

PETROLOGY OF THE GRANITIC PLUTON AT
OAK CREEK, FREMONT COUNTY, COLORADO

by

James M. Stone

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Kansas State University
Manhattan, Kansas

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Major Professor

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INTRODUCTION

The Precambrian geologic record of Colorado begins with deposition of graywacke, shale, and volcanic rock 1800 - 2000 Ma. These rocks subsequently were metamorphosed to amphibolite facies. The metamorphic rocks were then intruded by granitic rocks (mainly granodiorite) at catazonal depths (greater than 14 km) approximately 1700 Ma (Tweto, 1980) during the later stages of folding and metamorphism known as the Boulder Creek event (Hedge et al., 1967). These Boulder Creek rocks are believed to belong to the 1690 - 1780 Ma orogenic belt of the Mid-continent (Van Schmus and Bickford, 1981).

Younger granites approximately 1360 - 1460 Ma in age were emplaced throughout Colorado during the Silver Plume event (Peterman and Hedge, 1968; Tweto 1980). Hutchinson and Hedge (1967) used Buddington's (1959) criteria to suggest Silver Plume plutons in Colorado were primarily emplaced in the epizone and upper mezozone (less than 15 km deep). These approximately 1.4 b.y. old plutons (Figure 1) are believed to be related to anorogenic magmatic mobilization of lower crustal source resulting from either tensional forces (Anderson, 1983) or from a tectonically thickened crust (Van Schmus and Bickford, 1981).

Granitic intrusions of Boulder Creek and Silver Plume age occur in the Wet Mountains of Colorado (Figure 2). The

Figure 1: Distribution of approximately coeval rocks in the Midcontinent region (from Anderson 1983)

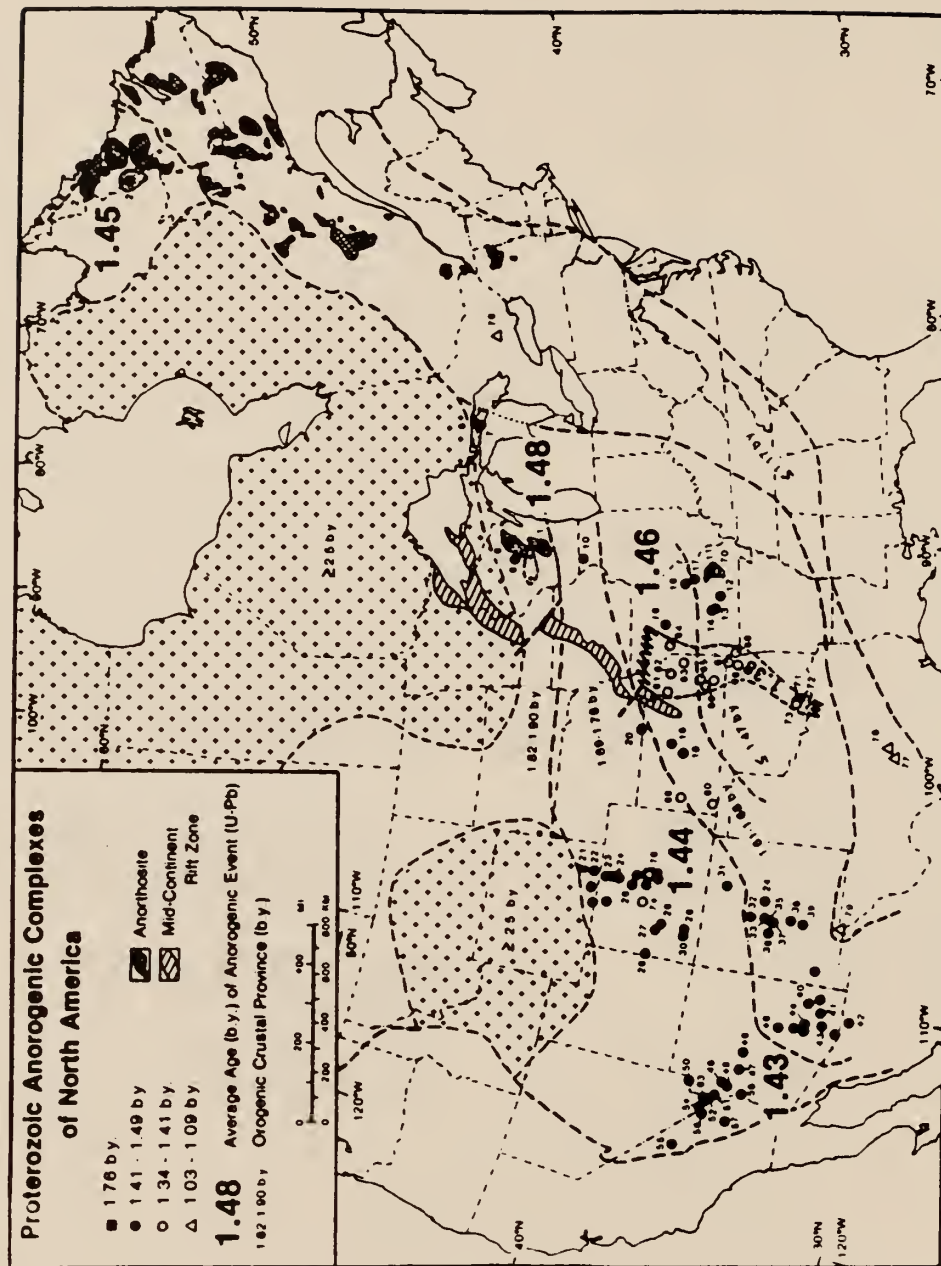
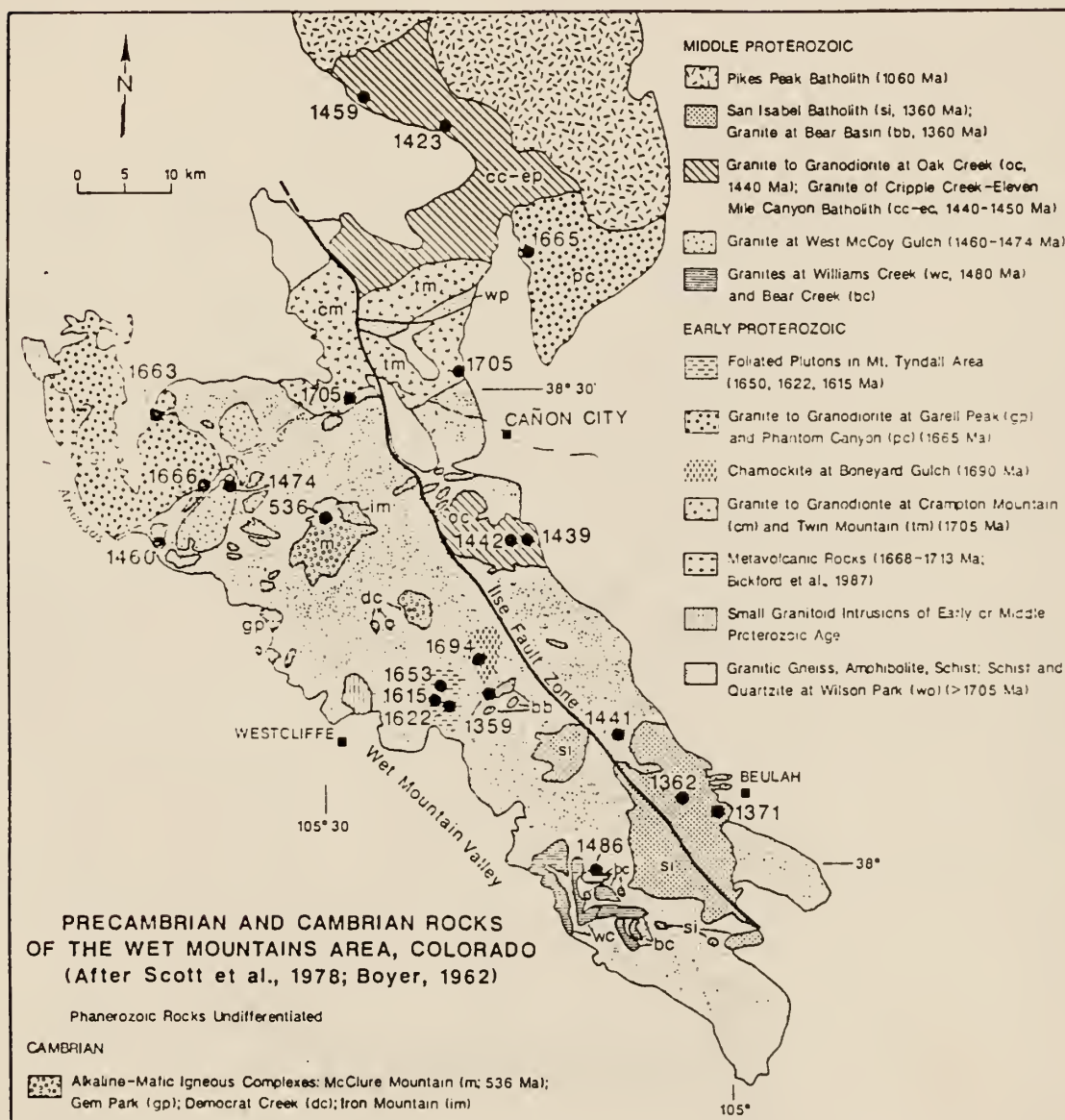


Figure 2: Precambrian and Cambrian Rocks of the Wet Mountains area, Colorado (Bickford, 1986)



foliated granodiorite plutons of Garell Peak (1665 Ma; Cullers and Bickford, 1983), and Crampton-Twin Mountain (1700 Ma; Peterman and Hedge, 1968) are of Boulder Creek age. Plutons of Silver Plume age include the San Isabel batholith (weakly foliated) and the granite of West McCoy Gulch with U/Pb ages of 1360 m.y and 1460 Ma, respectively (Cullers and Bickford, 1983). The moderately foliated pluton of the Oak Creek area is in the northeastern Wet Mountains south of Canon City approximately 15 km (see Figure 2). A U/Pb age of zircons indicate crystallization to be 1440 Ma (Bickford, 1986).

PURPOSE OF STUDY

The purpose of this study is to investigate the petrology of the pluton of the Oak Creek Area. Field relationships, petrographic observations, and major and trace element data are used to describe and characterize the different rock types. Petrogenic models will be used in order to constrain chemical formation. Processes such as partial melting, restite unmixing, magma mixing, assimilation, fractional crystallization, and cumulate unmixing will be investigated to determine their possible influence in the evolution of this pluton.

This study contributes to a better understanding of the intrusive events that compose the geologic history of the Wet Mountains and how this might relate to the crustal

evolution that occurred across the Midcontinent during the Precambrian.

REGIONAL SETTING

Wet Mountains

The Wet Mountains are located in the Southern Rocky Mountain physiographic province and are part of the Laramide upthrust belt. The Canon City Embayment forms the northern boundary of the Wet Mountains (Figure 2). The Wet Mountain Valley separates the Wet Mountains from the Sangre de Cristo Range to the west. Huerfano Park bounds the Wet Mountains to the south. The Wet Mountain Fault zone, represented by upturned Paleozoic and Mesozoic sedimentary rocks of the Denver Basin, is the eastern boundary of the Wet Mountain complex.

Proterozoic layered schist and gneiss of sedimentary and volcanic origin are the oldest rocks of the Wet Mountains (Murray, 1970; Logan, 1966; Christman et al., 1959) dated at approximately 1800 Ma (Tweto, 1980). These metasedimentary and metavolcanic sequences have been intruded successively by metagabbro, foliated granodiorite and quartz monzonite (1660-1700 Ma), and unfoliated to foliated quartz monzonite-granite plutons (1360-1460 Ma; Figure 2).

The foliated granodiorite to quartz monzonite plutons that are approximately 1700 Ma are generally located in the northern Wet Mountains (Figure 2). Hedge et al. (1967) recognized that late tectonic deformation was concurrent with crystallization and emplacement of these Boulder Creek plutons.

Relatively unfoliated plutons (~ 1400 Ma) occur in the northern Wet Mountains (West McCoy Gulch; 1470 Ma), and in the central Wet Mountains (Bear Basin Granite; 1360 Ma). Lack of pervasive metamorphic foliation reflects the post-tectonic mesozonal emplacement (10-15 km) suggested for plutons of this age (Cullers and Wobus, 1986; Anderson, 1983). The San Isabel Batholith (1360 Ma), in the southern Wet Mountains, is moderately foliated. The Oak Creek pluton (1400 Ma) has stronger foliation than plutons of similar age in the Wet Mountains. The Oak Creek and San Isabel batholiths may represent deeper-seated intrusions of the Silver Plume event than the unfoliated plutons.

Pluton of Oak Creek Area

The pluton in the Oak Creek Area is located in the northeastern Wet Mountains, south of Canon City, Colorado (Figure 2). This foliated, granodiorite-granite pluton is bounded on the east by the Wet Mountain Fault Zone

and the Paleozoic and Mesozoic sediments of the Denver Basin (Logan, 1966; Mann, 1958; Scott and Taylor, 1974). The pluton has been emplaced on the northern and southern boundaries into layered gneisses, chiefly feldspathic-biotite-quartz-plagioclase gneiss with minor amounts of hornblende gneiss, and calc-silicate gneiss (Taylor et al., 1975). The gneisses are often garnetiferous, sillimanitic and variably migmatitic (Taylor et al., 1975). The western boundary of the pluton appears to be the Ilse Fault zone along the east side of Grape Creek (Taylor et al., 1975; Singlewold, 1966; Christman et al., 1959). The Central Wet Mountains are transected by the Isle Fault zone from its northern limits to the area of the San Isabel batholith. The fault zone has a major strike slip movement.

The pluton of Oak Creek has topographic relief of 600 meters in the northeast map area to 1000 meters in the west along Grape Creek. Elevations range up to 3000 meters above sea level (Taylor et al 1975).

PREVIOUS INVESTIGATIONS

The earliest geologic study of the area was reported by Cross (1896 from Logan, 1966). He noted abundant granites and gneisses along with scattered felsic and mafic bodies in the Silver Cliff area southwest of the Oak Creek area. Darton (1906) published the first geologic map of the

eastern margin of the Wet Mountains. A geologic study of the Chandler syncline by Mann (1959) resulted in a map of the sedimentary rocks and the Wet Mountain fault zone immediately east of the study area.

Logan (1966) investigated the structure and petrology of the eastern margin of the Wet Mountains which included a strip approximately 1.6 km wide along the eastern margin of the pluton of Oak Creek. He identified two textural facies in this portion of the pluton: a medium-grained, porphyritic facies and a fine-grained granular facies. Logan's ten samples (6 porphyry and 4 medium grained) ranged from quartz syenite to granodiorite with 60% of these rocks monzogranite to quartz-bearing monzonite.

Reconnaissance maps were completed in the area by Scott and Taylor (1974) and Taylor et al. (1975) using photogeology and field checks. Taylor et al. (1975) refer to the rocks of the Oak Creek area as medium to coarse-grained granodiorite with lesser amounts of quartz monzonite and quartz diorite. They proposed that the Oak Creek area pluton in Fremont County was of Boulder Creek age presumably based on the well-foliated texture of these rocks.

METHODS

Field Techniques

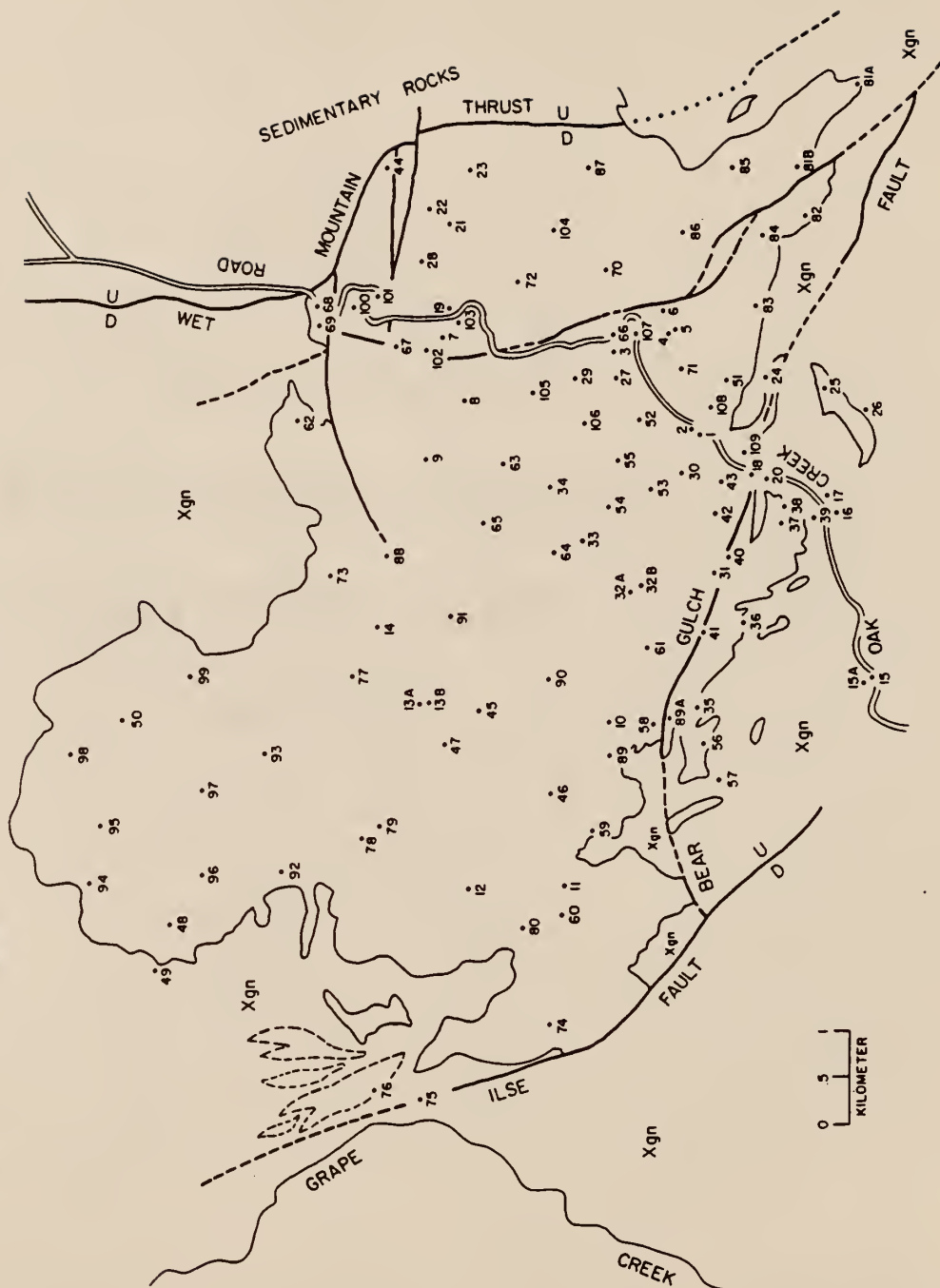
Field investigation of the pluton included the following: 1) identifying the number and distribution of each of the textural and petrographic facies, 2) mapping and evaluating the contact relationships of these facies to each other and to the country rocks, 3) collecting fresh samples while considering geographic distribution (Figure 4) over the entire pluton, 4) noting variations within each facies, 5) identifying fault zones and foliation trends, and 6) producing a detailed geologic map.

Field mapping was done on United States Department of Agriculture photographs (1:15,550) and transferred to USGS topographic maps (1:25,000). Field locations were transferred to topographic sheets by resection as described by Compton (1962).

Petrographic Techniques

Stained thin sections were prepared for 68 selected samples of the plutonic rocks. Eight thin sections were prepared from xenoliths and country rocks. Enlarged thin sections (1/2 x 3 in) and stained slabs were used for the porphyritic and coarse-grained samples. The slabs were etched with hydrofluoric acid and stained with sodium

Figure 3: Location of samples at pluton of the Oak Creek Area



cobaltinitrite for definitive feldspar determination. Point counting methods (Chayes; 1949) were used to determine modes in thin section and stained slabs. Phenocryst to groundmass ratios were determined from the stained slabs and then equated with groundmass mineral contents taken from thin section. Opaque minerals were identified by reflective light microscopy. Surface II (Sampson, 1975) computer mapping procedures were applied to investigate mineral and elemental variation across the pluton and Statistical Analysis System packages were employed for statistical evaluation (Helwig, 1983).

Chemical Techniques

Rock samples were selected for major and trace element analyses using fresh samples that represented the range in variation of mineralogy and geographic distribution. Atomic absorption (AA) and emission spectrophotometry methods (Medlin et al., 1969; Shapiro, 1978) were used for major element compositions on 48 samples. Fifteen samples were analyzed for trace elements using instrumental neutron activation analysis (INAA). The 15 samples were representative of the range of composition, differentiation index, and geographic location. Differentiation index calculations are the sum of CIPW normative quartz, orthoclase, albite, nepheline, leucite, and potassium metasilicate. Details for

AA and INAA procedures are in Appendix A and B, respectively. Loss on ignition (LOI) was done gravimetrically to determine total volatile content.

$$\text{LOI} = (\text{Weight of sample before ignition} - \text{weight of sample after ignition}) / (\text{Weight of sample before ignition})$$

Trace - Element Modeling

The non-modal aggregate melting relationship developed by Shaw (1970) is used to model partial melting processes. Fractional crystallization processes are modeled by equations by Haskin et al (1970). These equations are shown in appendix C.

RESULTS

Field Relations

The pluton at Oak Creek is of batholithic proportions with an outcrop area of approximately 100 km². It varies from granodiorite to granite and can be divided into four textural/mineralogic facies (Figure 4). The facies in order of increasing differentiation are as follows: 1) a moderate to well-foliated, granodiorite-granite porphyry, 2) medium-grained leucogranites, 3) coarse-grained leucogranites, and 4) alaskite dikes and veins (not mappable at 1/25000). The alaskite dikes are very similar to the medium-grained leucogranite bodies except for lower mafic contents of the former (less than 5%).

The porphyritic facies makes up approximately 70% of surface outcrops and the medium-grained leucogranites and alaskite dikes represent about 25% of surface outcrops. The coarse-grained leucogranites make up less than 5 percent of surface outcrop area.

Field relationships indicate intrusion to be in the order granodiorite-granite porphyry, medium-grained leucogranite, coarse-grained leucogranite, and finally late stage dikes and veins of leucogranite (alaskite). The contacts between the porphyritic facies and the country rocks are sharp, concordant to subconcordant, and they lack chill margins or baked zones. Exceptions are along fault

Figure 4: Geologic map of the pluton of Oak Creek area
Fremont County, Colorado

LEGEND

QUATERNARY

Os Alluvium

PRECAMBRIAN Y

Pegmatites (pg)

Ymg Medium-Grained Leucogranite

Ycg Coarse-Grained Leucogranite

Yp Granodiorite Porphyry ~14 by

PRECAMBRIAN X

Xgn Migmatitic Gneisses (Biotite-Quartz Plagioclase Gneiss, Hornblende-Plagioclase Gneisses and Schists)

— Fault (Dashed where inferred, dotted where concealed)

SEDIMENTARY ROCKS

WET MOUNTAIN THRUST

THRUST

GRADE

ROAD

WET MOUNTAIN

ILSE

GRAPE CREEK

OAK CREEK

FAULT

13°

Mag North

True North

APPROXIMATE MEAN DECLINATION

COLORADO

MAP LOCATION

0 0.5 1 KILOMETER



zones, particularly the Ilse Fault zone, where contacts are gradational and/or occur as an interfingering of the rocks. Tweto (1980) noted the probable repeated and variable movement of the Ilse Fault zone during its history. In this location, the porphyritic facies grades from medium-grained granodiorite to porphyritic monzogranite and quartz-bearing monzonite. The medium-grained and coarse-grained leucogranites occur as small bodies and dikes usually within the porphyritic facies. The leucogranites exist predominantly in the central and southern portions of the pluton and are in contact with the country rocks at the southern boundary.

The medium-grained leucogranites in general vary from small, mafic-poor dikes and veins (alaskites) which are always in sharp contact with the porphyritic facies rocks, and larger, more biotite-rich leucogranite bodies which have contacts that vary from well defined to gradational. The alaskite dikes and veins are similar in composition and texture to the irregular bodies of leucogranite and vary from 0.25 to 1.5 meters wide. The dikes crosscut and are concordant with foliation trends. Most alaskite dikes appear to follow fractures in the porphyritic facies rocks. They meander at times and pinch out over short distances. However, the alaskites are not confined to small dikes and sills. A large alaskite body, up to .5 km wide, crops out

along the southern boundary and is in sharp contact with the porphyritic facies and the country rocks. Due to the low mafic content, the alaskites tend to have a fresher, less weathered appearance than the medium-grained leucogranites. The alaskites and medium-grained leucogranites apparently were emplaced after the less differentiated porphyritic facies.

Foliation is concordant to subconcordant with the country rock and is most prominent near fault zones and contacts. Feldspars rarely show alignment except in the zones of strongest foliation in the southeast portion of the pluton. Foliation is represented by the preferential alignment of biotite. Foliation strikes follow contacts and regional trends except where some alaskite intrusions occur (Figure 5).

Pegmatites are abundant, and some are quite large in the northcentral portions of the pluton (Figure 4). Many are associated with the leucogranite and may be related to the medium-grained leucogranite and/or alaskite phases. Many pegmatites are also found in the migmatites north of the pluton. Porphyritic granite and country rocks appear to be metasomatically altered in the zone associated with the hydrothermal activity from the pegmatites.

Small xenoliths of plagioclase-hornblende gneiss, biotite-quartz-plagioclase gneiss and biotite schist occur throughout the pluton. The largest concentrations of

Figure 5: Foliation measurements of Oak Creek Area



xenoliths are in the southcentral area. These foreign lithologies vary from schlieren to rounded xenoliths with sharp contacts with its host. A few large bodies (up to 1 km long) of mafic gneiss similar in composition to the country rocks have been enclosed by the porphyritic facies. These tend to be located near major fault zones and have well defined boundaries.

The Wet Mountain fault zone is marked by the near vertical attitude of the sedimentary units to the east. Several other faults were inferred within the pluton based on topographic lineations and contact relationships of different facies. Relative movement cannot be discerned along the fault zones since they are heavily weathered.

Petrography

Introduction

The mineralogy of 27 porphyritic samples, 9 medium-grained leucogranites, 9 alaskites, and 3 coarse-grained leucogranites are summarized in Table 1. Mean values and ranges of mineral compositions are summarized for each facies in Table 2. Classifications based on quartz, alkali feldspar and plagioclase contents of the Oak Creek rocks are given in Figure 6.

Table 1: Modal analysis of the Oak Creek batholith
(55 - 60 wgt % SiO₂)

PORPHYRITIC FACIES						
Sample #	JS-80	JS-65	JS-44	JS-85	JS-86	JS-106
SiO ₂ (wgt %)	55.4	55.8	56.5	56.6	57.1	58.2
Total Micr (Phen/gm)	44.8 (44/tr)	45.5 (32/13)	39.6 (39/ 1)	20.8 (18/ 3)	15.2 (11/ 4)	41.1 (26/15)
Total Plag (Phen/gm)	29.1 (19/10)	26.3 (0/26)	36.5 (15/21)	43.5 (14/30)	38.0 (12/26)	36.2 (17/19)
Quartz	11.8	12.1	10.3	13.5	24.6	10.1
Biotite	13.8	14.1	10.1	17.8	21.0	10.8
Magnetite	0.1	0.8	1.3	4.0	0.8	1.8
Muscovite	----	0.4	----	----	----	----
Sphene	0.4	0.4	2.3	----	----	tr
Apatite	0.1	0.1	tr	0.2	0.3	tr
Zircon	tr	0.1	tr	0.2	0.1	tr
PORPHYRITIC FACIES						
Sample #	JS-102	JS-96	JS-89	JS-95	JS-42	JS-3
SiO ₂ (wgt %)	58.2	58.3	58.4	59.4	59.5	59.6
Total Micr (Phen/gm)	21.9 (21/ 1)	31.9 (20/12)	16.9 (11/ 6)	48.4 (36/12)	32.6 (25/ 7)	43.1 (32/11)
Total Plag (Phen/gm)	31.4 (7/24)	37.1 (11/27)	44.6 (15/30)	29.7 (8/22)	28.8 (13/16)	33.8 (15/19)
Quartz	26.3	5.7	19.2	11.4	25.6	7.6
Biotite	18.6	24.8	17.6	9.1	10.4	11.7
Magnetite	1.7	0.5	1.5	1.2	2.6	1.6
Muscovite	----	----	----	----	----	tr
Sphene	----	tr	----	----	----	2.2
Apatite	0.1	tr	0.1	0.2	----	----
Zircon	0.1	tr	0.1	tr	0.1	tr

Table 1: Modal analysis of the Oak Creek batholith
(60 - 63 wgt % SiO₂)

PORPHYRITIC FACIES						
Sample #	JS-100	JS-81a	JS-32b	JS-77	JS-87	JS-61
SiO ₂ (wgt%)	60.2	60.3	60.5	60.7	60.7	61.0
Total Micr (Phen/gm)	22.1 (22/ 0)	15.3 (8/ 7)	47.8 (35/13)	30.7 (25/ 6)	31.7 (22/10)	18.4 (17/ 1)
Total Plag (Phen/gm)	44.3 (5/39)	38.0 (13/25)	20.8 (6/15)	35.6 (0/36)	36.9 (11/26)	42.3 (0/42)
Quartz	15.9	20.2	22.3	18.1	12.1	19.9
Biotite	15.2	23.5	8.5	11.5	17.3	15.2
Magnetite	1.2	2.5	0.5	3.5	1.4	2.2
Muscovite	1.0	0.5	tr	----	----	1.8
Sphene	----	----	tr	----	0.2	----
Apatite	0.1	tr	tr	0.1	0.3	0.1
Zircon	0.1	tr	tr	0.6	0.1	0.2
PORPHYRITIC FACIES						
Sample #	JS-2	JS-51	JS-98	JS-93	JS-18	JS-23
SiO ₂ (wgt %)	61.1	61.1	61.1	61.2	61.7	62.8
Total Micr (Phen/gm)	22.4 (14/ 8)	13.2 (9/ 4)	13.3 (12/ 1)	21.4 (15/ 6)	37.1 (25/12)	29.9 (25/ 5)
Total Plag (Phen/gm)	44.9 (21/24)	43.6 (10/33)	43.6 (0/44)	40.4 (8/32)	27.1 (5/22)	31.4 (7/24)
Quartz	21.3	25.4	23.3	14.2	19.2	22.5
Biotite	8.9	16.5	18.1	22.8	13.7	14.6
Magnetite	1.1	1.2	1.3	1.1	0.9	1.6
Muscovite	1.4	0.1	----	----	2.0	0.1
Sphene	tr	----	----	----	----	----
Apatite	tr	----	tr	0.1	tr	tr
Zircon	tr	0.1	0.4	0.1	tr	tr

Table 1: Modal analysis of the Oak Creek batholith

(63 - 65 wgt % SiO₂)

PORPHYRITIC FACIES			
<hr/>			
Sample #	JS-41	JS-84	JS-29
SiO ₂ (wgt%)	63.0	63.3	64.9
Total Micr	29.9	43.0	43.4
(Phen/gm)	(28/ 2)	(32/11)	(29/14)
Total Plag	29.8	33.8	33.7
(Phen/gm)	(0/30)	(0/34)	(18/16)
Quartz	19.7	6.6	9.5
Biotite	15.9	11.8	10.0
Magnetite	2.0	2.8	1.9
Muscovite	2.2	0.8	0.1
Sphene	----	----	0.1
Apatite	tr	0.1	0.1
Zircon	0.5	1.0	1.2

Table 1: Modal analysis of the Oak Creek batholith
(67 - 72 wgt % SiO₂)

MEDIUM-GRAINED LEUCOGRANITE FACIES

Sample #	JS-101	JS-33	JS-78	JS-109	JS-9
SiO ₂	67.2	67.9	68.4	68.8	69.4
Total Micr	37.3	34.0	22.3	22.7	29.3
Total Plag	30.1	24.6	33.2	36.8	33.9
Quartz	27.1	35.3	33.2	33.7	28.6
Biotite	4.8	3.9	4.8	5.5	5.7
Magnetite	0.5	1.6	0.3	0.7	1.5
Muscovite	tr	0.5	----	0.6	1.0
Sphene	tr	tr	0.1	tr	----
Apatite	tr	tr	tr	0.1	tr
Zircon	0.2	tr	0.1	tr	0.1

