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Abstract

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SOUTHEASTERN GEOLOGY

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1965

AREAL MODAL VARIATION IN THE FARRINGTON IGNEOUS COMPLEX, CHATHAM AND ORANGE COUNTIES, NORTH CAROLINA

by

H. D. Wagener
The Citadel

ABSTRACT

The Farrington complex consists primarily of two adjacent stocks with a total outcrop area of about 55 square miles. Modal data was obtained from thin sections of 65 regularly spaced specimens. The western stock has dioritic margins and a granodioritic center. Potassium feldspar and quartz generally increase and plagioclase and color index generally decrease toward the center. The eastern stock has generally porphyritic quartz monzonitic margins and an equigranular granodioritic central zone. Potassium feldspar and plagioclase vary inversely, but quartz and color index are nearly invarient. High potassium feldspar content occurs mostly in marginal rocks, and is coincident with relatively low quartz percentage and a plagioclase-poor micropegmatitic groundmass.

Data from the complex exhibit a linear trend on a plagioclase-K feldspar-quartz ternary diagram. Crystallization of the western stock probably proceeded from the margins inward in accordance with Bowen's reaction series. Crystallization of the eastern stock may have begun in the equigranular central zone. If so, the apparently potassium-rich granophyric margins represent late residua. Micropegmatite in the complex apparently survived only in rocks that were not subjected to intensive deuteric or post-magmatic metasomatism.

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INTRODUCTION

General Geology

The Farrington Igneous complex consists of at least six separate intrusions, and has a total surface area of about 55 square miles. The complex is one of several small, generally granitic plutons west of the Durham Triassic basin in the Slate Belt of central North Carolina. A brief examination of data (Hayes, 1962) from the Chapel Hill stock (Fig. 1) indicated that rocks of the Farrington and Chapel Hill plutons are nearly identical. The two plutons are certainly related in origin, and may have been emplaced contemporaneously. The complex underlies continental Triassic deposits along its eastern edge and is certainly pre-Triassic in age (Harrington, 1948).

The Slate Belt, into which the Farrington complex was intruded, is characterized in the Chapel Hill area by a heterogeneous series of early Paleozoic (?) metasedimentary rocks, interbedded with porphyritic volcanic rocks, lithic crystal tuff, devitrified glassy rocks, breccia and volcanic conglomerate (Butler, 1963). Available chemical data indicate that the volcanic rocks are chemically similar to rock types in the Farrington complex. The sedimentary section includes laminated pelitic rocks and poorly sorted arenaceous graywacke (?) with a very fine grained matrix.

The regional strike of Slate Belt rocks in the vicinity of the complex is approximately as shown by the overlay pattern on Figure 2. Little significant structural data is available concerning country rocks immediately surrounding the complex. Regional metamorphism has produced mineralogy typical of the greenschist facies throughout the Slate Belt and locally well developed slaty cleavage in the pelitic rocks. The partial alteration of hornblende to chlorite in Farrington rocks could have occurred during the same metamorphic period, but may represent deuteric reactions. The major rock types, and probably all rocks in the area of study, are cut by Triassic diabase dikes and by post-intrusion sheer zones, quartz veins, and epidote-quartz veins of uncertain age.

Objectives and Field Procedure

This study was undertaken to obtain quantitative information on areal mineralogical variations in a granitic pluton through modal analysis. Sampling was based on a grid of one square mile per grid section (Fig. 2). In order to obtain uniform distribution of specimens in the complex, one specimen was collected as closely as possible to the center of each grid square. Outcrops are generally good, and little difficulty was experienced in collecting specimens at or near desired locations. Fresh specimens were easily obtained by use of an eight-pound sledge. Much of the sampling had been completed before it was established that the western portion of the complex is a separate stock. Because of the smaller size of the western stock, additional specimens were collected in relatively regular distribution. The resulting specimen density in the western stock is about 2.4 specimens per square mile. A total of 65 specimens was collected from the complex to study

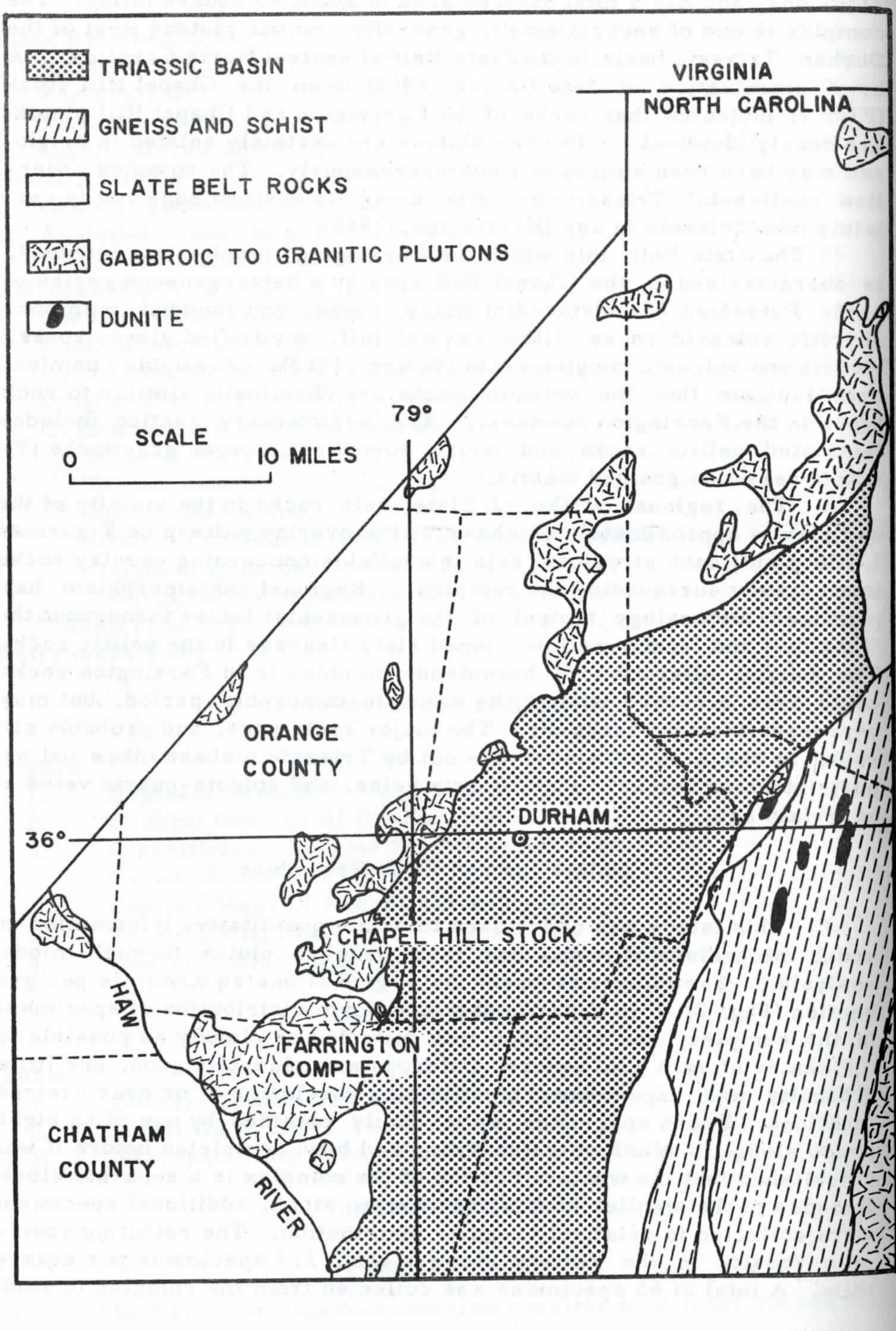

Figure 1. Regional geology. After Geologic Map of N. C. (1958).

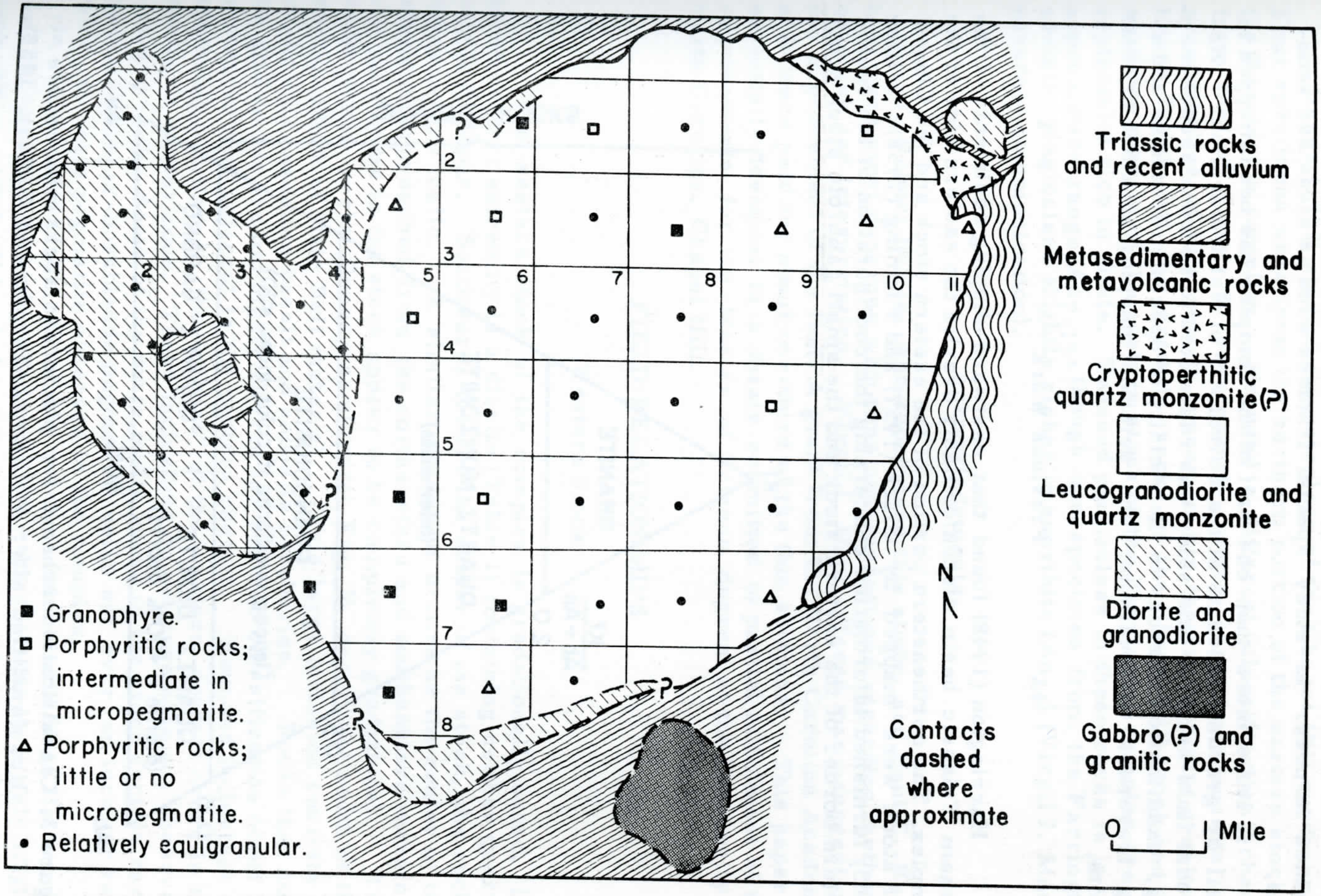

Figure 2. General geology of the Farrington complex. Sampling grid is superimposed. Only specimens used to construct Figure 4 are shown.

general variations in mineralogy. Twenty additional specimens were obtained in order to study special features such as dikes and xenoliths.

A little more than one half of the complex has been mapped in detail by graduate students at the University of North Carolina. Additional field work for this study was restricted to reconnaissance mapping, examination of rocks in the vicinity of specimen locations and along traverses to locations, and detailed mapping at a few critical points.

Previous Work

Harrington (1948) found that eastward-dipping sediments of the Durham Triassic basin disconformably overlie the eastern side of the complex. The northeastern portion of the eastern stock and the Chapel Hill stock were mapped by Clark (1957) and Fleming (1958). Miller (1963) furnished information concerning the configuration of the southeastern border of the eastern stock and the small gabbroic stock south

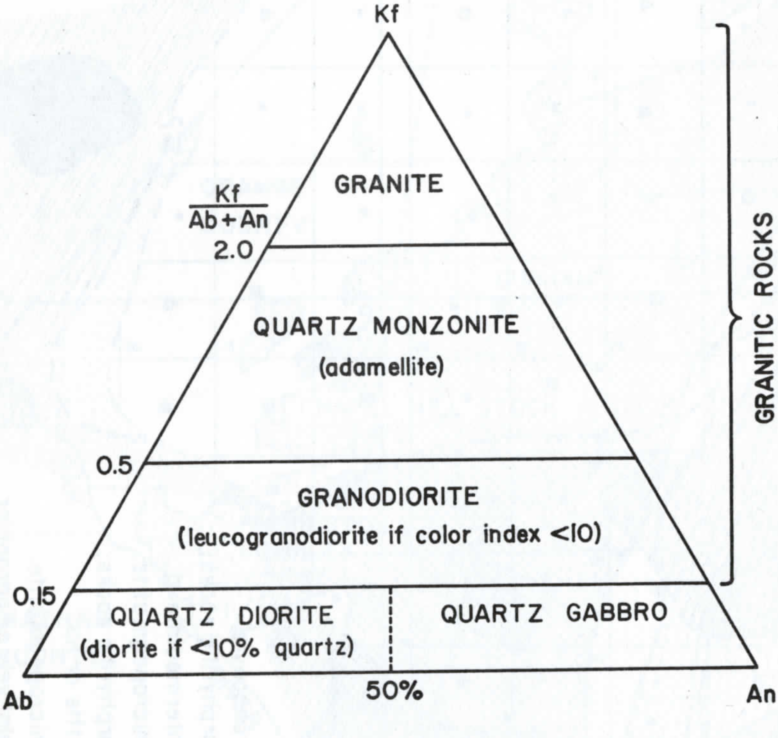

Figure 3. Classification scheme for phaneritic rocks with excess silica (modified after Williams, Turner and Gilbert, 1958). Color index generally increases toward the base. Kf, potassium feldspar; Ab, albite; An, anorthite.

of the eastern stock.

Hayes (1962) studied the petrology of the Chapel Hill quadrangle. Four specimens were from the northern portion of the eastern stock of the Farrington complex. He used a different classification scheme from that of Figure 3; consequently, some quartz monzonites and granodiorites of this report appear in his thesis as albite granites. Hayes found that the granitic rocks of the Chapel Hill stock and the northern margin of the eastern stock of the Farrington complex are exceptionally rich in albite. Twinned plagioclase in these rocks is in the approximate range An_{7-15}, though one specimen from the Farrington contains plagioclase slightly richer in anorthite (An_{24}) (Virgil I. Mann, personal communication).

Acknowledgments

J. Robert Butler, who supervised this study, and Paul C. Ragland were most generous with time and suggestions regarding methods of attack and interpretation. Virgil I. Mann offered many suggestions for improvement of the text. A grant from the North Carolina Academy of Science paid for about one-third of the thin sections. This paper is essentially identical to a thesis submitted in partial fulfillment of the requirements for the Master of Science degree at the University of North Carolina, Chapel Hill.

FIELD RELATIONSHIPS

Western Stock

The western stock of the complex is gradationally zoned. Its northwestern extremity is a diorite (Table 1) containing neither quartz nor K-feldspar. Southward, toward the center of the stock, the rocks become less mafic. A similar gradation occurs as the center of the stock is approached from the northeastern and southeastern margins. All rock types in the stock appear to be completely gradational. The least mafic rocks (leucogranodiorite; Fig. 3) occur just south of the central block of Slate Belt material. This large inclusion consists of rocks that resemble basalt and andesite porphyries. Rocks that may be gabbro but are too highly altered for positive classification occur in a narrow zone adjacent to the eastern contact. Rounded inclusions of material similar to the "gabbro" at the eastern contact occur in the southern border zone. These inclusions do not resemble any observed country rock. Some of the more mafic rocks of the stock contain rare quartz-feldspar-hornblende pegmatite veins not over an inch or two wide, the only pegmatite observed in the complex.

Observed contacts of the western stock with Slate Belt rocks are sharp. Diorite and granodiorite near the contacts have only slightly reduced grain size and are not porphyritic. No lineate, foliate or cataclastic features were observed in the field or in thin section. Angular to sub-rounded inclusions of fine to medium-grained, relatively mafic material are ubiquitous, but vary greatly in size and distribution. Stretched or preferentially oriented xenoliths were not observed.

