q.S.	H.W.	Fe	+ Fe
		mm/s			mm/s			mm/s			mm/s				
C1	1051.43	1.08	2.60		1.04	2.16		0.48	0.88		0.39	0.42		0.224	
CR5	706.46	1.08	2.59		1.03	2.13		0.48	0.87		0.39	0.41		0.188	

Abbreviations:

C.S.: center shift

Q.S.: quadrapole splitting

H.W.: half width

mm/s: millimeters per second

TABLE 3

Source and assignment of ferric/ferrous ratios for hornblendes and chlorites of this study.

Sample	$\text{Fe}_2\text{O}_3/\text{FeO}^*$	Source
Hornblende	0.340	Dodge, Papike, and Mays (1968); average of Bca-20 and MT-4
Chlorite	0.378	Dodge (1973); MT-1

*Weight percent

for hornblende, 22 for biotite, and 28 for chlorite.

FIELD RELATIONS

Red Lake Pluton

An outline and sample locality map of the Red Lake pluton is shown in Figure 3a. Near Red Mountain and Bear Butte the degree of exposure approaches 100% over large expanses, but it is more limited over most of the pluton. Many outcrops are either weathered or quite small due to glacial deposits, alluvium, and vegetation. In addition, Tertiary basalt caps Red Mountain and Chinese Peak.

The main body of the pluton consists of light-gray weathering fine-grained equigranular granodiorite. Grain size averages about 1-2mm. Plagioclase, alkali feldspar, biotite, and quartz are readily identifiable in hand specimen, although the feldspars are not easily distinguished from one another. Sphene and hornblende are common accessories. Hornblende occurs in small needles less than 2 mm long and ranges up to subhedral prisms 5 mm x 2 mm. Sphene commonly exhibits euhedral faces in grains as large as 3 mm. The presence or absence of sphene and hornblende, the only marked heterogeneity in the pluton, was mapped, but no orderly distribution was observed. Two variations from the main type are the west lobe of the pluton (between Boneyard Meadow and Highway 168), which has identical mineralogy and is slightly finer grained than the main body of the pluton, and the north lobe (in the vicinity of and including Bear Butte), which is distinctly finer grained (about 1 mm) than the rest of the pluton, weathers pale gray, has rusty red alteration spheres about 1 to 2 cm in diameter, contains abundant sericite, and is extremely indurated.

Figure 3a: Sample locality and geological map, Red Lake pluton.

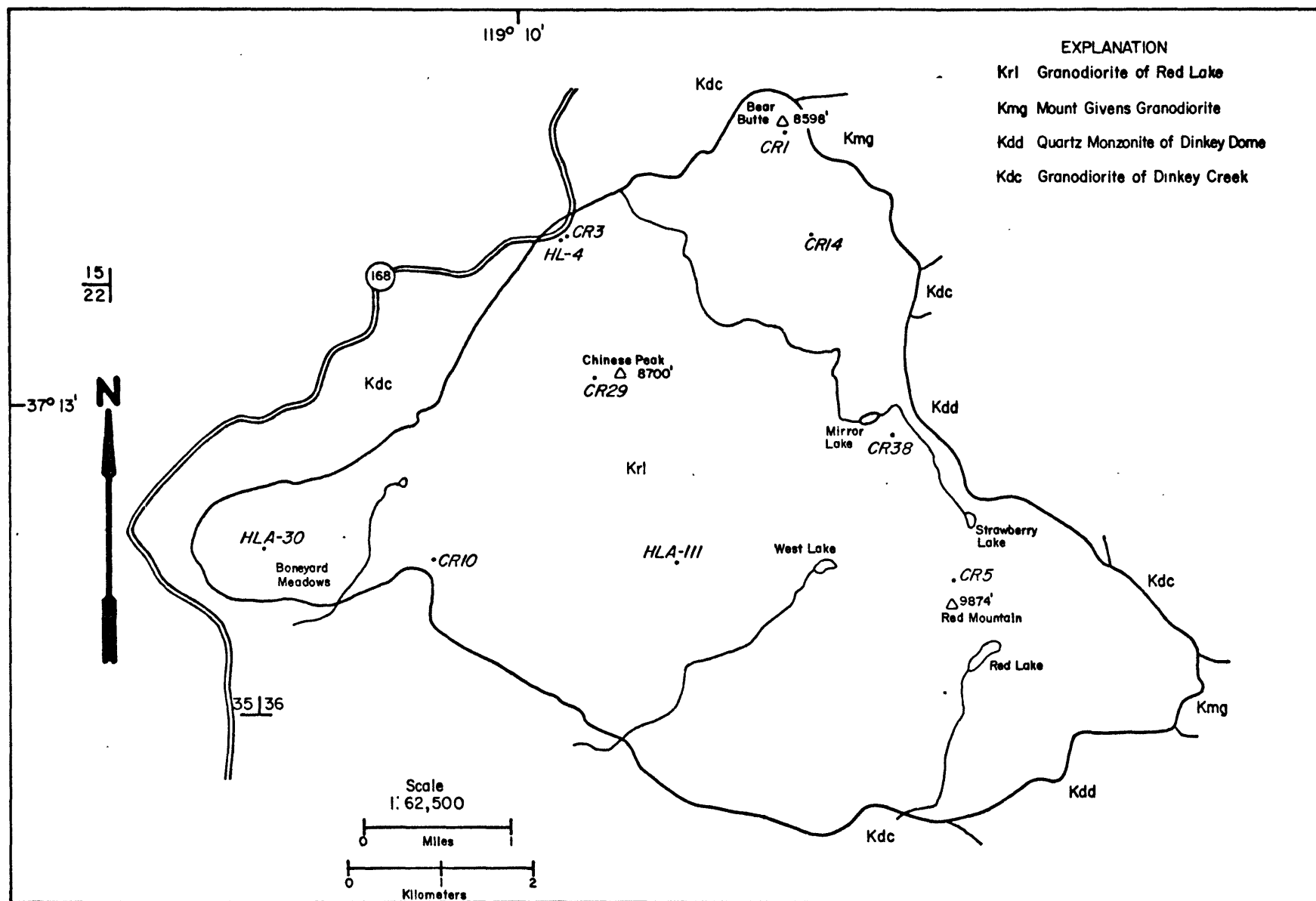


Figure 3a

The contacts of the pluton, determined by Bateman and Wones (1972b), are not continuously exposed, but indicate the pluton is younger than all surrounding rocks. Essentially the entire west side of the pluton is in contact with the Granodiorite of Dinkey Creek. Northwest of Boneyard Meadow near Highway 168 the contact has abundant pegmatites and aplites transecting both units and extensive hydrothermal alteration has developed in the Red Lake pluton. West of Bear Butte and near the intersection of Big Creek and Highway 168 abundant aplites are present in the Red Lake pluton, but no alteration is present. At the other contacts hydrothermal alteration is lacking and pegmatites, aplites, and mafic inclusions are only occasionally present.

Eagle Peak Pluton

Bateman and Wones (1972a;1972b) recognized two zones in the Eagle Peak pluton. These are readily distinguished in the field and are shown on the generalized geologic and sample locality map in Figure 3b. The outer zone is fine grained, equigranular, and pinkish gray in color with average grain size from 1 to 2 mm. Adjacent to the country rock it is somewhat finer grained and deeper gray which results from a greater proportion of mafic minerals. Near the margins of the pluton these minerals define a foliation parallel to the contact. The core is defined by the presence of pink alkali feldspar phenocrysts. Over most of the core these phenocrysts are surrounded by a fine-to-medium grained groundmass closely resembling the marginal zone of the pluton. Phenocrysts appear euhedral, weather in positive relief, are lath-like, and range up to maximum dimensions of 2 x 7 cm. Locally they are aligned forming a well defined lineation. Phenocrysts vary in abundance

Figure 3b: Sample locality and geological map, Eagle Peak pluton.

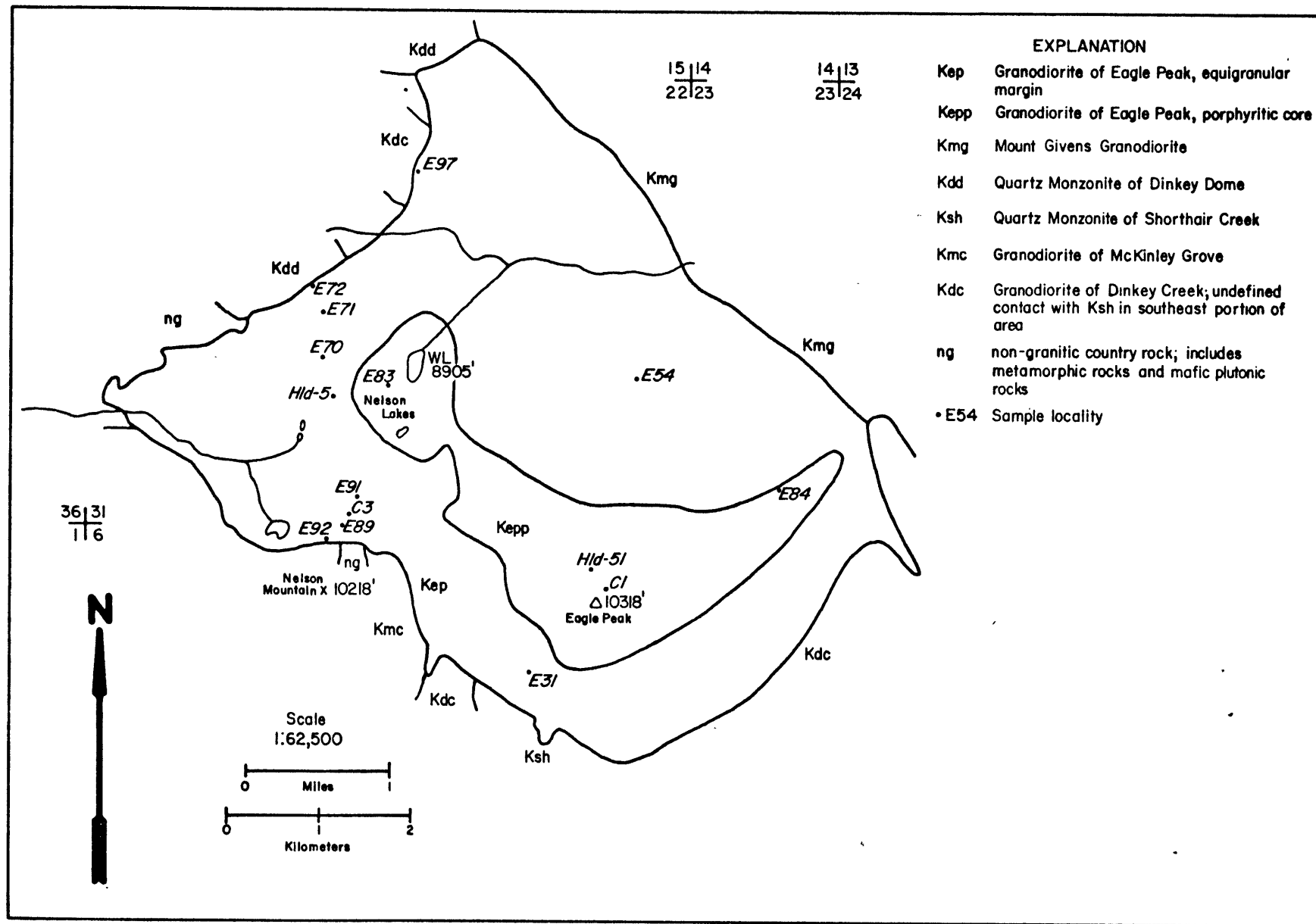


Figure 3b

locally and in some areas they are densely concentrated in discrete ellipsoids of up to several hundred square centimeters in outcrop area, occupying up to 60% of the ellipsoid. In other parts of the core they occupy only about 10% of the surface area. The mineralogy of the ellipsoids is identical to that of the surrounding core facies.

The contact between the two Eagle Peak zones is gradational over less than one meter and well exposed on the ridge between Nelson Mountain and Eagle Peak. Scattered alkali feldspar phenocrysts appear and greatly increase in abundance. The groundmass of the core appears similar to the equigranular margin in grain size, color, and mineralogy. There is no evidence suggesting an intrusive relationship. The distinction between the two units is based solely on the presence or absence of phenocrysts and is unambiguous in the field. The contact is somewhat irregular, with undulations of up to several meters.

A textural variant of the porphyritic core occurs in the western portion of the core near Nelson Lakes (Figure 3b, outcrop E83). Here alkali feldspar phenocrysts are surrounded by a gray-weathering fine grained groundmass with average grain size about 1/2 to 1 mm, slightly finer grained than the major part of the core. Pleistocene and recent alluvium limit the exposure and prohibit determining the relationship of this variant to the other types. The outcrop is too small to be mapped and it is the only known occurrence of this type in the Eagle Peak pluton.

The contacts with the country rock are abrupt and essentially vertical. Dikes of the Eagle Peak pluton occasionally penetrate several meters into adjacent units. Hydrothermal alteration and

metasomatism are rare and of minor extent where present. Angular blocks of unaltered adjacent country rock are found near some contacts. This study demonstrates that the Eagle Peak pluton extends into the Blackcap Mountain Quadrangle, where it was not recognized by Bateman (1965b).

Pegmatites and Aplites

Simple pegmatites and aplites are found in variable proportion and abundance at the contacts and interiors of both plutons. The aplites are usually pale gray, very fine grained, less than 10 cm wide, and in most cases, are traceable only several hundred meters before terminating or becoming covered with overburden. Attitudes range from vertical to near flat-lying. Mineralogically the aplites consist of plagioclase, alkali feldspar, quartz, and trace amounts of biotite. Minor phenocrysts of plagioclase and quartz are present. Clots of granitic rock, usually mineralogically quite similar to the adjacent rock, are found in some aplites. Pegmatites are similar in occurrence and attitude to the aplites. They are pink, consist of alkali feldspar, quartz, biotite, magnetite, and some plagioclase. Grain size is highly variable; alkali feldspar crystals up to approximately 12 cm in length and biotite books over 3 cm across are relatively common. Pegmatite width seldom exceeds 10 cm; most can be traced only several meters before terminating. Offset intersections of pegmatites and aplites indicate at least two generations of development. Irregular, layer-like intergrowths of pegmatites and aplites are also observed as in other similar plutons (Bateman and others, 1963).

Several differences between the pegmatites and aplites of the two

plutons are apparent in the field. Many of the larger pegmatites in the Eagle Peak pluton have internal disc-like voids up to several centimeters wide and one meter in diameter, which is rarely observed in the Red Lake pluton pegmatites. Aplites of the Eagle Peak pluton are invariably gray, whereas some aplites in the Red Lake pluton are pervasively stained pink by hematite.

The number, size, and orientation of pegmatites and aplites were recorded at all stations. Pegmatite and aplite orientation are plotted in Figures 4a and 4b; no preferred orientation is apparent. Visual estimation of the percentage of surface area covered by pegmatites and aplites is inaccurate because of the small area actually covered by these features. A semiquantitative approach was adopted of measuring the width of all pegmatites and aplites in a randomly selected square meter of outcrop at each station. Figures 5a and 5b plot total width per square meter of outcrop and demonstrate that the Eagle Peak pluton has both greater abundance and greater local concentrations of pegmatites and aplites than the Red Lake pluton. Less extensive exposure in the Red Lake pluton as contrasted to that in the Eagle Peak pluton make these observations somewhat uncertain.

Xenoliths

Xenoliths of two types are present in both plutons: angular blocks of country rock and mafic inclusions. Country rock xenoliths are relatively rare; they are usually found near contacts and can be readily related to the intruded wall rock. These xenoliths are usually well under 50 cm in maximum dimension.

The mafic inclusions found in the two plutons are identical in all respects to those discussed by Bateman and others (1963) and

Figure 4a: Attitudes of pegmatites and aplites, Red Lake pluton.

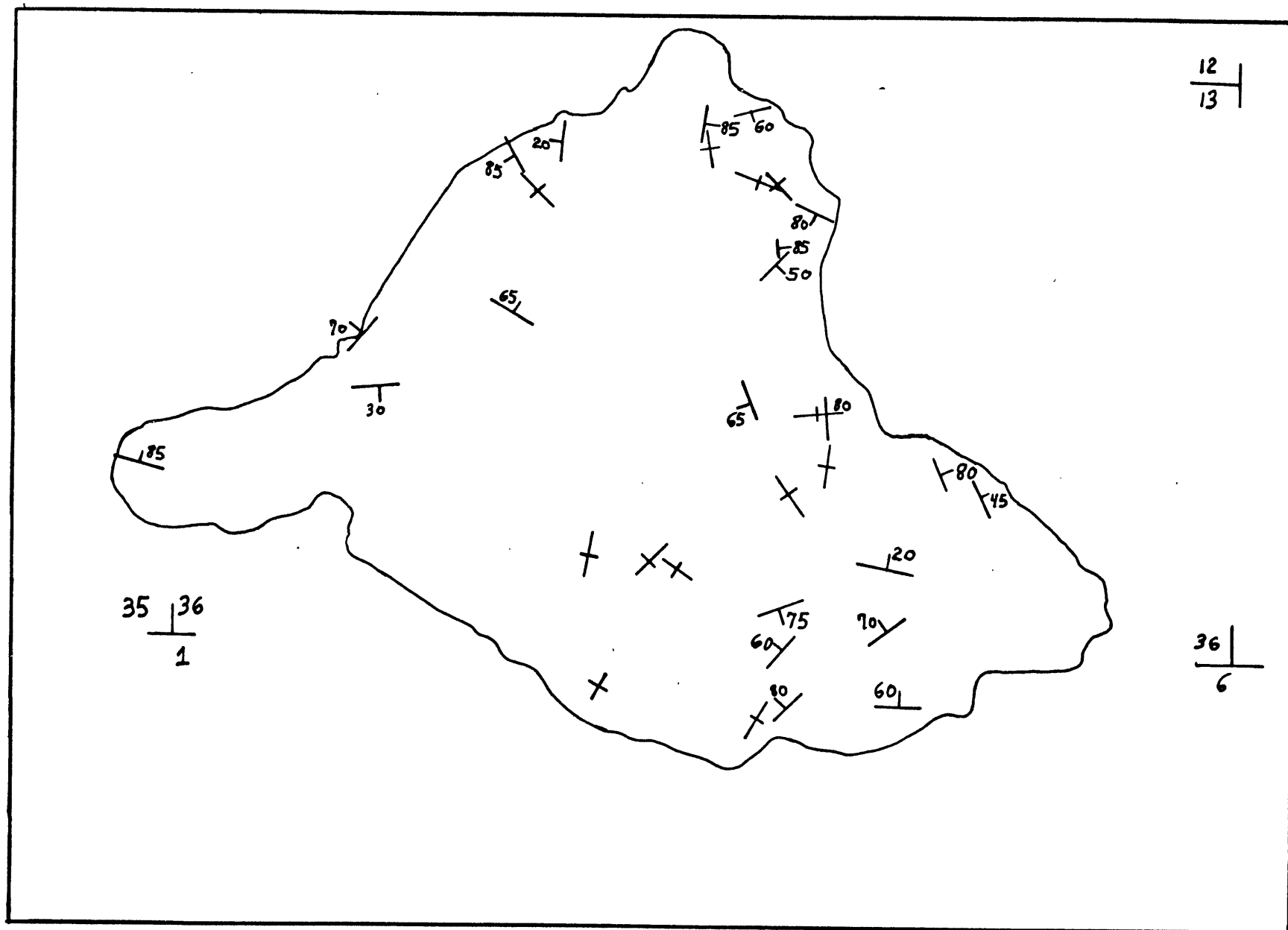


Figure 4a

Figure 4b: Attitudes of pegmatites and aplites, Eagle Peak pluton.

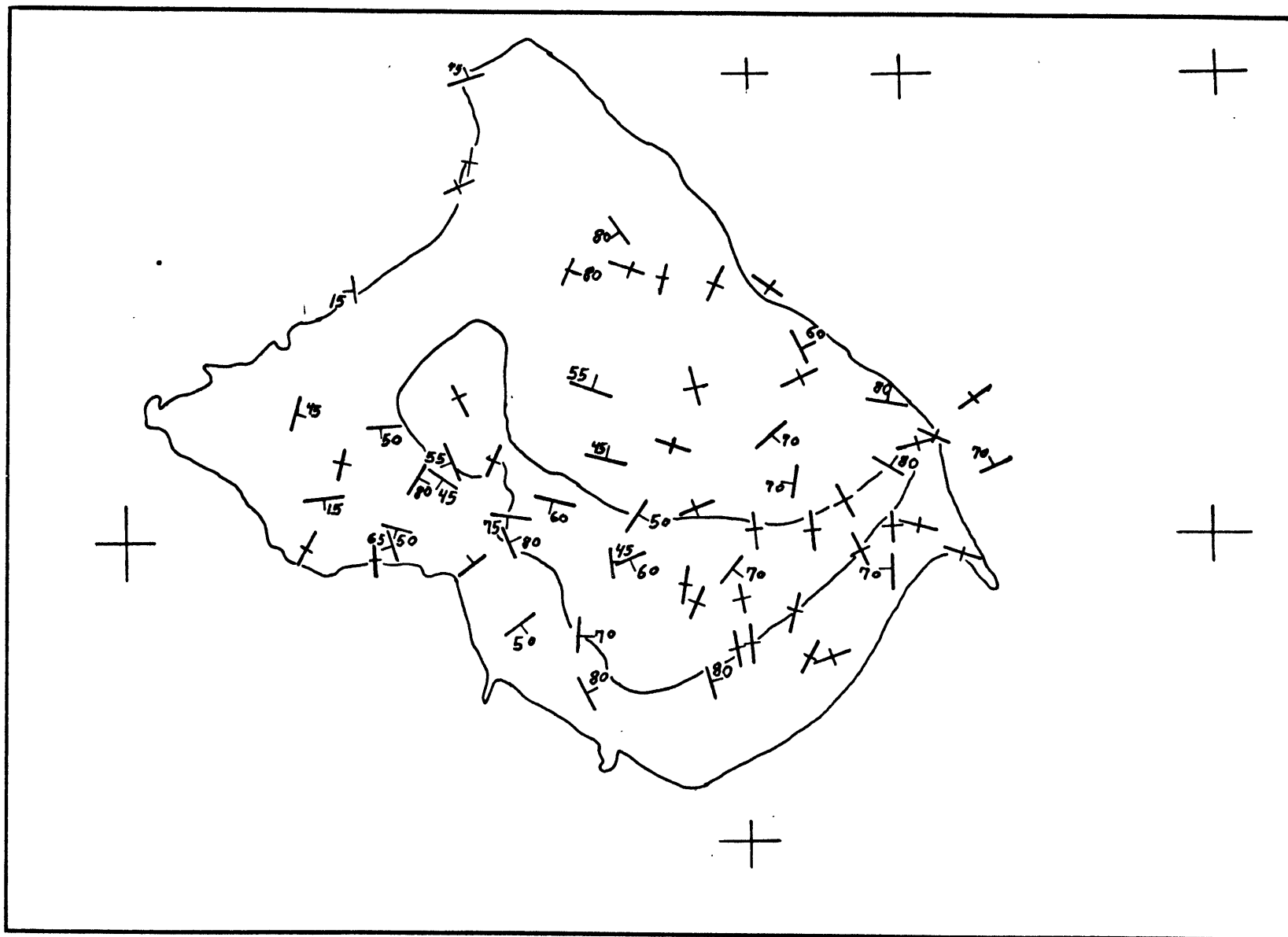


Figure 4b

Figure 5a: Relative abundances of pegmatites and aplites, Red Lake pluton. Numbers refer to total aplite and pegmatite width at each outcrop.

Figure 5b: Relative abundances of pegmatites and aplites, Eagle Peak pluton. Numbers refer to total aplite and pegmatite width at each outcrop.

much earlier by Pabst (1928). They are triaxial ellipsoids composed dominantly of plagioclase, biotite, and hornblende, with sphene, quartz, magnetite, alkali feldspar, and other minor constituents as accessories. Maximum dimensions range from 1 cm to about 1 meter. Elongation varies widely. Inclusion abundance varies widely between outcrops, but only rarely do inclusions cover more than one per cent of an outcrop.

Bateman and others (1963) have noted several relationships between mafic inclusions and their host rocks: mafic inclusions tend to decrease in abundance toward the interiors of plutons, commonly accompany hornblende in the host rock, but are absent in hornblende-free host rocks. These relationships are not valid for the Red Lake and the Eagle Peak plutons. Mafic inclusions are irregularly distributed in both plutons, their abundance does not decrease inwardly, and numerous outcrops contained mafic inclusions in hornblende-free host rocks.

The abundance and distribution of mafic inclusions are similar in both plutons. Several dense concentrations of inclusions occur in the Eagle Peak pluton. These dense concentrations of inclusions are similar to the inclusion dikes described by Link (1969).

Mafic schlieren, local bands of mafic enriched granodiorite, are common in the plutons. They are curvilinear with a well defined foliation and may extend for tens of meters. Their width ranges up to several meters, and contacts with surrounding granodiorite are gradational, not intrusive. Mafic minerals occupy up to 30% of the schlieren in contrast to the 10% found in the granodiorite.

PETROGRAPHY

Red Lake Pluton

Plagioclase: Plagioclase occurs as subhedral to euhedral grains with abundant albite twinning and minor Carlsbad and Pericline twins. Individual grains show strong concentric normal zoning with thin bands of oscillatory zoning. Inclusions of hornblende and biotite are common. Quartz is partially surrounded by the marginal albite rich zones of some plagioclase grains. Very weak sericitic alteration with trace epidote and carbonate are present in plagioclase in most thin sections.

Alkali feldspar: Alkali feldspar forms anhedral, anastomosing, optically continuous masses interstitial to plagioclase, quartz, hornblende, opaques, and sphene. It is colorless and shows slight pervasive kaolinitic alteration. Microcline twinning is patchy in development. Exsolution is minor to absent and when present the lamellae are too thin to identify the plagioclase compositions. Inclusions of all other primary minerals are present in alkali feldspar.

Myrmekite: Myrmekite is a common minor accessory, commonly developed at plagioclase-alkali feldspar interfaces, but neither restricted to or ubiquitous at these sites. The intergrowth usually occurs within the plagioclase near the margins of strongly zoned grains.

Quartz: Quartz is present as anhedral, irregular grains, as equant grains, and rarely as hexagonal inclusions in alkali feldspar. The grains are colorless and they commonly show undulose extinction. Anhedral grains partially surround plagioclase, hornblende, and biotite; quartz apparently crystallized after these minerals. Boundaries between quartz and alkali feldspar are irregular, but hexagonal

inclusions of quartz in alkali feldspar indicate quartz crystallized earlier than alkali feldspar.

Hornblende: Hornblende forms prismatic needles with minor simple twinning. Pleochroism is dark brown-yellow green-dark green. Extinction is abrupt, not undulose. With the exception of distinct altered areas and simple twinning, grains are optically homogeneous. Some grains show well-formed cross sections, others have corroded margins. Minor marginal chloritic alteration is found on some grains. Minor inclusions of opaque, sphene, apatite, and rarely biotite are present in variable amounts. Intergrowths of biotite-hornblende-sphene-opaque-chlorite indicate that some of the inclusions may be reaction products. The abundance and grain size varies irregularly in outcrop and in thin sections.

Biotite: Biotite forms equant or elongate plates and less commonly euhedral books. It is strongly pleochroic, dark brown to light yellow brown. Minor inclusions of apatite, opaques, and zircon are present in some grains and pleochroic haloes are commonly developed around zircon. Inclusions of plagioclase are rarely found. Along cleavage planes chlorite and granular sphene are common alteration products. Hornblende is partially included by biotite in some grains, although the reverse relationship is also found. Irregular grain margins are common.

Sphene: Yellow bronze sphene is present in euhedral wedges and anhedral granular masses. Wedges are most common as isolated grains but they also occur as partial inclusions in biotite. Plagioclase inclusions are found in some well-formed grains. Granular sphene is best developed along the interface between biotite and the associated

chloritic alteration. Inclusions of opaques are present in both varieties.

Magnetite: Opaques are present as equant grains included in biotite, hornblende, and sphene, and also as isolated grains. Examination in reflected light indicates that magnetite is the sole phase.

Chlorite: Chlorite is pleochroic green and it is a pennine variety. It most commonly develops as an alteration product along cleavage planes in biotite. Approximately 10-15% of the biotite has been replaced by chlorite.

Allanite: Allanite, subhedral to anhedral, is pleochroic from dark red brown to light brown with common oscillatory zoning and exhibits rare simple twinning. The margins are generally lighter in color than the cores. Rarely grains are partially rimmed by sphene or epidote. Allanite occurs as inclusions near the margins of biotites and as isolated grains. When included in biotite it is surrounded by a pleochroic halo. The form and intergrowth with biotite strongly suggest that allanite began crystallization before crystallization of biotite was complete.

Apatite: Apatite forms colorless stubby needles. It is most abundant as inclusions in biotite; also, isolated grains are included in feldspars and quartz. Local concentrations of apatite are present near margins of biotite and opaques.

Zircon: Zircon forms elongate, subhedral, colorless inclusions in biotite and it is accompanied by pleochroic haloes.

Kaolinite, sericite, epidote, carbonate: These minerals are weakly developed throughout most of the pluton. Kaolinite is

restricted to alkali feldspar. Sericite is the most common alteration product of plagioclase. Some plagioclase samples show alteration of cores to epidote and carbonate. Carbonate is also found as minor, localized, interstitial masses. Carbonate and epidote are not found in all samples.

Bear Butte Facies of the Red Lake Pluton

The major petrographic distinction between the Bear Butte facies and the equigranular facies is the development of different alteration assemblages. In the Bear Butte facies alkali feldspar shows moderate kaolinitic alteration in contrast to its slight alteration in the equigranular facies. Plagioclase shows the most extensive alteration, with nearly complete replacement of cores by sericite. Intergrowths in the more altered grains suggest minor replacement of plagioclase by quartz. Carbonate and epidote are also commonly present in the altered cores.

Mafic minerals are minor constituents of the Bear Butte facies. For example, hornblende is absent and only trace amounts of biotite, almost all altered to chlorite, are present. Cleavage plane intergrowths of sericite and chlorite are common in altered biotite grains. Also, opaques are only present in trace amounts. Sphene, commonly found in chloritically altered biotite in other parts of the pluton, is nearly absent.

Eagle Peak Pluton

Petrographic examination reveals both zones of the Eagle Peak pluton are mineralogically similar. Plagioclase, alkali feldspar, quartz, and biotite are the major constituents. Hornblende, sphene,

apatite, zircon, opaques, and allanite are accessories. Sericite, kaolinite, chlorite, and carbonate are alteration minerals. The detailed petrography and mineral paragenesis of the outer zone are nearly identical to that of the Red Lake pluton. The major differences are modal abundances and distribution of hornblende (Table 13a, 13b). Hornblende is more abundant in the Eagle Park pluton and its distribution is less erratic than in the Red Lake pluton.

Subhedral alkali feldspar phenocrysts (2 to 4 cm long) mark the petrographically distinct core facies of the Eagle Peak pluton. These phenocrysts are surrounded by a groundmass identical in mineralogy, texture, and grain size to the outer zone. Their margins are diffuse with thin projections of optically continuous alkali feldspar anastomosing into the groundmass. Inclusions of all other primary minerals within the alkali feldspar from both Eagle Peak zones imply late crystallization of alkali feldspar. Microcline twinning, Carlsbad twinning, and exsolution are locally developed. Faint, concentric variations in extinction suggest relict zoning. Kaolinitic alteration is pervasive but affects only a small proportion of the feldspar.

Textural variant E83 has alkali feldspar phenocrysts surrounded by a groundmass that is finer grained (1/2 to 1 mm) than that of the remainder of the pluton. Mineralogy and paragenesis are identical to other parts of the pluton, except that sphene and hornblende are absent. Trace amounts of unzoned allanite are found as isolated grains. Some mineral grains are equivalent in size to their counterparts in the remainder of the pluton. This results in subphenocrysts of euhedral plagioclase and anhedral quartz. Alkali feldspar, larger

in size than plagioclase and quartz, occurs as distinct well-formed subhedral phenocrysts. The anastomosing margins present in phenocrysts from the rest of the core are absent. Grain size, inclusions, twinning, alteration, and exsolution are similar to their development in other parts of the core. Zoning is present only in the distribution of inclusions: a band of small, anhedral, equant quartz grains is concentrated around the periphery of alkali feldspar phenocrysts.

Aplites

The aplites consist of many of the same minerals as the granitic rocks, have an average grain size of 1 mm, and hornblende is absent in all samples. Grains are generally anhedral and produce the aplitic texture. Some plagioclase grains are subhedral, albite twinned, and normally zoned. Inclusions of other minerals are rare. Alkali feldspar is anhedral to anastomosing, with rare subhedral groups. Grains contain inclusions of all other minerals, show abundant microcline grid twinning, and are not exsolved. Kaolinitic alteration is more common in aplitic plagioclase and alkali feldspar than in the granitic rocks. Biotite is present in very limited amounts; most has been altered to chlorite and sphene. Sphene is found as isolated grains and as inclusions in plagioclase. Epidote and sericite are minor alteration products of plagioclase. Opaques are rare, anhedral, and usually associated with altered biotite. Allanite is present in samples C3 and CR14, but it is not present in sample C10. Some quartz partially surrounds plagioclase and is usually anhedral.

Mineral Paragenesis

Mineral paragenesis is identical for both plutons and is summarized in Figure 6. Textural relations indicate alkali feldspar formed after plagioclase, quartz, biotite, hornblende, sphene, opaque, and allanite. Hornblende and biotite appeared early, possibly before and during crystallization of plagioclase. Most of the quartz formed after all the preceding minerals except alkali feldspar. Sphene is dominantly late stage, forming after all major minerals. Allanite formed before alkali feldspar and possibly partially overlapped in crystallization with biotite. Minor inclusions of opaques in plagioclase indicate that not all opaques are deuteric. In addition, inclusions of opaques, apatite, and zircon in biotite and minor euhedral grains of apatite and sphene disseminated throughout the granitic rocks suggests these minerals began crystallization on the liquidus. Sphene, chlorite, epidote, sericite, kaolinite, carbonate, and some opaques formed as late-stage alteration products of the pre-existing minerals.

Aplite paragenesis is similar to that of the granitic rock. Plagioclase and biotite are earliest, followed by allanite, quartz, and alkali feldspar, in that order, with deuteric alteration forming the kaolinite, sericite, epidote, sphene, and chlorite.

MINERAL CHEMISTRY

Alkali Feldspar

An unsuccessful attempt was made to determine alkali feldspar compositions using the $\bar{2}01$ position on homogenized specimens according to the method of Wright (1968). Heating fine grained powders of alkali feldspar at 850°C. , 1 atmosphere, for 10 days failed to sanidinize the feldspars. All compositions were therefore determined by electron microprobe using a beam diameter ranging from five to fifty microns. The

Figure 6: Mineral paragenesis in the Red Lake and the Eagle Peak
plutons: approximate sequence of crystallization.

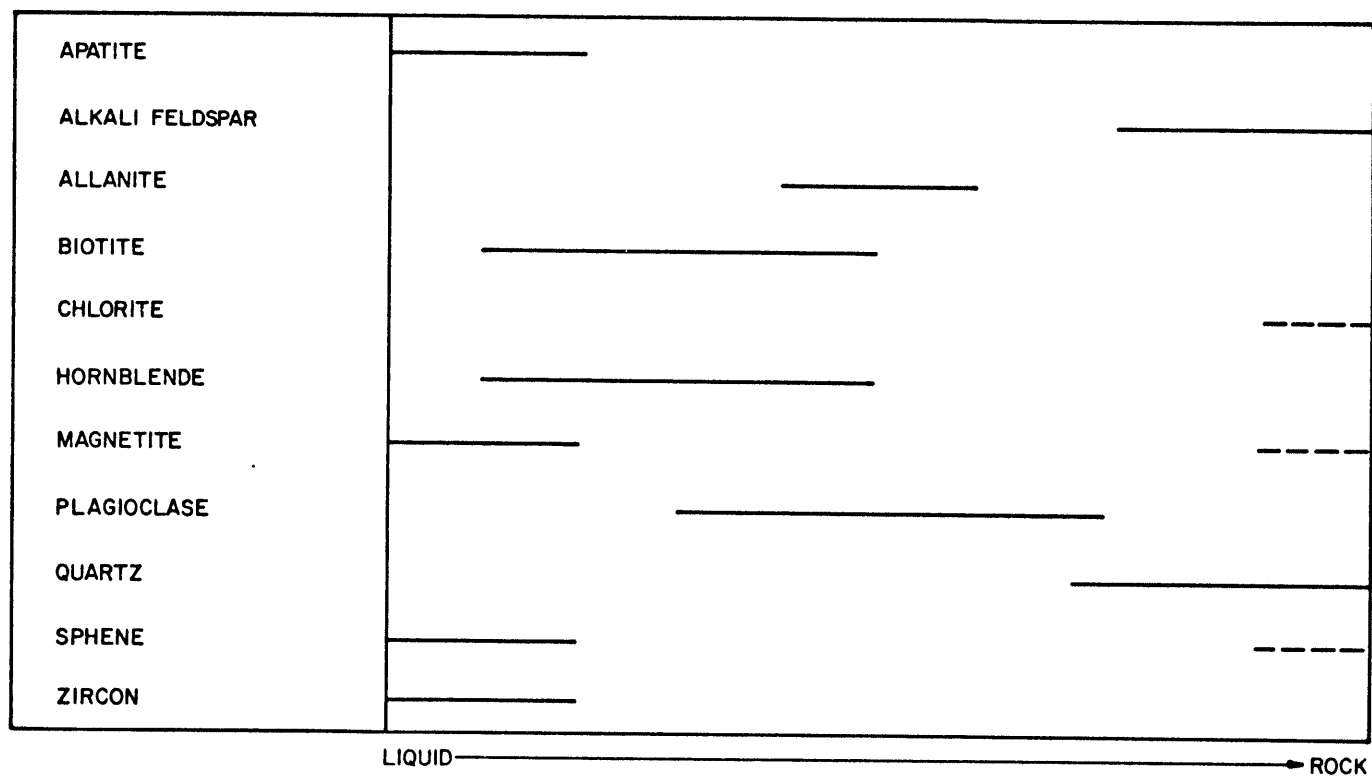


Figure 6

rather minor amount of exsolution suggests this approach is adequate. In addition, alkali feldspar compositions determined with this method agree quite well with those obtained by instrumental neutron activation analysis on bulk feldspar separates.

Alkali feldspar structural state was determined using the three peak method of Wright (1968). This requires measuring the 2θ position of the $\bar{2}01$, 060, and $\bar{2}04$ diffraction peaks and relating these peak positions to the $2\theta(060)-2\theta(\bar{2}04)$ plot of Wright and Stewart (1968) for feldspars of known structural state. Because two peaks were present between 50° and $51^\circ 2\theta$, an unambiguous selection of $\bar{2}04$ was made following the instructions of Wright (1968) and required measurement of 2θ ($\bar{1}13$) and 2θ (002). Table 4 lists the 2θ positions of 060, $\bar{2}01$, and $\bar{2}04$. These data are used to characterize the feldspars in Figure 7. Also listed in Table 4 is the difference between the measured $\bar{2}01$ position and that interpolated from Figure 7 based on the positions of 060 and $\bar{2}04$. Wright (1968) classifies as anomalous those feldspars for which this parameter exceeds $0.1^\circ 2\theta$. The alkali feldspars from these plutons are sanidine or orthoclase with anomalous cell dimensions. The degree of anomalous character does not appear related to rock type for these specimens. The most likely cause of anomalous cell dimensions for these feldspars is strain between perthite components (Smith, 1974; 1976). This effect is greatest in the initial stages of exsolution and decreases as the perthite coarsens. All specimens in Table 4 are exsolved, although only slightly. Albite is identified in the X-ray patterns as the exsolved phase in all samples. No correlation was found between the extent of exsolution as seen in thin section and

TABLE 4

X-ray reflections* and anomalous indices of potassium feldspars

Reflection	Red Lake Pluton Eagle Peak Pluton					
	Equigranular facies		Equigranular margin		Porphyritic core	
	CR29	CR5	E92	E91	C1	E83
$\bar{2}01$	21.05	21.05	21.03	21.05	21.05	21.07
060	41.76	41.75	41.75	41.76	41.77	41.74
$\bar{2}04$	50.69	50.67	50.65	50.66	50.69	50.70
$\bar{2}01_o - \bar{2}01_p^{**}$	0.22	0.17	0.12	0.16	0.23	0.18

* CuK α radiation** Difference between observed (o) $\bar{2}01$ position and that predicted (p) using the methods of Wright and Stewart (1968)

Figure 7: Alkali feldspar structural state determined from X-ray diffraction data. Diagram after Wright (1968).

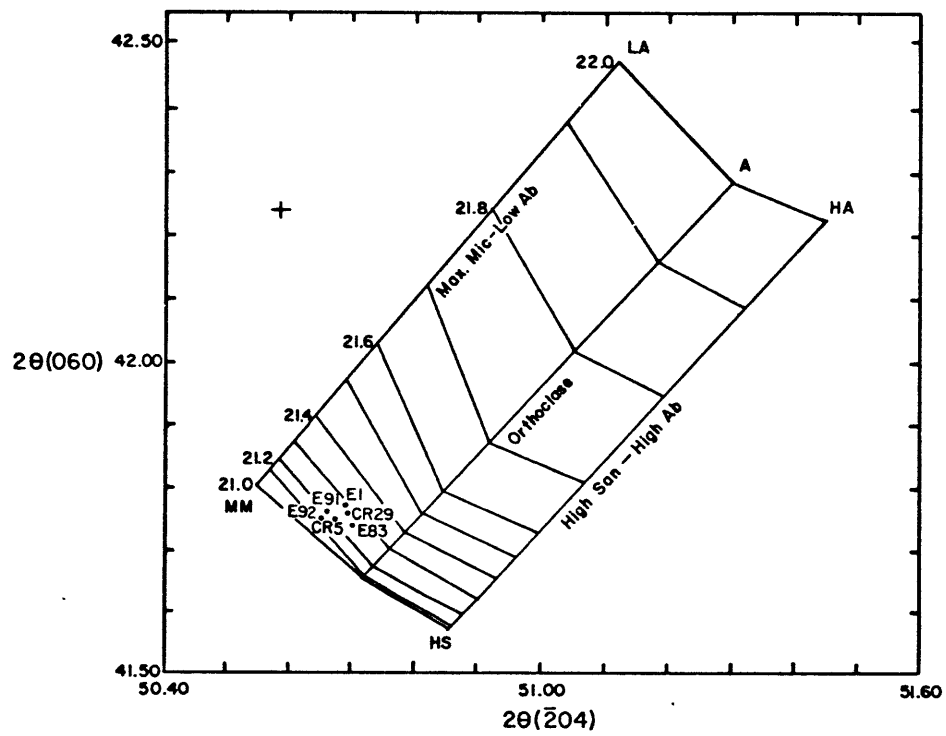


Figure 7

the relative magnitude of the $\bar{201}$ anomaly. Although such correlation would support strain reduced anomalous character, the lack of correlation does not eliminate this hypothesis.

The single peak identified between 29° and 30° 2θ (Cu K α radiation) corresponds to the orthoclase 131 peak and indicates a monoclinic feldspar (Tilling, 1968; Parsons and Boyd, 1971), and is consistent with the near-absence of grid twinning in these feldspars. Thus, the feldspars of this study are all monoclinic, slightly anomalous, microperthitic, and have an apparent intermediate structural state.

Alkali feldspar compositions determined by electron microprobe are given in Table 5. Each analysis represents the average of ten or more determinations from at least two grains in a single microprobe section. A maximum of 5 mole per cent variation in Or content was observed in any one section. No distinct zoning was noted. This contrasts with the determinations on Sierran alkali feldspars by Piwinski (1968a), who found margins slightly richer in Or content than interiors.

Alkali feldspar compositions for the granitic rocks range from Or_{87.1} to Or_{91.3}, similar to that found by Piwinski (1968a). Feldspars in the aplites from both plutons are more Or rich than granitic feldspars.

Modal and chemical data, presented later, support a differentiation trend within the Red Lake pluton of CR29-CR5-CR14 (aplite). Alkali feldspars from those samples become richer in Or content in the same sequence. Sample CR1 from the Bear Butte facies has a composition similar to that of CR29 and CR5, in spite of the extensive alteration

TABLE 5

Potassium feldspar analyses* by electron microprobe

Sample number and rock type		Or	Ab	An
<u>Red Lake Pluton</u>				
CR29	Equigranular facies	87.6	12.0	0.4
CR5	Equigranular facies	91.3	8.5	0.2
CR1	Bear Butte facies	90.8	9.0	0.2
CR14	Aplite dike	93.6	6.2	0.2
<u>Eagle Peak Pluton</u>				
E92	Equigranular margin	88.7	11.0	0.3
E91	Equigranular margin	88.2	11.4	0.4
C1	Porphyritic core	88.2	11.5	0.3
E83	Porphyritic core	87.1	12.6	0.3
C3	Aplite dike	90.1	9.7	0.2

*Feldspar components in mole percent

in that rock. The alkali feldspar of the Eagle Peak pluton rocks are all similar in composition in spite of the much greater variation in their host rock composition.

The compositional trend noted for the feldspars of the Red Lake pluton and for the relationship of the aplite feldspar to the granitic feldspars of the Eagle Peak pluton are not those generally observed for feldspars coexisting with plagioclase in a cooling liquid. Experimental studies by Seck (1971) and Yoder, Stewart, and Smith (1956) indicate albite content increases in both alkali feldspar and plagioclase during cooling. However, textural relations indicate alkali feldspar is the last major phase to form from what must be a potash enriched residual liquid. Thus, a disequilibrium relationship may exist in which the feldspars are not completely in equilibrium with one another. The alkali feldspar is precipitating from a potassic liquid which through differentiation becomes even more potassic and finally produces aplites and pegmatite dikes. During this stage the Or activity of the melt apparently increases and allows formation of more Or rich alkali feldspars.

Plagioclase

Plagioclase analyses obtained by electron microprobe are given in Table 6. Each analysis is the average of three or more determinations from two or more grains in a single microprobe section.

The microprobe analyses confirm that plagioclase of the granitic rocks is strongly zoned and plagioclase of the aplites is only weakly zoned. All analyzed plagioclases have a more albite rich margin.

Piwinskii (1968a) observed similar compositions and zoning in other

TABLE 6

Plagioclase analyses* by electron microprobe

Sample number and rock type		Core			Rim		
		An	Ab	Or	An	Ab	Or
<u>Red Lake Pluton</u>							
CR29	Equigranular facies	50.5	48.2	1.3	17.5	80.9	1.6
CR5	Equigranular facies	47.8	51.1	1.1	13.9	84.1	2.0
CR1	Bear Butte facies	8.7	90.2	1.1	1.0	98.0	1.0
CR14	Aplite dike	15.1	83.8	1.1	8.4	91.0	0.6
<u>Eagle Peak Pluton</u>							
E92	Equigranular margin	44.5	54.6	0.9	21.6	77.5	0.9
E91	Equigranular margin	42.4	56.6	1.0	24.4	74.1	1.5
C1	Porphyritic core	39.6	59.4	1.0	18.7	80.0	1.3
E83	Porphyritic core	38.8	60.3	0.9	18.0	80.1	1.9
C3	Aplite dike	20.6	78.7	0.7	11.7	87.8	0.5

*Feldspar components in mole percent

Sierran granitic rocks.

In the granitic rocks, plagioclase core compositions from the Eagle Peak pluton are somewhat more albitic than those of the Red Lake pluton, whereas the reverse is true for the rim compositions. In the Eagle Peak pluton, the albite content increases for both cores and rims of plagioclase in the sequence: equigranular exterior--porphyritic core--aplite dikes. A similar trend is present for the Red Lake pluton in the sequence CR29--CR5--aplite dike. Although granitic plagioclases from the Red Lake pluton are more albite rich than those of the Eagle Peak pluton and aplitic plagioclases are the most albitic in both plutons, aplitic plagioclase of C3 is less albitic than that of CR14. There appears to be no overlap in plagioclase composition between aplites and the granitic rocks.

Plagioclase rims have higher Or contents than the cores of grains from granitic rock while the opposite relationship is found in the aplitic plagioclases. In addition, aplite plagioclases have lower rim Or contents than do granitic plagioclases.

Plagioclases from the Bear Butte facies of the Red Lake pluton are the most albitic analyzed in this study.

Biotite

Biotite analyses obtained by electron microprobe are given in Table 7. Averages for each rock are given in Table 8 with accompanying structural formulas. Determination and assignment of ferrous/ferric contents was discussed earlier.

The biotite compositions are similar to those obtained by Dodge, Smith, and Mays (1969) for a larger number of Sierran granitic rocks.

TABLE 7

Electron microprobe analyses of biotites^a

Red Lake pluton						
Equigranular facies						
	CR29-6	CR29-4	CR29-2	CR29-5	CR29-1N	CR29-1S
SiO ₂	36.67 $\pm$ 0.41	36.54	35.79	36.97	36.65	37.01
Al ₂ O ₃ ^b	14.05 $\pm$ 0.19	14.33	14.49	13.95	14.06	14.03
Fe ₂ O ₃ ^b	4.47	4.47	4.55	4.42	4.40	4.27
FeO ^b	17.40 $\pm$ 0.12	17.41	17.71	17.23	17.13	16.65
MgO	10.62 $\pm$ 0.18	10.91	10.19	10.73	10.65	10.75
MnO	0.40 $\pm$ 0.04	0.42	0.39	0.46	0.42	0.49
TiO ₂	3.16 $\pm$ 0.12	2.65	3.23	3.23	2.99	2.46
CaO	0.0	0.0	0.0	0.0	0.0	0.0
Na ₂ O	0.08 $\pm$ 0.03	0.13	0.13	0.10	0.08	0.13
K ₂ O	9.40 $\pm$ 0.12	9.36	9.64	9.39	9.54	9.25
Total	96.25	96.22	96.12	96.48	95.92	95.04
N ^c	7	5	3	2	4	1

TABLE 7, continued

Electron microprobe analyses of biotites^a

Red Lake pluton						
Equigranular facies						
	CR5-6	CR5-2S	CR5-3	CR5-5	CR5-2M	CR5-4
SiO ₂	36.98	36.28	36.68	36.50	36.24	36.63
Al ₂ O ₃ ^b	14.82	14.81	13.94	14.70	14.32	14.35
Fe ₂ O ₃ ^b	4.66	4.62	4.66	4.59	4.56	4.64
FeO ^b	18.15	18.00	18.14	17.89	17.78	18.08
MgO	9.70	9.61	9.51	9.43	9.66	9.28
MnO	0.47	0.47	0.45	0.48	0.42	0.48
TiO ₂	2.75	3.07	3.25	3.00	2.90	2.88
CaO	0.0	0.01	0.0	0.0	0.0	0.0
Na ₂ O	0.11	0.07	0.08	0.12	0.14	0.11
K ₂ O	8.98	9.18	9.44	9.36	9.04	9.74
Total	96.62	96.12	96.14	96.07	95.06	96.19
N ^c	5	4	3	3	2	2

TABLE 7, continued

Electron microprobe analyses of biotites^a

Eagle Peak pluton									
Equigranular margin									
	E92-1	E92-6	E92-7	E92-5N	E92-5S	E92-24	E91-4	E91-3	E91-7
SiO ₂	36.46	36.82	36.56	36.74	36.68	37.11	36.20	36.64	36.45
Al ₂ O ₃ ^b	14.69	14.50	14.50	14.68	14.47	15.17	14.48	14.48	14.40
Fe ₂ O ₃ ^b	5.57	5.47	5.57	5.41	5.37	5.28	5.69	5.64	5.76
FeO ^b	16.70	17.01	17.31	16.82	16.70	16.43	17.68	17.53	17.92
MgO	10.06	10.45	9.60	9.90	9.82	10.41	9.16	9.59	9.02
MnO	0.46	0.48	0.46	0.42	0.47	0.52	0.55	0.54	0.59
TiO ₂	2.66	2.10	3.04	3.07	3.10	2.35	3.14	2.62	3.42
CaO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01
Na ₂ O	0.26	0.15	0.15	0.17	0.14	0.17	0.09	0.09	0.11
K ₂ O	9.10	9.26	9.40	9.60	9.55	9.53	9.40	9.34	9.09
Total	95.76	96.24	96.59	96.81	96.30	96.97	96.39	96.48	96.77
N ^c	4	4	3	3	5	3	5	5	5

TABLE 7, continued

Electron microprobe analyses of biotites^a

Eagle Peak pluton									
Porphyritic core									
	C1-5S	C1-1	C1-2	E83-1	E83-2	E83-6	E83-5S	E83-5N	E83-4
SiO ₂	36.98	36.98	36.79	36.94	37.10	36.67	36.99	36.90	37.46
Al ₂ O ₃ ^b	14.48	14.61	14.43	14.20	14.56	14.39	14.67	14.76	14.64
Fe ₂ O ₃ ^b	5.52	5.51	5.57	5.31	5.16	5.24	5.26	5.28	5.11
FeO ^b	17.18	17.15	17.33	16.53	16.05	16.30	16.37	16.42	15.88
MgO	9.81	9.44	9.50	10.59	10.61	10.48	10.55	10.18	10.56
MnO	0.54	0.58	0.52	0.51	0.43	0.54	0.49	0.50	0.37
TiO ₂	2.73	3.24	3.03	2.62	2.59	2.72	2.75	2.70	2.56
CaO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Na ₂ O	0.13	0.11	0.09	0.10	0.13	0.08	0.14	0.12	0.14
K ₂ O	9.52	9.34	9.23	9.29	9.56	9.69	9.62	9.59	9.60
Total	96.89	96.96	96.49	96.09	96.19	96.11	96.84	96.45	96.32
N ^c	5	4	5	6	7	5	6	2	3

^aStandard deviation calculated from seven analyses of CR29-6^bSee text for distribution of ferrous and ferric iron^cN=number of analyses

All analyses in weight percent.