MEDIUM-GRAINED LEUCOGRANITE FACIES

Sample #	JS-1	JS-16	JS-14	JS-31
SiO ₂	70.7	71.0	71.3	72.0
Total Micr	33.1	33.6	34.6	31.1
Total Plag	32.2	33.0	30.3	32.5
Quartz	30.3	29.7	28.9	32.2
Biotite	3.1	2.6	5.6	3.5
Magnetite	0.3	0.2	0.6	0.5
Muscovite	1.0	0.9	----	0.2
Sphene	tr	tr	0.1	----
Apatite	tr	tr	----	tr
Zircon	tr	tr	tr	tr

Table 1: Modal analysis of the Oak Creek batholith

(73 - 75 wgt % SiO₂)

COARSE-GRAINED LEUCOGRANITES			
<hr/>			
Sample #	JS-73	JS-59	JS-64
SiO ₂ (wgt %)	72.8	74.3	75.4
Total Micr	39.6	45.0	37.1
Total Plag	13.2	19.9	26.0
Quartz	45.0	31.0	33.1
Biotite	2.0	3.1	3.3
Magnetite	0.1	0.6	0.5
Muscovite	tr	0.3	tr
Sphene	----	----	----
Apatite	----	tr	----
Zircon	tr	tr	tr

Table 1: Modal analysis of the Oak Creek batholith
(68 - 75 wgt % SiO₂)

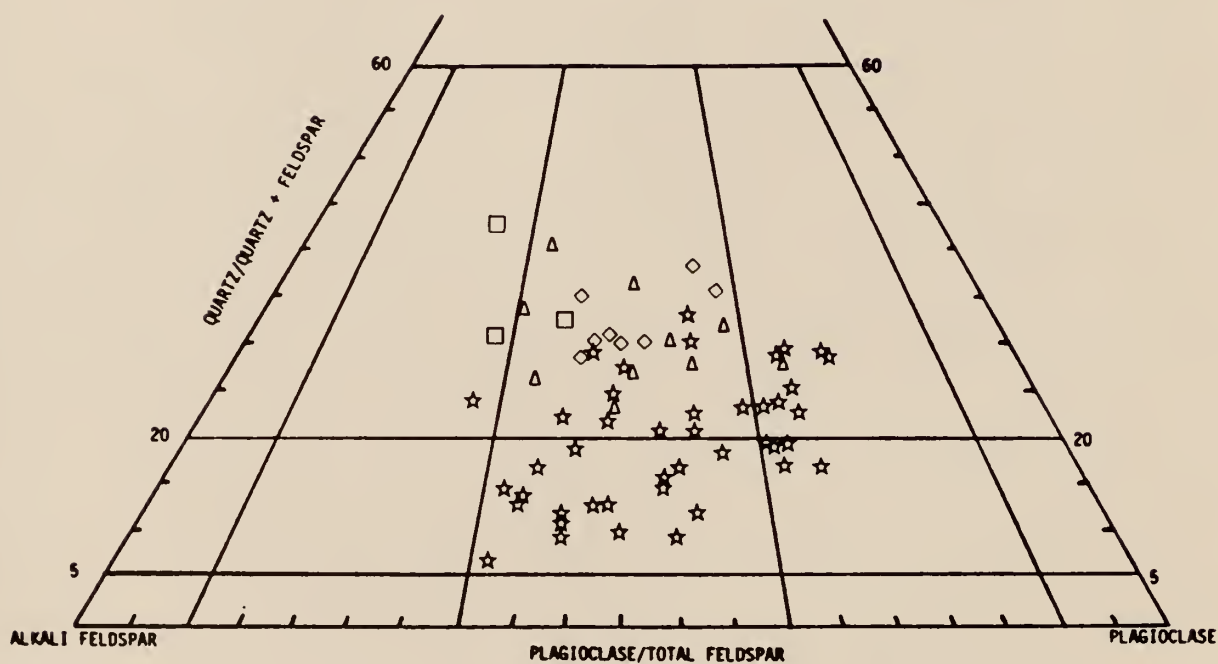
"ALASKITE" FACIES					
Sample #	JS-60	JS-46	JS-81b	JS-5	JS-70
SiO ₂	68.1	69.0	69.9	70.7	71.0
Total Micr	21.6	42.3	38.3	35.1	23.5
Total Plag	49.1	21.8	35.1	35.6	40.7
Quartz	27.9	33.2	23.7	27.1	30.7
Biotite	1.2	2.0	2.5	1.9	3.2
Magnetite	0.1	0.6	0.2	0.3	0.3
Muscovite	----	----	0.1	----	1.5
Sphene	----	----	----	tr	----
Apatite	0.1	tr	----	----	tr
Zircon	tr	tr	0.2	tr	tr
Garnet	----	0.6	----	----	----
"ALASKITE" FACIES					
Sample #	JS-37	JS-72	JS-36	JS-88	
SiO ₂	71.3	72.8	73.5	74.7	
Total Micr	28.5	33.5	27.7	31.1	
Total Plag	37.2	20.0	40.5	30.9	
Quartz	33.3	43.1	28.6	36.9	
Biotite	tr	1.5	----	1.0	
Magnetite	tr	1.0	tr	tr	
Muscovite	1.0	0.7	2.1	----	
Sphene	----	----	----	----	
Apatite	tr	tr	tr	tr	
Zircon	----	tr	tr	0.1	
Garnet	tr	0.5	1.1	----	

Table 2: Summary of modal means and ranges of Oak Creek
plutonic rocks

	PORPHYRITIC MEDIUM-GRAINED COARSE-GRAINED ALASKITES			
	FACIES	LEUCOGRANITES	LEUCOGRANITES	(DIKES)
n =	27	9	3	9
SiO ₂	59.9 (55.4 - 64.9)	69.6 (67.2 - 72.0)	74.1 (72.8 - 75.4)	71.2 (68.1 - 74.7)
Micr*	30.4 (13.2 - 48.4)	30.9 (22.3 - 37.3)	46.1 (39.6 - 53.6)	31.3 (21.6 - 42.3)
Plag*	35.4 (14.4 - 44.9)	31.8 (24.6 - 36.8)	19.8 (13.2 - 26.3)	34.5 (20.0 - 49.1)
Quartz	16.9 (5.7 - 28.8)	31.7 (27.1 - 39.4)	31.3 (17.9 - 45.0)	31.6 (23.7 - 43.1)
Biotite	15.0 (8.9 - 24.8)	4.4 (2.6 - 5.7)	2.3 (1.9 - 3.1)	1.5 (0 - 3.2)
Magnetite	1.6 (0.04 - 3.98)	0.7 (0.2 - 1.6)	0.3 (0.1 - 0.6)	0.3 (0.01 - 0.10)
Muscovite	0.4 (0 - 2.17)	0.5 (0 - 1.0)	0.1 (0 - 0.3)	0.6 (0 - 2.05)
Sphene	0.2 (0 - 2.26)	< 0.1 (0 - 0.02)	0	< 0.1 (0 - 0.01)
Apatite	0.1 (0 - 0.3)	0.2 (0 - 0.1)	< 0.1 (0 - 0.01)	0.2 (0 - 1.13)
Zircon	0.2 (0 - 1.20)	< 0.1 (0 - 0.2)	0.1 (0 - 0.10)	< 0.1 (0 - 0.17)
Garnet	0	0	0	< 0.1 (0 - 1.1)

* Micr = Total Microcline Plag = total plagioclase

Figure 6: Modal classification of Oak Creek plutonic rocks



LEGEND

- ☆ Porphyritic facies
- ◇ Medium-grained leucogranite
- Δ Alaskite
- Coarse-grained leucogranite

The four facies can be distinguished by texture and/or mineralogy. The porphyritic facies has generally lower quartz and higher plagioclase contents relative to alkali feldspar than found in the leucogranite bodies and dikes. The porphyritic facies is also distinguished by higher mafic contents (10 to 27%) than found in the medium-grained leucogranite (4 to 8% mafics), the coarse-grained leucogranites (2 to 4% mafics) or the alaskites (1 to 5% mafics). Biotite is the major mafic phase in all facies. Magnetite and sphene are rarely more than 1 to 2 percent of the rock by volume.

Porphyritic Facies

Phenocrysts range from 12% to 64% of the rock volume. Perthitic microcline is the dominant phenocryst (8% to 45% of rock volume) with crystals up to 30mm. These alkali feldspars are always tartan twinned and in most cases exhibit string or braided perthite. Plagioclase phenocrysts occur in 80% of the porphyritic samples as crystals 5 to 18 mm; they make up to 21% of the rock volume. Plagioclase generally exhibits albite, pericline and albite twinning, and it is seritized in most cases. Weak oscillatory zoning in the plagioclase is rare but it is present in a few phenocrysts. Continued growth in later stages of crystallization result in predominantly anhedral boundaries

and intergrowths of the phenocrysts with groundmass minerals. The resulting texture in the strictest sense is subhedral-granular with seriate feldspars reaching phenocrystic proportions. Phenocrysts, for statistical purposes, are all feldspars greater than 4 mm in the longest dimension.

The porphyritic facies contains a mean of 23.5% phenocryst of alkali feldspar (subhedral to anhedral perthitic microcline, up to 30 mm) and 9.2 % plagioclase (subhedral to anhedral andesine, up to 18 mm) in a medium-grained ground mass (up to 3 mm) of subhedral to anhedral andesine (26%), anhedral quartz (16.9%), subhedral to anhedral biotite (15.0%), anhedral microcline (6.9%), anhedral magnetite (1.6%) and generally trace amounts of anhedral to subhedral muscovite (up to 2.2%). Accessory minerals include zircon, apatite, sphene and acicular rutile. Albitic rims and myrmekite are common as small reaction boundaries between plagioclase and microcline phenocrysts.

The modes (Figure 6) vary from granodiorite and quartz monzodiorite ranging to quartz-bearing monzonite and monzogranite for the porphyritic facies. Mean values of quartz/quartz + total feldspar and alkali feldspar/total feldspar are 20.5% and 54.8%, respectively. The average falls on the boundary of quartz-bearing monzonite and monzogranite fields.

Biotite (dominant mafic mineral) occurs as glomerocrysts which contain most of the accessory phases (sphene, zircon, and apatite) as inclusions. Magnetite and some sphene are generally associated with these mafic glomerocrysts but tend to be interstitial to the earlier biotite. Magnetite replaces the biotite in some samples. Late stage biotite is also present in all specimens, and it occurs as interstitial grains with quartz, microcline and plagioclase. Small, euhedral crystals of biotite appear as inclusions in some feldspar phenocrysts. Quartz grains often occur as polycrystalline aggregates that exhibit wavy undulose extinction +/- included suboriented rutile needles. The order of crystallization is summarized in Figure 7.

Medium-grained Leucogranite

The medium-grained leucogranite is equigranular with a mean composition (Table 2) of 31.8% subhedral to anhedral plagioclase (andesine up to 3 mm), 31.7% anhedral quartz (up to 2 mm), 30.9% anhedral microcline (up to 3 mm), 4.4% anhedral to euhedral biotite (up to 2 mm), and trace to minor amounts (<1%) of magnetite and muscovite. Accessory minerals include apatite, zircon, sphene, and acicular rutile needles. The mean of this facies is monzogranite with alkali feldspar/total feldspar and quartz/(quartz + total feldspar) equal to 51.0 and 33.6, respectively (Figure 6).

Figure 7: Order of crystallization for Oak Creek rocks by facies

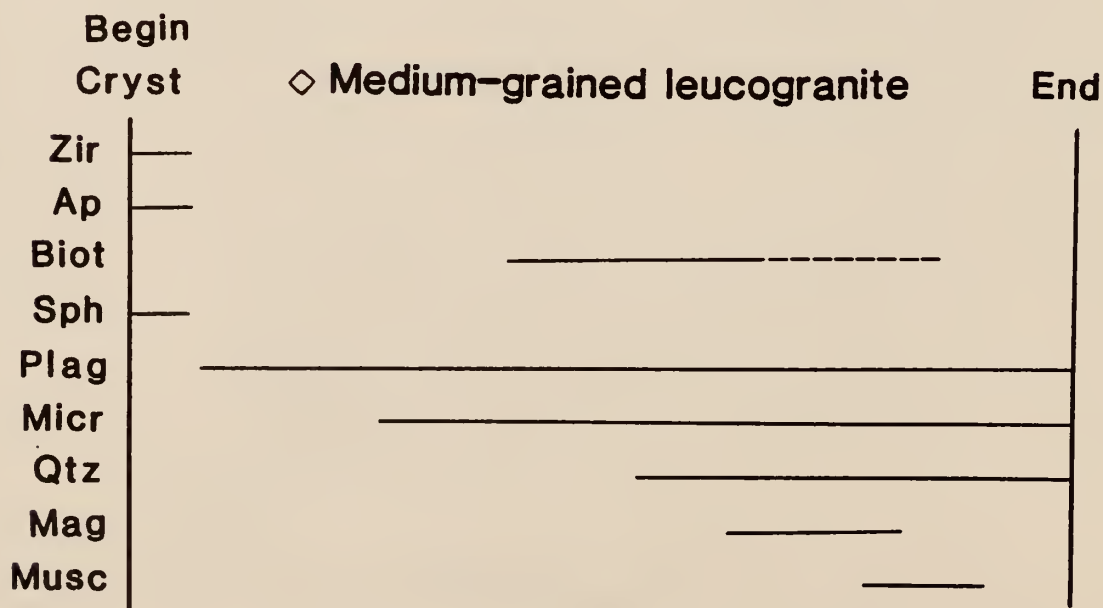
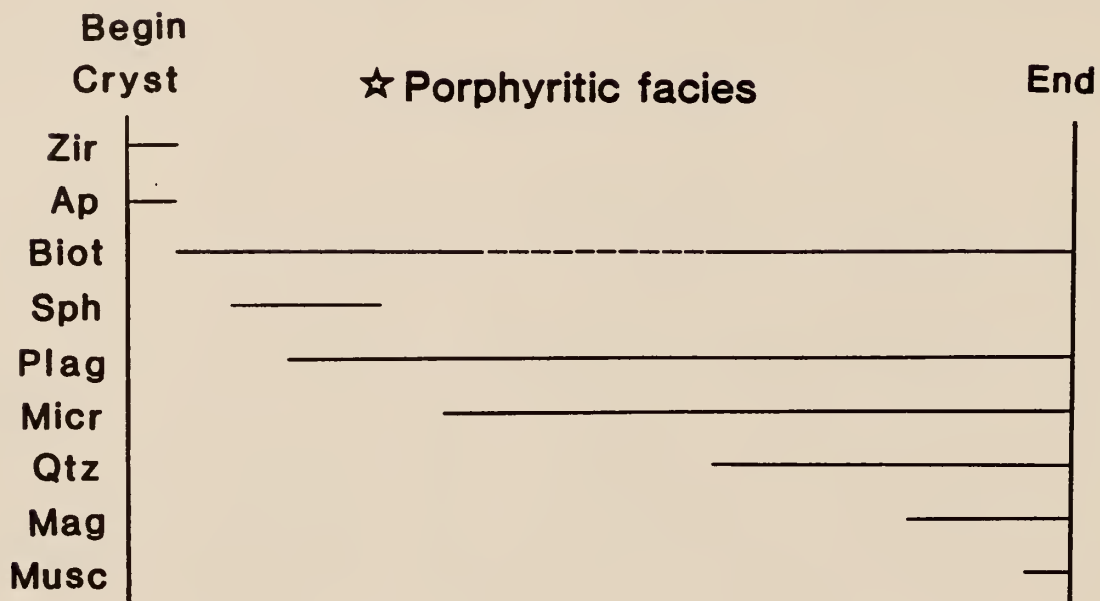
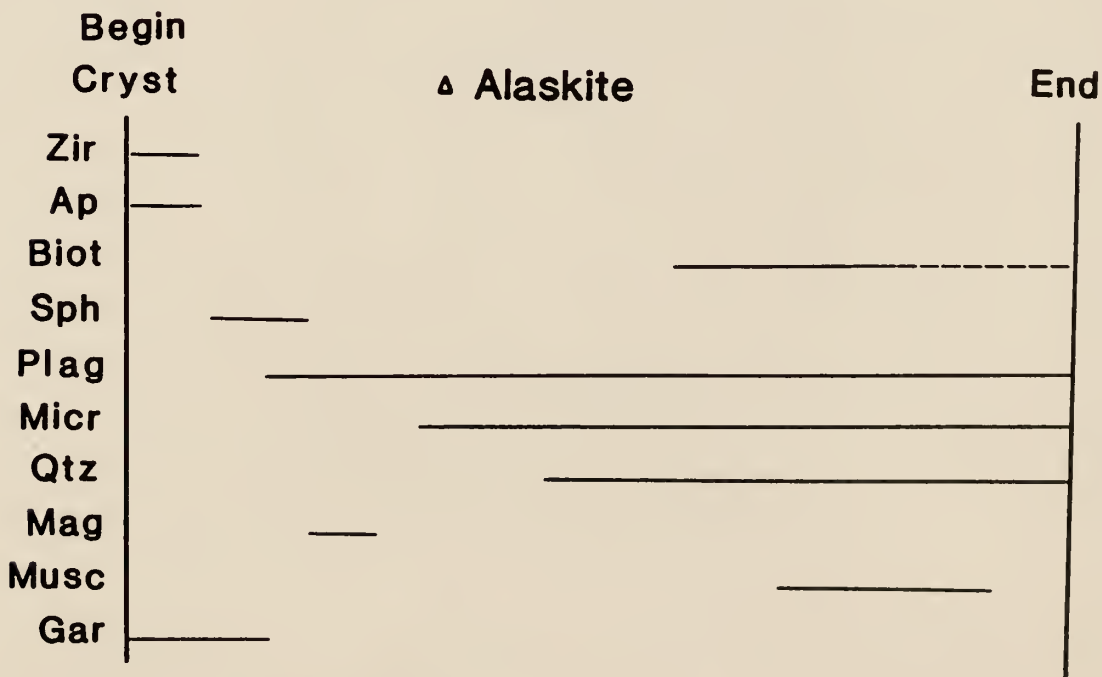
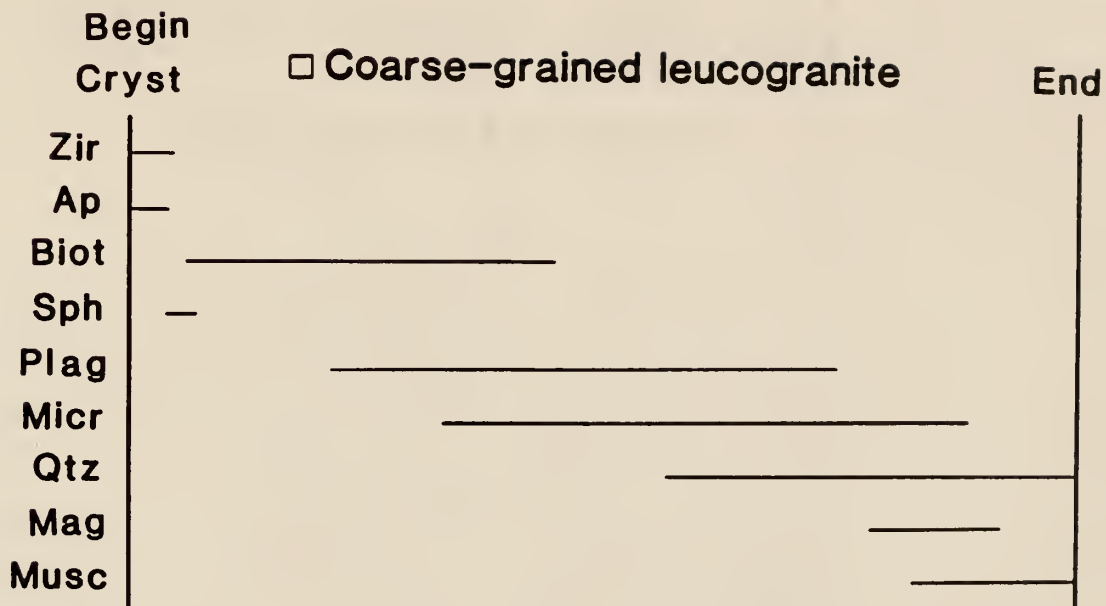


Figure 7, continued



The sequence of crystallization is illustrated in Figure 7. Simultaneous crystallization of plagioclase, microcline, and biotite with later quartz occurs in these medium-grained, equigranular rocks. Accessory magnetite, sphene, zircon, and apatite form as inclusions in the major mineral phases. Similar to the porphyritic facies, occurrences of myrmekite, poikilitic feldspars, sericitized plagioclase, and crenulated rutilated quartz are present in these leucogranites.

In contrast, the medium-grained leucogranites have less variation of plagioclase/microcline and quartz/total feldspar than the porphyritic facies. Also, the medium-grained leucogranites have much less biotite than the porphyritic facies. The biotite occurs as disseminated euhedral to anhedral grains instead of glomerocrysts.

Coarse-grained Leucogranite

The coarse-grained leucogranites have an average composition (Table 2) of 46.1% anhedral alkali feldspar (perthitic microcline up to 18 mm), 31.3% anhedral quartz (up to 8 mm), 19.8% subhedral to anhedral plagioclase (andesine, up to 10 mm) and 2.3% subhedral biotite (up to 1 mm). Modally they are monzogranite to granite (Figure 6). Accessories are magnetite, muscovite, zircon, apatite and

rutile needles. These coarse-grained rocks are subhedral-granular with interstitial mafics that exhibit a moderate foliation. Similar to the medium-grained leucogranite and porphyritic facies, the coarse-grained leucogranites have myrmekite, seriticized plagioclase, and accessory inclusions. The coarse-grained leucogranites have high quartz and alkali feldspar contents.

Alaskite dikes and veins

The alaskites are equigranular and have an average composition of 34.5% subhedral to anhedral plagioclase (andesine, up to 3 mm), 31.6% anhedral quartz (up to 2mm), 31.3% anhedral microcline (up to 3 mm) 1.5% subhedral-anhedral biotite (up to 1.5 mm), and trace to minor muscovite and magnetite (up to 1.0 mm). Euhedral apatite, zircon, sphene, rutile needles and garnet occur as accessory minerals. The mineralogy of the alaskites is remarkably similar that of the medium-grained leucogranites with the exception of lower biotite contents, the presence of garnet, and greater variation of plagioclase/total feldspar (granodiorite to monzogranite) in the alaskites. The alaskites have less than 3% biotite, and the medium-grained leucogranites have greater than 3% biotite. The order of crystallization is summarized in Figure 7.

Major Element Geochemistry

Major element data (Table 3) are listed in order of increasing SiO_2 (weight %) for each facies. Correlation of SiO_2 vs D.I. (Figure 8) illustrates how silica percent is a good indicator of differentiation of the various facies ($r = .9505$). The differentiation index (D.I.) represents the norm of late forming, sialic minerals in an igneous suite that have evolved by magma differentiation (Thorton and Tuttle, 1960).

The means and ranges for each element are summerized by facies in Table 4. Silica increases in the order porphyritic facies, medium-grained leucogranites, and coarse-grained leucogranites. The porphyritic facies is characterized by a larger silica variation (55.4 to 64.9 percent SiO_2) than the medium-grained leucogranites (65.7 to 72.0 percent SiO_2), or the coarse-grained leucogranites (72.8 to 75.4 percent SiO_2). Silica concentrations of the alaskites overlap the medium-grained and coarse-grained leucogranite fields (68.1 to 74.7%).

Major elements are plotted against silica in Figure 9. A compositional gap (65% to 67% SiO_2) occurs between the medium-grained leucogranites and the porphyritic facies for Si, Ca, Fe, Mg, Ti and Mn (This may be biased due to very little sampling in gradational zones, which tend to be areas of heavy weathering and cover).

Table 3: Major Element contents of the Oak Creek batholith (porphyritic facies, medium-grained-leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

PORPHYRITIC FACIES						
Sample #	JS-80	JS-65	JS-44	JS-85	JS-86	JS-106
SiO ₂ (wgt %)	55.4	55.8	56.5	56.6	57.1	58.2
Al ₂ O ₃	17.2	17.3	16.8	17.3	17.6	18.2
TiO ₂	2.6	2.2	2.3	1.5	1.2	1.5
Fe ₂ O ₃	8.0	8.3	7.6	8.6	8.2	6.5
MgO	2.4	2.5	2.3	2.7	2.7	1.7
CaO	4.0	5.2	5.4	5.4	4.0	3.4
NaO ₂	3.8	3.5	3.4	2.7	3.2	3.6
K ₂ O	4.7	3.8	3.9	3.7	4.3	6.0
MnO	0.12	0.15	0.17	0.13	0.13	0.12
Rb*	149	153	138	115	163	177
Sr*	623	573	452	817	468	548
LOI	1.41	1.08	1.33	0.85	1.28	0.59
Total	99.47	99.68	99.73	99.48	99.69	99.80

PORPHYRITIC FACIES						
Sample #	JS-102	JS-96	JS-89	JS-95	JS-42	JS-3
SiO ₂ (wgt %)	58.2	58.3	58.4	59.4	59.5	59.6
Al ₂ O ₃	17.4	18.7	17.7	17.9	16.7	18.7
TiO ₂	1.3	1.2	1.3	1.2	1.7	1.1
Fe ₂ O ₃	7.7	6.9	8.3	6.5	7.6	5.4
MgO	2.5	2.1	2.5	1.9	2.0	1.4
CaO	2.9	4.1	3.9	3.2	3.2	3.0
NaO ₂	3.2	3.9	3.5	3.5	3.6	3.7
K ₂ O	4.8	4.2	3.7	5.6	5.2	5.8
MnO	0.14	0.11	0.14	0.12	0.14	0.09
Rb *	196	148	151	179	203	156
Sr *	389	764	527	533	363	596
LOI	0.91	0.57	0.55	1.05	0.76	0.45
Total	99.00	100.01	100.07	100.41	100.37	99.17

* ppm

Table 3: Major Element contents of the Oak Creek batholith (porphyritic facies, medium-grained-leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

PORPHYRITIC FACIES						
Sample #	JS-100	JS-81a	JS-32b	JS-77	JS-87	JS-61
SiO ₂ (wgt%)	60.2	60.3	60.5	60.7	60.7	61.0
Al ₂ O ₃	17.4	15.9	17.4	15.7	17.4	17.4
TiO ₂	1.4	1.2	1.1	1.3	1.0	0.93
Fe ₂ O ₃	7.0	8.5	5.9	7.8	6.6	6.0
MgO	2.2	2.6	1.8	1.8	1.9	1.8
CaO	3.6	3.6	3.1	3.4	2.7	3.3
NaO ₂	3.3	3.1	3.5	3.5	3.3	3.5
K ₂ O	4.0	3.9	5.9	4.0	5.0	4.7
MnO	0.13	0.17	0.10	0.17	0.11	0.10
Rb*	159	118	224	167	191	165
Sr*	406	478	346	410	427	451
LOI	1.24	0.67	0.93	0.72	1.1	1.14
Total	100.51	100.02	100.07	99.05	99.79	99.56

PORPHYRITIC FACIES						
Sample #	JS-2	JS-51	JS-98	JS-93	JS-18	JS-23
SiO ₂ (wgt %)	61.1	61.1	61.1	61.2	61.7	62.8
Al ₂ O ₃	17.6	17.0	16.4	17.5	17.0	17.4
TiO ₂	1.0	1.1	1.2	1.0	1.1	0.8
Fe ₂ O ₃	6.1	7.3	7.8	6.3	6.9	5.0
MgO	1.9	2.2	2.4	1.9	2.4	1.7
CaO	2.1	3.1	2.9	2.5	2.3	3.0
NaO ₂	3.5	3.3	3.3	3.0	3.4	3.3
K ₂ O	5.1	4.0	4.1	5.9	4.8	5.5
MnO	0.10	0.13	0.11	0.12	0.10	0.11
Rb *	217	191	131	201	254	164
Sr *	293	392	594	433	260	415
LOI	1.10	0.96	0.98	0.68	1.27	1.25
Total	99.50	100.23	100.36	100.08	100.98	100.73

* ppm

Table 3: Major Element contents of the Oak Creek batholith (porphyritic facies, medium-grained-leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

PORPHYRITIC FACIES

Sample #	JS-41	JS-84	JS-29
SiO ₂ (wgt%)	63.0	63.3	64.9
Al ₂ O ₃	17.2	17.5	17.9
TiO ₂	0.7	1.1	0.5
Fe ₂ O ₃	4.9	4.7	4.3
MgO	1.5	1.1	1.0
CaO	2.7	2.4	2.0
NaO ₂	3.1	3.4	3.7
K ₂ O	5.2	5.6	4.8
MnO	0.09	0.12	0.09
Rb*	156	211	172
Sr*	469	404	330
LOI	1.28	0.76	0.77
Total	99.75	99.90	99.95

MEDIUM-GRAINED LEUCOGRANITE FACIES

Sample #	JS-101	JS-33	JS-78	JS-109	JS-9
SiO ₂	67.2	67.9	68.4	68.8	69.4
Al ₂ O ₃	16.6	16.3	16.5	16.3	15.4
TiO ₂	0.5	0.4	0.2	0.3	0.4
Fe ₂ O ₃	2.9	2.4	2.7	2.3	2.8
MgO	0.8	0.4	0.6	0.7	0.6
CaO	1.3	1.2	1.5	1.6	0.7
NaO ₂	3.2	3.3	3.7	3.2	2.9
K ₂ O	6.5	6.9	5.4	6.0	7.2
MnO	0.04	0.04	0.05	0.03	0.06
Rb *	230	286	184	221	231
Sr *	314	156	306	187	197
LOI	0.66	0.78	0.79	0.48	0.95
Total	99.60	99.57	99.80	99.53	100.31

* ppm

Table 3: Major Element contents of the Oak Creek batholith (porphyritic facies, medium-grained-leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

MEDIUM-GRAINED LEUCOGRANITE FACIES

Sample #	JS-1	JS-16	JS-14	JS-31
SiO ₂	70.7	71.0	71.3	72.0
Al ₂ O ₃	16.1	15.7	14.9	14.7
TiO ₂	0.2	0.1	0.3	0.2
Fe ₂ O ₃	1.9	1.4	2.2	1.6
MgO	0.2	0.3	0.4	0.3
CaO	1.2	0.9	1.2	1.2
NaO ₂	3.1	3.3	2.8	3.4
K ₂ O	6.5	6.7	6.0	5.0
MnO	0.03	0.02	0.05	0.03
Rb*	213	239	199	182
Sr*	307	221	240	141
LOI	0.57	0.67	0.51	0.86
Total	100.51	100.14	99.66	99.23

"ALASKITE" FACIES

Sample #	JS-60	JS-46	JS-81b	JS-5	JS-70	JS-37
SiO ₂	68.1	69.0	69.9	70.7	71.0	71.3
Al ₂ O ₃	17.2	17.1	15.5	15.3	15.9	16.7
TiO ₂	0.2	0.1	0.2	0.2	0.2	0.1
Fe ₂ O ₃	1.3	1.2	2.1	1.5	0.9	0.8
MgO	0.2	0.1	0.3	0.2	0.2	0.04
CaO	1.1	0.8	0.5	0.7	1.0	0.7
NaO ₂	3.9	3.2	3.0	3.2	4.8	4.1
K ₂ O	6.6	7.6	7.0	7.4	5.2	5.7
MnO	0.02	0.05	0.03	0.03	0.05	0.07
Rb *	189	224	186	211	163	167
Sr *	85	116	112	116	51	60
LOI	0.85	0.58	1.05	0.38	0.46	0.87
Total	99.41	99.67	99.51	99.58	99.57	100.38

* ppm

Table 3: Major Element contents of the Oak Creek batholith (porphyritic facies, medium-grained-leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