The contact with the granitic eastern stock is actually a zone containing: discontinuous screens of country rock; dioritic rock into which irregular veins of less mafic material have been injected; fine to medium-grained granitic inclusions in diorite; and very coarse to medium-grained altered "gabbro". Where screens of country rocks are absent, diorite of the western stock is progressively enriched in granitic inclusions as the contact with the eastern stock is approached. At a single locality in the dike-like northeastern extension of the western stock a zone of diorite flooded with partly to wholly recrystallized xenoliths was observed. The xenoliths appear basaltic in hand specimen. Very small dioritic intrusions (not mapped) occur along the entire northwestern border of the eastern stock. These intrusions would probably plot near the An_{50} line on Figure 3, but the feldspars are largely altered.

Eastern Stock

The eastern stock of the complex is gradationally zoned. Rocks highest in K-feldspar generally occur in border zones. The central portion of the stock consists primarily of medium grained, equigranular leucogranodiorite. A small central subzone of granophyre (Fig. 2) is quartz monzonitic. Leucogranodiorite in the central zone is nearly indistinguishable in hand specimen from the least mafic leucogranodiorite in the south-central portion of the western stock. The eastern and western border areas of the eastern stock are quartz monzonitic. Border rocks are generally finer grained than the leucogranodiorite, contain less than about 30 percent plagioclase phenocrysts, and are granophyric or non-granophyric but porphyritic. The terms granophyre and granophyric are used in this paper as follows: granophyre refers to porphyritic rocks that have a groundmass of cuneiform and less regular micropegmatite; granophyric is used as an inclusive adjective to refer to granophyre and porphyritic rocks whose groundmass has a micropegmatite content intermediate between granophyre and the non-granophyric porphyritic rocks (porphyritic rocks that contain little or no micropegmatite; see Fig. 2). The granophyres contain cavities about 1 mm or less in diameter, into some of which surrounding crystals project. Fine grained rocks are not everywhere associated with an exposed contact; they were observed but not mapped in several restricted areas in the central zone. The equigranular central zone is gradational with granophyre and the non-granophyric porphyritic rocks.

The northwestern border of the eastern stock is a complex zone about one-quarter of a mile wide, in which leucogranodiorite is crowded with andesitic inclusions. The leucogranodiorite at the contact is generally medium grained and equigranular, but some porphyritic rock with a very fine-grained groundmass occurs. Magmatic material surrounding xenoliths has been contaminated (1.7, 9.0, Table 2) and does not fall on any of the trends in variation diagrams for the complex. At some localities, the marginal zone is separated from the remainder of the stock by a zone of granophyric rocks. Dioritic rocks containing granitic inclusions, and rocks resembling the cryptoperthitic quartz monzonite (Fig. 2) also crop out in the marginal zone.

Xenoliths occur in all stages of assimilation. The first megascopic change is a generally uniform increase in grain size, accompanied by growth of needle-like hornblende crystals, and, at some localities, plagioclase porphyroblasts. In rare instances, hornblende rods less than 1 mm in diameter extend completely across recrystallized xenoliths one or two inches in diameter. The number of mineral grains that take a sodium cobaltinitrite stain increases with increasing xenolith grain size. In the final stages of assimilation, the former existence of inclusions is indicated in thin section by local concentrations of small opaque iron oxide grains. Xenoliths occur throughout the stock in all sizes from microscopic to about 1/5 square mile in outcrop area. The population density of inclusions large enough to appear on Figure 2 is a little less than one per square mile (Fleming, 1958). Any large boulder will generally contain at least one inclusion an inch or more in diameter.

Lack of preferred orientation and deformation is a general feature of inclusions through the complex, although elongated xenoliths were observed in a contact zone at the southwestern extremity of the eastern stock. No other lineation or foliation was observed in the field.

Satellitic Stocks

The cryptoperthitic quartz monzonite (Fig. 2) is apparently a separate intrusion, and was chilled in contact with the country rock. The composition of the specimen from this intrusion could not be determined accurately, but point counting at 450x indicated a value of about 0.5 for $\frac{Kf}{Ab + An}$ (Fig. 3). Application of the term "cryptoperthitic" is based on an apparent gradation from very finely lamellar microperthite to microscopically homogeneous feldspar that occurs around the edges of some plagioclase grains. The Na-feldspar of the intergrowths is optically continuous with the plagioclase cores.

Near the northwestern extremity of this intrusion, about 2000 feet north of the contact, the country rock is laminated slate that tends to split along bedding planes. The slate is interbedded with rocks resembling graywacke. About 1000 feet north of the contact, the "slate" is well jointed and laminated, but slaty cleavage and fissility have been destroyed. Near the contact, "graywacke" tends to break across, rather than around larger grains. No other contact metamorphic effects were observed.

The small diorite stocks at the southern and northeastern extremities of the eastern stock are very similar to diorite in the western stock. Contacts are very sharp, and a marked decrease in grain size occurs at the contacts. The diorite at the southern extremity is separated from the eastern stock by a narrow zone of mixed rock types similar to those along the boundary between the eastern and western stocks, including discontinuous screens of country rock. Similar mixed rock types occur in the dike-like northeastern extension of the stock. Part of the southern boundary of this small stock consists of a network of innumerable small dikes intruded along joints and around joint blocks in apparently shattered country rock (James A. Miller, personal communication).

The small separate stock south of the eastern stock is a composite intrusion containing altered "gabbro" that is very similar to the more mafic rocks along the eastern border of the western stock. A dike of similar material crops out about one mile northwest of the center of the eastern stock. The mode for this dike (4.0, 7.7, Table 2) is identical to the mode for one specimen from the altered gabbroic stock. Granitic rocks occur in the northern part of the gabbroic stock but were not investigated.

Light-colored Dikes

Trondhjemitic dikes (Table 1, Table 2) crop out in the eastern stock, primarily in the northwestern portion, but are rare in the western stock. The dike rock weathers readily and is usually represented by easily broken light gray boulders. The few dikes investigated are medium grained and exhibit perfectly gradational contacts with medium-grained granitic host rock. One sampled transition takes place in about 30 inches: The ratio $\frac{Kf}{Ab + An}$ decreases from approximately .40 in leucogranodiorite to .15 in the dike. One set of 8 dikes from 6 inches to 2 feet wide crops out in a 200-foot road cut. Larger dikes (?) occur, but were not mapped.

The eastern stock has been intruded by fine-grained dikes that exhibit pink or darker purplish hues. Some of the dikes are porphyritic. Restricted sections of some dikes have been strongly epidotized. Less severe epidotization has extended into the country rock adjacent to epidotized dikes, but all observed contacts of the dikes are very sharp. Only one dike was sampled, and is called aplite (Table 2). The term aplite was subsequently applied to all fine-grained pink or purplish dikes observed in the field.

Table 1

General characteristics of rock types

Rock Type	Grain Size	Color and percentage K-feldspar	Color and percentage Plagioclase	Kf / Ab + An	Quartz %	Color Index	Mafic minerals ** observable in hand specimen
Altered gabbro or diorite	Medium to coarse	None	White (altered) 40-55	0	<5	~45	Chlorite; Dark green hornblende; Ferrous oxides and sulfides
Diorite and quartz diorite	Medium	White 0-10	White to greenish gray 55-65	0 - 0.15	0-15	20-30	As above
Grano-diorite	Medium	White, less commonly pink 10-15	White to greenish gray 50-55	.15 - .3	15-25	10-20	Dark green horn-blende, partly chloritized; Biotite (vari-able); Ferrous oxides
Leucograno-diorite	Medium to porphyritic with fine groundmass	Generally pink 15-25*	White 45-50	.3 - .5	20-30	5-10	Dark green horn-blende rods, largely altered to chlorite
Quartz monzonite	As above	Pink, less commonly white 25-30*	White 40-45	.5 - .75	20-30	~5	As above
Granophyric quartz monzonite	Porphyritic with fine groundmass	White to pink 30-34	White 35-40	.75-1.0	20-25	~5	Varied
Aplite (one specimen)	Fine	Purplish or pink 34	White 12	3.5	52	2	Iron oxides only
Trondhje-mitic dikes	Medium	Gray ~10	Gray ~60	.15	~25	~5	Varied

* Abundance of microperthite invites high estimates of amount of pink K-feldspar in hand specimen.

** Secondary epidote is not uncommon.

Table 2

Modal data

Volume percent; Kf + Pl + Q + C.I. = 100%. See Figure 2 for specimen locations. North-south coordinate of specimen location is given first.

	K-feldspar	Plagioclase	Quartz	Color Index
Western stock				
2.1, 2.7	0	71.0	0	28.6
2.5, 2.6	0	60.1	12.7	27.2
3.0, 2.6	0.5	59.5	11.0	29.0
3.1, 2.2	8.2	54.7	16.9	20.2
3.3, 5.3	17.6	66.3	6.2	9.9
3.3, 5.3[1]	35.3	28.6	31.7	4.4
3.5, 2.6	8.9	51.3	19.8	20.0
3.5, 3.6	10.5	53.0	16.7	19.8
3.5, 5.0	7.2	53.1	4.5	35.2
3.6, 2.2	7.3	55.7	16.5	20.5
3.8, 3.9	10.9	52.9	16.3	19.9
4.1, 3.3	16.6	49.5	20.5	13.3
4.3, 1.9	18.1	53.7	10.6	17.6
4.3, 2.8	13.7	53.4	13.1	19.8
4.4, 4.5	21.6	56.8	7.4	14.2
4.4, 4.8	0	55.6	0	44.4
4.4, 5.0	2.5	56.7	5.1	35.7
4.7, 3.7	12.3	51.3	25.7	10.7
4.9, 2.9	16.7	45.8	21.6	15.9
4.9, 4.2	15.8	44.7	24.3	15.2
4.9, 4.9	17.5	46.1	22.2	14.3
5.1, 2.2	13.1	49.3	16.7	21.0
5.5, 2.6	13.3	49.0	18.3	18.4
5.5, 4.5	22.3	43.8	22.4	11.5
5.9, 3.6	9.1	46.2	19.4	25.3
6.1, 3.1	22.3	43.8	22.4	11.5
6.1, 4.2	15.7	57.1	15.5	11.7
6.5, 3.6	16.1	49.1	23.8	11.0
6.4, 4.6	7.9	58.7	9.0	24.4
6.8, 3.5	14.9	47.8	21.5	15.8
Eastern stock				
1.7, 9.0[2]	21.3	58.5	14.7	5.5
2.5, 6.8	28.9	42.3	22.4	6.4
2.5, 7.6	18.9	49.5	25.2	6.4
2.5, 8.6	21.3	50.4	24.0	4.3
2.6, 9.4	20.6	49.3	24.3	5.8

Table 2 (Continued)

	K-feldspar	Plagioclase	Quartz	Color Index
2.5, 10.5	30.6	39.9	24.2	5.3
3.4, 5.5	25.0	44.1	25.3	5.7
3.5, 6.6	23.0	48.6	23.5	4.9
3.5, 7.7	18.4	49.7	22.6	9.3
3.6, 8.5	33.0	39.6	22.8	4.8
3.6, 9.7	22.4	50.2	22.1	5.3
3.4, 10.5	27.7	40.4	28.6	3.3
3.5, 11.5	28.4	41.2	24.8	5.6
4.6, 5.7	28.2	42.4	23.5	5.9
4.5, 6.6	20.9	50.8	22.4	5.9
4.6, 7.7	19.1	50.9	26.9	3.1
4.5, 8.6	22.7	52.2	28.1	4.0
4.3, 9.5	23.1	48.4	24.8	3.7
4.4, 10.5	23.4	46.6	25.8	4.2
5.4, 5.6	22.0	48.8	24.0	5.1
5.6, 6.5	23.7	45.5	25.8	5.2
5.4, 7.4	17.9	52.5	24.9	4.7
5.4, 8.5	21.4	49.5	24.2	4.9
5.4, 9.5	24.3	47.8	22.4	5.5
5.5, 10.6	22.6	45.5	28.2	3.7
6.5, 5.6	34.5	38.7	21.7	5.5
6.5, 6.5	28.1	39.8	26.0	6.1
6.5, 7.5	16.0	52.5	25.5	6.0
6.5, 8.6	21.7	51.5	23.1	3.7
6.5, 9.6	23.0	48.1	24.4	4.5
6.6, 10.4	20.7	48.5	25.2	5.6
7.4, 4.7	36.2	33.9	26.0	3.9
7.4, 5.5	36.1	34.3	24.8	4.8
7.6, 6.7	34.1	38.5	21.6	5.8
7.6, 7.7	16.3	52.9	27.1	3.7
7.5, 8.6	24.3	45.9	26.3	3.5
7.5, 9.5	24.2	43.8	27.2	4.8
8.6, 5.5	33.4	36.6	25.6	4.4
8.5, 6.6	23.7	45.6	25.3	5.4
8.4, 7.4	22.9	49.6	23.1	4.4
Diorite stocks				
2.4, 11.4	0	59.4	9.3	31.3
9.3, 5.5	1.6	63.2	4.6	30.6
Gabbroic rocks				
1.5, 9.3	0.4	52.3	0.3	47.0
4.0, 7.7[3]	0	41.7	3.1	55.2

Table 2 (Continued)

	K-feldspar	Plagioclase	Quartz	Color Index
9.3, 6.6	0	53.5	1.7	44.8
9.6, 8.6	0	41.8	3.1	55.1
10.3, 8.6	0	50.3	2.5	47.2
Trondhjemitic dikes				
3.0, 7.3	9.1	60.9	27.2	2.8
4.5, 5.8	11.2	61.9	24.8	2.1
6.4, 5.6	9.2	60.5	23.3	7.0
Aplite				
3.2, 10.8	33.5	12.3	52.5	1.9
Cryptoperthitic stock				
2.7, 11.4	25.4	47.9	22.4	4.3

[1]Granitic inclusion in diorite specimen 3.3, 5.3.

[2]Contaminated by reaction with andesitic inclusions.

[3]Dike; very similar to "gabbro" at 9.6, 8.6.

MODAL ANALYSIS

General Statement

Modal data were obtained from all Farrington specimens by point counting of thin sections by use of a mechanical stage. The data obtained for all stocks in the complex (Table 2) were plotted on several types of binary and ternary diagrams. The diagrams and illustrations of modal variations selected for publication (Fig. 4, 5, and 6) exhibit all significant trends observed. All data are presented as volume percentages in the sense that data obtained by point counting of thin sections are volume percent data.

Third-order regression surfaces and their residual maps were fitted to modal data from the complex by Paul C. Ragland (Ragland and Wagener, 1963) by use of the least squares method and a digital computer. The trend surfaces obtained offered no significant information not obtainable from raw data contour maps, and tended to obscure local inhomogeneities of petrogenetic significance.

Analytical Procedure

Untwinned plagioclase found in many Farrington specimens prompted the utilization of staining to differentiate plagioclase and K-feldspar. Uncovered thin sections were inverted and suspended about 1/4 inch above concentrated hydrofluoric acid for one minute. The extended etch period (instead of the 15-second etch recommended by Bailey and Stevens, 1960) was found necessary for satisfactory staining of microperthite and micropegmatite. Condensed vapor was allowed to evaporate and the sections were emersed in a saturated solution of sodium cobaltinitrite for at least three minutes. Staining of plagioclase was unnecessary because of ubiquitous alteration. Cover glasses were applied for the counting operation.

The IC number (number of major mineral identity changes in 25 mm) for Farrington rocks varies from 50 to 65. A 700 mm^2 thin section of IC 50 falls just within the one thin section field of Chayes' (1956, p. 83) chart for maximum analytical error less than 2.45 percent. Consequently, one thin section having a surface area of at least 700 mm^2 was prepared for each specimen. The horizontal counting intercept distance was 0.32 mm. The distance between counting traverses (1.43 mm) approximates the average grain size of medium-grained Farrington rocks. Fifteen hundred points were counted per thin section.

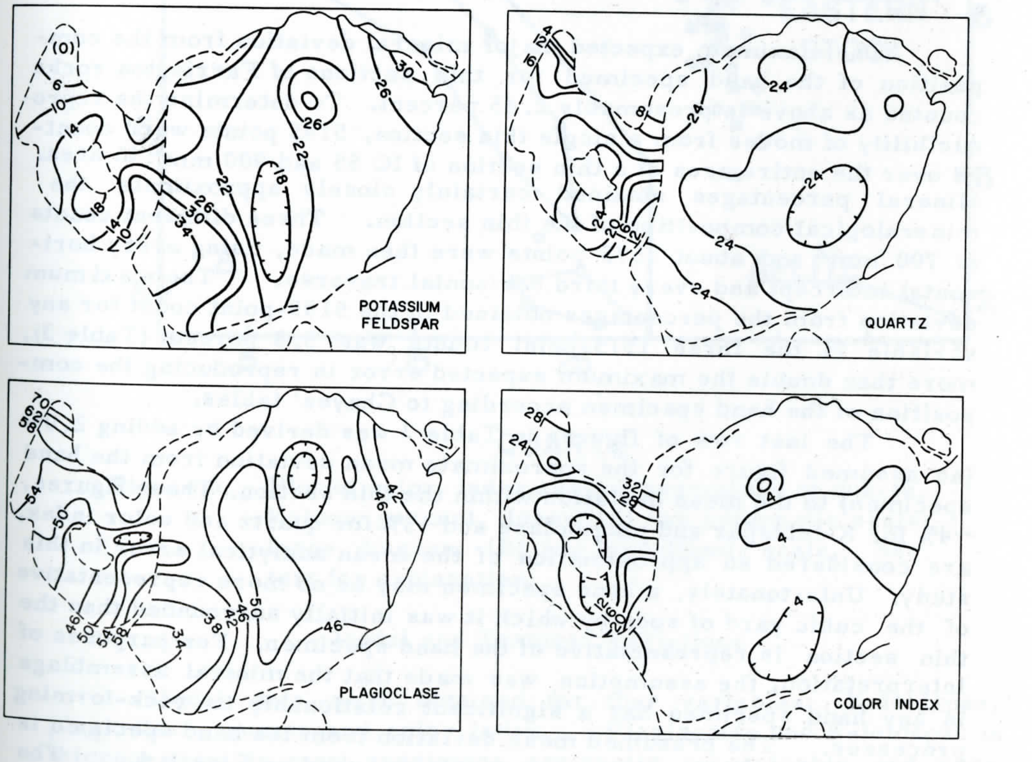

Figure 4. Contour maps of mineralogical variations, based on the raw data.
Volume percent. Contour interval 4 percent.