TABLE 8

Averaged biotite electron microprobe analyses and ions per 23 oxygen atoms*

	Red Lake Pluton		Eagle Peak Pluton			
	Equigranular facies		Equigranular margin		Porphyritic core	
	CR29	CR5	E92	E91	C1	E83
SiO ₂	36.56 $\pm$ 0.44	36.59	36.72 $\pm$ 0.23	36.43	36.91	36.99
Al ₂ O ₃	14.17 $\pm$ 0.21	14.56	14.64 $\pm$ 0.27	14.45	14.50	14.50
Fe ₂ O ₃ **	4.46 $\pm$ 0.10	4.62	5.41 $\pm$ 0.10	5.69	5.53	5.23
FeO*	17.35 $\pm$ 0.37	18.03	16.82 $\pm$ 0.30	17.71	17.22	16.27
MgO	10.65 $\pm$ 0.24	9.56	10.04 $\pm$ 0.34	9.26	9.59	10.54
MnO	0.42 $\pm$ 0.04	0.46	0.47 $\pm$ 0.03	0.56	0.54	0.48
TiO ₂	3.00 $\pm$ 0.33	2.96	2.72 $\pm$ 0.42	3.06	2.98	2.66
CaO	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.10 $\pm$ 0.03	0.10	0.17 $\pm$ 0.04	0.10	0.11	0.12
K ₂ O	9.44 $\pm$ 0.14	9.24	9.40 $\pm$ 0.19	9.28	9.36	9.55
Total	96.15	96.12	96.39	96.54	96.74	96.34

TABLE 8, continued

Averaged biotite electron microprobe analyses and ions per 23 oxygen atoms

	Red Lake Pluton		Eagle Peak Pluton			
	Equigranular facies		Equigranular margin		Porphyritic core	
	CR29	CR5	E92	E91	C1	E83
Si	5.563	5.579	5.568	5.544	5.585	5.595
Al	2.437	2.421	2.432	2.456	2.415	2.405
Σ (tet)	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.104	0.195	0.184	0.136	0.171	0.180
Fe ³⁺	0.511	0.530	0.617	0.652	0.630	0.595
Fe ²⁺	2.208	2.299	2.132	2.254	2.179	2.058
Mg	2.416	2.173	2.269	2.101	2.163	2.377
Mn	0.054	0.059	0.060	0.072	0.069	0.061
Ti	0.343	0.339	0.310	0.350	0.339	0.303
Σ (M ₁ -M ₂)	5.636	5.595	5.572	5.565	5.551	5.574
Ca	0.0	0.0	0.0	0.0	0.0	0.0
Na	0.030	0.030	0.050	0.030	0.032	0.035
K	1.832	1.797	1.818	1.802	1.806	1.843
Σ (A)	1.862	1.827	1.868	1.832	1.838	1.878
Fe/Fe+Mg	0.530	0.566	0.548	0.580	0.565	0.527

*Standard deviations calculated from six averaged analyses of CR29 and E92.

**Red Lake pluton values calculated assuming Fe⁺³/Fe⁺² = 0.2309; Eagle Peak pluton values calculated assuming Fe⁺³/Fe⁺² = 0.2894.

All analyses in weight percent.

These authors find the sum of F and H_2O^+ ranges between approximately 3 to 4 weight per cent, with F generally less than 0.5 weight per cent. These components were not measured in this study, but the totals listed are consistent with the results of Dodge, Smith, and Mays (1969). The inferred abundance of fluorine is not considered significant in subsequent discussions on biotite stability.

Biotites from all zones of both plutons are quite similar in composition, with MgO and FeO showing the greatest variation. Figure 8 demonstrates that these two components are inversely related, as may be expected for the major components in the octahedral sites of biotite. Most analyses from a given rock show only limited overlap with other samples from the same pluton. For the Red Lake pluton, sample CR5 contains more FeO total and less MgO than CR29. No distinct trend relating FeO-MgO and rock type or position in the pluton is noted for the Eagle Peak biotites. For example, equigranular sample E92 lies between porphyritic core samples E83 and C1 on Figure 8.

Mossbauer studies indicate sample C1 has a greater $\text{Fe}^{+3}/\text{Fe}^{+2}$ ratio than biotite CR5. Thus, sample C1 may represent a more oxidizing environment of formation than does CR5. It may be significant that sample C1 is porphyritic and CR5 is equigranular. Thus, although samples CR5 and C1 have different $\text{Fe}^{+3}/\text{Fe}^{+2}$ ratios they plot in similar fields on Figure 8.

Dodge, Smith, and Mays (1969) interpreted significant variations in $\text{Fe}^{+3}-\text{Fe}^{+2}-\text{MgO}$ for Sierran biotites as crystallization from a buffered system.

Figure 8: Biotite compositional diagram. MgO and FeO(total) concentrations in weight percent.

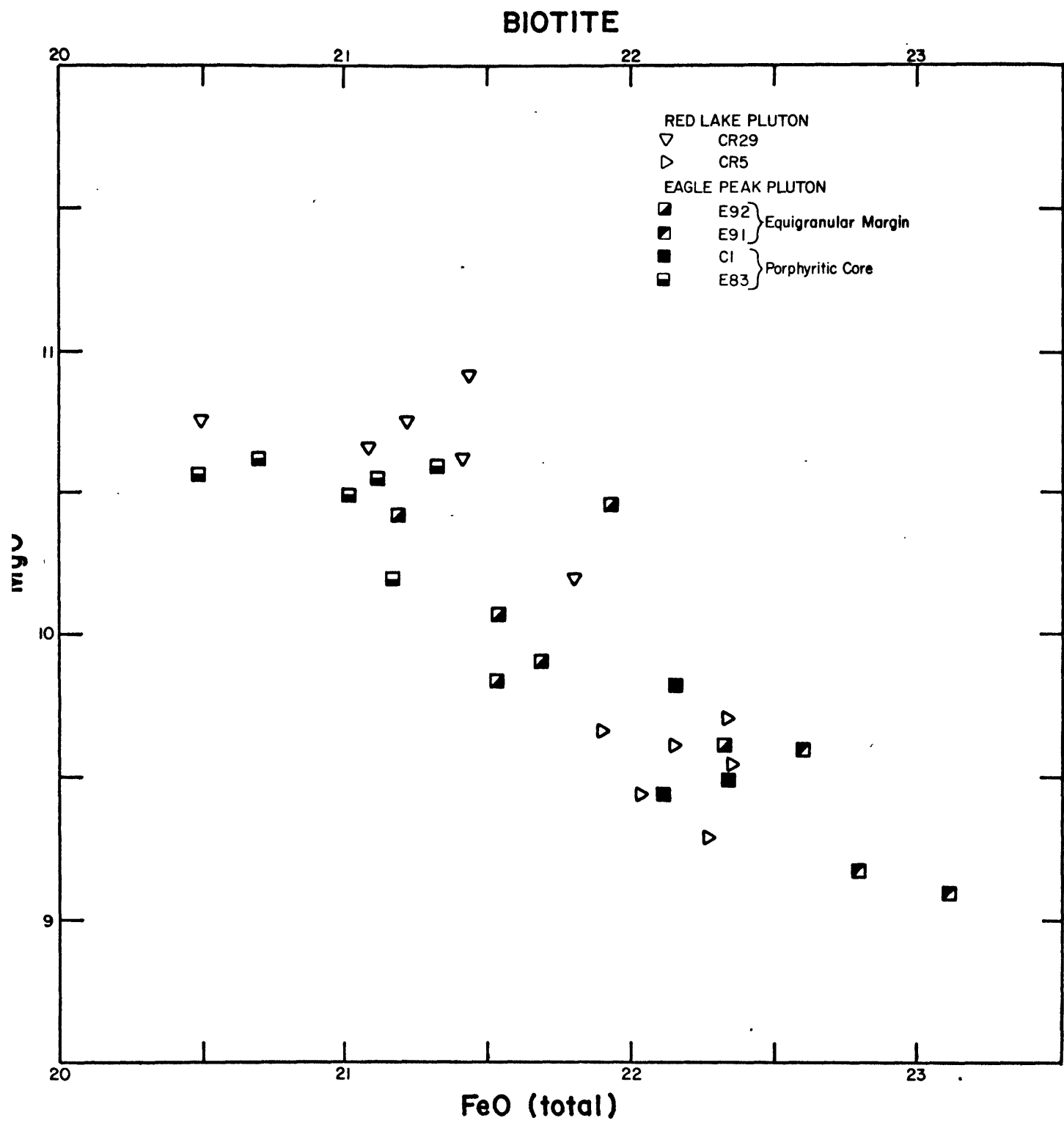


Figure 8

Chlorite

Chlorites, present as alteration products of biotite, were analyzed during analysis of biotite. Results are tabulated in Table 9. Wet chemical analyses of chlorite from Sierran granitic rocks by Dodge (1973) contain approximately 11 weight per cent water, indicating that the analyses in Table 9 have satisfactory totals, and that they are broadly similar to those reported by Dodge (1973). Minor differences among the analyses of Table 9 probably result from incomplete alteration of biotite. The most noticeable differences between coexisting biotite and chlorite are the greatly reduced TiO_2 and K_2O contents and smaller $\text{Fe}/\text{Fe}+\text{Mg}$ of the chlorites. The Fe-Mg relationships are shown in Figure 9. These are similar to the relationship found by Dodge (1973) for chlorite-biotite pairs from other Sierran granitic rocks. A large difference in $\text{Fe}/\text{Fe}+\text{Mg}$ of chlorites exists between samples from the Red Lake pluton and does not exist between the two Eagle Peak samples. A similar relationship is found in biotites from these samples.

Hornblende

Microprobe analyses and structural formulae of hornblendes for two samples of the Red Lake pluton and from four samples of the Eagle Peak pluton are presented in Table 10. The totals are satisfactory assuming the balance is composed of halogens and water, since all analyzed constituents fall within the range observed in Sierran hornblendes studied by Dodge, Papike, and Mays (1968).

Samples from the Eagle Peak pluton contain more Al_2O_3 and FeO and less SiO_2 and MgO than those of the Red Lake pluton. Exceptions

TABLE 9
Chlorite electron microprobe analyses and ions per 28 oxygen atoms

	Red Lake pluton		Eagle Peak pluton	
	CR29**	CR5	E92-4	E83-2
SiO ₂	25.96 $\pm$ 0.18	26.13	26.27	27.83
Al ₂ O ₃	20.08 $\pm$ 0.31	19.49	20.94	18.84
Fe ₂ O ₃ *	7.20	8.02	6.96	7.25
FeO*	19.04 $\pm$ 0.23	21.20	18.39	19.16
MgO	15.57 $\pm$ 0.56	13.41	15.72	13.37
MnO	0.74 $\pm$ 0.04	0.82	0.81	0.70
TiO ₂	0.06 $\pm$ 0.08	0.04	0.02	0.98
CaO	0.01 $\pm$ 0.02	0.00	0.00	0.77
Na ₂ O	0.02 $\pm$ 0.02	0.03	0.04	0.07
K ₂ O	0.05 $\pm$ 0.08	0.06	0.01	0.83
Total	88.73	89.20	89.16	89.80
Si	5.366	5.448	5.370	5.705
Al	2.634	2.552	2.630	2.295
$\Sigma(Z)$	8.000	8.000	8.000	8.000
Al	2.258	2.236	2.414	2.257
Fe ³⁺	1.120	1.258	1.070	1.118
Fe ²⁺	3.291	3.696	3.143	3.284
Mg	4.798	4.168	4.790	4.086
Ti ⁴⁺	0.001	0.006	0.003	0.151
Mn	0.130	0.145	0.140	0.121
Ca	0.002	0.000	0.000	0.169
Na	0.008	0.012	0.016	0.028
K	0.013	0.016	0.003	0.217
$\Sigma(Y)$	11.621	11.537	11.579	11.431
Fe/Fe+Mg	0.479	0.543	0.468	0.519
N***	6	6	1	1

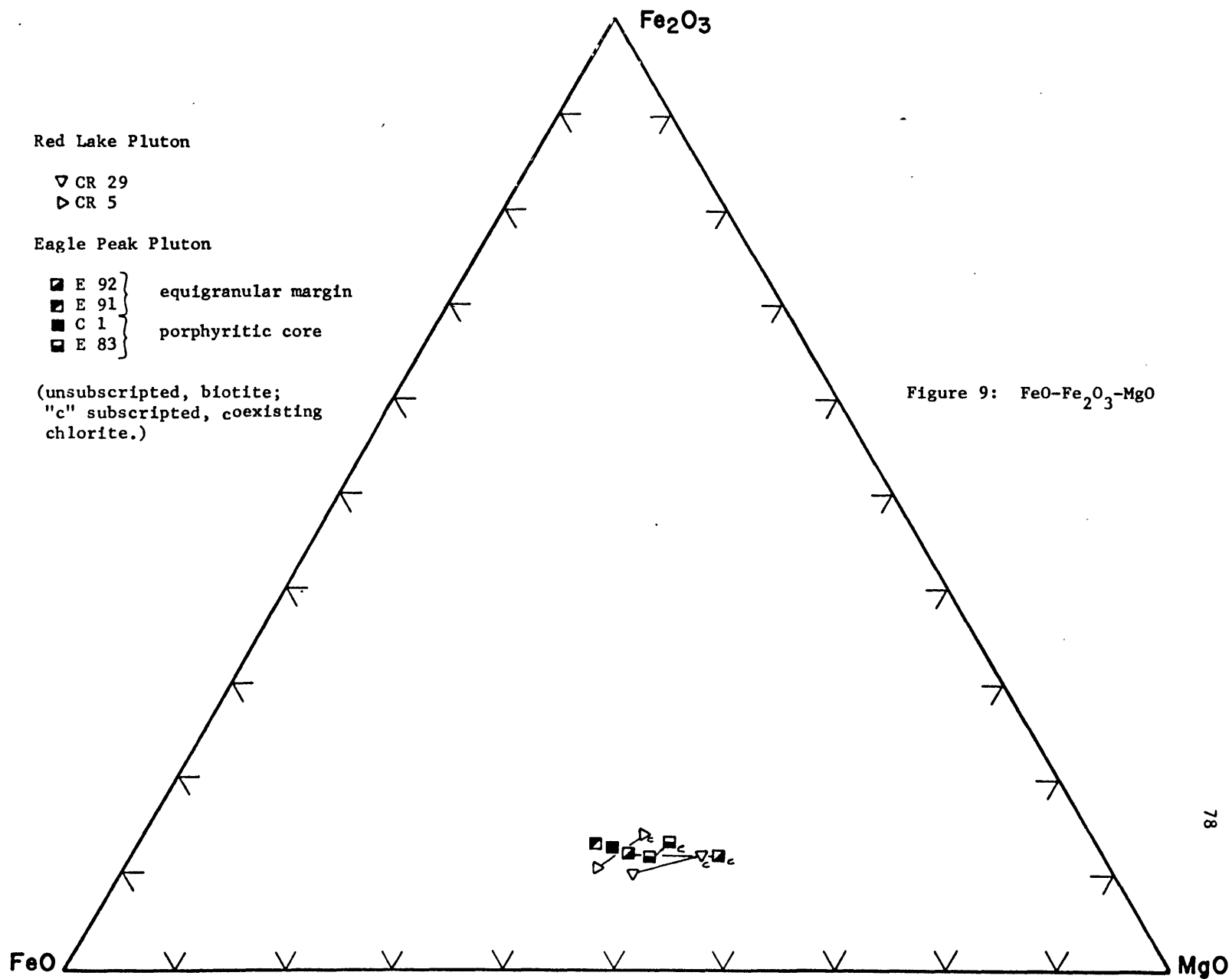
* See text for assignment of ferrous and ferric iron

** Standard deviation calculated from six analyses of CR29

*** N=number of analyses

All analyses in weight percent.

Figure 9: FeO-Fe₂O₃-MgO diagram showing relative compositions of coexisting biotite and chlorite. Oxide concentrations in weight percent.



to this generalization are samples E92 and CR29 which have similar FeO and MgO contents (Figure 10). No simple relationship exists between hornblende composition and sample location within the pluton for the Eagle Peak samples.

Most analyzed samples are compositionally uniform as indicated by the standard deviations for sample CR29. Sample E31 contains two compositional domains characterized by SiO_2 , Al_2O_3 , and MgO variations similar to those which distinguish the Red Lake and the Eagle Peak samples. Optical zoning was not observed in hornblende from sample E31. These compositional domains are similar to those observed by Czamanske and Wones (1973) and interpreted as local heterogeneous readjustments to changing magmatic conditions.

Lack of direct correlation between hornblende composition and location within the pluton agrees with the observation of Dodge, Papike, and Mays (1968) that hornblende composition is unrelated to host rock composition for Sierran plutons.

Magnetite

Electron microprobe analyses of magnetite, Table 11, indicate the oxides are essentially end-member Fe_3O_4 . No compositional domains or exsolution were observed, and no significant compositional variations are present between samples.

TABLE 10

Hornblende electron microprobe analyses and ions per 23 oxygen atoms

	Red Lake pluton		Eagle Peak pluton				
	Equigranular facies		Equigranular margin				P. Core
	CR29	CR38	E92	E97	E31-A	E31-B	E84
SiO ₂	44.99 ⁺ 1.10	46.88	44.82	44.46	44.80	43.45	44.13
Al ₂ O ₃	7.98 ± 0.77	7.34	9.05	8.64	8.25	9.00	9.06
Fe ₂ O ₃ *	4.60	4.00	4.53	5.33	4.94	5.51	5.15
FeO*	13.56 ± 0.87	11.77	13.34	15.70	14.56	16.22	15.17
MgO	11.18 ± 0.82	13.16	10.88	9.36	10.28	8.59	9.55
MnO	0.69 ± 0.06	0.65	0.61	0.66	0.70	0.91	0.78
TiO ₂	1.11 ± 0.09	1.06	1.09	1.04	1.26	1.15	1.14
CaO	11.26 ± 0.05	11.33	11.32	11.19	11.34	11.26	11.10
Na ₂ O	1.21 ± 0.11	1.21	1.09	1.28	1.06	1.08	1.26
K ₂ O	0.91 ± 0.12	0.78	0.94	0.95	1.00	1.14	1.06
Total	97.49	98.18	97.67	98.61	98.19	98.31	98.40
N***	5	4	5	5	6	6	7

* See text for assignment of ferrous and ferric iron

** Standard deviation calculated from five analyses of CR29

*** N=number of analyses

All analyses in weight percent.

TABLE 10, continued

Hornblende electron microprobe analyses and ions per 23 oxygen atoms

	Red Lake pluton		Eagle Peak pluton				
	Equigranular facies		Equigranular margin				P. Core
	CR29	CR38	E92	E97	E31-A	E31-B	E84
Si	6.747	6.883	6.691	6.673	6.710	6.586	6.626
Al	1.253	1.117	1.309	1.327	1.290	1.414	1.374
Σ (tet)	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.158	0.153	0.283	0.201	0.166	0.194	0.229
Fe ³⁺	0.519	0.442	0.509	0.602	0.557	0.628	0.582
Fe ²⁺	1.698	1.408	1.665	1.970	1.824	2.056	1.905
Mg	2.500	2.880	2.421	2.094	2.295	1.941	2.138
Ti ⁴⁺	0.125	0.117	0.122	0.117	0.142	0.131	0.129
Mn	-	-	-	0.016	0.016	0.050	0.017
Σ (M ₁ -M ₃)	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Ca	1.809	1.782	1.810	1.799	1.820	1.828	1.786
Mn	0.088	0.081	0.077	0.068	0.073	0.067	0.082
Fe ²⁺	0.003	0.037	0.000	0.000	0.000	0.000	0.000
Na	0.100	0.100	0.113	0.133	0.107	0.105	0.132
Σ (M ₄)	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.252	0.244	0.202	0.239	0.191	0.212	0.235
K	0.174	0.146	0.179	0.182	0.201	0.220	0.203
Σ (A)	0.426	0.390	0.381	0.421	0.392	0.432	0.438
Fe/Fe+Mg	0.470	0.391	0.473	0.551	0.509	0.580	0.538

Figure 10: FeO-MgO weight percent diagram of hornblende compositions.

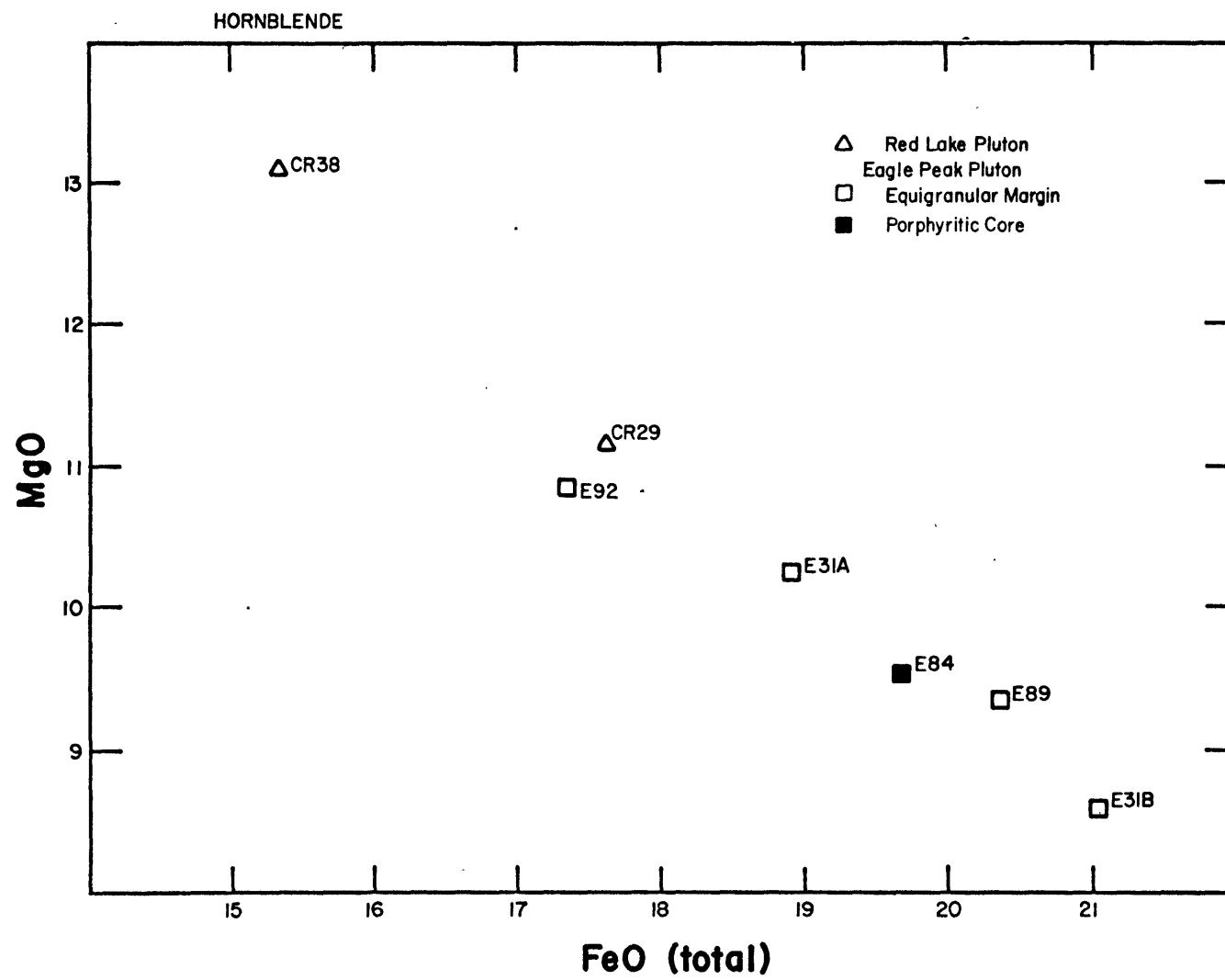


Figure 10

TABLE 11

Magnetite analyses by electron microprobe

	Red Lake Pluton							
	Equigranular facies						Bear Butte facies	
	CR3-1	CR3-2	CR29-2	CR29-5	CR5-5	CR5-7	CR1-1	CR1-2
MnO	0.21	0.09	0.06	0.10	0.16	0.14	0.13	0.13
FeO	90.02	90.72	90.40	90.78	90.69	90.68	90.46	90.24
TiO ₂	0.04	0.01	0.00	0.14	0.06	0.00	0.01	0.02
Cr ₂ O ₃	0.12	0.03	0.04	0.04	0.09	0.09	0.04	0.05
V ₂ O ₅	0.21	0.24	0.22	0.22	0.20	0.14	0.23	0.14
Al ₂ O ₃	0.44	0.08	0.08	0.06	0.09	0.04	0.11	0.05
SiO ₂	0.02	0.14	0.04	0.02	0.01	0.00	0.12	0.05
CaO	0.00	0.04	0.00	0.02	0.00	0.02	0.03	0.07
MgO	0.07	0.07	0.10	0.08	0.14	0.04	0.07	0.04
Total	91.13	91.42	90.94	91.46	91.43	91.16	91.19	90.80

TABLE 11, continued

Magnetite analyses by electron microprobe

	Eagle Peak Pluton						
	Equigranular margin					Porphyritic core	
	E92-42	E92-43	E89-1	E91-8	E91-7	C1	E83
MnO	0.11	0.11	0.14	0.10	0.23	0.16	0.08
FeO	90.13	89.89	90.14	89.71	89.54	90.50	90.43
TiO ₂	0.06	0.02	0.07	0.05	0.04	0.09	0.02
Cr ₂ O ₃	0.05	0.05	0.09	0.07	0.08	0.07	0.04
V ₂ O ₅	0.25	0.21	0.32	0.20	0.40	0.28	0.30
Al ₂ O ₃	0.16	0.11	0.13	0.09	0.18	0.10	0.07
SiO ₂	0.07	0.09	0.09	0.04	0.09	0.08	0.09
CaO	0.00	0.02	0.00	0.00	0.00	0.02	0.02
MgO	0.05	0.05	0.05	0.06	0.04	0.05	0.02
Total	90.88	90.56	91.03	90.32	90.61	91.32	91.09

Analyses in weight percent.

MODAL ANALYSES

Twenty-eight stained slab modal analyses obtained in this study from representative samples of both plutons are combined with the forty-one of Bateman and Wones (1972a) and plotted on exploded plagioclase-alkali feldspar-quartz-mafic (K-P-Q) tetrahedra in Figures 11 and 12 with modes of aplites of the Red Lake pluton (2) and the Eagle Peak pluton (1). Both plutons have restricted fields of composition which are elongate. Aplites plot in separate areas.

The trend of data points on the K-P-Q triangles is similar to that for other Sierran plutons (Bateman and others, 1963; Bateman and Wones, 1972a) and is elongate in a direction slightly inclined to the P-K sideline. Aplites plot nearest the Q-K sideline. Porphyritic samples of the Eagle Peak pluton lie closer to the Q-K sideline than do equigranular samples from that pluton and most samples of the Red Lake pluton. The data plot toward the K vertex on both the Q-K-M and the P-K-M diagrams. Aplites and porphyritic samples of the Eagle Peak pluton plot nearer the alkali feldspar vertex than the equigranular facies of either pluton.

In the P-M-Q plot, the data are elongated toward the Q end of the P-Q sideline, and aplites plot nearest the P-Q sideline. The data from the Red Lake pluton form a much better trend than the data for the Eagle Peak pluton. Samples of the Eagle Peak porphyritic core do not plot in as restricted a range as on the other diagrams.

Modal data for granitic rocks of the two plutons, summarized in Table 12, show that the porphyritic core of the Eagle Peak pluton contains more alkali feldspar and less plagioclase and mafics than

Figure 11: Exploded KPQM modal tetrahedron, Red Lake pluton;
stained slab modal analyses, volume percent.

K: alkali feldspar

P: plagioclase

Q: quartz

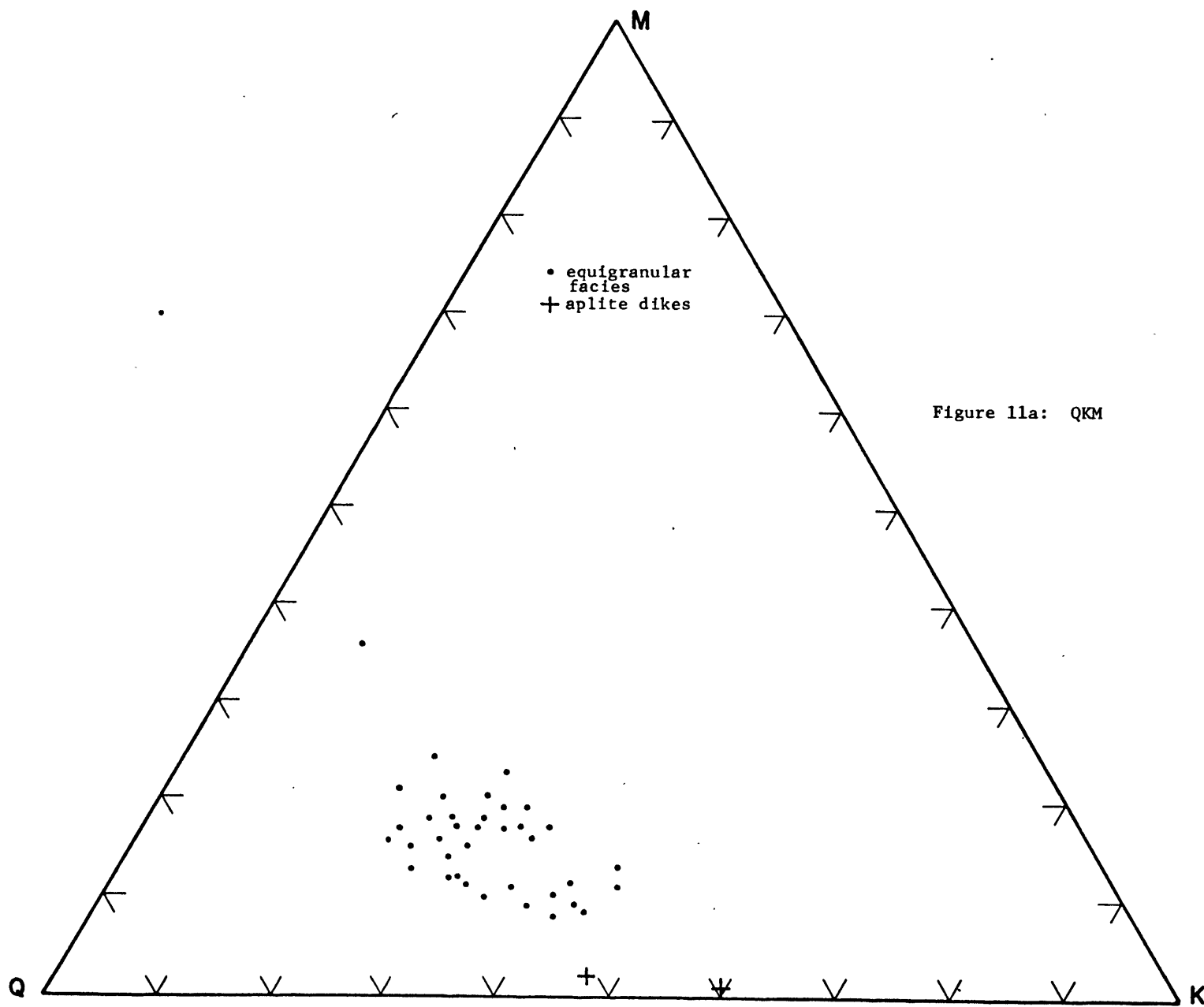
M: mafics

Figure 11a: QKM

Figure 11b: PQM

Figure 11c: KPM

Figure 11d: PKQ



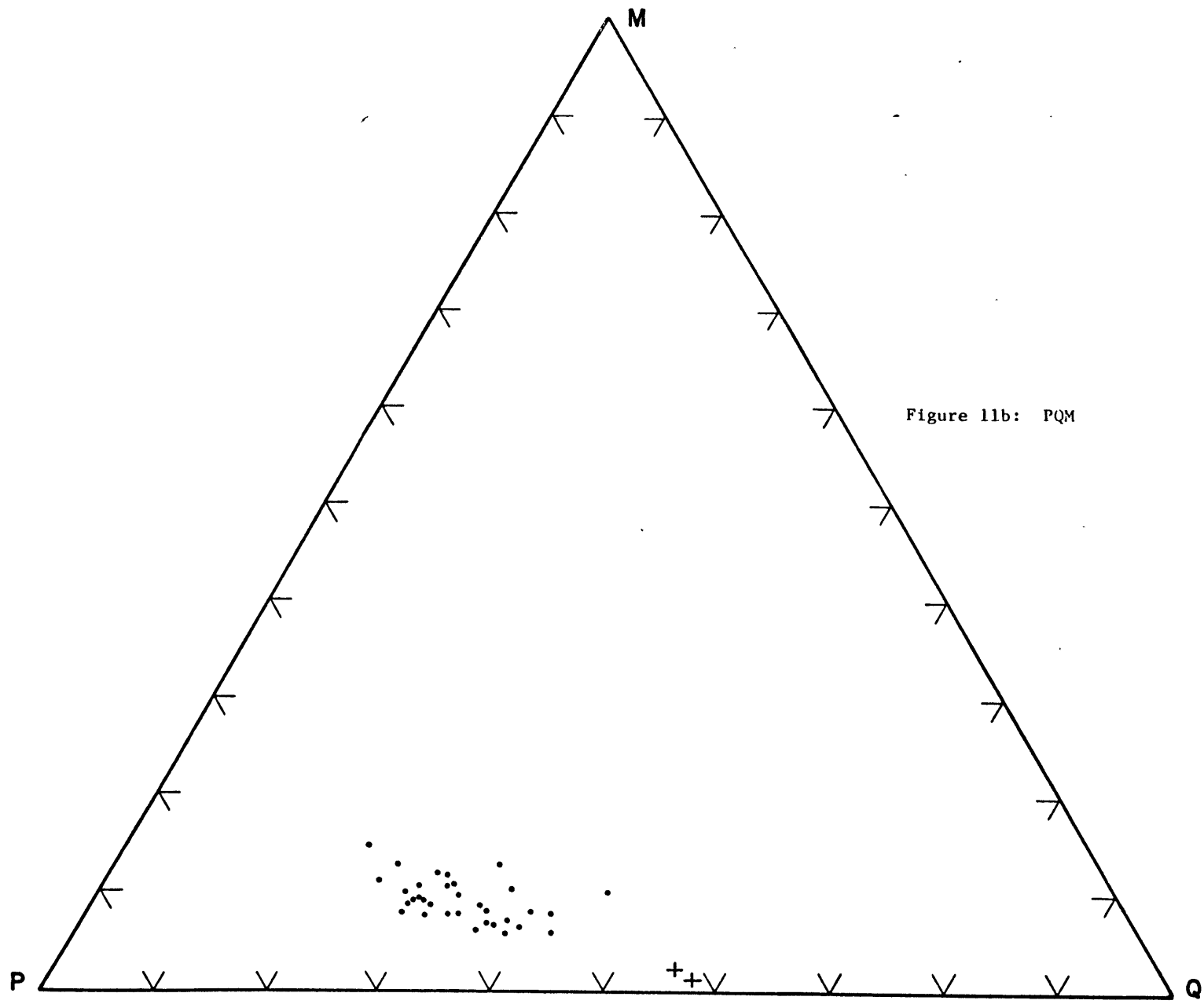
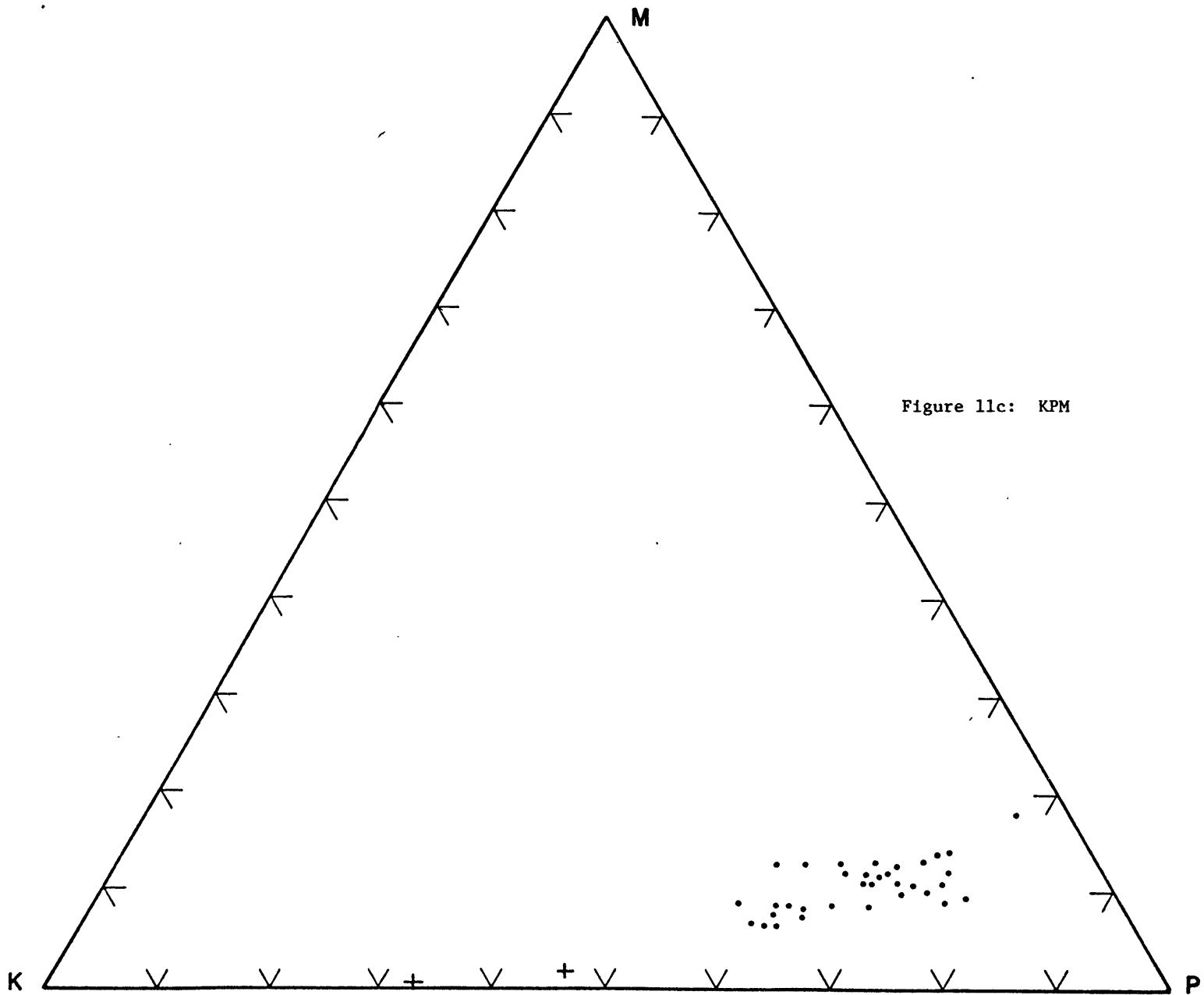


Figure 11b: PQM



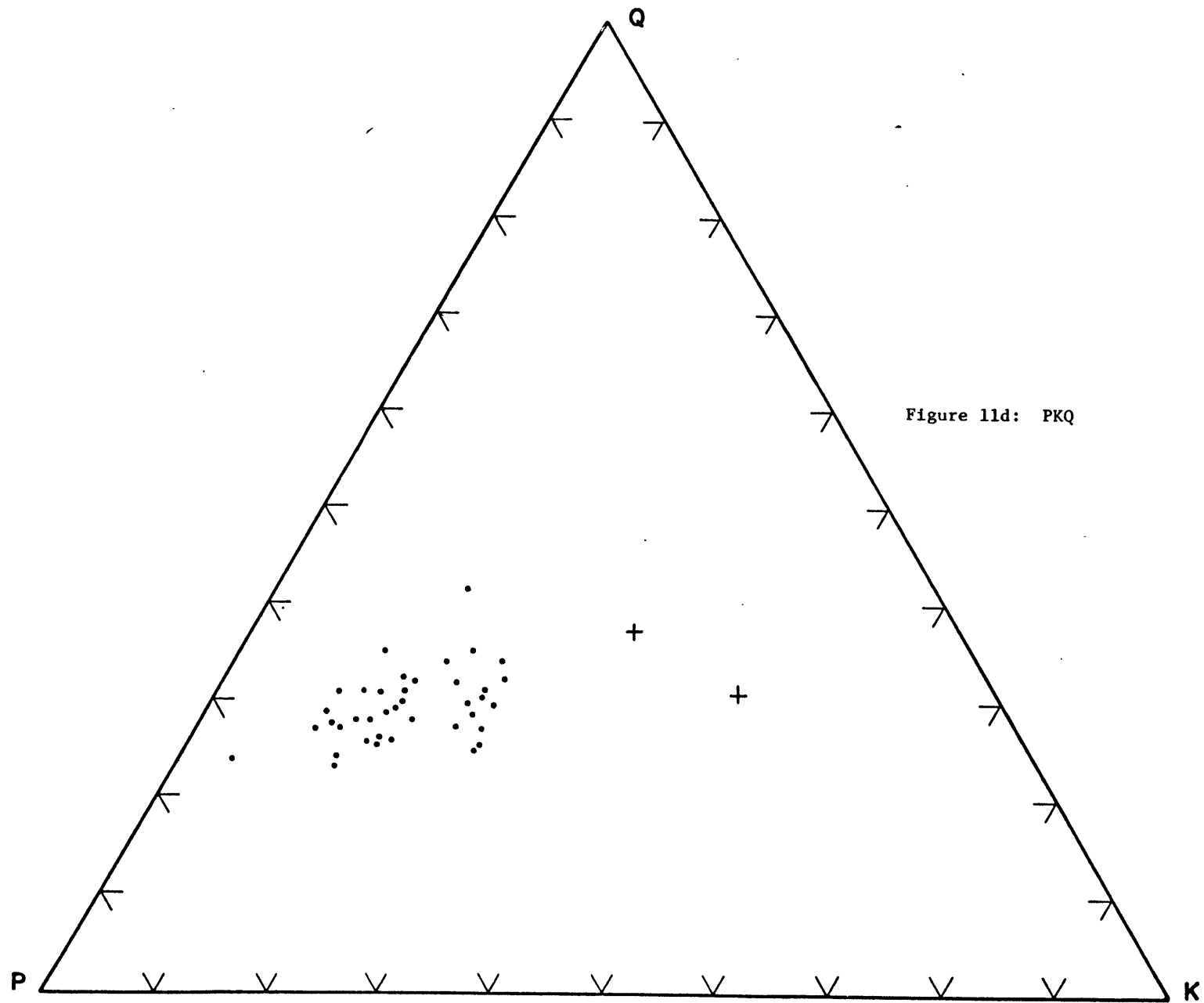


Figure 12: Exploded KPQM tetrahedron, Eagle Peak pluton;
stained slab modal analyses, volume percent.

K: alkali feldspar

P: plagioclase

Q: quartz

M: mafics

Figure 12a: QKM

Figure 12b: PQM

Figure 12c: KPM

Figure 12d: PKQ

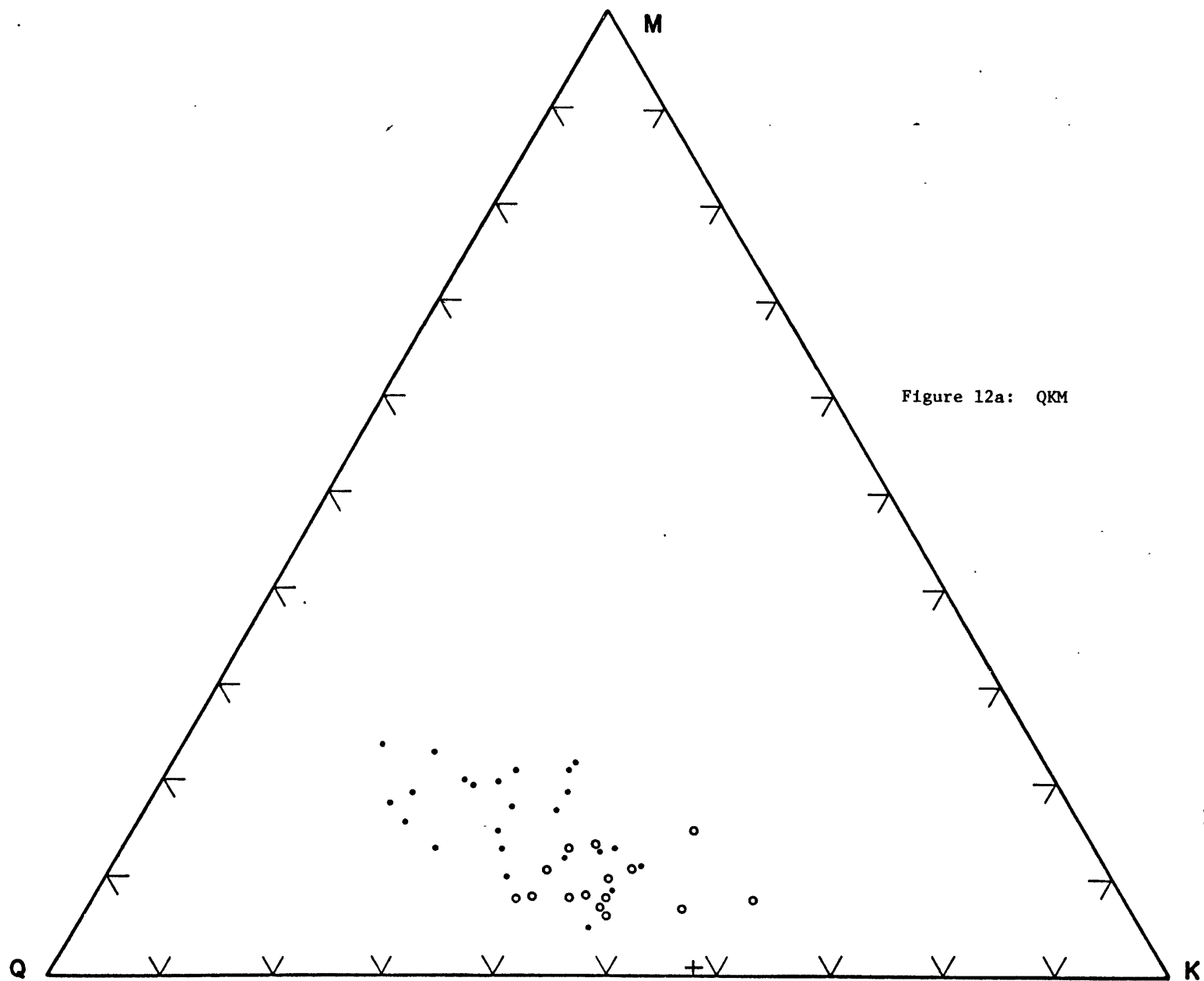


Figure 12a: QKM

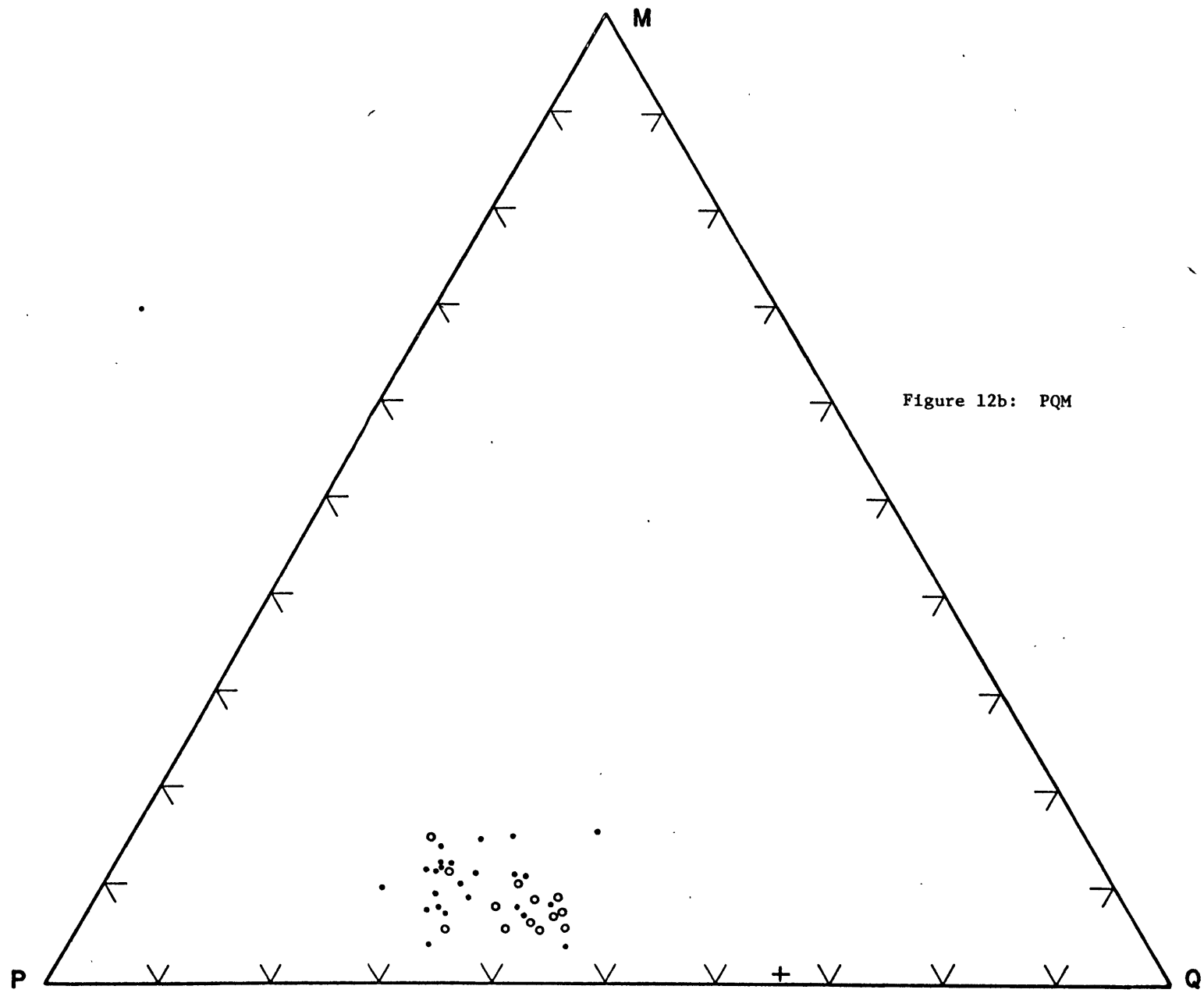


Figure 12b: PQM

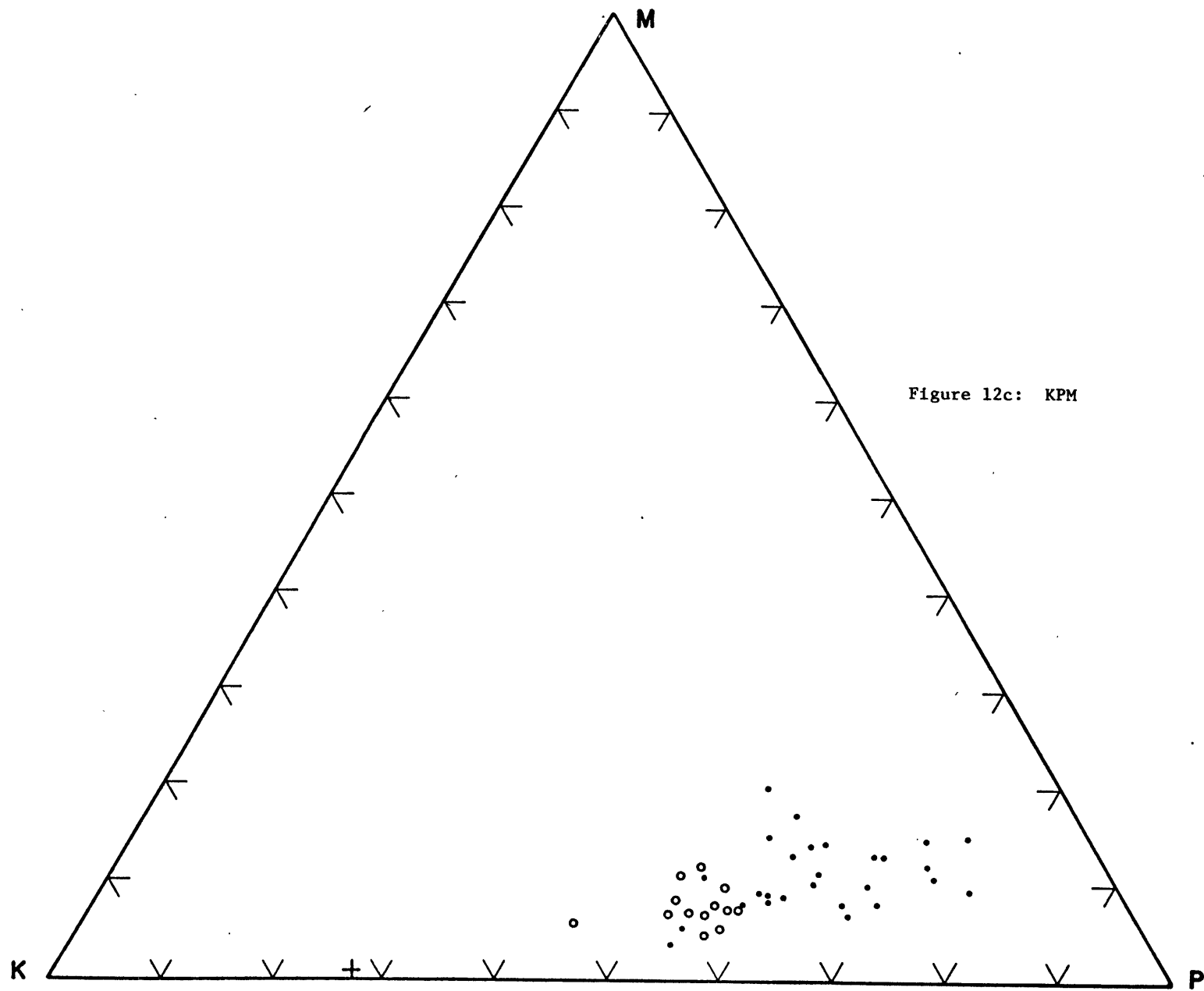


Figure 12c: KPM

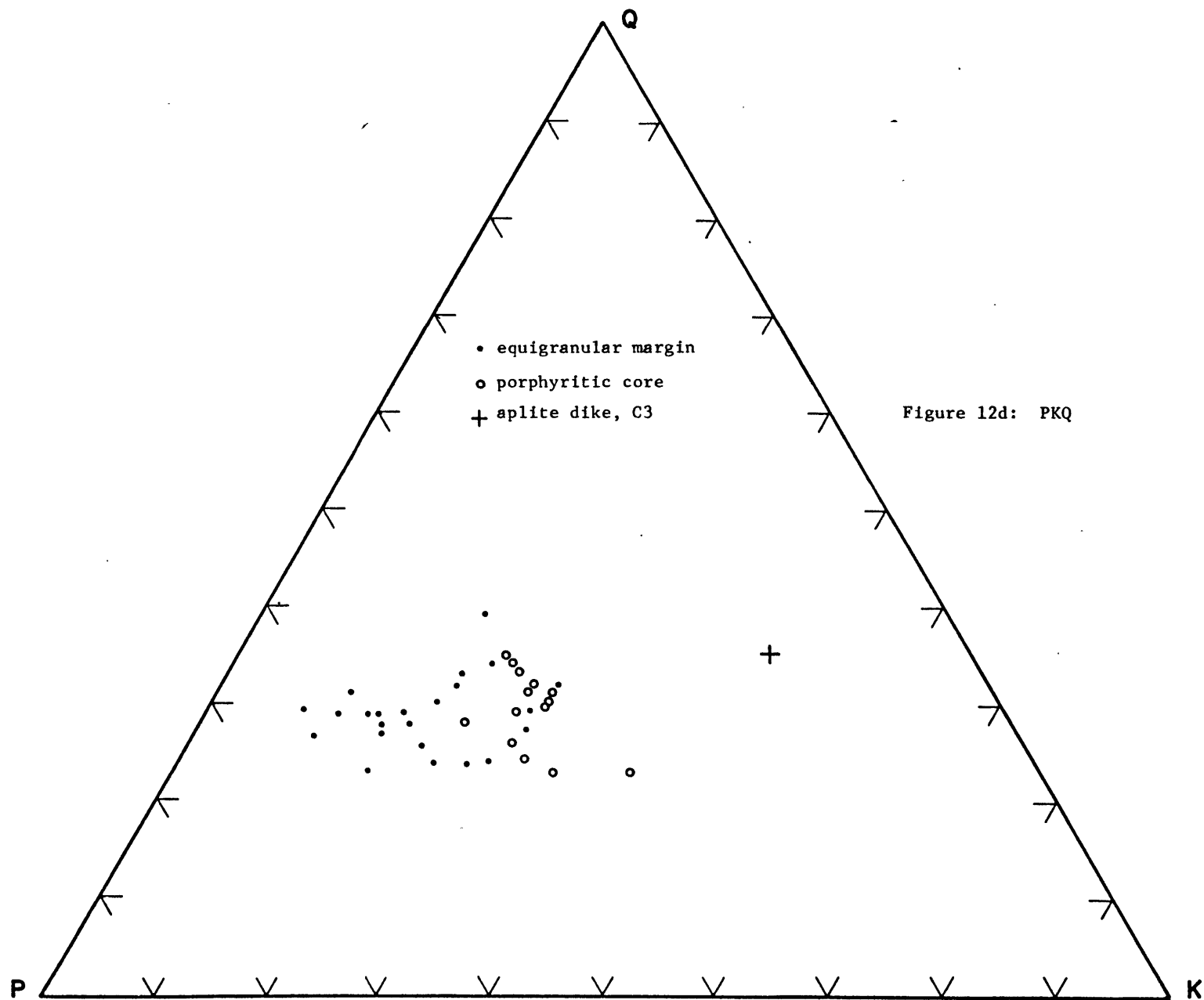


TABLE 12

Summary of modal analyses of plutonic granitic rocks

	Red Lake Pluton		Eagle Peak Pluton			
			Equigranular margin		Porphyritic core	
	Average	Range	Average	Range	Average	Range
Quartz	27	38 - 21	27	32 - 21	28	33 - 21
Alkali feldspar	16	25 - 4	18	28 - 8	27	39 - 22
Plagioclase	49	61 - 38	47	58 - 37	39	45 - 34
Mafic minerals	8	14 - 5	8	12 - 5	6	9 - 4
Number of analyses	37		24		15	

Summary includes only stained slab modes; analyses from Bateman and Wones (1972a) are included with 36 new analyses of this study. Modes from aplites are not included. Values in volume percent.

does the equigranular facies of the Red Lake pluton. Quartz is similar in abundance in all zones.