"ALASKITE" FACIES

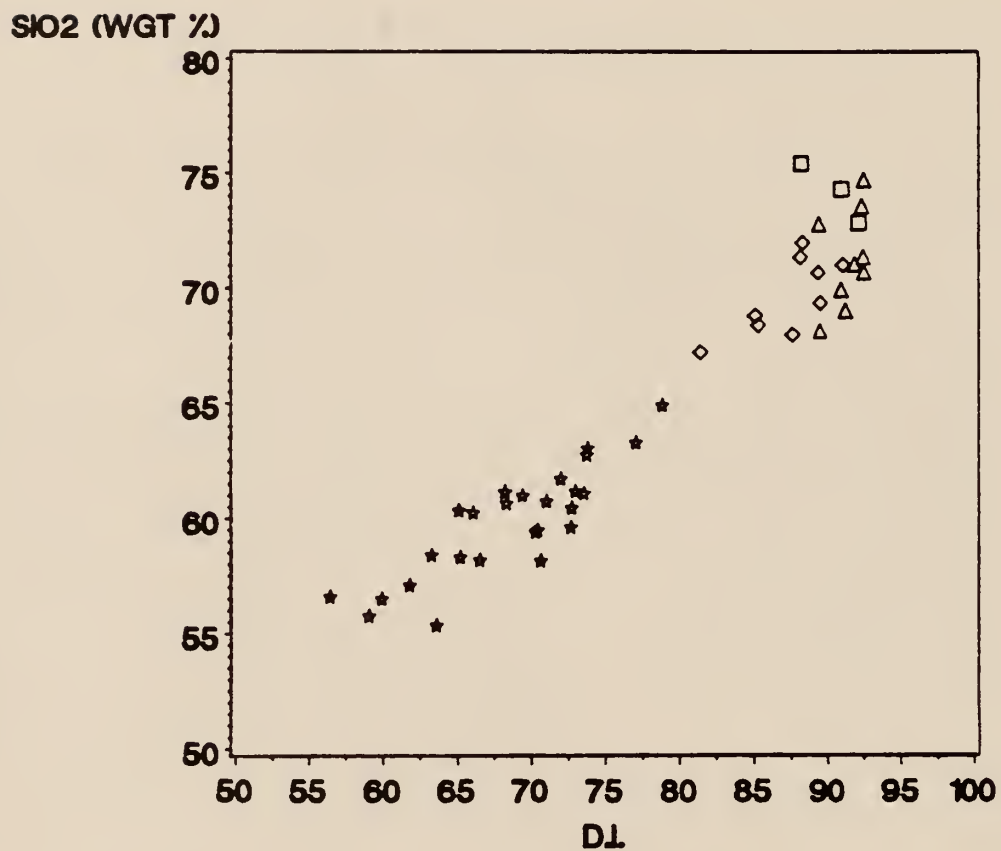
Sample #	JS-72	JS-36	JS-88
SiO ₂	72.8	73.5	74.7
Al ₂ O ₃	14.1	14.9	13.4
TiO ₂	0.2	0.1	0.1
Fe ₂ O ₃	2.3	0.7	1.2
MgO	0.5	0.1	0.04
CaO	1.0	0.6	0.7
NaO ₂	2.9	4.0	2.6
K ₂ O	5.7	4.6	6.0
MnO	0.04	0.17	0.02
Rb	270	225	161
Sr	25	86	110
LOI	0.36	0.69	0.54
Total	99.74	99.27	99.33

COARSE-GRAINED LEUCOGRANITES

Sample #	JS-73	JS-59	JS-64
SiO ₂ (wgt %)	72.8	74.3	75.4
Al ₂ O ₃	14.0	13.8	12.1
TiO ₂	0.3	0.2	0.4
Fe ₂ O ₃	1.8	1.6	2.5
MgO	0.3	0.5	0.7
CaO	0.5	1.1	1.3
NaO ₂	2.4	2.8	2.5
K ₂ O	7.0	5.9	4.9
MnO	0.03	0.04	0.06
Rb *	240	235	177
Sr *	81	91	93
LOI	0.65	0.37	0.56
Total	99.89	100.54	100.37

* ppm

Figure 8: Silica vs D.I. for Oak Creek pluton



LEGEND

- ☆ Porphyritic facies
- ◇ Medium-grained leucogranite
- △ Alaskite
- Coarse-grained leucogranite

Table 4: Summary of Major Element means and ranges for the Oak Creek batholith (porphyritic facies, medium-grained leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

	PORPHYRITIC FACIES	MEDIUM-GRAINED LEUCOGRANITES	COARSE-GRAINED LEUCOGRANITES	ALASKITES (DIKES)
n =	27	9	3	9
SiO ₂	59.9 (55.4 - 64.9)	69.6 (67.2 - 72.0)	74.1 (72.8 - 75.4)	71.2 (68.1 - 74.7)
Al ₂ O ₃	17.3 (15.7 - 18.7)	15.8 (14.7 - 16.6)	13.3 (12.1 - 14.0)	15.6 (13.4 - 17.2)
TiO ₂	1.27 (0.5 - 2.6)	0.28 (0.13 - 0.46)	0.3 (0.18 - 0.42)	0.14 (0.05 - 0.22)
Fe ₂ O ₃	6.8 (4.3 - 8.6)	2.2 (1.4 - 2.9)	1.9 (1.6 - 2.5)	1.3 (0.7 - 2.3)
MgO	2.0 (1.0 - 2.7)	0.5 (0.2 - 0.8)	0.5 (0.3 - 0.7)	0.17 (0.04 - 0.51)
CaO	3.3 (2.0 - 5.4)	1.2 (0.7 - 1.6)	1.0 (0.5 - 1.3)	0.8 (0.5 - 1.1)
Na ₂ O	3.4 (2.7 - 3.9)	3.2 (2.8 - 3.7)	2.6 (2.4 - 2.8)	3.5 (2.6 - 4.8)
K ₂ O	4.7 (3.7 - 6.0)	6.2 (5.0 - 7.2)	5.9 (4.9 - 7.0)	6.2 (4.6 - 7.6)
MnO	0.12 (0.1 - 0.2)	0.04 (0.02 - 0.06)	0.04 (0.03 - 0.06)	0.05 (0.02 - 0.17)
Rb*	172 (115 - 254)	220 (182 - 286)	217 (177 - 240)	199 (161 - 270)
Sr*	473 (260 - 817)	229 (141 - 314)	88 (81 - 93)	85 (25 - 116)
LOI	0.95 (0.5 - 1.4)	0.70 (0.5 - 0.9)	0.50 (0.4 - 0.6)	0.60 (0.4 - 1.0)

* ppm

Figure 9: Major element contents versus silica content for Oak Creek Area pluton

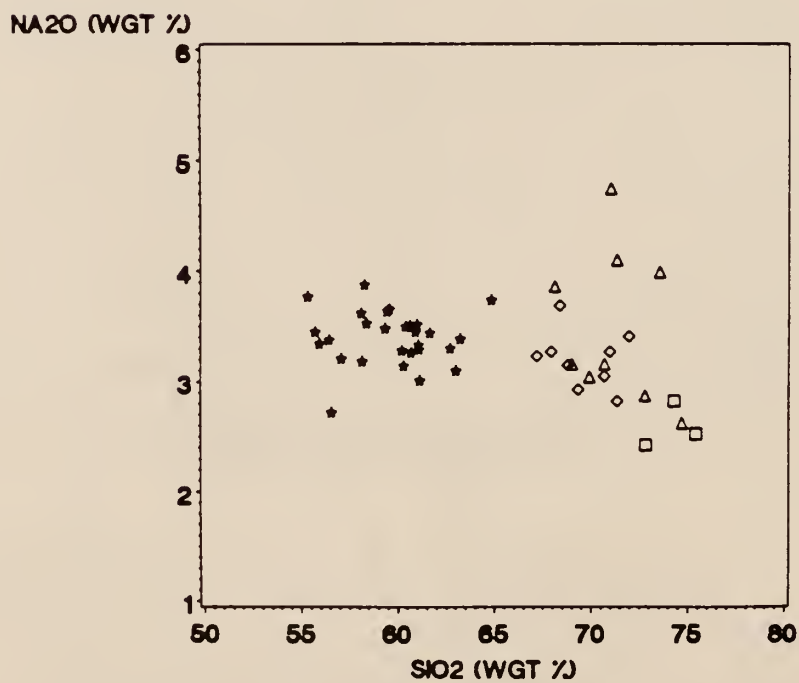
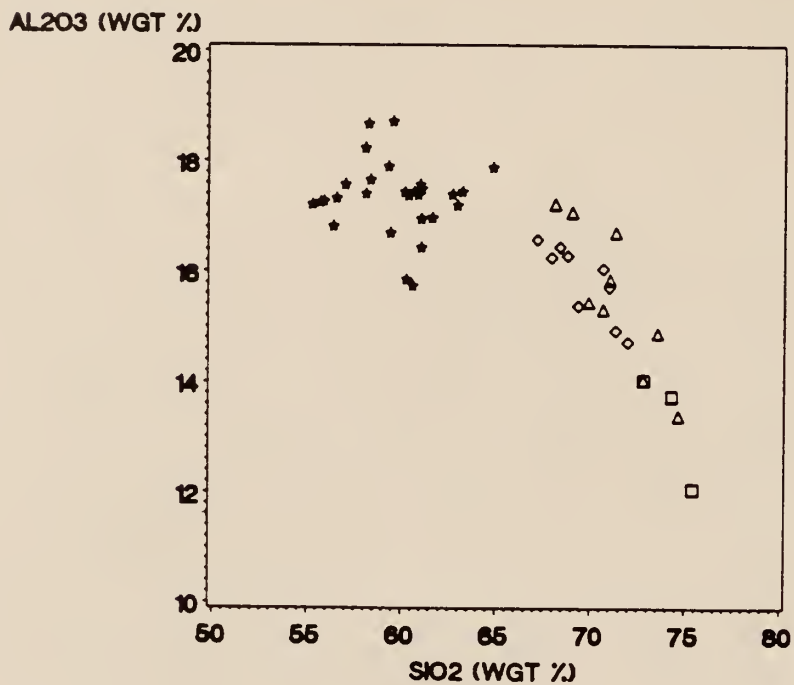


Figure 9, continued

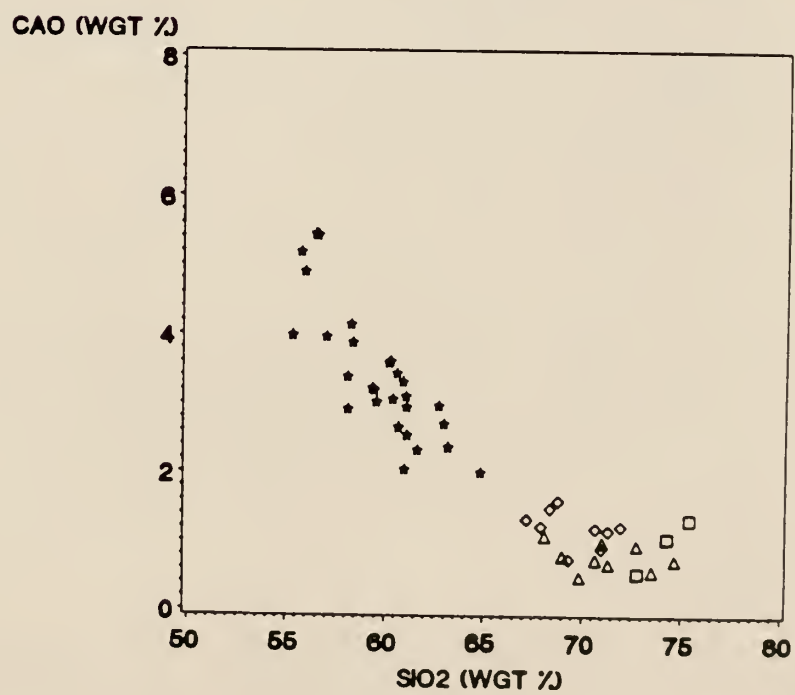
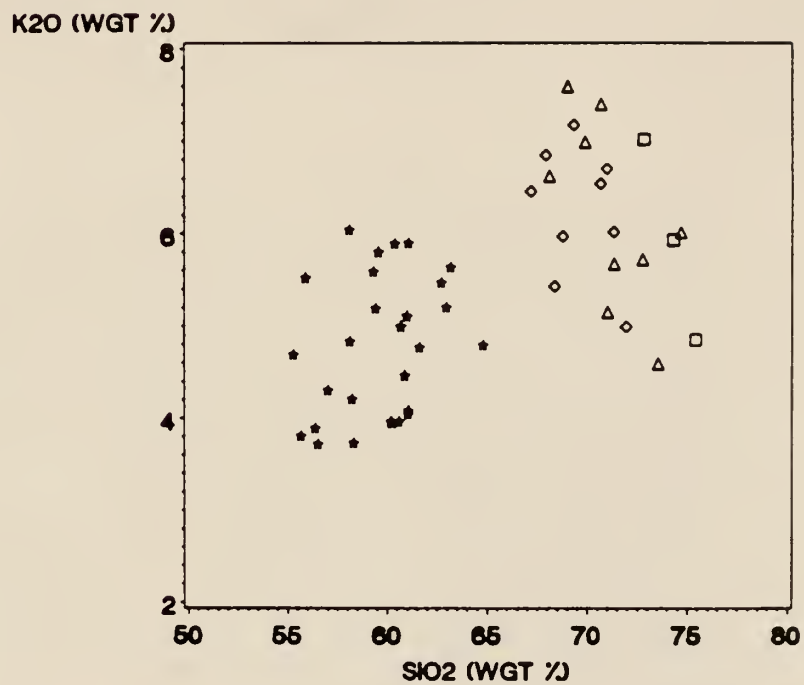


Figure 9, continued

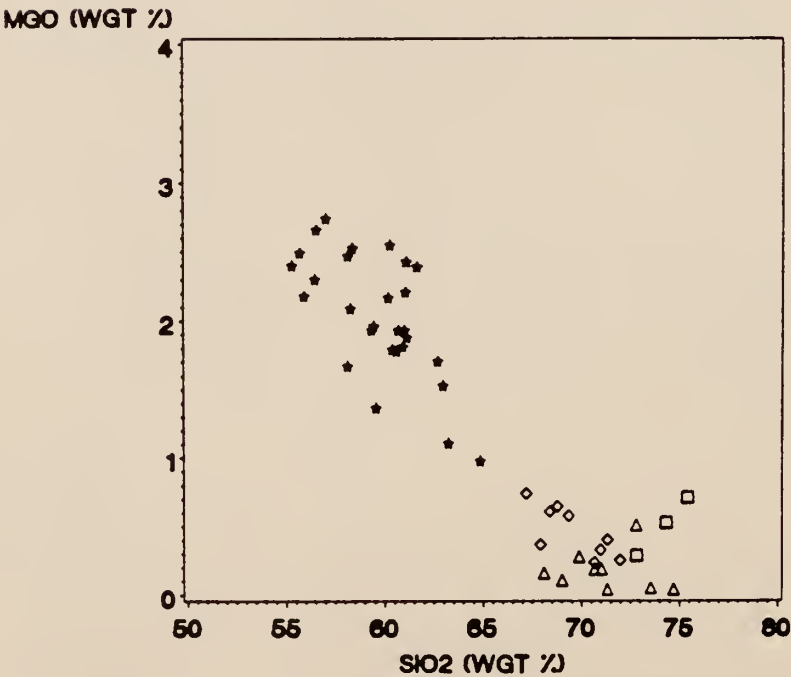
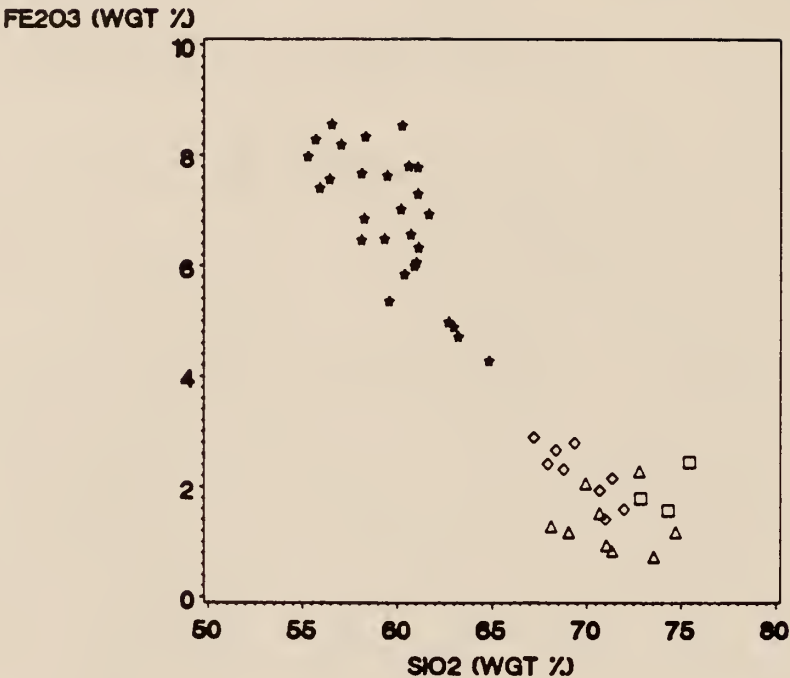
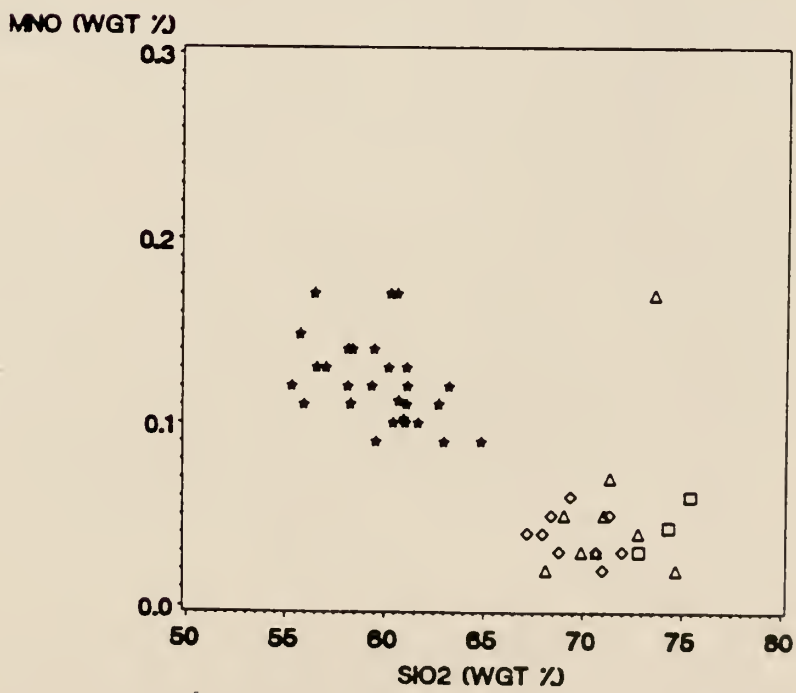
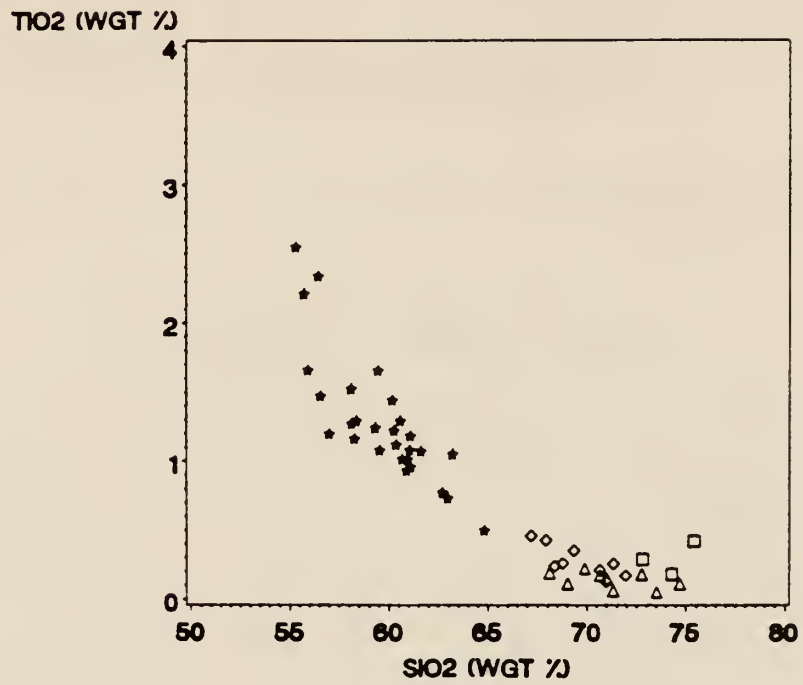


Figure 9, continued



K₂O increases and CaO, Fe₂O₃, MgO, TiO₂, and MnO decrease with increasing silica (Figure 9). The Na₂O concentration tends to remain constant or decrease slightly ($r = -.2516$) for all facies as SiO₂ increases. (Na₂O + K₂O)/Ca increases with increased differentiation from porphyry to the leucocratic facies (Figure 10) although the alaskites and coarse-grained leucogranites have considerable scatter.

Iron (FeO) enrichment relative to MgO is shown in the FeO/(FeO + MgO) (FER) vs SiO₂ plot (Figure 11). The rocks of Oak Creek are too Fe rich to be calcalkaline. A Peacock (1931) plot (Figure 12) does not have intersecting trends of CaO and total alkali. A projection of the trends allows intersection at about SiO₂ = 50 to 52%, suggesting the Oak Creek rocks may be alkali-calcic. The porphyritic facies plots mostly in the alkalic field in Na₂O + K₂O vs SiO₂ plot (Figure 13), but the leucogranites vary from alkalic to subalkalic.

Shand (1951) used the ratio of molecular Al₂O₃/(Na₂O + K₂O + CaO) (Shand Index) to characterize the degree of aluminum saturation. The leucogranites are slightly peraluminous (Shand Index > 1) while the porphyritic facies rocks are metaluminous to slightly peraluminous (Figure 14).

Generally, the porphyritic facies and the medium-grained leucogranites have linear trends with little scatter

Figure 10: Plot of $\text{Na}_2\text{O} + \text{K}_2\text{O}/\text{CaO}$ vs SiO_2 for Oak Creek Area plutonic rocks

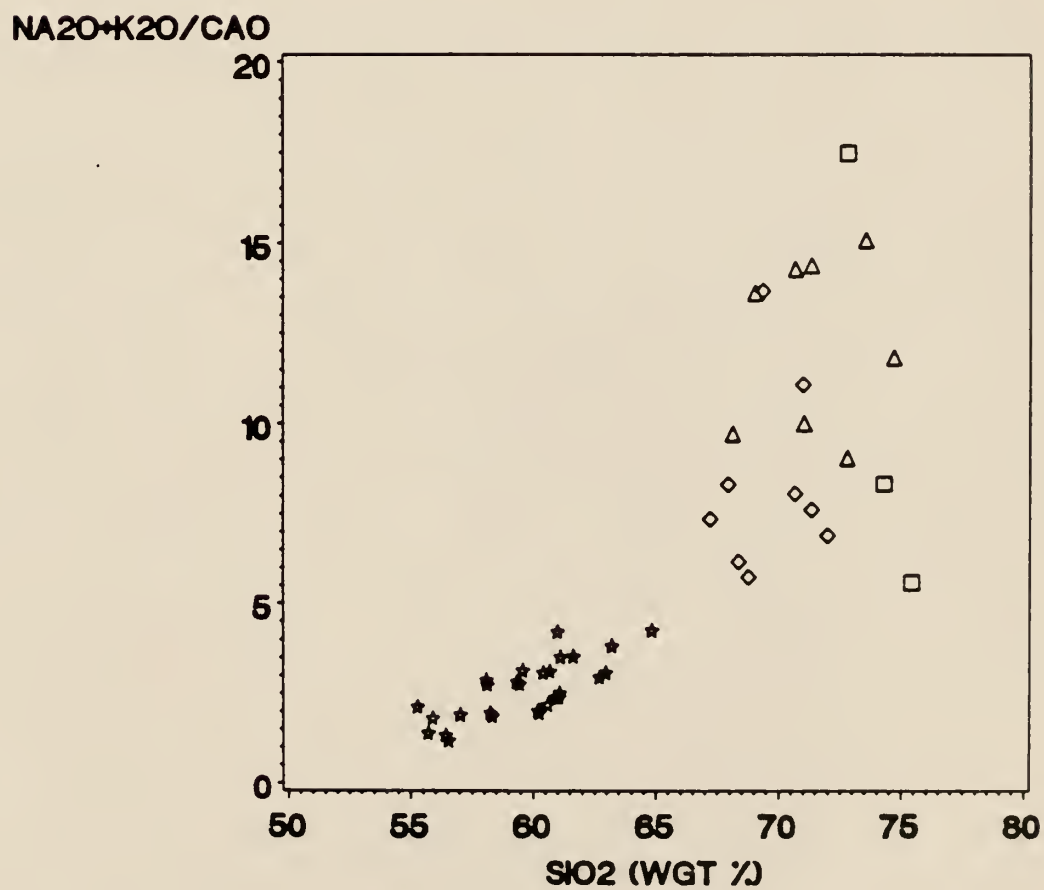


Figure 11: Plot of $\text{FeO}/(\text{FeO} + \text{MgO})$ vs SiO_2 for Oak Creek area plutonic rocks

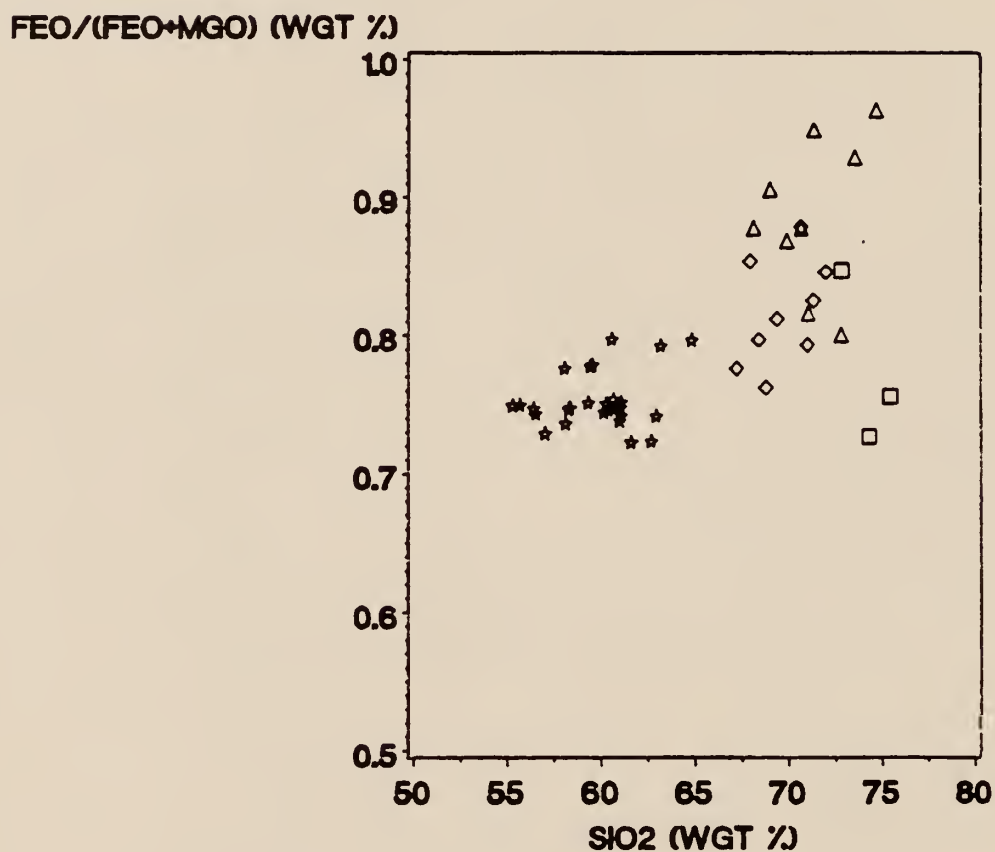
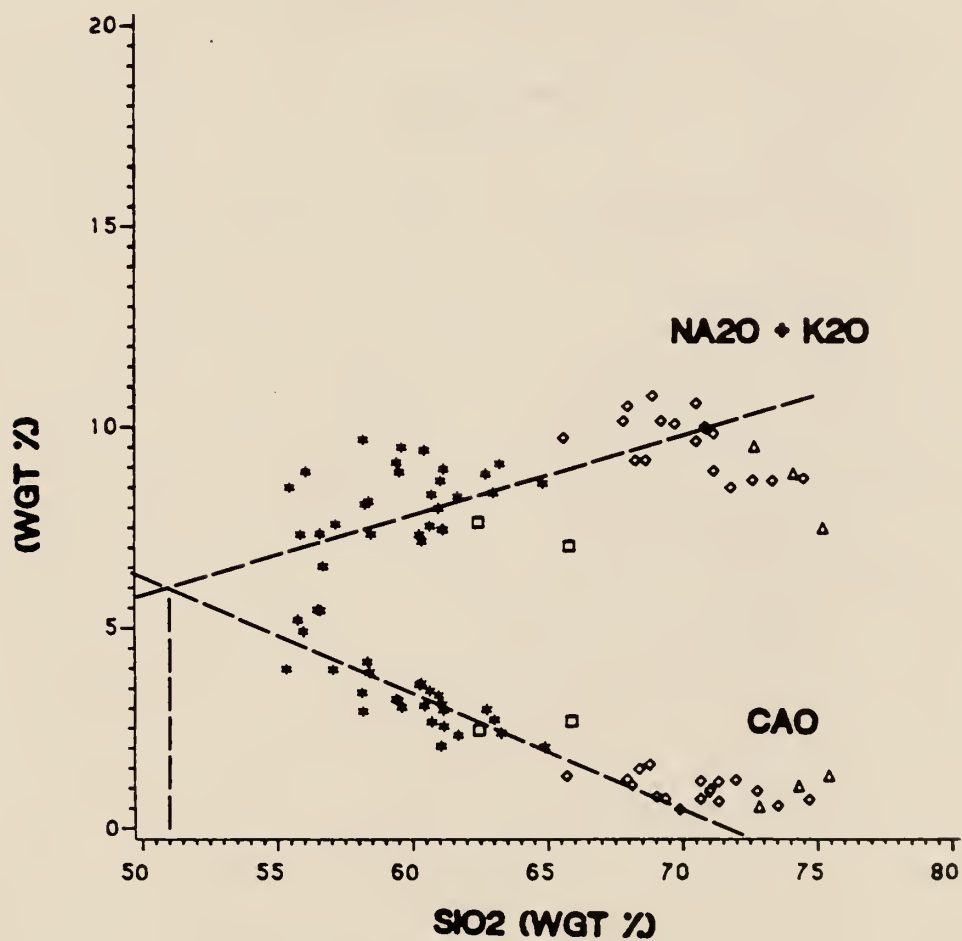
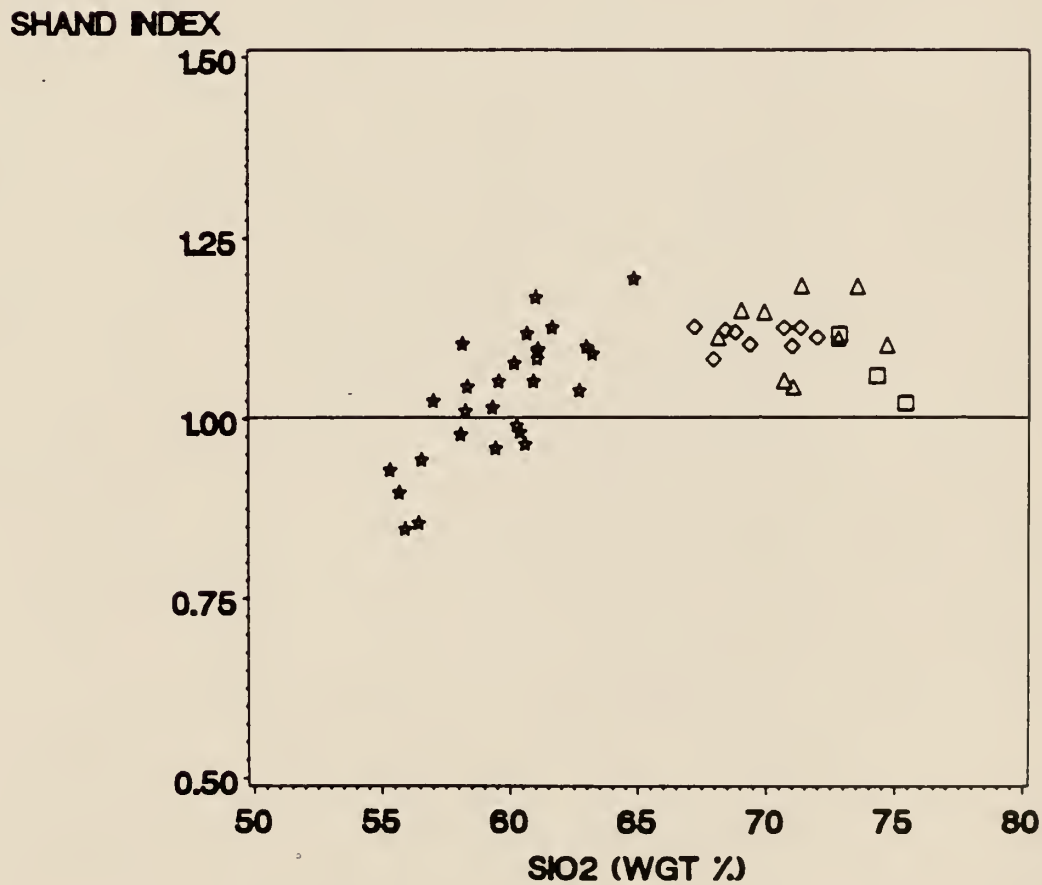


Figure 12: Peacock plot of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and CaO vs SiO_2 for Oak Creek area plutonic rocks



$$\text{Na}_2\text{O} + \text{K}_2\text{O}$$


Figure 14: Shand Index vs SiO_2 for Oak Creek Area
plutonic rocks



in most diagrams, but the coarse-grained leucogranites and alaskite dikes and veins produce more scatter on major element diagrams.