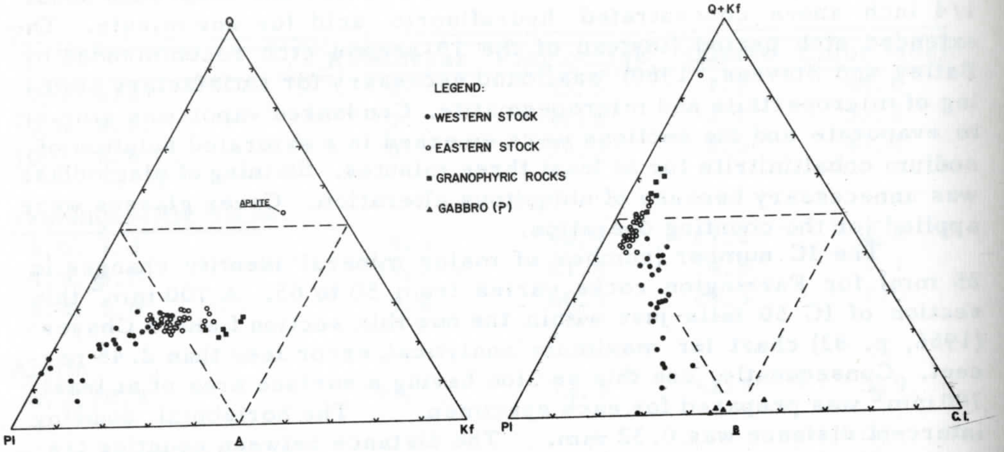

Figure 5. Ternary diagrams; volume percent.
A. Quartz-plagioclase-potassium feldspar. B. Quartz + potassium feldspar-plagioclase-color index.

The maximum expected major mineral deviation from the composition of the hand specimen for thin sections of Farrington rocks counted as above is presumably 2.45 percent. To determine the reproducibility of modes from a single thin section, 5195 points were counted over the entire area of a thin section of IC 55 and 900 mm^2 in area. Mineral percentages obtained certainly closely approximate the mineralogical composition of the thin section. Three different counts of 700 mm^2 and about 1575 points were then made, using every horizontal intercept and every third horizontal traverse. The maximum deviation from the percentages obtained in the 5195-point count for any variable in the three 1575-point counts was 5.8 percent (Table 3), more than double the maximum expected error in reproducing the composition of the hand specimen according to Chayes' tables.

The last row of figures in Table 3 was derived by adding 2.0% (an assumed figure for the approximate mean deviation from the hand specimen) to the mean deviation within the thin section. These figures, ~4% for K-feldspar and plagioclase and ~5% for quartz and color index, are considered an approximation of the mean analytical error in this study. Unfortunately, a hand specimen may be no more representative of the cubic yard of rock by which it was initially surrounded than the thin section is representative of the hand specimen. For purposes of interpretation, the assumption was made that the mineral assemblage in any hand specimen has a significant relationship to rock-forming processes. The presumed mean deviation from the hand specimen is equal to or greater than the contour interval used on Figure 4. The small contour interval was used because it is more illustrative of the trends shown by larger contour intervals.

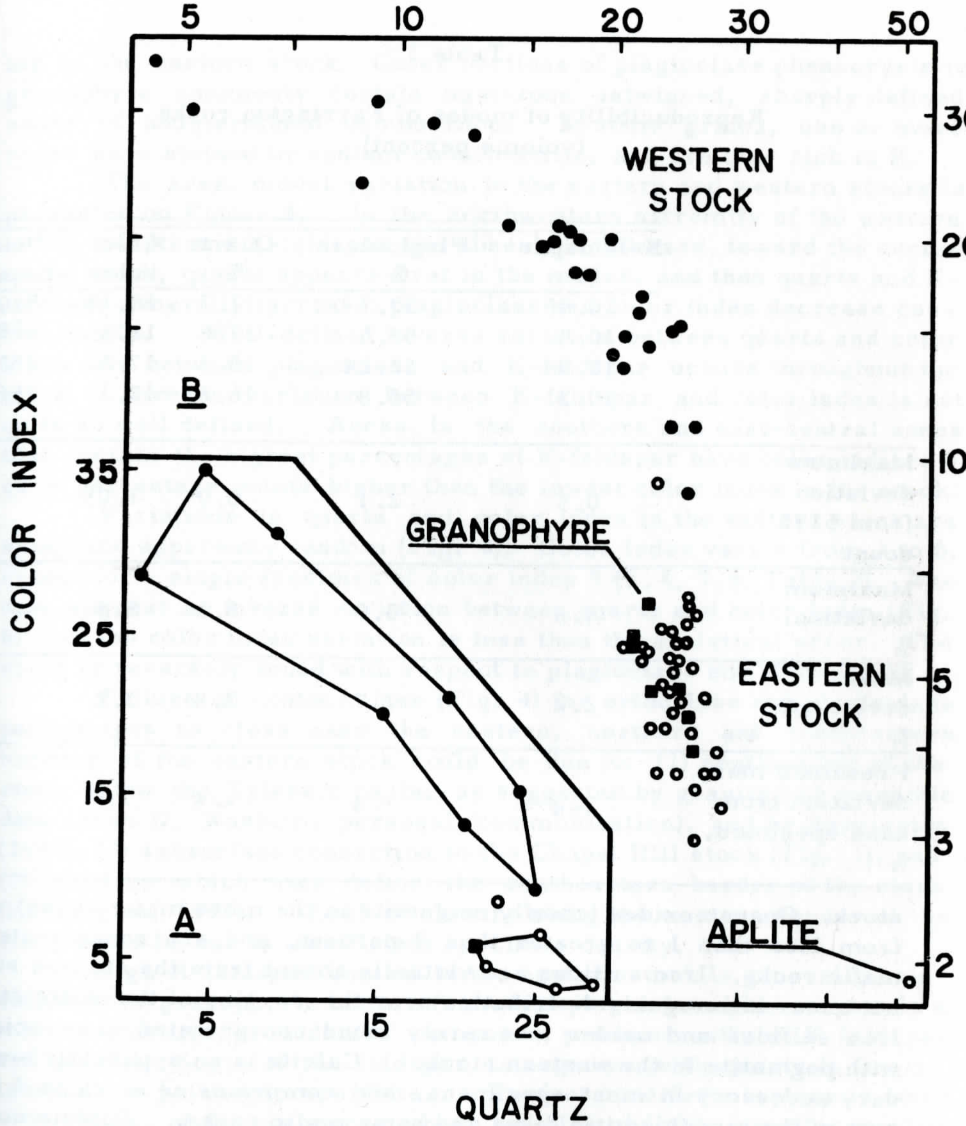

Figure 6. Plot of color index against percentage of quartz. Volume percent. Insert (A) has arithmetic scale; large diagram (B) has logarithmic scale. See text for explanation.

Modal and Textured Variations

Modal data were obtained for four variables: K-feldspar, plagioclase, quartz and color index. Plagioclase and K-feldspar in microperthite in most specimens are easily recognizable and were counted separately. Color index includes minerals of specific gravity 2.75 or greater. Common green and brown hornblende and brown biotite are partly to completely chloritized, especially in gabbroic rocks and in the eastern stock. Biotite varies irregularly from 0 to 9 percent in the western stock, and is a minor accessory in the eastern

Table 3

Reproducibility of modes of Farrington rocks
(volume percent)

	K-feldspar %	Plagioclase %	Quartz %	Color index	Points counted
	10.45	53.7	17.7	18.15	5195
	10.4	53.6	17.8	18.2	1580
	10.94	53.24	18.3	17.5	1572
	10.3	55.8	16.8	17.1	1568
Maximum deviation from 5195 count	0.5	2.1	0.9	1.05	
Maximum deviation, %	4.8	3.9	5.1	5.8	
Mean deviation, %	2.2	1.7	2.8	3.2	
Presumed mean deviation from hand specimen, %	~4	~4	~5	~5	

stock. Opaque oxides (chiefly magnetite in the more mafic rocks) vary from less than 1 to greater than 7 percent, and are concentrated in mafic rocks. Iron sulfides are virtually absent from the eastern stock, but occur in irregular distribution near the margins of the mafic stocks. Iron sulfides and oxides are rarely found concentrated in association with pegmatite in the western stock. Calcite is an apparently secondary accessory in most specimens, and comprises as much as 3 percent of the trondhjemitic dikes and some mafic rocks. Epidote occurs as a deuteric or post-magmatic alteration product. Mafic minerals replaced by epidote were included in the color index; partly epidotized plagioclase is less common and was counted as plagioclase. Exact determination of anorthite content of plagioclase was not attempted in most specimens, primarily because of sericitization. The maximum anorthite content apparently decreases from about An_{50} in mafic portions of the western stock to about An_{20} south of the center. Normal zoning is common. Twinned plagioclase in the eastern stock varies from a minimum of An_7 to a maximum of at least about An_{20} (extinction angles of some grains are near 0). Zoning of plagioclase is pronounced in some granophyres, but visible zoning is generally lacking in the eastern stock. Outer portions of plagioclase phenocrysts in granophyre commonly contain numerous untwinned, sharply defined zones of undetermined composition. In some grains, one or more zones were stained by sodium cobaltinitrite, and are thus rich in K.

The areal modal variation in the eastern and western stocks is presented on Figure 4. In the northwestern extremity of the western stock, quartz and K-feldspar are absent. Southward, toward the center of the stock, quartz appears first in the modes, and then quartz and K-feldspar generally increase; plagioclase and color index decrease concomitantly. Well-defined inverse variation between quartz and color index and between plagioclase and K-feldspar occurs throughout the stock. Inverse variation between K-feldspar and color index is not quite so well defined. Rocks in the southern and east-central zones that contain the highest percentages of K-feldspar have color indices 3 or 4 percentage points higher than the lowest color index in the stock.

Variations in quartz and color index in the eastern stock are small and apparently random (Fig. 4). Color index varies from 3 to 6, except for a single specimen of color index 9 (3.4, 7.6; Table 2). The data suggest an inverse variation between quartz and color index (Fig. 6), but the color index variation is less than the analytical error. The stock is reversely zoned with respect to plagioclase and K-feldspar.

Failure of contour lines (Fig. 4) for orthoclase and plagioclase percentages to close near the eastern, northern and southeastern borders of the eastern stock could be due to: (1) continuation of the stock below the Triassic basin, as suggested by gravity and magnetic data (John D. Waskom, personal communication), and by Harrington (1948); (2) subsurface connection to the Chapel Hill stock (Fig. 1); and (3) faulting, which may define the southeastern border of the stock (Harrington, 1948). Lack of closure along the western border of the stock could be due to insufficient specimen density.

High K-feldspar content in the eastern stock is generally coincident with granophyric texture (euhedral plagioclase phenocrysts in a micropegmatitic groundmass composed predominantly of K-feldspar and quartz). Some of the feldspar intergrown with quartz is finely lamellar or patch microperthite. Perfect cuneiform texture is common. Many of the phenocrysts have mantles of finely lamellar microperthite or K-feldspar that have been partly replaced along fluted and embayed edges by quartz. The microperthite generally contains roughly equivalent amounts of Na- and K-feldspar. Some of the mantles appear to be optically homogeneous alkali feldspar when examined at relatively low magnification. Such mantles can be only lightly stained, although K-feldspar in adjacent micropegmatite is heavily stained. At higher magnification (450x) very fine laminations can be observed in portions of the mantles. This relationship indicates that the apparently homogeneous mantles may be cryptoperthite that has locally exsolved to microperthite. Fine-grained porphyritic rocks in the northeastern sector of the stock are relatively rich in K-feldspar but are generally non-granophyric.

As micropegmatite decrease in amount, the percentage of K-feldspar decreases and the degree of exsolution of microperthite increases. In the relatively equigranular central zone of the stock (Fig. 2) the microperthite mantling plagioclase is patchy or partly lamellar, and micropegmatite is rare. The inner limit of penetration of microperthite in plagioclase is generally linear and parallel to the edge. Discrete grains of patch perthite and partly lamellar perthite are common and contain roughly equivalent amounts of Na- and K-feldspar. A small percentage of the microperthite occurs as elongated intergrowths in quartz. This relationship is common in the porphyritic rocks intermediate in micropegmatite content.

The apparent enrichment of the granophyric rocks in potassium may be less than the data indicate. Very finely lamellar microperthite can be completely covered with stain if the etching is sufficiently severe. Some Na-feldspar may have been counted as K-feldspar where fine laminations went unnoticed. Much apparently homogeneour K-feldspar in relatively unaltered granophyre may actually be cryptoperthite containing sufficient potassium to react with the cobaltinitrite solution. The total effect of such errors can only be determined by chemical analysis.

PETROGENESIS

General Sequence of Intrusion

The western stock trends (Fig. 5 and 6) have slopes indicative of crystallization from the margins inward in accordance with Bowen's reaction series. Points at the salic ends of the trends represent the south-central portion of the stock. In Figure 6A, all points for the western stock fall within the lines connecting solid dots. The negative slope of this trend could have been predicted from Figure 4. Eastern stock points are relatively evenly distributed within the lines connecting hollow dots, with a single exception, as illustrated. The exceptional point (3.4, 7.6; Table 2), if other evidence were lacking, could be assigned to either trend. It might be possible to connect the two trends by increasing the specimen density in the vicinity of the specimen represented by the exceptional point. In Figure 6B the exceptional point plots in the western stock trend.

If field evidence to the contrary were not available (p. 55-56), one might assume that the combined trend for both stocks on Figure 5A represents a continuous trend for a single intrusion. Continuity of the total trend suggests to me that the eastern and western stocks were derived from a single magma. The close megascopic and modal similarity of rocks from the central portion of each stock supports this interpretation. Specimens of the small diorite intrusions at the southern and northeastern extremities of the eastern stock (Fig. 2) were plotted in Figures 5 and 6 and fall in the trends near the mafic end. This fact and the general megascopic similarity of the diorite of these two small intrusions to western stock diorite are evidence that the three dioritic intrusions were derived from a single source. The three dioritic stocks are probably comagmatic with the eastern stock.

Buddington's (1959) statement that earlier members of an intrusive complex generally exhibit chilling supports a proposal that the eastern stock is the oldest intrusion. The cryptoperthitic quartz monzonite may also have been early, but its exact position in the sequence of intrusion is not known. The limited field data obtained are inconclusive, but the three dioritic stocks seem to have been initially injected along fractures surrounding the partly or wholly crystalline eastern stock. Subsequent enlargement of the western stock was accomplished at least in part by stoping.

The eastern stock could be a differentiation product of a large, possibly subjacent diorite magma, of which the dioritic stocks are smaller representatives. However, the complex could as well have been produced by anatexis and intrusion of first the salic and then the more mafic constituents of the Slate Belt series. The data of this study offer no means of determining conclusively whether either of these processes was operative.

Depth of Emplacement

Buddington (1959, p. 677-80) has discussed the emplacement of granitic intrusions in the epizone (less than about 4-6 miles below the surface). The Farrington complex possesses nearly all of the epizonal features listed by Buddington. The complex apparently is discordant, though data on the adjacent country rocks are scarce. Among the other important epizonal features are the composite nature of the complex; the lack of lineation and foliation; association with a chemically similar volcanic series; low-grade metamorphism of country rock outside the contact-metamorphic zone; sharp contacts; the occurrence of miarolitic granophyre; and apparent chilling.