Thin section modal analyses of selected samples are shown in Tables 13a and 13b. These modes better define characteristics not apparent from stained slab modal analyses. In the Eagle Peak pluton, plagioclase and mafics, most notably hornblende, decrease whereas alkali feldspar increases in abundance toward the interior of the pluton. Careful comparison shows that opaques, sphene, and the ratio chlorite: biotite are slightly greater in the Red Lake pluton than in the Eagle Peak pluton. These differences are consistent with the petrographic observation of biotite alteration to chlorite, magnetite, and sphene. Hornblende, obviously present in outcrops CR29 and CR3 is only present in trace amounts in the thin sections. This is consistent with the sporadic hornblende distribution observed during mapping.

MAJOR ELEMENT CHEMISTRY

Major element analyses of whole rocks and aplites from both plutons and CIPW norms are given in Table 14. Modal analyses for analyzed samples are given in Table 13a. Sample localities are shown in Figures 3a and 3b. Average analyses are given in Table 15 and show that the two plutons are similar, except for higher $\text{Na}_2\text{O}/\text{K}_2\text{O}$ in the Red Lake pluton. These data, excluding sample CR1, are representative of typical Sierra Nevada granodiorites and granites. SiO_2 varies from a low of 67.2 to a maximum of 71.3 weight per cent. Both aplite compositions are similar to one another and are enriched in

TABLE 13a

Modal analyses of chemically analyzed granitic rocks*

Red Lake Pluton										
	Equigranular facies							Bear Butte Aplites		
	CR29	CR3	CR5	HL-4 (1)	HL-4 (2)	HLa-30	HLa-111	CR1	CR14	CR10
Quartz	26.6	27.1	28.6	28	-	26	19	35.1	36.7	30.8
Alkali feldspar	18.7	20.7	19.2	14	-	15	26	12.1	33.7	46.2
Plagioclase	47.0	42.4	43.5	50	-	50	46	36.7	28.5	22.6
Biotite	5.2	6.1	6.3	-	-	-	-	-	tr	0.4
Hornblende	tr	tr*	-	-	-	-	-	-	-	-
Opaque	0.3	0.8	0.9	-	-	-	-	tr	tr	tr
Chlorite	0.9	0.9	0.9	-	-	-	-	2.4	tr	tr
Sphene	0.5	1.0	0.6	-	-	-	-	-	tr	tr
Myrmekite	0.3	0.8	tr	-	-	-	-	-	tr	tr
Muscovite	tr	tr	tr	-	-	-	-	10.8	tr	tr
Carbonate	tr	tr	tr	-	-	-	-	1.8	-	-
Mafic minerals	-	-	-	9	-	9	9	-	-	-

* Volume per cent.

Modes for samples prefixed by "H" from Bateman and Wones (1972a); analyses showing "mafic" are stained slab modes, 1000-2000 points per slab, at least six square inches per slab; all others are thin section modes, 1000-1500 points per section, rectangular grid; only trace element analyses are available for samples CR10 and E83.

TABLE 13a, continued

Modal analyses of chemically analyzed rocks

Eagle Peak Pluton								
	Equigranular margin				Porphyritic core		Aplite	Core
	E92	E89	E91	HLd-5	HLd-51	C1	C3	E83
Quartz	26.5	23.5	26.0	27	28	32	34.5	21
Alkali feldspar	13.6	23.0	30.4	18	28	24	47.1	30
Plagioclase	42.7	40.4	31.7	50	37	39	17.9	40
Biotite	11.5	9.1	8.2	-	-	-	tr	-
Hornblende	2.6	2.3	0.3	-	-	-	-	-
Opaque	0.4	0.4	0.4	-	-	-	tr	-
Chlorite	1.6	0.3	1.1	-	-	-	tr	-
Sphene	0.4	0.3	0.3	-	-	-	tr	-
Myrmekite	0.2	0.6	1.1	-	-	-	tr	-
Muscovite	tr	tr	tr	-	-	-	tr	-
Carbonate	tr	tr	tr	-	-	-	-	-
Mafic minerals	-	-	-	5	6	5	-	9

* Volume per cent.

Modes for samples prefixed by "H" from Bateman and Wones (1972a); analyses showing "mafics" are stained slab modes, 1000-2000 points per slab, at least six square inches per slab; all others are thin section modes, 1000-1500 points per section, rectangular grid; only trace element analyses are available for samples CR10 and E83.

TABLE 13b

Supplementary modal analyses of the equigranular margin, Eagle Peak pluton

	Outer margin	Intermediate margin	Inner margin	Outer margin	Inner margin
	E72	E71	E70	E97	E54
Quartz	27.9	20.6	19.4	22.8	24.6
Alkali feldspar	6.1	16.8	23.7	23.6	31.7
Plagioclase	49.1	41.3	42.6	42.6	34.9
Biotite	12.0	13.0	8.1	8.3	5.6
Hornblende	3.8	2.1	1.9	0.8	0.8
Opaque	0.3	0.9	0.6	0.2	0.3
Chlorite	0.4	1.2	0.9	0.2	0.3
Sphene	0.2	0.1	0.9	0.6	0.3
Myrmekite	0.6	3.2	1.9	0.4	1.2

Thin section modes, rectangular grid, 1000-1500 points per section.
 Values in volume percent.

TABLE 14
Chemical analyses and CIPW norms of representative granitic rocks

Red Lake Pluton									
	Equigranular facies							Bear Butte	Aplite
	CR29	CR3	CR5	HL-4(1)	HL-4(2)	HLa-30	HLa-111	CR1	CR14
Chemical analyses (weight percent)									
SiO ₂	68.6	69.0	69.8	68.6	70.0	69.7	68.3	73.2	75.8
Al ₂ O ₃	15.9	15.8	16.1	16.0	15.2	15.5	15.8	13.9	13.3
Fe ₂ O ₃	1.3	1.2	1.2	1.9	1.3	0.39	1.3	0.60	0.52
FeO	1.8	1.6	1.5	1.6	1.4	2.1	2.0	1.0	0.36
MgO	1.1	0.92	0.76	0.92	0.90	0.74	1.2	0.33	0.08
CaO	3.3	3.2	2.8	3.0	3.3	2.8	3.1	1.1	0.53
Na ₂ O	3.6	3.6	3.4	3.3	3.7	3.3	3.4	3.3	3.6
K ₂ O	2.7	3.0	2.9	3.0	2.8	3.8	2.8	3.4	4.3
H ₂ O ⁺	0.86	0.86	0.81	0.50	0.57	0.80	1.0	1.1	0.61
H ₂ O ⁻	0.11	0.05	0.09	0.12	0.07	0.13	0.31	0.08	0.09
TiO ₂	0.49	0.52	0.45	0.51	0.46	0.47	0.52	0.18	0.10
P ₂ O ₅	0.14	0.15	0.12	0.24	0.16	0.14	0.12	0.04	0.00
MnO	0.03	0.03	0.02	0.11	0.05	0.05	0.08	0.01	0.01
CO ₂	< 0.05	< 0.05	< 0.05	0.05	< 0.05	< 0.05	< 0.05	0.93	0.05
Total	100	100	100	100	100	100	100	99	99

TABLE 14, continued
Chemical analyses and CIPW norms of representative granitic rocks

Red Lake Pluton									
	CR3	CR29	CR5	HL-4(1)	HL-4(2)	HLa-30	HLa-111	CR1	CR14
CIPW norms (weight percent)									
Quartz	28.5	28.4	31.8	30.5	29.5	28.0	28.9	40.9	37.2
Corundum	1.5	1.3	2.7	2.4	0.5	1.2	1.8	5.0	1.9
Orthoclase	16.0	17.7	17.1	17.8	16.6	22.5	16.6	20.1	25.4
Albite	30.5	30.5	28.8	28.0	31.3	27.9	28.8	26.6	30.5
Anorthite	15.2	14.6	12.8	13.3	15.3	13.0	14.6	0.0	2.3
Hornblende	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wollastonite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Enstatite	2.7	2.3	1.9	2.3	2.2	1.8	3.0	0.8	0.2
Ferrosilite	1.5	1.1	1.1	0.7	0.8	2.9	1.9	1.1	0.1
Magnetite	1.9	1.7	1.7	2.8	1.9	0.6	1.9	0.9	0.8
Ilmenite	0.9	1.0	0.8	1.0	0.9	0.9	1.0	0.3	0.2
Apatite	0.3	0.4	0.3	0.6	0.4	0.3	0.3	0.1	0.0
Fluorite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Calcite	0.1	0.1	0.1	0.0	0.0	0.0	0.0	1.9	0.1
Total	99.1	99.1	99.1	99.4	99.4	99.1	98.8	97.7	98.7

Analyses prefixed by "H" taken from Bateman and Wones (1972a); all others analyzed in U.S.G.S. rapid rock analysis laboratory by L. Shapiro.

TABLE 14, continued
Chemical analyses and CIPW norms of representative granitic rocks

Eagle Peak Pluton							
	Equigranular margin				Porphyritic core		Aplite
	E92	E89	E91	HLd-5	HLd-51	C1	C3
Chemical analyses (weight percent)							
SiO ₂	67.2	67.2	69.5	68.3	70.9	71.3	76.2
Al ₂ O ₃	15.6	15.8	15.2	15.9	15.2	15.0	13.2
Fe ₂ O ₃	1.4	1.4	1.3	1.8	1.0	1.5	0.49
FeO	2.5	2.7	2.0	2.3	1.5	1.0	0.20
MgO	1.4	1.5	1.0	1.1	0.67	0.70	0.07
CaO	3.6	3.6	2.9	3.1	2.5	2.3	0.71
Na ₂ O	3.2	3.2	3.2	3.0	3.1	3.4	2.6
K ₂ O	3.0	2.7	3.4	3.4	3.8	3.5	5.7
H ₂ O ⁺	1.1	0.92	0.80	0.73	0.64	0.67	0.46
H ₂ O ⁻	0.08	0.08	0.10	0.09	0.07	0.06	0.08
TiO ₂	0.57	0.61	0.50	0.53	0.36	0.42	0.06
P ₂ O ₅	0.14	0.15	0.14	0.15	0.12	0.10	0.00
MnO	0.06	0.06	0.05	0.07	0.04	0.03	0.00
CO ₂	0.09	0.05	0.05	< 0.05	< 0.05	0.05	0.05
Total	100	100	100	100	100	100	99

TABLE 14, continued
Chemical analyses and CIPW norms of representative granitic rocks

Eagle Peak Pluton							
	E92	E89	E91	HLd-5	HLd-51	C1	C3
CIPW norms (weight percent)							
Quartz	26.8	27.5	29.8	28.9	31.7	32.6	37.6
Corundum	1.1	1.5	1.4	2.0	1.7	1.8	1.5
Orthoclase	17.7	16.0	20.1	20.0	22.5	20.7	33.7
Albite	27.1	27.1	27.1	25.3	26.3	28.8	22.0
Anorthite	16.4	16.6	13.2	14.3	11.6	10.4	3.5
Hornblende	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wollastonite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Enstatite	3.5	3.7	2.5	2.7	1.7	1.7	0.2
Ferrosilite	2.6	2.9	1.9	2.0	1.4	0.0	0.0
Magnetite	2.0	2.0	1.9	2.6	1.5	2.1	0.5
Ilmenite	1.1	1.2	1.0	1.0	0.7	0.8	0.1
Apatite	0.3	0.4	0.3	0.4	0.3	0.2	0.0
Fluorite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Calcite	0.2	0.1	0.1	0.0	0.0	0.1	0.0
Total	98.8	99.0	99.3	99.2	99.4	99.2	99.1

Analyses prefixed by "H" taken from Bateman and Wones (1972a); all others analyzed in U.S.G.S. rapid rock analysis laboratory by L. Shapiro.

TABLE 15

Average* chemical compositions of the Red Lake pluton and the Eagle Peak pluton.

	Red Lake Pluton	Eagle Peak Pluton	
		Equigranular margin	Porphyritic core
SiO ₂	69.1	68.3	71.1
Al ₂ O ₃	15.8	15.6	15.1
Fe ₂ O ₃	1.1	1.5	1.2
FeO	1.8	2.3	1.2
MgO	0.94	1.2	0.68
CaO	3.0	3.2	2.4
Na ₂ O	3.5	3.1	3.2
K ₂ O	3.0	3.2	3.6
H ₂ O ⁺	0.87	0.82	0.66
H ₂ O ⁻	0.14	0.09	0.06
TiO ₂	0.49	0.55	0.38
P ₂ O ₅	0.13	0.15	0.11
MnO	0.04	0.06	0.04
CO ₂	~ 0.05	~ 0.05	0.05
Total	100	100	100

*Red Lake pluton: average of CR3, CR5, CR29, HLa-30, HLa-111. Eagle Peak pluton, equigranular margin: average of E89, E91, HLa-5. Eagle Peak pluton, porphyritic core: average of C1, HLa-51. See text for discussion of individual analyses; sample locations identified on locality map. Analytical values in weight percent.

SiO_2 and alkalis and depleted in ferromagnesian compared to the host rocks. These aplite compositions are similar to that of the Rocky Hill Stock, a small Sierran pluton described by Putnam and Alfors (1965).

In an AFM diagram, Figure 13, the samples lie along an alkali enrichment trend, with aplites most enriched in alkalis. Samples of the Eagle Peak pluton occupy a more extensive field than those of the Red Lake pluton. For the Eagle Peak pluton, alkali enrichment roughly correlates with sample distance from the margin of the pluton.

Relative oxidation state, Figure 14, shows a linear range in ferrous-ferric ratio in which a porphyritic sample (C1) and the aplites are the most oxidized. Considering only granitic samples collected in this study, the Red Lake samples are more oxidized than the equigranular margin samples of the Eagle Peak pluton. The samples decrease in $\text{MgO}/\text{MgO}+\text{FeO}$ with increasing $\text{Fe}_2\text{O}_3/\text{FeO}$.

A decrease of lime to alkalis accompanied by a decrease of $\text{MgO}/\text{MgO}+\text{FeO}$ is shown as a linear trend in Figure 15 and is similar to the distribution shown in Figure 13; that is alkali enrichment is accompanied by a decrease in the ratio of $\text{CaO}/\text{Na}_2\text{O}+\text{K}_2\text{O}$ and $\text{MgO}/\text{MgO}+\text{FeO}$. In the granitic rocks of the Eagle Peak pluton SiO_2 tends to increase and TiO_2 decrease along this same trend (Table 14).

CIPW Norms

CIPW norms, recalculated in terms of Ab-Or-Q-An, are plotted on the exploded granite tetrahedra of Figure 16. Experimentally determined minima for selected synthetic systems are plotted on the

LEGEND:

RED LAKE PLUTON

Equigranular facies

- △ CR 3
- ▽ CR 29
- ▷ CR 5
- ◁ HL-4(1)
- ▲ HL-4(2)
- ▼ HLa-30
- HLa-111

Bear Butte Facies

- ◄ CR 1

Aplite Dike

- CR 14

EAGLE PEAK PLUTON

Equigranular Margin

- ▣ E 92
- ▤ E 89
- ▥ E 91
- ▧ HLd-5

Porphyritic Core

- HLd-51
- C 1

Aplite Dike

- ⊕ C 3

Figure 13: AFM diagram of whole-rock major element data from the Red Lake and the Eagle Peak plutons: normalized weight percent oxides; includes data of Bateman and Wones (1972a).

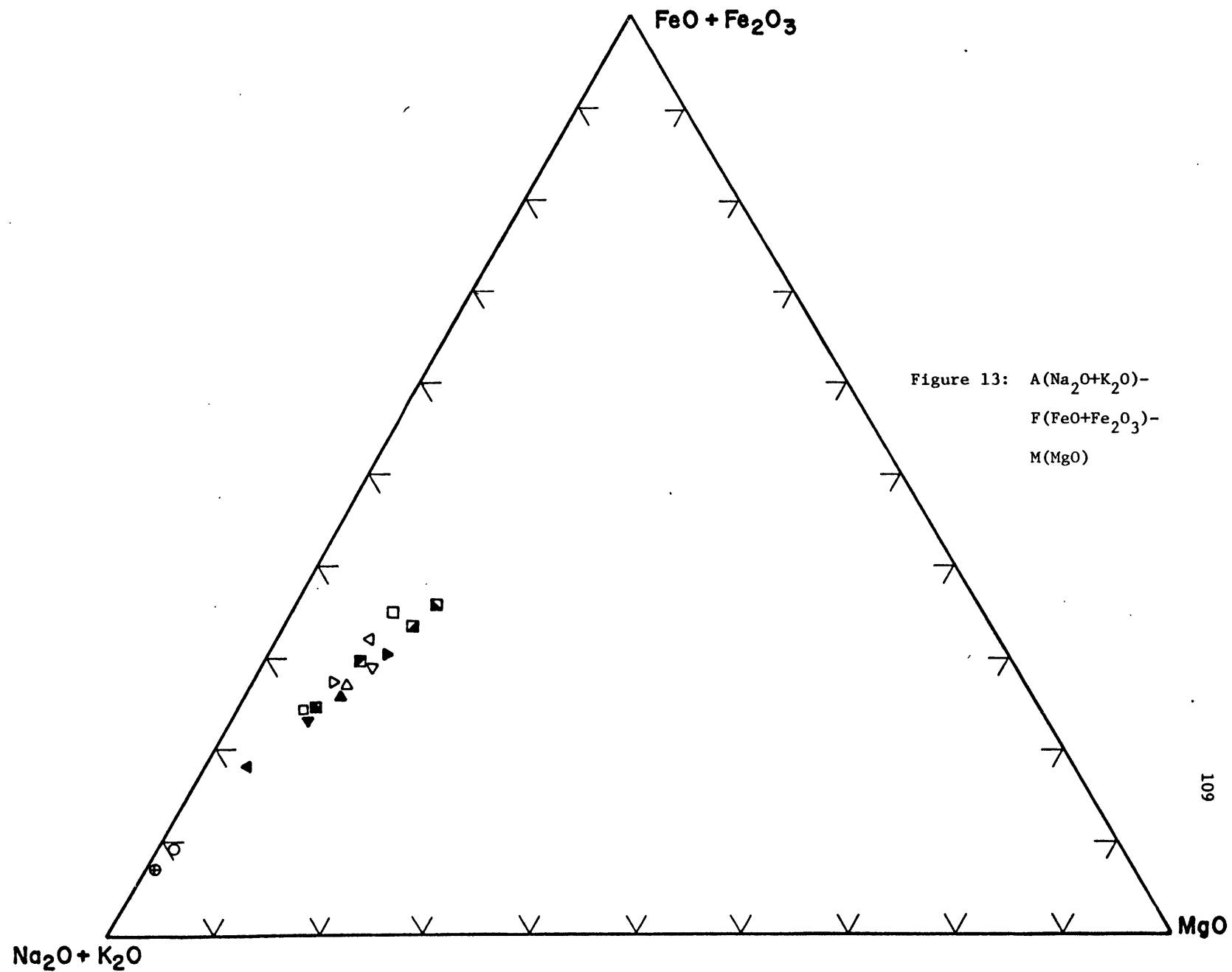


Figure 13: A($\text{Na}_2\text{O} + \text{K}_2\text{O}$)-
F($\text{FeO} + \text{Fe}_2\text{O}_3$)-
M(MgO)

Figure 14: Ferromagnesian diagram of whole-rock major element data from the Red Lake and the Eagle Peak plutons; normalized weight percent oxides; includes data of Bateman and Wones (1972a); symbolism as in Figure 13.

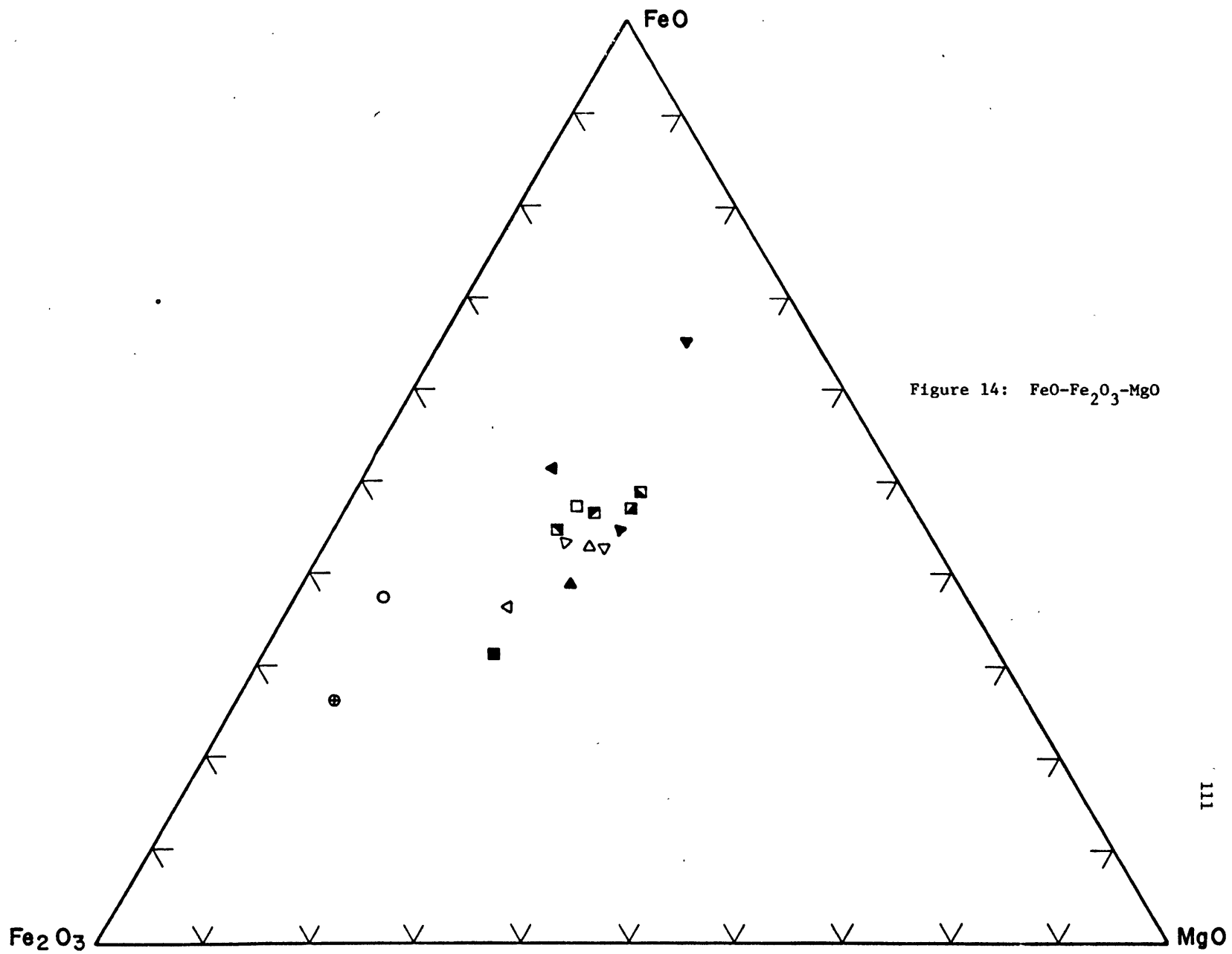


Figure 15: Alkali-mafic diagram of whole-rock major element data from the Red Lake and the Eagle Peak plutons: weight percent oxides; includes data from Bateman and Wones (1972a); symbolism as in Figure 13.

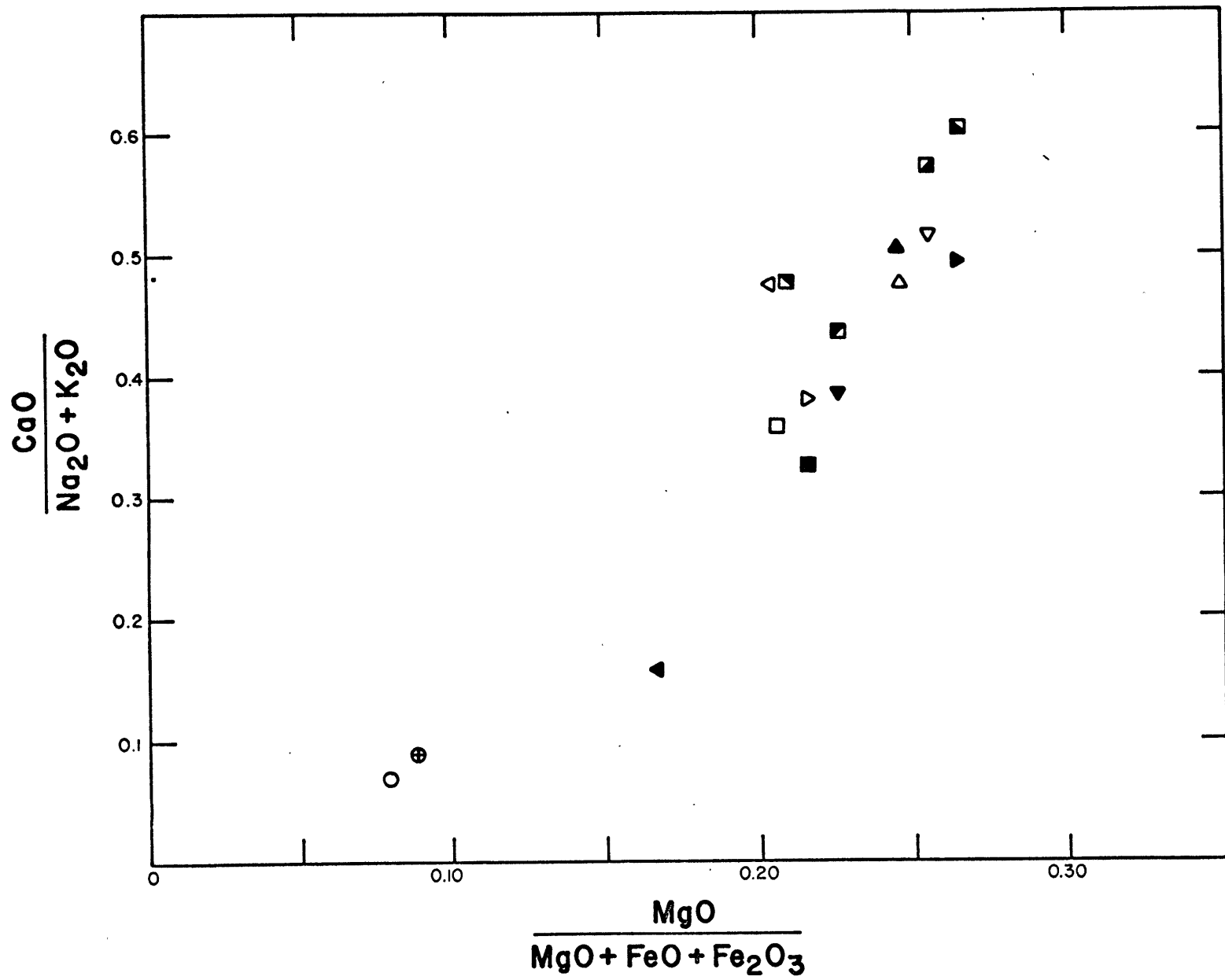


Figure 15

Ab-Or-Q base. The granitic samples follow the general trend noted by Bateman and others (1963) in a similar plot of Sierran granitic rocks which is away from the An apex and toward the Ab-Or-Q base. The samples of this study trend toward the Or-Q sideline. Aplite analyses were not obtained by Bateman and others (1963). Those in this study lie near the base of the tetrahedron on the extension of the trend established by the granitic samples. The sample distribution away from the An apex is similar to that shown on Figures 13 and 15 related to alkali enrichment.

Important features observed on the Ab-Or-Q diagram are:

1. Most samples lie within the plagioclase field for most ternary minima or near the quartz-plagioclase boundary for lower pressures.
2. Aplites lie on the Or-Q side of the trend established by the granitic samples.
3. Both aplites lie along the 1/2 kilobar boundary, although aplite C3 is much closer to the Or-Q sideline.
4. Eagle Peak pluton samples form a more coherent trend away from the Ab vertex than do Red Lake pluton samples.
5. Porphyritic core samples of the Eagle Peak pluton plot closer to the Or-Q sideline than do the equigranular margin samples.

Bear Butte Facies of the Red Lake Pluton

Because sample CR1 of the Bear Butte facies shows significant mineralogical and chemical differences from all other rocks of the pluton, this facies is interpreted as having formed by extensive hydrothermal alteration of

Figure 16: Exploded normative granite tetrahedron showing CIPW normative compositions of the Red Lake and the Eagle Peak plutons: norms in weight percent; normalized to four components: Ab, An, Or, Q; includes data of Bateman and Wones (1972a); symbolism as in Figure 13.

Ab: albite

An: anorthite

Or: orthoclase

Q: quartz

Figure 16a: Ab-An-Q

Figure 16b: Q-An-Or

Figure 16c: Or-An-Ab

Figure 16d: Ab-Q-Or

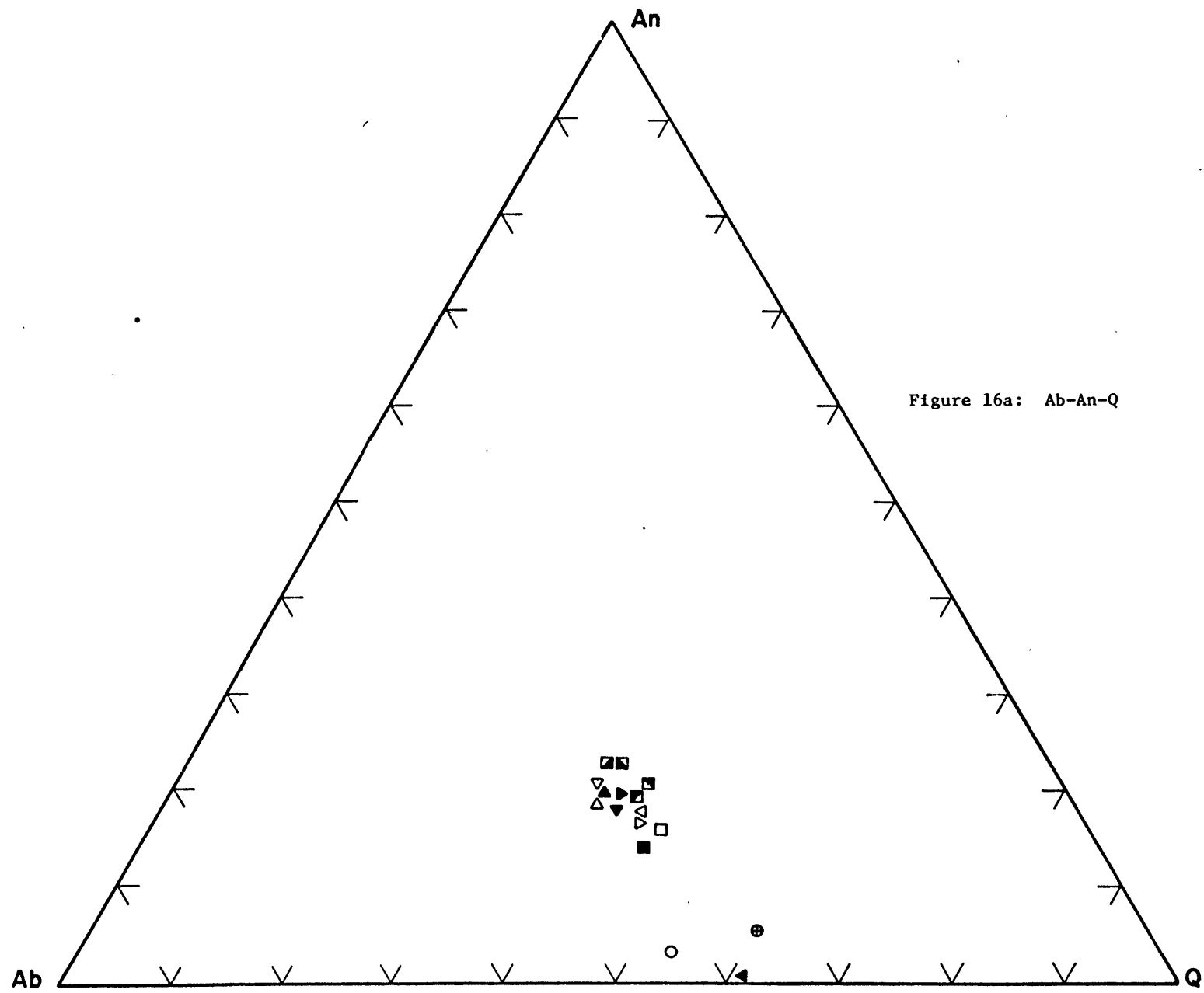
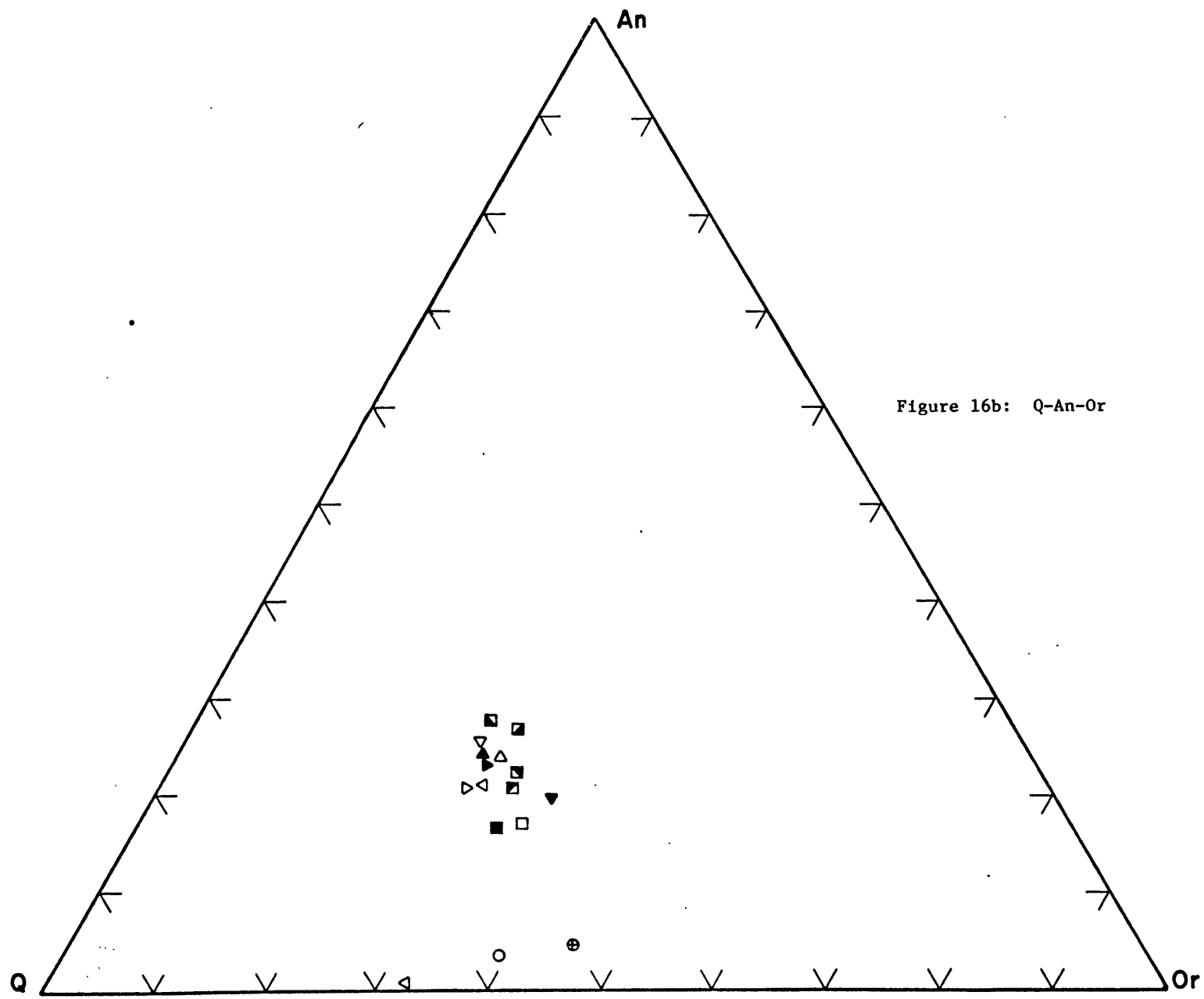
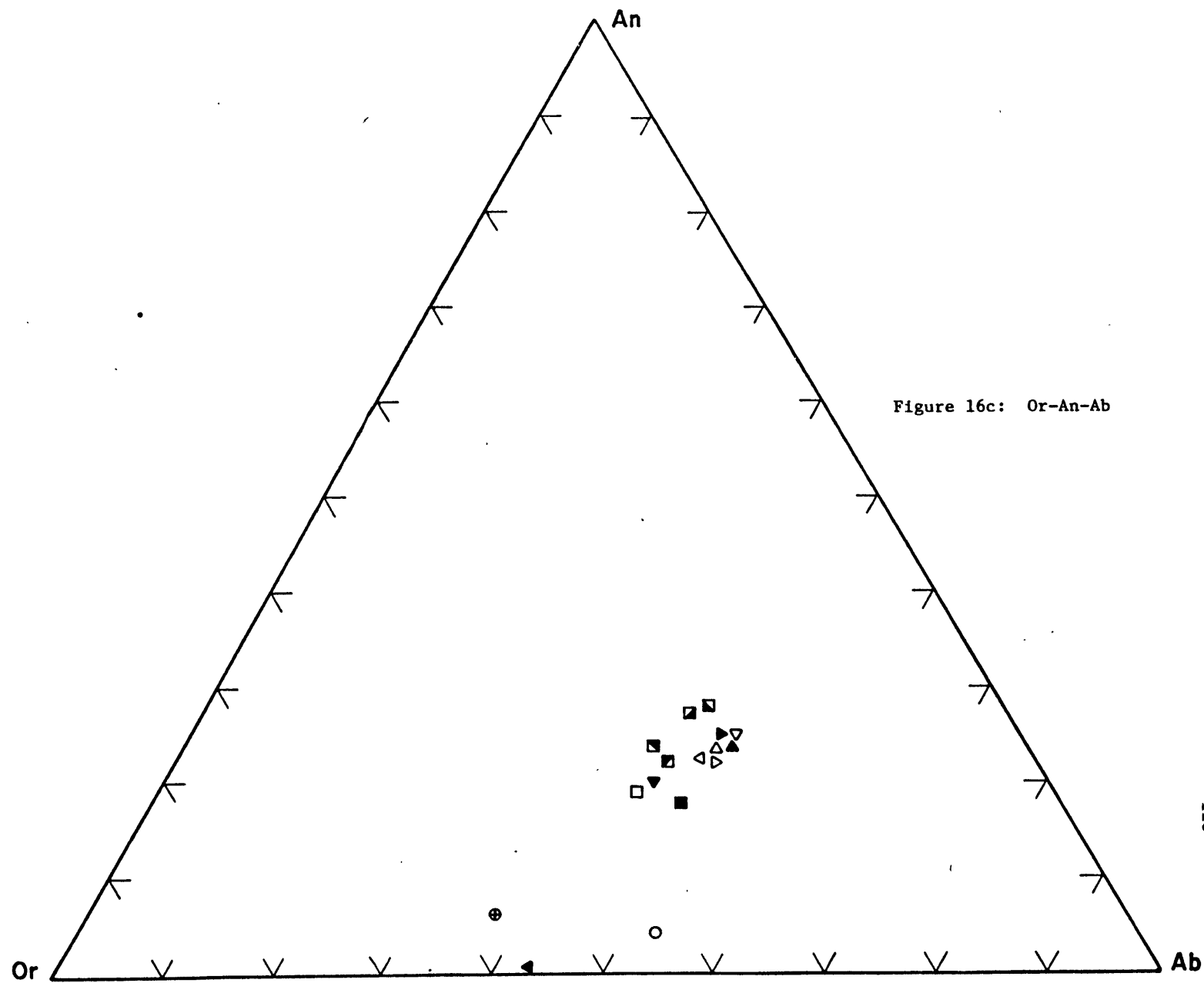


Figure 16a: Ab-An-Q





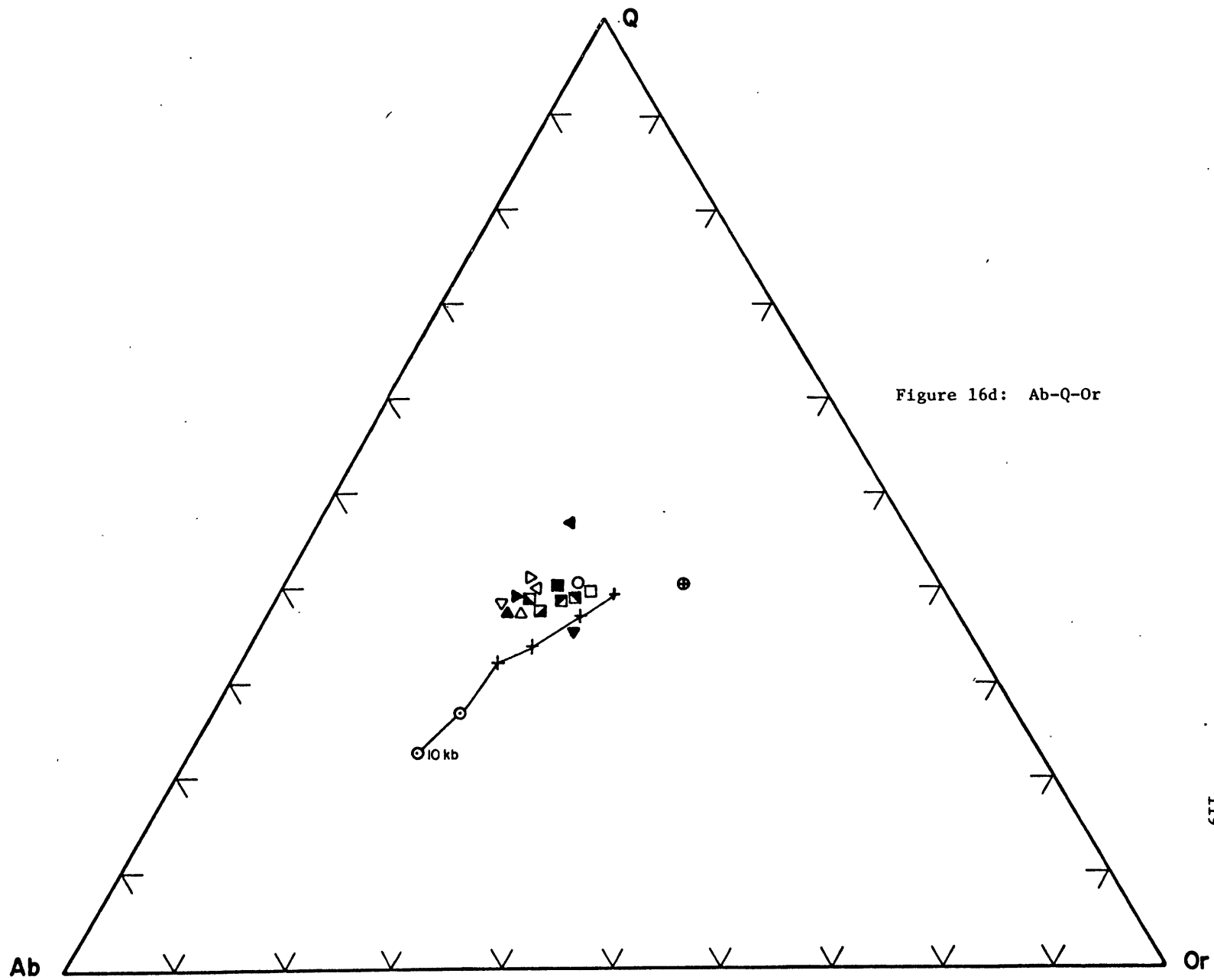


Figure 16d: Ab-Q-Or

typical Red Lake granitic rocks. The Bear Butte facies is enriched in SiO_2 , CO_2 , H_2O , and K_2O , and depleted in Al_2O_3 , Fe_2O_3 , FeO , MgO , CaO , TiO_2 , P_2O_5 , and MnO when compared to unaltered Red Lake rocks. The sum of plagioclase and sericite in CRI is quite similar to the average plagioclase abundance for the pluton, and it is interpreted as representing extensive sericitization of plagioclase. Sample CRI has greater quartz and carbonate abundance than normal samples of the pluton and reflects the increased SiO_2 and CO_2 concentrations in the altered sample. In spite of the extensive hematitic stain and low abundance of mafic minerals in the Bear Butte facies, this unit has a lower $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio than most samples of the Red Lake pluton.

Significant changes in major element composition have been reported or implied in studies of hydrothermal alteration. Neiva (1974) has discussed the problem quantitatively for a greisenized biotite-muscovite-albite granite. She found the greisenized granite to contain consistently more SiO_2 , K_2O , and H_2O and less TiO_2 , Fe_2O_3 , MgO , and Na_2O than the fresh granite. Al_2O_3 , MnO , CaO , and P_2O_5 showed less consistent trends. The mineralogical changes in her study are similar to those observed here: plagioclase altered to sericite or muscovite, decrease in An content of plagioclase, and increase in quartz abundance. The few chemical and mineralogical differences between the alteration products of the two areas are possibly due to differences in initial mineralogy and major element composition, and the alteration environment. For example, the parent granite in the Neiva (1974) study contains primary muscovite, is more silicic and more alkalic, and contains more P_2O_5 than the average sample from the Red Lake pluton.

Similar studies have not been done on hydrothermally altered Sierran granites. Bateman (1965) concludes extensive quantities of material are transported by escaping volatiles from hydrothermally altered granitic intrusives and deposited in surrounding sedimentary rocks associated with tungsten deposits. The greater abundance of CO_2 in the Bear Butte facies suggests CO_2 was a component of the escaping fluid and may have aided the removal of some components as carbonate complexes. The Bear Butte area is a structurally favorable site for the loss of fluids and the interaction with metasediments. It is a triple contact between three granitic intrusions, the older two of which are separated by metasediments about two kilometers to the northwest. These metasediments contain carbonate sequences (Bateman and Kistler, 1966) and may have provided the carbonate enrichment of the Bear Butte facies.

INTERPRETATION OF MODAL AND MAJOR ELEMENT DATA

Modal data from both plutons define a path within the P-K-Q-M tetrahedron away from plagioclase and mafics and toward alkali feldspar and quartz. The chemical data from each pluton, plotted normatively in the granite tetrahedron, define a path away from the plagioclase volume toward the quartz-alkali feldspar boundary. Within the Eagle Peak pluton, both trends have a close correspondence to sample locality within the pluton and is reflected in the modal contour diagrams of Figures 17 and 18 by the general concentric inward increase in alkali feldspar and decrease in mafics and plagioclase. In the Red Lake pluton these trends are not as closely related to sample location. For example, major element data and norms for samples CR29-CR3-CR5, in that sequence, parallel the trend of the margin-to-core sequence of the Eagle Peak pluton, but the modal contour diagrams of the Red Lake pluton, Figure 17, indicate only a poorly defined eastward increase in alkali feldspar and decrease in plagioclase and mafics similar to the concentric variations of the Eagle Peak pluton. The Eagle Peak pluton is texturally, chemically, and mineralogically concentrically zoned, whereas the main mass of the Red Lake pluton is not texturally zoned, and only slightly chemically and mineralogically zoned.

These modal and chemical trends can be explained by crystal-liquid fractionation. This is especially true for the concentric zoning of the Eagle Peak pluton. Petrographic and experimental data support the crystal-liquid fractionation model for the modal and chemical trends and the zoning. Textural evidence shows that plagioclase

Figure 17: Contoured modal analyses diagrams of the Red Lake
 pluton; values represent volume percent of minerals
 determined from stained slab modal analyses.