Trace Element Geochemistry

Trace elements (Table 5) are also listed in order of increasing SiO_2 for each facies. The porphyritic rocks generally have larger concentrations of Ba, Sr and light rare-earth element (LREE) contents than the leucogranites (Tables 3 and 6), but the Rb concentration is similar for all facies. Th is variably enriched in some porphyritic samples. High Th samples also contain higher than average sphene and zircon contents although these minerals are still in trace amounts.

Sr, Ba, and Cr contents decrease (Figure 15) but Rb contents increase slightly with increasing SiO_2 for porphyritic and leucogranite facies.

The range of Eu/Sm values (Table 6 and Figure 16) is greater for porphyritic facies than the medium-grained leucogranites. The range of Eu/Sm values for the alaskites are similar to the porphyritic facies.

Sr vs Rb (Figure 17) illustrates the distinction between the various leucogranite facies. The medium-grained leucogranites overlap with the more differentiated end of

Table 5: Trace Element contents (ppm) of the Oak Creek batholith (porphyritic facies, medium-grained-leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

PORPHYRITIC FACIES

Sample #	JS-80	JS-86	JS-77	JS-61
Ba	3510	3130	3200	2390
La	237	187	192	151
Ce	578	366	397	277
Sm	46.8	30.9	26.4	29.0
Eu	10.0	4.8	6.0	4.8
Tb	5.1	3.4	2.3	4.0
Lu	1.7	1.3	.8	1.7
Sc	25.5	18.7	12.8	13.8
Cr	31.0	59.0	21.5	34.0
Th	25.6	19.3	19.8	14.0

PORPHYRITIC FACIES

Sample #	JS-98	JS-23	JS-29
Ba	3490	3000	2340
La	841	110	320
Ce	1554	251	716
Sm	75.6	30.4	68.3
Eu	7.9	6.2	3.8
Tb	2.74	3.83	5.4
Lu	0.3	1.1	1.0
Sc	11.4	16.2	10.7
Cr	39.0	26.3	19.0
Th	236	12.5	185

Table 5: Trace Element contents (ppm) of the Oak Creek batholith (porphyritic facies, medium-grained-leucogranites, coarse-grained leucogranites, and alaskite dikes and veins).

* MEDIUM-GRAINED and COARSE-GRAINED LEUCOGRANITES				
Sample #	JS-78	JS-109	JS-9	* JS-64
Ba	857	1310	1090	395
La	117	61.5	150	270
Ce	282	115	337	520
Sm	18.7	7.6	22.3	23.3
Eu	1.5	1.1	1.9	2.1
Tb	1.1	0.5	1.3	1.5
Lu	0.8	0.2	0.6	0.4
Sc	4.3	3.8	4.7	---
Cr	13.9	12.0	9.6	18.6
Th	90	31.2	129	41.8
ALASKITES				
Sample #	JS-60	JS-70	JS-37	JS-72
Ba	584	153	139	148
La	17.5	22.0	11.0	68.6
Ce	36.0	46.3	20.7	142
Sm	4.3	6.3	1.7	12.5
Eu	0.8	0.3	0.4	0.5
Tb	0.9	1.6	0.3	1.7
Lu	1.2	1.8	0.5	2.0
Sc	2.9	18.1	2.1	---
Cr	13.0	14.0	9.9	12.0
Th	23.3	36.7	6.8	---

Table 6: Summary of Trace Element means and ranges for the Oak Creek batholith (porphyritic facies, medium-grained leucogranites, coarse-grained leucogranites, and alaskite dikes and veins) in ppm.

	PORPHYRITIC FACIES	MEDIUM-GRAINED LEUCOGRANITES	COARSE-GRAINED LEUCOGRANITES	ALASKITES (DIKES)
n =	7	3	1	4
Ba	3008 (2340 - 3510)	1085 (857 - 1310)	395	256 (139 - 584)
La	291 (110 - 841)	110 (62 - 150)	270	30 (11 - 69)
Ce	591 (251 - 1554)	245 (115 - 337)	520	61 (21 - 142)
Sm	44 (26 - 75)	16 (8 - 22)	23	6.2 (1.7 - 12)
Eu	6.2 (3.8 - 10)	1.5 (1.1 - 1.9)	2.1	0.5 (0.3 - 0.8)
Tb	3.8 (2.3 - 5.4)	0.9 (0.5 - 1.3)	1.5	1.1 (0.3 - 1.7)
Lu	1.1 (0.3 - 1.7)	0.5 (0.21 - 0.76)	0.4	1.4 (0.5 - 2.0)
Sc	15 (11 - 26)	4.3 (3.8 - 4.7)	-na-	7.7 (2.1 - 18)
Cr	33 (19 - 59)	12 (9.6 - 14)	19	12 (10 - 14)
Th	73 (13 - 236)	83 (31 - 129)	42	22 (6.8 - 37)

na = not available

Figure 15: Plots of trace element vs SiO₂ for Oak Creek area plutonic rocks

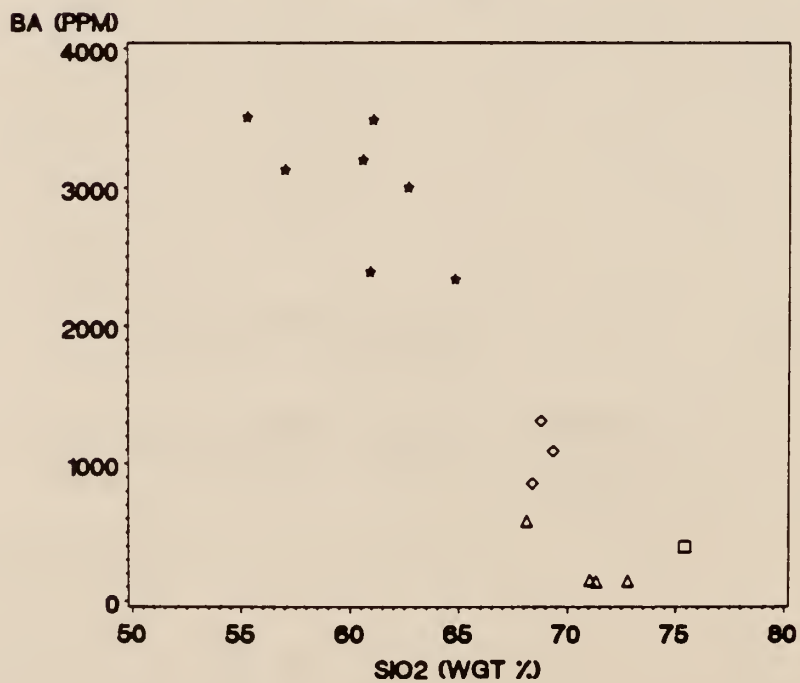
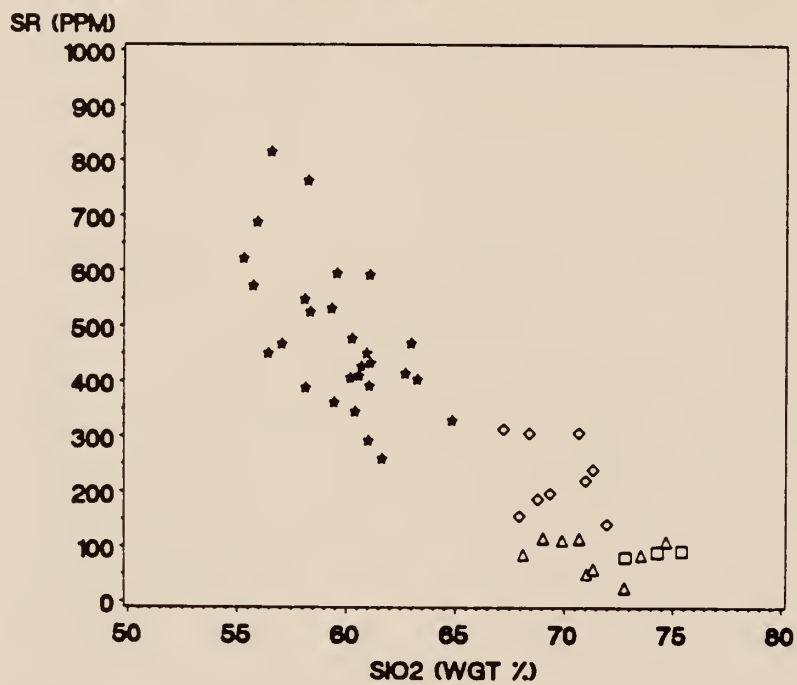


Figure 15, continued

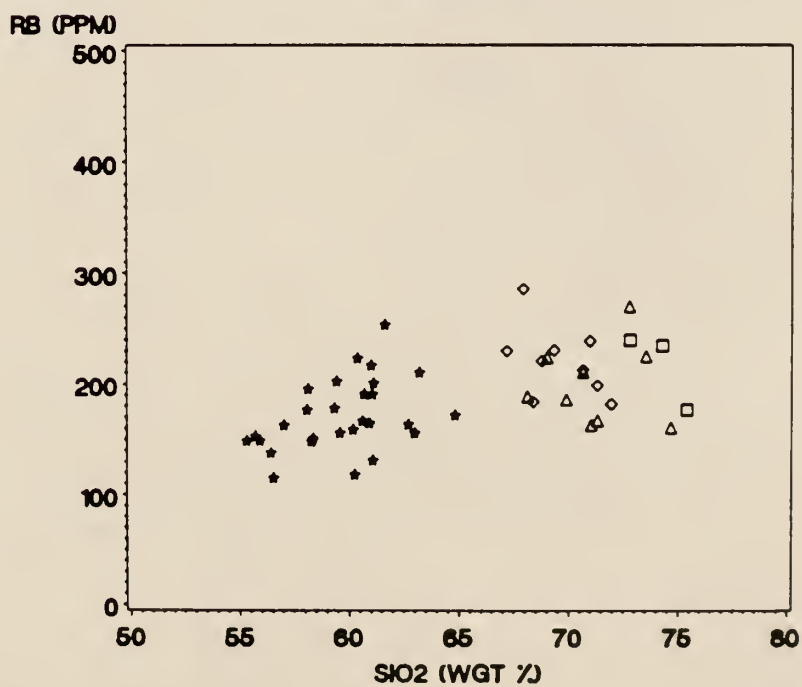
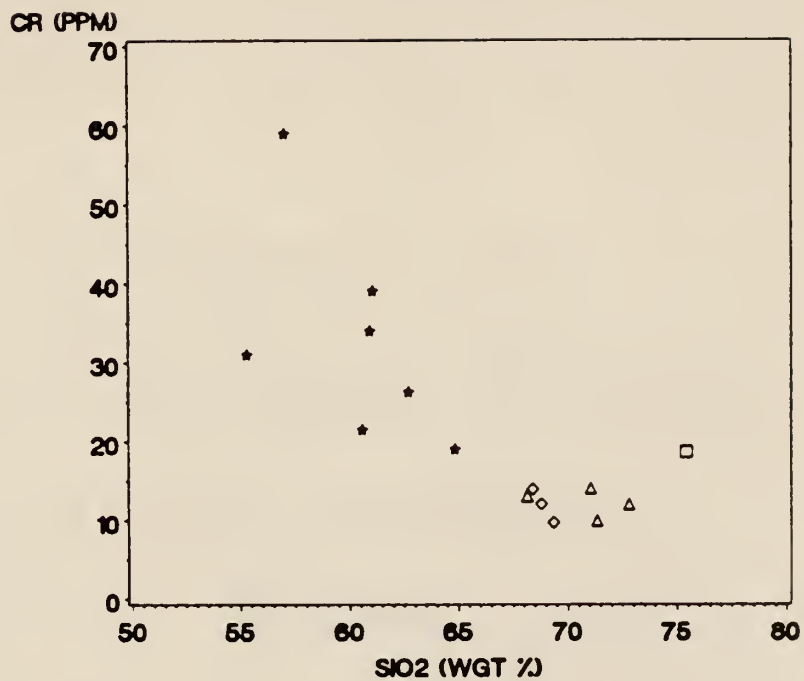


Figure 16: Eu/Sm ratio vs SiO₂ for Oak Creek Area plutonic rocks

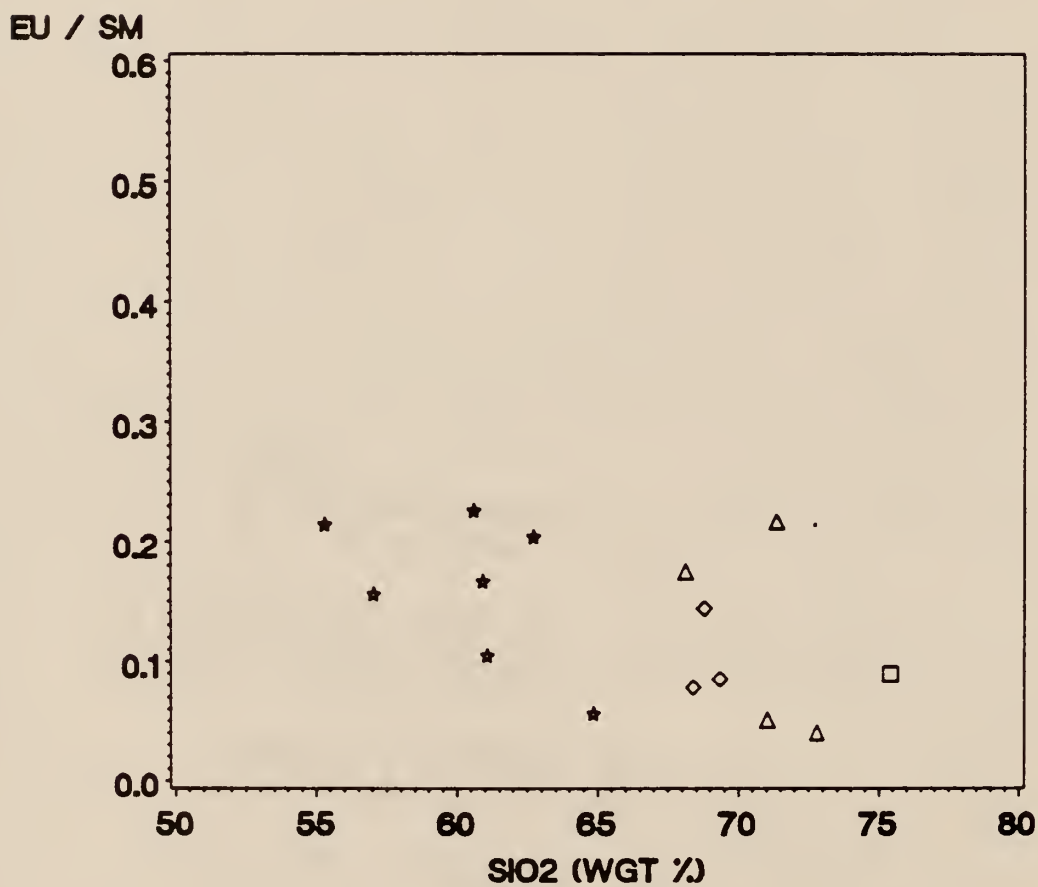
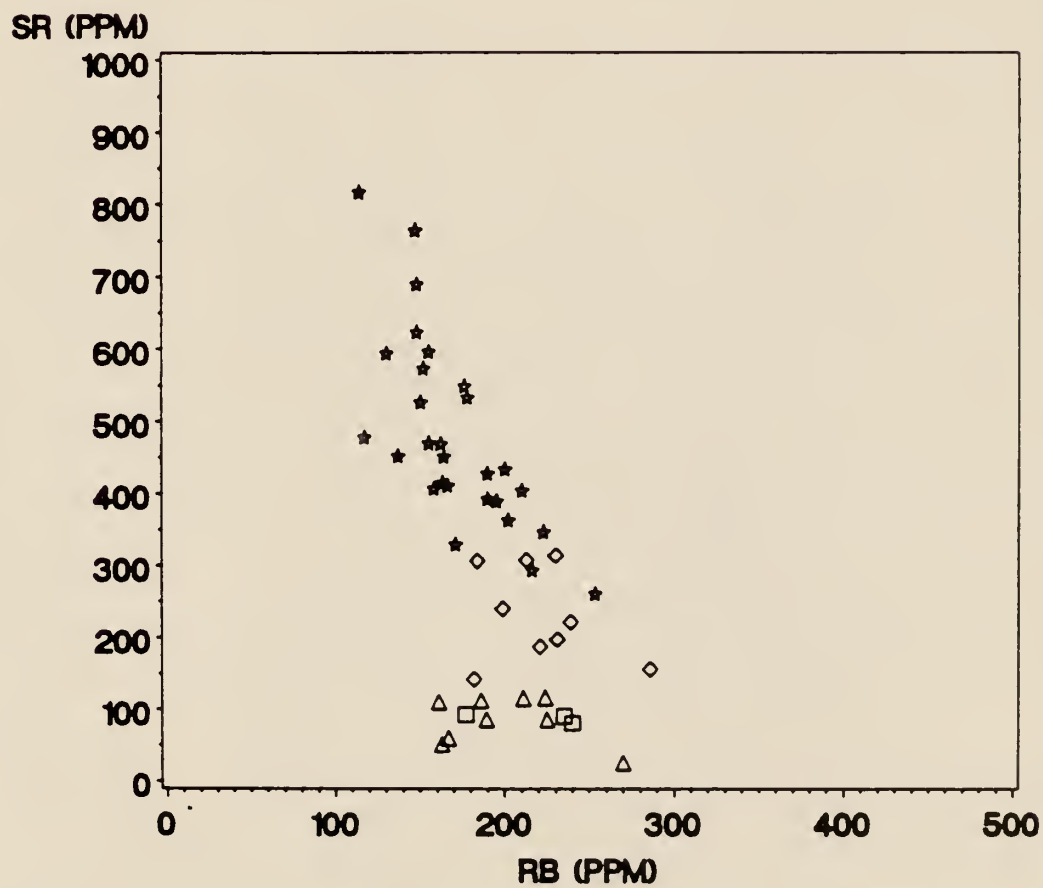


Figure 17: Sr vs Rb for Oak Creek area plutonic rocks



the porphyritic facies. A Sr gap separates the above two facies with the coarse-grained leucogranites and alaskites which plot in a field that is lower in Sr and a slightly lower in Rb concentration.

DISCUSSION

Introduction

The porphyritic facies of the Oak Creek batholith is coeval in space and time with the widespread anorogenic magmatism of the mid-continent 1.4 - 1.5 b.y. in age. Anderson (1983) describes a 600-1000 km wide belt extending from Labrador to California as the location of 70 percent of this igneous activity. If the rocks of the Oak Creek area are truly anorogenic in nature, similarities should be present when compared to these anorogenic plutons.

Anorogenic granites (A-type) are compared to I-type and S-type granites worldwide in Table 7. Source rock and tectonic setting have been used to classify granitic rocks (Ishahara, 1977; White and Chappell, 1977; Hine et al., 1978; Taylor, 1980; Collins et al., 1982; Didier et al., 1982; White and Chappell, 1983). A-type granites represent either non-compressional or tensional tectonic environments. I-type granites form from melting of metigneous sources during orogenic events while S-type result from melting of metapelitic sources.

The associated larger bodies of leucogranite in the Oak Creek area could be related to the porphyritic facies as a differentiate or formed by melting from a similar source at about the same time since they both have colinear chemical variation trends, and spacial occurrence (occasionally

Table 7: Comparison of A, S, and I-type granites (from Griffin, 1987)

A-type	I-type	S-type
abundant K-spar, K-spar megacrystic, K-spar usually perthitic, interstitial mafics, biotite crystallizes late and occasionally contains thin strips of fluorite, microscopic intergrowths between feldspars are very common, accessory apatite	oligoclase-andesine, biotite and sphene common, hornblende common in more mafic rocks, may have pyroxene, epidote, and allanite, opaques: magnetite ± ilmenite ± pyrite, muscovite rare, accessory apatite in minute inclusions	cordierite, garnet, biotite common; muscovite in felsic varieties, allanite inclu- sions may be present, accessory monazite, feldspar is commonly white, opaques: ilmenite ± pyrrhotite ± graphite, no hornblende, apatite in sparse grains
Na ₂ O + K ₂ O high (higher than I-type), metalumino-peraluminous- some peralkaline, high FeO/FeO+MgO, high Ca/Al, high Nb,Ta,Zr,Y, and REE's, high F in metaluminous- peraluminous varieties, high Cl in peralkaline rocks, SiO ₂ : generally high (commonly near 77%), low CaO and MgO, low Co,Sc,Cr, and Ni, Zr: 300-340 ppm, biotite has high Fe/Mg	Na ₂ O greater than 3.2%, weakly peraluminous-metalum- inous (Shand Index less than 1.1), low FeO/FeO+MgO, high TiO ₂ , high MgO and CaO, (CaO greater than 3.7% at 66% SiO ₂), SiO ₂ : low (53-76%), high Co,Sc,Cr, and Ni, Zr: less than 150 ppm, biotite has low Fe/Mg, normative corundum less than 1%	Na ₂ O less than 3.2%, peraluminous (Shand Index greater than 1.5), CaO less than 3.7% at 66% SiO ₂ , SiO ₂ : 63-76%, Zr: ² greater than 150 ppm, alumina oversaturated, normative corundum greater than 1%
anorogenic	orogenic	orogenic or anorogenic
anhydrous melt, few pegmatites, xenoliths uncommon, usually not associated in space and time with inter- mediate rocks	hydrous melt, pegmatites common, xenoliths are hornblende and mafic rich, usually associated in space and time with intermediate rocks	hydrous melt, pegmatites common, xenoliths of shale and sandstone common, association with intermediate rocks varies depending on tectonic setting
initial ⁸⁷ Sr/ ⁸⁶ Sr : .703- .712, low-moderate O ₂ fugacity	initial ⁸⁷ Sr/ ⁸⁶ Sr less than .706, higher O ₂ fugacity than S-type	initial ⁸⁷ Sr/ ⁸⁶ Sr greater than .706, low O ₂ fugacity due to interaction with C- bearing pelitic rocks

* Compiled from the following sources: Ishahara (1977), White and Chappell (1977), Hine et al. (1978), Taylor (1980), Collins et al. (1982), and White and Chappell (1983).

grading from one to the other). In addition, the same major mineral phases and accessories occur in both facies. The medium-grained leucogranites, however, are lower in biotite and accessory mineral content and contain more quartz than the porphyritic facies. If the leucogranites are of the same age as the porphyry (1.44 Ga), anorogenic characteristics should be imposed on both.

The medium-grained leucogranites of Oak Creek are slightly peraluminous, and they have large silica, K_2O , Na_2O , and REE concentrations, large $FeO/FeO+MgO$ ratios and small MgO , CaO and Sr contents typical of A-type granites. The porphyritic rocks are metaluminous to slightly peraluminous, have smaller SiO_2 concentrations, and larger CaO , MgO , and TiO_2 contents which are more similar to I-type granites. Also the porphyritic rocks contain an abundance of hornblende-rich xenoliths. The presence of muscovite, normative corundum, and the absence of hornblende, is consistent with some S-type component in the source.

The mean values from 30 anorogenic granitoids of the 1.4 - 1.5 b.y. event (Anderson, 1983) are in Table 8. The medium-grained leucogranites of Oak Creek (Table 3) appear to be more similar in composition to typical Silver Plume age anorogenic rocks than do the porphyritic facies rocks of Oak Creek. If the somewhat limited chemical variation of anorogenic granite-rhyolite terrane of the Mid-continent is

Table B: Range of average values (wgt %) for Proterozoic A-type granites of the midcontinent (Anderson, 1983)

Range of average values for 30 A-type plutons		Means (n = 30)
SiO ₂	64.9 - 76.6	71.7
Al ₂ O ₃	11.9 - 16.3	13.7
TiO ₂	0.05 - 1.20	0.4
FeO	0.8 - 6.1	2.9
MgO	0.1 - 1.6	0.5
CaO	0.4 - 3.0	1.4
Na ₂ O	2.2 - 4.2	3.3
K ₂ O	3.4 - 5.9	4.9
MnO	0.01 - 0.13	0.06
Rb*	95 - 339	197
Sr*	10 - 320	135
Ba*	183 - 1627	842

* ppm

a result of melting of similar tonalite/granodiorite crustal source rocks (Anderson, 1983; Anderson and Cullers, 1978), then the porphyritic facies may represent consequences of depth of emplacement and/or magma evolution processes that are not generally dominate in the formation of A-type granites studied in this region. The following discussion will focus on identifying intensive parameters, tectonic setting, and possible petrogenic models that might help explain the chemical characteristics (e.g., high trace element concentrations) of the Oak Creek batholith.

Tectonic Setting

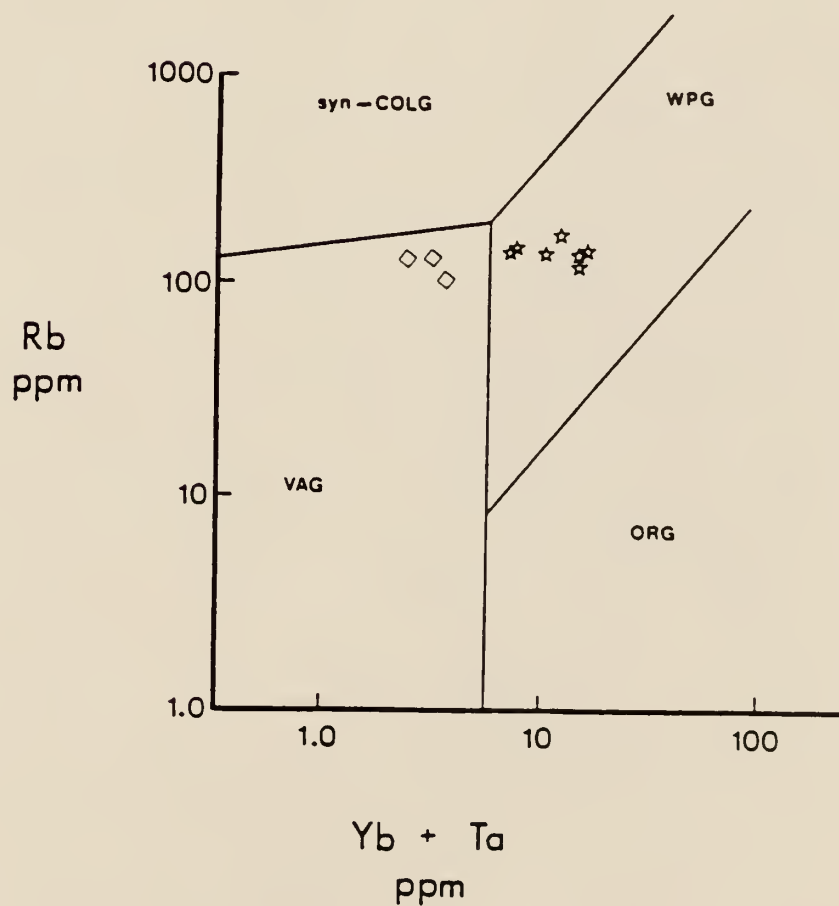
Pearce et al. (1984) used Rb, Yb, and Ta concentrations to differentiate tectonic settings of granites. Four groups are represented in the discrimination diagram in Figure 18:

- 1) ocean ridge granites (ORG)
- 2) volcanic arc granites (VAG)
- 3) within plate granites (WPG)
- 4) collision granites (Syn-COLG)

Oak Creek porphyritic samples plot in the WPG field.

Granites that belong to this group are considered to be anorogenic (A-type granites). The medium-grained leucogranites plot outside the WPG field. The more differentiated members of some suites have lower concentrations of Yb and Ta allegedly resulting from volatile complexing of these elements in late stage-fluids (Pearce et al., 1984).

Figure 18: Rb vs Yb + Ta discrimination diagram for syn-collision (syn-COLG), volcanic arc (VAG), within-plate (WPG), and normal and anomalous ocean ridge (ORG) granitic rocks



Intensive Parameters

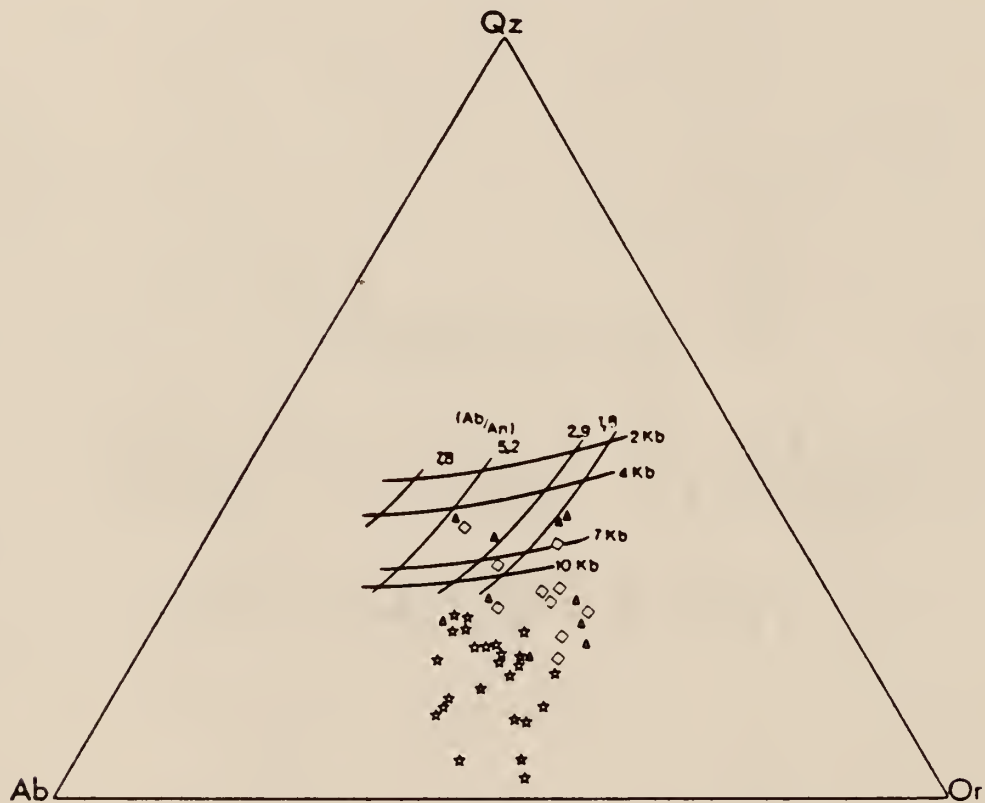
Buddington (1959) defined depth of emplacement criteria based on field relationships (Table 9). The Oak Creek batholith is probably a mesozonal-catazonal pluton by the following evidence: 1) regional metamorphism to amphibolite facies; 2) no volcanics or miarolitic cavities; 3) absence of chill zones in batholith; 4) foliation best developed as borders are approached; 5) concordant to subconcordant with country rocks generally having sharp contacts; 6) migmatites and pegmatites common, and 7) generally, coarse-grained rocks. Mesozonal-catazonal emplacement suggests depths of 10-15 km, temperatures 400-700 °C, and pressures greater than 3 Kb (Buddington, 1959).