Crystallization of the Western Stock

The western stock was apparently entirely or almost entirely liquid at the time of intrusion. The lack of phenocrysts and flow structures suggests intrusion in a highly fluid state. Grain size is remarkably uniform throughout the stock, except at the contacts, where some slight chilling apparently occurred. Trends for the western stock in Figures 4, 5, and 6 are indicative of fractional crystallization in accordance with Bowen's reaction series. Early crystallizing marginal phases were effectively separated from all later liquids, except perhaps very late fluids that may have caused the feldspar alteration found in most specimens. Judging by the distribution of the more mafic components (Fig. 4), crystallization began at the northwestern, northeastern and southeastern extremities of the stock and proceeded southward and westward. Two explanations are available for the concentration of the least mafic material near the southwestern border: (1) gravity and magnetic data (John D. Waskom, personal communication) suggest a subsurface western and possibly southwestern extension of the stock; (2) gabbroic xenoliths along the southwestern border may represent stoped portions of an early crystallizing marginal phase similar to rocks along the eastern contact. Stoping of such material would have been facilitated by the gentle dip of the southwestern contact suggested by geophysical data. The remaining liquid would have occupied the former position of the stoped material, resulting in the present distribution of the least mafic rocks.

Origin of the Cryptoperthite Quartz Monzonite

The cryptoperthitic quartz monzonite contains some interstitial micropegmatite, but generally differs from the eastern stock in texture. Potassium feldspar is nearly white and plagioclase is buff in hand specimen. Feldspars and biotite are relatively unaltered, and K-feldspar forms very finely lamellar and possibly cryptoperthitic intergrowths with roughly equivalent amounts of plagioclase. Much of the microperthite mantles plagioclase grains, but the maximum depth of penetration of microperthite into plagioclase is commonly very irregular. Tuttle and Bowen (1958, p. 138) determined experimentally that finely lamellar intergrowths of Na- and K-feldspar can escape further exsolution only if cooled in a very dry environment following crystallization. The fine microperthite of the cryptoperthitic quartz monzonite is very similar to that illustrated by Tuttle and Bowen (Plate 2, p. 139).

The cryptoperthitic intrusion may have been derived from a lower, dryer level in the eastern stock. Boulders of rock identical in hand specimen to the cryptoperthitic quartz monzonite are sparingly admixed with diorite boulders in the diorite intrusions along the northwestern and southern borders of the eastern stock. These granitic boulders may be inclusions of eastern stock material picked up at a lower level by dioritic magma.

Crystallization in the Eastern Stock

General Statement. Textural variations in the eastern stock are rather complex. Crystallization did not proceed as a continuous, ordered process. Apparent chilling, for example, occurs adjacent to some large inclusions but not others. The non-granophyric porphyritic rocks (triangular points, Fig. 2) may represent rapid crystallization in the early stages of intrusion or upon the later addition of cooler stoped material. Evidence of initial chilling at the contacts is scant. At several locations granophyric quartz monzonite is separated from the contact by medium-grained equigranular leucogranodiorite crowded with xenoliths. The significance of this occurrence is not clear. Zones of apparently chilled rocks in the interior of the stock and the abundance of inclusions suggest that the present erosion surface is near the former roof of the stock.

Contamination. The eastern stock was apparently intruded discordantly as a quartz monzonite magma containing less than 30 percent unevenly distributed plagioclase crystals. Stoping was certainly a major factor in the enlargement of the chamber. Contamination by assimilation of stoped material seems to have been quantitatively important only where marginal zones are crowded with xenoliths. Comparison of the systems quartz-albite-orthoclase (Schairer, 1950) and quartz-anorthite-orthoclase (Schairer and Bowen, 1947; see also Levin and others, 1956, Fig. 421, p. 155) suggests that the trend for the eastern stock in Figure 6A represents crystallization along the quartz feldspar boundary in a four component system (quartz-albite + anorthite-orthoclase). A magma undergoing large-scale contamination by dissimilar material during crystallization is not likely to follow an experimentally determined crystallization trend and exhibit relatively little point scatter.

Autometasomatism. In the non-granophyric zones of the eastern stock K-feldspar occurs only in microperthite, much of which mantles plagioclase grains. The Na-feldspar of the microperthite mantles is optically continuous with the plagioclase cores. One might conclude from this evidence that the magma was initially trondhjemitic, most of the K-feldspar having been added later by metasomatic vapor-crystal or liquid-crystal reactions. According to Orville (1963, p. 227) "Vapors that reach equilibrium with alkali feldspars at high temperatures will, on cooling, be capable of replacing a certain amount of sodium feldspar by potassium feldspar." If the eastern stock solidified and cooled in the presence of a pervasive vapor phase, vapor-crystal reactions could have caused replacement of sodium by potassium throughout the stock. If this process operated on a large scale, the microperthites in the stock are replacement rather than exsolution perthites. Judging by the miarolitic texture of the granophyres and the alteration of feldspars and mafic minerals, vapor apparently was present at the time of crystallization of the stock.

Although metasomatic replacement processes were probably operative to some extent, exsolution offers a more satisfactory explanation of microperthite in the Farrington complex. Much of the microperthite intergrown with quartz in the granophyres is very finely lamellar and apparently contains equivalent amounts of Na- and K-feldspar. This type of intergrowth has been interpreted to be a product of exsolution (Tuttle and Bowen, 1958). Microperthite in the central zone is coarser grained and patchy, but the distribution of Na- and K-feldspar in some intergrowths is very regular, and may simply represent a more advanced stage of exsolution. If Schwartz's (1931, p. 195) findings on the exsolution of sulfides are applicable to feldspar mixtures, patch perthites should be an expected intermediate stage between the initial growth of very finely lamellar microperthite and the final separation into individual grains of Na- and K-feldspar (Tuttle and Bowen, 1958, Plate 6, p. 141).

Order of Crystallization in the Central Portion. Plagioclase grains mantled with microperthite in the central portion of the stock may indicate the occurrence of "an element of fractionation during crystallization" (Tuttle and Bowen, 1958, p. 134). Failure of early formed plagioclase crystals to react with the liquid for any reason enhances the possibility that alkali feldspar will precipitate around plagioclase cores during the late stages of crystallization.

If a granitic melt were crystallizing alkali feldspar at its solidus, and if the vapor pressure were increasing at a faster rate than the temperature was decreasing, resorption of alkali feldspar would result (Tuttle and Bowen, Fig. 38, p. 75). The next phase to crystallize when the solidus temperature was reattained would be quartz, if the melt were rich enough in SiO_2. Although the actual composition of the initial and late liquids of the eastern stock is not known, marked embayment of microperthite mantles and grains by quartz in the central zone and elsewhere indicates that resorption did occur, possibly as outlined above. Clusters of several subhedral plagioclase grains comprise more than one-third of many thin sections. The internal grain boundaries in these groups of crystals generally have not been affected by any sort of replacement, but the outer edges of grains on the outer margins of the crystal groups are embayed. Vapor pressure in the central zone apparently did not increase sufficiently to cause resorption until the plagioclase clusters had formed.

The least mafic granitic rocks in the Chapel Hill stock, according to Hayes' (1962) data are exceptionally rich in albite. Plagioclase phenocrysts in the eastern stock of the Farrington complex, while also Na-rich, appear to be richer in oligoclase, especially in the central portion of the stock. Sodium-rich plagioclase in granitic rocks can be explained by assuming that Tuttle and Bowen's data (1958, Fig. 66, p. 135) are applicable to plutonic rocks. There seems to be no theoretical objection to making the extrapolation from extrusive to plutonic rocks. Yoder, Stewart and Smith (1957) have shown that an increase in water pressure decreases the slopes of tie lines in the system Ab-Or-An-H_2O, so that alkali feldspar is in equilibrium with sodium-rich plagioclase. The distribution of albite in the Farrington complex may have been a function of water pressure, but the data obtained on the An content of plagioclase are not sufficient to make a determination.

Crystallization of the equigranular central zone of the stock may have proceeded as follows: (1) precipitation of phenocrysts in the oligoclase range, until a mush of clusters of these crystals existed; (2) reaction of the crystals with the liquid, which became increasingly interstitial as alkali feldspar and relatively large grains of quartz began to form; (3) crystallization of an interstitial melt of quartz and alkali feldspar, some of the alkali feldspar forming mantles on the exposed portions of early-formed plagioclase grains. A final stage involved resorption of some alkali feldspar, followed by the crystallization of quartz, as the vapor phase exerted a higher pressure due to expulsion during cyrstallization of the melt. Alteration of plagioclase and mafic minerals probably intensified at this stage. Some of the late SiO_2-rich liquid-vapor phase escaped fo form aplite dikes. Exsolution of alkali feldspar began as soon as the temperature permitted.

Origin of Granophyric Texture. The origin of granophyric texture is of obvious importance in interpreting the crystallization history of the eastern stock. Rocks at specimen location 7.5 near the southwestern extremity of the stock exhibit strongly developed granophyric texture. This specimen contains relatively unaltered plagioclase phenocrysts, a small amount of unaltered biotite, and very finely lamellar microperthite. Some of the other granophyre specimens exhibit relatively more altered plagioclase, but also contain very finely lamellar microperthite. The logical conclusion is that the granophyric zones remained relatively dry during the cooling period that followed crystallization. In contrast, in the central zone and the non-granophyric porphyritic rocks plagioclase and mafic minerals are more severely altered, alkali feldspar has exsolved so that patch perthites predominate, and micropegmatite is virtually absent. The porphyritic rocks intermediate in micropegmatite (Fig. 2) exhibit textural features of both the granophyres and rocks of the equigranular central zone, and may have had cooling rates and water content intermediate in relation to the granophyres and equigranular rocks.

Potassium feldspar in granodiorite and leucogranodiorite in the south-central portion of the western stock is buff to pink, in contrast to the gray tones of the remainder of the stock. Transition from gray to pink, where studied, takes place in granodiorite and is completed in about 200 feet. The only consistent detectable mineralogical change is a marked increase in the degree of alteration of feldspars and mafic minerals in the pink feldspar rocks. The degree of exsolution of microperthite is slightly greater in the pink rocks. Micropegmatite was not observed in the pink rocks, whereas the gray feldspar rocks contain small amounts of interstitial micropegmatite. The vapor phase of the western stock probably accumulated in the south-central portion with the late residua and caused the alteration and pink coloration of the feldspar. However, the alteration could have been caused by localized post-magmatic metasomatism. In either case micropegmatite occurs in the western stock only in rocks that have not been strongly altered. A similar situation exists in the eastern stock, as outlined above. Micropegmatite in the Farrington complex has apparently survived only in those rocks where recrystallization of the quartz-feldspar intergrowths was inhibited by suppression of the fluxing effect of the vapor phase. In the western stock the vapor content of rocks containing micropegmatite was apparently very low during and following crystallization.

Miarolitic texture indicates that the granophyric zones of the eastern stock, although not severely altered, were saturated with a vapor phase during crystallization. The seeming conflict of the above statement with conclusions reached in the preceding paragraph can be resolved by assuming that the vapor phase in the granophyres was lost during or immediately following crystallization. Morey and Hesselgesser (1951) have shown experimentally that alkali silicates are extremely soluble in superheated water at high pressure, and that release of pressure causes a sharp decrease in solubility. The inception of fracturing around the eastern stock could have resulted in rapid loss of vapor and a concomitant decrease in pressure. Much of the alkalis dissolved in the vapor would have remained behind the escaping vapor due to the solubility decrease (Kennedy, 1955, p. 498). If such a process did operate, textural relationships in the granophyre (euhedral plagioclase "floating" in micropegmatite) suggest that the saturated marginal melt was at its liquidus at the time of rupture of the walls. Loss of a substantial amount of vapor would have caused rapid crystallization of the alkali-rich melt and the expulsion of more vapor. Provided the fractures remained open, crystallization would have been completed much more rapidly than if temperature alone had been the controlling factor. Rapid disequilibrium crystallization would account for the very fine-grained micropegmatitic groundmass in some of the granophyres, the multiple zoning of plagioclase phenocrysts, and the mantling of some plagioclase phenocrysts with K-rich feldspar (Stewart and Roseboom, 1962, p. 309). Loss of most of the vapor would certainly have retarded post-crystallization alteration, exsolution and recrystallization reactions in the granophyres.

If crystallization of the eastern stock proceeded as in the system quartz-albite + anorthite-orthoclase, the alkali-rich granophyric margins represent late residua, and must have crystallized last. Kennedy (1951) has shown that volatile constituents in a rock melt should tend to be so distributed that the total vapor pressure at all points in the melt will be equal. Consequently, the vapor phase will tend to concentrate in the cooler portions of the melt, lowering the freezing point of mineral constituents in that portion of the melt. Provided that the cooler zones are marginal, and the vapor cannot escape, crystallization of a magma from the center outward is theoretically feasible.

The small central subzone of granophyre may mark the location of an eroded roof pendant. Unless the magma were in contact with a pendant, a persistent inward negative temperature gradient would be implausible, and no avenue of escape for volatile constituents would exist.

Enrichment of the granophyric zones in alkalis may have been partly due to migration of the highly soluble alkali ions in solution in the vapor phase. The extent to which this process occurred could not be determined from the available data.

<u>Two-intrusion Hypothesis</u>. Much of the discussion of eastern stock data is based on the assumption that the stock represents a single

intrusion, differentiated in place. This assumption is based on the gradational mineralogical and textural variations in the stock, and may not be valid; that is, the melt could have been differentiated at a lower level and intruded as a series of stocks. The initial intrusion in the complex could have been an alkali-rich melt represented by the granophyres. The equigranular central zone of the eastern stock could have been intruded later, but before the initial intrusion had cooled. Extensive reaction between the second magma phase and the first intrusion, facilitated by any associated vapor, could presumably have produced a transition between the two intrusions. If so, the fact that the cryptoperthitic quartz monzonite (apparently an early intrusion) and some of the granophyre escaped significant alteration during the intrusion of the central zone must be explained.

SUMMARY OF PREFERRED THEORY

The eastern stock of the Farrington complex was emplaced discordantly in the epizone as a quartz monzonite magma containing less than 30 percent plagioclase crystals. Stoping was a major factor in the enlargement of the stock. Crystallization apparently began in the equigranular central zone, the alkali-rich residua meanwhile accumulating in the granophyric zones. Crystallization of the granophyric zones was apparently delayed by the fluxing action of the vapor phase, until crystallization had advanced to an undetermined stage in the central zone. The granophyres crystallized rapidly, though apparently late, possibly upon loss of vapor by fracturing of the walls.

The survival of micropegmatite in the plutonic environment of the complex seems to have been greatly enhanced by cooling of the rocks in a fairly dry environment. The dry environment was apparently produced by crystallization from a fairly dry melt, as in the western stock, or by loss of the vapor phase, as in the granophyres of the eastern stock. The fine-grained, non-granophyric porphyritic rocks of the eastern stock may have resulted from chilling in the presence of a vapor phase.

All intrusions in the complex are apparently comagmatic. The western stock and the two small diorite stocks were apparently initially injected along fractures around the eastern stock. Stoping was an important factor in the enlargement of the western stock. Crystallization of the western stock apparently began at the northwestern, northeastern, southeastern and possibly southwestern margins and proceeded inward in accordance with Bowen's reaction series. Late residua and the vapor phase accumulated in the south-central portion of the stock.

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VIRGINIA METAMICT MINERALS: COMMENTS ON A URANIUM-NIOBIUM OXIDE FROM POWHATAN COUNTY

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ABSTRACT

A metamict olive-brown uranium-niobium mineral occurs at the old White Peak No. 1 mica mine, Powhatan County, Virginia. The rough, weathered crystals were presumably orthorhombic, although the mineral is now amorphous to X-rays. Samples heated at 300° C and above develop a hexagonal UNb_2O_8 phase which probably is not equivalent to the original unmetamict material. Physical, X-ray, and chemical data are presented, and the occurrence is briefly described. The material may be a new mineral; or possibly it is a very altered uranium-rich samarskite.

INTRODUCTION

During an investigation of various metamict minerals which occur in Virginia a material quite unlike the well-known species was noticed. The mineral, discovered in 1954 by W. D. Baltzley of Amelia, Virginia, occurs in a weathered dump at the abandoned White Peak No. 1 mica mine, near Flat Rock, Powhatan County, Virginia. At least 10 pounds of the mineral have been collected.

Acknowledgments

The writer wishes to express his thanks to W. D. Baltzley, Amelia, Virginia, who supplied specimens for study; and to D. Gottfried, U. S. Geological Survey, who investigated the optical properties. F. B. Fitzgerald, III, and L. M. Ferguson, students at the University of Virginia, kindly assisted in some phases of the work. This research was supported in part by a grant from the Sigma Xi-RESA Research Fund.

PHYSICAL AND CHEMICAL PROPERTIES

The mineral occurs as irregular masses and rough tabular crystals. The largest piece is a cluster of imperfect crystals which weighs 1.4 pounds and measures 4.25 inches in its greatest dimension. Although it was not possible to establish the crystal morphology with accuracy, because of the altered and rough condition of the faces, for the sake of a description the writer has assumed the crystals are orthorhombic, flattened parallel to the {010} and elongated slightly along {001}. The habit is rather simple, consisting of {010}, {100}, and a well-developed macrodome {h0l}. The interfacial angle between {100} and {h0l} is from 130° to 135°. The habit is analogous to many samarskite crystals. On one of the crystals the line joining the {h0l} and {$\bar{h}$0l} faces appears to be slightly oblique rather than perpendicular to the assumed {100}. If true this would cast some doubt on the orthorhombic symmetry. Some single crystals measure over 1.5 inches in length.