Figure 17a: quartz

Figure 17b: alkali feldspar

Figure 17c: plagioclase

Figure 17d: mafics

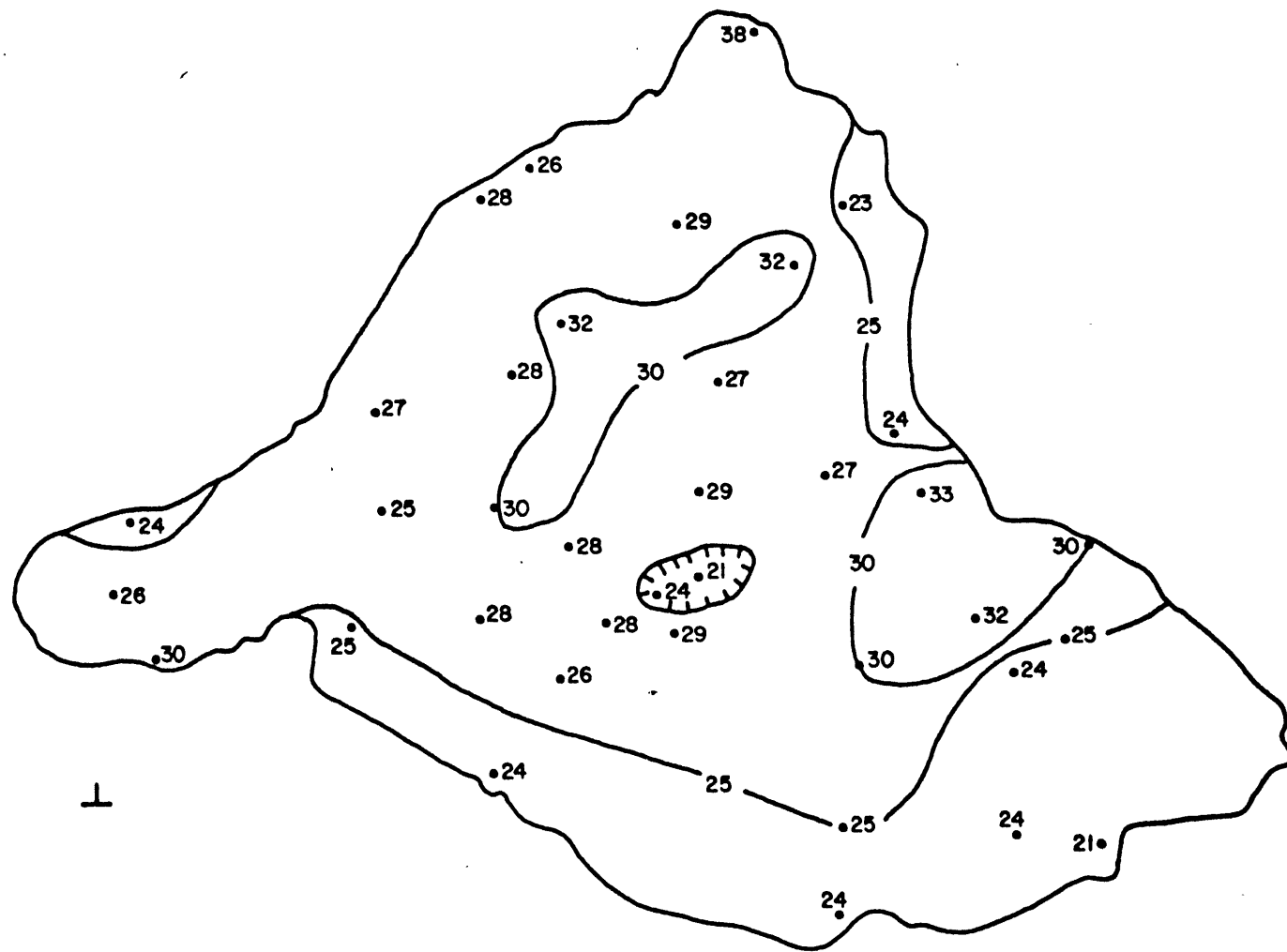


Figure 17a

RED LAKE PLUTON QUARTZ

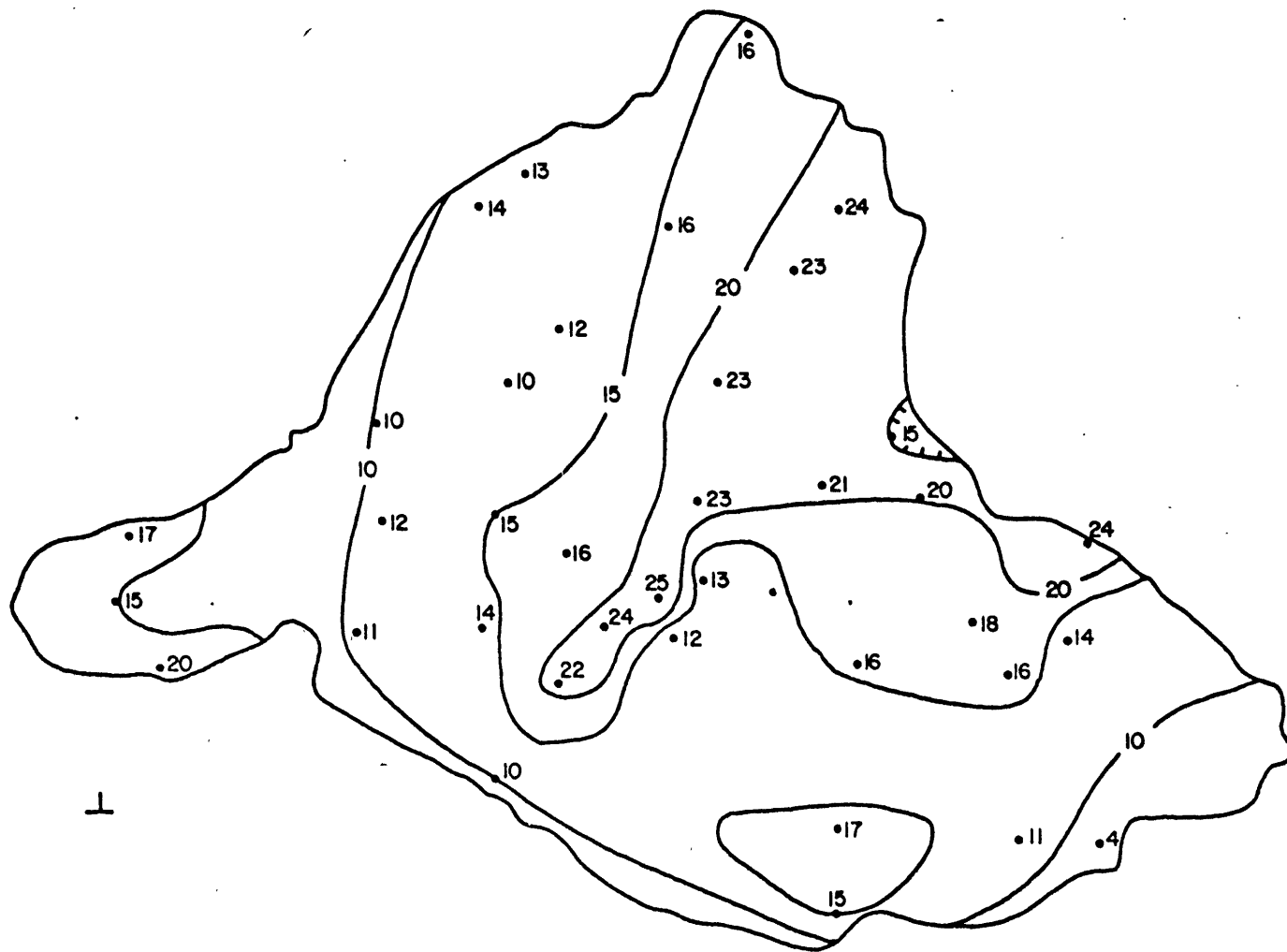


Figure 17b
RED LAKE PLUTON ALKALI FELDSPAR

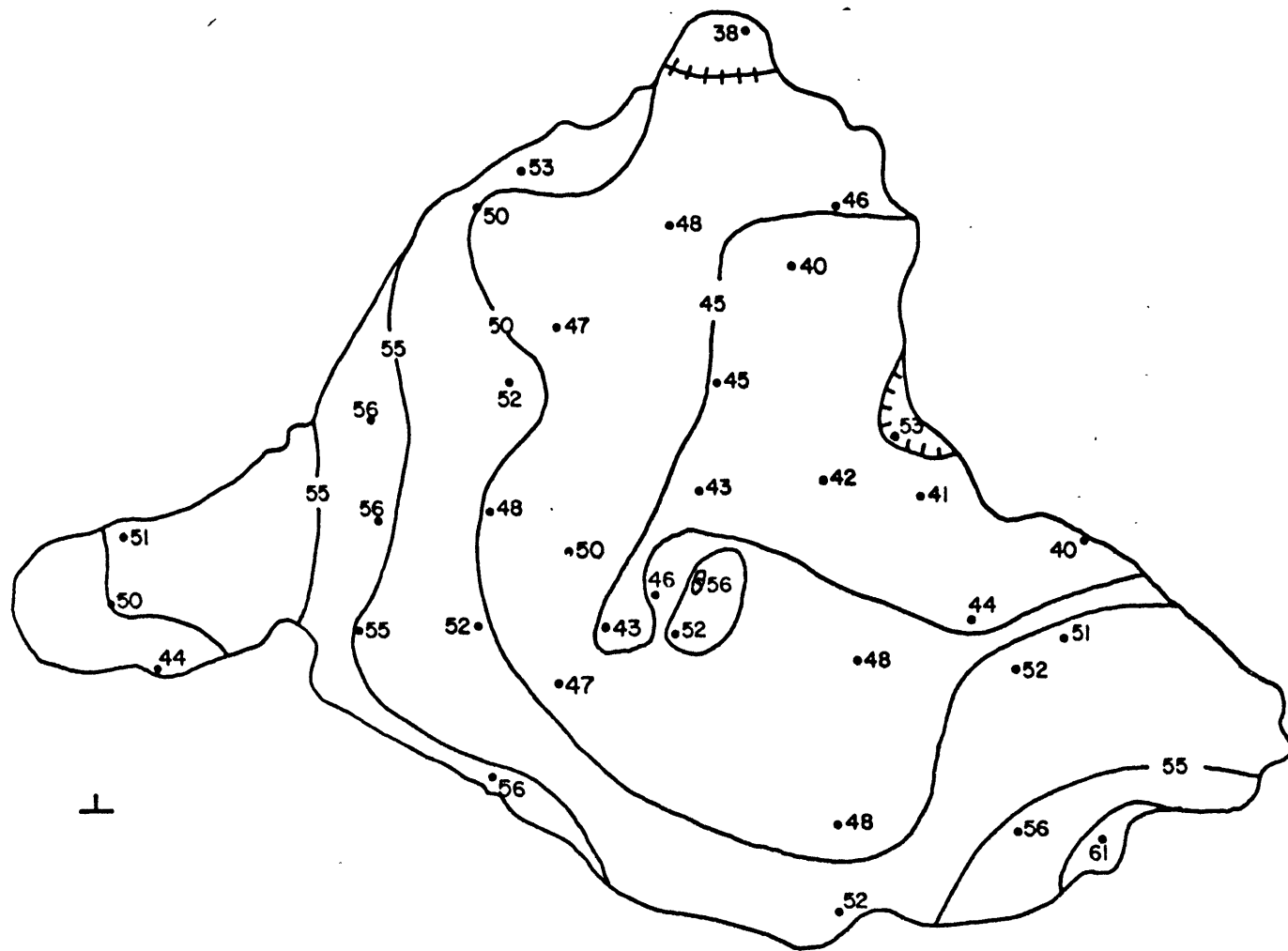


Figure 17c

RED LAKE PLUTON PLAGIOCLASE

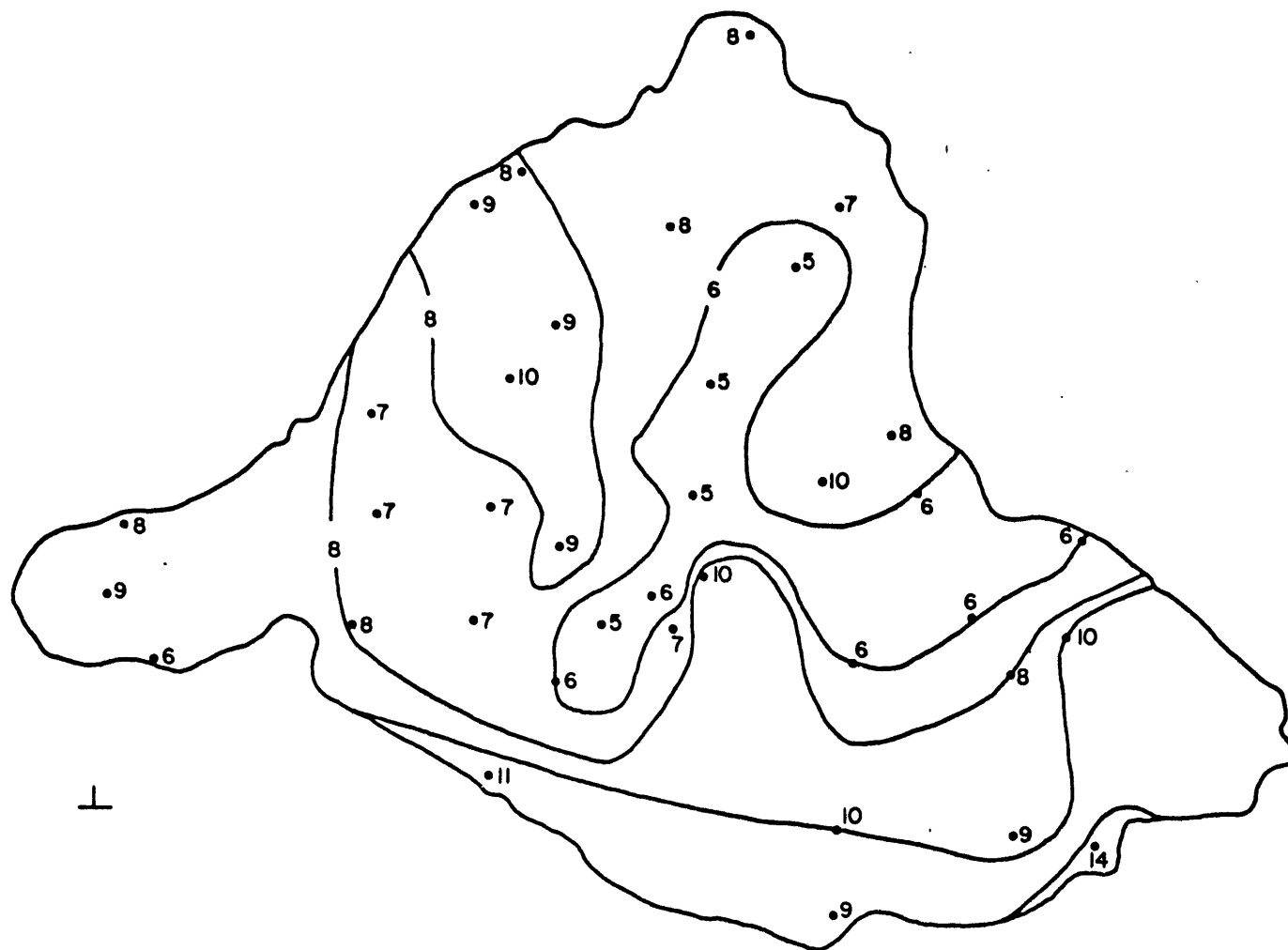


Figure 17d

RED LAKE PLUTON MAFICS

Figure 18: Contoured modal analyses diagrams of the Eagle Peak pluton; values represent volume percent of minerals determined from stained slab modal analyses.

Figure 18a: quartz

Figure 18b: alkali feldspar

Figure 18c: plagioclase

Figure 18d: mafics

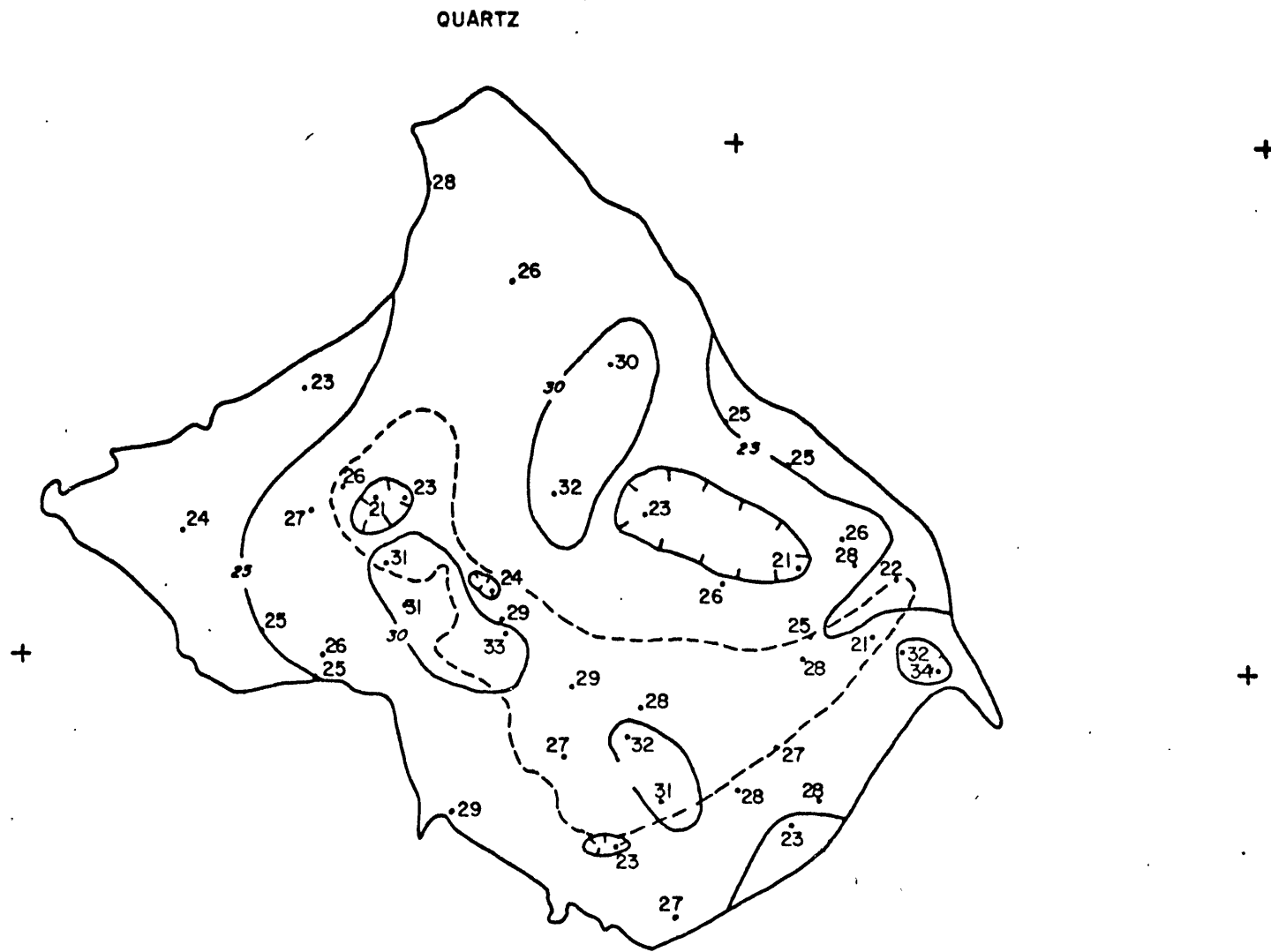


Figure 18a

EAGLE PEAK PLUTON QUARTZ

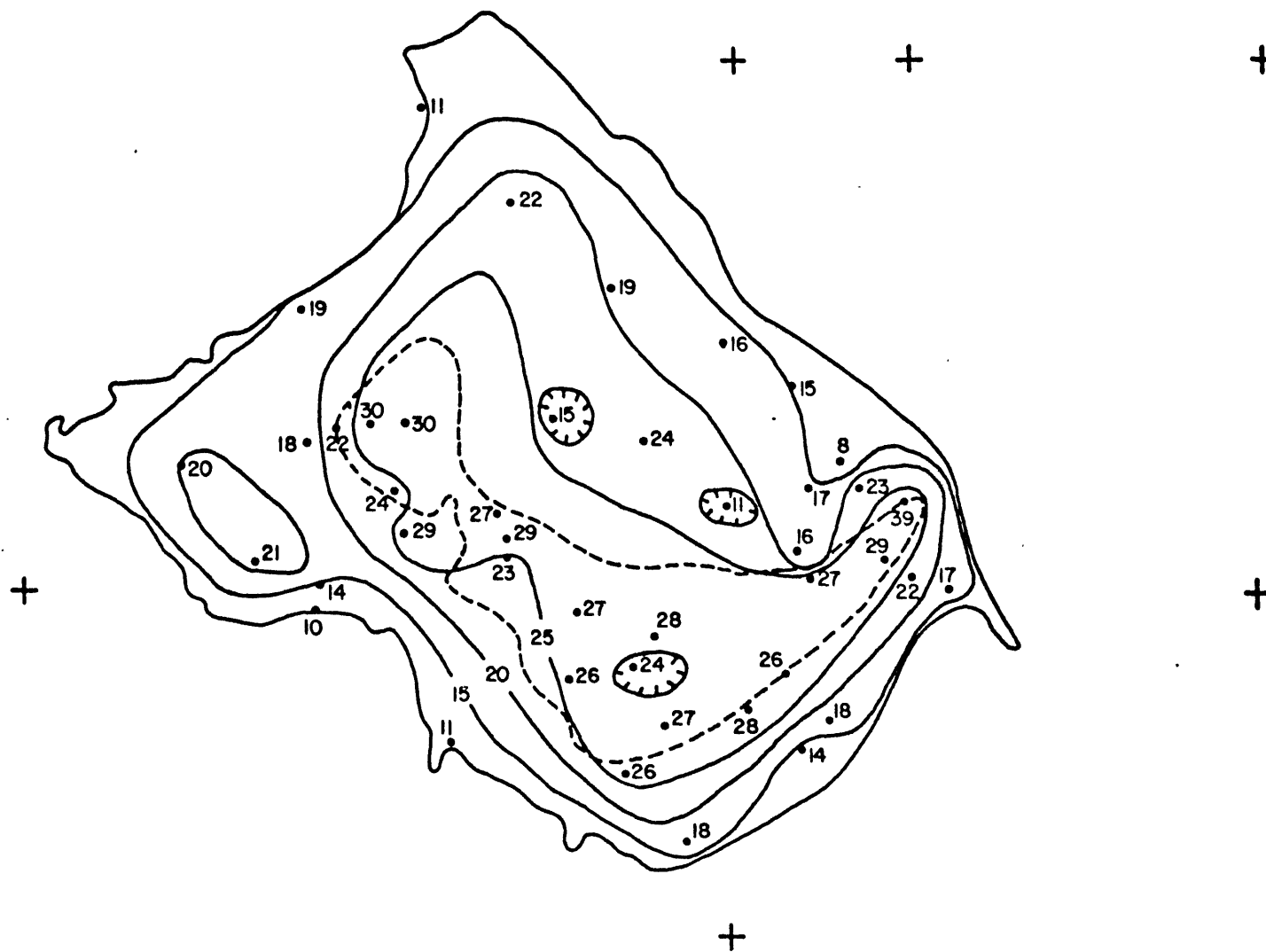


Figure 18b

EAGLE PEAK PLUTON ALKALI FELDSPAR

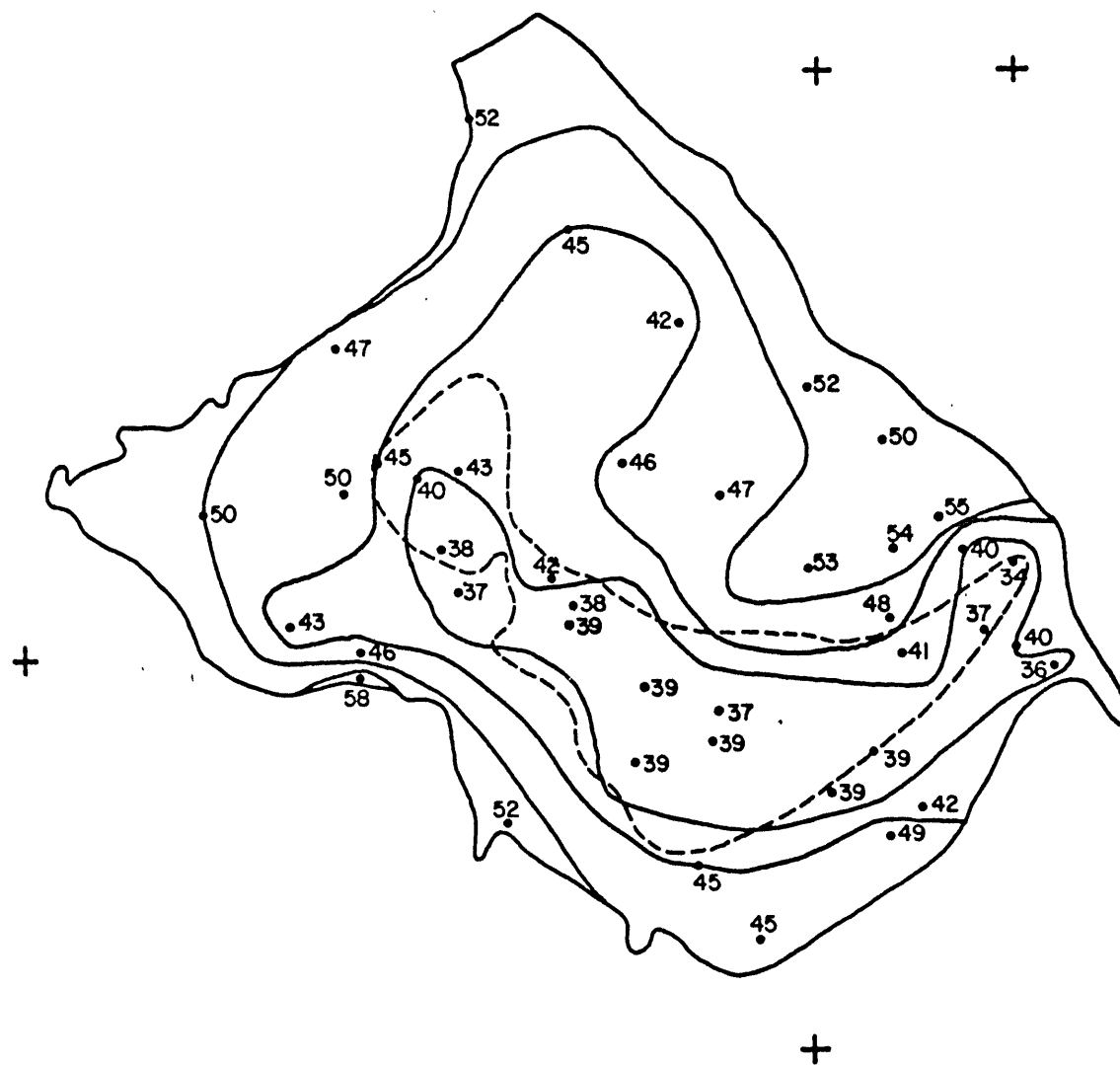


Figure 18c

EAGLE PEAK PLUTON PLAGIOCLASE

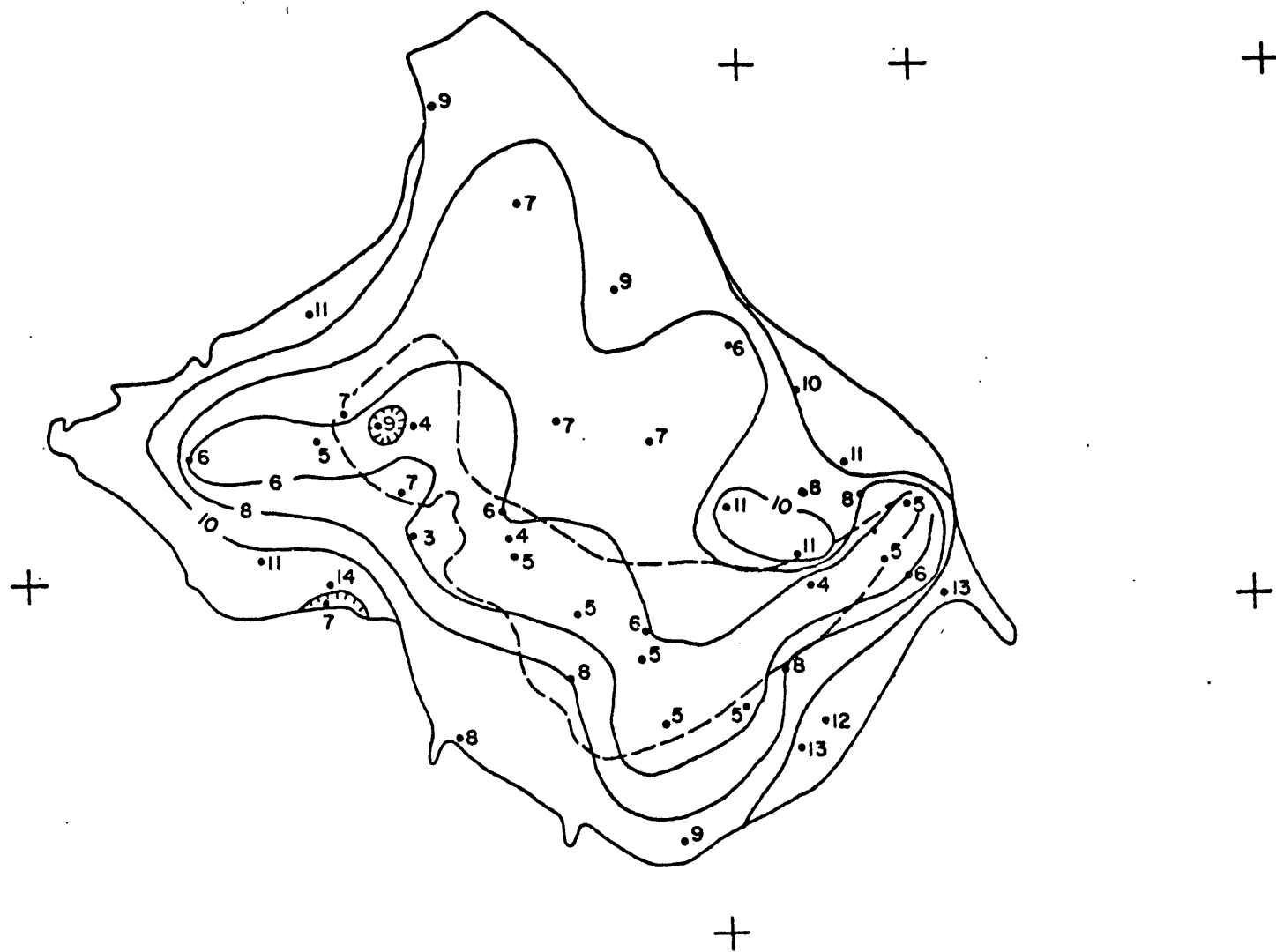


Figure 18d

EAGLE PEAK PLUTON MAFICS

and hornblende crystallized earliest, followed by quartz, and later by alkali feldspar. The results of any mechanical process acting on the crystal-liquid aggregate would be dependent upon the stage of crystallization.

The experimental studies of Piwinskii (1968b; 1973), summarized in Figure 19, support the petrographically determined crystallization sequence. They also show a significant temperature interval between the appearance of hornblende or plagioclase and alkali-feldspar over a wide range of pressures. This may result in a significant time-temperature interval during which fractionation may occur.

Whitney's (1975) study is consistent with the data of Piwinskii (1968b; 1975) and amplifies the effect of varying water pressure on crystallization sequence.

The modal trends present on the K-P-Q-M diagrams and the normative trends present in the granitic tetrahedron would result by crystal fractionation beginning with the most mafic compositions. Plagioclase and mafics are the earliest formed minerals; their subtraction drives the remaining liquid to the quartz-alkali feldspar fields. Later, quartz becomes a liquidus phase and further fractionation forces the remaining liquid to become enriched in the alkali feldspar component.

Removal from the liquid of the early mafic silicates produces the silica enrichment and FeO-MgO depletion observed for the samples. The Mg/Fe ratio of the mafic silicates is greater than their host rocks; thus, their subtraction will produce liquids with lower Mg/Fe ratios. This trend is shown in Figure 13. It is culminated

Figure 19: Pressure-temperature water-saturated melting diagram
of Sierra Nevada granodiorite; from Piwinskii (1973),
Mount Givens Granodiorite.

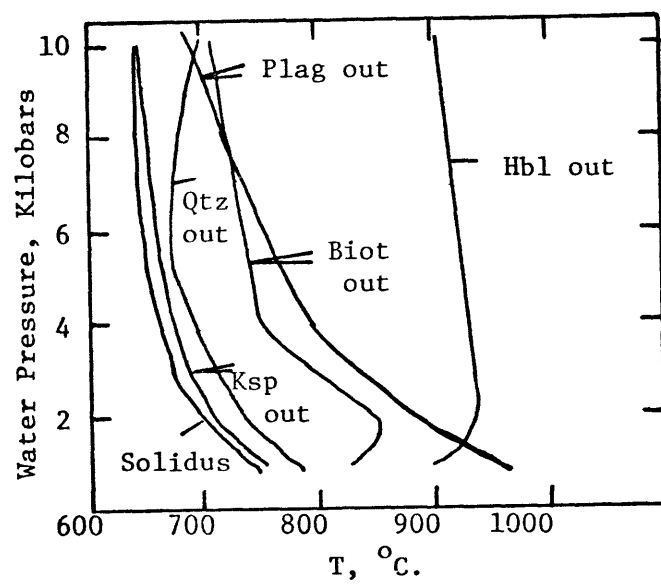


Figure 19

by the very low Mg/Fe ratio of the aplites which also have the greatest alkali enrichment. Viewed in the granitic tetrahedron the initial subtraction of plagioclase will force the residual liquid towards the Ab-Or-Q base and towards the Or-Q sideline. This is the trend followed by the granitic samples, and the aplites lie at the most Or-Q extent of the trend. The data trends are reasonably well explained by crystal-liquid fractionation, but note that the separation of solids from liquid can result from several different physical processes (discussed in the next section).

CRYSTAL-LIQUID FRACTIONATION MECHANISMS

Convection and Gravitational Settling

Gravitational settling is believed by this author to be a dominant process in producing the zoning of the Eagle Peak pluton. This process would take place after intrusion of the magma and during crystallization inwards from the pluton margin. Gravitational settling would affect crystals in all parts of the pluton, but would be more extensive in the more slowly cooling core. Since the early formed minerals are mafics and plagioclase the residual interior liquid would become more felsic than the original magma or the marginal zones. Crystal settling is an accepted process for mafic systems (Carmichael, Turner, and Verhoogen, 1974). Shaw (1965) presents data indicating hornblende, biotite, plagioclase, and alkali feldspar of the grain size encountered in these plutons could be expected to settle approximately 1 meter per year in a granitic magma. The analyses by Jaeger (1957) indicate that a pluton of approximately 7 kilometers in diameter, the size of the Eagle Peak pluton, would

require over 700,000 years to completely solidify, and about 300,000 years to reach 50% crystallization, thereby providing ample time for gravitational differentiation. This model may be modified by convection. Filter pressing of residual liquid toward the core by the crystallizing margin is not evaluated here, but it also is very likely contributory. Presnall and Bateman (1973) believe filter pressing is largely responsible for the zoning observed in Sierran plutons. This process does not explain the absence of hornblende from the interior of the pluton if hornblende were suspended in the initial magma.

Gravitational settling as a fractionation mechanism applies less well to the Red Lake pluton, which instead of concentric zoning has a minor lateral, crescentic zoning. One possible factor is residual heat in the Mount Givens granodiorite, the youngest pluton intruded by the Red Lake pluton. This could retard crystallization on the east side of the Red Lake magma. Alternatively, part of the zoning in the Red Lake pluton may result from selective interaction with wall rock. Table 16 gives representative analyses of the Red Lake pluton, the Dinkey Creek pluton to the west, and the Dinkey Dome pluton to the east. Clearly, the compositional gradient is consistent with selective interaction between the intrusive magma and the wall rocks. However, there is no evidence at or near the contacts to support this hypothesis.

Gravitational settling is strongly dependent upon magma viscosity, which is dependent upon H_2O content and magma temperature. An increase in the viscosity of the Red Lake magma by early loss

TABLE 16

Representative analyses of the Dinkey Creek, Red Lake, and Dinkey Dome plutons.

	Dinkey Creek	Red Lake		Dinkey Dome
	HL-9 ^a	CR-29 ^b	CR-5 ^b	HL-29(2) ^c
SiO ₂	66.3	68.6	69.8	75.4
Al ₂ O ₃	16.1	15.9	16.1	13.5
Fe ₂ O ₃	1.2	1.3	1.2	0.00
FeO	2.8	1.8	1.5	0.64
MgO	1.6	1.1	0.76	0.10
CaO	4.6	3.3	2.8	1.0
Na ₂ O	3.2	3.6	3.4	4.0
K ₂ O	2.7	2.7	2.9	4.6
H ₂ O ⁺	0.67	0.86	0.81	0.34
H ₂ O ⁻	0.07	0.11	0.09	0.04
TiO ₂	0.54	0.49	0.45	0.15
P ₂ O ₅	0.14	0.14	0.12	0.07
MnO	0.07	0.03	0.02	0.04
CO ₂	0.05	0.05	0.05	0.05
Total	100	100	100	100

^aGranodiorite of Dinkey Creek, sample HL-9, Bateman and Wones (1972a)

^bAnalyses from this study

^cQuartz monzonite of Dinkey Dome, sample HL-29(2), Bateman and Wones, (1972a)

Analytical values in weight percent.

of H_2O would strongly inhibit crystal settling. The extensive hydrothermal alteration in the vicinity of Bear Butte may reflect early and continuing loss of exsolving magmatic water. The absence of comparable alteration in or near the Eagle Peak pluton suggests that this magma retained its H_2O until the final aplitic-pegmatitic stage. The lesser abundance of pegmatites and aplites in the Red Lake pluton is a logical result of periodic losses of H_2O so that late stage high ambient pressures cannot develop. The slight zoning present in the Red Lake pluton probably represents the thermal effect of the Mount Givens granodiorite on the initial Red Lake magma which lost its volatiles and was too viscous for significant differentiation. The well developed normative and modal trends may reflect, in part, local filter pressing.

Flow Differentiation

Flow differentiation is widely accepted as producing mineralogical and chemical variation in mafic dikes and sills. Studies by Komar (1972a; 1972b) and Bhattacharji and Smith (1964) provide a theoretical basis and examples indicating the effects of flow on suspended crystals. In general, during flow through a conduit the phenocrysts tend to migrate toward the interior of the flowing magma. The distribution of phenocrysts is dependent on a variety of parameters, including abundance and size distribution of phenocrysts, viscosity of the magma, and flow rate. There are two models which apply this mechanism to the mineralogical zoning of the Eagle Peak pluton. In the first, the intrusion of magma is during the initial stages of crystallization, when, based on petrography, plagioclase and

mafics are the only phenocrysts. Flow differentiation would produce a greater abundance of these minerals in or toward the center of the pluton. This is the reverse of the observed zoning and makes this model untenable. The second model is the intrusion of a magma containing alkali feldspar phenocrysts. Petrography and experimental petrology indicate all other major minerals would also be present in the magma as a dense assemblage of phenocrysts. Komar (1972a, 1972b) approached this problem in two ways. If phenocrysts are in low enough abundance to prevent grain interaction they should be distributed in a gradational manner unless variations in their size or density are present. However, the large alkali feldspar phenocrysts are not distributed gradationally; they are nearly absent from the equigranular margin. Furthermore, there is no tendency for the smaller phenocrysts to increase in abundance toward the core. An alternative approach is to consider a dense assemblage of phenocrysts in which grain interaction is significant, and phenocrysts will be sorted predominantly by size. In this case the absence of size sorting of alkali feldspar phenocrysts near the core-margin contact suggests that flow differentiation is not responsible for the zoning.

Other observations suggest flow differentiation is not responsible for the zoning. When grain interaction is minimal the sorting is dependent on magma viscosity. Sorting is observed in mafic systems, but viscosities of granitic systems are 10 to 100 times greater than those of basaltic magmas (Shaw, 1965), and sorting should be much less important and possibly less efficient. The total number of alkali feldspar phenocrysts present within the Eagle Peak magma

would quite likely produce fractured phenocrysts during extensive flow; these are not observed. If flow produced two distinct zones with respect to phenocryst size (and therefore composition) modal plots would be discontinuous for the core and the margin rather than gradational as observed. Mafic inclusions, in spite of their density, should be present in greater abundance and size toward the core assuming they were present in the initial magma. Just the reverse is seen for most Sierran plutons (Bateman and others, 1963) and no particular distribution is present in the Eagle Peak pluton. Therefore, flow differentiation cannot explain the zoning in the Eagle Peak pluton whether or not alkali feldspar is present.

Additional Processes

The preceding discussion indicates crystal-liquid fractionation after intrusion can adequately produce the chemical and mineralogical zoning within the Red Lake and the Eagle Peak plutons. Other possible mechanisms and reasons for discounting them are discussed below.

1. Intrusion of a heterogeneous source magma with subsequent solidification preserving the initial variations. This still requires explanation of the initial process and leads to the preceding fractionation discussion.
2. Selective interaction of the cooling magma with the wall rock. Extensive interaction with wall rock is not indicated by any of the contacts. In addition, much of the wall rocks are granitic plutonics more felsic than the marginal parts of the Eagle Peak and incapable

of producing the observed variations. The relationships are not quite as clear for the Red Lake pluton.

3. Autointrusion; this mechanism is applicable only to producing the porphyritic core of the Eagle Peak pluton. However, the contact between the porphyritic core and the equigranular margin is gradational; there is no evidence of autointrusion.
4. Differential transport of inclusions and xenocrysts. This mechanism was partially eliminated in the section on flow differentiation. There can be no question the xenocrysts, mafic inclusions, and disaggregated mafic inclusions contribute to compositional variations within the plutons. However, they are not the dominant influence on compositional variation.

The preceding processes are all potentially important in magmatic systems. Some may be contributory to zoning in the Red Lake pluton and the Eagle Peak pluton, but none are believed dominant.

INTERPRETATION OF MINERAL CHEMISTRY

Alkali feldspars

X-ray data reveals close similarity in the apparent structural states of the alkali feldspars in the granitic rocks. Variations in structural state of alkali feldspar within plutons have been related by Ragland (1969) and Tilling (1968) to changes in water fugacity, temperature, and reheating by subsequent intrusions. Because of their similarity the feldspars of this study appear to

reflect a limited range of conditions with no indication of later reheating and subsequent changing of structural state. This is consistent with the contact relationships indicating the porphyritic core of the Eagle Peak pluton forming in situ rather than representing a subsequent intrusion. Furthermore, these are the youngest plutons in the area and they should have the simplest thermal history.

Alkali feldspar compositional variation in the granitic samples is very limited, both within grains and throughout both plutons. It is possible that late stage alkali metasomatism, allowing exchange of sodium and potassium, could have eliminated any original zoning within grains and subdued variations within the plutons. The common hydrothermal alteration of biotite to chlorite in both plutons may have released K_2O and thereby provided a mechanism for alkali exchange. However, Ragland (1969) observes a range of alkali feldspar composition from only Or_{87} to Or_{91} in the Enchanted Rock batholith for host rock compositions fairly similar to the range covered by the samples of this study.

Plagioclase

The strong zoning of the plagioclase of this study is typical for Sierran granitic rocks. Several factors may contribute to zoning: convection in the magma chamber, variation inherited from a source region (i.e., magma is introduced as a crystalline mush), changes in pressure and temperature conditions of the magma chamber. In addition, Steiner, Jahns, and Luth (1975) have observed erratic variation in tie line orientation during final stages of

crystallization in the much simpler haplogranite system. For the compositions involved here the first three factors are probably responsible for the zoning. The close similarity in plagioclase core composition of all granitic samples, in spite of the extensive zoning, suggests a close genetic association of all plagioclase crystals and that processes such as flow differentiation or gravitational settling did not completely remove the early formed crystals from any area. Convection would aid in preventing such depletion; Bartlett (1969) indicates convection is possible in granitic plutons.

Aplite Feldspars

Alkali feldspar and plagioclase in aplites from both plutons are richer in Or and Ab, respectively, than feldspars of the host granitic rocks. The aplite plagioclase is not extensively zoned. Core compositions for aplite plagioclases are very similar to marginal compositions of host rock granitic plagioclase. No aplite plagioclases were found to have core compositions similar to those of granitic plagioclase. This indicates plagioclase in the aplites represents a later generation of crystallization, probably from a residual liquid. Field observations indicate uncommon phenocrysts of plagioclase and other minerals in some aplites which are probably xenocrysts torn from the surrounding rocks during intrusion. Small xenoliths of granitic rock observed in the aplites support this interpretation.

Feldspar Compositional Trend

The crystallization sequence implied for the Eagle Peak pluton is from the margin toward the core, and approximately from west to east for the Red Lake pluton, with aplites crystallizing from the residual liquid in both plutons. Carmichael (1963) and Tuttle and Bowen (1958) indicate that in natural and experimental systems, crystallization of two feldspars is accompanied by an increase in Ab component of both feldspars. Plagioclase follows a sodium enrichment trend in these plutons, but alkali feldspar does not. The Red Lake pluton alkali feldspars actually show an increase in Or content during the inferred crystallization sequence; those of the Eagle Peak core are essentially of constant composition, but those of the corresponding aplite are richer in Or. This Or enrichment trend for the alkali feldspars would appear to be a result of extensive plagioclase, mafics, and quartz crystallization, producing a residual liquid with increasing Or activity.

Mafic Silicates and Oxides

An initial goal of this study was to utilize the mineral assemblages to determine intensive parameters. This goal was thwarted by the absence of coexisting Fe-Ti oxides. Only one oxide is present, essentially pure magnetite. Magnetite occurs as discrete grains and also as inclusions in biotite and hornblende. In some biotites and hornblendes the magnetite is clearly associated with chloritic alteration.

Biotite

There is very little variation in the composition of the biotites in the Eagle Peak and the Red Lake plutons, either within or between the two bodies. $\text{Fe}/\text{Fe}+\text{Mg}$, one of the more important variables in interpreting biotite assemblages, varies between 0.53 and 0.58. Dodge and Moore (1968) noted that this ratio varied between 0.43 and 0.47 in biotites for samples from the Cartridge Pass pluton. They concluded that this minor variation was caused by a late stage hydrothermal phase permeating the entire pluton and re-equilibrating the biotites. As these two plutons show signs of alteration, it is possible that their biotites have also re-equilibrated.

Careful analysis of the compositional trend of the FeO-MgO diagram (Figure 8) and its relation to sample locality (Figure 3) and stage of crystallization, suggests that biotites with greater $\text{Fe}/\text{Mg}+\text{Fe}$ (CR5 and E91) are from more differentiated (excluding the Eagle Peak core) and therefore lower temperature rocks. This trend in $\text{Fe}/\text{Mg}+\text{Fe}$ is that expected for plutons crystallizing along an oxygen buffer. Dodge, Smith, and Mays (1969) have suggested such a trend is followed collectively by the biotite from the Sierra Nevada batholith. Samples collected from the Red Lake pluton are too homogeneous to evaluate this process. Samples from the core of the Eagle Peak pluton (E83, C1) have lower $\text{Fe}/\text{Mg}+\text{Fe}$ than interior equigranular samples (E91). Cooling along an oxygen buffer such as Ni-NiO does not explain the compositional relation of the core samples to the marginal samples. A mechanism explaining this trend is rupturing of the system with evolution of

water, as suggested by Wones and Eugster (1965). More rapid diffusion of H_2 relative to H_2O would produce an effective increase in fO_2 . This would oxidize the existing biotite, producing a more MgO rich variety. Clearly, late stage rupturing of the Eagle Peak pluton occurred, as indicated by the abundance of pegmatites and aplites. Furthermore, the fine grained groundmass of porphyritic sample E83 indicates a rapid quench and porphyritic sample C1 has an equigranular, medium grained groundmass, with alkali feldspar overgrowths on alkali feldspar phenocrysts, that suggest nearly complete crystallization at the time of quenching. Exhalative oxidation would thus be more extensive in sample E83, producing an Fe/Mg+Fe ratio even less than that of C1. Oxidation of biotite in this environment would form magnetite as a product. Thin section modal analyses were not made for samples of E83 and C1, as grain size and texture prohibit meaningful thin section modes. However, the relation between major element chemistry of the host rock and biotite compositions provides an evaluation of the process. Whole rock C1 has greater Fe/Mg+Fe than rock E91, which is inverse to that for the biotites. Another Fe bearing phase besides biotite must be present in greater abundance in C1 than in E91. Hornblende is essentially absent in both rocks, sphene contains very little Fe, thus magnetite must provide the balance. A major element analysis is not available to evaluate this effect for sample E83. However, magnetite is intergrown with biotite in both samples E83 and C1. Although some of this appears to form during chloritization, much is found without any associated alteration. This evidence supports internally

buffered crystallization, interrupted in the Eagle Peak pluton by late stage rupturing and exhalation leading to oxidation.

Whole rock Fe_2O_3 and FeO data indicate that the samples of the Red Lake pluton are more oxidized than those of the Eagle Peak pluton. Sample C1 is a significant exception and also has a greater $\text{Fe}^{+3}/\text{Fe}^{+2}$ ratio for its biotite. Thus the $\text{Fe}^{+3}/\text{Fe}^{+2}$ calculated for biotite of the Eagle Peak pluton are based on that of C1 and may actually be too high. CR5 may be a more appropriate standard for the equigranular samples. C1 is more oxidized than CR5 which has similar Fe/Mg+Fe and total Fe and MgO concentration. This is expected in a more oxidized system, although the variation in oxidation state may have occurred in the subsolidus as well as during magmatic conditions.

Hornblende

As with the biotites, iron concentration variations in hornblende are those most readily related to intensive parameters. However, hornblende compositions do not always reflect magmatic conditions. Dodge, Papike, and Mays (1968) observed hornblende compositional variations in the Sierra Nevada batholith unrelated to host rock composition. For self-consistency the interpretation of the hornblende compositions must be consistent with other data.

If the magmas cooled along an oxygen buffer the later formed hornblendes should be more FeO enriched than earlier formed hornblendes. In the Eagle Peak pluton samples E92 and E31A (Table 10), near the outer margin of the pluton, and sample E84 from the core, conform to the trend. Marginal samples E97 and E31B are exceptions. An explanation for these exceptions, assuming crystallization along

a buffer, is post-magmatic alteration of E31B and E97. Aplites and pegmatites occur at outcrops of these samples and late stage water evolution could have altered the hornblende. Samples CR38 and CR29 of the Red Lake pluton appear to reflect the inferred buffer influence: CR29 is nearer the interior of the pluton, presumably crystallized later than CR38, and contains more Fe total than CR38. The apparently greater MgO content of Red Lake hornblendes may reflect a more oxidizing environment in that pluton than in the equigranular margin of the Eagle Peak pluton. This would result from the periodic or continuous degassing inferred from other data.

INTENSIVE PARAMETERS

Introduction

Knowledge of the intensive parameters P (pressure), T (temperature), f_{H_2O} (water fugacity), and f_{O_2} (oxygen fugacity) can aid in understanding the petrogenesis of the two plutons. The mineral and rock compositional data of this study are combined with experimental data on mineral stability and melting relationships of granitic liquids to estimate these parameters.

Aplites

The aplites of this study have been interpreted as representing the water saturated residual melt of the granitic liquid. Since they consist of greater than 95% normative Ab, Or, Q they may be compared with reasonable confidence to the experimental data of Tuttle and Bowen (1958). Figure 20 shows pertinent experimentally determined equilibria in the Ab-An-Or-Q- H_2O system as well as several 1/2

Figure 20: Normative quartz-albite-orthoclase diagram showing experimentally determined ternary minima (Tuttle and Bowen, 1958), minima in An-bearing systems (James and Hamilton, 1969), liquidus contours (Tuttle and Bowen, 1958), and aplite compositions from the Red Lake and the Eagle Peak plutons.

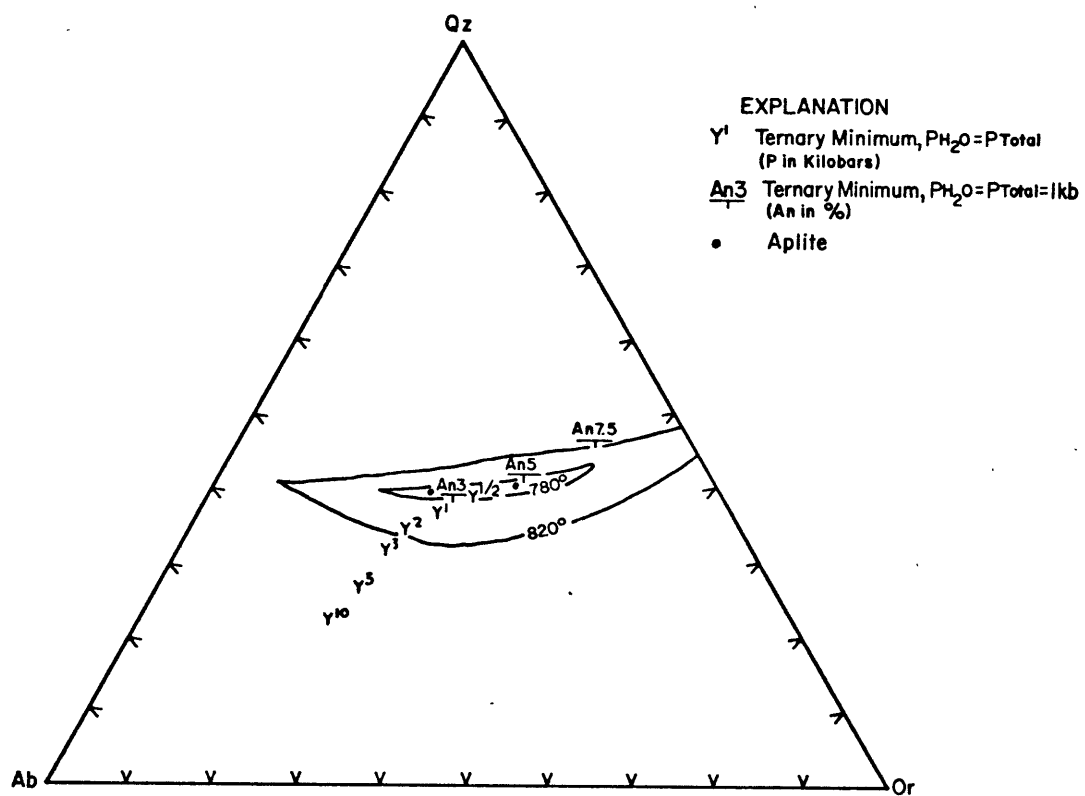


Figure 20

kilobar temperature contours in the system Ab-Or-Q-H₂O (Tuttle and Bowen, 1958). Both aplites plot near the 1/2 kilobar thermal trough in the Ab-Or-Q-H₂O system. A temperature of about 780°C. is indicated for aplite CR14 with a slightly higher temperature for aplite C3. Aplite C3 actually lies across the thermal minimum from its host rocks.