Crystallization pressures in excess of 7 Kb are suggested by normative quartz-albite-orthoclase compositions (Figure 19). These predicted pressures are from water-saturated experimental systems and may be higher than those actually incurred if the melt was anhydrous (Steiner et al., 1975) or if the rock samples are not representing minimum melt compositions (Anderson and Cullers, 1978). The abundance of pegmatites throughout the Oak Creek batholith, some early biotite, and the absence of fluorite do suggest hydrous conditions. Nevertheless, less than water-saturated conditions (1.5-2.5% water in melt) are suggested by the presence of late, interstitial biotite simultaneously

Table 9: Buddington criteria for depth of emplacement.

Epizone	0 - 4 mi. (250 - 300° C)	<ul style="list-style-type: none"> -Related volcanic rocks common -No planar foliation except near borders -Miarolitic cavities common -Late stage aphanitic, porphyritic and lamprophyre dikes are common -Distinct pegmatite dikes are rare -[±] chilled borders -Sharp contact with country rocks
<hr/>		
Mesozone	4 - 8 mi. (300 - 500° C)	<ul style="list-style-type: none"> -Planar foliation [±] lineation often well developed, generally parallel contact -Pegmatites and aplites common -Sharp-gradtional contact with country rocks -Discordant to concordant contacts -Crumpling of bedding or dikes adjacent to pluton -Regional metamorphism to greenschist facies -No related volcanic rocks
<hr/>		
Catazone	8 - 12 mi. (500 - 700° C)	<ul style="list-style-type: none"> -Foliation well developed -Migmatites common -Regional metamorphism to amphibolite or granulite facies in country rocks -No associated volcanic rocks -May crosscut the structural trends of more rigid members -Consists of domes, lens-shaped intrusions emplaced in folded rocks, and sheets

Figure 19: Normative Quartz-Albite-Orthoclase diagram for rocks of the Oak Creek batholith



LEGEND

- ☆ Porphyritic facies
- ◇ Medium-grained leucogranite
- ▲ Alaskite
- Coarse-grained leucogranite

crystallizing with late quartz (White and Chappell, 1977; Collins et al., 1982; Maaloe and Wyllie, 1975; Wyllie et al., 1976).

Temperature estimates at the time of emplacement can be approximated by the presence of primary muscovite which is unstable at temperatures greater than 725 °C at about 5 Kb pressure (Barth, 1969). Also, the occurrence of microcline containing approximately 30% perthite coexisting with plagioclase (An₂₅₋₃₅) suggests temperatures of 600-700 °C (Barth, 1951). Field relations, normative Ab-Or-Qtz compositions and sequence of crystallization indicate conditions at time of emplacement were about 600-725 °C, 5-7 Kb, and water contents of approximately 1.5-2.5%.

Petrogenesis

Introduction

The source material that melted to form the parent magma and the processes that occurred during emplacement and crystallization of the melt must be considered when studying the origin of silicic plutonic rocks in anorogenic settings. Depaolo (1981) and Nelson and Depaolo (1982), based on Nd isotopes, concluded that anorogenic granites from the midcontinent are derived from heterogeneous, 1.8 Ga old Proterozoic crust. Barker et al., (1975) and Fountain et al., (1981) proposed that potassic granites of the Colorado Front Range formed by melting of mainly granodiorite to granitic crust. In addition, syenitic liquids, produced from melting quartz-poor, granulitic lower crust, may have mixed with the K-granites to form the entire compositional range of magmas (Barker et al., 1975). Anderson and Cullers (1978), Anderson et al., (1980) and Cullers et al., (1981) predicted melt compositions of these K-granites from Wisconsin and Missouri that matched observed compositions by 10 to 30 percent melting of a quartz diorite to granodiorite crustal source. This predicted source represents the synorogenic, calc-alkaline metaigneous rocks that comprise much of the Proterozoic host terrains for these plutons (Anderson, 1983).

This study will evaluate the above possibilities for generating the granodioritic to granitic rocks of the Oak Creek batholith. Trace element modeling will be used to constrain the composition of a possible parent magma, possible source rocks that could melt to produce this magma, and processes that may be responsible for the formation of the more differentiated leucogranites.

The following processes will be modeled for the generation of a magma of the Oak Creek batholith:

- 1) Fractional crystallization/partial melting of primary magmas
- 2) Partial melting of lower crustal rocks
- 3) Restite unmixing (melt and residual material)
- 4) Assimilation of crustal material during ascent and emplacement
- 5) Fractional crystallization - variable unmixing of cumulate and residual liquid

Constraints

A common assumption is that the most primitive rocks of a magma series are representative of the original composition of a melt from which the remaining rocks may be derived by differentiation. A source would need the following characteristics to produce rocks of the porphyritic facies:

- 1) It must be quartz-bearing or at least quartz normative (Wyllie et al., 1976).
- 2) It must have a K-rich phase that completely melts to account for the high Ba and K (Cullers and Graf 1984).
- 3) Moderate to high Sr contents in Oak Creek rocks suggest a high Sr source and the necessity for melting of most of the plagioclase in the source although Eu anomalies suggest the presence of some residual feldspar.
- 4) The source must have high REE with little or no residual garnet (Cullers and Graf, 1984) to produce high REE with moderate LREE/HREE ratios.

Fractional Crystallization/Partial Melting of Primary Magma

Fractionation of a basaltic (or gabbroic) liquid to produce granitic rocks was first proposed by Bowen (1928) in which a continuous series of liquids are generated by the removal of early crystallized material. Granodioritic to granitic liquids can be produced by fractionation of a basaltic magma (Arth et al., 1978). However, Anderson and Cullers (1987) demonstrated that fractional crystallization of feldspars and a mafic mineral from a basaltic magma, to form granitic liquids, would deplete the residual liquids with respect to Sr and Sc. Sr values in the melt above 306 ppm and Sc values above 16 ppm are unattainable by typical modeling techniques. Undifferentiated Oak Creek rocks have

Sr and Sc values as high as 815 ppm and 25 ppm respectively. Extremely small degrees of partial melting of basalt (or gabbro) to produce the Oak Creek rocks is also unlikely for the same reasons (Anderson and Cullers, 1987). Also, an extremely large volume of basaltic magma would be necessary to produce a granitic batholith the size of Oak Creek. A few gabbroic intrusions occur in the Wet Mountains but none were found in the Oak Creek area.

Partial Melting of Lower Crustal Rocks

Melting models for the origin of 1.4 - 1.5 Ga old anorogenic granites, based on previous studies of the Midcontinent (e.g., Barker et al., 1975; Fountain et al., 1981; Anderson and Cullers, 1978, Anderson et al., 1980), suggest source rocks with crustal ages of about 1.7 - 1.9 Ga that approximate tonalite/granodiorite/quartz-diorite compositions and contain little or no Eu anomaly. These source rocks also might melt to produce the rocks at Oak Creek. Calc-alkaline, metaigneous rocks of granodioritic composition and approximately 1.7 Ga are abundant in the midcontinent, including the Wet Mountains of Colorado (Figure 2: Garell Peak, Royal Gorge and Twin Mountain). Ranges of trace element compositions for some of these 1.7 Ga old tonalite-granodiorite rocks of the Midcontinent are summarized in Table 10.

Mathematical melting models (Shaw, 1970) are used to match trace element compositions of the Oak Creek rocks with hypothetical melts derived from melting of the range of synorogenic tonalites to granodiorites. Reasonable assumptions can be made for mode, major and trace element compositions of the source, distribution coefficients (Table 11), the proportions of melting, and the type of melting model. Aggregate (batch) melting is used in this modeling exercise. The trace elements Ba, Rb, and Sr occur

Table 10: Elemental concentrations (ppm) of selected
1.7 Ga old granitoids of the Wet Mountains

	Wet Mountains			Other 1.7 Ga granitoids in the Midcontinent
	Garell Peak	Twin Mountain	Royal Gorge	
Rb	110 - 358	108 - 417	154 - 225	50 - 200
Sr	27 - 200	66 - 339	114 - 141	300 - 940
Ba	401 - 875	287 - 2300	806 - 1225	900 - 2000
La	.05 - 153	39 - 446	105 - 467	-----
Ce	5.3 - 324	124 - 222	167 - 297	42 - 76
Sm	1.4 - 39	11 - 16.9	14.9 - 24.9	3 - 8
Eu	.03 - 2.74	1.7 - 3.3	2.37 - 4.25	1.0 - 2.7
Yb	3.0 - 25	2.64 - 6.06	2.73 - 6.65	1.1 - 3.4
Lu	.44 - 3.12	.46 - .8	.40 - .94	.2 - .6
Sc	.09 - 14	4.5 - 35.5	-----	1 - 43
Cr	8 - 30	19 - 51	-----	-----

Data is compiled from McCabe (1984), Cullers (1986), Cullers and Wobus (1985), and Anderson and Cullers (1978).

Table 11: Distribution coefficients for silicic melts used in trace element modeling

Element	Plag	K-spar	Qtz	Biot	Hbl	Sph	Mag	Zir	Ap	Gar
<hr/>										
Rb	.041	.37	.001	2.2	.014	---	---	---	---	.08
Sr	4.4	3.87	.001	.12	.022	---	---	---	---	.015
Ba	.31	6.1	.001	9.7	.044	---	---	---	---	.017
Ce	.27	.044	.001	.32	1.52	139	---	2.6	35	.35
Sm	.13	.018	.001	.26	7.77	70	---	3.1	63	2.7
Eu	2.2	1.13	.001	.24	8.9	61	---	8	60	6.5
Yb	.049	.012	.001	.44	8.4	---	---	270	24	40
Lu	.046	.006	.001	.33	5.5	21	---	323	20	42
Sc	.02	.06	.001	11	15	---	2	---	.3	13.6
Cr	.06	.01	.001	12	2	---	7	---	.2	3.7

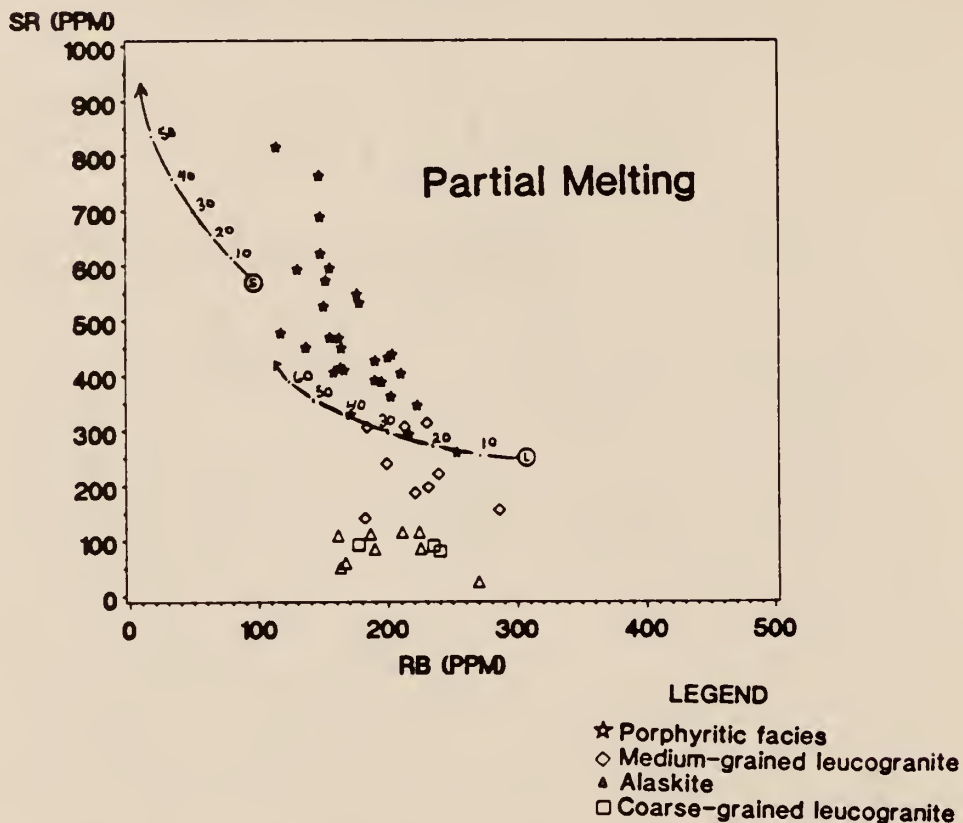
Distribution coefficients compiled from: Berlin and Henderson (1969), Ewart and Taylor (1969), Griffin and Murthy (1969), Higuichi and Nagasawa (1969), Schnetzler and Philpotts (1970), Tanaka and Nishizawa (1975), Arth and Barker (1976), Condie and Hunter (1976), and Cullers and Graf (1984).

exclusively in the major silicate phases of granitic systems rather than in the accessory phases, REE concentrate primarily in accessories, and Sc generally reflects mafic mineral trends (Table 10).

Model curves which could account for trace element trends are superimposed on plots of Sr, Ba, Rb, Sc and REE data from the Oak Creek batholith (Figures 20 and 21). The curves predicted by the model reflect the distribution of the various trace elements between residual solid and the melt during partial melting of the source rock. The circles (O) on the plots indicate the predicted concentration in the residual solid (S) and the liquid (L) at 1.0% melting. The respective lines demonstrate the change in residual solid and melt compositions and are noted at 10% intervals of melting. Predicted REE concentrations also are illustrated on chondrite normalized plots (Figure 22) for Eu anomaly comparisons.

Compositions of the least differentiated portions of the medium-grained leucogranites can be approximated by 20 to 30 percent aggregate melting of a tonalite-granodiorite with an initial mode of plag/K-spar/qtz/biot/hbl/sph/zir/mag/ap = .42/.08/.238/.14/.10/.01/.001/.01/.001, and a melting ratio of .30/.30/.16/.16/0.0/.05/.01/.01/.01 (Figures 20, 21, and 22a). At 30 percent melting most or all of the K-feldspar, sphene, zircon and apatite have gone

Figure 20: Partial melting models utilizing Sr vs Rb, Ba vs Rb, and Sc vs Rb



Source and melt ratios for partial melting model used in medium-grained leucogranite formation (Figures 20 and 21)

1		
Source mode	Original composition	Melting ratio
Plag = .42	Rb = 100	Plag = .30
K-spar = .08	Sr = 550	K-spar = .30
Qtz = .238	Ba = 2000	Qtz = .16
Biot = .14	Ce = 76	Biot = .16
Hbl = .10	Sm = 8	Hbl = 0
Mag = .01	Eu = 2.7	Mag = .01
Sph = .01	Yb = 3.4	Sph = .01
Zir = .001	Lu = 0.6	Zir = .01
Ap = .001	Sc = 25	Ap = .01

1 Tonalite/granodiorite (Anderson and Cullers, 1978)

Figure 20, continued

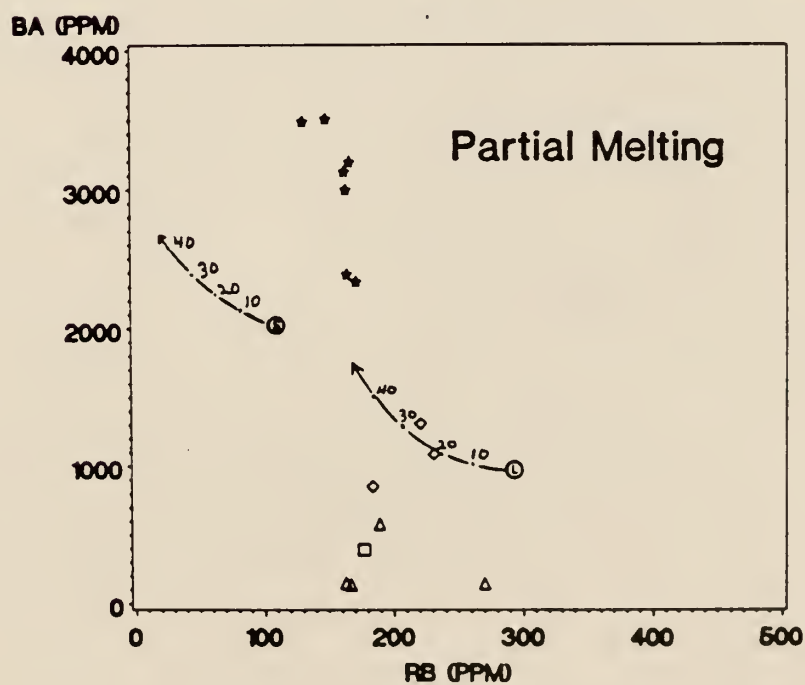
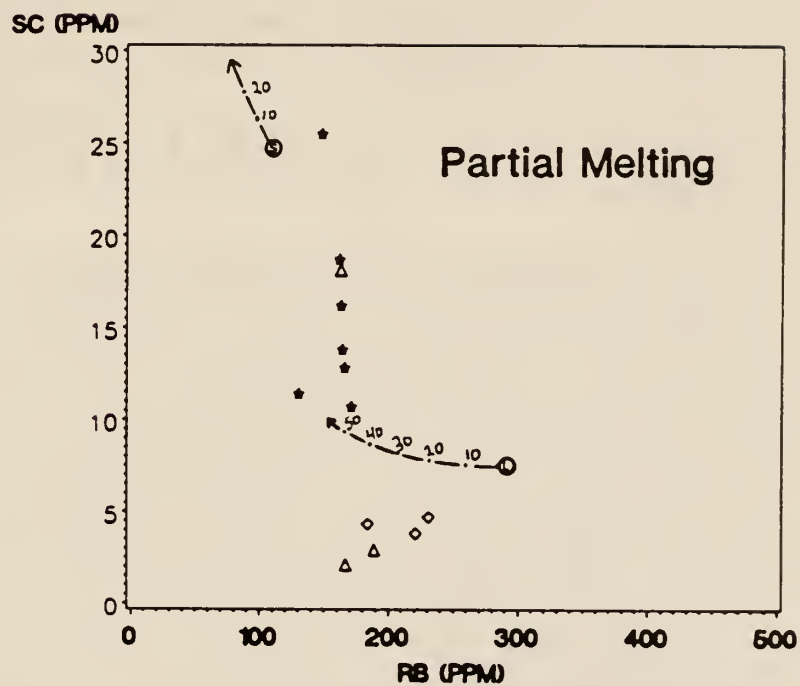


Figure 21. Partial melting models utilizing REE's vs Rb

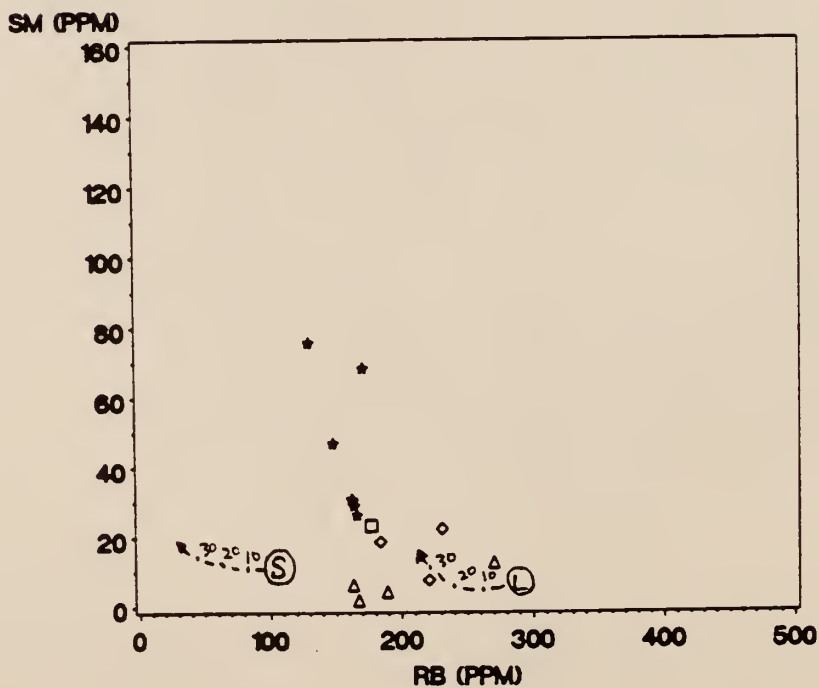
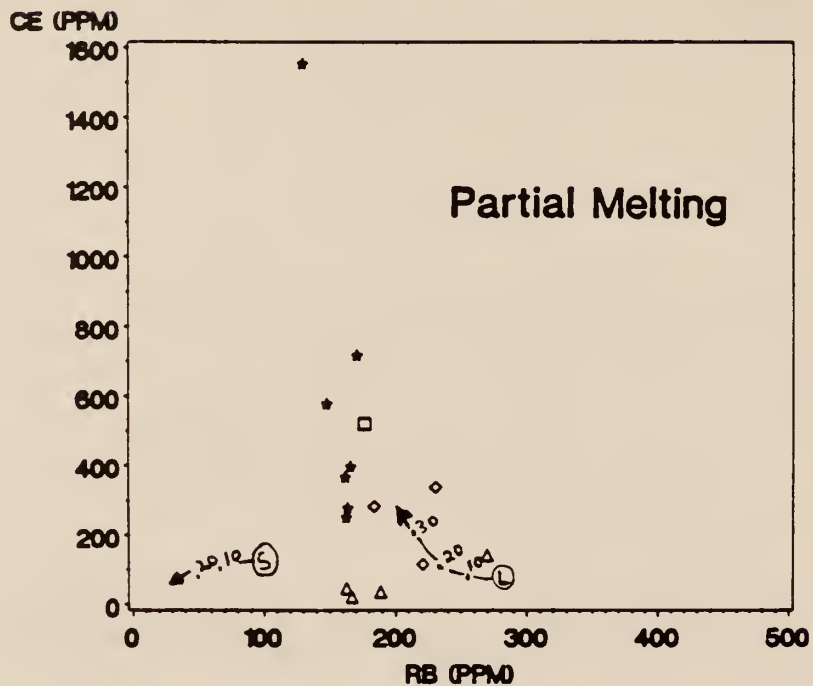


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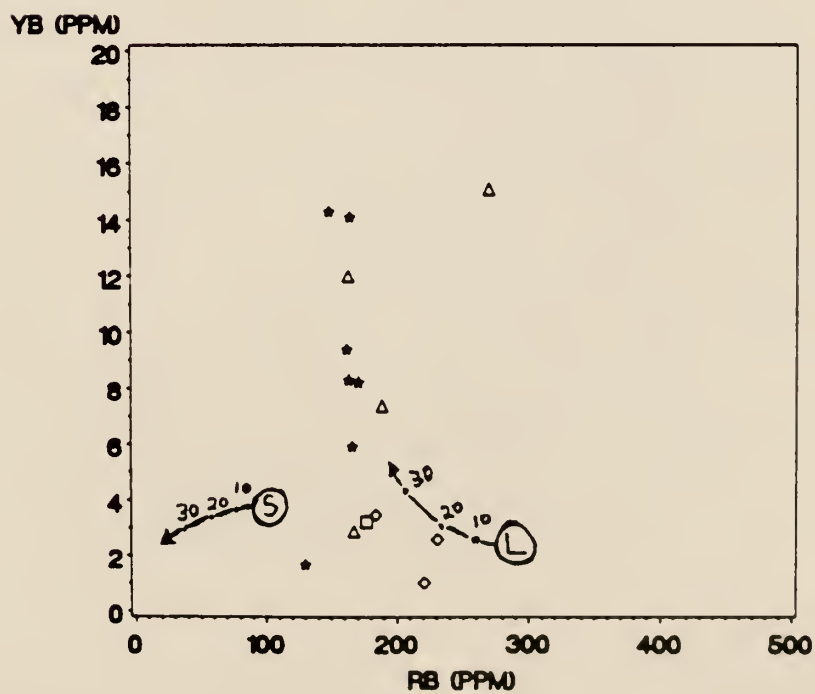
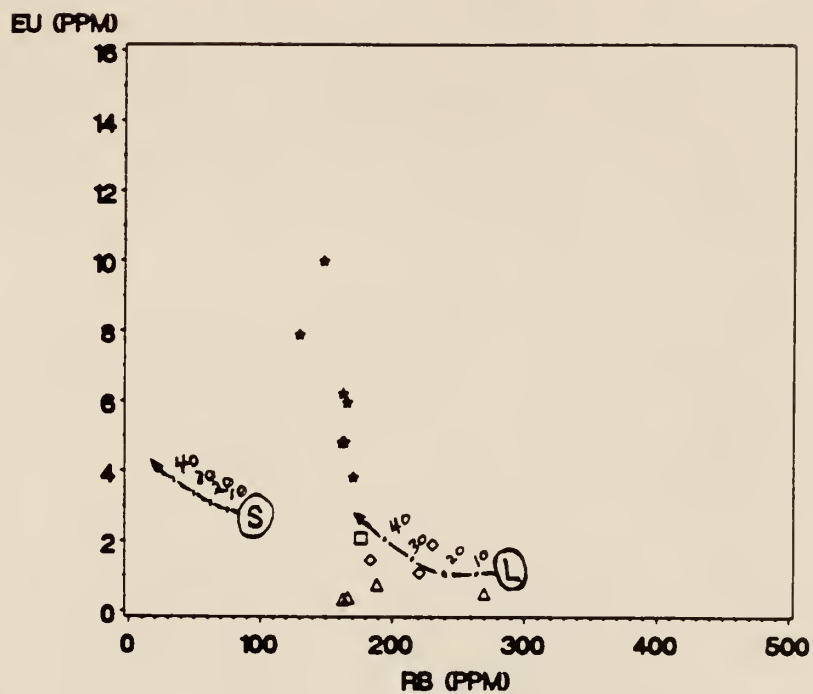
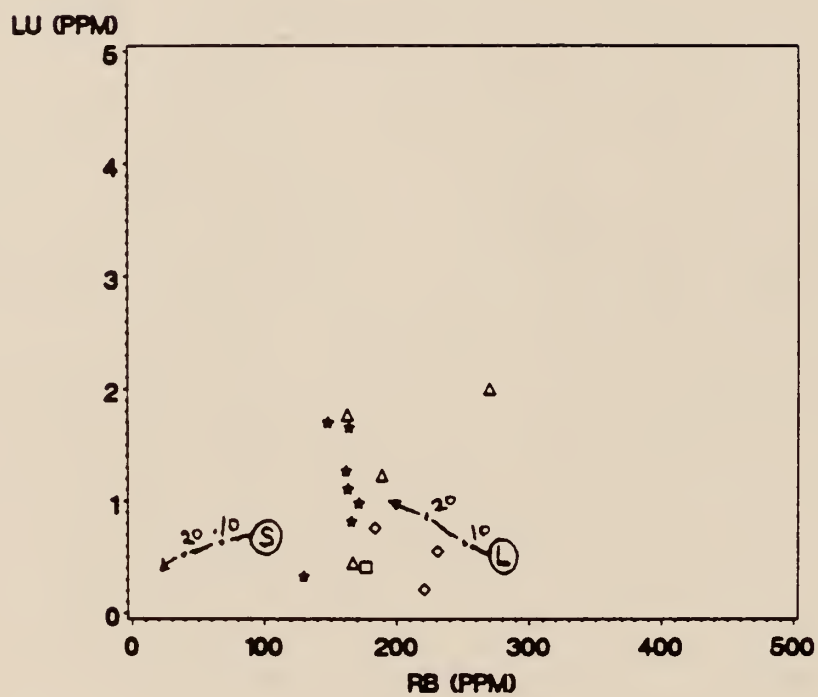


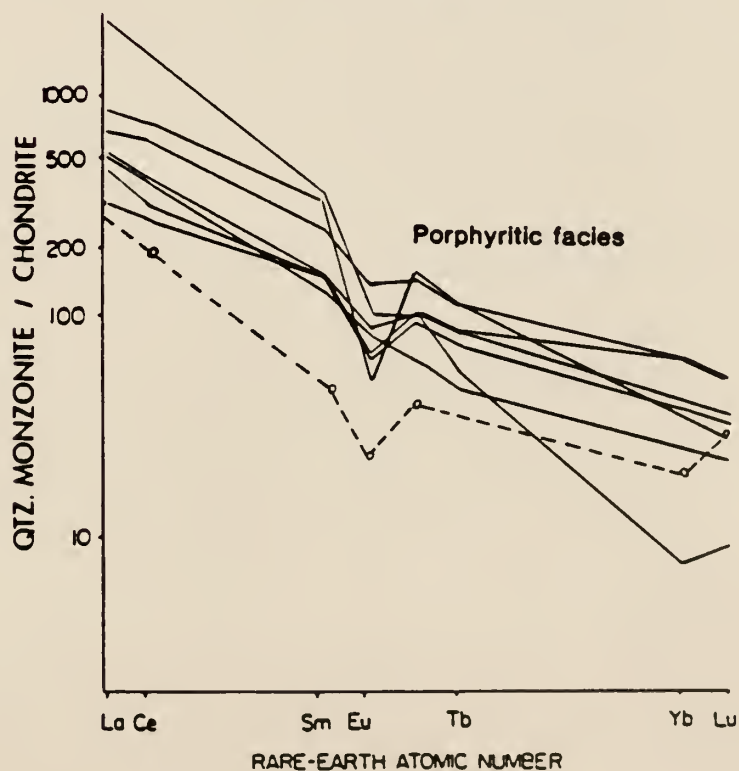
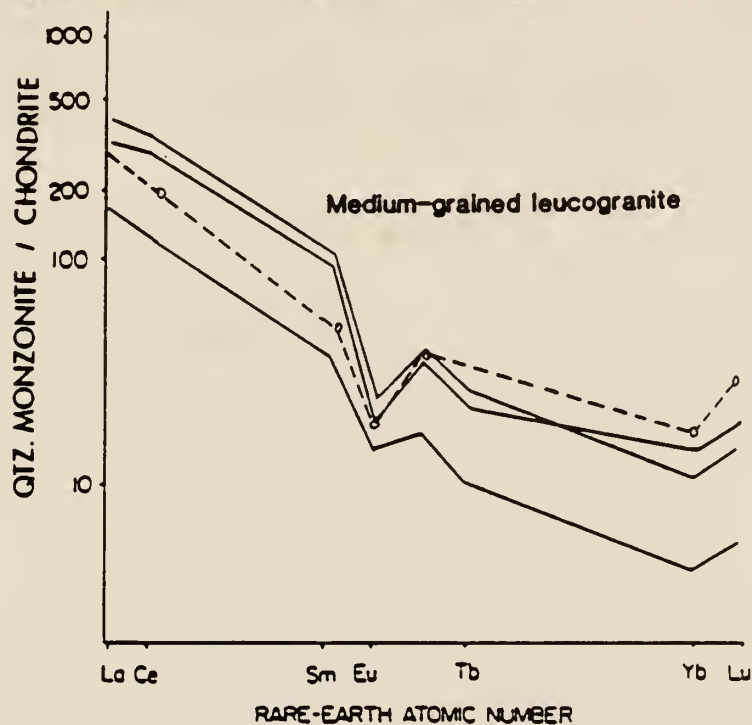
Figure 21, continued



LEGEND

- ★ Porphyritic facies
- ◇ Medium-grained leucogranite
- ▲ Alaskite
- Coarse-grained leucogranite

Figure 22: Chondrite normalized REE patterns for medium-grained leucogranites and porphyritic facies of Oak Creek batholith (solid lines). Predicted liquid at 30% partial melting of a tonalite/granodiorite (dashed lines).



into the melt.

Partial melting of typical tonalite-granodiorite with little or no Eu anomaly cannot reasonably produce liquids compatible with the large concentrations of Sr, Ba, Sc, or REE found in the porphyritic facies of the Oak Creek batholith (Figures 20, 21, and 22b). Enrichment of these elements could be caused by processes such as entrainment of restite during ascent of the melt, or accumulations of minerals during crystallization.