The mineral is light to moderate olive brown, with a yellowish-gray streak. It is brittle and has a conchoidal fracture which is resinous to adamantine. The hardness is about 5, and the specific gravity which is somewhat variable, is approximately 3.8. Although the optical properties are quite variable the mineral is essentially isotropic and has an index of refraction near 1.83 (D. Gottfried, personal communication, 1964). Very low birefringence was noted in some fragments. The mineral is strongly radioactive. Most of the specimens have a thin, moderate orange-pink alteration crust. X-ray diffraction photographs indicate this dull earthy crust is composed mainly of a single compound with the pyrochlore structure. Its three most intense diffraction lines are at 3.03 Å, 1.86 Å, and 1.59 Å, and $\underline{a}$ = 10.52±0.05 Å.

X-ray powder films of the apparently fresh mineral show no reflections, a condition typical of amorphous metamict substances. The effect of heat on the mineral was studied. Separate samples were heated in air for one hour each at 100° intervals from 200° through 1000° C. The 200° sample was amorphous; the 300° sample showed the strongest X-ray reflection for a hexagonal UNb_2O_8 phase. Samples heated at intervals from 400° through 800° showed nearly pure UNb_2O_8. In these the intensities and sharpness of the lines increased with increasing temperature. At 900° the material showed very sharp UNb_2O_8 reflections with a few additional weak lines. The 1000° sample showed a very strong UNb_2O_8 pattern with distinct lines of an additonal phase or phases, including the extra lines observed in the 900° sample. Specimens heated for longer times showed no essential differences for the given temperatures. Impurity lines for columbite-tantalite occasionally were observed on some of the X-ray films, but this was expected because of the intimate association of the mineral with columbite-tantalite. The UNb_2O_8 phase was easily identified because of its similarity to UTa_2O_8 reported by Gasperin (1960). The measured X-ray powder data for UNb_2O_8, listed in Table 1, are the averaged values obtained from 8 films made in two cameras (11.46 cm diameter) with CuKα radiation. The calculated interplanar spacings were derived from the following hexagonal unit cell values determined from partially indexed powder data: $\underline{a}$ = 6.39 Å, $\underline{c}$ = 4.02 Å; $\underline{a}$:$\underline{c}$ = 1:0.629. After considerable study the writer

Table 1. X-ray powder diffraction data for hexagonal UNb_2O_8 phase formed when U-Nb oxide mineral is heated in air.

hk. l	d (calc.)	d(obs.)	I (obs.)
10.0	5.53		
00.1	4.02	4.02	s
10.1	3.25		
11.0	3.20	3.19	vs
20.0	2.77		
11.1	2.50	2.50	ms
20.1	2.28		
21.0	2.09		
00.2	2.01	2.01	w
10.2	1.89		
21.1	1.86		
30.0	1.85	1.84	m
11.2	1.70	1.70	mw
30.1	1.68	1.67	mw
20.2	1.63		
22.0	1.60	1.60	w
31.0	1.54		
22.1	1.49	1.48	w
21.2	1.45		
31.1	1.43		
40.0	1.38		
30.2	1.36	1.36	w
00.3	1.34		
40.1	1.31		
10.3	1.30		
32.0	1.27		
22.2	1.25	1.25	vw
11.3	1.24		
31.2	1.22		
32.1, 41.0, 20.3	1.21	1.21	vw
41.1	1.16	1.16	vw

was still unable to identify the additional lines in samples heated at 900° and above. Typical X-ray data for a 1000° sample are given in Table 2. Data for the UNb_2O_8 phase in this table are underlined. Although the UNb_2O_8 structure dominates all X-ray patterns of heat-treated material, it is not likely this is the composition of the original mineral. The crystals have habits which are not compatible with the hexagonal structure of UNb_2O_8.

Table 2. X-ray powder diffraction data for U-Nb oxide mineral heated in air at 1000° C. Definite UNb_2O_8 reflections are underlined. CuK_α radiation; camera diameter 11.46 cm.

d (obs.)	I (obs.)	d (obs.)	I (obs.)
5.91	w	2.17	vw+
4.98	w	2.02	m
4.04	s	1.83	ms
3.58	w	1.79	vvw
3.44	vw	1.73	vvw
3.34	vvw	1.70	ms-
3.18	vs	1.67	ms
3.03	vw	1.59	m
2.91	mw	1.57	vvw
2.75	vvw	1.51	vvw
2.50	s-	1.48	m
2.45	vvw	1.43	vw
2.37	vw	1.36	m
2.29	vw	1.25	mw
2.19	vw+		

Semiquantitative spectrographic analyses were made of two specimens. These data are presented in Table 3. The principal constituents are U and Nb, but there are considerable amounts of Y, Si, Fe, etc. The mineral is probably an oxide of uranium and niobium, containing considerable yttrium rare earths. Quantitative chemical analyses will be necessary before a formula can be established. Weight lost by heating at 600° for 12.5 hours was 10.41%. The water may be nonessential, a result of metamictization.

ASSOCIATED MINERALS AND OCCURRENCE

The U-Nb oxide mineral is frequently associated with columbite-tantalite. They are often intergrown, and apparently there is sometimes a preferred orientation of one with respect to the other, although this is difficult to prove because of the weathered condition of the specimens. Several large masses of black splendent samarskite, and a small amount of massive, greasy, brownish-black euxenite, have also been found at the deposit. Brief descriptions of the pegmatite have been published by Jahns and Griffitts (1953, p. 178) and Brown (1962, p. 96). The body is an asymmetrical nearly vertical lens, with an overall length of at least 220 feet, a maximum width of about 30 feet, and a keel at least 45 feet deep. The lens is discordant to the foliation of the enclosing migmatized biotite gneiss. A light-gray massive quartz core, with a maximum thickness of 12 feet, extends throughout the length of the dike. Casts and remnants of kaolinized feldspar crystals (perthite), up to 6 feet across, occur in the

Table 3. Semiquantitative spectrographic data on metamict U-Nb oxide mineral. Analyst: F. W. Barley, American Spectrographic Laboratories, San Francisco.

Element (as oxide)	Specimen #V3023d	Specimen #V3029d
Mg	< .005	.05
Al	1.	1
Si	3.5	1.5
Ca	.02	.03
Sc	.01	
Ti	1.	1.5
Mn	.005	.2
Fe	2.5	4.
Cu	.01 (?)	.01 (?)
Y	2.5	10.
Zr	.75	.75
Nb	20.	30.
Sn	.1 (?)	.1 (?)
Ba	.2	.2
Gd	.2	.25
Dy	-	1.
Er	-	.03
Yb	.03	.05
Ta	1.	-
Pb	.5	-
Th	1.5 (?)	5
U	40.	P.C. *

*P.C. = principal constituent.

quartz. Graphic granite, plagioclase (kaolinized), muscovite (one block weighed about 900 pounds), and biotite also occur in the deposit. The rare earth and niobium minerals were found only in the weathered dump subsequent to mining operations which ceased in 1944.

DISCUSSION

Although considerable data are now available the writer hesitates to assign a definite name to the mineral. A consideration of Van Wambeke's (1960) classification of metamict minerals, based on chief chemical components, shows the material may fall into his category (2) Nb, Ta metamict minerals, poor in Ti (<10% TiO_2); (a) Rich in rare earths, Nb, Ta, with Nb > Ta. In this category he places fergusonite and samarskite. Other categories were eliminated from consideration because they require considerable Ti (betafite, euxenite, priorite), or Ta (yttrotantalite, formanite), or Ca (pyrochlore), etc.

Some of these also involve a different crystal habit. Because of a similarity in the X-ray data for heated samples of the U-Nb oxide mineral and data reported by Frondel (1958, p. 325) for heated samiresite (lead-rich betafite), it was earlier believed the U-Nb oxide might be betafite (Fitzgerald and Mitchell, 1961). This possibility is now eliminated on the basis of chemical composition and crystal morphology. The similarity is due to the fact that ignited betafite under certain circumstances also contains the UNb_2O_8 structure (Gasperin, 1960).

Fergusonite was eliminated as a possibility on the basis of X-ray data, and crystal morphology. Also fergusonite generally requires more rare earths and less uranium in its structure.

Samarskite, on the other hand, needs more consideration. Chemically samarskite, which is an oxide of rare earths (as well as U, Ca, Fe, etc.) and niobium (as well as Ta, Ti, etc.), compares rather well with the semiquantitative spectrographic analyses for the U-Nb oxide given in Table 3. A possible difference may be the very high U and relatively low rare earth content of the U-Nb oxide mineral. However, analyses in which U oxides exceed rare earth oxides are known for samarskite (Palache, et al., 1944, p. 798). Ishikawaite, for example, is a samarskite (Strunz, 1957, p. 158) with 21.88% UO_2 and 8.40% $(RE)_2O_3$. Although the morphology of the U-Nb oxide is somewhat uncertain, the interpretation outlined earlier compares well with that for samarskite. The angle between {100} and {h0l} is from 130° to 135° while the angle between 100} and {101} for samarskite is 133°30' (Palache et al., 1944, p. 797). The chief problem arises when the X-ray data are considered. Van Wambeke (1960), in his study showing the identity of ampangabeite with samarskite, gave X-ray data for 17 specimens heated in air at 950° C. Each of these patterns contains UNb_2O_8 lines, but these are subordinate to other lines, including those for the pyrochlore structure. In each of these 17 cases the most intense lines fall either at approximately 2.97 Å or 2.90 Å, lines missing on the U-Nb oxide patterns. On the other hand Van Wambeke (1960) also gave X-ray data for 9 samples of altered samarskite (and ampangabeite). In these the most intense reflection is at approximately 3.16 Å (close to the most intense UNb_2O_8 line), while the lines at approximately 2.97 Å and 2.90 Å are present but relatively weak. The UNb_2O_8 structure definitely dominates these patterns; but the pyrochlore pattern, as well as other reflections, are still present. Aside from the UNb_2O_8 pattern, the writer found no good correlation between these extra lines and the extra lines found on his films for the U-Nb oxide mineral heated above 900°. Van Wambeke (1960) showed that in the weathering of samarskite there is a very pronounced leaching of Y and a less pronounced leaching of U. Other rare earths and Ca are also leached. The Nb, Ta, and Th content is not changed, and Pb is enriched. The specific gravity of altered samarskite (and ampangabeite) reported by Van Wambeke (1960) varies from 3.37 to 3.88, which is in agreement with the U-Nb oxide mineral value of 3.8

In conclusion, the U-Nb oxide may be a new mineral, but the possibility that it is an altered uranium-rich samarskite cannot be eiliminated.

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COMPOSITION OF MINERAL WITHIN THE WALL ROCKS OF A GRANITIC BATHOLITH

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ABSTRACT

Samples from metamorphic wall rocks of the Enchanted Rock batholith, Llano Uplift, Texas, were collected along four profiles from margins of the batholith outward. Major and trace element analyses were performed on biotite, K-feldspar, and plagioclase separates, as well as on the bulk rocks. Evidence is presented to demonstrate that (1) some of the rocks apparently have been metasomatized; (2) others have been at least partially fused; and (3) compositions of constituent minerals within the remainder have not been noticeably affected by processes accompanying the intrusion of the granite.

INTRODUCTION

Factors which may affect the nature of compositional variations within the wall rocks of a pluton are: (1) original composition and geologic history of the country rock; (2) composition of the intrusive; (3) temperature and water pressure within the intruding body; (4) depth of burial; (5) regional tectonics; and (6) size and shape of the intrusive. If a series of heterogeneous rocks has been subjected to regional as well as contact metamorphism, it becomes extremely difficult, if not impossible, to determine to what extent the above factors exerted an influence upon the compositions of the wall rocks and their constituent minerals. An attempt can be made, however, to determine to what degree the composition is controlled by the effect of (1) contact metamorphism and metasomatism, (2) regional metamorphism, and (3) pre-metamorphic rock type and composition.

The purpose of this investigation is to assess the variability in the composition of biotite, potassium feldspar, and plagioclase within the gneisses and schists around the Enchanted Rock batholith, Llano Uplift, Texas. An attempt was made to determine to what extent the composition of the minerals and bulk rocks was affected by contact metamorphism, regional metamorphism, and composition of the rocks before metamorphism. In this way the study will hopefully elucidate the petrogenesis of the various rock types within the wall rocks. This batholith was chosen because (1) it and the surrounding wall rocks have been well mapped (Hutchinson, 1956); (2) good outcrops are available; (3) it is a large pluton which has intruded several metamorphic lithologies; (4) it is reported to be a syntectonic intrusion (Hutchinson, 1956); and (5) its shape at depth and attitude against the wall rocks are known.

ACKNOWLEDGMENTS

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PREVIOUS WORK

Previous studies concerning chemical effects in contact aureoles have almost all been confined to studies of the bulk rocks. They illustrate that the most important factor governing systematic chemical variations is the pre-intrusion composition of the country rocks. Systematic chemical trends within a contact aureole are masked when an intrusive is injected into a heterogeneous rock unit. Higazy's (1952) study of an epidiorite and its associated skarns illustrates this point. The contact aureole around the epidiorite is non-systematically enriched and depleted in major elements. Their distribution is probably best explained by heterogeneity within the country rocks before intrusion.

Chao (1951) has studied chemical variations in several aureoles around granitic plutons, and his data lead to some interesting observations. Chemical changes associated with the intrustion of a Jurassic granophyre into a sandstone on the island of Skye are exemplified by the progressive increase of silica and decrease of the other rock-forming cations from the contact into the wall rocks. The contact aureole around a pegmatite which has been intruded into a limestone from Sweden is progressively enriched in calcium and depleted in the other major rock-forming cations away from the contact. These trends are not surprising; indeed, there would be cause for alarm if they were not observed. However, Chao did observe more complex patterns. For example, chemical changes associated with the contact between the Breven dolerite dike and a granophyre in Sweden suggest the formation of a "basic front." Compositional variations along a zone within the contact aureole are characterized by the enrichment of Fe, Ca, and Mg associated with the depletion of the alkali metals and silica.

The intrusion of some granitic bodies apparently has had only minor chemical effects upon the surrounding country rocks. Pitcher and Sinha (1957) have described a granodioritic pluton and its associated hornfels from County Donegal, Ireland. Apparently the granodiorite has had little chemical effect upon the surrounding hornfels. The only major rock-forming cation that systematically varies is Mg, which is progressively depleted toward the contact.

Other general studies of wall rock and xenolith alteration include: Evans (1964), Compton (1960), Farrand (1960), Leake and Skirrow (1960), Tilley (1951), Walker and Mathias (1946), and Nockolds (1933). Many studies of wall-rock alteration around ore bodies have been published, but they are outside the scope of this paper and will not be considered here.

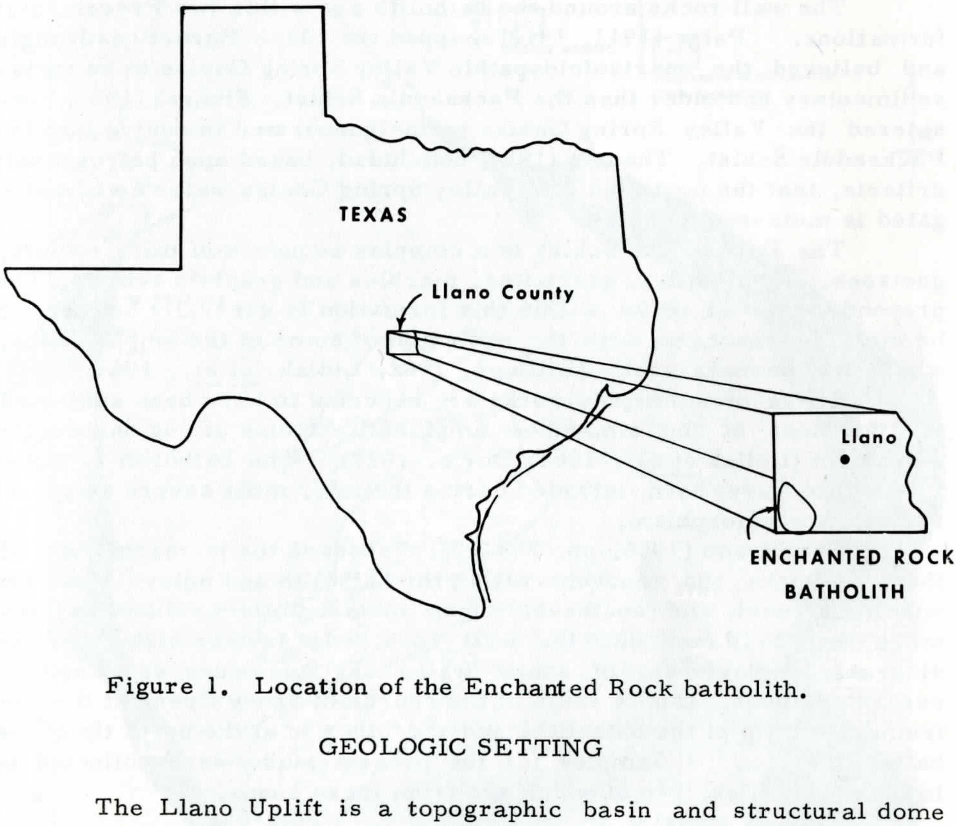

Figure 1. Location of the Enchanted Rock batholith.