Melting Data

Water saturated melting studies on the Mount Givens granodiorite which is modally and chemically similar to the granitic samples of this study have been performed by Piwinskii (1968b; 1973). His results were summarized previously in Figure 19. A magma which crystallized at the same pressure as the aplites would require a liquidus temperature of at least 800°C. An H₂O undersaturated magma would require a greater temperature. The formation of aplites as discussed in this paper requires water saturation of the magma only near the end of crystallization. Initial temperatures of at least 800°C. are therefore implied for the parent magmas of the Red Lake and Eagle Peak plutons.

Feldspar Geothermometer

Temperature estimates using the feldspar geothermometer of Stormer (1975) are given in Table 17. The extensive zoning of plagioclase makes the method difficult to use, especially in granitic rocks. Temperatures were calculated for both core and marginal compositions of plagioclase, at a pressure of 500 bars. Clearly, the temperatures calculated by this method are much lower than those estimated from melting equilibria. The relative values are as expected, with those of the aplites lower than their host plutons,

TABLE 17

Temperature estimates and pressure dependence using the feldspar thermometer of Stormer (1975)

		<u>Pressure, bars</u>			
Feldspar pair* and sample locality	Plagioclase analysis:	<u>500</u>	<u>1000</u>	<u>5000</u>	
		<u>Core</u>	<u>Margin</u>	<u>Margin</u>	<u>Margin</u>
		T, °C.			
<u>Red Lake pluton</u>					
CR29	Equigranular facies	560	440	450	490
CR5	Equigranular facies	480	390	400	430
CR1	Bear Butte facies	390	370	380	420
CR14	Aplite dike	360	340	350	380
<u>Eagle Peak pluton</u>					
E92	Equigranular margin	510	440	440	490
E91	Equigranular margin	510	450	460	500
C1	Porphyritic core	500	440	450	490
E83	Porphyritic core	520	450	460	500
C3	Aplite dike	420	400	410	440

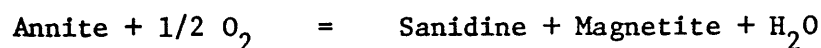
*Feldspar compositions used in all calculations are those reported in this table.

CR5 is lower than CR29, and the Bear Butte facies is between the aplites and CR5. Granitic samples of the Eagle Peak pluton have very similar temperatures. Hon (1976) applied a similar feldspar thermometer to granitic rocks of central Maine. He found the method yielded reasonable results except when the feldspars showed even minimal sericitic-kaolinitic alteration, which yielded very low and unacceptable temperatures. He attributed the effect to post magmatic conditions. The feldspars of this study show some kaolinitic alteration, so that the calculated temperatures probably indicate the lowest temperature at which they were in equilibrium. The chloritic alteration of biotite releases potassium which exchanges with sodium in the alkali feldspar (Chayes, 1955) to produce lower indicated temperatures.

Petrographic observation indicates up to 10 to 15% of the biotite in these rocks has been altered to chlorite. Assuming the rocks of this study contain 10% biotite and 20% alkali feldspar, the amount of potassium released during the biotite alteration could exchange approximately 25% of the sodium in an alkali feldspar of composition Or_{80} . Chayes (1955) suggests some of this potassium may be lost from the system instead of forming alkali feldspar. However, it is clear that such exchange may produce lower calculated feldspar temperatures.

Biotite Equilibria

The compositions of coexisting magnetite, alkali feldspar, and biotite can be used to estimate fO_2 , T , and fH_2O by evaluation of the reaction:



for which Wones (1972) has determined the equilibrium constant:

$$\begin{aligned} \log fH_2O &= 7409/T + 4.25 + 3 \log a_{\text{annite}} \\ &\quad - \log a_{\text{magnetite}} - \log a_{\text{sanidine}} \\ &\quad + 1/2 \log fO_2, \end{aligned}$$

where T is the temperature in $^{\circ}K$., and a , the activities of the subscripted phases, are determined as follows:

1. $a_{\text{magnetite}} = 1$
2. $a_{\text{sanidine}} = X_{\text{Or}}^{\text{Af}}$ (mole fraction of orthoclase in alkali feldspar, based on the data of Waldbaum and Thompson, 1969)
3. $a_{\text{annite}} = Fe^{+2}/6$ (fraction of total octahedral biotite sites occupied by ferrous iron; see Wones, 1972).

Biotite stability is also a function of F content (Czamanske and Wones, 1973) and Al content (Rutherford, 1973). Fluorine was not analyzed in the biotites of this study. Analyses of other Sierran biotites (Dodge, Smith, and Mays, 1969) indicate only about 5% of the OH positions are occupied by F and this amount is considered insignificant for the purpose of this study. Rutherford (1973) indicates only a qualitative significance to Al content, with greater stability resulting from increased aluminum content. Al values

are similar for all biotites of this study and thus no stability differences are expected as a result of Al.

The preceding equation was used to evaluate the stability relations of biotite from rock samples CR5 and C1 of the Red Lake and the Eagle Peak plutons, respectively. Mineral activities were calculated from coexisting assemblages analyzed in this study. Because the magmas appear to have been internally buffered near the Ni-NiO oxygen buffer, the above equation was evaluated as a function of temperature with fO_2 determined from two different buffers: the Ni-NiO buffer (Huebner and Sato, 1970), and a hypothetical buffer one-third of the way between Ni-NiO and magnetite-hematite (Czamanske and Wones, 1973), lying closer to Ni-NiO. The results are plotted in Figure 21. Also plotted is the water saturated solidus for the Mount Givens granodiorite determined by Piwinski (1968b) which is similar to the Or-Ab-Q-H₂O minimum determined by Tuttle and Bowen (1958). The Mount Givens granodiorite is mineralogically and chemically very similar to the plutons of this study (Bateman and Wones, 1972a) and its melting relations should be quite applicable to this study.

Stability curves for both biotites are very similar. Biotite CR5 appears stable at lower temperatures, but the difference between the curves in Figure 21 is not considered significant. More important is the rather large shift in the stability curves to lower temperatures with the larger oxygen fugacities of the hypothetical buffer. The intersection of a stability curve with the Mount Givens solidus indicates the minimum temperature and water pressure at which the biotite may crystallize from a granitic melt. The preceding discussion

Figure 21: T-fH₂O stability curves for biotites CR5 and C1 from the Red Lake and Eagle Peak plutons, respectively; also shown is the experimentally determined solidus curve for the Mount Givens granodiorite (Piwinskii, 1968b).

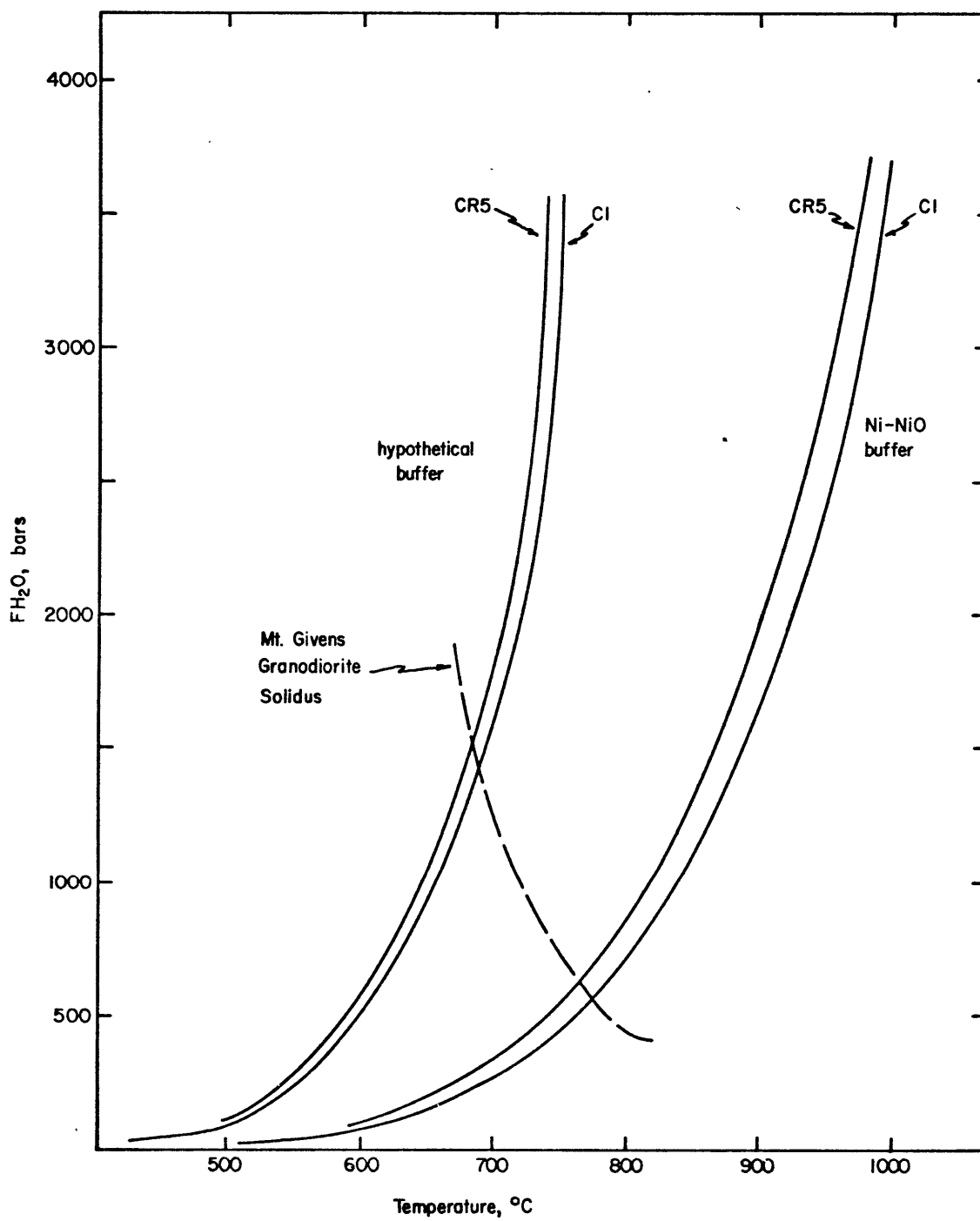


Figure 21

suggests those curves calculated with the hypothetical buffer are more appropriate. Temperature and water fugacity minima for biotites CR5 and C1 are therefore approximately 700^{+50}_{-50} °C. and $1.4^{+0.5}_{-0.5}$ kilobars. This water fugacity corresponds to a pressure of approximately 2.1 kilobars (Burnham, Holloway, and Davis, 1969). This temperature is much higher than those calculated from the feldspars (approximately 400°C.) and somewhat less than the 780°C. implied by the aplite data. However, the aplite data implies a water fugacity of approximately 500 bars, which in terms of Figure 21 suggests the Ni-NiO buffer curves may be most applicable. These curves indicate a temperature minimum of approximately 780°C., similar to that implied by the aplite data. The data point to a minimum temperature of approximately 750^{+50}_{-50} °C. and a water fugacity of approximately 1000 ± 500 bars.

Oxygen fugacity-temperature relations calculated for biotite CR5 at several assigned total pressure values are plotted in Figure 22 with the reference assemblages magnetite-hematite and Ni-NiO. Values of f_{H_2O} used in the biotite stability equation were taken from Burnham, Holloway, and Davis (1969). Stability curves for biotite C1 would plot at slightly higher f_{O_2} values than those for biotite CR5. Biotite is stable only at temperatures above and oxygen fugacities below a given stability curve. The Ni-NiO assemblage is considered to define the maximum T and minimum f_{O_2} . The 500 bar stability curve allows a maximum T of approximately 725°C., whereas that for 2000 bars is approximately 875°C. Any pressure between these extremes would require temperatures reasonably consistent with the

Figure 22: T-fO₂ stability curves for biotite CR5 from the Red Lake pluton; curves for C1 are nearly identical and are not shown; curves calculated for several total water pressures; reference Ni-NiO and Fe₃O₄-Fe₂O₃ buffer curves shown.

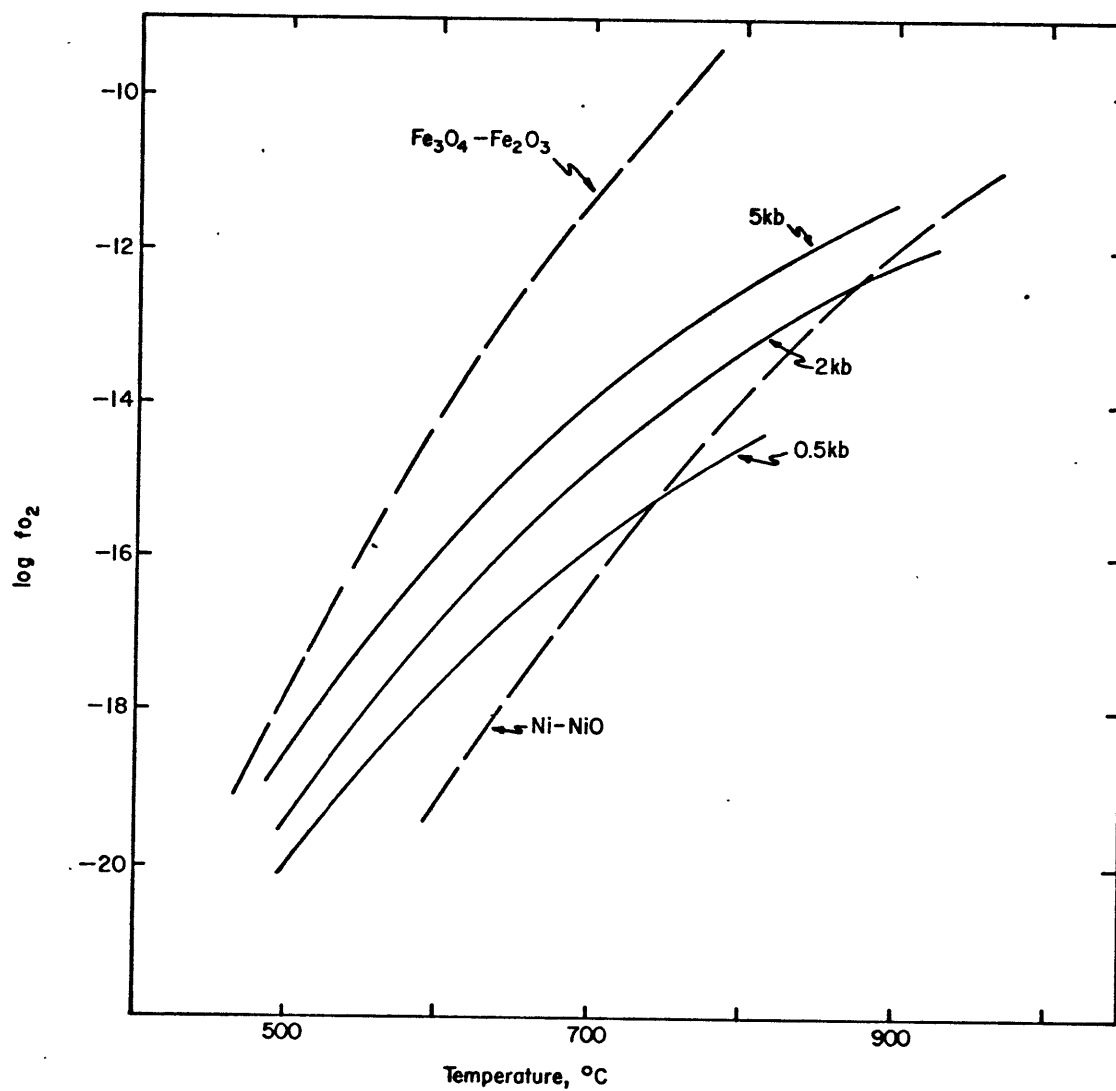


Figure 22

f_{H_2O} -T relations, the aplite data, and experimental studies.

A corresponding oxygen fugacity would be -14.5 ± 1 log units, as compared to -13 log units obtained by Dodge and Moore (1968) for the Cartridge Pass pluton.

DEVELOPMENT OF ALKALI FELDSPAR PHENOCRYSTS

The most significant petrologic difference between the core and the margin of the Eagle Peak pluton is the mode of occurrence of alkali feldspar. In the margin it is entirely interstitial, in E83 it occurs as distinct phenocrysts, and in the major portion of the core it has both characteristics. Field relations indicate in-situ development for most of the core.

Other texturally zoned plutons have been observed in the Sierra Nevada batholith. The Cartridge Pass pluton, described by Moore (1963), has a fine grained margin and a porphyritic core containing alkali feldspar phenocrysts. Most of the contact between the core and the margin is gradational. In discussing the similarity in biotite composition across the pluton, Moore concludes the bulk of the porphyritic core developed in place and that a hydrous phase developed late during crystallization, penetrated the system, and re-equilibrated the biotite. Putman and Alfors (1969) propose a different interpretation for the Rocky Hill Stock. This pluton has a medium grained margin which grades into a fine grained subporphyritic core. They conclude that as the pluton crystallized from the margin inwards it became saturated with volatiles, and upon rupturing the pluton's

interior was quenched. In both plutons the core is found locally to intrude the marginal zones.

The Eagle Peak pluton possesses features similar to the Rocky Hill and the Cartridge Pass plutons. E83 is broadly similar texturally to the core of the Rocky Hill stock, although it is very limited in extent. The conclusions reached by Moore (1963) and Putman and Alfors (1969) may be applicable to this study. Juxtaposition of two textural variants of the core is explained if E83 is a later intrusive from deeper levels of the crystallizing magma. Lack of exposure prevents thorough evaluation of this process, but it is supported by the limited occurrence of E83 and the absence of intermediate textures gradational between C1 and E83. In addition, movements of the core have been observed in other plutons.

In this study the texture of E83 substantiates that alkali feldspar is a liquidus phase in the core. Consideration of the crystallization model developed for the Eagle Peak pluton and experimental studies reveals several important features which explain the development of alkali feldspar phenocrysts in both parts of the core:

1. Decreasing anorthite component of the melt causes a shift of the minimum toward albite (see Figure 20).
2. Increasing water pressure shifts the minimum toward albite (see Figure 20).
3. Crystallization from the margin inwards increases orthoclase activity in the interior melt.
4. Increasing water pressure lowers the viscosity of the magma, aiding diffusion.

5. Crystal settling produces a pluton interior with fewer mafics and possibly more magma.

The first three factors accelerate the approach of the residual liquid to the alkali feldspar-plagioclase boundary and the last two allow ready, uninhibited alkali feldspar growth once that boundary is reached.

APLITE FORMATION

It is interpreted that the aplites in these plutons formed from the residual melt of crystallizing granitic liquids. Modally and chemically the aplites are found to lie at the extreme end of postulated crystal fractionation-differentiation trends. Petrographic observations of mineral paragenesis also indicate the residual liquid should become more enriched in quartz and alkali feldspar components and depleted in mafics and plagioclase during crystallization. Extreme crystallization in these plutons apparently produced a silicic, potassic residual liquid which intruded fractures formed late during crystallization. Rapid chilling of the liquid by loss of gas produced the very fine grained aplitic texture. The uncommon phenocrysts were possibly carried as xenocrysts from the host pluton. The close association of the pegmatites and aplites, and the cavities present in the interior of some pegmatites within the Eagle Peak pluton suggests the pegmatites were formed from the same residual liquid as the aplites. The aplites formed when the vapor was suddenly exsolved, whereas it was retained by the pegmatites. The several periods of aplite development recognized through field observations is consistent with periodic buildup and explosive release of H_2O within the melt during the later stages of crystallization.

SUMMARY

The intrusion and crystallization history of the Red Lake and the Eagle Peak plutons can be summarized as follows:

1. Intrusion of a crystal-bearing magma to a pressure of approximately 1000 bars, corresponding to a depth of approximately 3 kilometers, at a temperature in excess of 750°C.
2. Crystallization with internally defined oxygen fugacities.
3. Crystal-liquid fractionation, producing the observed variations in composition within each pluton and leading to a potassic-silicic residuum.
4. Concentric fractionation in the Eagle Peak pluton, resulting in a porphyritic core with alkali feldspar phenocrysts.
5. Late stage volatile buildup and escape, producing aplites, pegmatites, and the oxidation of biotite in the Eagle Peak pluton.
6. Deuteric alteration and post magmatic mineralogical compositional adjustments.
7. Early and continuing, possibly episodic degassing of the Red Lake pluton which produced the hydrothermally altered Bear Butte facies, and prevented as extensive a development of pegmatites and aplites as found in the Eagle Peak pluton. The degassing may also contribute to the more oxidized nature of the Red Lake pluton as compared to the Eagle Peak pluton.

The earlier degassing of the Red Lake pluton is probably the result of greater initial water content than in the Eagle Peak pluton, as aplite data suggest a similar load pressure for both plutons. Similarities in mineralogical composition suggest the difference was relatively minor.

Textural, petrologic, and chemical variations within the Eagle Peak pluton are explained in terms of a crystallizing magma having only minor interaction with wall rock. Crystallization proceeded inwards from the margins. Gravitational segregation of early formed crystals may have been accompanied by convection. After extensive crystallization, saturation with volatiles occurred and the system ruptured, forming aplites and pegmatites. Several stages of this are indicated by intersecting aplites and pegmatites and by the fine grained groundmass of textural variant E83.

CHAPTER II

TRACE ELEMENT GEOCHEMISTRY OF SIERRAN PLUTONS

INTRODUCTION

The magmatic history of the Red Lake pluton and the Eagle Peak pluton of the Sierra Nevada batholith was investigated in a previous section using field and petrologic techniques.

To further elucidate the petrogenesis of these plutons a trace element study of selected whole rocks, aplites, and mineral separates was undertaken. The results and their relevance to the Sierra Nevada batholith and granite petrogenesis are presented and discussed in the following sections.

SAMPLING, SAMPLE PREPARATION, AND ANALYTICAL METHOD

Samples selected for trace element analysis were collected from the freshest possible representative outcrops. Bulk samples at least 1000 times the volume of the maximum observable heterogeneity were collected. Jaw crushers and hammers were used to reduce the samples to pass through splitters.

Mineral separations were performed using a combination of heavy liquids, Frantz Magnetic Separator, hand magnet, and hand picking. All sieving was performed with a plexiglass sieve frame and plastic sieving screen.

An instrumental neutron activation procedure (INAA) similar to that used by Buma, Frey, and Wones (1971) and Lopez (1974) was used

to obtain the trace element data. The analyses of this study were performed in accordance with the procedures discussed by Lopez (1974) and with standards prepared by him.

Estimates of the precision and accuracy of the method are given in Tables 18 and 19. Trace element values of G-2 obtained in this study are comparable with those obtained by other investigators. The standard deviation for duplicate analyses of whole rock sample CR5 is less than 10% for all elements except Ho (25%) and U (11%). Counting statistics on rocks and mineral separates calculated after the method of Quittner (1969) are less than 10% for all elements except Ho (24%), Lu (13%), and U (14%). The estimated accuracy is believed to be within 10% for all elements except Ho (25%), U and Lu (15%). Duplicate analyses of Ta from CR5 were not obtained. However, the statistical uncertainty of CR5 and standard deviation calculated from G-2 indicate an accuracy of about $\pm 10\%$.

GRANITIC ROCKS

Rare Earth Elements (REE)

Whole rock trace element abundances are given in Table 20 and chondrite normalized rare earth element plots of selected whole rock data are shown in Figures 23, 24, and 25. Both plutons have a strong relative enrichment in light rare earth elements (LREE) over heavy rare earth elements (HREE) compared to the chondritic REE distribution. All rocks have significant negative europium anomalies. The LREE enrichment is common in granitic rocks (Condie and Lo, 1971; Buma, Frey, and Wones, 1971; Arth and Hanson, 1973), and the absolute

TABLE 18

Estimation of accuracy and precision of trace element abundance determinations

Analyses of G-2 ^d								CR5	
Isotope dilution		Instrumental neutron activation analysis (INAA)							
Arth (1973)	Hooker et al ^c (1975)	Brunfelt et al (1974)	Randle (1974)	Hertogen (1974)	Masuda et al (1974)	Noyes, this study	Flanagan (1973)	This study ^a	
La	-	96.8	90	90±4	87.4	88.6	81±1	96	32±2
Ce	165	155	149	154±10	161	155	164±8	150	61±3
Nd	51.1	57.4	57	49±7	54.9	-	51±2	60	24±2
Sm	6.93	7.3	7.31	7.4±0.2	6.98	6.8	7.0±0.3	7.3	3.8±0.1
Eu	1.35	1.42	1.35	1.18±0.09	1.35	1.44	1.25±0.06	1.5	0.843±0.008
Ho	-	-	-	-	0.39	-	0.53±0.03	-	0.4±0.1
Yb	0.543	0.49	0.73	< 1	0.79	0.72	0.75±0.08	0.88	0.74±0.03
Lu	0.0775	-	0.112	0.113±0.014	0.109	0.11	0.130±0.002	0.11	0.130±0.001
Sc	-	-	-	3.50±0.09	3.37	3.4	3.66±0.01	3.7	3.61±0.07
Hf	-	-	-	8.1±0.5	8.18	7.4	8.7±0.3	7.35	5.1±0.2
Ta	-	-	-	0.84±0.11	0.97	-	1.1±0.1	0.91	8.883
Th	-	-	-	25.4±0.5	24.5	25.6	22.1±0.7	24.2	9.0±0.3
U	-	-	-	-	1.96	-	2.6±0.1	2.0	1.9±0.2
Rb	169	-	188	164±12	160	-	168±4 (b)	168	93±2
Cs	-	-	1.41	1.23±0.14	1.3	-	1.4±0.1 (b)	1.4	2.6±0.2
Ba	1872	-	1540	1840±50	1940	1840	1740±50	1870	1100±100

All abundances in parts per million

a: Standard deviation and mean of two analyses

b: G-2 is used as a standard for Rb and Cs in this study; values from Flanagan (1973) accepted

c: Average of two analyses

d: See original references for detailed discussion of experimental procedure.

TABLE 19

Precision and uncertainty of trace element abundance determinations of this study

	Duplicate analyses of identical splits (ppm)				Statistical uncertainty (%)*		
	G2		CR5		Whole	Alkali	Biotite
	A	B	A	B	Rock	Feldspar	
La	80.6	82.3	30.5	34.0	1	2	1
Ce	156	170	59.0	63.7	2	1	2
Nd	49.6	52.0	22.2	24.8	4	—	4
Sm	6.78	7.19	3.76	3.91	1	3	1
Eu	1.21	1.29	0.849	0.837	3	5	3
Ho	0.526	0.530	0.299	0.487	24	—	24
Yb	0.802	0.696	0.719	0.757	4	—	13
Lu	0.132	0.129	0.131	0.129	13	8	6
Sc	3.67	3.65	3.66	3.56	1	2	1
Hf	8.86	8.45	5.21	4.94	2	2	2
Ta	0.992	1.14	—	0.883	10	—	10
Th	21.6	22.6	9.18	8.82	2	2	2
U	2.69	2.48	2.02	1.78	14	8	14
Rb	0.146	0.141	93.9	91.4	8	1	8
Cs	0.532	0.493	2.47	2.70	5	1	5
Ba	1710	1775	1030	1180	7	3	7

*Uncertainty calculated from counting statistics of CR5 (whole rock) and C1 (mineral separates). See Lopez (1974) for discussion of method.

TABLE 20
Trace element abundances of granitic rocks (ppm)^a

Red Lake Pluton						
	Equigranular facies			Bear Butte facies	Aplites	
	CR29	CR3	CR5	CR1	CR14	CR10
La	29.3	24.4	32.2	26.5	8.07	13.5
Ce	59.8	51.5	61.4	51.4	19.1	15.8
Nd	22.9	21.0	23.5	18.4	13.6	5.12
Sm	3.82	3.80	3.84	2.66	3.85	0.826
Eu	0.919	0.851	0.843	0.565	0.286	0.167
Ho	0.362	0.372	0.393	0.400	0.800	0.310
Yb	0.919	0.872	0.738	0.608	1.76	0.149
Lu	0.153	0.146	0.130	0.120	0.285	0.078
Sc	4.72	4.29	3.61	1.81	2.69	1.09
Hf	4.55	4.42	5.08	3.29	3.65	3.45
Ta	0.895	1.04	0.883	0.750	2.43	0.469
Th	9.30	8.19	9.00	8.53	16.5	25.8
U	2.11	2.25	1.90	1.95	6.03	4.41
Rb	88.6	107	94.0	108	169	193
Cs	3.09	3.01	2.58	3.86	2.46	24.2
Ba	1220	1040	1100	1250	130	308
Eu/Eu* ^c	0.84	0.77	0.70	0.67	0.23	0.54
La/Yb	32	28	44	44	4.6	91 (25) ^b
Th/U	4.4	3.6	4.7	4.4	2.7	5.8
K/Rb	250	230	260	260	310	-
K/Cs	7200	8300	9500	7300	1400	-
Rb/Cs	29	36	36	28	69	8.0

a See text for error discussion

b Value in parentheses calculated from interpolated Yb value

c Calculated as quotient of analyzed Eu and Eu interpolated between Sm and Ho on chondrite normalized diagrams.

TABLE 20, continued
Trace element abundances of granitic rocks (ppm)^a

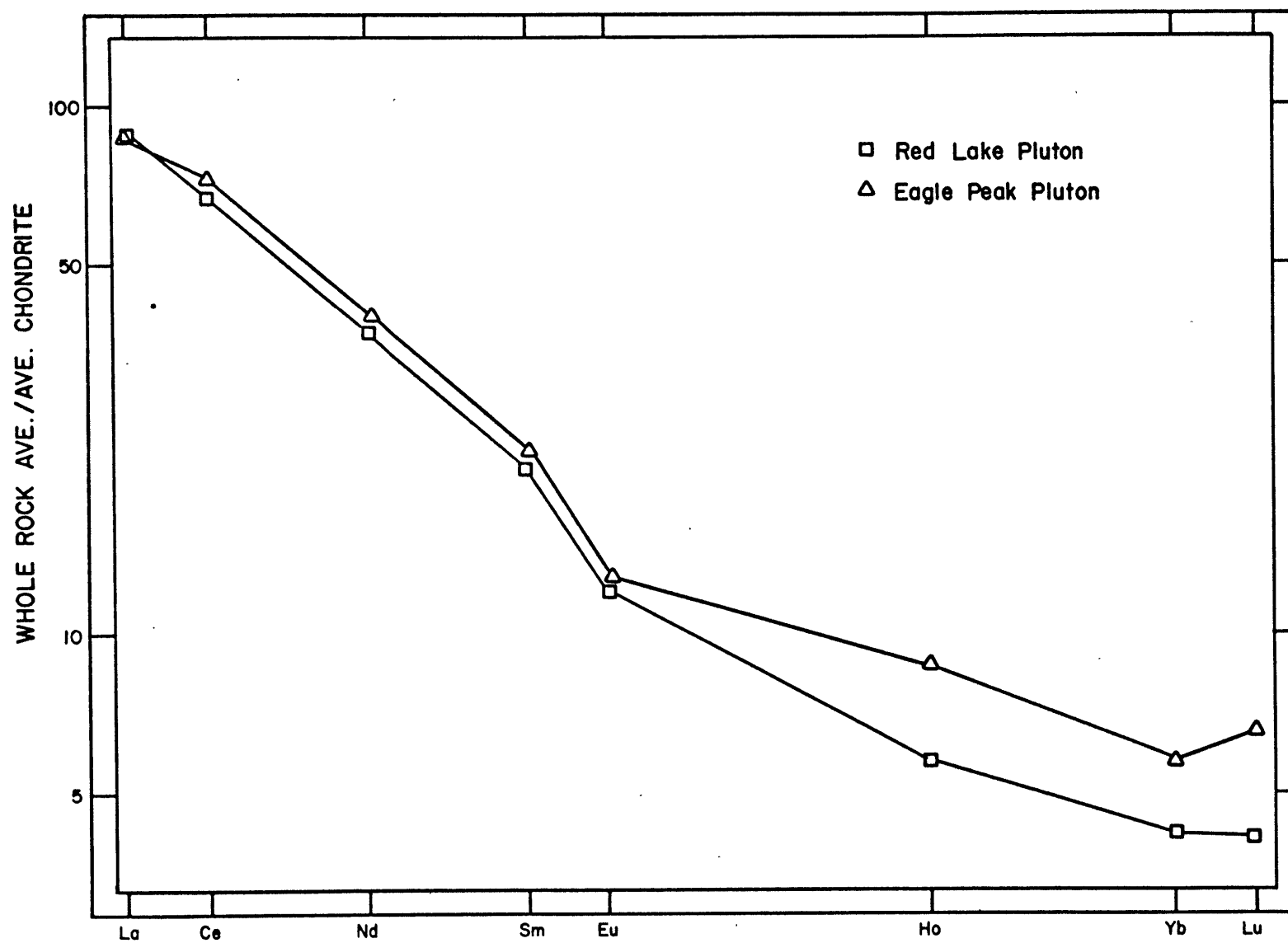
Eagle Peak Pluton						
	Equigranular margin			Porphyritic core		Aplite
	E92	E89	E91	C1	E83	C3
La	20.1	30.9	31.8	24.6	37.6	4.15
Ce	47.3	64.6	67.2	66.9	75.9	10.1
Nd	20.2	26.0	23.8	24.2	26.5	7.38
Sm	3.82	4.92	4.14	3.76	3.60	1.90
Eu	0.877	0.965	0.892	0.823	0.862	0.201
Ho	0.481	0.873	0.553	0.648	0.524	0.889
Yb	1.61	1.52	1.22	0.875	0.660	1.63
Lu	0.308	0.290	0.209	0.216	0.113	0.353
Sc	7.19	6.90	4.90	3.05	2.74	1.57
Hf	4.32	4.90	5.11	5.14	5.04	2.72
Ta	2.22	2.01	2.40	1.54	0.924	3.62
Th	15.7	20.5	20.0	20.4	15.7	15.7
U	6.47	9.00	5.66	9.96	3.00	18.8
Rb	132	148	167	147	160	176
Cs	4.17	7.62	7.53	7.75	5.92	5.74
Ba	770	862	856	865	1210	168
Eu/Eu* ^c	0.76	0.60	0.69	0.67	0.77	0.27
La/Yb	12	20	26	28	57	2.5
Th/U	2.4	2.3	3.5	2.0	5.2	0.8
K/Rb	190	150	170	200	-	270
K/Cs	6000	2900	3800	3800	-	8200
Rb/Cs	32	19	22	19	27	31

a See text for error discussion

b Value in parentheses calculated from interpolated Yb value

c Calculated as quotient of analyzed Eu and Eu interpolated between Sm and Ho on chondrite normalized diagrams.

Figure 23: Average chondrite normalized rare earth element abundances for the Red Lake and the Eagle Peak plutons.



ATOMIC NUMBER

Figure 23

Figure 24: Chondrite normalized rare earth element abundances for whole-rock samples of the Red Lake pluton.

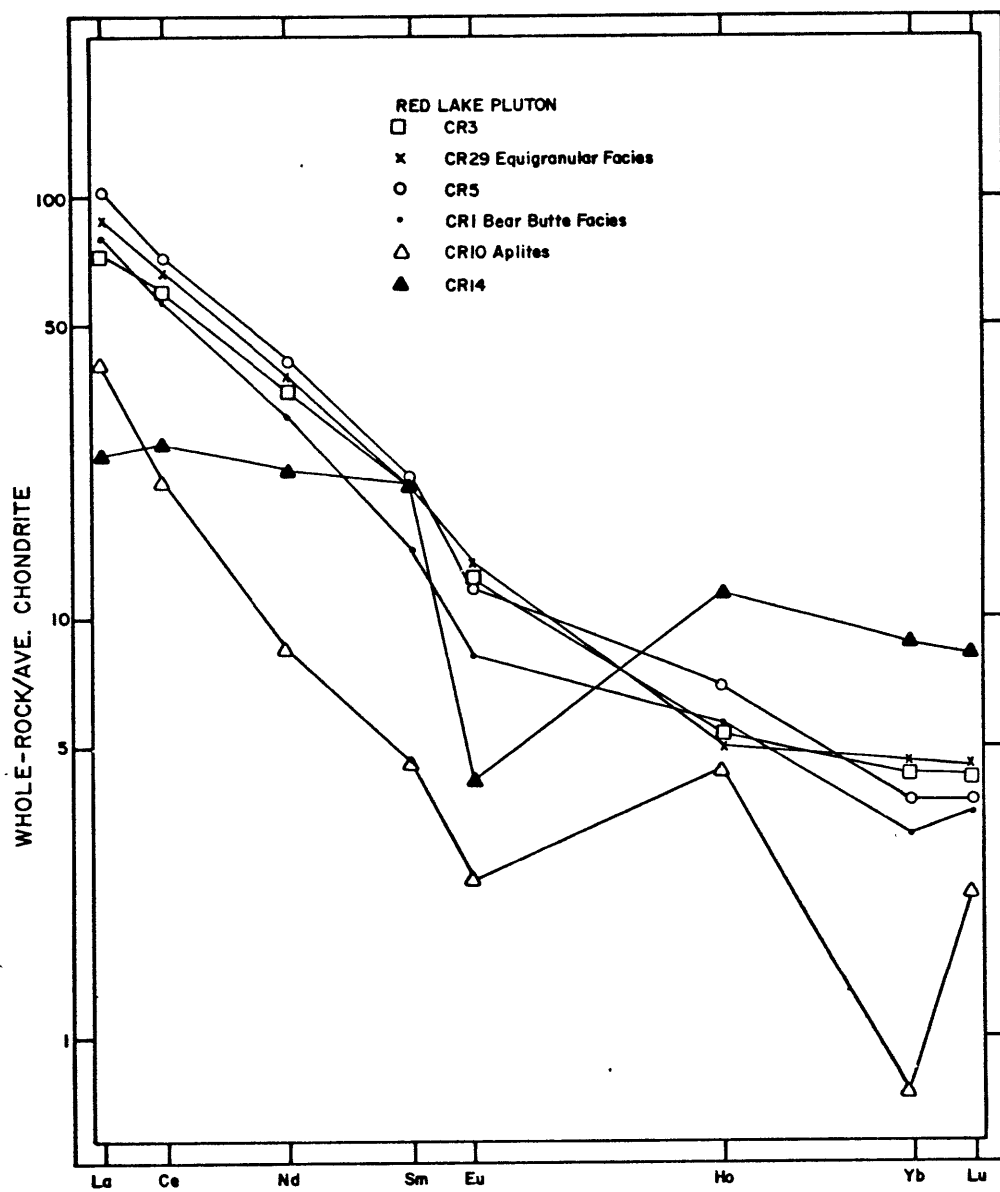


Figure 24

Figure 25: Chondrite normalized rare earth element abundances for whole-rock samples of the Eagle Peak pluton.

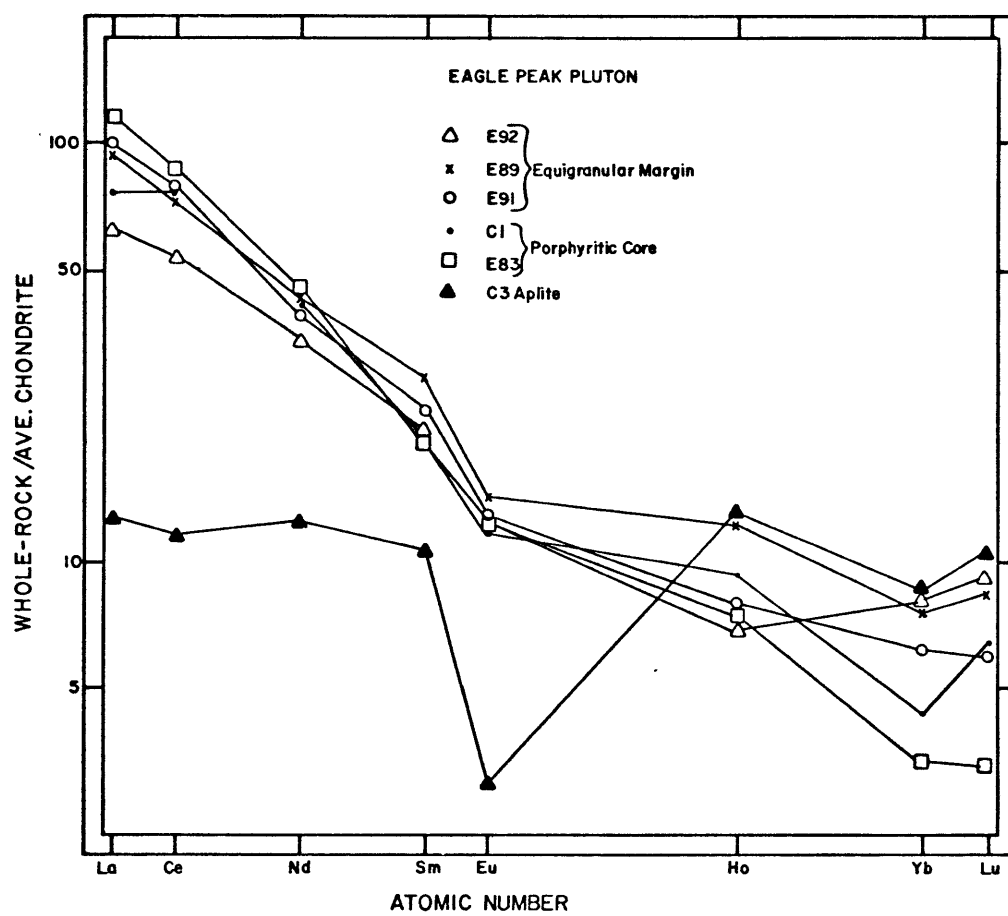


Figure 25

abundances are similar to the Rubidoux Mountain leucogranite and the Woodson Mountain granodiorite of the Southern California batholith (Towell, Winchester, and Spirn, 1965). Compared to the Eagle Peak pluton, the Red Lake pluton is slightly depleted in HREE.

Figures 24 and 25 show analyses of individual samples from representative parts of each pluton. It was shown in a previous section that the major element chemistry and modal composition of the Red Lake pluton varies less than that of the Eagle Peak pluton. This limited variation is also seen in the REE data from the Red Lake pluton. For the granitic samples two populations can be recognized in the Red Lake pluton: CR3, CR29, and CR5 from the main mass of the pluton and sample CR1 from the hydrothermally altered Bear Butte facies. Samples CR29, CR3, and CR5 are quite similar in REE composition but do show a decrease in HREE in the respective sequence. This same sequence was interpreted from petrologic and major element data as resulting from crystal-liquid fractionation of a differentiating magma. Sample CR1 is depleted in HREE and Eu compared to the other granitic samples. Kosterin (1959) and Mineyev (1963) have related relative HREE depletions to loss in a final late stage volatile phase; such a phase is indicated by the petrologic data as responsible for the mineralogical and chemical alteration of the Bear Butte facies.

Granitic samples of the Eagle Peak pluton are less depleted in HREE than the Red Lake pluton samples but are more variable in absolute REE abundances. Most have significant europium depletions greater than in the Red Lake pluton samples (Table 20). Yb and Lu

abundances decrease and La/Yb increases in the sequence E92-E89-E91-C1-E83, and this is essentially the crystallization sequence deduced from petrologic data. However, the relationship of C1 to E83 was not determined from that data, as field relations are inconclusive and a major element analysis is not available for E83. Pronounced trends are not present in the other REE data. Core sample E83 is the most enriched in LREE and the most depleted in HREE. Core sample C1 has a slight La depletion and marginal sample E92 is the most depleted in LREE. Equigranular interior samples E89 and E91 have very similar LREE abundances which are intermediate between core sample E83 and marginal sample E92.

Sc, Hf, Ta, Th, U, Rb, Cs, and Ba

Trace element abundances for Sc, Hf, Ta, Th, U, Rb, Cs, and Ba are given in Table 20. The Red Lake pluton contains lower abundances of Sc, Ta, Th, U, Rb, and Cs, and a greater abundance of Ba than the Eagle Peak pluton; Hf abundances are similar in both plutons. The two plutons also show a bimodal distribution of the petrogenetically useful ratios K/Rb, K/Cs, Rb/Cs, and Th/U (Table 20), with the greater values in the Red Lake pluton. The only significant trend within either pluton is the decrease in Sc abundance in the Eagle Peak pluton in the previously recognized sequence E92-E89-E91-C1-E83 and in the sequence CR29-CR3-CR5-CR1 in the Red Lake pluton. Figure 26 summarizes the preceding relationships.

Figure 26: Relative abundance diagram of Rb, Cs, Ba, Sc, Hf, Ta, Th, and U in the Red Lake and the Eagle Peak plutons: average Red Lake pluton abundance/ average Eagle Peak pluton abundance.

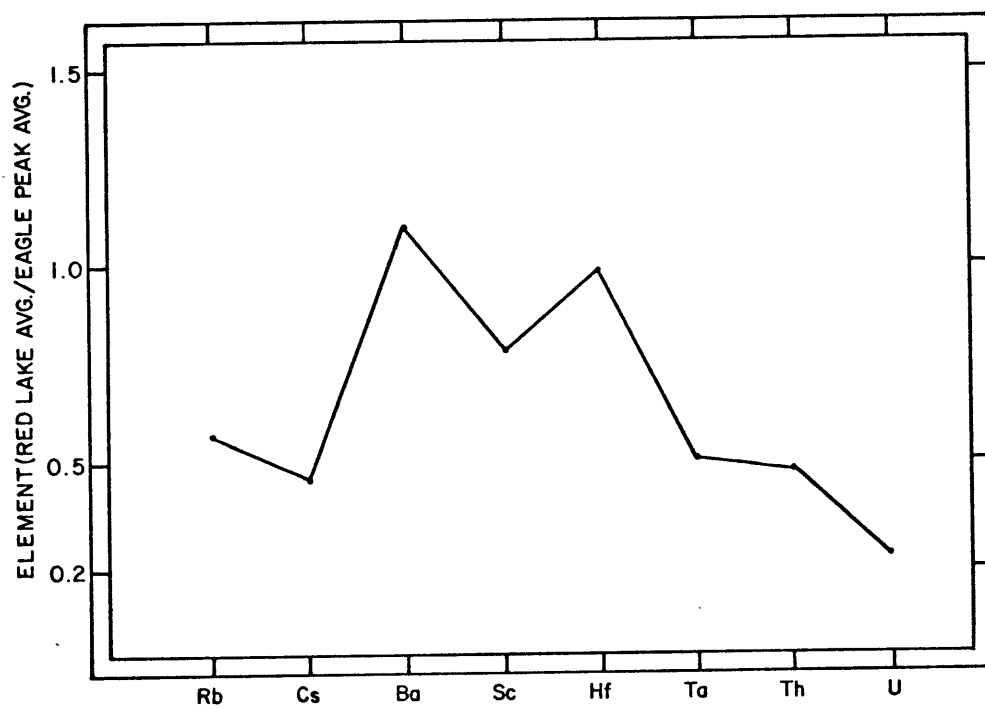


Figure 26

APLITES

Chondrite normalized REE plots for three aplites are plotted with the respective granitic data from each pluton in Figures 24 and 25 and normalized to average host rock abundances in Figure 27. All show a LREE depletion relative to the granitic rocks of their respective plutons and have strong negative Eu anomalies (-0.54 , Table 21), especially CR14 and C3. Aplites CR14 and C3 also are relatively enriched in HREE relative to the REE distribution of the host granitic rocks. This relationship was noted for aplite and granitic samples of the Susamyr batholith (Balashov, 1963). Aplite CR10 is depleted in all REE relative to the host granites; this type of relationship was noted in the Louis Lake batholith by Condie and Lo (1971). The extreme and anomalous Yb depletion in sample CR10 is not understood, although it is very likely an analytical problem.

As a group the aplites of this study tend to be depleted in Sc, Ba, and Hf and similar to or enriched in Rb, U, and Th relative to the host rocks. Samples CR14 and C3 have greater Ta, K/Rb, K/Cs, and Rb/Cs and lower Th/U than their host rocks, whereas sample CR10 contains the least Ta and the greatest Cs of any sample analyzed. These trace element relationships are summarized in Figure 28.

Figure 27: Aplite rare earth element abundances for the Red Lake
and the Eagle Peak plutons, normalized to average pluton
rare earth element abundances, respectively.

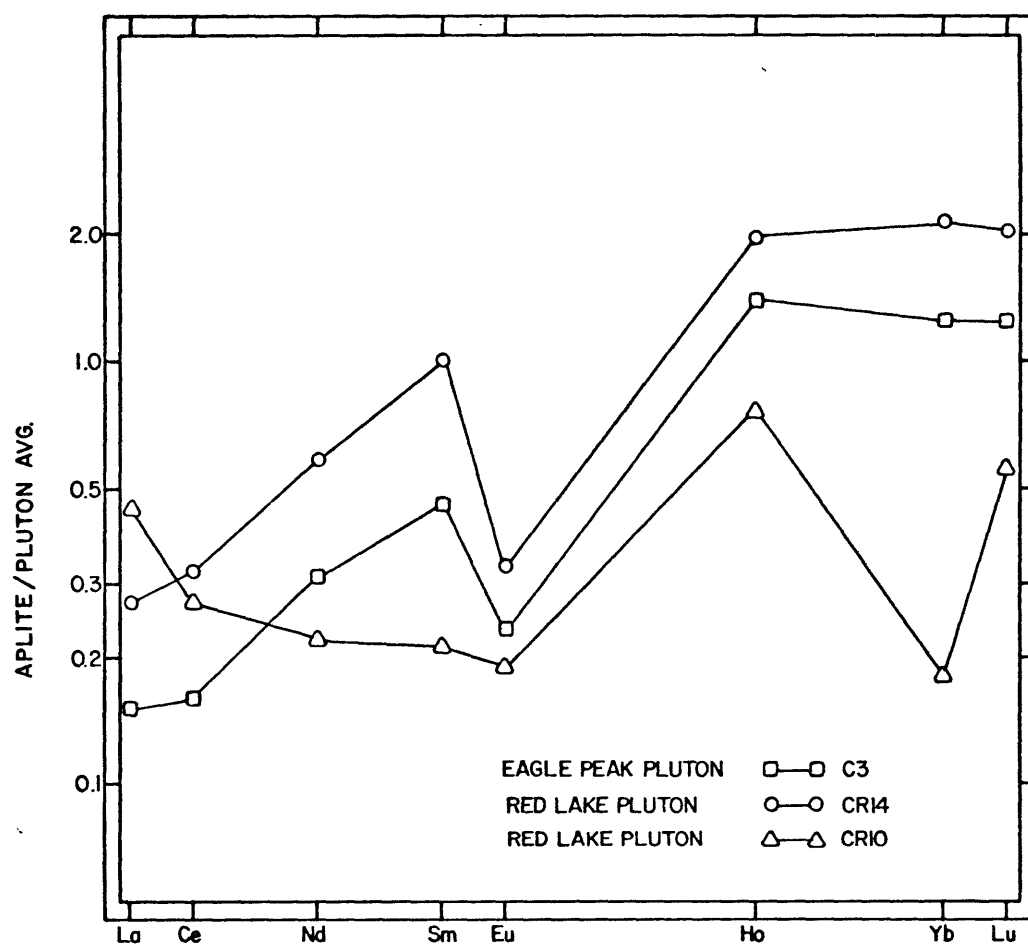


Figure 27

Figure 28: Aplite trace element abundances (Rb, Cs, Ba, Sc, Hf, Ta, Th, and U) for the Red Lake and the Eagle Peak plutons, normalized to average pluton trace element abundances, respectively.