Restite Unmixing

A near minimum rhyodacitic melt generated by partial melting of intermediate source material might partially separate from restite (residual phases in equilibrium with the melt at depth) to produce compositional variation in granitoids (Chappell and White, 1977; Scambos et al, 1986). The range of compositions observed in the Oak Creek rocks might be attributed to variable separation of silica-rich minimum melt from more mafic residual phases. Restite unmixing should be represented by linear variation diagrams (Chappell and White, 1977).

The cumulate nature of the mafic glomerocrysts in the porphyritic facies, the abundance of mafic xenoliths throughout the pluton, and the linear appearance of variation diagrams suggest restite unmixing could be an important process that might produce compositions observed

in the least differentiated porphyritic rocks of Oak Creek. Also, accessory phases (sphen, zircon, and apatite) are typically included in early biotite grains of the mafic glomerocrysts. These accessory minerals tend to concentrate the REE. As restitic refractory phases, accessories might be partially responsible for the high REE concentrations. The leucogranites of the Oak Creek batholith could represent a silica-rich liquid that variably unmixes from restite. In this case, the composition of the porphyritic facies would plot in a linear fashion between the concentrations of the melt and residual solid material at 20 to 30% melting of tonalite/granodiorite. The model represented in Figure 20 demonstrates that a liquid (L) generated by 20 - 30% partial melting of a tonalite/granodiorite can have compositions of Sr, Ba, and Rb similar in composition to the medium-grained leucogranites and moderate to high Sr in the residuum (S). However, the predicted residuum is too depleted in Ba and Rb to represent the least differentiated (highest Ba and lowest Rb) porphyritic rocks in the Oak Creek batholith. Abundance of perthitic microcline phenocrysts in the porphyritic facies also suggests restite unmixing might be an insignificant process because microcline is less likely to be a refractory phase of the restite. Another more dominant process with or without minor restite unmixing more likely explain the trace element trends at Oak Creek.

Magma Mixing/Assimilation

The compositional variation of the porphyritic Oak Creek rocks might be explained by two magma mixing and assimilation models. Two end member mixing, like restite unmixing, can plot in linear variation diagrams (McBirney, 1980; Reid et al., 1983). Barker et al. (1975) suggested syenitic liquids mixed with granitic liquids and thus, explain the compositional range of the anorogenic potassic granites of the Pikes Peak batholith. Mixing of syenitic and granodioritic liquids might also explain the range of composition of quartz, alkali-feldspar, and plagioclase in the Oak Creek porphyritic rocks. Major and trace-element chemistry of syenites or monzonites is similar to that of the porphyritic facies (Table 12). However, mixing of granodioritic liquids with syenitic/monzonitic liquids fails to explain Ba values greater than 2600 ppm (Barker et al., 1975; Miller 1978). Oak Creek porphyritic rocks have Ba concentrations up to 3510 ppm.

Assimilation of mafic-rich country rock could also be responsible for generating the compositional variation found in Oak Creek rocks. Assimilation of felsic rocks could help give high K, Ba and Sr contents to the melt and contribute to the peraluminous chemistry. The following evidence for assimilation is present: 1) abundant rounded mafic xenoliths throughout the pluton, 2) mafic (biotite-rich)

Table 12: Major and trace element contents for selected syenites/monzonites (Miller, 1978)

Syenite / Monzonite

(wgt %)

SiO ₂	52.1 - 64.9
Al ₂ O ₃	17.0 - 19.7
TiO ₂	0.2 - 1.2
FeO	2.1 - 8.9
MgO	0.08 - 4.2
CaO	2.2 - 8.2
Na ₂ O	3.9 - 5.3
K ₂ O	2.5 - 5.6
MnO	0.09 - 0.15

(ppm)

Rb	65 - 170
Sr	1090 - 1500
Ba	1200 - 2600
La	19 - 56
Sm	2.5 - 8.1
Eu	0.63 - 2.3
Lu	0.17 - 0.31

schlieren up to 2 meters in length. Factors that suggest assimilation to be minimal are: 1) sharp contacts between the xenoliths and batholithic rocks, 2) abundant hornblende in many xenoliths while no hornblende is present in Oak Creek rocks, and 3) good correlations in variation diagrams that involve Sr and Ba.

Fractional Crystallization/Cumulate Unmixing

Fractional crystallization has long been recognized as a widely occurring mechanism in granitoid rocks that can explain compositional variations (Presnall and Bateman, 1973; Cox et al., 1980; Cullers and Graf, 1984; Robb, 1984). A cumulate association is suggested with segregations of feldspar phenocrysts and mafic minerals locally abundant (Figures 23 and 24). A problem is the lack of petrographic criteria as in many silicic rocks to estimate the amount of cumulate material vs. liquid (intercumulate material; Robb, 1984). Thus, in this section, trace element modeling is used to test the possible importance of fractional crystallization in the formation of the porphyritic facies, and the relation of the porphyritic facies to the medium-grained leucogranites.

The porphyritic rocks contain high Ba, Sr and REE concentrations. Fractional crystallization by itself is not

Figure 23: Isopleth map of total pherocryst content in the
Oak Creek batholith

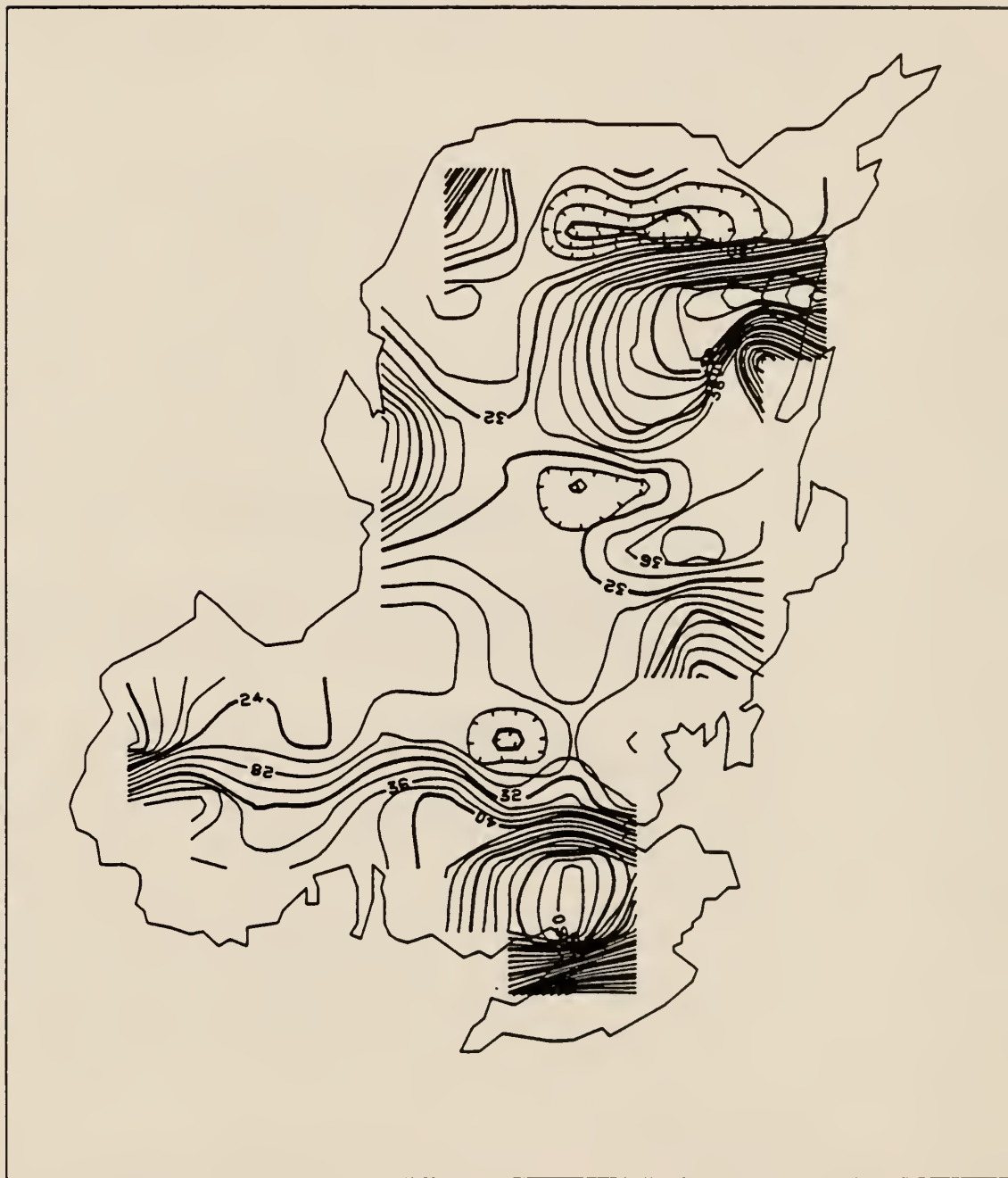
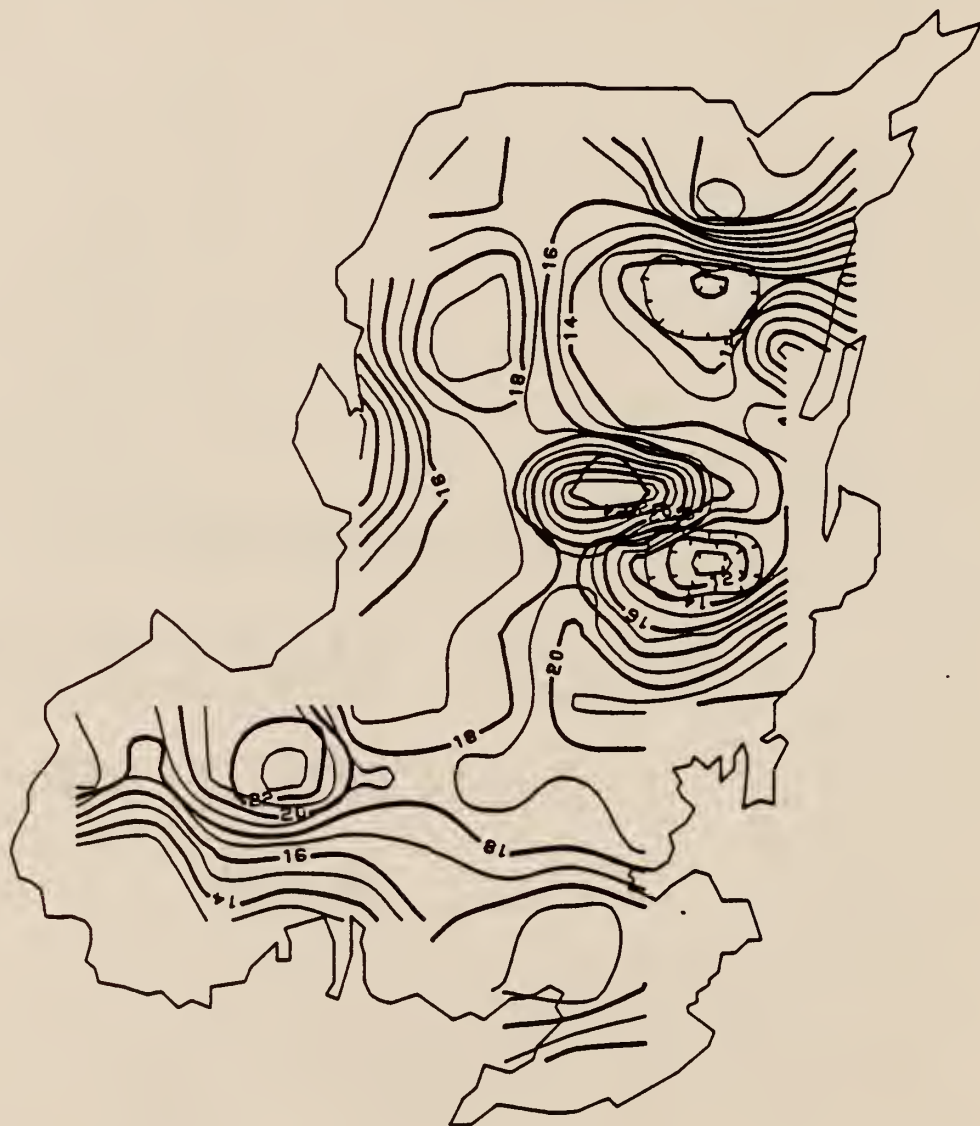


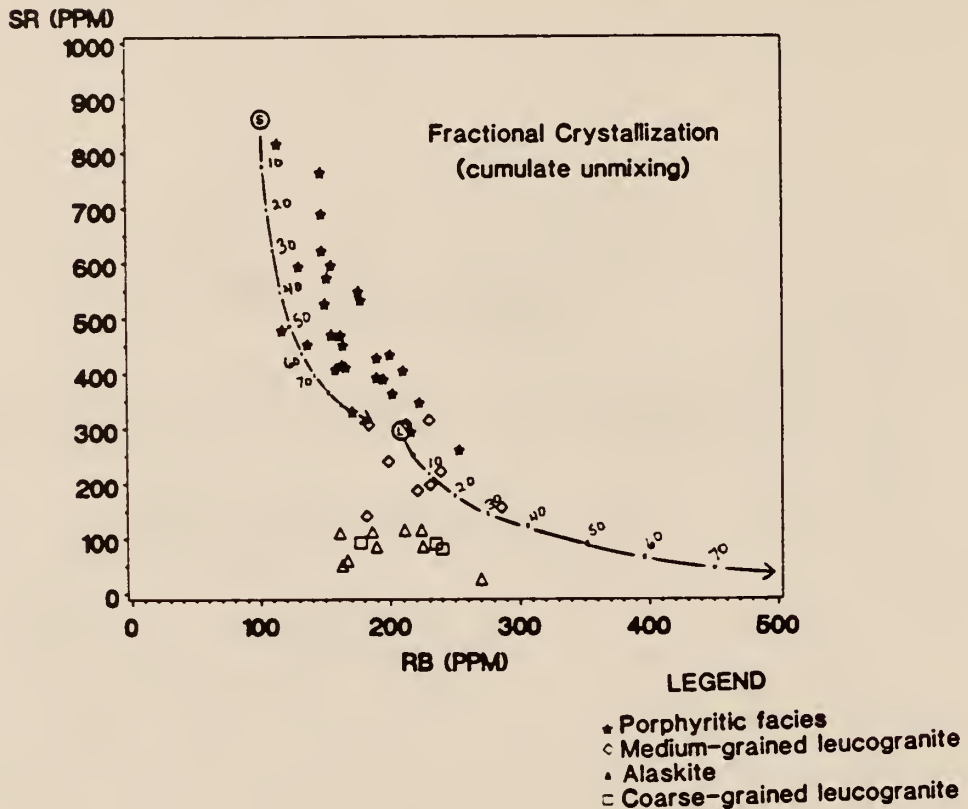
Figure 24: Isopleth map of total mafic mineral content in the Oak Creek batholith



a viable process to explain the compositional variation among Oak Creek rocks. Removal of early crystallized material depletes the remaining liquid, thus, requiring a parent liquid with unrealistically large concentrations of Ba, Sr and REE. This suggests that the porphyritic facies could have accumulated feldspars and biotite during fractional crystallization. The decrease in Sr, Ba and Al_2O_3 with increase in silica in the medium-grained leucogranites (Figures 9 and 15) are qualitatively consistent with depletions in the liquid due to alkali-feldspar and biotite crystallization. Accumulations of some of these minerals could account for the high concentrations Sr, Ba, and Sc observed in the porphyritic facies.

Again, model curves which attempt to account for trace element trends are superimposed on plots of Sr, Ba, Rb, Sc, Cr, and REE data from the Oak Creek batholith (Figures 25 - 27). In this model, curves reflect the distribution of the various trace elements between early-crystallized solids (cumulate) and the remaining melt during fractional crystallization of the parent melt. The circles (O) in Figures 25 and 26 indicate the predicted concentration in the cumulate solid (S) and the liquid (L) at 1.0% fractional crystallization. The respective lines demonstrate the change in solid and melt compositions and are recorded at 10% intervals of crystallization. Variable unmixing of cumulate and residual trapped liquid could explain the compositional range in the

Figure 25: Fractional crystallization/cumulate unmixing models for porphyritic facies utilizing Sr, Rb, Ba, Sc, and Cr



Parent liquid composition and crystallization mode for fractional crystallization model used in porphyritic facies formation (Figures 25 - 27)

Parent melt composition

Crystallizing mode

Rb = 210
Sr = 300
Ba = 1250
Ce = 200
Sm = 20
Eu = 2.0
Yb = 4.5
Lu = 0.5
Sc = 5
Cr = 17

Plag = .44
K-spar = .21
Qtz = .13
Biot = .18
Hbl = 0
Mag = .04
Sph = .001
Zir = .002
Ap = .002

Figure 25, continued

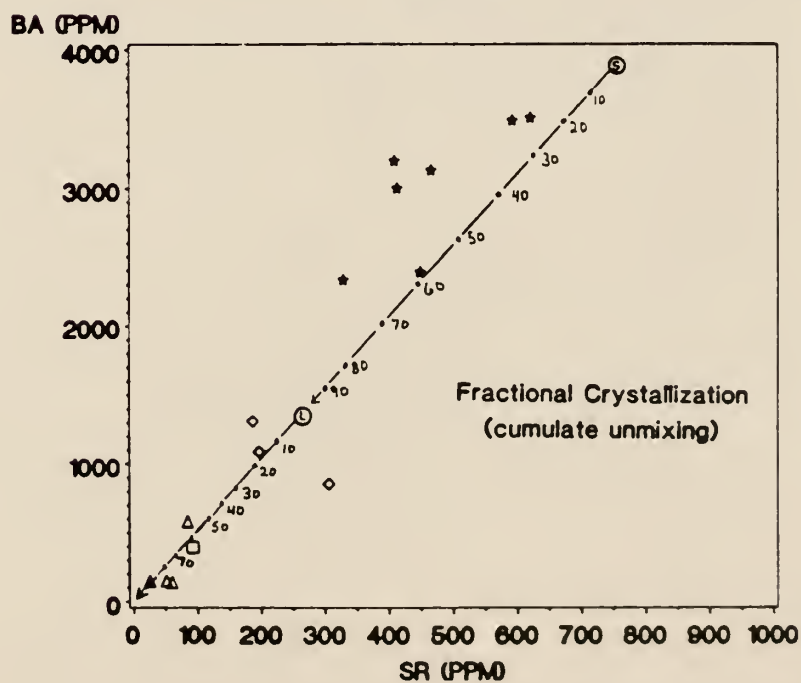
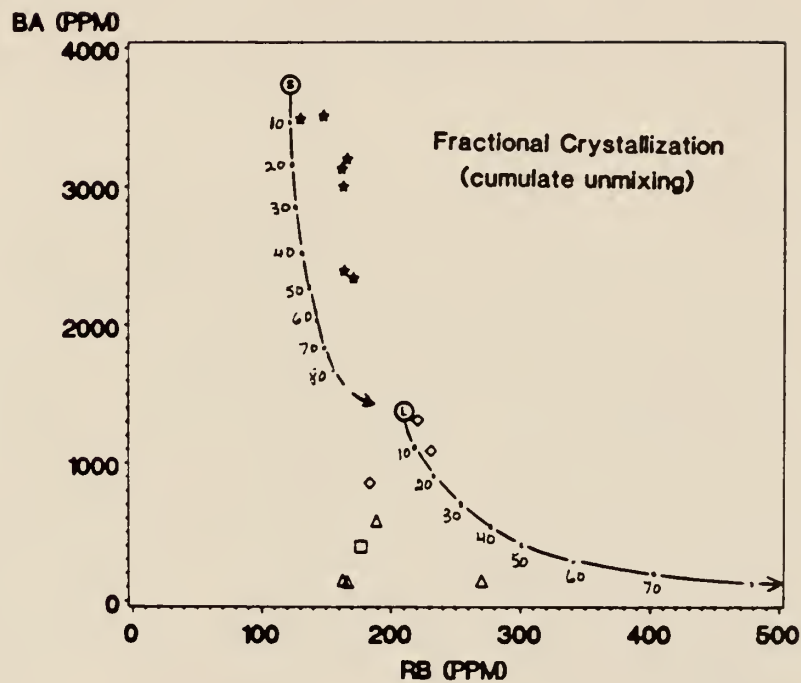


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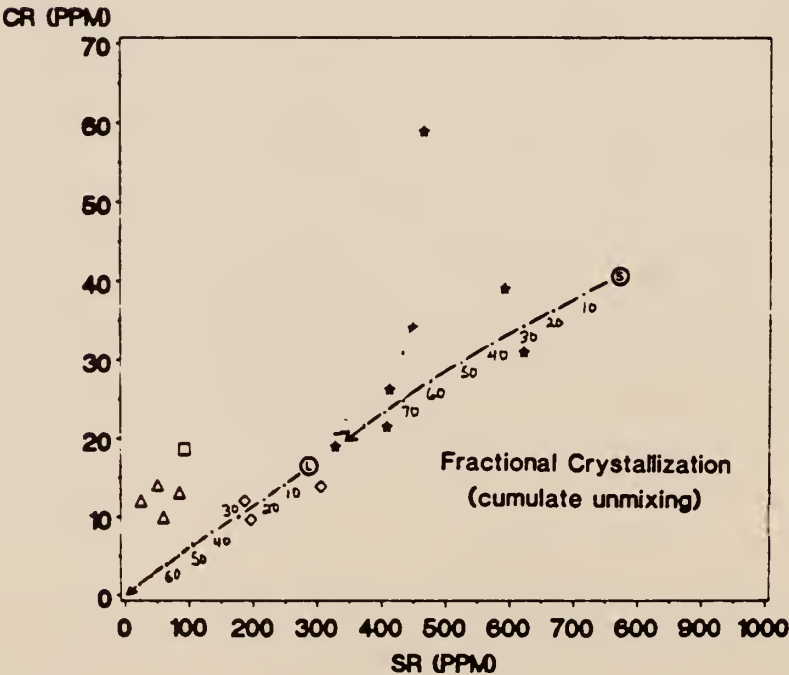
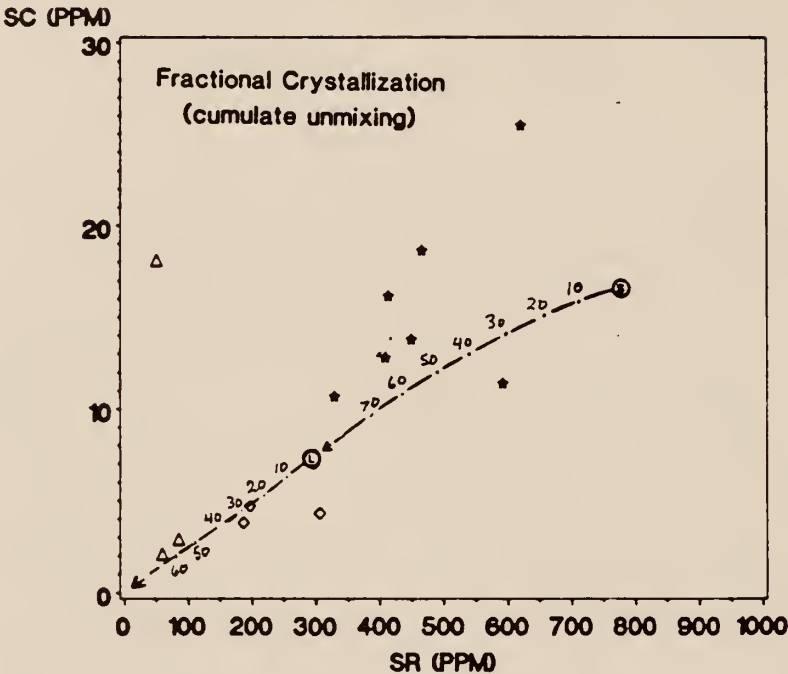


Figure 26: Fractional crystallization/cumulate unmixing models for porphyritic facies utilizing REE

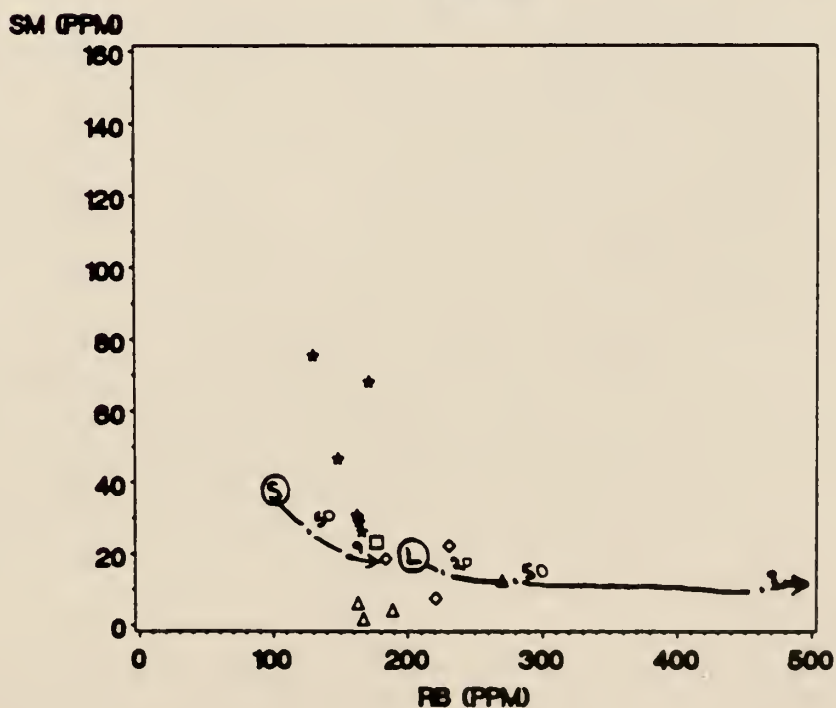
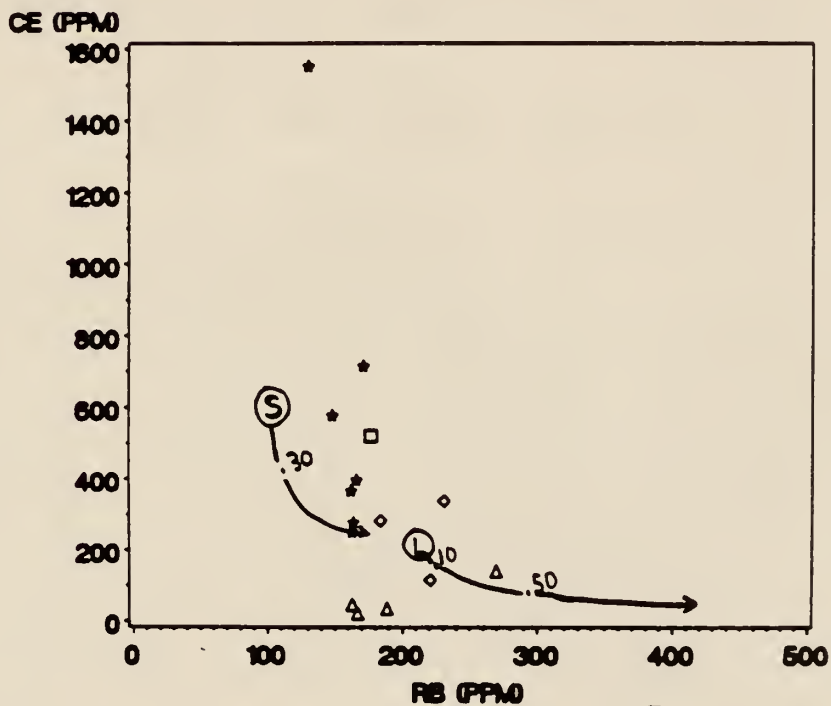


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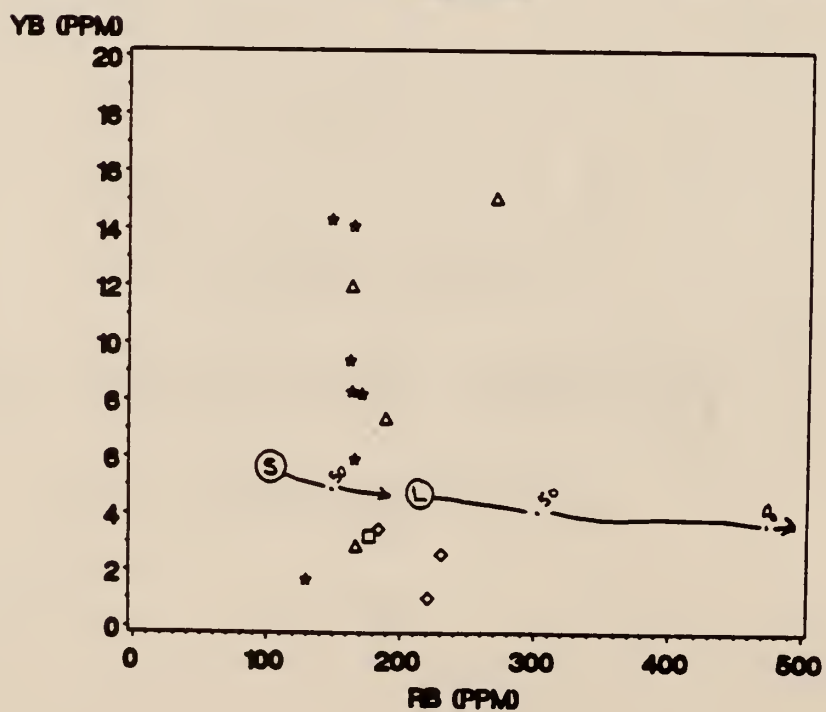
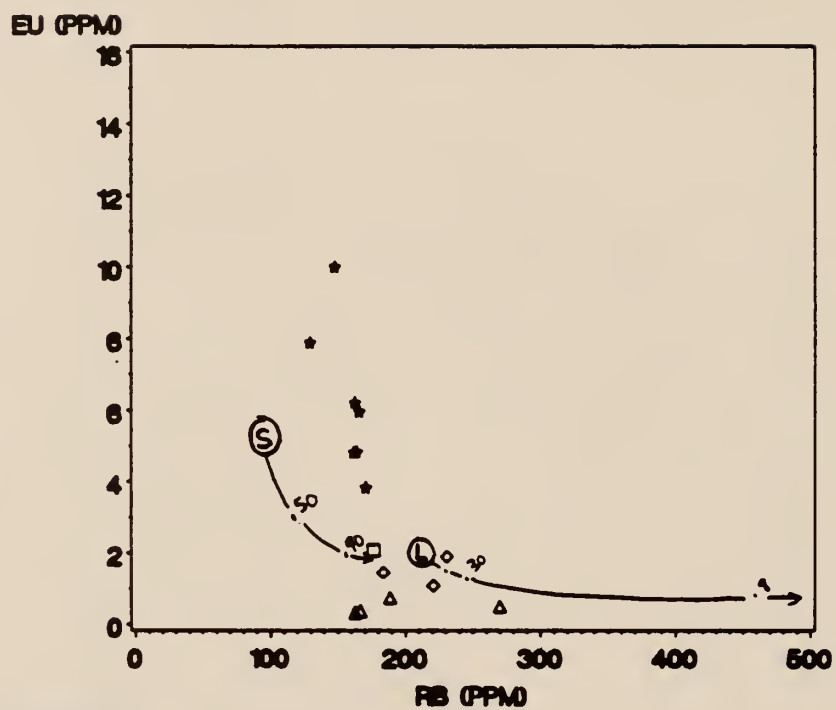