GEOLOGIC SETTING

The Llano Uplift is a topographic basin and structural dome consisting of extensively eroded Precambrian metamorphic and igneous rocks flanked by Cretaceous limestones. The Enchanged Rock batholith is one of several granitic plutons lying within the framework of the Precambrian schist and gneiss complexes in the Llano Uplift. The batholith crops out over an area of approximately 90 square miles in the southwestern corner of Llano County and the northern portion of Gillespie County, Texas (Figure 1). It is pear-shaped and elongate NW-SE, parallel to the regional strike of the tightly folded metamorphic wall rocks.

Hutchinson (1956) has noted that the northern third of the pluton.

is phacolithic and is in contact with the Valley Spring Gneiss. The southern two-thirds of the pluton is generally discordant against the approximately vertically dipping Packsaddle Schist, although foliation within the schist boxes the compass around the pluton. The batholith is intruded into the southeasterly plunging (35^{o} - 40^{o}) Castell Syncline.

Geophysical data on the shape of the pluton at depth are limited to a magnetometer survey along the southwestern flank of the body (Barnes et al., 1954). The survey indicates that the granite-schist contact dips steeply to the southwest.

The wall rocks around the batholith are within two Precambrian formations. Paige (1911, 1912) mapped the Llano-Burnet quadrangle and believed the quartzofeldspathic Valley Spring Gneiss to be meta-sedimentary and older than the Packsaddle Schist. Stenzel (1934) considered the Valley Spring Gneiss meta-igneous and intrusive into the Packsaddle Schist. Thames (1957) concluded, based upon petrographic criteria, that the portion of the Valley Spring Gneiss which he investigated is meta-sedimentary.

The Packsaddle Schist is a complex sequence of mica schists, gneisses, amphibolites, quartzites, marbles and graphite schists. The preponderance of rocks within this formation is generally believed to be meta-sedimentary, with the exception of some of the amphibolites, which may be metabasalts (Billings, 1962, Lidiak, et al., 1961).

These metamorphic rocks are reported to have been subjected to conditions of the almandine amphibolite facies of regional metamorphism (Lidiak et al., 1961, Doyle, 1957). The batholith is considered to have been intruded during the late, most severe stages of regional metamorphism.

Hutchinson (1956, pp. 789-792) discusses the metasomatism of the wall-rocks and xenoliths within the batholith and notes "Along the northeast, east, and southeast edges metasomatism seldom extends more than 5-10 feet into the wall rock." He further states: "Considerable replacement of schist wall rocks has occurred along two separated zones. One is south of the source of Sandy Creek at the extreme south tip of the batholith, and the other is at the north tip of the batholith ...." Samples for the present study were collected along four profiles, two of which are from these zones.

METHODS OF INVESTIGATION

Samples were collected along four profiles from the margins of the batholith outward (Figure 2 and Table 1). Three of the profiles, the western, southeastern, and southern were collected in the Packsaddle Schist, whereas the northern profile was collected in the Valley Spring Gneiss. Rocks from the southern profile, which Hutchinson (1956) has mapped as "migmatite", and the northern are those thought by Hutchinson to have undergone considerable replacement.

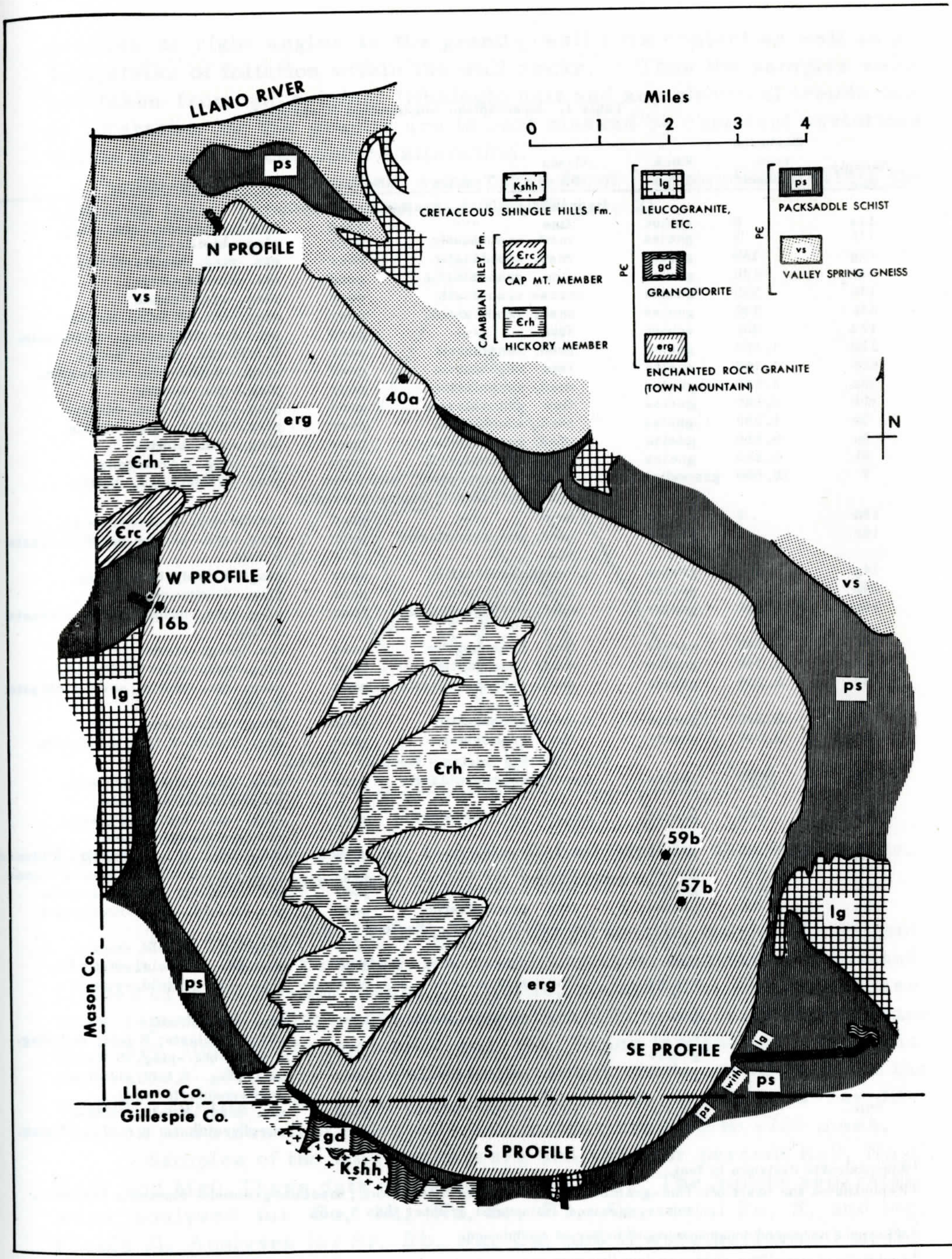

Figure 2. Sample locality map showing the locations of the four profiles and the xenoliths (geology modified from Hutchinson, (1956).

Unfortunately, it was impossible to collect samples along

Table 1. Description and location of samples.

Sample No.	Distance from Contact[1]	Rock Type	Grain Size[2]	Texture	Foliation	Mineralogy[3]
			Packsaddle Schist - Southeastern Profile			
13e	0	schist	fine	---	good	biotite-muscov. -qtz. -plag.
13f	5	gneiss	med.	xenoblastic	poor	plag. -biotite-qtz.
13g	130	gneiss	med.	xenoblastic	poor	qtz. -plag. -biotite-K feld.
13i	130	gneiss	fine	granoblastic	good	qtz. -biotite-plag.
13n	530	gneiss	coarse	xenoblastic	poor	plag. -qtz. -biotite
13t	790	gneiss	med.	xenoblastic	poor	plag. -qtz. -K feld. -biotite
13l	900	schist	fine	---	good	sericite-biotite-qtz. -sillimanite
12a	1,160	gneiss	med.	xenoblastic	poor	K feld-qtz. -plag. -biotite
12b	1,160	gneiss	fine	xenoblastic	good	plag. -biotite-qtz. -sillimanite
10a	2,640	gneiss	med.	xenoblastic	poor	plag. -qtz. -biotite
10b	2,640	gneiss	fine	granoblastic	good	plag. -qtz. -K feld. -biotite
9a	5,280	gneiss	med.	xenoblastic	poor	plag. -K feld. -qtz. -biotite
8a	6,850	gneiss	med.	xenoblastic	poor	plag. -qtz. -biotite
8b	6,850	gneiss	fine	granoblastic	good	qtz. -plag. -hornblende
7	10,500	granodiorite	med.	xenomorphic	massive	plag. -K feld. -qtz. -biotite
			Packsaddle Schist - Southern Profile			
14b	0	schist	fine	---	good	biotite-qtz. -muscov. -plag.
14c	0	gneiss	med.	porphyroblastic	poor	plag. -qtz. -biotite, porphyroblasts: K feld.
14g	200	gneiss	f. -med.	xenoblastic	poor	plag. -K feld. -biotite-qtz.
14h	320	gneiss	med.	xenoblastic	poor	plag. -biotite-qtz.
14i	780	gneiss	med.	porphyroblastic	poor	plag. -qtz. -biotite, porphyroblasts: K feld.
14l	1,340	gneiss	fine	granoblastic	good	qtz. -plag. -biotite
14m	1,340	gneiss	med.	xenoblastic	poor	plag. -qtz. -chlorite-K feld.
14o	2,230	gneiss	med.	porphyroblastic	poor	plag. -qtz. -biotite, porphyroblasts: K feld.
14p	2,230	gneiss	f. -med.	xenoblastic	good	plag. -qtz. -biotite
14r	2,540	gneiss	fine	granoblastic	good	qtz. -biotite-K feld. -actinolite
			Valley Spring Gneiss - Northern Profile			
15b	100	gneiss	coarse	porphyroblastic	poor	plag. -qtz. -biotite-h'blende porphyroblasts: K feld.
15d	300	gneiss	coarse	porphyroblastic	poor	plag. -qtz. -biotite-h'blende porphyroblasts: K feld
15f	380	gneiss	coarse	xenoblastic	poor	plag. -qtz. -K feld. -biotite-h'blende
15e	430	gneiss	med.	xenoblastic	poor	plag. -qtz-K feld. -biotite-h'blende
15g	640	gneiss	fine	granoblastic	poor	qtz. -plag. -K feld. -muscovite
15h	780	gneiss	fine	granoblastic	poor	qtz. -K feld. -plag. -muscovite
			Packsaddle Schist - Western Profile			
16e	20	gneiss	med.	xenoblastic	poor	plag. -qtz. -K feld. -biotite
16f	400	gneiss	fine	granoblastic	good	qtz. -plag. -K feld. -biotite
16g	640	gneiss	fine	granoblastic	good	plag. -qtz. -K feld. -biotite
				Xenoliths[4]		
16b	---	gneiss	fine	porphyroblastic	poor	qtz. -plag. -biotite porphyroblasts: K feld, and plag.
40a	---	gneiss	med.	xenoblastic	poor	K feld. -qtz. -plag. -h'blende
57b	---	gneiss	fine	porphyroblastic	poor	qtz. -plag. -K feld. -biotite porphyroblasts: plag.
59b	---	gneiss	fine	porphyroblastic	good	qtz. -plag. -K feld. -biotite porphyroblasts: K feld. and plag.

[1] Approximate distance in feet.

[2] Reported on the basis of: fine-grained - diameter less than 1 mm.; medium-grained - diameter 1-5 mm.; coarse-grained - diameter greater than 5 mm.

[3] Minerals arranged in approximate order of abundance.

[4] Location of xenoliths shown on locality map.

profiles at right angles to the granite-wall rock contact as well as along strike of foliation within the wall rocks. Thus the samples were not taken from an original lithologic unit and any chemical trends due to alteration by the granite are in part masked by chemical variations within the wall rocks before alteration.

In addition, samples were taken from four xenoliths within the batholith (nos. 16b, 40a, 57b, and 59b, Figure 2).

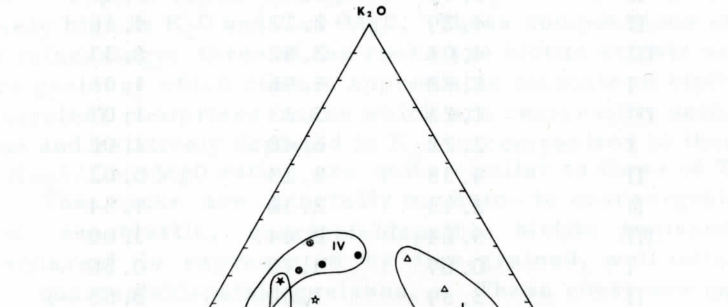

Figure 3. Ternary plot of K_2O-Na_2O-CaO+MgO in the bulk rocks. Roman numerals refer to rock types.

The samples were initially crushed to -100 mesh. An aliquot of each was then removed for partial major element analysis and further crushed to -200 mesh. Biotite, K-feldspar, and plagioclase were separated, where possible, from the -100 mesh fraction by means of heavy liquids (bromoform) and the Franz isodynamic magnetic separator. Mineral separations were not made on rocks from the southern profile. Each separate was checked for purity by x-ray diffraction and refractive index oils and further crushed to -200 mesh.

Samples of the bulk rocks were analyzed for percent K_2O, Na_2O, CaO, and MgO. These data are given in Table 2. The biotite separates were analyzed for Co, Ni, Na, Sr, Rb, Ca, total Fe, K, and Mg (Table 3). Analyses for Sr, Rb, Na, Ca, and K were performed on the K-feldspar and plagioclase separates (Tables 4 and 5). The analytical techniques employed and the precision of each are given in Table 6. The location and a brief description of each sample are listed in Table 1.

Table 2. Na_2O, K_2O, CaO, and MgO analyses of bulk **rocks.**

Sample No.	Rock Type	Na_2O	K_2O	CaO	MgO
7		4.05	3.95	4.34	2.27
8a	II	4.60	2.40	4.32	2.41
8b	III	3.17	0.30	5.14	1.03
9a	II	3.35	3.77	3.06	1.82
10a	II	4.29	2.12	4.16	2.04
10b	III	4.04	2.82	2.33	3.24
12a	I	1.58	5.96	1.05	1.80
12b	III	1.23	3.23	1.07	2.14
13e	I	2.22	6.40	1.02	4.66
13f	II	4.35	3.25	3.02	3.99
13g	II	2.13	2.36	1.54	3.47
13i	III	3.64	2.64	3.00	1.80
13l	I	0.67	4.78	0.38	4.30
13m	II	3.89	3.00	3.55	2.29
13t	II	3.40	3.49	2.93	1.86
14b	I	1.73	5.63	1.72	4.08
14c	II	3.46	3.69	2.46	1.25
14g	III	2.56	5.50	4.12	5.03
14h	II	3.79	3.43	4.39	2.74
14i	II	3.84	4.27	3.76	2.60
14l	III	2.36	2.49	1.84	2.87
14m	II	3.68	2.67	2.65	1.78
14o	II	3.37	2.43	3.16	1.39
14p	III	2.30	4.54	2.06	2.95
14r	I	1.27	5.66	1.22	2.52
15b	V	3.26	3.63	2.46	0.96
15d	V	3.67	3.09	2.42	1.21
15e	V	3.23	4.19	1.71	0.61
15f	V	3.78	3.22	3.21	1.51
15g	IV	2.42	4.70	0.64	0.59
15h	IV	1.97	5.35	0.58	0.61
16b	VI	4.20	3.43	1.34	0.21
16e	IV	3.08	5.25	0.68	0.26
16f	IV	1.86	3.82	0.40	0.16
16g	IV	3.72	3.98	0.49	0.06
40a	VI	3.35	4.98	0.59	0.20
57b	VI	3.61	3.47	1.14	0.56
59b	VI	3.60	3.99	1.53	4.40

Figure 3, a ternary plot of Na_2O-K_2O-CaO+MgO, demonstrates the gross chemical relationships between the various sampled rock types. Six rock types are recognized on the basis of their bulk chemistry, lithology, and location. Each rock type is represented by the same symbol on all figures.

Types I, II, and III comprise rocks from within the Packsaddle Schist. Type I (open triangles) is characterized by compositions relatively high in K_2O and CaO+MgO. These compositions are reflected in the mineralogy; three of the rocks are biotite schists and the other two are gneisses which contain appreciable amounts of biotite. Type II (open circles) comprises rocks which are remarkably uniform in composition and relatively depleted in K_2O in comparison to those of Type I. Their Na_2O/CaO+MgO ratios are quite similar to those of Type I, however. The rocks are generally medium- to coarse-grained, poorly foliated, xenoblastic, quartzofeldspathic biotite gneisses. Type III (open squares) is represented by fine-grained, well foliated, granoblastic, quartzofeldspathic gneisses. These rocks are quite variable in K_2O; however, their Na_2O/CaO+MgO ratios are similar to those of previous types.