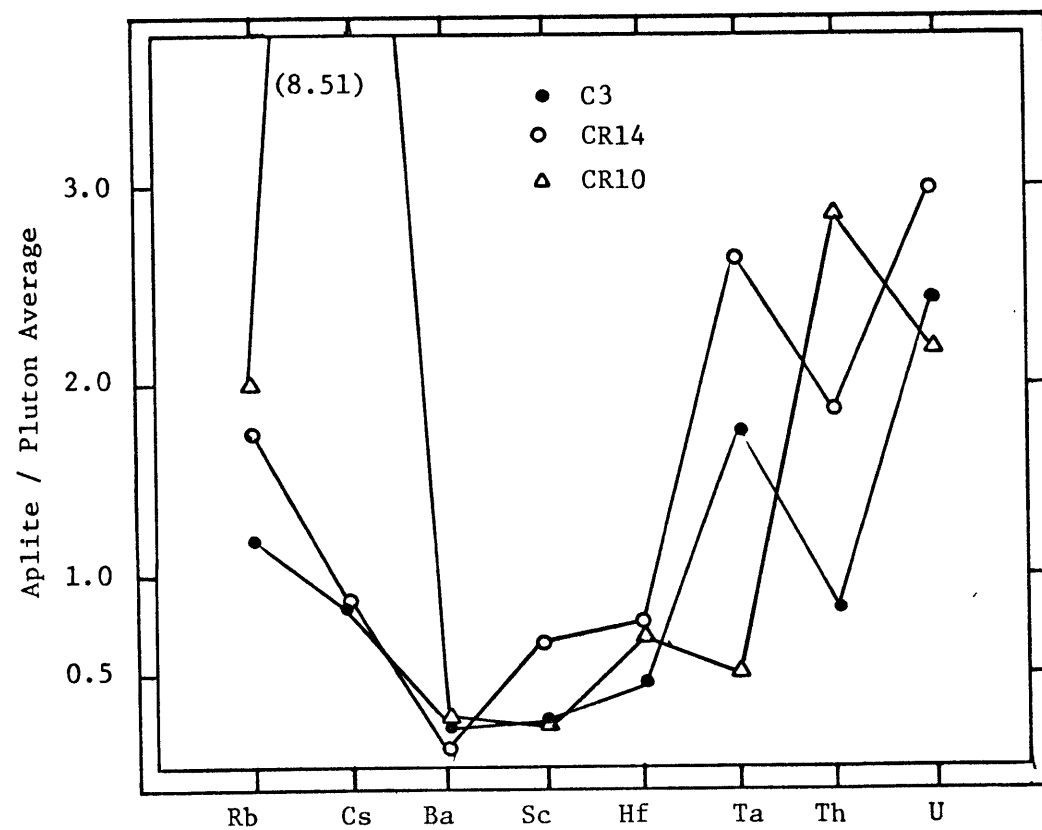


Figure 28

MINERALS

Introduction

Trace element abundances were determined for plagioclase, alkali feldspar, and biotite separates from samples C1 (porphyritic core) and E91 (equigranular margin) of the Eagle Peak pluton and from sample CR29 of the Red Lake pluton. Hornblende and sphene were also analyzed from sample CR29. The results are listed in Table 21, and the REE abundances are plotted normalized to host rock abundances in Figures 29, 30, and 31. The data are replotted in Figures 32, 33, and 34 as comparison diagrams for alkali feldspar, plagioclase, and biotite, respectively.

Feldspars

Normalized to their host rocks the feldspars of this study have similar REE distributions (Figures 32 and 33). All are depleted in REE relative to the host rocks, and plagioclase and alkali feldspar show the characteristic relative enrichment in Eu, with alkali feldspar having the greatest enrichment in each sample. The distribution of REE between alkali feldspar and plagioclase is shown in Figure 35. Plagioclase contains a greater proportion of REE than does alkali feldspar; this difference is even greater than indicated when it is recognized that the plagioclase separates contain about 30% quartz. Studies by others (i.e., Buma, Frey, and Wones, 1971) indicate quartz contributes negligible amounts of REE to the total. The erratic variations in Yb/Lu ratios probably results from inaccurate data because of the very low concentrations of these elements in these

TABLE 21

Trace element abundances of mineral separates from granitic rocks (ppm)^a

	Potassium feldspar			Plagioclase		
	Host rock ^b : CR29	E91	C1	CR29	E91	C1
La	1.78	3.37	1.80	6.08	7.08	3.42
Ce	2.27	6.09	9.60	7.35	8.62	6.64
Nd	N.D. ^c	N.D.	N.D.	2.28	3.66	1.67
Sm	0.112	0.290	0.118	0.296	0.498	0.221
Eu	0.289	0.318	0.335	0.442	0.350	0.247
Ho	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Yb	N.D.	N.D.	N.D.	0.080	0.116	0.0589
Lu	0.0169	0.0254	0.0186	0.023	0.027	0.101
Sc	0.127	0.184	0.063	0.128	0.149	0.0539
Hf	0.650	1.11	0.707	1.17	1.60	1.40
Ta	N.D.	N.D.	N.D.	N.D.	0.023	0.0424
Th	1.03	0.774	0.818	2.15	3.10	1.42
U	0.228	0.616	0.723	0.542	1.95	1.82
Rb	259	388	358	6.77	11.3	5.31
Cs	2.87	5.85	6.61	0.427	0.395	0.258
Ba	3860	4190	3760	219	93.1	89.7
Eu/Eu*	9.3	4.7	12	6.2	3.4	5.0

^a See text for error discussion^b See locality map^c Not detected

TABLE 21, continued
Trace element abundances of mineral separates from granitic rocks (ppm)^a

	Biotite			Hornblende	Sphene	Perthite
	E91	C1	CR29	CR29	CR29	PEG
La	11.0	25.6	12.3	47.6	1330	0.619
Ce	25.9	47.9	26.0	118	4210	0.926
Nd	13.2	20.7	12.0	84.3	2770	0.208
Sm	2.15	2.06	1.41	19.5	557	0.070
Eu	0.530	0.590	0.266	2.81	90.8	0.212
Ho	0.433	0.488	0.283	0.256	49.2	N.D.
Yb	N.D.	N.D.	N.D.	4.53	168	N.D.
Lu	0.224	0.339	0.194	0.962	15.8	0.010
Sc	19.8	41.4	27.8	95.1	18.2	0.008
Hf	9.59	15.8	6.91	N.D.	62.4	N.D.
Ta	1.96	0.723	0.990	N.D.	154	N.D.
Th	9.78	8.36	3.28	N.D.	305	N.D.
U	4.34	9.16	1.08	4.44	135	1.06
Rb	914	966	474	N.D.	N.D.	404
Cs	49.7	69.9	15.2	N.D.	N.D.	2.41
Ba	1550	1100	3740	356	N.D.	240
Eu/Eu*	1.1	1.3	0.68	0.57	0.76	

a See text for error discussion

b See locality map; PEG from Eagle Peak pegmatite alkali feldspar.

c Not detected

TABLE 22

Purity of mineral fractions

Mineral	Purity*	Possible Contaminants
sphene	> 95	magnetite, biotite
hornblende	~ 98	magnetite, biotite
biotite	> 95	chlorite, zircon, apatite
plagioclase	~ 70	quartz, trace magnetite
potassium feldspar	~ 99	quartz, plagioclase

*Estimated volume percent, petrographic observation.

Figure 29: Host rock normalized rare earth element abundances for mineral separates from the Red Lake pluton, rock CR29.

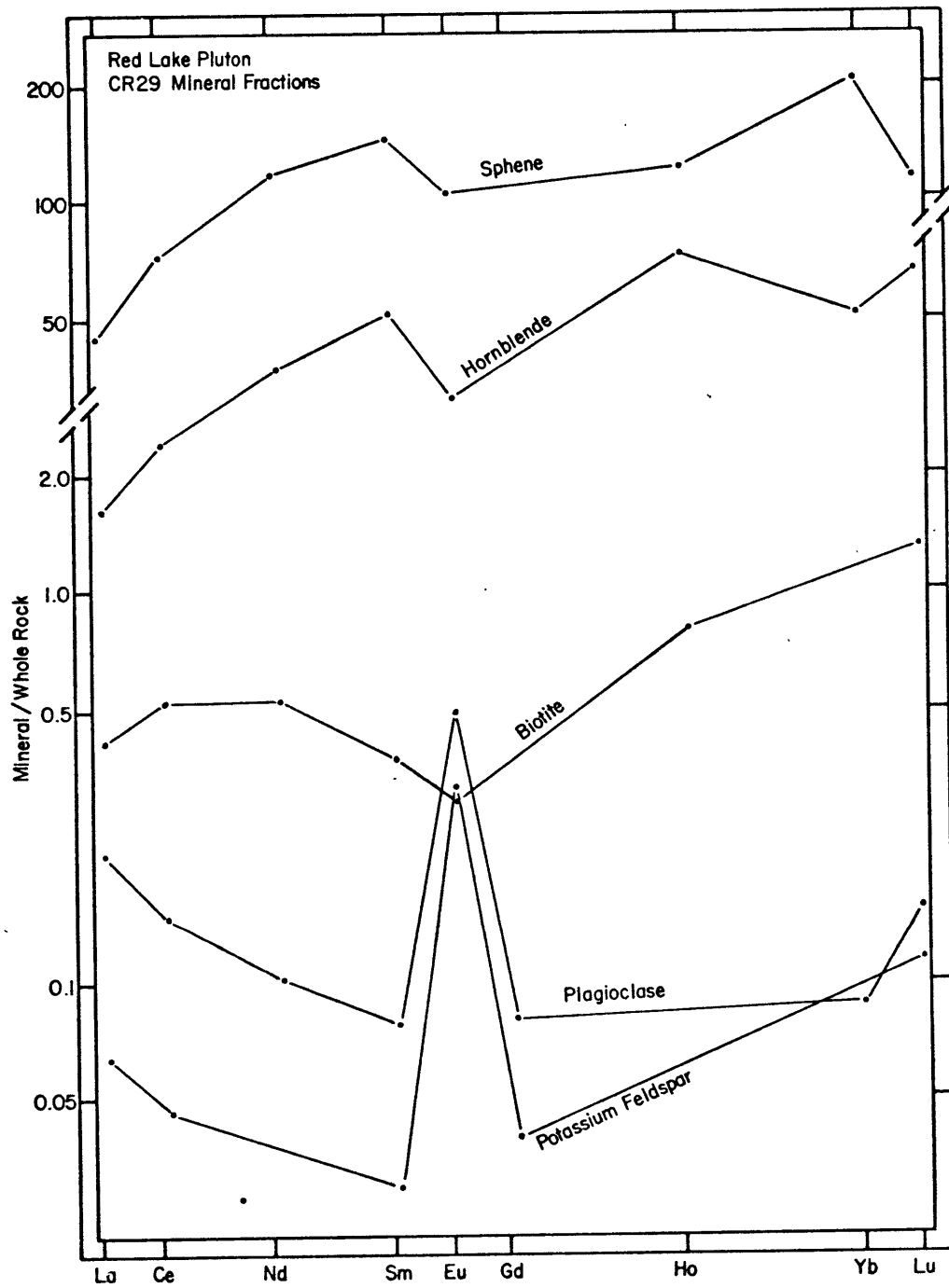


Figure 29

Figure 30: Host rock normalized rare earth element abundances for mineral separates from sample E91 of the equigranular margin of the Eagle Peak pluton.

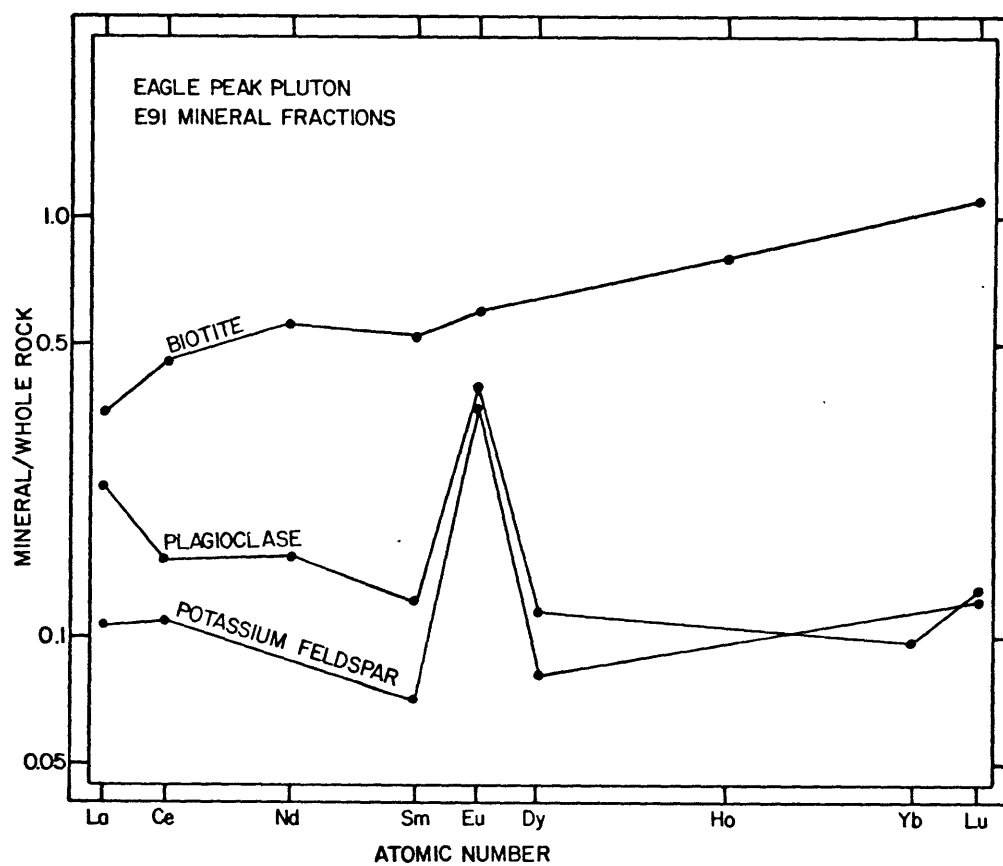


Figure 30

Figure 31: Host rock normalized rare earth element abundances for mineral separates from sample C1 of the porphyritic core of the Eagle Peak pluton.

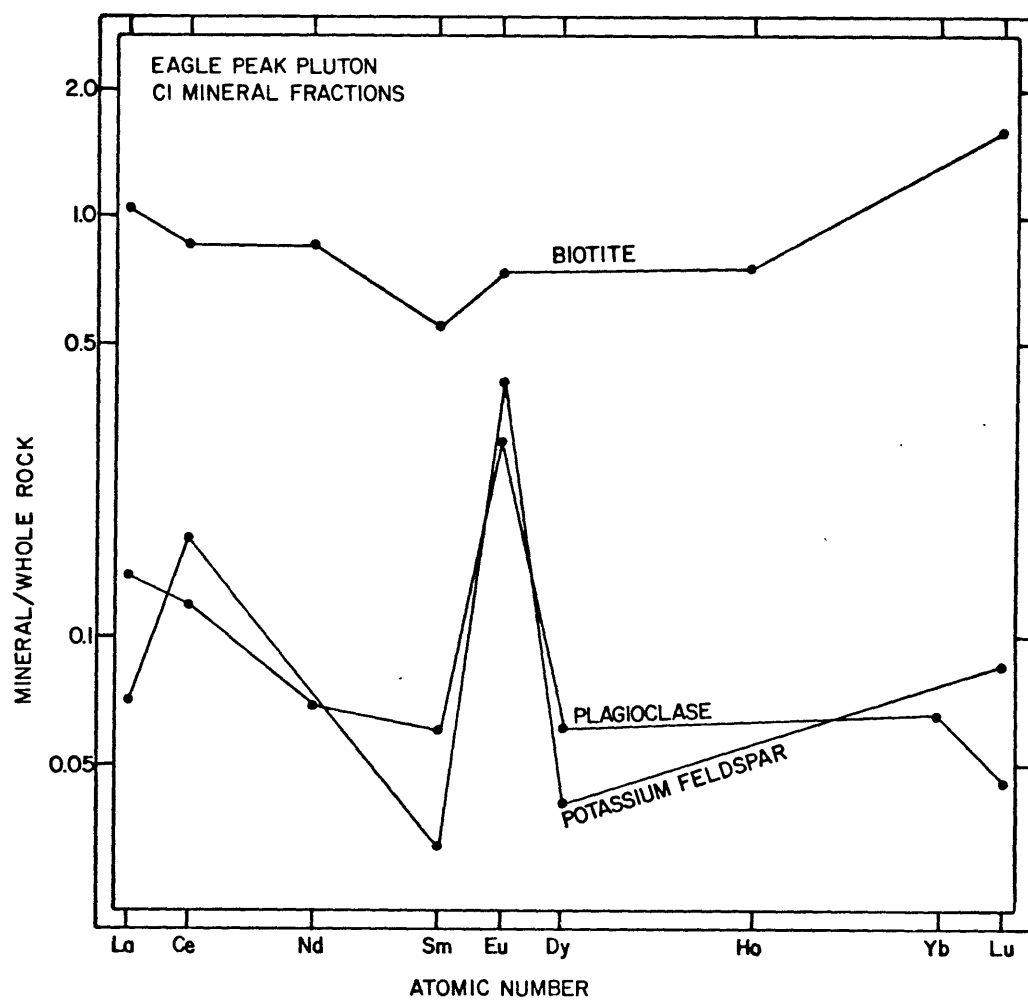


Figure 31

Figure 32: Comparative diagram of host rock normalized rare earth element abundances for alkali feldspar separates from the Red Lake and the Eagle Peak plutons.

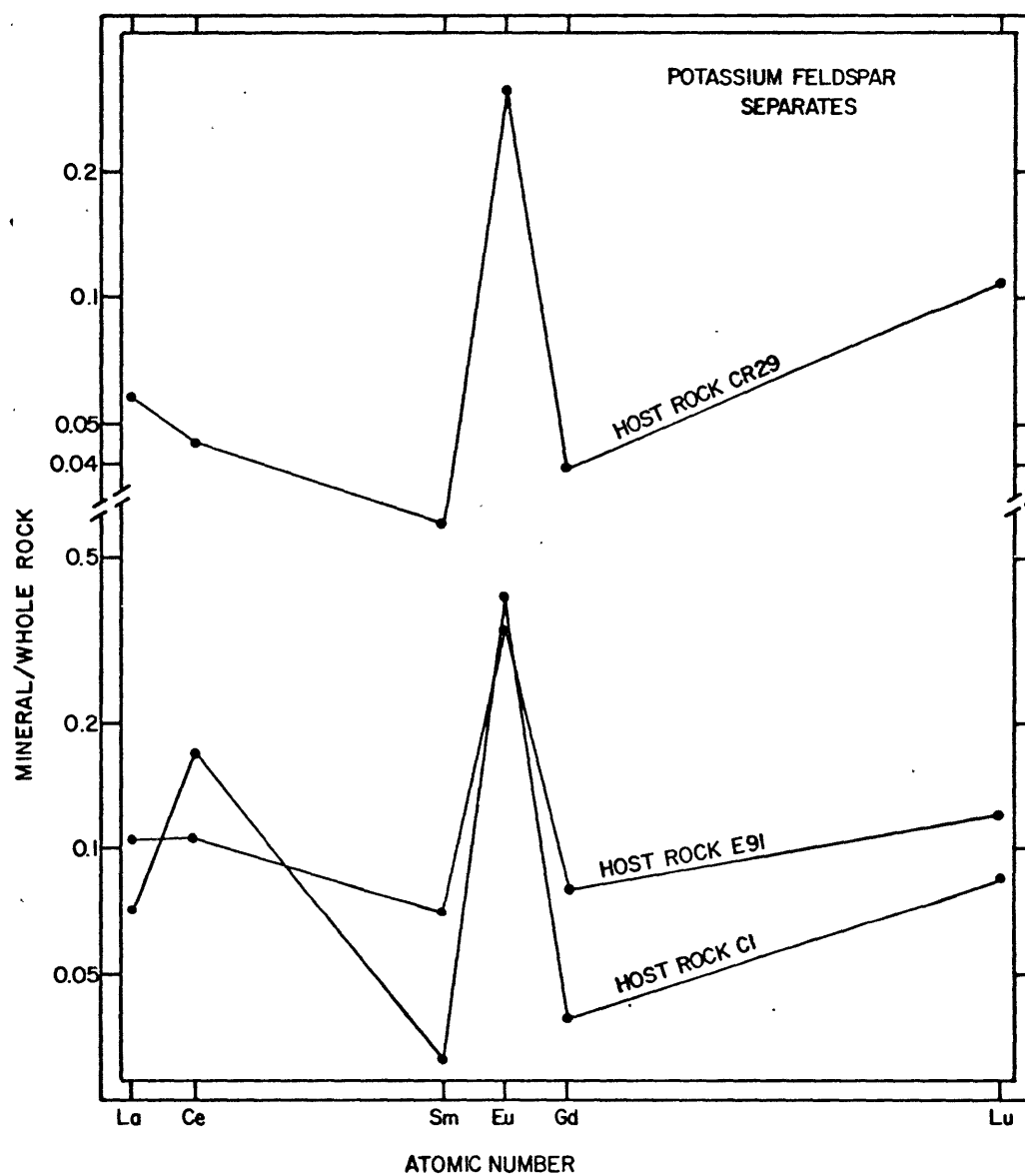
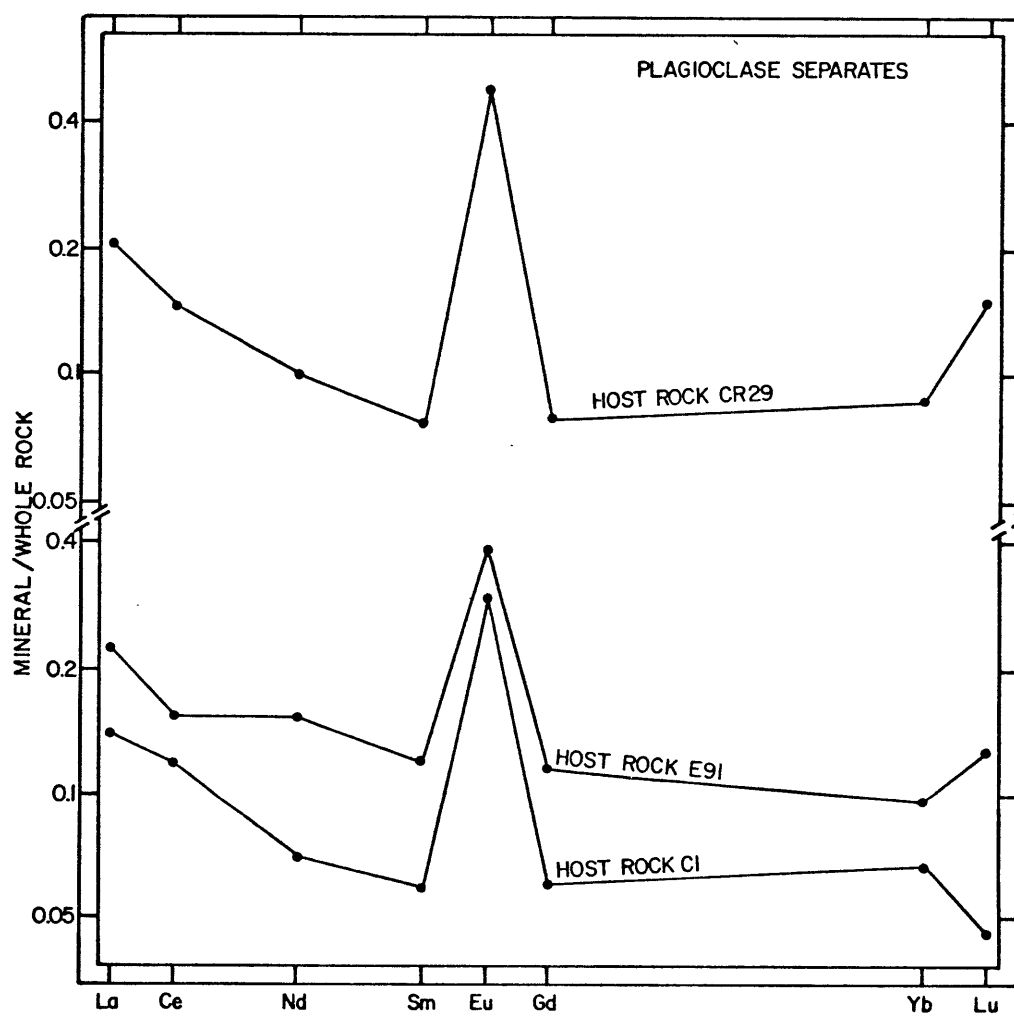


Figure 32

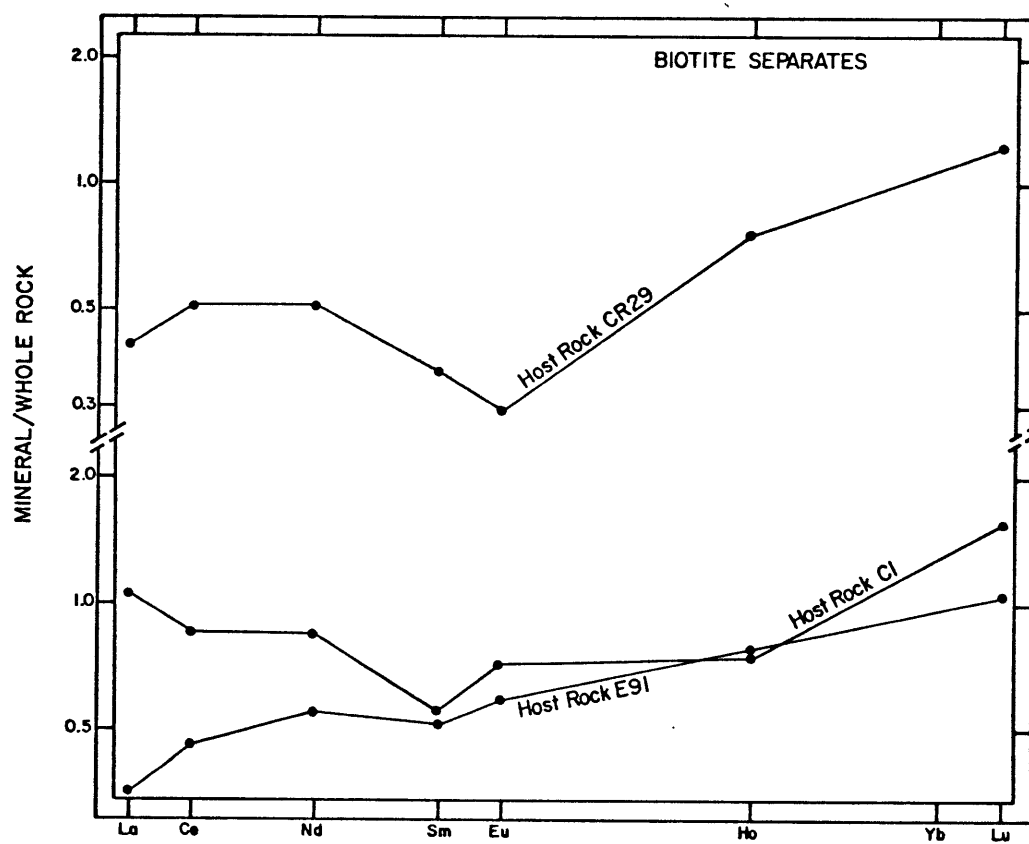
Figure 33: Comparative diagram of host rock normalized rare earth element abundances for plagioclase separates from the Red Lake and the Eagle Peak plutons; data not corrected for quartz dilutions.



ATOMIC NUMBER

Figure 33

Figure 34: Comparative diagram of host rock normalized rare earth element abundances for biotite separates from the Red Lake and the Eagle Peak plutons.



ATOMIC NUMBER

Figure 34

Figure 35: Distribution of rare earth elements between alkali feldspar and plagioclase for mineral separates from the Red Lake and the Eagle Peak plutons: rare earth element abundance in alkali feldspar/rare earth element abundance in plagioclase.

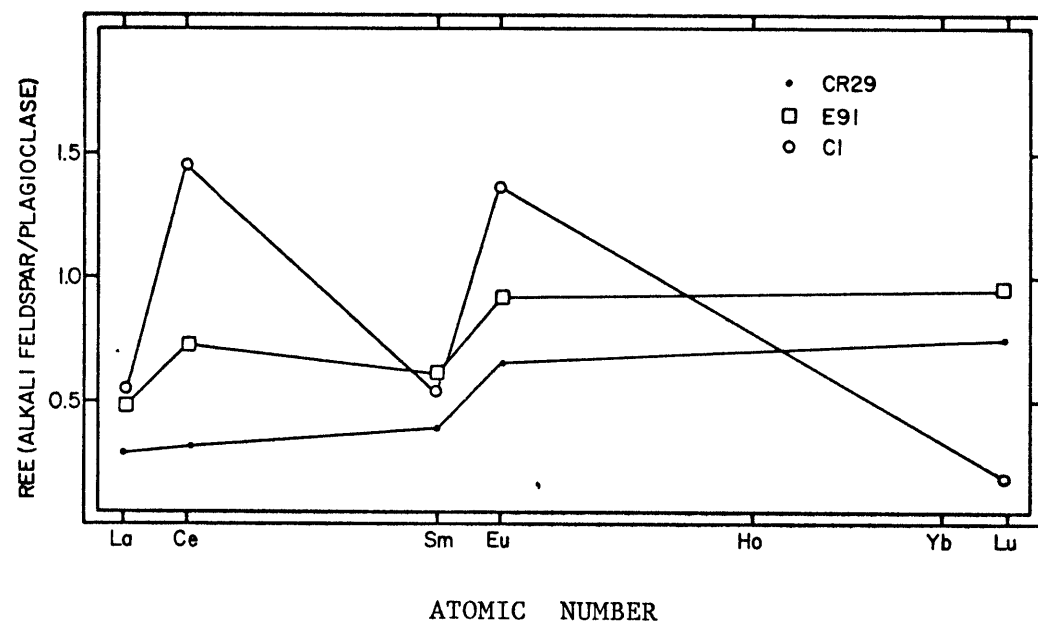


Figure 35

feldspars. The REE distributions of these feldspars are similar to those for other granitic rocks (Buma, Frey, and Wones, 1971; Condie and Lo, 1971; Towell, Winchester, and Spirn, 1965; Nagasawa, 1971). The La-Ce anomaly of alkali feldspar C1 is believed to be real and is discussed later. In general, the distribution of REE between the feldspars is similar to that observed by Nagasawa (1971) for other granitic rocks in which feldspars are believed to be in equilibrium. Nagasawa (1971) shows a wide range in partition coefficients for sets of feldspars from different plutons. The samples of this study fall within that range, with those of the Red Lake pluton having the smallest values.

Sc, Hf, Ta, U, and Th are present in minor to negligible amounts in feldspars of both plutons. Rb and Ba are enriched in the alkali feldspars relative to the host rocks and Cs abundances approach host rock values. Abundances of these elements in the plagioclase separates are significant but are less than in the coexisting alkali feldspars. The feldspar Cs and Ba data partly reflect the host rock variations in these data. Cs in the Red Lake pluton is about half that of the Eagle Peak pluton and Cs abundances in the alkali feldspar separates from these plutons show this same relationship. Ba in the Red Lake pluton is about 30% greater than in the Eagle Peak pluton and the Red Lake pluton plagioclase has greater than twice the Ba abundance of the Eagle Peak plagioclase.

Biotite

Host normalized REE patterns for the biotites (Figure 34) indicate that all are slightly enriched in HREE relative to the host rocks and absolute abundances are 0.4 to 2.0 times those of the host rocks. Biotites C1 and CR29 appear to be slightly more enriched in LREE than biotite E91. This may be a result of trace allanite or apatite impurities in these biotite separates; petrographically these minerals are associated. Trace element data on apatite and allanite by other investigators (Lee and Bastron, 1967; Lee and others, 1973; Nagasawa, 1970) indicate these minerals are capable of causing important REE contributions in mineral separates. The general distribution of the biotite REE abundances is similar to that from granitic biotite of New England reported by Buma, Frey, and Wones (1971) and from the Southern California batholith reported by Towell, Winchester, and Spirn (1965).

Sc and Hf are enriched in the biotite relative to the host rocks, with Sc in biotite C1 fourteen times that of the host rock. Ta, Th, and U are present in appreciable amounts in the biotites, either similar to or approaching host rock abundances. Rb, Cs, and Ba are all enriched in the biotite relative to the host rocks. The relative abundances of U, Th, Rb, Cs, and Ba in the biotites are similar to the relative average abundances of these elements in the host plutons: U, Th, Rb, and Cs are greater and Ba lesser in abundance in the Eagle Peak pluton than in the Red Lake pluton and similarly for the respective biotites.

Hornblende

The host rock normalized REE pattern for hornblende CR29 is convex upwards, slightly enriched in HREE, has a slight Eu depletion, and is enriched in REE relative to the host rock CR29 (Figure 29). Hf, Ta, Th, Rb, and Cs are below detection limits and Ba is a significant constituent but less abundant than the host rock value. U is present in twice the abundance as in the host rock. Sc is strongly concentrated in the hornblende, approximately twenty times the whole rock value. Concentration of Sc in hornblende has been observed by other workers: Buma, Frey, and Wones (1971) report a similar enrichment factor for amphibole from the Quincy Granite of Massachusetts.

Sphene

Sphene is strongly enriched in REE relative to the host rock CR29. Figure 29 indicates this enrichment is 50 to 200 times whole rock abundances, with the greatest enrichment in HREE. Lee and others (1969) report a broadly similar host rock normalized pattern for sphene from a Nevada calc-alkaline granitic pluton. However, the LREE from that sample are much less enriched than in sphene CR29, with La only five times the host rock abundance.

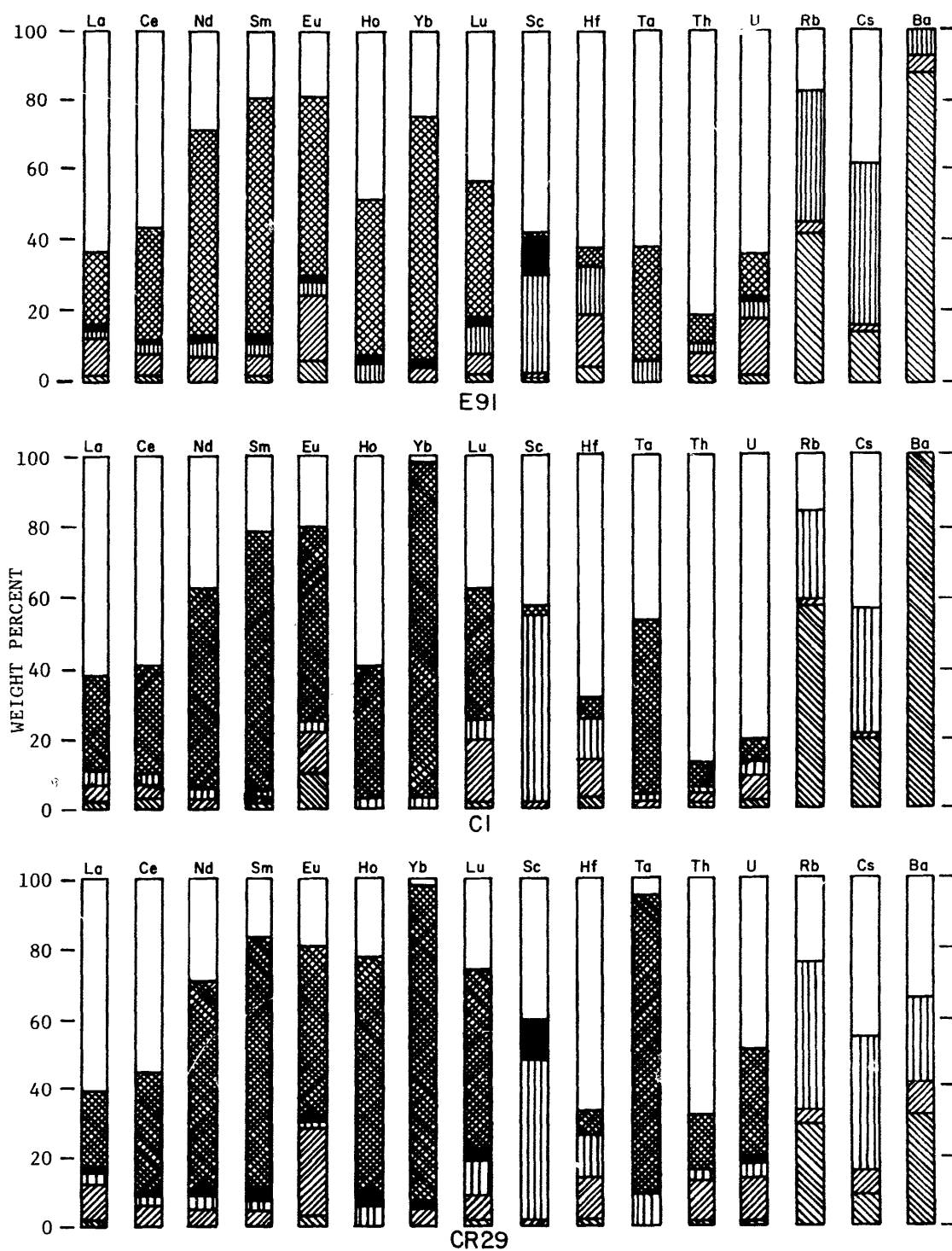
Sphene is also a very favorable host for Sc, Hf, Ta, U, and Th. These elements are greatly enriched over host rock values. Ta is enriched 100 times over host rock values; Clark (1974) reports similar concentrations of Ta in sphene. Hurley and Fairbairn (1957) give U and Th analyses of sphene showing abundances similar to that of CR29. Sc, Ta, U, and Th also show enrichment in sphene from

granitoid rocks of the Mount Wheeler mine area in Nevada (Lee, Mays, Van Loenen, and Rose, 1969).

Mass Balances

The percentage of each element in the various minerals is shown in Figure 36. Modes used in preparing this figure were those from the petrology section of this paper modified so each rock contained 0.5 volume per cent sphene. This is an approximate abundance determined from thin sections of several samples from each pluton. Notice that in each pluton this small amount of sphene contains the greatest proportion of REE, Ta, Th, and U of any mineral analyzed. Biotite and hornblende are the main hosts for Sc. Rb, Cs, and Ba are dominantly contained in biotite and alkali feldspar. A large proportion of LREE, U, Th, Sc, and Hf are not present in the analyzed minerals. The most probable hosts for these elements are apatite and allanite. Hurley and Fairbairn (1957) report large abundances of U and Th in apatite and epidote (allanite belongs to the epidote group) and Lee and Bastron (1967) report enrichment in LREE in allanites from a granodiorite intrusive. Frondel (1964) reports similar REE data for allanite. A significant amount of Hf may be incorporated in the minor amount of zircon present in these rocks. The mass balance result for Cl contains more Ba than does the whole rock. This is quite likely an analytical problem; Ba data are believed to be accurate to only $\pm 10\%$, and the dominant host for Ba is alkali feldspar which comprises over 30% of this sample. The

Figure 36: Trace element mass balances for whole rock samples of the Red Lake and the Eagle Peak plutons for which mineral separates were analyzed: contributions of each mineral to the total trace element abundance of the host rock.



LEGEND

PLAGIOCLASE

BIOTITE

SPENE

K-FELDSPAR

HORNBLende

OTHER

Figure 36

host for the unaccounted Sc may be allanite where the Sc substitutes for Al^{+3} and Fe^{+3} (Fron del, 1968).

INTERPRETATION OF WHOLE ROCK DATA

Introduction

An interpretation of the petrogenesis of the plutons was made in Chapter I based on petrologic and field data. It was concluded that crystal-liquid fractionation was responsible for most of the variations present in each pluton. Late stage formation of volatiles with minor deuteritic alteration was postulated for the Eagle Peak pluton, whereas a periodic or continuous evolution of volatiles was suggested for the Red Lake pluton. These conclusions will guide the interpretation of the trace element data. Quantitative models are not developed in the following section; these are explored in a subsequent chapter.

Red Lake Pluton

On the basis of petrologic and major element data the sequence of increasing differentiation for the Red Lake pluton samples is CR29-CR3-CR5. This is also a sequence of decreasing Sc and HREE. The absence of hornblende in CR5 suggests that the Sc and HREE decrease could have resulted from fractionation of hornblende (about 1 weight per cent) or possibly sphene. There are no consistent trends for other trace elements in the sequence CR29-CR3-CR5.

Because the slope of the REE distribution increases erratically in this sequence, hornblende fractionation was probably accompanied by another phase with different REE partition coefficients, such

as plagioclase. Also, hornblende in this study and in dacitic volcanics (Hanson and Arth, 1976; Nagasawa, 1971) have negative Eu anomalies, and extensive fractionation of hornblende alone will produce residual liquids with positive Eu anomalies. The increasing Eu depletion in this sequence ($\text{Eu}/\text{Eu}^* = 0.84$ to 0.70) provides strong evidence for the role of plagioclase which must have counteracted the tendency of hornblende to cause Eu enrichment with increasing fractionation.

Irregular variations in Ba, Cs, Rb, and possibly Hf could be produced by coprecipitation of plagioclase and biotite. Biotite CR29 is enriched and plagioclase CR29 depleted compared to the host rock in these elements. The tendency of these elements to increase with plagioclase fractionation would be counteracted with biotite removal and result in their limited variation with differentiation.

Sphene is strongly enriched in U, Th, Hf, and Ta over the host rock values. The general tendency of these elements to increase with fractionation would be repressed by even minor subtraction of sphene. Sphene fractionation could also contribute to relative HREE depletion.

The trace element data are generally consistent with minor precipitation of plagioclase, hornblende, biotite, and sphene. The minor variation in the trace element data correlates with the minor variation in the petrologic and major element data and suggests that differentiation within the pluton was quite limited. For example, extensive plagioclase fractionation would require compensatory hornblende fractionation. The Sc variation between CR29 and CR5 limits the removal of hornblende to approximately 1 weight per cent, assuming surface equilibrium, Rayleigh fractionation, and a hornblende/liquid

partition coefficient of 20(hornblende/host rock Sc, sample CR29). Subtraction of this quantity of hornblende would reduce Eu to 0.86 ppm in the residual liquid, assuming a hornblende/liquid Eu partition coefficient of 5.9 (Nagasawa and Schnetzler, 1971). This value is quite similar to that of CR5 (0.84 ppm).

Bear Butte Facies

Hydrothermally altered sample CR1 has a trace element composition surprisingly similar to the unaltered samples. Since this sample is from near the edge of the pluton it could tentatively be assumed to have had an initial trace element composition similar to CR3. Compared to CR3 it has been slightly depleted in the REE Nd to Lu. Russian investigators (Kosterin, 1959; Mineyev, 1963; Vlasov, 1966) and Buma, Frey, and Wones (1971) suggest removal of HREE as complexes in late stage volatiles. Carbonate complexes may have been important in this case, as CR1 contains more CO₂ than any of the other samples, possible evidence of a transient carbonate-rich vapor phase. In addition, the extensive sericitic alteration clearly indicates the presence of a vapor or fluid phase. The decrease in Hf, Ta, Sc, and HREE compared to CR3 correlates well with the near absence of hornblende and sphene and the extensive alteration of biotite in CR1. Hon (1976) suggests these elements are quite mobile during hydrothermal alteration of granitic rocks. Rb, Th, U, and Ba abundances are quite similar in both CR1 and CR3 and Cs is only slightly greater in CR1. Hon (1976) indicates these elements are also quite mobile in a hydrothermal environment. A number of other authors (Condie and Lo, 1971;

Olade and Fletcher, 1975; Ellis and Wilson, 1960; Murad, 1974; Hahn-Weinheimer and Ackermann, 1967) have found evidence for hydrothermal transport of several of these elements. Lack of significant enrichment or depletion of these elements in sample CR1 as compared to CR3 may be merely a result of the intensive parameters peculiar to the Red Lake pluton. Similarly, it was noted in the petrology discussion that major element alteration of CR1 was not entirely consistent with that reported for some other granitic plutons. An additional possibility, explored more thoroughly in a following section, is that hydrothermally mobile elements such as U, Th, Rb, Cs, and Ba may have equilibrated with a solution pervasive throughout the pluton during the weak chloritization-sericitization alteration period. For example, chloritization of biotite releases potassium (Chayes, 1955) and presumably the Cs, Rb, and Ba which substitute for it. The details of hydrothermal complexing and transport are beyond the scope of this investigation, but the previously cited investigators indicate that such geochemical dispersion occurs and that the resultant effects are variable among plutons. In particular, on the basis of oxygen isotope studies Taylor (1976) has concluded that significant interaction occurs between plutons and meteoric water, and Cathles and Norton (1974) concluded that introduction of ground water may be in part responsible for the hydrothermal alteration associated with porphyry copper deposits. The Red Lake pluton is within two kilometers and on strike with the older, calcic (marble, calc-silicates) Dinkey Creek roof pendant (Bateman and Kistler, 1966). The anomalously high Ba abundance in the Red Lake pluton may be an

indicator of pluton-meteoric water interaction.

Eagle Peak Pluton

The petrologically inferred crystallization sequence for the Eagle Peak pluton is the sequence E92-E89-E91-C1-E83. Samples C1 and E83 are two texturally different porphyritic core samples for which petrologic data did not imply a genetic sequence. In this sequence La/Yb increases, but absolute REE abundances show no distinct trend. However, core sample E83 is slightly enriched in LREE over marginal samples and marginal sample E92 is depleted in LREE. There is little variation in the intermediate REE. Lu and Yb do however show a consistent decrease in abundance from E92 to E83. As with the Red Lake pluton, the decrease in HREE with increasing fractionation could result from coprecipitation of biotite, hornblende, and sphene, probably accompanied by plagioclase. This mineral combination allows for variations in La/Yb while producing relatively minor variation in the absolute REE abundances. Failure to produce increasingly more negative Eu anomalies suggests coprecipitation of hornblende and plagioclase, a suggestion consistent with the regular decrease in Sc throughout the sequence. The remaining trace elements show no regular variation.

Several relationships require special consideration. Sample C1 shows a distinct La depletion compared to the other samples. Allanite is present in all rocks analyzed from the pluton. Frondel (1964) and Hasegawa (1957) have shown allanite is often enriched in LREE. An allanite analysis from Hasegawa (1957) has a La/Ce ratio of approximately 1.0. Thus, precipitation of allanite

could significantly reduce La in the residual liquid. Calculations given in a later section indicate the required amount of allanite will have negligible effect on the other trace element abundances. Feldspar separates from C1 support this interpretation. The plagioclase, which began precipitation quite early, shows no anomalous La-Ce behavior. Alkali feldspar C1, which was the last major mineral to crystallize, shows a La depletion and Ce enrichment relative to the host rock. This could result by precipitation of alkali feldspar from a liquid already depleted in La. This La anomaly is useful in interpreting the genetic relation between samples E83 and C1. If sample E83 were a derivative of C1 it also should have a La anomaly. Since it does not, an alternative relationship must be sought. Geochemically, C1 could be a derivative of E83; however, E83 has a fine grained groundmass which has been interpreted as indicating rapid quenching. Quenching of the core would effectively stop crystal fractionation, thus preventing formation of the C1 La depletion. Consequently, the most reasonable interpretation is that C1 and E83, although both core samples, represent different crystallization regions within the pluton. Semi-independent histories could result from the existence of two crystallization centers within the core. Inspection of the Eagle Peak map indicates this to be a distinct possibility as a result of the near pinch out of the core between samples E83 and C1. Bateman (verbal communication) has postulated several crystallization centers within the adjacent, much larger Mount Givens granodiorite.

Sample E83 contains less Yb, Lu, Ta, Th, U, and Cs and more Ba than the pluton average. Crystal fractionation or

late stage volatile loss are most likely responsible for this.

Subtraction of sphene could reduce Ta, Th, U and HREE but should also significantly reduce Hf, which is not observed. The texture of E83, combined with the interpretation of the E83 biotite major element data, suggests that volatile removal of these elements is a more acceptable process. This would allow possible addition of Ba by partial re-equilibration with the vapor phase and also allow depletion of Cs, which is not explicable by sphene subtraction.

Petrologic data for the Eagle Peak pluton indicate a minor amount of deuteric alteration followed crystallization and formation of aplites. This appears to provide a possible explanation for the relative uniformity or lack of regular variation in Rb, Cs, Ba, U, Th, and possibly Ta. This is especially true in samples E83, E91, and C1. As indicated previously, work by other investigators suggests these elements to be readily mobilized during alteration. The erratic U abundances of E89-E91-C1 are readily explained in this manner.

Marginal sample E92: Marginal sample E92 is fine grained, foliated, and was taken approximately three meters from the well exposed contact with the granodiorite of Dinkey Creek. It has the lowest concentrations of LREE, Hf, Th, Cs, Rb, and Ba, suggesting that it is the least differentiated sample. Explanation of these variations is severely restricted by the major element chemistry, which is essentially identical to that of E89 (Table 14). Fractional crystallization of major minerals to increase the REE concentrations to those of E89 is not supported by the major element chemistry or by other trace element data. Interaction with mafic inclusions

during or soon after intrusion cannot be entirely responsible, as the major element chemistry of mafic inclusions is significantly different (Pabst, 1928). Petrographic observations indicate the accessory minerals sphene, apatite, and allanite are present in only minor amounts in this sample as compared to the other rocks. Intrusion of the magma with suspended crystals could produce a concentration of the early formed crystals near the margin of the pluton. This resembles the model proposed by Presnall and Bateman (1973). The later forming accessory minerals would not occur in the solidifying magma formed at the margins of the pluton of only early precipitated minerals. Until the precipitation of accessory minerals the residual, interstitial fluid becomes enriched in REE. If this fluid is at least partially expelled from the crystallizing marginal rocks, these rocks will be depleted in apatite or allanite and therefore depleted in LREE (but enriched in HREE because of hornblende), U, and Th. Ba, Rb, and Cs depletions can be explained by similar processes, as the lower abundance of alkali feldspar, the major host of these elements, in E92 severely limits the amount of these elements that can be retained. This process eliminates the need for the extensive crystallization that would be required to produce the increase in trace element concentrations from E92 to E89. It is also consistent with the major element data. Essentially, marginal sample E92 appears to be an unrepresentative crystal cumulate of the initial magma.

Aplites

Granitic aplites are generally believed to represent the residual liquid from crystallization of granitic magmas. A number of studies (Barker and others, 1975; Putman and Alfors, 1969) relate the composition of the aplites to the load pressure of the associated plutons. Several lines of evidence support such an origin for the aplites of this study. The modal, major element, and normative compositions of the aplites lie at the most differentiated extreme of trends defined by the plutonic rocks, and field evidence indicates the aplites formed later than their host rocks. In the section on petrology and geology it was concluded that these aplites resulted from crystal fractionation of a cooling liquid.

The trace element data are especially useful in assessing the origin of the aplites. REE plots, both chondrite and host rock normalized (Figures 24, 25, 27), show major negative Eu anomalies. This is consistent with subtraction of large amounts of feldspar from the parent magma. Furthermore, prior fractionation of mafic minerals would result in aplitic liquids with low absolute abundances of REE, thereby counteracting the concentrating effect caused by plagioclase subtraction. Subtraction of hornblende would also partly compensate the Eu effect produced by plagioclase. Removal of accessory minerals such as allanite and sphene would also tend to decrease the relative abundance of REE. This in part explains the lower abundance of Sc and Hf in the aplites as compared to the host rocks. Sample CR10 is anomalous to the other aplites by its comparative enrichment in

LREE. The easiest explanation for this is that aplite CR10 contains accidental xenocrysts of allanite. Allanite is present in all the rocks. This is consistent with the Th but not the U data. As will be shown later, however, Th and U data may be difficult to interpret.

The Ba data are also useful in evaluating the origin of the aplites. Barium is strongly partitioned into the liquid coexisting with plagioclase and hornblende, slightly enriched in biotite over liquid, and strongly concentrated in alkali feldspar. Early and continued precipitation of plagioclase and mafics would tend to produce a Ba enriched residual liquid, but after formation and loss of alkali feldspar, the liquid would become depleted in Ba. All three aplites are strongly depleted in Ba relative to the host rocks. Condie and Lo (1971) noted a similar relationship for granites and aplites of the Louis Lake batholith but they concluded that Ba was carried away from the aplites in the accompanying vapor phase.

A variety of other element abundances and relationships are also readily explained in terms of vapor phase transport. U abundances are greater in all aplites than in their associated host rocks. Precipitation of accessories from the parent magma would tend to reduce the concentration of U in the residual liquid. Oxidation of U to the hexavalent state allows it to form more stable complexes (Cotton and Wilkinson, 1967) and be carried in the aqueous phase. The oxidation may be a result of the rupturing which formed the aplite; deposition in the aplite apparently results from instability of the complex.

Th abundances in the Red Lake aplites are greater than host granite abundances; the reverse is found in the Eagle Peak pluton. This may result from differing environments for the two plutons.

Rb tends to be greater in the aplites than in the host rocks. Removal of biotite and alkali feldspar from the magma should produce a residuum depleted in Rb. Extensive subtraction of plagioclase could compensate for this. However, both Rb and Cs are found enriched in geothermal fluids (Ellis and Wilson, 1960) and Condie and Lo (1971) and Hon (1976) conclude late stage fluids associated with granitic magmas are enriched in Rb and Cs. Additional complications are the uniform abundances of Rb, Cs, and Ba in the main mass of the plutons which earlier was suggested due to deuteric alteration and transport. Deuteric alteration appears the only reasonable explanation for the extremely high Cs value for aplite CR10.

The tendency for greater K/Rb, K/Cs, and Rb/Cs ratios in the aplites as compared to the host rocks may also result from vapor fractionation. As the cation size increases it is more difficult for it to substitute for K and it should be preferentially incorporated into the vapor. This is consistent with the aplites forming with an associated vapor phase which is subsequently lost.

The trace element data for these aplites are consistent with aplites forming from the residual liquid of a crystallizing pluton and that a vapor phase was associated with the aplites. This vapor may have provided the driving force for rupturing the pluton,

injecting residual liquids into the main body of the pluton, and selectively transporting some elements. Aplites apparently formed when the associated vapor escaped, whereas pegmatites formed when the vapor was retained.