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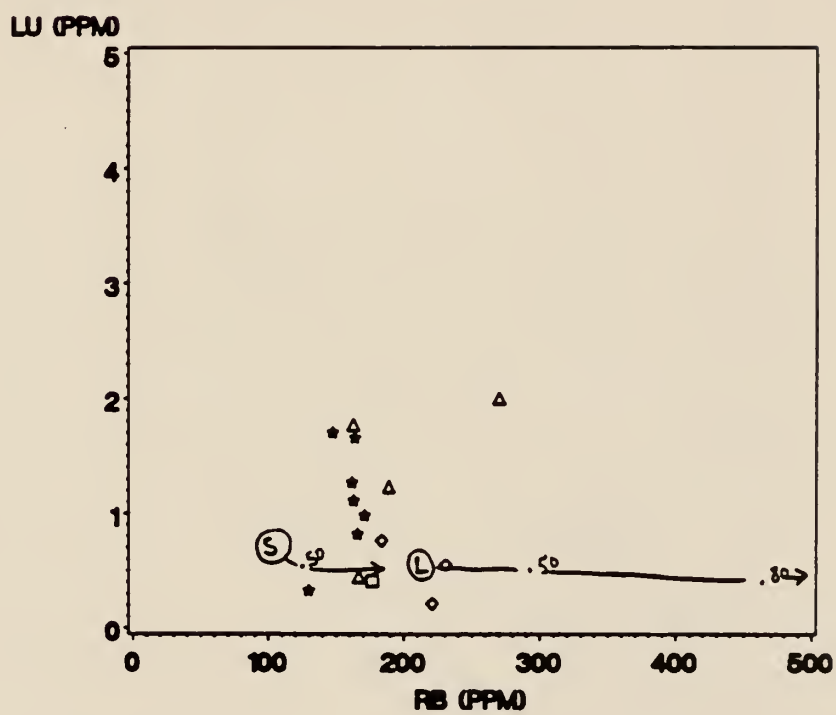
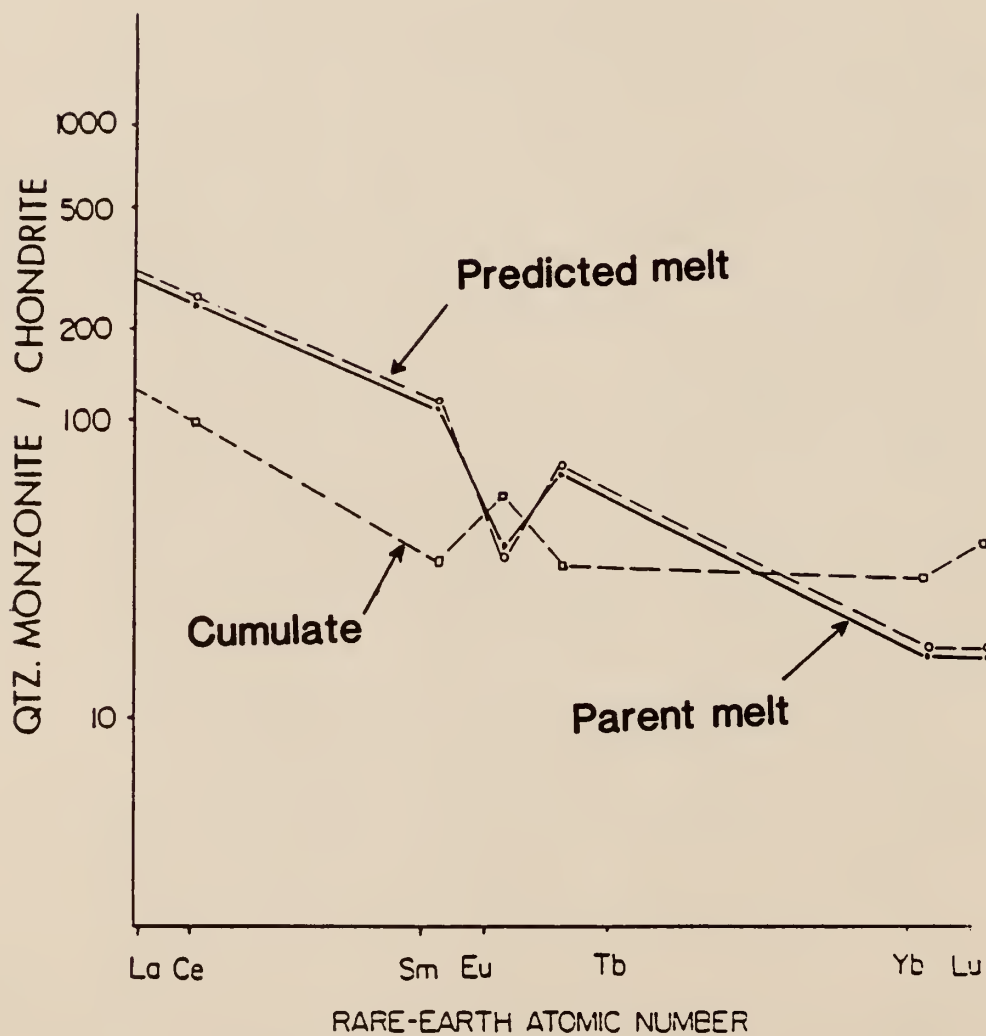


Figure 27: Predicted chondrite normalized concentrations for 10% fractional crystallization of a granitic liquid



porphyritic facies. This would result in linear variation diagrams represented by the rock samples that plot between cumulate and liquid end member compositions (McCarthy and Robb, 1978). The most primitive porphyritic samples (containing largest Sr and Ba concentration) would be represented with at least 90% cumulate material and 10% remaining melt and the inverse of these percentages would represent the most differentiated porphyritic samples.

Approximately 10 percent fractional crystallization of a parent melt, similar in composition to the medium-grained leucogranites (Figure 25) and crystallizing solids at a ratio of plag/micr/qtz/biot/sph/zir/ mag/ap = .44/.21/.13/.18/.001/.003/.035/.001, could result in cumulate concentrations that approximate Sr and Ba concentration observed in the least differentiated porphyritic samples at Oak Creek. Mixing of cumulate and remaining liquid at approximately 10% fractional crystallization could represent the compositional variation present in the porphyritic facies at (Figure 25). Sc and Cr values in the porphyry at Oak Creek also are approximated in this model (Figure 25) which reflects the effect of 18% cumulate biotite in the mode.

One problem with this model, as in partial melting models, is that high REE concentrations in some of the porphyritic rocks cannot be explained by the observed low

concentrations of accessory minerals (sphen, zircon, apatite; Figures 26 and 27). Large concentrations of the HREE (Yb and Lu) observed in the porphyry can be approximated in the model by 5 to 10 percent fractionation of the liquid with approximately 1.0 percent zircon in the cumulate (Figures 28 and 29). Porphyritic rocks with up to 1.2 percent zircon in the mode are present at Oak Creek. Actual percentages may be greater than indicated by the Chayes method because the zircons tend to cluster as inclusions in biotite glomerocrysts. Also, early cumulates would have to contain excessively large amounts of sphen (> 5%) and apatite (> 2%) to be consistent with observed LREE concentrations present at Oak Creek. The porphyritic facies rarely has more than a trace to 0.5% of any of these phases. Predicted high REE concentrations would be similar to that observed only if minute amounts of a mineral with high REE concentrations such as monazite are present as either early cumulate or as a refractory restite phase. Monazite is extremely similar to zircon petrographically and normally can only be distinguished in granites by electron microprobe analysis (Middlefelt and Miller, 1982). Distribution coefficients for La, Sm, and Eu in monazite were estimated at approximately 1000, 800, and 500 respectively (Lyakhovich, 1967). Figures 28 and 29 illustrate that about 0.8 percent monazite in the cumulate result in large concentrations of the LREE in the cumulate

Figure 28: Fractional crystallization model of REE with 0.8% monazite in the cumulate

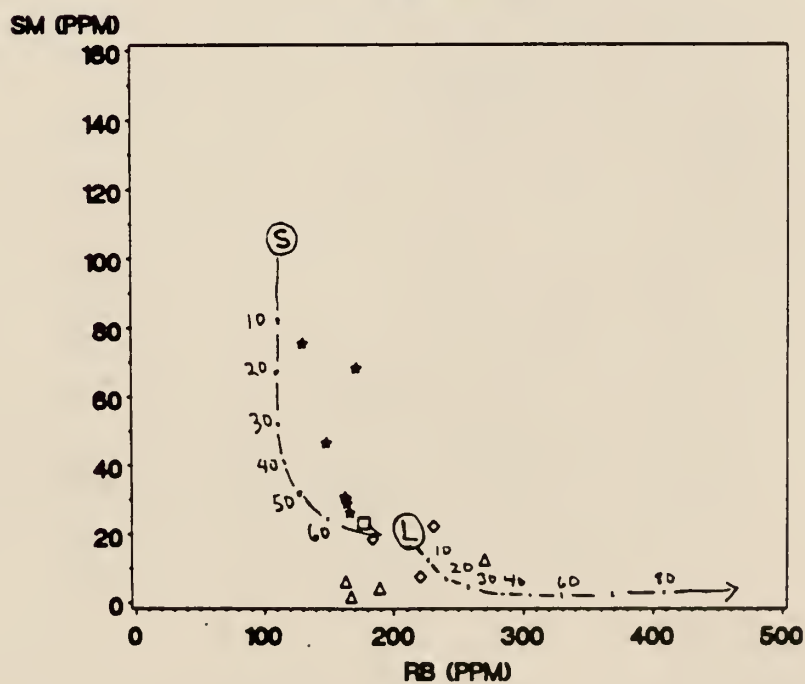
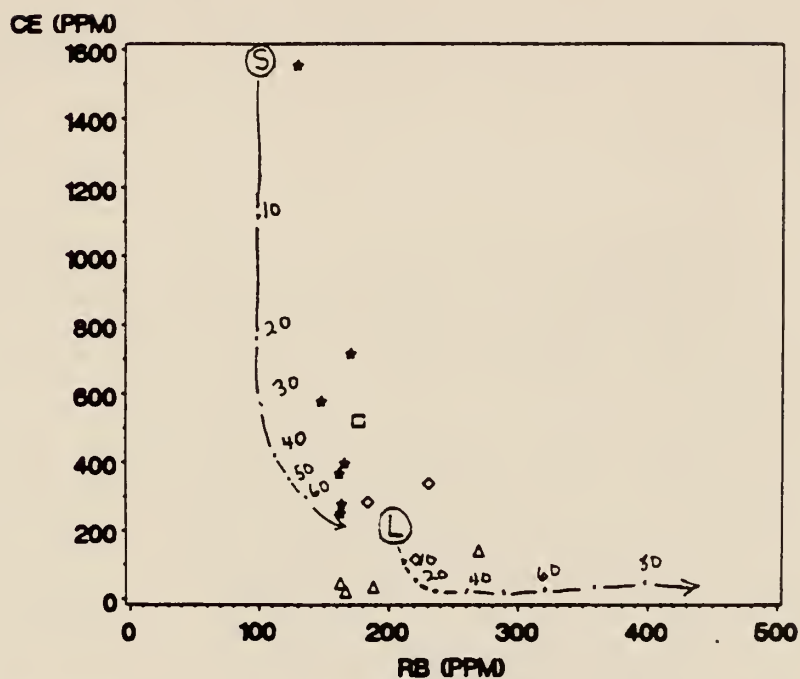


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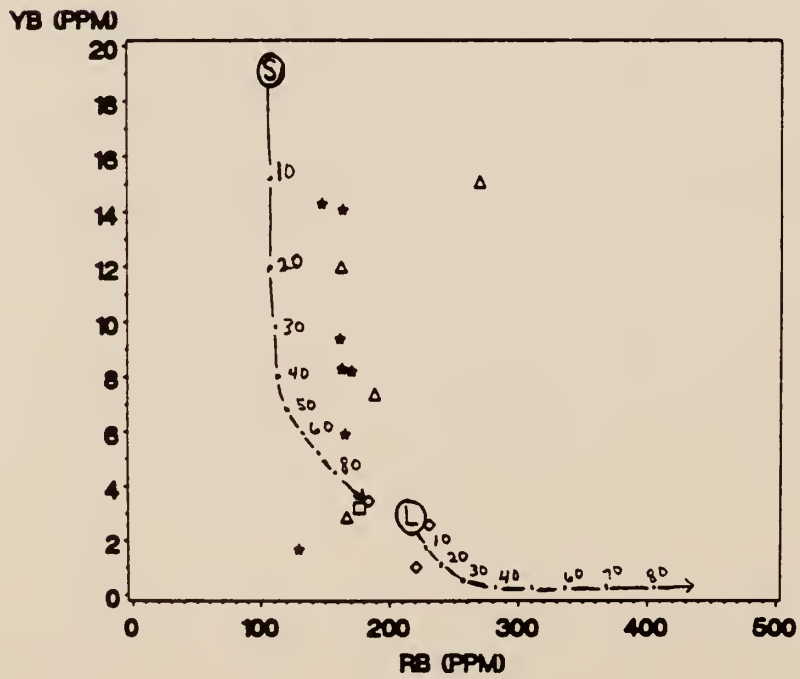
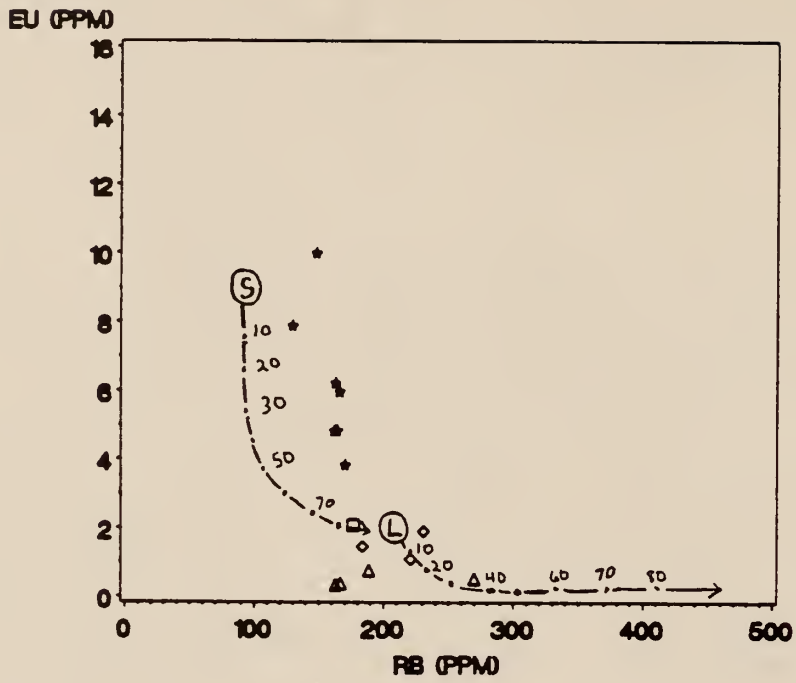


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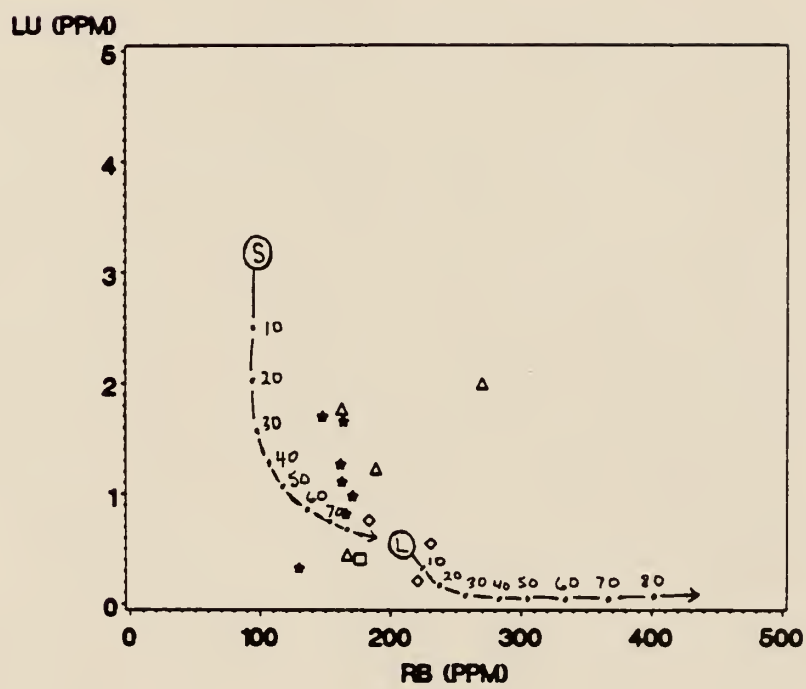
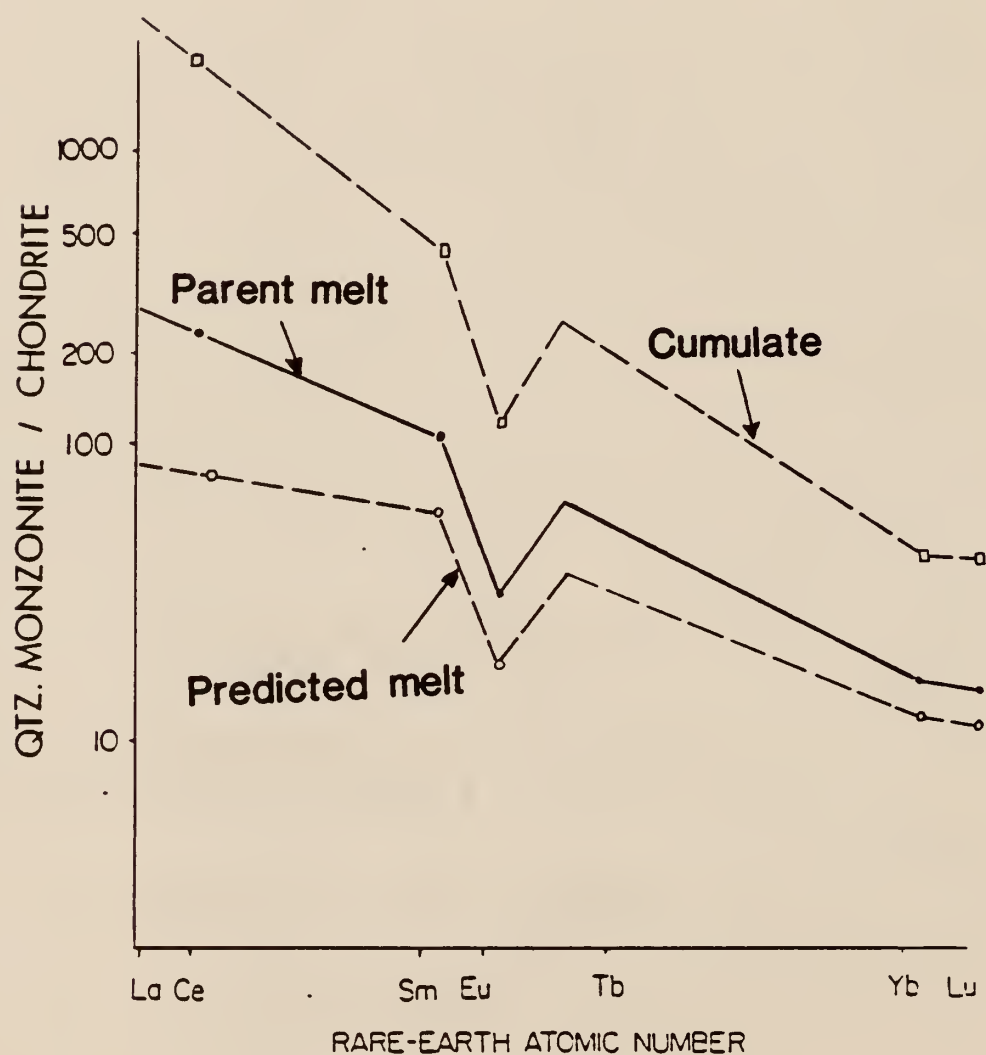


Figure 29: Predicted chondrite normalized concentrations for parent melt, cumulate, and liquid concentrations at 10% fractional crystallization of a granitic liquid with .8% monazite in the mode



and moderate concentrations in the remaining liquid at 5 to 10 percent fractional crystallization. These two end members appropriately bracket the observed concentrations in the medium-grained leucogranites and the porphyritic facies. Variable mixing of the cumulate and remaining liquid could account for the apparently linear compositional trend of the medium-grained leucogranite and porphyritic rocks at Oak Creek.

Alaskites and Coarse-grained leucogranites

Field relations of the alaskites and coarse-grained leucogranites suggest they crystallized after the medium-grained leucogranites and porphyritic facies. The porphyry, however, is the only facies that has been dated, using U-Pb in zircons. The alaskites and coarse leucogranites are the most differentiated rocks at Oak Creek. Partial melting or fractional crystallization processes are the most realistic possibilities that could have formed these leucocratic rocks. Partial melting of a tonalite-granodiorite (similar chemically and mineralogically to the one suggested for the formation of the medium-grained leucogranites), or fractionation of a parent magma similar to the leucogranites to form late, volatile-rich, near-pegmatitic fluids are possibilities considered in this section.

SiO₂, Rb, Sr, and Ba concentrations are similar for

alaskites and the coarse-grained leucogranite. REE concentration for the coarse-grained leucogranite (Figure 30) consists of LREE enrichment and negative Eu anomaly comparable to that found in the medium-grained leucogranites. This may be suggesting that the coarse-grained leucogranites and medium-grained leucogranites have similar histories. Alaskite samples, however, are generally lower in LREE concentration than the medium-grained leucogranite and range from large, negative Eu anomalies to small, negative Eu anomalies. A single, simple process is unlikely to produce variation representative of this range of REE concentration.

Partial melting of a low-Sr, hornblende-biotite tonalite or granodiorite (similar mineralogically to the source suggested for the medium-grained leucogranites) could produce a melt comparable to some of the alaskites of Oak Creek (Figure 31). Sr, Rb, Ba, and LREE values for some of the alaskites are approximated by the partial melting model (Figures 31 - 33), although up to 60 percent melting is necessary to represent the lower Rb samples. The range of REE contents cannot be explained by partial melting alone. Figure 33 illustrates that the 2 alaskite samples with lowest total REE and small negative Eu anomalies might be explained by partial melting of a granodiorite source. The presence of residual garnet and zircon in the alaskites could be responsible for the large HREE concentrations found

Figure 30: Chondrite normalized REE patterns for a coarse-grained leucogranite (dashed) and for alaskite dikes and veins (solid)

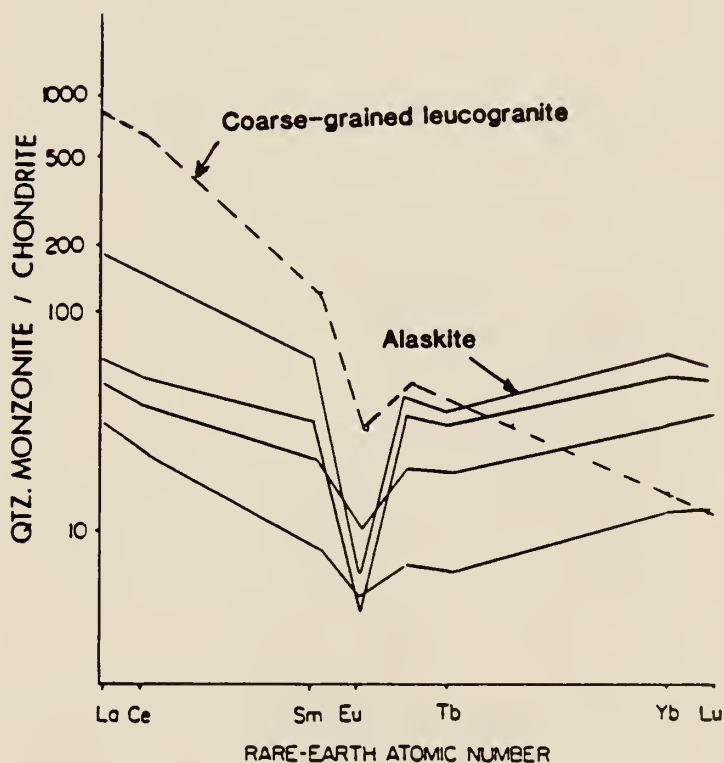
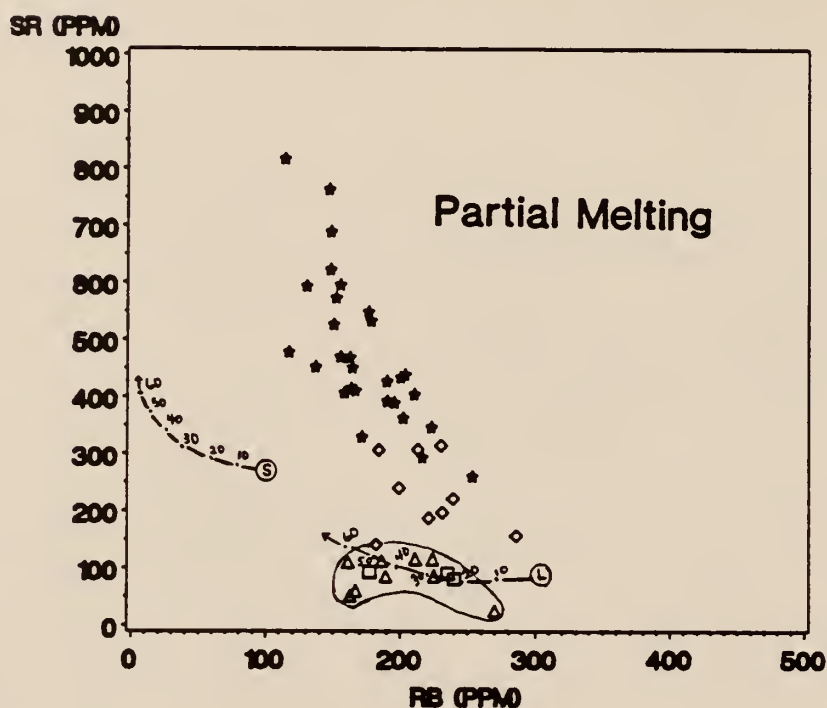


Figure 31: Partial melting models for alaskite formation utilizing Sr, Rb, and Ba

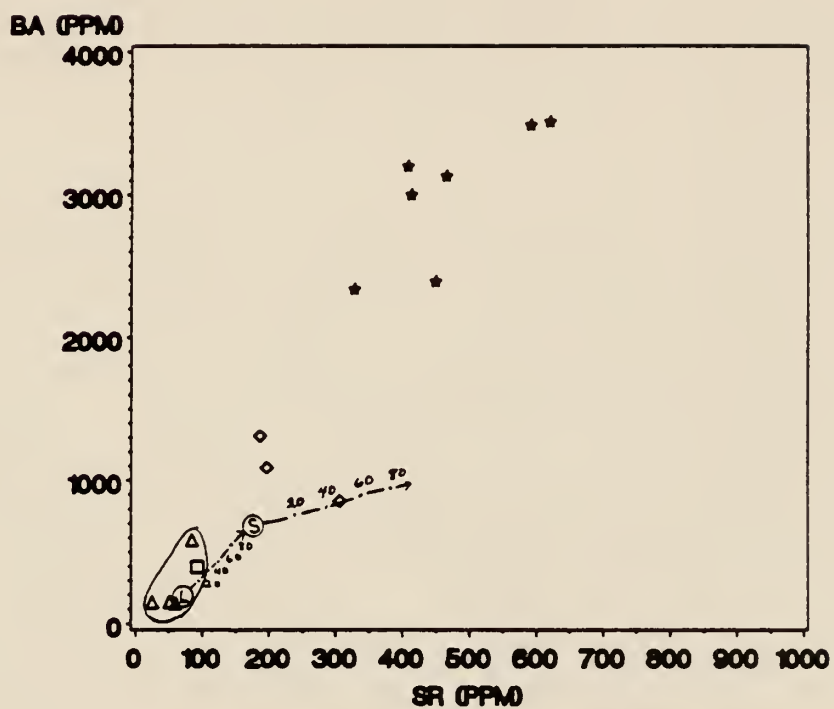


Source and melt ratios for partial melting model used in alaskite formation (Figures 31 - 33)

1		
Source mode	Original composition	Melting ratio
Plag = .42	Rb = 105	Plag = .30
K-spar = .08	Sr = 225	K-spar = .31
Qtz = .22	Ba = 500	Qtz = .30
Biot = .14	Ce = 160	Biot = .03
Hbl = .10	Sm = 8	Hbl = 0
Mag = .01	Eu = 1.5	Mag = .01
Sph = .01	Yb = 3.5	Sph = .02
Zir = .005	Lu = 0.6	Zir = .01
Ap = .005	Sc = 10	Ap = .003
Gar = .005	Cr = 25	Gar = .01
Monz = .005		Monz = .008

1 Tonalite/granodiorite (Anderson and Cullers, 1978)

Figure 31, continued



[illegible]

Figure 32, continued

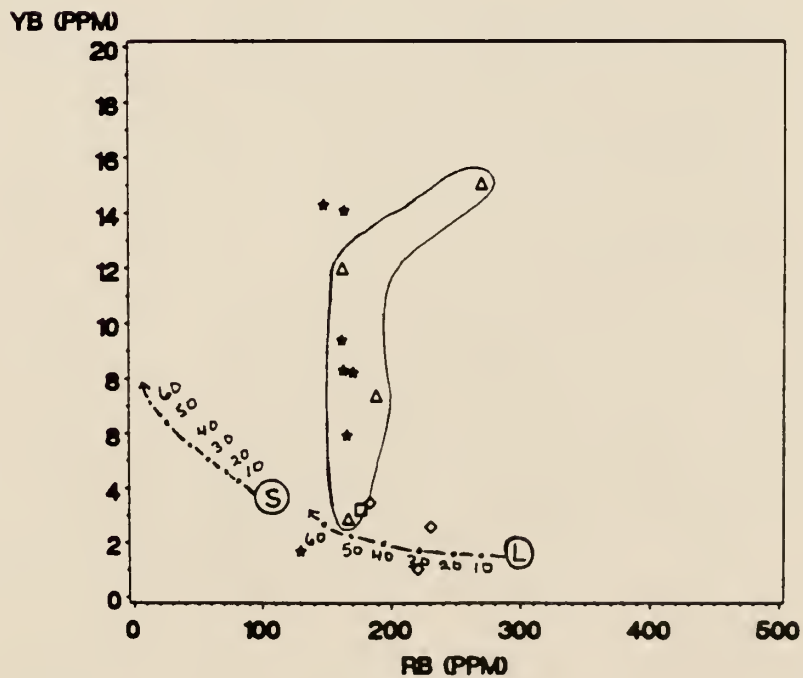
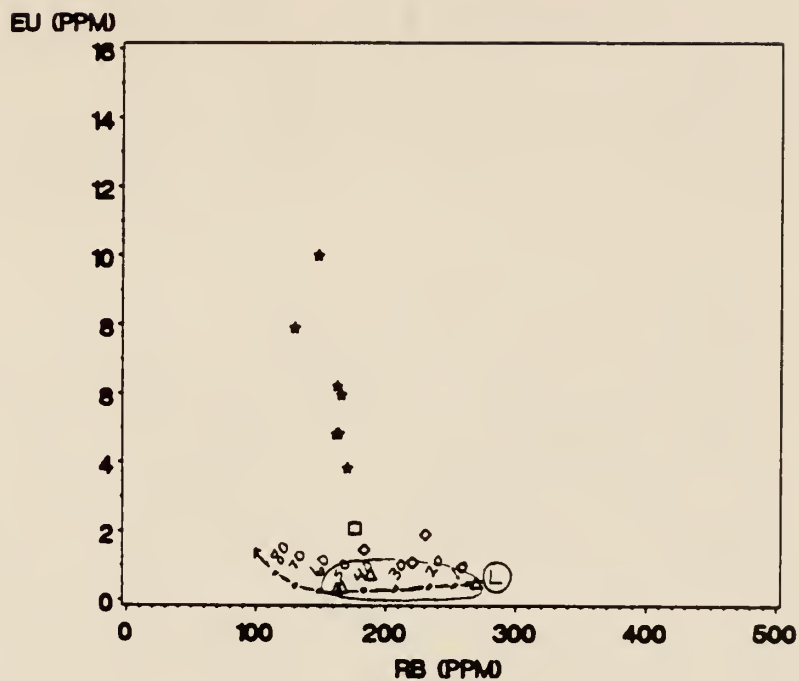
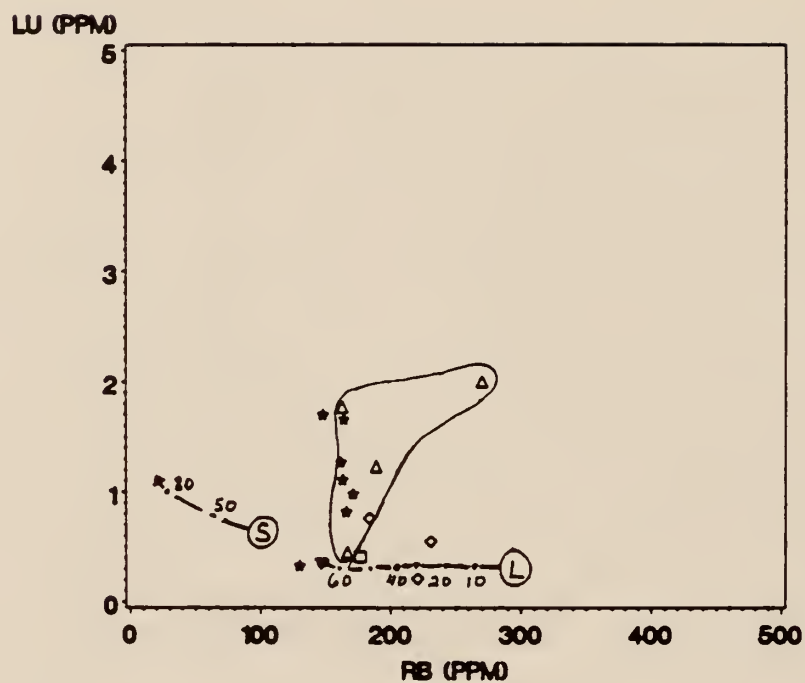