The rocks of type IV (closed circles) are within both the Valley Spring and Packsaddle units. They are generally fine-grained, poorly foliated, granoblastic, quartzofeldspathic gneisses. Those of type V (closed triangles) were collected along the northern profile within the Valley Spring Gneiss. With the exception of one sample, they fall within the compositional field of type II. They are coarse-grained, poorly foliated, porphyroblastic gneisses, containing subhedral microcline porphyroblasts up to five centimeters in length.

The xenoliths (closed stars) are plotted as type VI. They are characterized by relative enrichment in Na_2O, exemplified by the presence of albite and oligoclase porphyroblasts. The rocks are generally fine-to medium-grained, poorly foliated, porphyroblastic, quartzofeldspathic gneisses.

The open star represents the average composition of 79 analyzed granitic rocks from the Enchanted Rock Batholith (Billings, et. al., in press). The asterisk represents an analysis of a typical small granodiorite intrusive (sample no. 7) located at the eastern extremity of the southeastern profile. It falls in the center of the compositional field for type II.

The spatial relationships between these six rock types are complex. Within the Packsaddle Schist, rocks of types I, II, and III are interlayered. These layers are generally parallel to schistosity and vary from a few feet to several hundred feet in thickness. They box the compass around the southern margins of the batholith; their dip is nearly vertical. An individual unit is commonly not continuous for

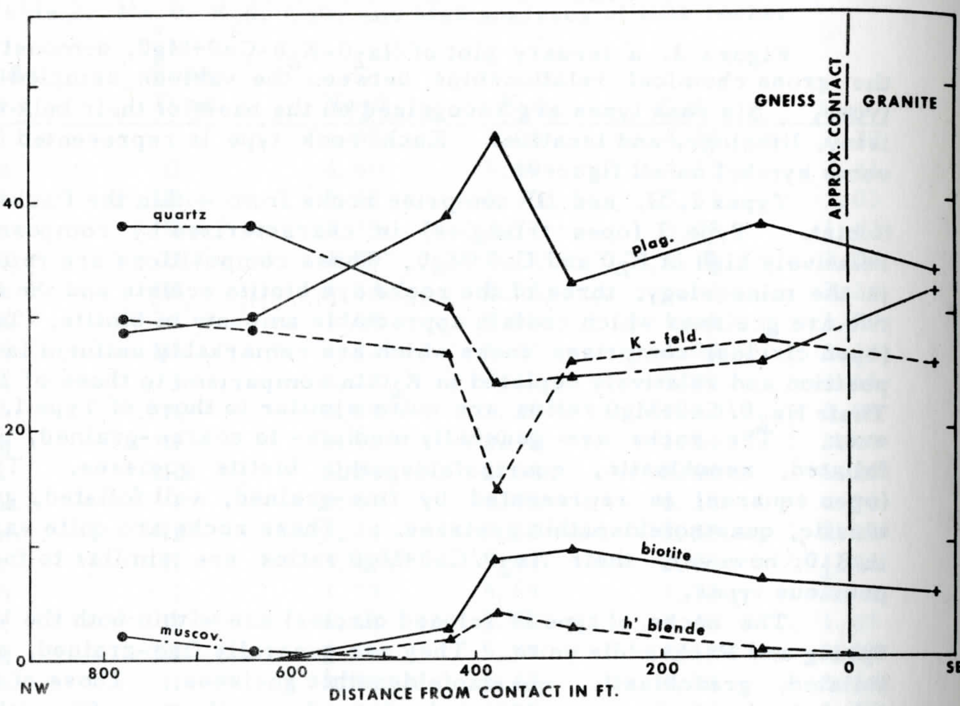

Figure 4. Mineralogical variations within the rocks of the northern profile.

distances over one mile.

This complex interlayering generally does not yield simple chemical and mineralogical trends from the granite-gneiss contact outward. Pre-metamorphic chemical variations may mask metasomatic trends. The only profile along which a consistent chemical pattern is developed is the northern. This pattern was also noted by Hutchinson (1956, p. 790, Figure 12). Both studies agree that there is ample evidence for the formation of a "basic front" approximately 300 feet from the contact. The modal data are listed in Table 7. The mineralogical and bulk chemical relationships are shown in Figures 4 and 5. A cross represents the northernmost granite samples; closed triangles, the "altered" gneiss (type V); and closed circles, the "unaltered" gneiss (type IV). Plagioclase, biotite, and hornblende culminate in the zone where K-feldspar and quartz contents are lowest. In general, variations in K_2O reflect K-feldspar contents; MgO, biotite; and Na_2O and CaO, plagioclase. Muscovite is found only in the unaltered gneiss. Successive biotite-rich and hornblende-rich zones were apparently formed at the expense of the muscovite-rich country rocks, while plagioclase was forming at the expense of K-feldspar. Tuttle and Bowen (1958) note that:

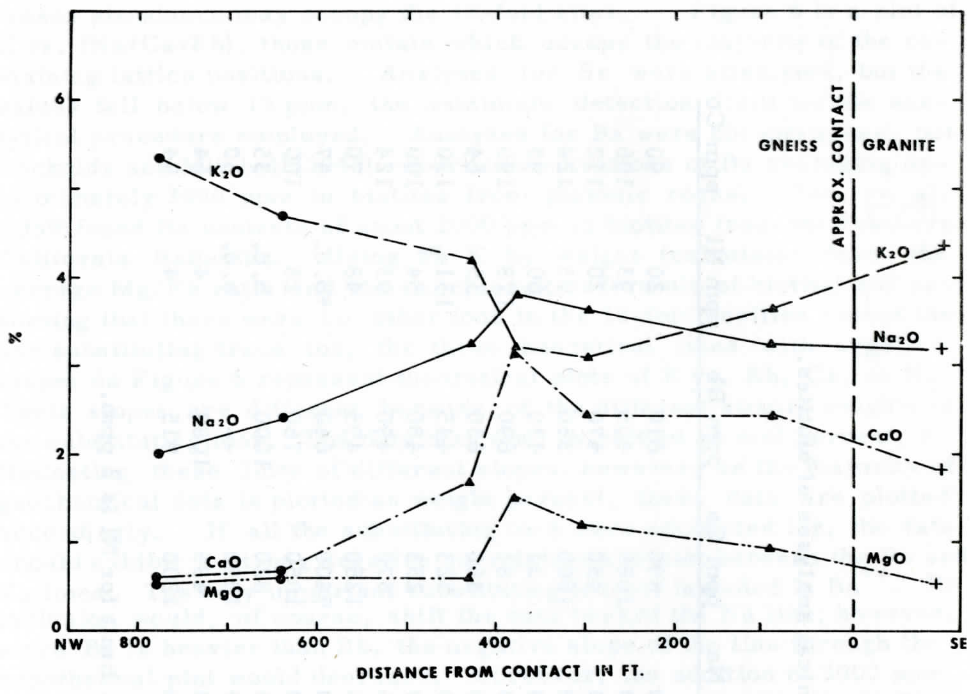

Figure 5. Chemical variations within the rocks of the northern profile.

> "This tendency for the oxides which are abundant in the 'basic' rocks to be relatively insoluble in the hydrous vapor suggests a possible mechanism for producing the basic zones commonly found at granitic contacts. If hydrous vapor, escaping from a cooling granite intrusive, passes along the contact the vapor at certain places can selectively dissolve feldspars and quartz and leave behind lime, magnesia, P_2O_5, and perhaps iron."

Thus these zones might be termed "basic rears" rather than "basic fronts".

VARIATIONS IN MINERAL COMPOSITIONS

Biotites

Analytical data for the biotites are presented in Table 3 and their chemical affinities are demonstrated in Figures 6-9.

K^{+1} is the principal occupant of the 12-fold lattice position in biotites; however, Rb^{+1}, Na^{+1}, Ca^{+2}, Sr^{+2}, Ba^{+2}, and trace cations of

Table 3. Partial chemical analyses of biotites.

Sample No.	Rock Type	% Fe	% Mg	% K	ppm Na	ppm Ca	ppm Rb	ppm Ni	ppm Co
7		17.4	5.35	6.60	530	890	610	20	90
8a	II	15.5	5.04	6.47	2380	1080	405	93	106
9a	II	17.7	5.05	6.40	530	430	470	20	112
10a	II	15.5	5.20	5.72	1660	1600	350	93	124
12b	III	18.6	2.57	6.07	1040	31	430	60	93
13e	I	18.9	4.26	6.80	820	81	690	178	190
13f	II	15.5	4.80	6.33	2050	860	630	35	64
13g	II	18.1	3.53	6.15	2030	323	445	131	130
13i	III	18.8	4.43	6.65	960	233	480	54	100
13n	II	18.4	5.26	6.29	325	570	490	93	124
13t	II	16.1	5.45	6.05	525	1250	495	48	70
15d	IV	22.0	3.00	5.40	1570	9400	640	*b.d.	47
15g	IV	18.4	5.16	5.75	940	1050	760	28	100
16b	VI	22.0	2.02	6.00	1690	820	1000	b.d.	35
16e	IV	22.0	2.67	--	660	1050	--	b.d.	60
57b	VI	21.0	2.95	6.40	680	485	1080	4	64
59b	VI	21.3	3.75	6.55	605	1200	915	4	94

* b.d. - below detection. The lower detection limit for Ni is 2 ppm.

lesser abundance may occupy the 12-fold sites. Figure 6 is a plot of K vs. (Na+Ca+Rb), those metals which occupy the majority of the remaining lattice positions. Analyses for Sr were attempted, but the values fell below 13 ppm, the minimum detection limit for the analytical procedure employed. Analyses for Ba were not attempted, but Nockolds and Mitchell (1948) report concentrations of Ba averaging approximately 3000 ppm in biotites from plutonic rocks. Sen, et. al. (1959) found Ba contents of about 2000 ppm in biotites from the Southern California Batholith. Using 8% K by weight (calculated from the average Mg/Fe ratio and the stoichiometric formula of biotite) and assuming that there were no other ions in the 12-fold position except the one substituting trace ion, the three theoretical lines with negative slopes on Figure 6 represent theoretical plots of K vs. Rb, Ca, or Na. Their slopes are different because of the different atomic weights of the substituting ions. The data may also be plotted as mol percent, eliminating these lines of different slopes; however, as the majority of geochemical data is plotted as weight percent, these data are plotted accordingly. If all the substituting ions were accounted for, the data should exhibit a strong negative correlation and plot between the Rb and Na lines. The only important substituting ion not included is Ba^{+2}. Its inclusion would, of course, shift the data toward the Na line; however, since Ba is heavier than Rb, the negative slope of the line through the hypothetical plot would decrease. Moreover, the addition of 3000 ppm would not account for the cation deficiency evidenced by Figure 6. The deficiency may be caused by: (1) some of the lattice positions are not filled; or (2) some or all of the analytical data are systematically low. Analyses of K-feldspars (Figure 10) indicate that K and Na data are accurate. Assuming the analytical data to be accurate within the limits quoted in Table 6, one may conclude that, by means of a process such as deuteric alteration or weathering, the 12-fold positions are not completely filled. A mechanism for deuteric alteration could be the soaking of the wall rocks by late-stage water-rich fluids emanating from the intruding magma.

Because of its proper ionic size, charge, and electronegativity, Rb^{+1} has long been known to proxy for K^{+1}. Thus these two cations commonly exhibit covariance. Figure 7 is a plot of K vs. Rb in the biotites. Two weak positive correlations are noted: (1) that for rock types I-III and the granodiorite; and (2) that for the remaining rocks. The plot reveals the general affinity between the biotites from the Valley Spring rocks, the xenoliths, and the granite, as opposed to those from the Packsaddle rocks and granodiorite. These affinities will be observed on subsequent plots. The relatively high K/Rb ratio in the Packsaddle biotites is probably a function of their original composition; all the evidence points to the Packsaddle Schist being more mafic. It is interesting to note that although the K-Rb plot yields two weak positive correlations, the K-(Na+Ca+Rb) plot reveals one weak negative correlation.

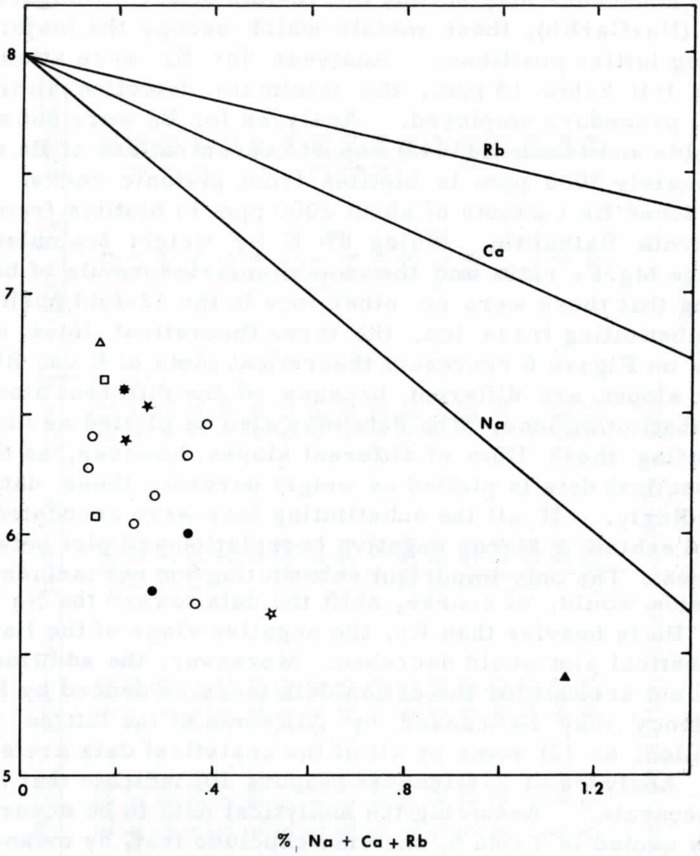

Figure 6. Plot of K vs. (Na+Ca+Rb) in the biotites.

The octahedral position in biotites can be occupied by Fe^{+2}, Mg^{+2}, Mn^{+2}, Fe^{+3}, Al^{+3}, Ti^{+4}, and several trace elements. Fe^{+2} and Mg^{+2} occupy the majority of the sites, but the other ions can occur in significant amounts. Figure 8 is a plot of Mg vs. total Fe in the biotites. The straight line with the negative slope is drawn through a theoretical negative correlation between Mg and Fe, assuming all the Fe to be in the ferrous state. The Fe is not all in the ferrous state, but if Fe^{+3} were in significant quantities, the data points would fall above the curve, rather than below. The fact that the data points fall below the curve is expected, since such ions as Mn^{+2} are not accounted for. The type I-III biotites are generally lower in Fe and higher in Mg than those of types IV-VI. Relatively high Mg^{+2}/Fe^{+2} ratios are generally found in biotites from more mafic rocks. Thus these compositions are probably inherent in the rocks before metamorphism and are in agreement with the interpretation of the K-Rb plot (Figure 7).

Ni^{+2} and Co^{+2} are trace ions which may proxy for Fe^{+2} and

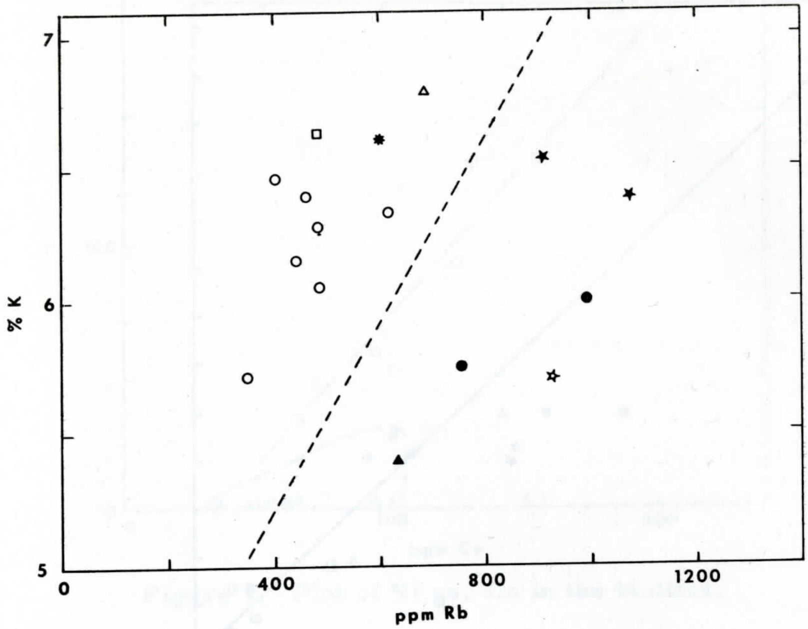

Figure 7. Plot of K vs. Rb in the biotites.