INTERPRETATION OF MINERAL DATA

Feldspars

Interpretation of magmatic history using feldspar trace element data requires the data to represent the magmatic environment. Host rock normalized REE feldspar data are shown in Figures 32 and 33 and alkali feldspar/plagioclase REE partition coefficients are plotted in Figure 35. Both plagioclase and alkali feldspar separates contain between 0.02 and 0.5 times the bulk rock REE abundances, with plagioclase more enriched relative to alkali feldspar. Europium is significantly enriched over the other REE, with anomalies reaching 12 in alkali feldspar Cl. Plagioclase tends to be somewhat more enriched in LREE relative to HREE. These plagioclase features are characteristic of a number of dacitic plagioclase phenocrysts reported by Nagasawa and Schmetzler (1971) and Dudas, Schmitt, and Harward (1971). Granitic plagioclase data reported by Buma, Frey, and Wones (1971) and Towell, Winchester, and Spurr (1965) is similar to that presented here, with no preferential enrichment in either HREE or LREE. A dacitic alkali feldspar phenocryst reported by Nagasawa (1971) is generally similar to the feldspars of this study, with the exception of a minor preferential enrichment in HREE. The

Ce enrichment of alkali feldspar C1 is an exception to this comparison. Alkali feldspars E91 and CR29 thus appear to reflect magmatic conditions, whereas C1 has a more complex history.

REE partition coefficients between alkali feldspar and plagioclase range between 0.20 and 1.5 (Figure 35). Samples E91 and CR29 have slightly greater HREE partition coefficients; all samples show Eu preference for alkali feldspar. The value of the partition coefficients is within the range reported for granitic feldspars by Buma, Frey, and Wones (1971), Towell, Winchester, and Spirn (1965), and Nagasawa (1971); these authors also report Eu preference for alkali feldspars. Dacitic phenocryst data of Nagasawa (1971), however, indicate preference of Eu for plagioclase. This may reflect the different environments of plutonic and volcanic rocks. The data of the preceding authors show LREE and HREE partition coefficients are generally similar with gradational increases toward either LREE or HREE similar to the data of Figure 35. Thus, partition coefficient data suggest E91 and CR29 represent magmatic conditions. C1 shows anomalously high Ce partition coefficients, nearly three times those for La and Sm. Condie and Lo (1971) present granitic feldspar data in which Ce partition coefficients are up to twice those for La and Sm; these authors attribute variable Ce behavior to variations in the oxidation potential of the magma and suggest Ce^{+4} has a greater affinity for feldspar than biotite. Feldspar C1 has a more complicated history than the other feldspars.

Feldspar Europium Anomalies

Philpotts (1970) and Drake (1975) have related Eu anomalies in feldspars to feldspar composition, temperature, and oxygen fugacity. Feldspars of a given type are similar in composition in both plutons. Thus, if the host rocks crystallized at similar temperatures the feldspar Eu anomalies should be indicative of magmatic oxygen fugacity. This interpretation assumes the feldspar REE abundances reflect magmatic conditions. Eu anomalies were calculated as the quotient of the host rock normalized Eu value divided by the normalized Eu value predicted by interpolating between Sm and the HREE. The values are given in Table 21. Anomalies for feldspars CR29 and C1 are similar and both are larger than those for E91. This result suggests rocks C1 and CR29 formed in more reducing environments than E91. $\text{Eu}^{+2}/\text{Eu}^{+3}$ increases with decreasing $f\text{O}_2$ and Eu^{+2} is preferentially incorporated into feldspars (Weill and Drake, 1973). Thus, if these magmas cooled with $f\text{O}_2$ controlled by a mineral buffer, as suggested in a previous section, the samples with the largest Eu anomalies should have formed at the lowest temperatures. This relationship is consistent with other data for Eagle Peak samples E91 and C1 indicating the core formed at a lower temperature than the margin. However, extension of this interpretation to feldspars from CR29 is difficult. Eu anomalies for the alkali feldspars suggest CR29 crystallized at a temperature- $f\text{O}_2$ intermediate between those of E91 and C1. However, the plagioclase data suggest CR29 crystallized at a temperature below that of C1. This latter observation would appear inconsistent with

most of the petrologic data which suggests CR29 is less differentiated than C1 and hence formed at a greater temperature. This discrepancy suggests the feldspar data may not completely reflect magmatic conditions. Lopez and Hon (personal communication) have obtained data implying elimination of Eu anomalies in feldspars during metamorphism. It has also been suggested that C1 experienced late stage oxidation. Depending on kinetics this could reduce the magnitude of pre-existing Eu anomalies. For this case plagioclase C1 would have originally had an anomaly greater than that of CR29. It should also be noted that these Eu anomalies suggest significant differences in $T\text{-}fO_2$ among the samples whereas temperatures calculated from feldspar compositions (Table 17) are all similar and less than magmatic. The feldspar partition coefficients plotted in Figure 35 are quite similar to those discussed by Nagasawa (1971). However, those for C1 deviate from the general pattern, showing larger Ce and Eu and lower Lu values. The Lu discrepancy may be dismissed as an analytical problem, but the Ce and Eu values appear to be significant. Late stage or post magmatic reduction of the Eu anomaly in plagioclase C1 would explain the anomalously high feldspar Eu partition coefficient for that sample seen in Figure 35. An initially larger Eu anomaly for plagioclase C1 would also be more consistent with the ratio of plagioclase/alkali feldspar Eu anomalies for the other samples. This value is 0.7 for CR29, 0.7 for E91, and 0.4 for C1. Quite possibly variable amounts of post magmatic adjustment are recorded in the data.

Two additional features of the data reflect on magmatic history. On the host rock normalized diagram (Figure 32) alkali feldspar of C1 plots below that of E91. This indicates the relative paragenesis of alkali feldspar in the two rocks. Alkali feldspar occurs as an interstitial mineral in rock E91; therefore, it crystallized from the residual liquid. Alkali feldspar in C1 occurs as phenocrysts; it crystallized from the melt in competition with additional solidus minerals for available trace elements, resulting in a wider distribution of these elements. As a result both feldspars in C1 contain lesser abundances of REE than those of E91.

Cerium Anomalies

The Ce anomaly in alkali feldspar C1 correlates with a La depletion in the host rock. Production of these relationships requires selective removal of La or Ce from the system. As stated previously, allanite is strongly enriched in LREE and Hasegawa (1957) reports analyses of allanite containing approximately equal amounts of La and Ce. Since in most of the rocks studied here this ratio is approximately 1/2, subtraction of a La enriched allanite would deplete the residuum (rock C1) and subsequently crystallized minerals in La and produce anomalous La/Ce behavior. Most REE are believed present in the magma as trivalent cations. However, Ce can be oxidized to the tetravalent state in which case it will not compete efficiently with La for sites in allanite. Apparently the effect is less important in minerals such as feldspars where REE are only trace constituents. Rock C1, based on $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, is also the most oxidized host rock of this study. The absence of the anomaly in

plagioclase and biotite data indicates: (1) the allanite was subtracted after these minerals formed but before alkali feldspar formed and (2) plagioclase and biotite failed to completely re-equilibrate with the later melt. Alternatively, the Ce anomaly can be interpreted as excess Ce in the alkali feldspar resulting from post magmatic processes. This is less desirable, as there is no reason to suspect an affinity of Ce^{+4} for alkali feldspar.

K-Rb Feldspar-Biotite Thermometer

Beswick (1973) experimentally determined the distribution of K and Rb between phlogopite and sanidine and determined the temperature dependence to be defined by

$$T_K^0 = \frac{0.406 \times 10^3}{\log K_D - 0.091}, \text{ where } K_D = \frac{(\text{K/Rb})_{\text{phlogopite}}}{(\text{K/Rb})_{\text{sanidine}}}$$

This equation was applied to the coexisting alkali feldspars and biotites of this study; K values were taken from electron microprobe analyses and Rb values were taken from Table 21. Although Beswick's experiments were conducted with pure end member phases the general results may be applicable to the samples of this study. Correct temperatures cannot be expected, but since mineral and rock compositions are generally similar for all samples the relative temperature values should be significant. The results are shown in Table 23. There is a surprising discrepancy between CR29 and the Eagle Peak samples. However, E91 and C1 show the expected trend, with C1 representing a lower temperature, but these temperatures are less than magmatic and in the range obtained by using the feldspar thermometer of Stormer (1975).

TABLE 23

Temperatures calculated from K-Rb abundances of coexisting biotite and
alkali feldspar

Host rock:	CR29	E91	C1
Rb/K, biotite	0.605×10^{-2}	1.19×10^{-2}	1.24×10^{-2}
Rb/K, alkali feldspar	2.12×10^{-3}	3.18×10^{-3}	2.44×10^{-3}
Rb/K (biotite)	2.8	3.7	5.1
Rb/K (alkali feldspar)			
Temperature, °C.	840	570	390

Sample CR29 on the other hand indicates a much higher temperature, quite possibly magmatic. This conflicts with results from the Stormer thermometer and with conclusions based on Eu anomalies in feldspars. Those data suggest similar temperatures for feldspars of both plutons.

The reason for the severe discrepancy in relative temperatures from the two plutons is unclear. Clearly, CR29 alkali feldspars and biotites contain less Rb than corresponding minerals of the Eagle Peak pluton, a characteristic shared by the host rock data. Two factors may contribute to the discrepancy. In previous sections it was concluded that a vapor phase was evolved early from the Red Lake pluton. Selective loss of Rb from early formed biotite would raise the indicated temperature; newly formed alkali feldspar would tend to be in equilibrium with the melt. Also, early loss of volatiles would tend to inhibit readjustment of mineral compositions to lowering temperatures. In the Eagle Peak pluton retention of volatiles to a later stage would allow continued re-equilibration of biotite and alkali feldspar. The indicated temperatures for the Eagle Peak pluton are submagmatic; they may be displaced because of the nonideal system, or possibly, result from the postmagmatic deuteric adjustment which is believed to have produced the similar Rb, Cs, and K abundances in most of the Eagle Peak rocks.

Sc Biotite Thermometer

Oftedal (1944) suggested Sc concentration in biotite increases with decreasing temperature. From absolute abundance and host rock normalized Sc data the sequence represented by the biotite data of this

study indicates a decreasing temperature in the order E91-CR29-C1. This trend is reasonably consistent with the Eu data, the results obtained by Stormer's feldspar thermometer, and the petrologic conclusions discussed earlier. Dodge and Moore (1968) have also noted that trace element trends in Sierran biotites appear to reflect magmatic conditions even when major element chemistry has re-equilibrated. The Sc data appear to reflect magmatic conditions whereas K and Rb values are questionable. Analyses of altered biotite (see section on petrology) indicate K and presumably Rb are readily and significantly changed during alteration. Al is less affected and presumably so is Sc which substitutes for Al. The difference in the degree of alteration of these elements is closely related to the sites into which they substitute.

Hornblende Europium Anomalies

It is known that subtraction of plagioclase will produce Eu depletion in the residual liquid. However, the data of this study indicates that coprecipitation of hornblende can compensate for this effect (see Hanson and Arth, 1976). Since hornblende contains larger abundances of REE, the ratio of hornblende to plagioclase can be much less than one without causing a Eu anomaly. Other elements, such as Sc, can be used in evaluating the relative abundances of the two minerals.

COMPARATIVE PETROGENESIS OF THE RED LAKE AND THE EAGLE PEAK PLUTONS

With respect to trace element data the two plutons can be distinguished by larger abundances of Ta, U, Sc, Th, Rb, Cs, higher U/Th, and HREE, and lower K/Rb, K/Cs, and Ba abundances in the Eagle Peak pluton relative to the Red Lake pluton. Several processes have been invoked in previous sections to correlate the trace element data with the petrogenesis of the plutons deduced from field and petrologic data.

Within both plutons HREE and Sc decrease with increasing fractionation. This is well explained by hornblende and sphene fractionation during differentiation.

Trends within the plutons for the other trace elements are not well developed. However, in the Eagle Peak pluton Hf tends to increase and Ta decrease with increasing fractionation. Sphene fractionation is again a possible cause for the Ta decrease.

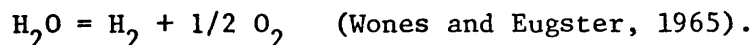
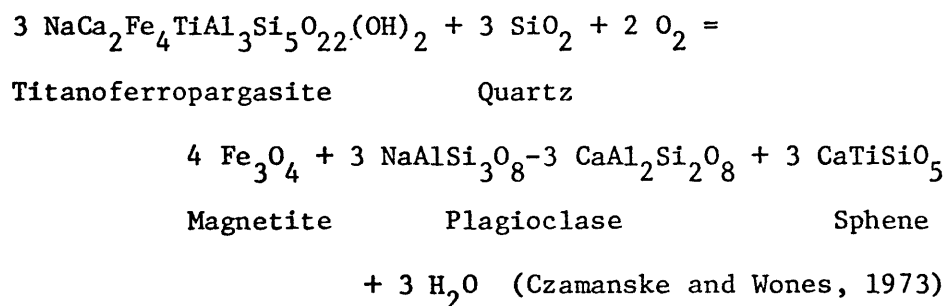
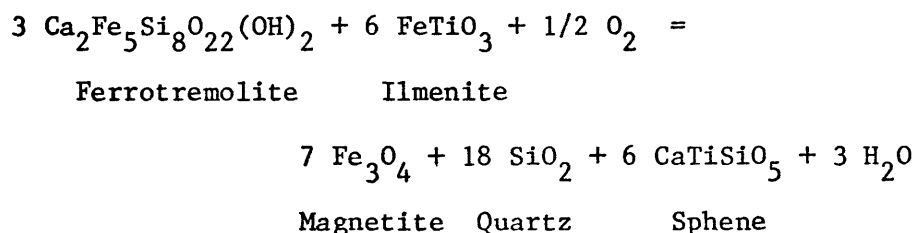
Aplites will show the effects of mineral fractionation and vapor transport. Fractionation effects are large Eu depletion from plagioclase subtraction and large Sc depletion from biotite, hornblende and sphene subtraction. Ba depletions may result from biotite and feldspar fractionation and LREE depletion is possibly related to allanite and apatite fractionation. Aqueous fluid effects are probably high HREE, U, Rb, and perhaps Ba. Low Hf abundances may be due to mafic fractionation or to a vapor phase. Vapor phase transport is suggested by the low Hf in the hydrothermally altered Bear Butte facies (CR1), whereas the more differentiated samples of the plutons tend to be enriched in Hf.

These processes can be applied to explain the differences between plutons. Marginal, least differentiated rocks of the Eagle Peak pluton (E89, E92) are more mafic (higher MgO, FeO, CaO; lesser Na₂O) than the least differentiated samples (CR29) of the Red Lake pluton. Higher HREE and Sc and lower Ba in the Eagle Peak pluton may result from less fractionation of hornblende and sphene (HREE and Sc) and plagioclase (Ba) or from more partial melting in a source region containing these phases. U, Th, and Ta data can be partially explained by sphene in either fractionation or melting models.

The sphene trace element analysis of this study shows large abundances of HREE, U, Th, and Ta and presumably some elemental differences between plutons may result from sphene fractionation. To account for the Th and U differences requires subtraction of about 4% sphene from the primary magma. Ta differences require only 1% sphene. Subtraction of 4% sphene would decrease CaO by approximately 0.9 weight per cent and would completely eliminate TiO₂ from the residual liquid. These major element constraints are not consistent with observed host rock data. Subtraction of 1% to 2% sphene is agreeable with the major element data. Lu and Yb depletions in the Red Lake pluton can be accounted for with as little as 0.3% to 0.7% sphene subtraction. Thus, minor sphene fractionation can explain Ta and HREE differences; U and Th require an additional source. Allanite may contain up to several per cent ThO₂ and several thousand parts per million U (Deer, Howie, and Zussman, 1969). However, allanite does not precipitate early enough in these rocks to

be an acceptable candidate in a fractionation model. Apatites in granites commonly contain approximately half as much U and Th (Hurley and Fairbairn, 1957) as sphene but twice as much CaO; thus it also is unreasonable in a fractionation model.

U as well as Rb and Cs variations may result from volatile evolution from the Red Lake pluton. Fluid interaction between the Red Lake pluton and adjacent limestone could have added Ba to that pluton. Volatile loss could contribute to the loss of other elements from the Red Lake pluton by consuming hornblende in the following reactions:



Biotite may also participate in this reaction as suggested by petrography and microprobe analysis. The apparently slightly greater sphene/biotite ratio in the Red Lake pluton may be significant in terms of these reactions.

Production of a larger Th/U ratio in the Red Lake pluton may result from a two stage process involving continuous evolution of volatiles and a somewhat more oxidizing environment, oxidizing the U and allowing formation of soluble, removable complexes. Selective removal of Rb and Cs in an aqueous phase would produce the increase of K/Rb , K/Cs, and Rb/Cs ratios over those of the Eagle Peak pluton. A slightly more oxidizing environment for the Red Lake pluton is suggested by most of the $\text{Fe}_2\text{O}_3/\text{FeO}$ whole rock analyses. The mafic silicate data, however, is more readily interpreted in terms of a mineralogically controlled buffer. The feldspar Eu data suggest a similar range of T and $f\text{O}_2$ in each pluton. Quite possibly the minor differences in host rock $\text{Fe}_2\text{O}_3/\text{FeO}$ for the two plutons do not adequately reflect the magmatic environment and the Th/U ratio for the Red Lake pluton can be accounted by selective removal of U complexes in the aqueous phase under prevailing, mineralogically controlled $f\text{O}_2$.

Partial melting at the lower crust-upper mantle interface of a basalt-graywacke sequence is a possible source of these magmas (Hurley and others, 1965). Variations between plutons could result from partial melting of source rocks of variable trace element composition. Large variations in trace element abundances of Precambrian graywackes are discussed by Wildeman and Haskin (1973) and Condie (1967). Compositional variations in the magma source region are discussed in Chapter IV.

Biotites: Th, U, Rb, Cs, Ba

Inspection of the biotite trace element data reveals some marked differences between Red Lake sample CR29 and samples from the Eagle Peak pluton. The most marked variation is in the biotite/host rock Ba values. For CR29 this value is about 3, whereas it is about 1 for samples C1 and E91. However, biotite/host rock values for Th, U, Rb, and Cs for the Eagle Peak pluton samples are greater than those of the Red Lake pluton. These elements are all readily susceptible to hydrothermal transport. Apparently Rb, Cs, U, and Th are more readily leached from biotite than is Ba in the Red Lake environment. In the Eagle Peak pluton the biotites apparently readjusted to the late stage deuteritic environment. Continuing evolution of vapor from the Red Lake pluton would tend to remove the soluble U, Th, Rb, and Cs; apparently Ba, which is also quite soluble, was deposited at the current exposed level of the pluton.

SUMMARY

The post intrusion history of the two plutons may be summarized as follows. Intrusion was followed by crystal fractionation, soon interrupted and restricted in the Red Lake pluton by evolution of a volatile phase. Degassing may have been sporadic or continuous; the Red Lake pluton may have been tapped by a volcanic vent. Relative depletions of HREE, U, Rb, and Cs may have been caused by incorporation of these elements in the escaping volatile phase. Extensive hydrothermal alteration in the vicinity of Bear Butte was apparently caused by this vapor phase.

Differentiation was more extensive within the Eagle Peak pluton. Hornblende and sphene fractionation produced increasing Sc and HREE depletion. Possibly different crystallization centers within the pluton are indicated by differing trace element abundances of two porphyritic core samples.

Aplite development within each pluton followed extensive fractionation of feldspars and mafics. Exsolution of a vapor phase possibly ruptured the plutons and injected the residual liquid into the fractures.

Trace element differences between the plutons may result from initial differences in source region trace element abundances, differing amounts of partial melting in the source region, or different crystallization histories. Early and continued evolution of a volatile phase from the Red Lake pluton with concomitant mineral reactions could produce most of the trace element differences between the two plutons.

Deuteric alteration within the Eagle Peak pluton may be responsible for minor or erratic variations in Rb, Cs, Ba, U, and Th abundances. This is consistent with petrologic data indicating weak sericitization of alkali feldspars and chloritization of biotite.

Mineralogical trace element data are generally similar to phenocryst data from volcanic rocks, suggesting the data in this study closely approach the magmatic environment. However, possible reduction of the Cl plagioclase Eu anomaly during post magmatic processes may have occurred. La and Ce variations in rock Cl and alkali feldspar Cl suggest an oxygen fugacity sufficiently high in the later stages of crystallization of the Eagle Peak pluton to produce Ce^{+4} . In general, the Eu anomalies in feldspars from both plutons are consistent with petrologic considerations indicating a relative decreasing temperature sequence of E91-CR29-Cl.

K-Rb distributions between alkali feldspar and biotite indicate magmatic temperatures for the Red Lake pluton. These distributions produce the expected temperature trend for the Eagle Peak pluton samples, but the absolute values are submagmatic and suggest partial low temperature re-equilibration of those samples.

Aplite major element compositional data, biotite stability relations, and experimental studies discussed in Chapter I suggest a minimum melting temperature for these granitic rocks near $750^{\circ}C$. This value is reasonably consistent with the Beswick thermometry of CR29 but much higher than that suggested for E91 and Cl. The Storrer

feldspar thermometry discussed in Chapter I also indicates submagmatic temperatures for both plutons, with the Eagle Peak pluton showing the lowest values. This data further illustrates that submagmatic changes in major and trace element chemistry have occurred. In general, the REE do not appear to have been subject to these processes.

Sc abundances in biotites indicate a relative temperature sequence consistent with petrologic considerations and most of the feldspar Eu data: E91-CR29-C1.

The most significant differences between the two plutons are the presence of a porphyritic core in the Eagle Peak pluton and a bimodal distribution of trace element data. The data of this study strongly suggest the differences result by retention or loss of a volatile phase. Whether this can be applied to all Sierran plutons similar in composition is not known. In this study extensive hydrothermal alteration is associated with the early devolatilization. This alteration is not common in Sierran plutons. However, when present it is often associated with tungsten mineralization. Some of the mineralized areas are associated with porphyritic plutons, indicating the initial water content of plutons is an additional important factor. Loss of fluids does not require associated hydrothermal alteration; its absence may be an exposure problem. For example, breccia pipes are absent(?) from the Sierra Nevada batholith but are quite commonly associated with more deeply buried granitic stocks of the Southwest. Only a relatively minor part of the Red Lake pluton shows any alteration; even this was apparently unrecognized in the original mapping.

Thus, extension of the results of this study requires closer evaluation of field data and trace element data from plutons of similar age and composition.

CHAPTER III
CRYSTALLIZATION MODELS OF THE RED LAKE
AND THE EAGLE PEAK PLUTONS

INTRODUCTION

Field and petrologic considerations suggest the Red Lake and the Eagle Peak plutons, Sierra Nevada batholith, were intruded as crystal-bearing liquids. This has been proposed for other Sierran plutons as well as many other granitic intrusives. Post-intrusion crystallization may occur in several manners. For example, a static magma chamber may develop and crystallize inwards from the margins with no convection or crystal settling or alternatively, the suspended crystals may settle as the magma cools. In addition, Presnall and Bateman (1973) suggested that in Sierran plutons convection transfers crystals from pluton interiors to the margins, where some collect on the walls with the remainder carried back into the interior by the convecting magma. Thus, magmatic processes may range from filter pressing to simple crystal fractionation.

The models investigated here involve simple crystal fractionation, that is, gravitational differentiation of suspended crystals from the magma as it cools from the margins inwards. Crystal fractionation in these plutons was discussed and justified in a previous chapter. The history of these plutons may well be more complex than this model

recognizes. However, this approach provides a quantitative framework in which to interpret the plutons.

Two methods are used to model crystallization. The Least Squares Mixing Program (LSMM) of Wright and Doherty (1970) is used to determine the most appropriate proportion of liquidus minerals required to relate the major element compositions of selected parent and differentiated rocks. All mineral and rock compositions are taken from representative samples of the plutons in this study. A similar program (Bryan and others, 1969) has been used in an analogous manner in studies of volcanic rocks (Zielinski and Frey, 1970). For the Eagle Peak pluton and the aplites, a trace element model is applied to the results of the major element models. This is discussed in more detail in the appropriate sections.

PLUTON CRYSTALLIZATION MODELS

Red Lake Pluton

The Red Lake pluton shows relatively minor internal variability in major and trace element composition (Tables 14 and 20). Samples were selected to represent parental (CR29) and differentiated (CR5) rocks. Field and petrologic evidence support a general crystallization sequence within the pluton consistent with this choice.

Modal analyses in Tables 12 and 13 and the alkali-mafic plot of Figure 14 indicate CR29 is the least differentiated and CR5 the most differentiated of the samples studied from the Red Lake pluton.

Two Red Lake pluton plagioclase analyses and average compositions of

CR29 biotite and hornblende used in the calculations are shown in Table 24. Ideal compositions of quartz, magnetite, and sphene were used (Table 24).

Results of seven models are given in Table 25. The difference between actual and calculated CR5 major element compositions are listed under "Residuals". Negative residuals indicate a calculated composition less than the actual composition by the tabulated weight percent. The models tested a variety of the most important liquidus minerals and two plagioclase compositions. Solutions A, Al, B, and Bl indicate only minor differences result from different plagioclase compositions. Solutions containing quartz require 3% to 5% more crystallization. Whether quartz was an important liquidus phase is uncertain; it definitely began crystallization after the mafic minerals but before complete solidification of the pluton. Its effect is probably over-estimated by the solutions A and Al in Table 25. Solutions A, Al, B, Bl, and E evaluate the effects of biotite, magnetite, and sphene. It is apparent that hornblende and plagioclase are the dominant fractionated minerals in all solutions. In all cases the amount of subtracted hornblende is greater than the maximum modal hornblende in any Red Lake pluton sample. Apparently, Fe, Mg, and Ti are balanced with hornblende rather than biotite, because of the small difference in K_2O between CR5 and CR29. It is likely that during crystallization some biotite would be fractionated.

The solutions indicate a maximum of about 12% crystal fractionation in the Red Lake pluton. This is generally consistent with the

TABLE 24

Major element compositions of minerals used in modelling studies

	Biotite		Hornblende		Plagioclase				Kspar	Mag	Sphene
	CR29	E92	CR29	E92	An18	An26	An32	An40	Or88		
SiO ₂	36.56	36.72	44.99	44.82	64.66	61.16	60.50	57.70	64.41	0.0	30.6
Al ₂ O ₃	14.17	14.64	7.98	9.05	22.39	25.79	24.86	25.71	18.50	0.0	0.0
FeO	21.35	21.68	17.70	17.41	0.0	0.0	0.0	0.0	0.0	93.09	0.0
MgO	10.65	10.04	11.18	10.88	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CaO	0.0	0.0	11.26	11.32	3.91	5.54	6.68	8.22	0.10	0.0	28.6
Na ₂ O	0.10	0.17	1.21	1.09	9.20	8.05	7.86	6.80	1.29	0.0	0.0
K ₂ O	9.44	9.40	0.91	0.94	0.24	0.30	0.23	0.20	14.73	0.0	0.0
TiO ₂	3.00	2.72	1.46	1.44	0.0	0.0	0.0	0.0	0.0	0.0	40.8

All compositions in weight percent.

Biotite and hornblende compositions are averages of analyses of the indicated samples. Plagioclase and alkali feldspar (Kspar) compositions are representative analyses from this study. Magnetite (Mag) composition is that of pure magnetite. Sphene analysis is that of pure sphene, CaTiSiO₅.

TABLE 25

Red Lake pluton major element fractional crystallization models

Model	A	A'	B	B'	C	D	E
<u>Phase proportions, weight %</u>							
CR5 (residual liquid)	90.55	88.48	93.95	93.40	93.40	89.48	93.54
plagioclase	4.36	5.68	2.49	2.92	2.92	5.13	2.79
biotite	0.00	0.27	0.00	0.00	-	-	-
hornblende	3.91	4.00	3.58	3.70	3.70	4.15	3.48
magnetite	0.00	0.00	0.00	0.00	-	-	-
quartz	1.20	1.60	-	-	-	1.26	-
sphene	-	-	-	-	-	-	0.21
plagioclase composition	An40	An32	An40	An32	An32	An32	An32
<u>Residuals, weight %</u>							
SiO ₂	-0.06	-0.07	-0.01	-0.01	-0.01	-0.07	0.01
Al ₂ O ₃	-0.10	-0.11	-0.14	-0.15	-0.15	-0.10	-0.12
FeO	-0.05	-0.07	-0.08	-0.09	-0.09	-0.07	-0.05
MgO	-0.02	-0.04	-0.01	-0.02	-0.02	-0.04	0.01
CaO	-0.03	0.00	0.07	0.08	0.08	-0.01	0.05
Na ₂ O	0.18	0.10	0.20	0.16	0.16	0.11	0.16
K ₂ O	0.04	0.06	-0.06	-0.04	-0.04	0.06	-0.05
TiO ₂	0.03	0.03	0.02	0.02	0.02	0.03	-0.06
MnO	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Calculation method: CR5 + Σ minerals = parent (CR29)

Sign convention: (-) residuals indicate calculated parent is greater than model parent by indicated amount in volume percent. Minerals not included in a solution are indicated by a dash (-).

minor variation in trace element compositions as well. With hornblende and plagioclase as the dominant fractionated minerals, only a small europium anomaly would tend to develop, which agrees with the REE data. Hornblende subtraction could produce the observed Sc depletion (Table 20). Plagioclase subtraction tends to increase and hornblende subtraction tends to decrease REE abundance in the residual liquid, and depending on their relative proportions and crystallization periods, these minerals could compensate one another with respect to REE abundances. However, resultant HREE depletion with increasing fractionation is observed in the Red Lake rocks. In Chapter II it was concluded that approximately 1% hornblende subtraction could explain the Sc and Eu decrease from CR29 to CR5. Major and trace element data limit crystal fractionation in the Red Lake pluton to less than 12%.

Eagle Peak Pluton: Major Element Models

The Eagle Peak pluton shows substantially greater internal variation than the Red Lake pluton. This is readily seen in the field, where an equigranular margin contrasts with a porphyritic core and mafics decrease in abundance towards the interior of the pluton. Major and trace element variations are also significantly greater than in the Red Lake pluton, and several distinct concentric trends are observed. The Eagle Peak pluton, therefore, is a better example for evaluating crystal fractionation models.

Major element compositions of parent (E89), residual liquid (C1), and fractionated minerals are shown in Table 24. Rock E89 was chosen

as the parent liquid, as it is near the margin of the pluton but it does not appear to have interacted with the wall rock. C1 is a sample from the porphyritic core and is the most interior sample analyzed. Biotite and hornblende compositions are averages of those from E92, near the pluton margin. Plagioclase compositions are from this pluton. Magnetite, sphene, and quartz compositions are ideal.

Results of several solutions using the LSMM are shown in Table 26. Solutions A, B, AQ, and C used unmodified E89 as the parent liquid. Solutions A and B did not allow quartz as a fractionated phase. They illustrate the minor importance of biotite, which was also excluded from solution B. Solution AQ illustrates the profound influence of adding quartz as a fractionated phase. As with the Red Lake pluton, quartz may have been a fractionating mineral, but only quite late in the sequence. Therefore, its effect is believed much less than indicated by solution AQ. Solution C is identical to solution AQ with the exception of plagioclase composition. Plagioclase composition is significant because An_{32} contains more SiO_2 than An_{40} , and in these solutions it nearly eliminates the need for quartz as a fractionated phase. The plagioclase in the Eagle Peak pluton is zoned from An_{45} to An_{18} , and therefore either of the above values may be valid. Early fractionation would favor An_{40} .

In all cases the amount of crystal fractionation is greater than in the Red Lake pluton, but as in the Red Lake pluton, all solutions except AQ require significant amounts of hornblende and only minor biotite fractionation. Although up to 9% hornblende and up to 1% biotite fractionation are required by the model, the modal difference

TABLE 26
Eagle Peak pluton major element fractional crystallization models

Parent magma	E89				E89-3% Hornblende			E89-5% Hornblende		
Model	A	B	AQ	C	D	E	EE	F	G	GG
<u>Phase proportions, weight %</u>										
Cl (residual liquid)	79.96	79.98	41.94	77.61	84.45	56.15	57.82	85.59	67.79	70.38
plagioclase	11.23	11.30	29.60	12.40	12.21	25.12	23.62	12.42	19.78	18.94
biotite	0.26	-	11.93	0.67	2.31	8.77	7.85	1.15	4.91	4.32
hornblende	7.91	8.05	0.91	8.62	3	3	3	5	5	5
magnetite	0.66	0.70	0.23	0.51	1.05	0.27	0.39	0.86	0.40	0.48
quartz	-	-	15.41	0.23	-	9.71	10.34	-	5.14	5.91
plagioclase composition	An40	An40	An40	An32	An40	An32	An40	An40	An32	An40
<u>Residuals, weight %</u>										
SiO ₂	0.08	0.06	0.04	0.05	0.11	0.05	0.14	0.10	0.05	0.11
Al ₂ O ₃	0.17	0.18	0.08	0.21	-0.04	0.16	0.21	0.11	0.20	0.25
FeO	0.05	0.04	0.03	0.03	0.04	0.04	0.09	0.05	0.03	0.08
MgO	0.06	0.07	-0.08	-0.04	0.38	-0.07	0.01	0.20	-0.07	-0.01
CaO	-0.05	-0.07	0.11	0.02	0.36	0.34	0.03	0.12	0.18	-0.07
Na ₂ O	-0.36	-0.37	-0.26	-0.50	-0.40	-0.59	-0.28	-0.45	-0.63	-0.38
K ₂ O	-0.21	-0.19	0.05	-0.18	-0.39	-0.04	0.00	-0.32	-0.14	-0.10
TiO ₂	0.16	0.16	0.10	0.15	0.17	0.11	0.13	0.17	0.14	0.15
MnO	0.04	0.04	0.00	0.04	0.01	-0.01	-0.01	-0.01	-0.02	-0.02

Calculation method: Cl + Σ minerals = parent.

Sign convention: (-) indicates calculated parent is greater than model parent by indicated amount.
Minerals not included in a solution are indicated by a dash(-).

in hornblende between E89 and C1 is approximately 4%, and that of biotite is about 3%.

In order to be consistent with modal and field observations, two additional parent magma compositions were considered. Hornblende never exceeds 5% modal abundance in any sample of the Eagle Peak pluton. This sets the upper limit on hornblende fractionation. Hypothetical parent magmas were obtained by subtracting 3% and 5% hornblende with composition as in E92 from parent magma E89. These compositions were then run with the LSMM program, retaining C1 as the residual liquid. The results are shown in Table 26 as solutions D, E, EE, FG, and GG. These solutions also evaluate the relative importance of quartz and plagioclase composition. Biotite assumes a greater importance in these models than in models A, B, and C. Adding quartz to the fractionating assemblage greatly increases the amount of crystallization allowed, especially with respect to biotite and plagioclase. Solutions D and F, without quartz, indicate little difference results if 3% or 5% hornblende is subtracted; total fractionation is about 15%. The remaining solutions, containing quartz, indicate a greater total fractionation is required for the 3% hornblende solutions. Since quartz fractionation is believed to be minor based on petrographic evidence, solutions D and F are most preferred.

It is not clear which of the solutions most accurately represents the differentiation of the pluton. None are exact, and all are

reasonably similar in their variation from the desired composition.

Several factors may be responsible for these discrepancies:

1. Mineral compositions in the differentiating liquid may have been different than the present mineral compositions; the importance of quartz is indicated by the models.
2. Some mineral re-equilibration with fluids, such as in deuteric alteration, may have caused changes in bulk rock composition. For example, biotite alteration to chlorite releases titanium and potassium; epidotization of plagioclase releases sodium. It is presumed these elements enter a fluid phase and are redistributed. Kaolinitic, sericitic, and chloritic alteration indicate a fluid phase was available to aid element migration. This may explain the minor differences in Na_2O and K_2O between E89 and C1. This was suggested in Chapter II to explain the similar Rb and Cs abundances in rocks of different major element composition.
3. The models may not be correct, either because the rocks are unrelated, which is unlikely, or the proper components have not been included in the models.

Residuals shown for modelling in both plutons range as high as -0.63. Wright (1974) indicates residuals greater than 0.1 for any element suggests other processes or components should be considered in the petrologic analysis. For the Red Lake pluton, Na_2O residuals tend to be the greatest. Fractionation of a more sodic plagioclase

would alleviate this problem; however, CIPW norms show bulk rock $Ab/Ab+An$ is about 0.60, and fractionated plagioclase would therefore be expected to be more An rich than An_{32} .

Na_2O residuals for the Eagle Peak models are negative and are accompanied by large negative K_2O residuals. Models D and E have large positive CaO residuals, and models D and F have large positive MgO residuals. Fractionation of a more An rich plagioclase would ease both the Na_2O and CaO residuals. However, whole rock normative $Ab/Ab+An$ is approximately 0.60 in marginal Eagle Peak samples, and calcic plagioclase cores analyzed are An_{45} . Fractionation of a plagioclase more calcic than An_{40} would therefore be required very early in the history of the pluton. Also, the existing plagioclase compositions may have evolved from a more calcic precursor. The large MgO and K_2O residuals are directly related to biotite fractionation. Subtraction of more biotite would reduce the MgO residual but increase the K_2O residual.

In spite of the above uncertainties, models D and F are preferred. They require a petrologically reasonable amount of hornblende subtraction, and they exclude quartz as an important fractionating mineral. In addition, they conform to a simple fractionation model. Solutions D and F will now be evaluated using calculated trace element distributions.

Eagle Peak Pluton: Trace Element Models

Trace element evaluations of selected major element models were performed assuming surface equilibrium between the fractionated minerals and residual liquid. Distribution of a trace element between liquid and solid phases is governed by the Rayleigh Fractionation Law (Gast, 1968):

$$\frac{C_a^1}{C_a^0} = F^{k_a - 1},$$

where:

C_a^1 = weight fraction of element a in the liquid;

C_a^0 = weight fraction of element a in the initial liquid;

F = fraction of liquid remaining after crystal subtraction; F ranges from 0 to 1.

k_a = the Nernst distribution coefficient for element a; concentration of a in the crystal divided by the concentration of a in the liquid. When more than one phase is crystallizing, k will be a weighted average of the individual distribution coefficients for the given element.

This equation and its limitations are derived and discussed by

Gast (1968). Primarily, this equation assumes crystals are removed from contact with the liquid as soon as they are formed. Zoned plagioclase approaches this limitation.

Using this equation, if C_a^0 , F , and k_a are known, C_a^1 can be calculated. In this study, values of C_a^0 are assumed to correspond to the values measured in rock E89. Most values for k_a are carefully selected from the literature. They represent values most appropriate to granitic systems and appear reasonable when compared to the mineral trace element data of this study (see Chapter II). The Sc distribution coefficient was calculated from the data of this study, as there were no literature values appropriate to this system. The distribution coefficients and their sources are given in Table 27. F is determined for each model by subtracting from 1 the total fractional amount of crystallized phases indicated by the LSMM for the major element data. Values of C_a^1 calculated in this manner are then compared to the concentrations of the same elements in Cl. This provides a test of the major element models.

Table 28 contains trace element modeling calculations for the best major element models. Notice that models A, B, and AQ have many calculated trace element values significantly different than those in Cl. In particular, model AQ reflecting the effect of quartz as a diluent (i.e., it is assumed quartz does not accept any of these elements in its structure), does not agree with the observed composition of Cl. In each of the models the most significant discrepancy is in the calculated and observed Sc concentrations. This difference

TABLE 27

Distribution coefficients* used in crystallization models

	Hornblende	Biotite	Plagioclase	Apatite
La	1.4 (c)	0.27 (e)	0.24 (f)	52.5 (f)
Ce	1.4 (c)	0.32 (e)	0.24 (b)	52.5 (a)
Nd	4.2 (c)	0.30 (f)	0.17 (b)	81.1 (a)
Sm	8.2 (c)	0.26 (e)	0.13 (b)	89.8 (a)
Eu	5.9 (c)	0.24 (e)	1.0 (f)	50.2 (a)
Yb	8.7 (c)	0.44 (e)	0.077(b)	37.0 (a)
Lu	5.9 (c)	0.33 (e)	0.062(b)	30.2 (a)
Ba	0.044(c)	6.36 (d)	0.36 (b)	
Rb	0.014(c)	3.26 (d)	0.048(b)	
Sc	25 (f)	10 (f)	0 (f)	
Hf	2 (f)	2 (d)	0 (f)	

* Sources:

- (a): Dacite 1A, Nagasawa (1970)
- (b): GSFC 218, An51, Schnetzler and Philpotts (1970)
- (c): Hornblende 1Hb, Nagasawa and Schnetzler (1971)
- (d): GSFC 218, mica(biotite), Philpotts and Schnetzler (1970)
- (e): Biotite, Higuchi and Nagasawa (1969)
- (f): Approximation based on literature values and/or concentration relations of specific phases in this study.

Host rocks for minerals in references (a) to (e) are dacites. See text for discussion of specific cases for (f).

TABLE 28

Trace element solutions to fractional crystallization models^a

	Model designation									Allanite
	E89	A	B	AQ	E	D	DD	DA	C1	
La	31	33	33	62	47	34	31	18	25	14.74
Ce	65	69	69	130	98	72	66	60	67	7.44
Nd	26	22	22	51	36	27	23	23	24	-
Sm	4.9	2.9	2.9	9.4	5.9	4.4	3.8	3.8	3.8	-
Eu	0.97	0.63	0.62	1.3	0.98	0.84	0.77	0.77	0.82	-
Yb	1.5	0.87	0.86	2.9	1.8	1.4	1.3	1.3	0.88	-
Lu	0.29	0.21	0.21	0.58	0.39	0.28	0.27	0.27	0.22	-
Ba	860	1000	1020	550	740	850	850	850	860	-
Rb	148	180	180	190	190	160	160	160	147	-
Sc	6.9	0.92	0.90	1.7	1.7	2.9	2.9	2.9	3.0	-
Hf	4.9	5.1	5.1	8.0	6.6	5.3	5.3	5.3	5.1	-

^aModel names refer directly to major element models. Models DD and DA are derived from model D by subtraction of an additional 0.15% apatite and 0.15% apatite + 0.01% allanite, respectively. Trace element compositions of whole rocks E89 and C1 are listed for comparison. Allanite analysis from Deer, Howie, and Zussman (1969), analysis 5. Allanite analysis in weight percent oxides; all other values in ppm.

results from the large proportion of hornblende in the fractionated assemblage and the large Sc partition coefficient for hornblende. Since large fractionation (greater than 5%) of hornblende was questioned earlier in the major element modelling, solution E was evaluated which constrains the model to a maximum of 3% hornblende fractionation. The Sc problem is still unrelieved, however, because quartz is included in this solution. Most other values are also inappropriate. Solution D is also constrained to 3% hornblende, and quartz is eliminated from the model. The trace element values calculated from this model agree with Cl concentrations more closely than any of the previous models. Reducing the amount of hornblende in the models increases the proportion of biotite and allows a closer fit in Ba, Rb, and Sc data. By the same effect, it produces greater calculated values of HREE. The major discrepancy between solution D and Cl occurs in various REE. These difficulties can be overcome by considering various accessory minerals.

Influence of Accessory Minerals

Apatite, allanite, zircon, and sphene are accessories in the Eagle Peak pluton. Numerous studies have shown these minerals are enriched in REE, U, Th, and Hf relative to biotite, hornblende, quartz, and feldspars. Subtraction of these minerals from the liquid can produce variations in selected trace element concentrations, but they have minor effect on the major element chemistry. Determining the relative importance of each of these minerals in producing the observed trace element abundances is hindered by the absence of

data for such minerals in these rocks. However, an approximation of their behavior can be made using distribution coefficients from the literature and concentration data from similar rocks. Based on such data, and assuming the Hf/Zr weight ratio is about 0.02 to 0.03 (Gottfried and Waring, 1964), it can be calculated that zircon will be of only minor importance, as the amount required to produce the observed REE variations is prohibited by the minor variation of Hf in these samples. Allanite is highly Ce group selective (Deer, Howie, and Zussman, 1966) and also develops late in the crystallization history of these plutons. It, therefore, cannot be very effective in producing the observed variations. Sphene in these rocks is preferentially enriched in HREE (Lee and others, 1969; Noyes, this study). It also contains significant amounts of U and Th (Hurley and Fairbairn, 1958; Noyes, this study). The minor variation of Th and U between E89 and C1, therefore, precludes significant sphene participation. Apatite tends to be more enriched in LREE than HREE and would appear to be more effective in preferentially reducing the LREE. Distribution coefficients for apatite in similar rocks are available. Major element constraints on apatite involvement are whole rock abundances of CaO and P_2O_5 . These components allow a maximum of 0.15 weight percent apatite to be subtracted. Incorporating this proportion of apatite in the trace element model for D produces model DD in Table 28. The correspondence between DD and C1 is greatly improved. La-Ce discrepancies remain, however. These

can be overcome by removing 0.01 percent of a La enriched allanite. An example composition from a pegmatite allanite given in Deer, Howie, and Zussman (1966) is used for the calculation. The results are shown in Table 28 as DA. Insignificant changes will occur for the remaining trace element values. For example, in the analysis listed thorium is the next most abundant "trace element" in allanite, with 1.7 weight % ThO_2 . Subtraction of 0.01% allanite of this composition would reduce Th by only 2 ppm in the residual liquid, a relatively insignificant change. If the unreported constituents in the listed analysis, approximately 0.4 weight percent, are assigned equally to the unanalyzed REE, essentially no effect is produced in these elements in the residual liquid. The remaining discrepancies may result from minor contributions of zircon, sphene, and experimental uncertainty. Considerations in a previous chapter (Chapter II) strongly suggest the allanite is Cl is a La enriched variety.

Summary

The trace element data of this study cannot be used to independently determine the petrogenesis of the Eagle Peak pluton. However, they do constrain models based on petrology and major element chemistry. Several observations may be made concerning the results of the modelling:

1. The model most acceptable for the trace element data is petrologically reasonable. Only a limited amount of crystal fractionation is required. Those minerals removed are present in the rocks, and their

relative abundances are consistent with petrography. Participation of apatite and allanite is supported by their close association with biotite in these rocks.

2. The role of hornblende is clarified. Major element data allow up to 10% hornblende fractionation, but trace element data permit only 3% to 5%. This limitation was suggested by petrologic considerations, but it could not be evaluated from petrologic and major element data. A consequence of this result is that inward decrease of hornblende appears to be due largely to crystal fractionation, not reaction of early formed hornblende crystals with the magma. In this system, the reaction products of hornblende are plagioclase, sphene, and magnetite (petrographic evidence; also, Czamanske and Wones, 1973). These minerals are poor hosts for Sc (Paster and others, 1974; Buma, Frey, and Wones, 1971; Noyes, this study), and therefore fractionation of these reaction products of hornblende cannot produce the observed inward depletion of Sc in the Eagle Peak pluton.
3. There remains a discrepancy concerning the role of allanite. The La depletion of Cl requires fractionation of allanite with anomalously high La/Ce ratios. Frondel (1964) indicates the La enrichment observed in older analyses of allanite may be an analytical

error. However, inspecting some of those analyses indicates they still have relatively high La/Ce ratios, even after recalculation. Analyses of allanites from granitic rocks compositionally similar to those of this study (Lee and Bastron, 1967) have La/Ce weight ratios less than one and contain up to five weight percent $\text{Nd}_2\text{O}_3 + \text{Sm}_2\text{O}_3$. The influence of allanite can only be resolved by analyses of allanite from the Eagle Peak pluton.

Variable La/Ce ratios in allanite should be a function of Ce oxidation state. La and Ce typically occur as trivalent cations, but Ce can be oxidized more readily to a tetravalent cation than La. A sufficiently oxidizing environment would favor La enriched, Ce depleted allanites. Fleischer and Altschuler (1969) report Ce depleted apatites of marine origin and ascribe them to formation in a cerium deficient environment, ultimately caused by formation of Ce^{+4} in an oxidizing environment. Based on $\text{Fe}^{+2}/\text{Fe}^{+3}$, sample C1 is the most oxidized whole rock sample. Inspection of the mineral data indicates alkali feldspar C1 is depleted in La, suggesting it crystallized from a La depleted magma. On host rock normalized plots, biotite C1, relative to biotite E91, is substantially enriched in all LREE except Ce. One explanation for this is contamination of biotite C1 by traces of Ce depleted allanite.

APLITE MODELS

Major Element Models

Petrologic and geochemical considerations in previous sections strongly suggest that the aplites associated with the Red Lake and the Eagle Peak plutons are derived from late stage residual magma. Major element compositions are available for aplites CR14 and C3 from the Red Lake and the Eagle Peak plutons, respectively. It is assumed the most differentiated rock in each pluton is the closest representative of the parent liquid which differentiated to produce the aplites. Thus, CR5 represents the parent liquid for aplite CR14, and C1 that of aplite C3. It is further assumed that at this stage of crystallization, plagioclase, orthoclase, biotite, magnetite, and quartz were all potential fractionating phases. An_{32} and Or_{88} were used in the models for feldspar compositions, as these are approximate means of the zoned feldspars within the plutons. Biotite analyses are those from the previous models for the respective plutons, and ideal compositions were used for quartz and magnetite. The results of the LSMM are shown in Table 29.

Aplite C3 requires about 53% total fractionation as compared to 92% for CR14. Only minor Or_{88} fractionation is required for C3 as compared to approximately 13% for CR14. Both models require extensive plagioclase subtraction. This agrees well with the large negative europium anomalies for these aplites. In summary, both aplites require substantial amounts of mineral fractionation to produce them

TABLE 29

Sierran aplites: major element fractional crystallization models

Model	CR5 to CR14	C1 to C3
<u>Phase proportions, weight percent</u>		
Aplite	7.81	47.46
Plagioclase	44.86	29.98
Magnetite	0.81	0.42
Quartz	25.21	13.83
Alkali feldspar	13.25	0.59
Biotite	8.09	7.75
Plagioclase composition	An32	An32
<u>Residuals, weight percent</u>		
SiO ₂	0.06	-0.03
Al ₂ O ₃	0.32	0.05
FeO	0.04	-0.02
MgO	-0.10	-0.11
CaO	-0.25	-0.03
Na ₂ O	-0.58	-0.21
K ₂ O	-0.25	-0.08
TiO ₂	0.20	0.19
MnO	-0.01	0.00

Calculations and symbolism as in Tables 25 and 26.

from the selected parents. However, the calculated values are significantly less than the generally cited figure that aplites represent "the final several percent of crystallization".

Trace Element Models

Trace elements were also used to quantitatively test the petrogenesis of these aplites. However, the approach used for the Eagle Peak rocks cannot be directly applied to the aplites. The solutions given in Table 29 produce residual liquids with REE abundances greater than the parent liquids. These elements, except for Yb and Lu, are actually greater in the parent rocks than in the aplites. Therefore, an extensive contribution of accessory minerals or vapor phase transport is required.

A different modelling approach has been used to avoid the arbitrary selection of accessory minerals and vapor phase transport. Note that the parent rocks (CR5 and C1) have small europium anomalies relative to the derivative aplites. The amount of feldspar subtraction required can be evaluated by modelling changes in Sm/Eu. Note this does not account for changes in the absolute abundances of these elements.

Haskin and others (1970) developed an equation describing the change in the ratio of two elements in the residual liquid during crystal fractionation. This is given as:

$$\frac{\frac{1}{C_{\text{Sm}}} / \frac{o}{C_{\text{Sm}}}}{\frac{1}{C_{\text{Eu}}} / \frac{o}{C_{\text{Eu}}}} = F^{(\alpha_{\text{Sm}} - \alpha_{\text{Eu}})},$$

where: α_i = distribution coefficient, concentration ratio of element i in solid phase to liquid phase.

F = fraction of liquid remaining after crystallization.

C_i^1 = concentration of element i in the residual liquid.

C_i^0 = concentration of element i in the parent liquid.

In this modelling study, C_i^1 values are taken from the aplites, C_i^0 values are taken from the respective plutonic parent (CR5 or C1), and the plagioclase distribution coefficients are taken from Table 27. Two models are presented: one assuming plagioclase is the only subtracted phase, and one assuming a mixture of two-thirds plagioclase and one-third quartz is subtracted. Distribution coefficients for quartz are assumed to be zero. As would be expected, solutions involving quartz (Table 30) require a greater amount of crystallization. For CR14, 84% feldspar removal is required compared to 58% based on major element data. For C3, 71% feldspar removal is required compared to 30% based on major element data. Similar to the major element models, these trace element models imply the aplites are produced by a lower amount of crystallization than is commonly believed for aplites.

Summary of Aplite Models

The aplite models presented probably represent the minimum amounts of crystal fractionation required to produce the aplites from the selected parents. An important aspect not evaluated in modelling the major element compositions are the effects of vapor phase

TABLE 30

Trace element models of aplite crystallization

Aplite	Crystallization required	
	Phase proportions	
	1.0 plagioclase	0.67 plag, 0.33 qtz
C3	57%	71%
CR10	6%	9%
CR14	70%	84%

Abbreviations:

plag: plagioclase

qtz: quartz

modification, especially for Na_2O and K_2O . Luth and Tuttle (1969) indicate incorporation of these components into a vapor phase associated with granitic melts. Trace elements are also subject to vapor phase transport. Studies referenced in a previous chapter suggest REE can be complexed and removed in the vapor phase associated with pegmatites. The close association of pegmatites and aplites suggests the same process may also apply to aplites. Finally, compositional readjustments in the aplites may actually reduce initial Eu anomalies, since large Sm and Eu compositional gradients exist between the aplites and the enclosing granitic rocks. Possibly because of these constraints, the preceding models predict aplites result from far less crystallization than is commonly believed.

CHAPTER IV

ORIGIN OF SIERRAN GRANITES

INTRODUCTION

Extensive field observations show that the Sierra Nevada batholith is a composite igneous intrusion of calc-alkaline granitic rocks (Bateman and Warhaftig, 1966). Studies by Bateman and Dodge (1970) and Evernden and Kistler (1969) indicate these intrusives were implaced in repetitive compositional cycles. During any one cycle the plutons become progressively more granitic as age decreases. These cycles are termed, "intrusive sequences", and at least eight have been identified for the batholith. Presnall and Bateman (1973) concluded that each compositional cycle can be explained by simple fractional crystallization of an initial melt.