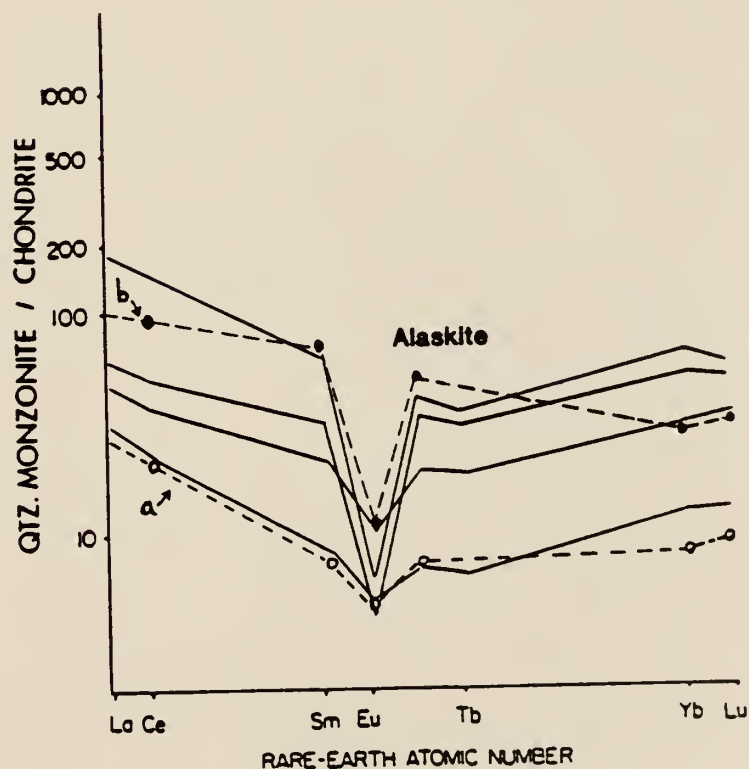
Figure 32, continued



LEGEND

- ☆ Porphyritic facies
- ◇ Medium-grained leucogranite
- ▲ Alaskite
- Coarse-grained leucogranite

Figure 33: Chondrite normalized REE patterns for alaskites
 Predicted concentrations (dashed) of liquids
 from:
 a) 10% partial melting of granodiorite/granite
 b) 50% fractional crystallization of medium-
 grained leucogranites

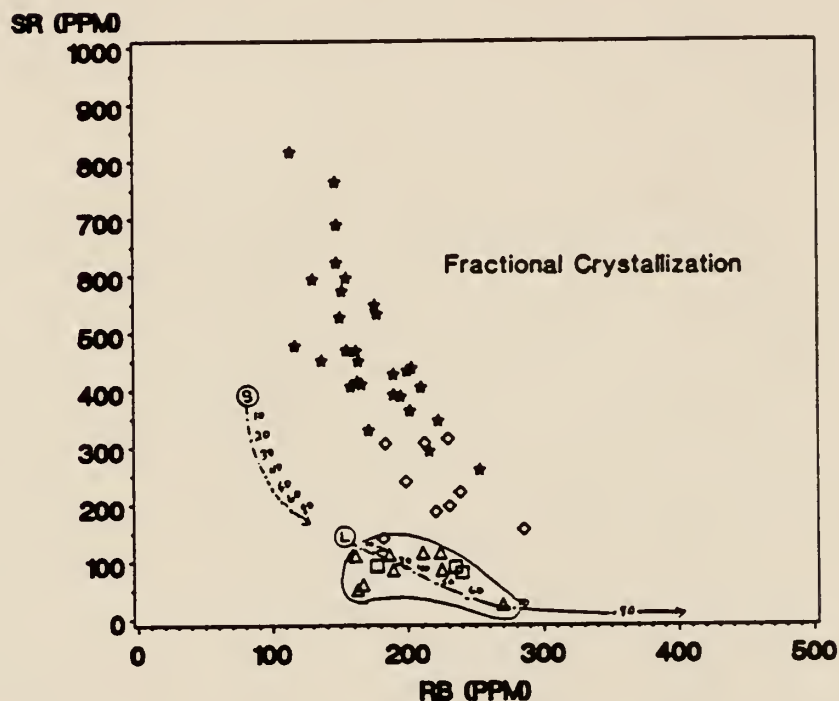


in other samples.

Fractional crystallization modeling (Figures 33 - 35) illustrates another possibility for observed concentrations in some of the alaskites. Approximately 50 percent fractionation of 45% plagioclase, 22% alkali-feldspar, 19% biotite, 14% quartz, and 0.2% apatite from a liquid with similar REE concentrations to the medium-grained leucogranites results in REE concentrations similar to the two alaskite samples that have large negative Eu anomalies. With mostly major phases removed from the melt, LREE and HREE concentrations increase in the remaining liquid along with an increase in negative Eu anomaly size (Figure 33).

The Sr vs Rb plot (Figure 34) illustrates the distinctive field (lower Sr and slightly lower Rb) occupied by the alaskites relative to the medium-grained leucogranites and porphyritic facies. Rb concentrations should increase with differentiation of a melt, even with fractional crystallization of large amounts of biotite. It would be bold, at this point, to suggest a definite relationship between the alaskites and the other rocks of the Oak Creek batholith without dated samples. Trace element modeling suggests some of the alaskites (JS-70 and JS-72) may be related to the medium-grained leucogranites as a differentiate (predicted REE concentrations increase in negative Eu anomaly size at 50% fractional crystallization;

Figure 34: Fractional crystallization model for alaskite formation utilizing Sr, Rb, and Ba



Parent liquid composition and crystallization mode for fractional crystallization model used in alaskite facies formation (Figures 33 - 35)

Parent melt composition	Crystallizing mode
Rb = 150	Plag = .45
Sr = 140	K-spar = .22
Ba = 450	Qtz = .138
Ce = 50	Biot = .19
Sm = 6	Ap = .002
Eu = 0.5	
Yb = 3.2	
Lu = 0.5	
Sc = 2.5	
Cr = 12	

Figure 34, continued

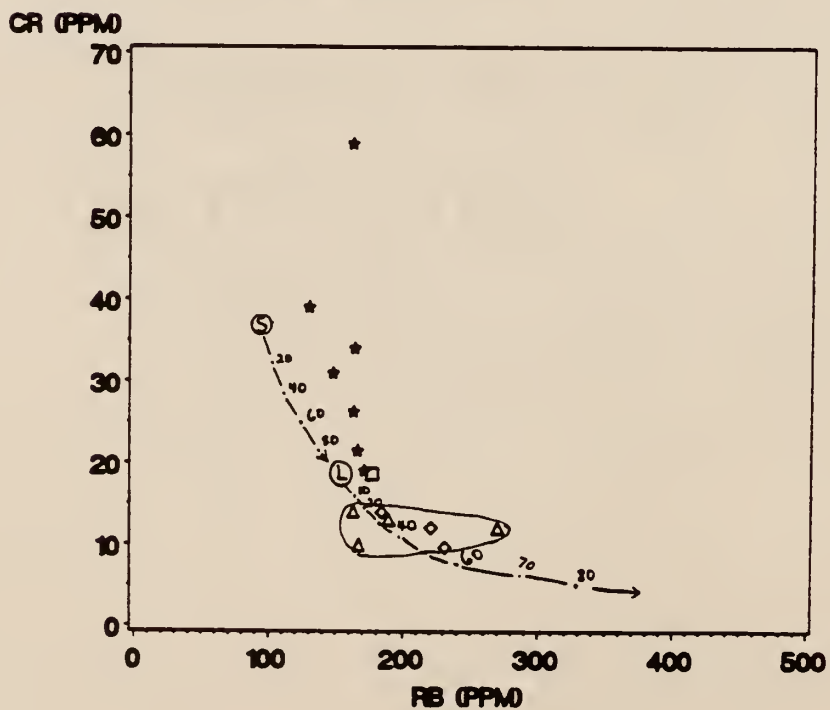
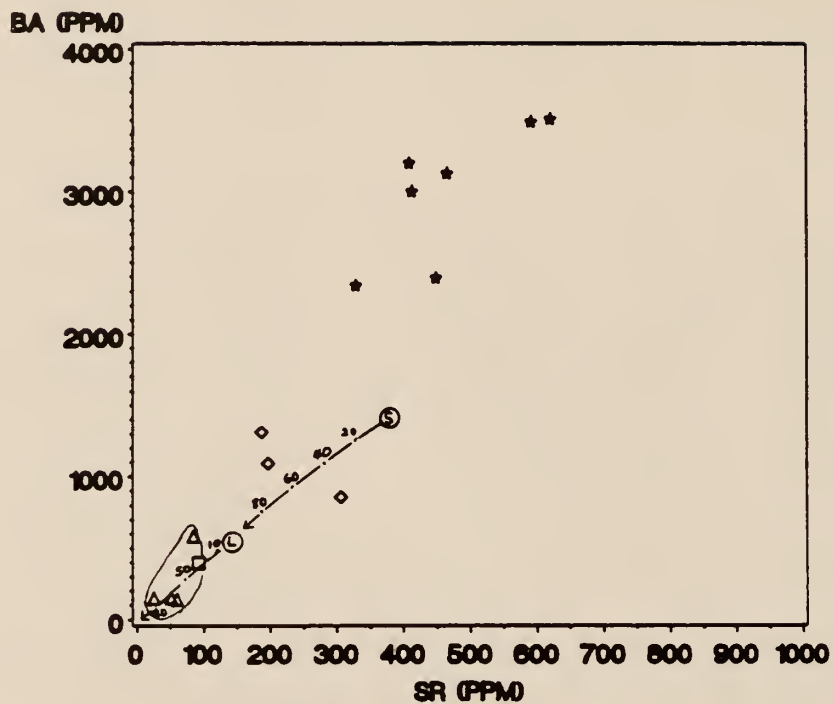


Figure 35: Fractional crystallization model for alaskite formation utilizing REE

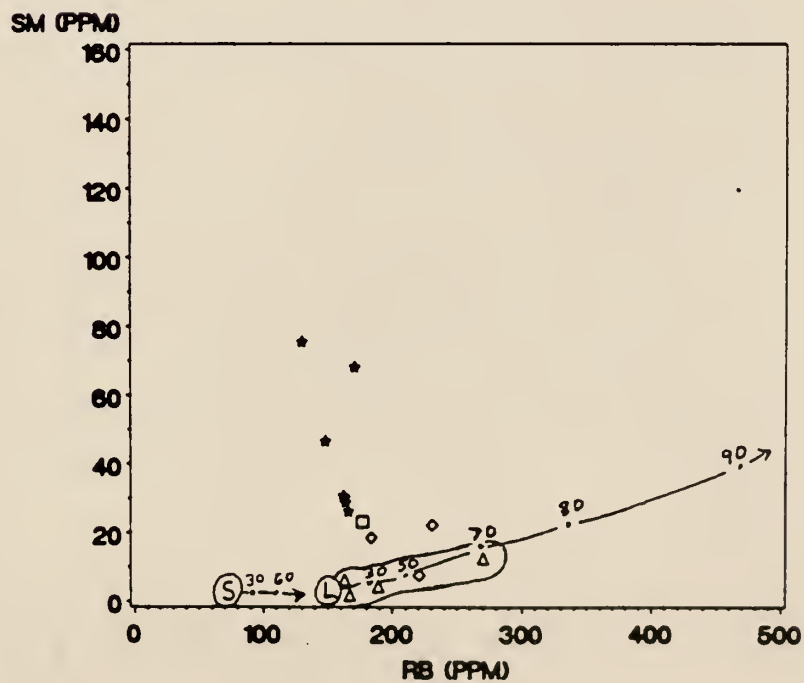
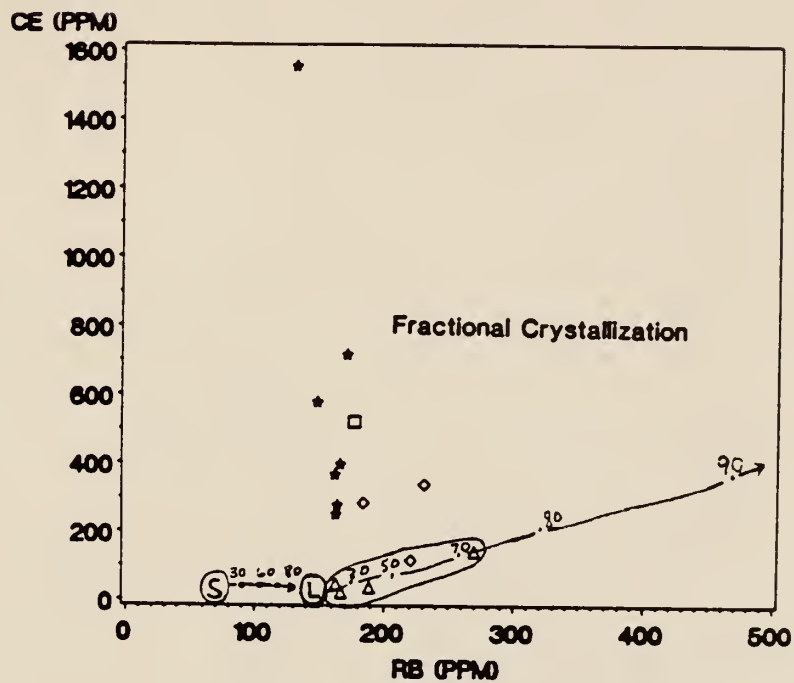


Figure 35, continued

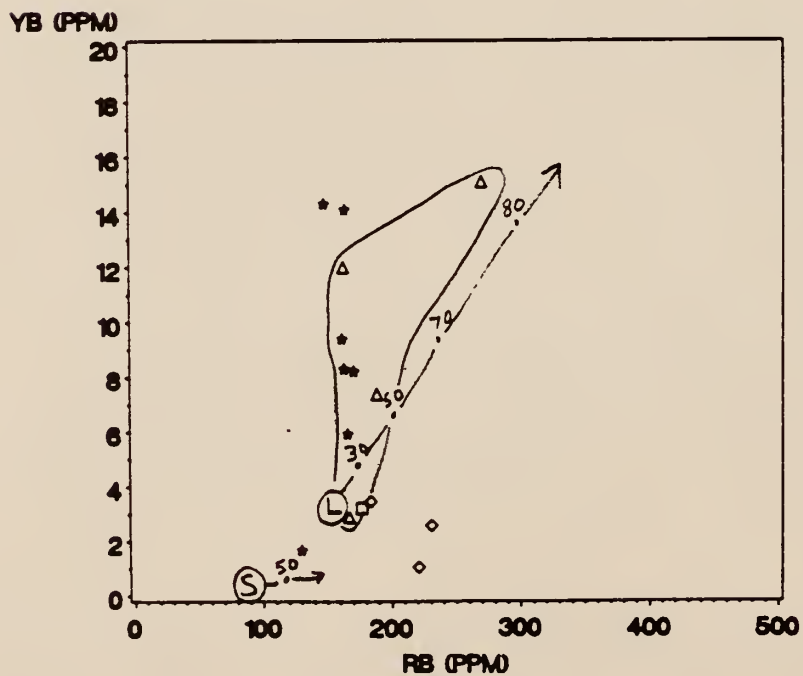
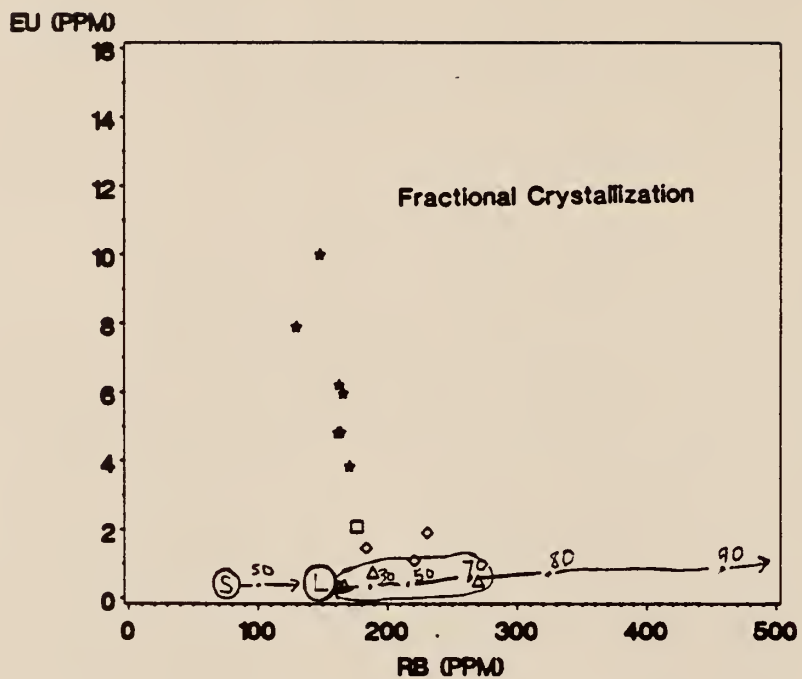


Figure 35, continued

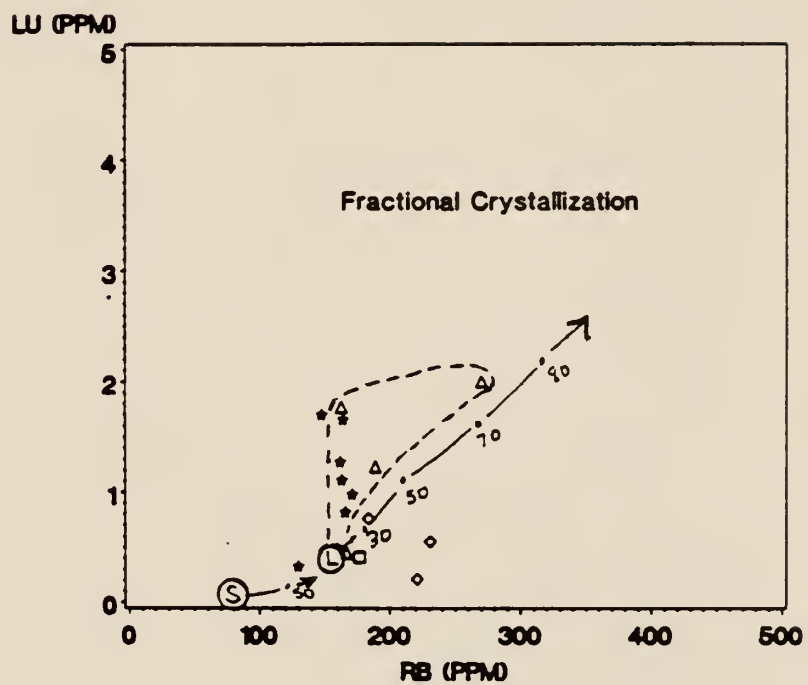


Figure 33). The remaining alaskites more closely resemble liquids that could be produced by approximately 10% melting of a granite/granodiorite (possibly a later melting event).

SUMMARY

Precambrian intrusions into the metamorphic host terrane of Colorado belong to one of three events: 1) 1.7-1.9 Ga old orogenic Boulder Creek intrusions, 2) 1.35 - 1.45 Ga old anorogenic Silver plume event, and 3) 1.1 Ga old Pikes Peak event (anorogenic). The 1.44 Ga old Oak Creek batholith is a foliated, granitic intrusion in the Wet Mountains of Colorado (Fremont County) that is coeval with the 1.35 - 1.45 Ga old anorogenic granite - rhyolite terrane occurring from Arizona to Wisconsin.

Four facies crop out within the batholith recognizable by their textural/mineralogical differences. The porphyritic facies has a cumulate nature with the rocks being composed of porphyritic granodiorite to quartz-bearing monzonite. This facies contains 5 to 65% phenocrysts (perthitic microcline and plagioclase) and 5 to 30% mafic glomerocrysts (biotite, magnetite, sphene, zircon, and apatite). Medium-grained and coarse-grained leucogranites (monzogranite-granite) occur as small bodies within the porphyritic facies. The medium-grained leucogranites could be differentiates of the porphyritic facies, but low Rb concentrations relative to Sr and the absence of dates for any of the leucogranites make it uncertain if the coarse-grained leucogranites are related. Late stage alaskite

dikes and veins of are also present. They differ from the other rocks of Oak Creek with the occurrence of garnet, and lower Rb, Sr, and LREE contents. Trace element modeling suggests some alaskites might have been produced from melting of a different source and another generation of alaskites may have formed by continued fractionation of the medium-grained leucogranite liquids.

The slightly peraluminous, medium-grained leucogranites are similar to these 1.35-1.45 Ga old anorogenic granites as they contain large Fe/Mg ratios, large K and REE concentrations, and small Mg, Ca, and Sr concentrations. Liquids similar in composition to the undifferentiated portions of the leucogranites could be produced by 20-30% melting of a tonalite to granodiorite crustal source.

The porphyritic facies has large variations in elements that concentrate both in mafic minerals (Fe, Mg, Ti, Cr and Sc) and feldspars (Ba, Sr). Although restite unmixing and/or two magma mixing/assimilation may have occurred in limited amounts, trace element models of these processes cannot account for Ba concentrations above 2500 ppm and Sr values above 600 ppm. Oak Creek has Ba and Sr concentrations up to 3510 and 815 ppm respectively in the least differentiated porphyritic facies samples. Accumulations of feldspars and biotite (glomerocrysts) are necessary to attain these large concentrations of Sr and Ba. Field evidence, major elements, and trace element

modeling suggest that minor amounts of medium-grained leucogranite could have formed as differentiated liquids separated during fractional crystallization from the larger mass of porphyritic facies containing varied amounts of cumulates and liquid.

Therefore, the Oak Creek batholith is part of the 1.35 - 1.45 Ga old anorogenic event of the midcontinent. The high $\text{Fe}/(\text{Fe}+\text{Mg})$, K_2O and REE contents of rocks at Oak Creek are similar to A-type granites of this age, but the low SiO_2 , and high ferromagnesian mineral contents of these rock are not typical. This may be due to a difference in depth of intrusion with the cumulate phases not having time to separate. Field relations and mineral associations suggest that the Oak Creek batholith to be deeper seated (lower mezozoneal to upper catozonal) than the typically epizonal and volcanic anorogenic terrane of 1.4 Ga ago. Trace element modeling suggests that crystal accumulation could be dominantly involved in the formation of this pluton.

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APPENDIX

APPENDIX A: Atomic absorption and emission spectrophotometry

Atomic absorption and emission techniques outlined by Medlin et al. (1969) and Shapiro (1978), were used to determine Rb, Sr, and major-element contents. Procedures are as follows:

- (1) Weigh out 0.2000 ± 0.0002 g of powdered rock sample.
- (2) Mix sample with 1.0000 ± 0.0002 g of LiBO_2 in a graphite crucible.
- (3) Place crucibles in furnace at 1000 C for 1 hour.
- (4) Allow fused samples to cool.
- (5) Place fused sample in 50 ml 1N HCl, 1% La solution (1% La solution = 25.697 g lanthanum chloride in 1 liter of distilled-deionized H_2O).
- (6) Place solutions with sample beads on magnetic stirrers until beads are completely dissolved (3-5 hours).
- (7) When beads are completely dissolved, filter solution with Whatman #2 filter paper to remove graphite particles and rinse 4 times with deionized water.
- (8) Blank solutions containing only 1.0000 ± 0.0002 g LiBO_2 are prepared exactly as described above.

Samples were analyzed using a Perkin-Elmer model 305B spectrophotometer. Elemental concentrations were determined by linear regression in which a Canadian soil sample (SO-4) and two United States Geological Survey (U.S.G.S.) samples (RGM-1, rhyolite; QLO-1, quartz latite) were used as standards for comparison.

Dilution Scheme

Solution A

Initial solution, 50 ml
(Ti, Sr, and Mn)

Solution B

20 ml of Solution A + 20 ml distilled-deionized H₂O
(Rb)

Solution C

6 ml of Solution B + 40 ml distilled-deionized H₂O
(Al, Si, and Ca)

Solution D

10 ml of Solution C + 20 ml distilled-deionized H₂O
(Na, Fe, and Mg)

Solution E

4 ml of Solution D + 20 ml distilled-deionized H₂O
(K)

APPENDIX B: Instrumental neutron activation analysis

Trace-element contents were determined by instrumental neutron activation techniques outlined by Gordon et al. (1968) and Jacobs et al. (1977). Procedures used in this study are:

(A) Weigh out approximately 0.3 g to the nearest ± 0.0002 g of powdered rock sample and standard (SO-4) and place in a plastic vial.

(B) Seal plastic vials and wrap them with approximately 0.1 g to the nearest ± 0.0002 g of Fe wire (Fe wire serves as a neutron flux monitor).

(C) Irradiate samples for 4 hours in a Triga Mark II reactor.

(D) Approximately two days after irradiation, place powdered samples in small plastic bags mount on 3 inch by 5 inch cards. Fe wires are coiled and then mounted in a similar manner.

(E) The samples and standards are counted on 5, 10, and 40-day intervals using a Canberra Model 8180 multichannel analyzer and a 25 cm³ Ge(Li) detector. Calibration of the Canberra Model 8180 multichannel analyzer was accomplished by using two radioactive sources: 1) ¹⁵²Eu (0.122 meV and 0.344 meV); and 2) ⁶⁰Co (1.333 meV).

Concentrations were determined by comparing the emission rates of gamma-ray energies for samples and standards and then correcting for variations in neutron flux and interference by elements that emit similar gamma-ray energies. The following equation adjusts results for variations in neutron flux.

$$C_s = C_{st} (st. \text{ wgt.}/s. \text{ wgt.}) (st. \text{ Fe}/s. \text{ Fe}) (s./st.)$$

C_s = concentration of element in sample

C_{st} = concentration of element in standard

st. wgt./s. wgt. = ratio of standard weight to sample weight

st. Fe/s. Fe = standard specific activity of Fe wires to sample specific activity of Fe wire ratio with respect to reactor flux

s./st. = activity ratio of sample to standard

APPENDIX C: Trace-element modeling

The development of a quantitative model to explain the range of chemical variation in the Oak Creek batholith must be consistent with major- and trace-element data, petrographic observations, field relationships, and results of experimental petrology (Haskin, 1984). Trace-elements are used to help explain the petrogenesis of granitic melts by utilizing distribution coefficients of the elements (Shaw, 1970; Hanson, 1978). The distribution coefficient (D.C.) is the ratio of the concentration of a given element in a solid phase relative to its concentration in a coexisting liquid. The non-modal aggregate melt formulation described by Shaw (1970) was used to model partial melting processes for Oak Creek rocks.

$$C_L / C_0 = 1/F(1-(1-PF/D_0)^{1/\beta})$$

C_L = trace-element concentration in derived melt

C_0 = trace-element concentration in residual source

F = fraction of source rock that has melted

P = proportionality constant = $P_1K_1 + P_2K_2 + \dots$

where P_i = proportion of phase i in the melt

K_i = distribution coefficient of a given
trace-element for phase i

D_0 = bulk distribution coefficient = $X_1K_1 + X_2K_2 + \dots$

where X_i = abundance of phase i in the source

K_i = distribution coefficient of a given
trace-element for phase i

Fractional crystallization modeling was accomplished
using the equation of Haskin et al. (1970).

$$C_L / C_0 = (1-X)^{K-1}$$

where C_L = trace-element concentration in the residual
liquid

C_0 = initial trace-element concentration in the magma

X = fraction of the original magma that has crys-
tallized

K = distribution coefficient of a given trace-element
for the crystallizing phase

PETROLOGY OF THE GRANITIC PLUTON AT
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by

James M. Stone

AN ABSTRACT OF A MASTER'S THESIS

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Department of Geology

KANSAS STATE UNIVERSITY

Manhattan, Kansas

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ABSTRACT

The 1.44 Ga old Oak Creek batholith is a foliated, granitic intrusion in the Wet Mountains of Colorado (Fremont County) that is coeval with the 1.35 - 1.45 Ga old anorogenic granite - rhyolite terrane occurring from Arizona to Wisconsin. The majority of the rocks are composed of porphyritic granodiorite to quartz-bearing monzonite containing 12 to 64% phenocrysts (perthitic microcline and plagioclase) and 10 to 27% mafic glomerocrysts (biotite, magnetite, sphene, zircon, and apatite). Medium-grained leucogranites (monzogranite) occur as small bodies within the porphyritic facies and could be differentiates of the porphyritic facies. Late stage alaskite dikes and veins cross-cut all other rock types. Field relations and pressure estimates suggest the Oak Creek batholith to be deeper seated than the typically epizonal and volcanic anorogenic terrane of this age.

The slightly peraluminous, medium-grained leucogranites are similar in composition to many 1.35-1.45 Ga old anorogenic granites. The leucogranites contain large Fe/Mg ratios, large K and REE concentrations, and small Mg, Ca, and Sr concentrations. These magmas could be produced by 20-30% aggregate melting of a tonalite to granodiorite crustal source of 1.8 Ga in age typical of those found in

the region. Compositional variations in the leucogranites may be related to subsequent fractional crystallization.

The porphyritic facies has large variations in elements that concentrate both in mafic minerals (Fe, Mg, Ti, Cr and Sc) and feldspars (Ba, Sr). Although restite unmixing and/or two magma mixing/assimilation may have occurred in limited amounts, trace element models of these processes cannot account for Ba values above 2500 ppm and Sr values above 600 ppm. Oak Creek has Ba and Sr values up to 3510 and 815 ppm respectively in the least differentiated porphyritic facies samples. Accumulations of feldspars and biotite (glomerocrysts) are necessary to attain these large concentrations of Sr and Ba. Field evidence and trace element modeling suggest that minor amounts of medium-grained leucogranite could have formed as a series of differentiated liquids separated during fractional crystallization from the larger mass of porphyritic facies containing varied amounts of cumulates and liquid.

Coarse-grained leucogranites and alaskite dikes appear to be late stage volatile-rich, near-pegmatitic intrusions that could be related by differentiation. REE distribution in the coarse-grained leucogranite suggests a similar history to that of the medium-grained leucogranite. The alaskites differ from the other rocks of Oak Creek with the occurrence of garnet, and lower Rb, Sr, and LREE contents. Trace element models suggest some of the alaskites may have

formed by continued fractionation of the medium-grained leucogranite liquids and another generation of alaskites may have been produced by a different melting event.

Therefore, the Oak Creek batholith is similar to granites of the 1.35 - 1.45 Ga anorogenic event of the midcontinent. The porphyritic facies of Oak Creek has high $\text{Fe}/(\text{Fe}+\text{Mg})$, K_2O and REE contents similar to the A-type granites of this age, but this facies however, is lower in SiO_2 , and higher in Fe and Mg than typical for A-type granites. Also, field relations and mineral associations suggest that the Oak Creek batholith to be deeper seated (lower mesozonal to upper catazonal) than the typically epizonal and volcanic anorogenic terrane of 1.4 Ga ago. Trace element modeling suggests that crystal accumulation could be dominantly involved in the formation of this pluton.