Several lines of evidence indicate that intrusion of the batholith was accompanied by contemporaneous volcanic activity. Ojakangas (1968) has shown that a volcanic cover was being eroded from the region of the current Sierra Nevada block during the Cretaceous and Jurassic, the time of intrusion for the batholith as determined by radiometric dating (Hurley and others, 1965; Kistler and Peterman, 1973). Bateman and Lockwood (1970) and Moore (1963) have shown that volcanic rocks are present in roof pendants of many of the intrusions; Fiske (1974) has related these volcanics to the host intrusives.

Studies of batholiths suggest the presence of associated volcanics. Field evidence suggests a direct relation between intrusive granitoids and overlying andesitic volcanics in the Andes (Pitcher, 1974). Lopez (1974) has shown that the geochemistry of associated Chilean andesites and granitoids is consistent with derivation of the intrusives by fractional crystallization of plagioclase, biotite, hornblende, apatite, and opaques from the andesites. Hamilton and Meyers (1967), in a summary study of batholiths, conclude that batholiths are intrusive equivalents of their own volcanic ejecta. Thus, a large portion of the compositional variety present in batholiths may result from upper crustal fractionation.

A number of other studies of calc-alkaline rocks are pertinent to an understanding of the Sierra Nevada batholith. For example, on the basis of trace element modelling, Arth and Hanson (1972) found that Precambrian quartz diorites of northeastern Minnesota could be derived by partial melting of eclogite and amphibolite. Barker and Arth (1976) conclude that trondhjemitic and tonalitic liquids may form by igneous differentiation or by partial melting of rocks of basaltic composition. They conclude that low Al_2O_3 partial melts formed in equilibrium with a plagioclase rich residue and that high Al_2O_3 partial melts formed in equilibrium with a hornblende rich residue. Condie and Lo (1971) proposed partial melting of quartz eclogite with a minor contribution of more highly differentiated rocks for the origin of the Precambrian Louis Lake batholith of Wyoming.

Lopez (1974) concluded from major element and trace element modelling that associated Andean andesites and granitoids of Chile are genetically related by fractional crystallization. Further, he attempted to model the origin of the andesites but found partial melting of peridotite, quartz eclogite, eclogite, amphibolite, and various other equivalents of oceanic Nazca plate basalt could not produce the trace element distributions of the andesites. He concluded altered basalt may be the most suitable source. Zielinski and Lipman (1976), in a study of the Summer Coon Volcano, found the extrusive sequence of andesites best explained by partial melting of an eclogitic source.

These studies suggest a variety of processes may be involved in producing the compositional variations present in a particular province and in the origin of andesites and calc-alkaline granitoids. Numerous petrologic studies (Kushiro, 1974; Green and Ringwood, 1968) have attempted to determine if partial melts of eclogite or peridotite are andesitic, but the results are inconclusive. The geochemical data are also subject to various interpretations. Models developed for one region may not be applicable to another region of similar petrology. This is illustrated by the work of Lopez (1974) and Zielinski and Lipman (1976) who find multiple models required for even one area. Consequently, it can be expected that variations in source composition, physical conditions of melting, and upper crustal crystal fractionation may all be involved in the development of the compositional variations of calc-alkaline complexes and the Sierra Nevada batholith.

STUDY AREA

Three plutons have been chosen to evaluate the relative importance of the preceding considerations in the development of the Sierra Nevada batholith. The plutons considered are the Red Lake pluton (Krl), the Eagle Peak pluton (Kep), and the Mount Givens granodiorite (Kmg). These plutons belong to the Cathedral Range intrusive epoch (Evernden and Kistler, 1969) and are located within the extensively studied cross section of the batholith investigated by the United States Geological Survey (Bateman and others, 1963). They are the youngest plutons in this area and therefore have not been subjected to the effects of later intrusions.

Bateman and Wones (1972a) briefly discuss the geology and petrology of these plutons and more extensive petrologic and geochemical discussions are presented by this author in previous chapters of this work. Areally, the Red Lake pluton and the Eagle Peak pluton each cover approximately 50 square kilometers and are much smaller than the Mount Givens granodiorite of approximately 1200 square kilometers. All three plutons are granodioritic in composition. Radiometric ages for the three plutons are overlapping and range from 85 to 90 million years (Bateman and Wones, 1972a). However, field relations clearly indicate that the Red Lake pluton and the Eagle Peak pluton intrude the Mount Givens granodiorite and therefore are geologically younger. Bateman and Wones (1972a) suggested on the basis of field relations and similarities in composition that these three plutons belong to a single intrusive sequence. According to the genetic

concepts discussed by Presnall and Bateman (1973), these three plutons should be related by fractional crystallization of a common magma. This common magma could be another pluton, one of these three plutons, or some unidentified precursor volcanic.

DATA PRESENTATION

Trace element data for the three plutons are presented in Table 31. Figure 37 shows chondrite normalized REE plots for each of the plutons; Averages of data from three to five samples of each pluton are plotted to enhance the differences between the plutons. Systematic differences between the plutons are readily seen. The slope of the REE plots (La/Yb), increases in the sequence Kmg-Kep-Krl. Rb, Cs, Sc, U, and Th show a general decrease in the same sequence, and Ba and Sr increase. Hf concentrations are quite similar for all samples. The concentration changes in the noted sequence are unequal; that is, there are relatively small differences between Kmg and Kep values as compared to Kep and Krl values. It is interesting to note that both Kmg and Kep have porphyritic interiors and Krl is entirely equigranular.

FRACTIONAL CRYSTALLIZATION MODELS

To evaluate the fractional crystallization model of Presnall and Bateman (1973), two models will be considered. Either the Red Lake pluton and the Eagle Peak pluton, as indicated by contact relations, are differentiates of the Mount Givens granodiorite, or

TABLE 31a
Selected trace element concentrations*, Mount Givens
granodiorite

	KPb-59	KPc-42	KPa-66	KMG-20
La	55.6	30.4	25.3	25.4
Ce	113	63.5	51.2	53.3
Nd	32.4	23.0	19.4	21.8
Sm	4.54	3.94	3.47	4.49
Eu	0.855	0.748	0.689	0.820
Ho	0.914	0.611	0.598	0.663
Yb	1.87	1.40	1.26	2.03
Lu	0.352	0.242	0.231	0.398

*All values in parts per million. Analytical method
discussed in Chapter 2. Sample locations discussed
in TABLE 31c.

TABLE 31b
Selected trace element abundances^a and ratios in Sierran granitic rocks

	Mount Givens Granodiorite				Granodiorite of Eagle Peak				
	KPb-59	KPc-42	KPa-66	KMG-20	E92	E89	E91	C1	E83
Sc	9.14	5.33	3.70	11.32	7.19	6.90	4.90	3.05	2.74
Hf	4.12	4.59	4.38	4.83	4.32	4.90	5.11	5.14	5.04
Ta	1.83	1.81	1.94	2.13	2.22	2.01	2.40	1.54	0.92
U	10.4	5.79	4.93	8.54	6.47	9.00	5.66	9.96	3.00
Th	43.4	26.9	28.5	21.3	15.7	20.5	20.0	20.4	15.7
Rb	155	159	179	154	132	148	167	147	160
Cs	7.64	9.79	5.25	8.38	4.17	7.62	7.53	7.75	5.92
Ba	748	748	870	739	770	862	856	865	1210
Sr ^b	300	300	300	300	350	350	350	350	350
Eu/Eu*	0.57	0.60	0.60	0.60	0.76	0.60	0.69	0.67	0.77
La/Yb	30	22	20	13	12	20	26	28	57
Th/U	4.2	4.6	5.8	2.5	2.4	2.3	3.5	2.0	5.2
K/Rb	190	210	190	180	190	150	170	200	-
K/Cs	3900	3400	6300	3400	6000	2900	3800	3800	-
Rb/Cs	20	16	34	18	32	19	22	19	27

a All values in parts per million. Analytical method discussed in Chapter 2.

b Sr analyses from semi-quantitative emission spectroscopy.

TABLE 31b, continued

Granodiorite of Red Lake				
	CR29	CR3	CR5	CR1
Sc	4.72	4.29	3.61	1.81
Hf	4.55	4.42	5.08	3.29
Ta	0.90	1.04	0.883	0.75
U	2.11	2.25	1.90	1.95
Th	9.30	8.19	9.00	8.53
Rb	88.6	107	94.0	108
Cs	3.09	3.01	2.58	3.86
Ba	1220	1040	1100	1250
Sr ^b	600	600	600	600
Eu/Eu*	0.84	0.77	0.70	0.67
La/Yb	32	28	44	44
Th/U	4.4	3.6	4.7	4.4
K/Rb	250	230	260	260
K/Cs	7200	8300	9500	7300
Rb/Cs	29	36	36	28

TABLE 31c
Major element analyses, Mount Givens granodiorite

	KPb-59*	KPc-42*	KPa-66*	KMG-20*
SiO ₂	68.2	70.4	71.8	67.4
Al ₂ O ₃	15.5	15.1	14.7	14.7
Fe ₂ O ₃	1.2	1.2	0.89	1.4
FeO	2.3	1.5	1.1	2.6
MgO	1.6	0.6	1.1	1.7
CaO	3.3	2.5	1.9	3.9
Na ₂ O	2.9	3.1	3.2	3.1
K ₂ O	3.6	4.0	4.0	3.4
H ₂ O ⁺	0.56	0.82	0.59	0.40
H ₂ O ⁻	0.03	0.05	0.10	0.07
TiO ₂	0.47	0.45	0.34	0.57
P ₂ O ₅	0.11	0.11	0.08	0.13
MnO	0.07	0.05	0.06	0.09
Total	100	100	100	99

*Analyses KPb-59, KPc-42, and KPa-66 from Bateman and Lockwood (1970); analysis KMG-20 from Bateman, Lockwood, and Lydon (1971). All values in weight percent.

Figure 37: Average chondrite normalized rare earth element abundances for the Granodiorite of Red Lake (Red Lake pluton), the Granodiorite of Eagle Peak (Eagle Peak pluton), and the Mount Givens granodiorite.

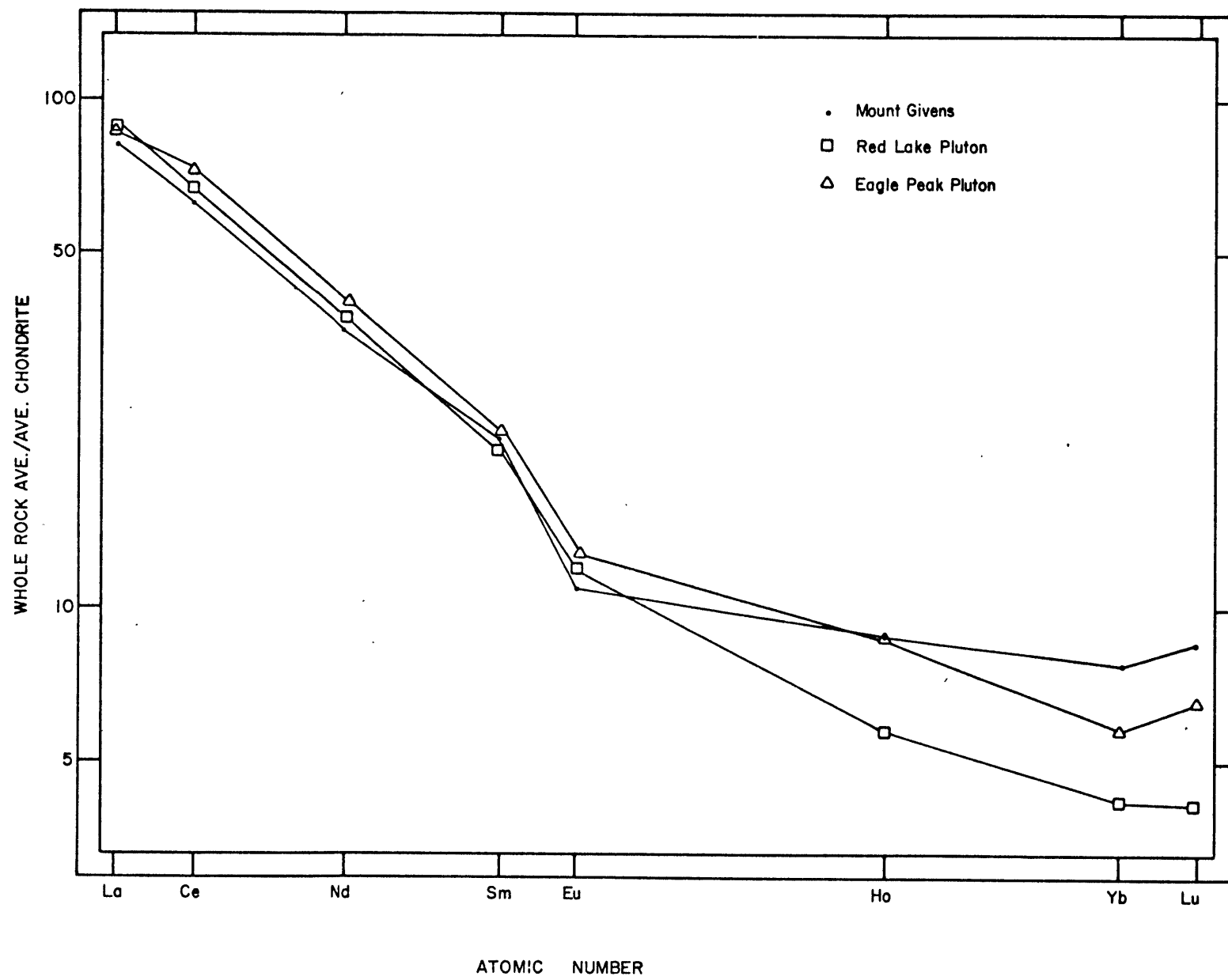


Figure 37

field relations have no genetic significance and the Mount Givens granodiorite may be a differentiate of one of the other plutons. This approach also tests the possibility that all three plutons differentiated from a common magma, such as an associated andesitic magma. Only the Mount Givens granodiorite and the Red Lake pluton are tested, as these occupy the most compositional extremes. The model is based on trace element distributions between magma and mineral phases, and a table of mineral-liquid distributions coefficients (Table 32) is included to aid in understanding the constraints.

The first model assumes the Red Lake pluton is a differentiate of the Mount Givens granodiorite. Rb, Cs, HREE, U, Th, Ta, and Sc are less abundant and Ba more abundant in the Red Lake pluton. The U and Th depletion in the Red Lake pluton could be caused by fractionation of sphene, apatite, or zircon without producing significant major element variations. HREE and Sc depletion could be caused by hornblende fractionation; zircon subtraction could contribute to the HREE depletion, and sphene fractionation could produce Ta and HREE depletion. Rb and Cs depletions could be produced by biotite fractionation. However, biotite fractionation would also reduce Ba in the residual liquid, although compared to Rb and Cs the depletion would be greater since Ba distribution coefficients for biotite are greater than those of Rb and Cs (see Table 32). In these rocks Ba increases when Rb and Cs decrease; biotite fractionation appears inappropriate as a major factor.

TABLE 32

Distribution coefficients used in partial melting models

	Clinopyroxene*	Amphibole*	Amphibole***	Biotite*	Ksp	Plagioclase*	Garnet*
Ce	0.21	0.09	0.900	0.04	0.044	0.241	0.35
Sm	0.681	0.336	3.99	0.058	0.018	0.125	2.66
Eu	0.635	0.358	3.44	0.145	1.13	2.11	1.50
Gd	0.875	0.509	5.47	0.082	0.01	0.090	10.5
Yb	0.90	0.46	4.90	0.18	0.012	0.077	39.9
Rb	0.002**	0.045	-	3.26	0.659	0.048	0.008
Sr	0.072**	0.188	-	0.12	3.87	2.84	0.015
Ba	0.002**	0.10	-	6.36	6.12	0.36	0.017

* Philpotts and Schnetzler (1970); (garnet, plagioclase, and biotite: GSFC218; hornblende: GSFC233; clinopyroxene: GSFC204; alkali feldspar, Ksp: GSFC266)

** Hart and Brooks (1974)

*** Arth and Barker (1976)

In addition, preservation of major element similarity between the plutons requires fractionation of both mafic and felsic minerals. Plagioclase will coprecipitate with the mafics. However, plagioclase removal will decrease Sr in the differentiate, but Sr abundance is greater in the Red Lake pluton than in the Mount Givens granodiorite. Lopez (1974) found fractionation of these minerals with minor additions of others was sufficient to explain the differentiation of Chilean andesites and granitoids, but they appear incapable of producing the Red Lake pluton as a differentiate of the Mount Givens granodiorite.

The alternative model assumes the Mount Givens granodiorite is a differentiate of the Red Lake pluton. Contact relations and major element compositions of the plutons strongly dispute this chronology but it is worthwhile to investigate the trace element variations from this perspective. U, Th, Rb, Cs, and Sc abundances increase by 50% to 80% from the Red Lake pluton to the Mount Givens granodiorite. Simple fractional crystallization, therefore, requires at a minimum removal of a similar proportion of phases not containing these elements to produce the differentiation trend. Decrease in Ba and Sr in this sequence requires crystallization of biotite and plagioclase. Compensatory biotite and plagioclase removal are also required to produce magmas of similar major element chemistry. Although the final results depend on the relative proportions of these two minerals, biotite removal will tend to lower Rb, Cs, and Sc in the residual

liquid. This is, of course, contrary to the observed trends. Qualitatively, a magma near a eutectic could undergo extensive crystallization with only minor major element compositional changes. However, the phases crystallizing would produce trace element trends contrary to those observed for these plutons.

Simple fractionation models cannot explain the geochemical data regardless of the differentiation sequence chosen. This conclusion also implies the granitoids are not derived by periodically tapping a common differentiating liquid. Because the plutons have similar major element chemistry and petrology, it is not acceptable to invoke a complex process of differentiation combined with crystal accumulation. A more acceptable explanation would have geochemically different andesitic liquids differentiating to produce petrologically similar plutons with diverse trace element geochemistry. Alternatively, the plutons themselves may represent discrete melts from compositionally different source regions. Either process relates the trace element variations to a heterogeneous source region. Source region variability is discussed next.

SOURCE REGION HETEROGENEITY

Studies of calc-alkaline provinces (Tilling, 1973; Doe and others, 1968; Doe and Delevaux, 1973) suggest heterogeneity in the magma source regions. For example, Arth and Hanson (1972) and Lopez (1974) demonstrated the plausibility of partial melting of metamorphosed oceanic crust in producing the trace element

distributions of some calc-alkaline provinces. Armstrong (1971) and Tatsumoto (1969) suggest oceanic sediments may be underthrust with oceanic crust and contribute to subsequent partial melts. Armstrong (1971) and Church (1973) discuss the isotopic constraints on the role of sediments and Gill (1974) has summarized the implications and geochemical differences between fresh and altered sea-floor basalt. Specifically, Rb, Cs, U, Th, and K increase, K/Rb and Fe decrease, and Ba behaves erratically during alteration of sea-floor basalt. These variations produce different normative compositions for the two types of basalt, as shown in Table 33. Most noteworthy is the greater proportion of garnet in the fresh basalt. During subduction both types of basalt may be subject to partial melting. For example, the hydrated altered exterior of the subducted plate should partially melt prior to the dry interior. This will produce two phases of melts, the first more enriched in Rb, Cs, U, Th, and K. Since the hydrated basalt will contain less garnet and garnet preferentially incorporates HREE compared to LREE, the earlier melt will have a flatter chondrite normalized REE pattern than later melts. This is, of course, a qualitative example, but it illustrates the importance of compositional heterogeneity in the source region of calc-alkaline rocks.

Mineralogical heterogeneity can also be expected in chemically similar rocks. For example, Boettcher (1973) and Jakes and White (1970) have suggested that at greater depths biotite will be stable relative to hornblende and that partial melting at greater

TABLE 33

Compositional differences between altered and unaltered
ocean floor basalts

	Basalt (3)	Altered basalt (4)
SiO ₂	49.61	50.6
TiO ₂	1.43	1.6
Al ₂ O ₃	16.01	15.1
Fe ₂ O ₃	2.00	4.3
FeO	9.69	6.0
MnO	0.18	0.18
MgO	7.84	6.4
CaO	11.32	10.9
Na ₂ O	2.76	2.7
K ₂ O	0.22	0.47
P ₂ O ₅	0.14	0.21
Eclogite norms		
Ap	0.3	0.3
Rut	1.4	1.6
Or	1.1	2.8
Ac	5.5	12.9
Jd	12.9	5.6
Di	20.9	35.0
Ga	51.5	20.2
Ky	1.1	13.8
Qz	6.1	7.7
Garnet composition	Alm ₃₂ Py ₃₇ Gr ₃₁	Alm ₂₇ Py ₄₂ Gr ₃₁
Omphacite composition	Jd ₃₃ Ac ₁₄ Di ₅₃	Jd ₁₀ Ac ₂₄ Di ₆₅

After Gill (1974); major element compositions in weight percent.

depths will thus produce lower K/Rb ratios in the melts as proportionately more biotite melts.

A variety of evidence indirectly also implies a heterogeneous source region for the Sierra Nevada batholith. For example, Hurley and others (1965) concluded from strontium isotope data that the parent magma of the Sierra Nevada batholith could be a combination of oceanic crust and lower continental crust. Kistler and Peterman (1973) greatly extended the strontium isotope data and determined a mapable, orderly variability (increasing toward the prebatholithic continental margin) in the initial strontium $^{87}/^{86}$ ratio. They found this ratio to vary from 0.704 to 0.708 and reported a value of 0.7071 for the Mount Givens granodiorite, the only pluton from this study for which strontium isotope data are available. They concluded that these values are all too large to represent partially melted oceanic crust and that a significant amount of lower continental crust is required to produce the enrichment in strontium 87. Sea floor alteration of oceanic crust increases the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio (Church, 1973; Dasch and others, 1973). Furthermore, Rb content increases with alteration (Hart, 1971); thus, with increasing time the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of altered basalt increases faster than in fresh basalt. However, neither alteration process appears dominant in producing the regular variations observed for the Sierra Nevada batholith because the geographical variations in initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios appear to be closely related to continental geology.

Preliminary lead isotope studies by Doe and Delevaux (1973) place significant constraints on the origin of Sierran granites. These authors suggest that only a minor proportion of Sierran lead is oceanic in origin and emphasize that partial melting solely of oceanic crust cannot produce the Sierran granites. Based on their lead data combined with the strontium isotope data of Kistler and Peterman (1973), Doe and Delevaux (1973) also excluded sources composed of oceanic crust and associated sediments. The most isotopically favorable model, they conclude, invokes partial melting in the lower crust-upper mantle region.

The preceding considerations strongly suggest a heterogeneous source region for the Sierra Nevada batholith. Specifically, strontium isotope data appear to indicate a laterally variable source and strontium and lead isotope data are best interpreted as resulting from lower crust-upper mantle melting. Clearly, then, lateral and vertical zoning may be expected in the source region of the Sierran plutonics.

Tilling (1973) presented evidence that the Boulder batholith of Montana resulted from partial melting of a vertically zoned source region. Some of his graphs are included here as they are applicable to the samples of this study. Figure 38 illustrates the major chemical differences between the Main Series and the Sodic Series, the two magma types recognized by Tilling. On most of the plots, the two groups lie in distinct fields. These

Figure 38: Variations in major and trace element geochemistry
for various intrusive phases of the Boulder batholith,
Montana (from Tilling, 1973).

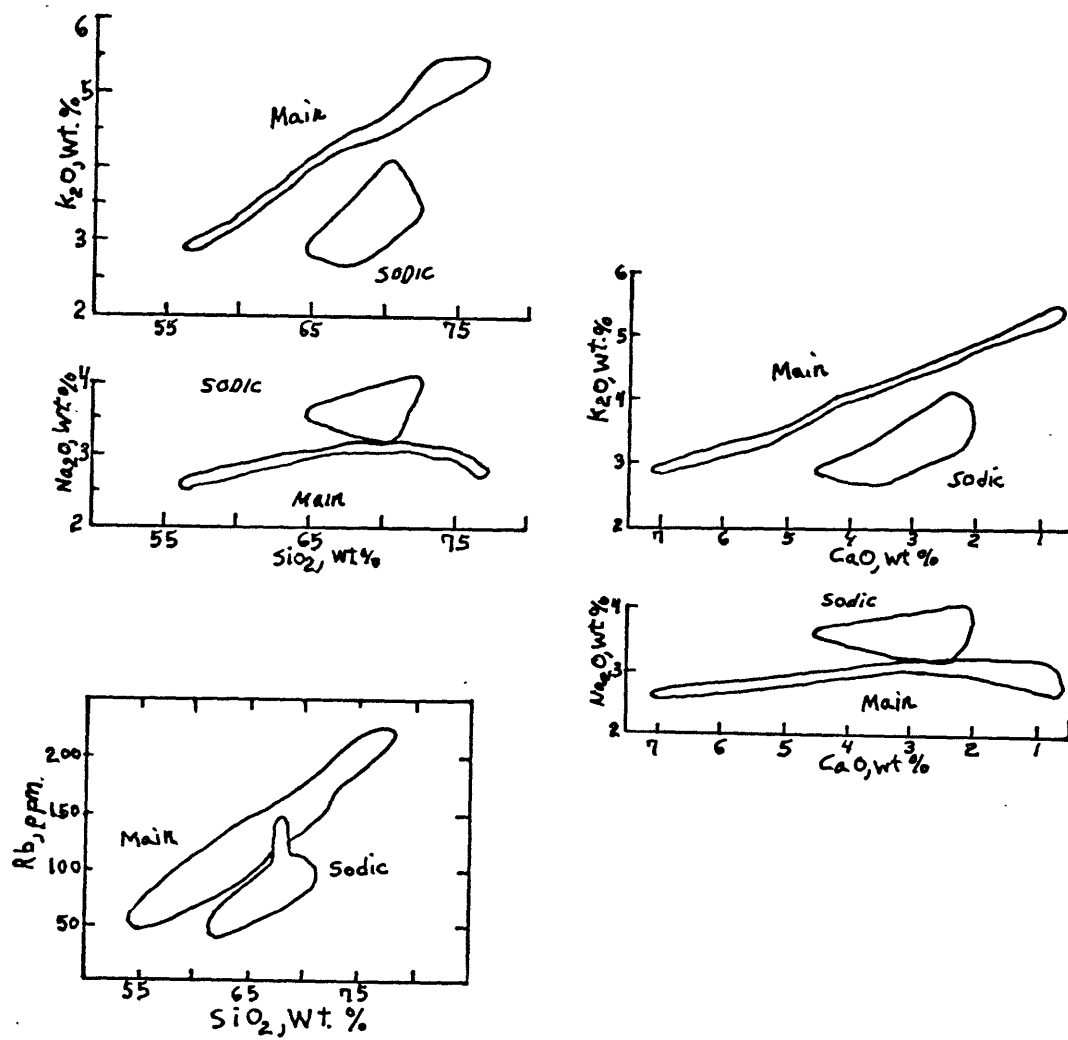


Figure 38

chemical distinctions lead Tilling to conclude the rocks represent two chemically distinct source regions.

Similar diagrams have been plotted with the data from the three plutons of this study (Figure 39). The trends observed for the Boulder batholith are broadly defined for these plutons also. The same relative positions observed on Tilling's plots for the Main and the Sodic Series are here taken by the Mount Givens granodiorite and the Red Lake pluton, respectively. The trends may not be as well defined because of the more compositionally restricted sample base for these Sierran plutons. Trends within the Sierra Nevada batholith as a whole may be obscured by the more extensive melting involved in its formation than in that of the Boulder batholith.

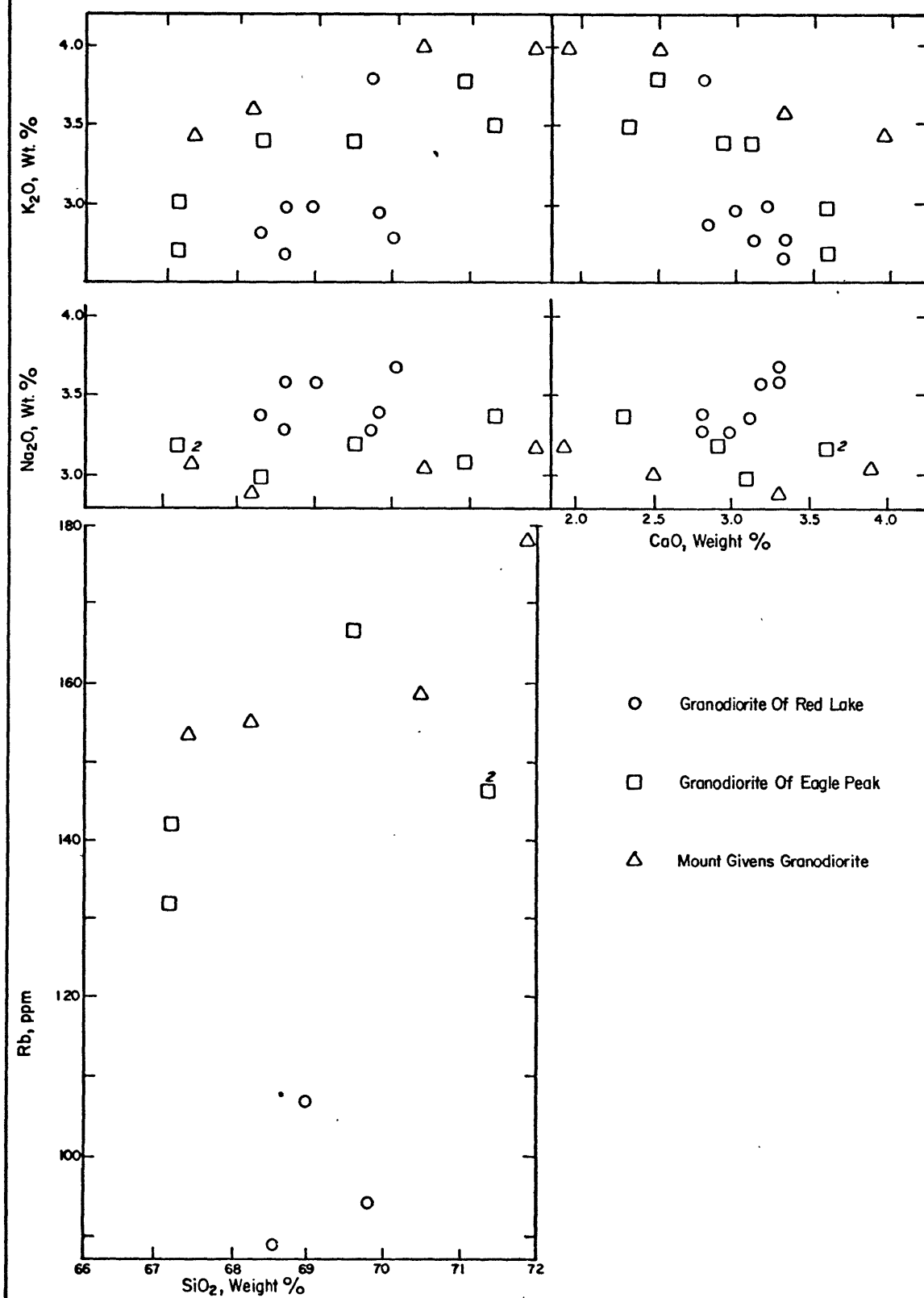
PARTIAL MELTING MODELS

The preceding considerations strongly suggest derivation of the Sierra Nevada magmas from a vertically and laterally heterogeneous source region. Several partial melting models have been constructed to aid in evaluating this mechanism.

The strontium isotope data can be interpreted as representing partial melting of a mixture of two-thirds basalt and one-third graywacke (Hurley and others, 1965). The lead isotope data (Doe and Delevaux, 1973) also suggest a lower crust-upper mantle origin. Therefore, a model parent composition was chosen of two-thirds basalt and one third graywacke. Both major and trace element

Figure 39: Variations in major and trace element geochemistry for three intrusives of the Sierra Nevada batholith: K_2O/SiO_2 , Na_2O/SiO_2 , K_2O/CaO , Na_2O/CaO , and Rb/SiO_2 distributions for the Granodiorite of Red Lake (Red Lake pluton), the Granodiorite of Eagle Peak (Eagle Peak pluton), and the Mount Givens Granodiorite; Rb in ppm and all oxides in weight percent. All data is presented in this study.

Figure 39



abundances were modelled. The Least Squares Mixing Model program (LSMM) of Doherty and Wright (1968) was used in the major element modelling to estimate the proportion of melting required to produce a selected magma from a source rock. Components of the source rock were taken from an associated Precambrian basalt-graywacke sequence in northern Minnesota (Arth and Hanson, 1975). A sample of the Eagle Peak pluton, E89, was selected to represent the partial melt composition.

Mineral compositions were selected from the studies of Holloway and Burnham (1972), Lambert and Wyllie (1972), and Green and Ringwood (1968). Major and trace element compositions of the mineral and rock components are given in Table 34. A calculated mode of the composite parent was obtained with the LSMM program and is given in Table 35.

Three basic major element partial melting models were considered. Model I has an initial assemblage amphibole, plagioclase, and quartz. Model II assumes part of the amphibole of model I has broken down to form garnet and clinopyroxene, according to the observations of Lambert and Wyllie (1972) at pressures greater than 10 kilobars, consistent with lower crust-upper mantle depths. Model III assumes amphibole has broken down to clinopyroxene and garnet and that some biotite is present, consistent with the suggestion of Boettcher (1973). It is assumed the transformation of amphibole to clinopyroxene, garnet, and biotite is essentially isochemical, consistent with the overall imprecision of the modelling. In all models using the LSMM program it is assumed that the residuals, the differences between actual and calculated compositions, would be accommodated in natural systems

TABLE 34

Chemical compositions of components used in modelling studies

	Avg. basalt *	Gray- wacke *	Compo- site **	E89	An56 (1)	Cpx (2)	Cpx (1)	Garnet (4)	Amp. (2)	Biotite (3)
SiO ₂	50.2	62.0	54.1	67.2	57.5	51.9	47.2	41.0	40.6	35.8
Al ₂ O ₃	13.7	15.3	14.2	15.8	26.3	3.1	10.0	22.0	14.5	18.6
TiO ₂	1.38	0.50	1.09	0.61	-	1.0	1.6	1.8	5.5	3.15
FeO***	13.7	5.72	11.0	4.0	-	6.2	7.0	17.7	13.4	15.2
MnO	0.22	0.07	0.17	0.06	-	-	-	-	-	-
MgO	6.65	3.42	5.57	1.5	-	17.1	11.6	12.6	12.0	9.01
CaO	8.33	2.76	6.47	3.6	9.0	20.1	21.6	7.8	9.6	0.12
Na ₂ O	2.76	3.51	3.01	3.2	6.5	1.5	0.7	-	2.1	0.29
K ₂ O	0.29	2.09	0.89	2.7	0.08	0.0	-	-	0.5	9.09
Rb	5.00	58.4	22.8	150						
Sr	130	457	239	350						
Ba	69.8	566	235	860						
Ce	17.0	32.6	22.2	65						
Sm	3.52	2.68	3.24	4.92						
Eu	1.22	0.785	1.08	0.965						
Gd	4.63	2.24	3.83	-						
Yb	2.98	0.845	2.27	1.5						

*Arth and Hanson (1973)

** Mixture of 2/3 average basalt and 1/3 graywacke

***Total iron as FeO

(1) Green and Ringwood (1968); 10kb, 920°C. (An56, plagioclase; Cpx, clinopyroxene)

(2) Holloway and Burnham (1972); 8kb

(3) Engel and Engel (1960); Table 15, group 1, amphibolite facies

(4) Green and Ringwood (1968); 18kb, 1230°C.

Oxide values in weight percent; trace element values in parts per million.

TABLE 35

Calculated modal analysis for composite parent in partial melting models

	Amphibole	Plagioclase	Quartz	Rock	Calculated	Difference
SiO ₂	40.6	57.5	99.99	54.10	54.16	-0.05
Al ₂ O ₃	14.5	26.3	0.0	14.20	13.95	0.26
FeO	13.4	0.0	0.0	11.04	8.69	2.36
MgO	12.0	0.0	0.0	5.57	7.78	-2.20
CaO	9.6	9.0	0.0	6.47	7.78	-1.30
Na ₂ O	2.1	6.5	0.0	3.01	2.49	0.53
K ₂ O	0.5	0.08	0.0	0.89	0.34	0.56
Solution	64.78	17.33	17.90			

All values in weight percent.

by the presence of accessory minerals and compositional adjustments of the major minerals.

The results of the major element modelling for model I are given in Table 36. E89 can be produced from the composite parent by 49% partial melting leaving a residue consisting entirely of amphibole. Because of previous considerations this amount of melting is considered appropriate for models II and III.

Trace element models assume partial fractional melting with the liquid incrementally removed. Equation 10 from Shaw (1970) was used to model selected trace element distributions. Trace element distribution coefficients used in the modelling are given in Table 32.

Various mineralogies and amounts of melting have been investigated for the composite parent. Models I, II, and III with 49% melting have been augmented with models VI, V, and IV, respectively, with 40% partial melting. The three latter models differ from the former only in amount of melting. Models IA, IIA, IIIA, IVA, and VII use a set of amphibole REE partition coefficients larger than those used in the previous models. In all other respects models IA, IIA, IIIA, and IVA are similar to models I, II, III, and IV, respectively. Model VII assumes only amphibole melts, leaving a residue of plagioclase, quartz, and amphibole. The modal abundances used in the partial melting models are given in Table 37 and the results of those models are given in Table 38.

Models II and III clearly demonstrate the utility of adding garnet

TABLE 36

Partial melting model results: production of E89 by partial melting
of COMP source rock

	AN56	Cpx	Amp	E89	COMP	CALC	DIFF
SiO ₂	57.50	51.90	40.60	67.20	54.10	53.68	0.43
Al ₂ O ₃	26.30	3.10	14.50	15.80	14.20	15.14	-0.93
FeO	0.00	6.20	13.40	3.96	11.04	8.76	2.29
MgO	0.00	17.10	12.00	1.50	5.57	6.84	-1.26
CaO	9.0	20.10	9.60	3.60	6.47	6.66	-0.18
Na ₂ O	6.50	1.50	2.10	3.20	3.01	2.65	0.37
K ₂ O	0.08	0.00	0.50	2.70	0.89	1.59	-0.69
Solution	0.00	0.00	50.84	49.17			

Abbreviations:

An56: Plagioclase of An56

Cpx: Clinopyroxene

Amp: Amphibole

E89: Whole rock sample E89, Eagle Peak pluton

COMP: Composite source rock (2/3 basalt, 1/3 graywacke)

CALC: Least squares mixing model calculated composite source rock

DIFF: Difference (COMP-CALC)

All values in weight percent.

TABLE 37

Modal abundances determined in partial melting models

	AN56	Cpx	Gar	Amp	Biotite	Quartz	Alkali feldspar
<u>Initial assemblage</u>							
I, VI, VII	0.17	-	-	0.65	-	0.18	-
II, V	0.17	0.05	0.05	0.55	-	0.18	-
III, IV	0.17	0.05	0.05	0.52	0.03	0.18	-
VIII, IX	0.56	-	-	0.13	0.14	0.11	0.06
<u>Melting proportions</u>							
I, VI	0.35	-	-	0.28	-	0.37	-
II, V	0.35	-	-	0.28	-	0.37	-
III, IV	0.35	-	-	0.28	-	0.37	-
VII	-	-	-	1.00	-	-	-
VIII, IX	0.49	-	-	0.03	0.05	0.28	0.15
<u>Residue, 49% melting</u>							
I	-	-	-	1.00	-	-	-
II	-	0.10	0.10	0.80	-	-	-
III	-	0.10	0.10	0.75	0.05	-	-
VII	0.33	-	-	0.32	-	0.35	-
<u>Residue, 40% melting</u>							
VIII	0.60	-	-	0.20	0.20	0	-

Abbreviations: AN56(plagioclase, An56); Cpx(clinopyroxene); Gar(garnet); Amp(amphibole); see text for discussion of mineral compositions. All values as weight fractions.

TABLE 38
Partial melting model results

Low amphibole distribution coefficients						
$f^* = 0.49$			$f = 0.40$			
I	II	III	IV	V	VI	
Ce	45.3	45.1	45.1	54.7	54.6	55.2
Sm	6.0	5.1	5.1	5.6	5.56	6.9
Eu	1.67	1.51	1.53	1.56	1.54	1.71
Gd	6.28	3.45	3.49	3.64	3.60	6.85
Yb	3.90	0.90	0.91	0.92	0.92	4.36
Ce/Yb	11.6	49.9	49.7	59.5	59.4	12.7
Sm/Eu	3.6	3.4	3.4	3.6	3.6	4.0
Rb	46.1	46.1	45.3	54.3	56.5	56.5
Sr	410	417	418	414	413	406
Ba	475	476	401	450	578	574

* f = weight fraction of melting

All trace element values in parts per million.

TABLE 38, continued
Partial melting model results

High amphibole distribution coefficients									
	f=0.49		f=0.40			f=0.40	f=0.30	COMP	E89
	IA	IIA	IIIA	IVA	VII	VIII	IX		
Ce	27.0	29.0	30.8	28.4	33.6	45.8	53	22.2	64.6
Sm	1.3	1.4	1.4	1.3	1.9	4.1	4.4	3.24	4.92
Eu	0.45	0.5	0.49	0.44	0.58	0.65	0.65	1.08	0.965
Gd	1.12	1.11	1.10	1.11	1.7	4.0	4.3	3.83	-
Yb	0.74	0.49	0.49	0.73	1.1	2.6	2.7	2.27	1.52
Ce/Yb	36.6	59.2	63.0	38.8	29.7	18	20	9.8	42.5
Sm/Eu	2.8	2.8	2.8	2.8	3.3	6.4	6.8	3.0	5.10
Rb	-	-	-	-	-	81	87	22.8	150
Sr	-	-	-	-	-	250	240	239	350
Ba	-	-	-	-	-	420	410	235	860

* f= weight fraction of melting
All trace element values in parts per million.

Figure 40: Chondrite normalized rare earth element abundances for selected partial melts and parent rocks used in modelling studies; sample E89 from the Eagle Peak pluton is shown for reference.

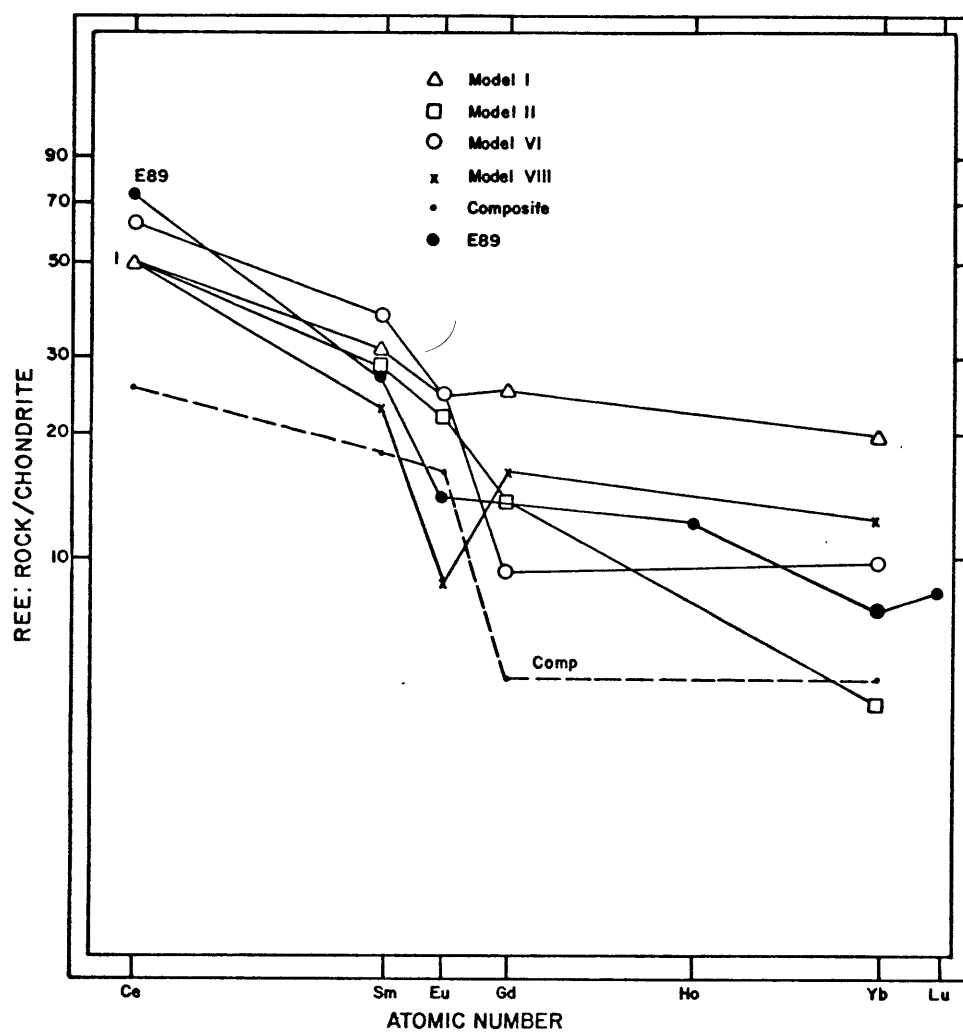


Figure 40

to the residue: this greatly increases the Ce/Yb ratio of the melt and produces a REE slope much more similar to E89 than developed by model I. Low melting (models II and III) tends to increase this ratio and provide even closer similarity to E89. Models II and III also indicate a slight increase in Sr abundance with increased Ce/Yb ratios. Model III illustrates the effect of a minor amount of biotite: a very slight decrease in Rb and a substantial decrease in Ba. Comparison of models I, II, and III with models IV, V, and VI indicates the effects of increased melting: decrease in absolute abundance and slope of REE, decrease of Rb and Ba, and increase of Sr in the derivative melt.

Models IA, IIA, IIIA, IVA, and VII with high amphibole REE distribution coefficients produce partial melts with lower REE abundances, smaller Sm/Eu ratios, and greater Ce/Yb ratios than corresponding models with low REE distribution coefficients. Sm/Eu ratios of the melts from these models (except model VII) are similar to those of the assumed parent, and lead to positive Eu anomalies as shown in Figure 40. Amphibole with high REE distribution coefficients as well as garnet can therefore produce HREE depletions in partial melts.

The data of Arth and Barker (1976) and from hornblende in this study (Chapter II, Figure 27) suggest high amphibole REE distribution coefficients are most appropriate for the melt compositions considered here. Addition of plagioclase to the residue produces liquids with greater Sm/Eu ratios (negative Eu anomalies) and REE abundances and lesser Sr abundances and Ce/Yb ratios.

None of the models explains the trends observed in the trace element data for the plutons of this study. Variations in the amount of melting produce similar changes in Rb and Ba abundances, but in these samples the two elements vary inversely. Strontium abundances in the plutons vary much more than is seen in the models as a result of melting proportions or from changes in modal mineralogy. The models are most useful in illustrating the effect of residual garnet and amphibole with high REE distribution coefficients in increasing Ce/Yb ratios and biotite in decreasing Ba abundances in the derivative melts. The models indicate mineralogical or melting variations greater than those investigated here are required to produce the trace element variations present in the Sierran granites of this study.

Zielinski and Lipman (1976) analyzed trace elements from associated andesites and rhyolites in Colorado and concluded the andesites formed by partial melting of a garnet-clinopyroxene assemblage containing negligible plagioclase or amphibole in the residue. Compared to the Colorado andesites, the Sierran granites of this study have quite similar REE distributions, greater U, Th, and Rb, and similar or lesser abundances of Ba and Sr. Strontium isotopic data prohibit any significant contribution of continental crust to partial melts forming the Colorado andesites (Zielinski and Lipman, 1976), but as discussed previously, this is permissible for Sierran granitic rocks. The less primitive parent inferred for the Sierran magmas probably explains the differences in melting assemblages and trace element distributions of the two provinces.

Condie and Swenson (1973) studied andesites and dacites from Cascade stratovolcanoes and concluded the magmas formed by variable amounts of partial melting of amphibolite, peridotite, or eclogite. The Cascade andesites are more primitive than the granitoids of this study, with SiO_2 less than 66 weight percent, REE less than 50 times chondrites, La/Yb less than 16, Eu/Eu^* approximately 1.0, and Rb, Cs, and Ba less and Sr similar to the abundances in the Sierran samples. Condie and Swenson (1973) suggest the geochemical differences within the volcanics at each volcano and between the volcanic centers can be explained by variable water content, variable amounts of melting, and variable element concentrations in the source region of the partial melts. As with the Colorado andesites, Sr isotopes indicate a primitive source region for the Cascade volcanics, with no contribution from continental crust, oceanic sediments, or eugeosynclinal sediments. Again, this more primitive source is probably responsible for the differences in inferred melting assemblages and resultant geochemical differences of the Sierran and Cascade provinces.

A number of the models considered here assume a plagioclase-free residue. The amount of siliceous continental crustal material involved in partial melting may be sufficient to allow significant contributions of plagioclase to the residue. Barker and Arth (1976) conclude low- Al_2O_3 tonalitic liquids may form by partial melting of amphibolite with plagioclase in the residue. Assuming high amphibole REE distribution coefficients requires plagioclase in the

residue to produce melts with negative Eu anomalies, which are found in the Sierran granites of this study. Presnall and Bateman (1973) conclude Sierran melts equilibrated with a dominantly plagioclase rich residue. However, the large Ce/Yb ratios and the lack of extreme negative Eu anomalies in Sierran granitoids indicates this is not likely but rather a significant amount of hornblende is probably present in the residue.

White and Chappell (1977) and Presnall and Bateman (1973) suggest the mafic inclusions common in batholithic granitoids are remnants of the partial melting residue. The mafic inclusions consist dominantly of plagioclase, hornblende, and biotite. Pabst (1928) indicates similar compositions of minerals in both mafic inclusions and the host rocks, suggesting a long contact time between the two and tending to support the view of White and Chappell and Presnall and Bateman. This mineralogy and mode of origin for the mafic inclusions is consistent with the trace element patterns of the Sierran samples studied here.

IMPLICATIONS FOR THE ORIGIN OF THE SIERRA NEVADA BATHOLITH

Several aspects discussed earlier now need to be reconsidered. Alteration of sea floor basalt increases Rb, U, Th, Cs, decreases Fe, and erratically varies Ba. This results in decreased garnet in the norm. The trends observed for the samples of this study could be produced with the mineralogies discussed in models II and III if:

1. the altered hydrated portions of basalt melt earlier;

2. the altered hydrated portions contain amphibole, possibly garnet, and some biotite (as chloritic alteration);
3. (1) and (2) will produce liquids with a steep REE slope (high La/Yb), and will produce liquids with abundant Rb, Cs, U, Th, resulting from sea-floor alteration; Ba will be retained in the residue in the biotite;
4. the less altered basalt melts later, possible at greater depths, and therefore contains more garnet in the residue;
5. (4) produces liquids with somewhat greater La/Yb ratios than (1); these liquids will also have less Rb, Cs, U, and Th than (1); Ba will be greater in these liquids because micas are less abundant in the residue.

Possibly augmenting the previous features is the close proximity of the altered, hydrated basalt to the siliceous crustal material which would tend to increase the feldspar component of the melting assemblage. Siliceous crustal material would also be more enriched in Rb, Cs, U, and Th and depleted in Fe compared to fresh basalt. The possibly greater amount of plagioclase in the residue of the earlier melting fraction would result in lesser Sr and greater Sm/Eu in those melts.

The preceding melting model explains the major trace element differences between the Mount Givens granodiorite and the Red Lake

pluton and is consistent with field relations indicating the Red Lake pluton is younger than the Mount Givens granodiorite.

A number of factors are involved in producing the trace element distributions of Sierran granitoids. Partial melting of a vertically layered source in the region of the lower continental-upper oceanic crust incorporates a range of chemical and modal compositions.

Strontium isotopic data allow a parent assemblage of two-thirds basalt and one-third graywacke. Partial melting leaving a residue of plagioclase, biotite, and hornblende will produce liquids with LREE enrichment and negative Eu anomalies. The magnitude of the LREE enrichment and the Eu anomalies depends on the relative proportions of hornblende and plagioclase in the residue. Increasing the proportions of various minerals in the residue reduces the abundances of selected elements in the partial melts: biotite, Ba and Rb; plagioclase, Sr, Eu, and possibly Ba; hornblende, HREE and Sc; garnet, HREE. Incorporation of altered oceanic crust will produce liquids with greater Rb, Cs, U, Th, and lesser HREE and possibly Ba than liquids derived from unaltered crust.

Relative vertical location within the sequence of rocks melted will produce different melting assemblages, different residues, and consequently different liquids. Rocks higher in the sequence may contain more felsic residue and consequently show lesser La/Yb ratios, greater Eu anomalies, and lesser Sr and Ba abundances than the more mafic, deeper rocks. Greater abundances of Th, Sc, U, Cs, and Rb in the felsic portion of the pile compared to the mafic

portion of the pile may outweigh the effect of a more felsic residue and produce melts relatively enriched in these elements. Clearly, these contributions must be limited as removal of the melting region from the interface between lower continental-upper oceanic crust will ultimately produce very different liquids.

Post intrusive crystal fractionation is also a source of trace element variations between plutons derived from a common source region. Variations within the Eagle Peak pluton in major and trace element abundances were explained in Chapter II by fractionation of hornblende, plagioclase, biotite, apatite, and sphene. Many of the variations between the Red Lake and the Eagle Peak plutons have been explained in terms of mineral fractionation, volatile degassing, and attendant fO_2 - fH_2O -T dependent reactions. However, these mechanisms do not adequately explain all the differences between the plutons and reaffirm the importance of source region variations.

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