Mg^{+2} in the octahedral position in biotites. Taylor (in press) reports that their sequence of entry into crystal lattices during magmatic crystallization is Mg^{+2}-Ni^{+2}-Co^{+2}-Fe^{+2}. Thus the Ni/Co ratio should be a good indicator of magmatic fractionation, lower Ni/Co ratios existing in more fractionated rocks. Figure 9, a plot of Ni vs. Co in the biotites, reveals a strong coherence between Ni and Co in the biotites from rock types I-III, but no apparent coherence and very low Ni/Co ratios in those from types IV-VI. The covariance of Ni-Co within the Packsaddle biotites may be inherited from the rocks before metamorphism. Ni-Co compositions of the Valley Spring and xenolith biotites are not so readily explained. The smaller ionization potentials and ionic potentials of Co^{+2} would suggest that it rather than Ni^{+2} would be preferentially leached from the lattice. The low Ni/Co ratio of these biotites may again be a function of their being from more felsic rocks. If the minimum detection limit of the analytical method were lower, a positive correlation with a different slope might become apparent.

Potassium Feldspars

Chemical analyses of the potassium feldspars are given in Table 4 and their relationships are plotted in Figures 10-12.

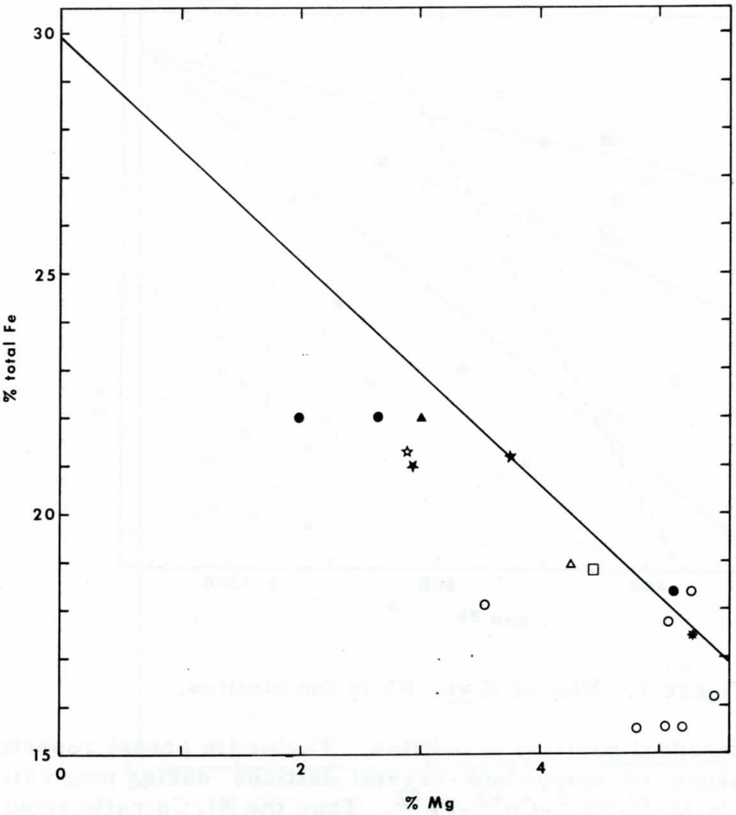

Figure 8. Plot of total Fe vs. Mg in the biotites.

Figure 10 is a plot of K vs. Na, with Ca being included along the ordinate by extending a vertical line above each data point. The curve with the negative slope is the theoretical K-Na plot, with the Ca content varying from 0% at 13.5% K to 0.4% at 7.25% K. In general, there is good agreement between the data and the theoretical curve. There is no apparent correlation between the rock types and the K content of their K-feldspars, with the exception that data points from type II and from type IV seem to be clustered. It has long been recognized that the Na content in K-feldspars coexisting with plagioclase increases with increasing temperature. This relationship apparently does not hold in this study, for the Na content is generally lowest in the K-feldspars from the xenoliths, in comparison to those from wall rocks at considerable distances from the contact.

Figure 11 is a plot of Ca vs. Sr in the K-feldspars and exhibits a strong covariance between Ca and Sr in those feldspars from types IV and V (the Valley Spring rocks). With the exception of one value

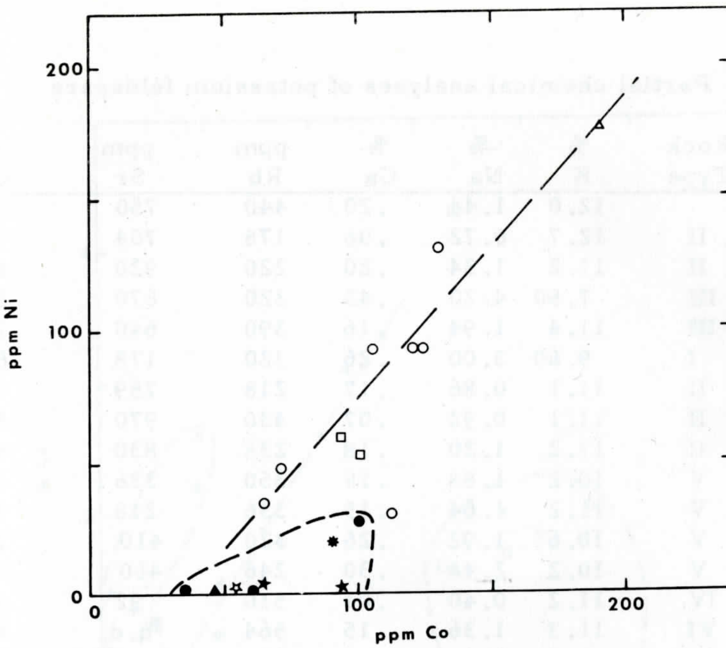

Figure 9. Plot of Ni vs. Co in the biotites.

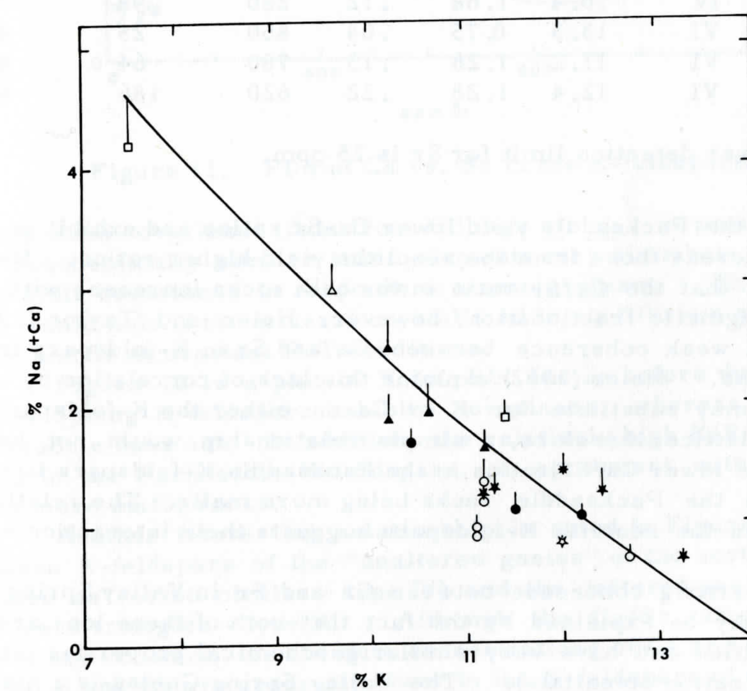

Figure 10. Plot of Na (+Ca) vs. K in the K-feldspars.

Table 4. Partial chemical analyses of potassium feldspars

Sample No.	Rock Type	% K	% Na	% Ca	ppm Rb	ppm Sr	% Or
7		12.0	1.44	.20	440	750	84
8a	II	12.7	0.72	.06	178	704	90
9a	II	11.2	1.34	.20	220	920	82
10b	III	7.50	4.20	.43	320	670	53
12b	III	11.4	1.94	.16	390	640	78
13e	I	9.60	3.00	.26	320	178	66
13f	II	11.1	0.86	.17	218	759	88
13n	II	11.1	0.92	.07	430	970	86
13t	II	11.2	1.20	.18	238	830	84
15b	V	10.2	1.88	.18	350	336	76
15d	V	11.2	1.64	.15	336	218	80
15e	V	10.6	1.92	.26	320	410	76
15f	V	10.2	2.48	.30	246	460	70
15h	IV	11.2	0.40	.04	510	92	80
16b	VI	11.3	1.36	.15	564	*b.d.	82
16e	IV	12.2	1.12	.08	620	113	87
16f	IV	11.5	1.15	.11	412	218	85
16g	IV	10.4	1.68	.12	280	98	79
40a	VI	13.3	0.75	.04	850	25	91
57b	VI	11.2	1.26	.13	780	64	84
59b	VI	12.4	1.28	.22	620	186	83

* b.d. - Lower detection limit for Sr is 25 ppm.

those from the Packsaddle yield lower Ca-Sr ratios and exhibit no coherence, whereas those from the xenoliths yield higher ratios. Heier (1962) notes that the Ca/Sr ratio in the bulk rocks increases with increasing magmatic fractionation; however, Heier and Taylor (1959) found only a weak coherence between Ca and Sr in K-feldspars from granitic rocks. Heier (1962) explains this lack of correlation by noting that Sr may substitute for K or Ca in either the K-feldspar or plagioclase lattice; therefore, a simple relationship would not be expected. The lower Ca/Sr ratios in the Packsaddle K-feldspars is consistent with the Packsaddle rocks being more mafic. The relatively low ratios in the xenolith K-feldspars suggests their interaction with the granite.

The strong coherence between Ca and Sr in Valley Spring K-feldspars may be explained by the fact that both of these ions are in trace quantities and have very similar geochemical properties (size, charge, ionization potentials). The Valley Spring Gneiss is a metamorphic rock, whereas evidence will be offered subsequently to demonstrate that the Packsaddle rocks of type II are rheomorphic. A plot of Ca vs. Sr in the K-feldspars from the Enchanted Rock Batholith shows

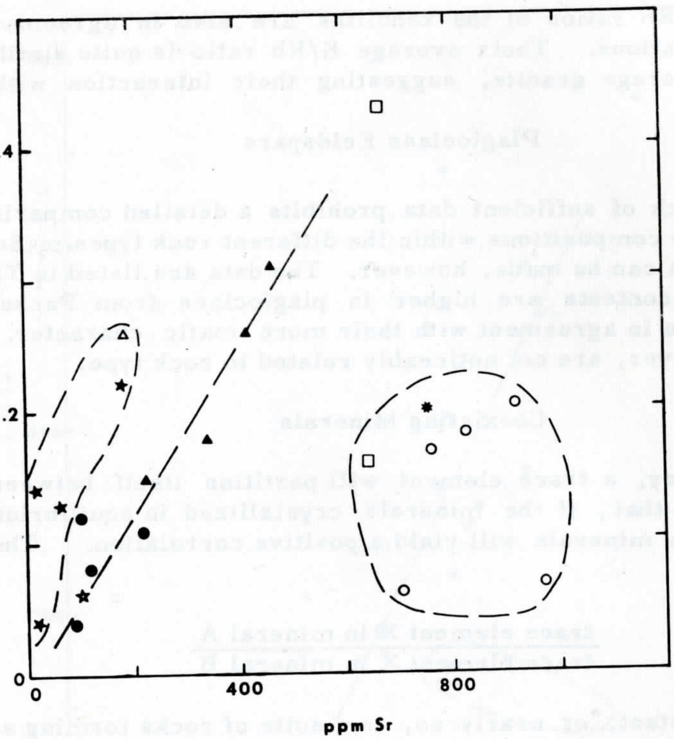

Figure 11. Plot of Ca vs. Sr in the K-feldspars.

a very weak covariance (data from Billings et. al., in press). Thus two geochemically similar trace elements may distribute themselves to exhibit covariance in response to metamorphism. This relationship would hold if the mineral crystallized in equilibrium with respect to Ca and Sr at constant P-T conditions.

Figure 12 is a plot of K vs. Rb, and as before the plot of the Valley Spring K-feldspars exhibits covariance, whereas that of the Packsaddle does not. In addition, the relatively high K/Rb ratios are found in the Packsaddle K-feldspars, in agreement with their being from more mafic rocks.

Another interesting relationship is noted in Figures 11 and 12 between K-feldspars of the "unaltered gneiss" of the northern profile (plotted as closed circles - type IV) and the "altered gneiss" (plotted as closed triangles - type V). Although the Ca/Sr ratios and K/Rb ratios are constant, the absolute concentrations of Ca and Sr are higher and K and Rb are generally lower in the K-feldspars of the "altered gneiss." These relationships are consistent with the "basification" of these rocks discussed earlier.

The K/Rb ratios of the xenoliths are also in agreement with earlier observations. Their average K/Rb ratio is quite similar to that of the average granite, suggesting their interaction with the granite.

Plagioclase Feldspars

The lack of sufficient data prohibits a detailed comparison of the plagioclase compositions within the different rock types. Several generalizations can be made, however. The data are listed in Table 5. In general, Sr contents are higher in plagioclase from Packsaddle rocks, which is in agreement with their more mafic character. Rb contents, however, are not noticeably related to rock type.

Coexisting Minerals

In theory, a trace element will partition itself between two minerals such that, if the minerals crystallized in equilibrium, its plot in the two minerals will yield a positive correlation. Thus the ratio

$$\frac{\text{trace element X in mineral A}}{\text{trace element X in mineral B}}$$

should be constant, or nearly so, in a suite of rocks forming at uniform P-T conditions. The absolute quantities of the element will be a function of the bulk composition of the rocks.

Figure 13 is a plot of Sr in the plagioclase feldspars vs. Sr in the K-feldspars. A positive linear correlation is noted, suggesting that the feldspars from these diverse rock types crystallized in equilibrium with respect to Sr and under rather similar P-T conditions. The Sr-plagioclase/Sr-K-feldspar ratio is 1.2 and the average composition of the granite and the granodiorite fall quite close to this line, suggesting that this ratio is insensitive to P-T differences between the metamorphic and igneous rocks.

Figure 14 is a plot of Rb in the biotite vs. Rb in the K-feldspars. Insufficient data are available to determine the degree of linearity of the curve; however, the Rb-biotite/Rb-K-feldspar ratio is approximately 1.8. This ratio is expected, for the larger Rb^{+1} ion can more readily proxy for K^{+1} in the 12-fold lattice site in biotite than in the 8-fold site in K-feldspar. As observed earlier, the values from the Packsaddle minerals fall on the mafic end of the curve.

An interesting observation is the remarkable similarity in composition of the minerals and bulk rocks of type II. For example, the Ab content in these plagioclases only varies from 60-62%. The similarity can be observed on the majority of diagrams (note the open

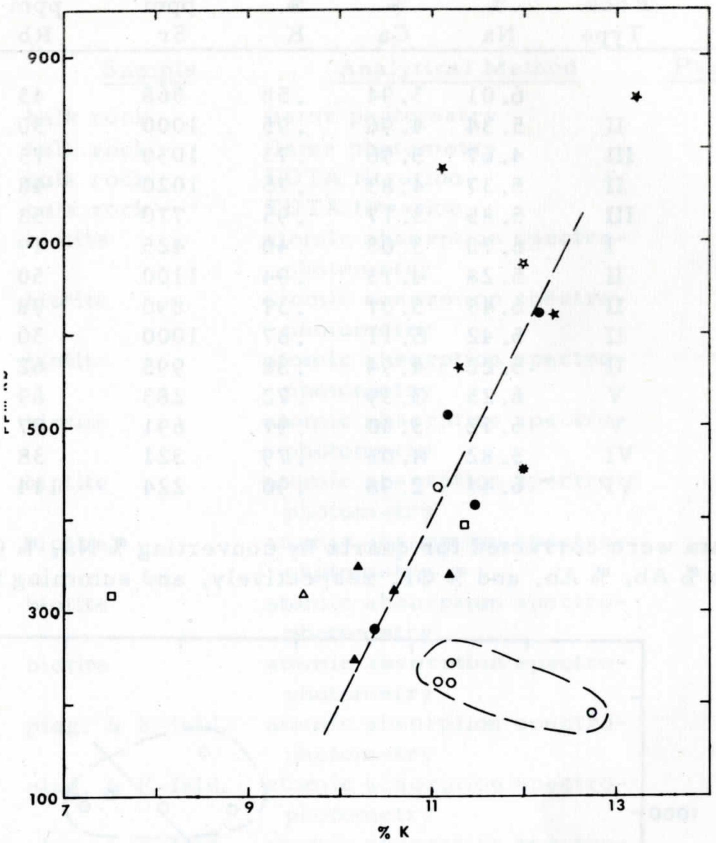

Figure 12. Plot of Rb vs. K in the K-feldspars.

circles on Figures 3, 7, 8, and 10-15). In addition, their average composition commonly falls close to that of the granodiorite and they have been called "recrystallized igneous-appearing Packsaddle Schist" by Hutchinson (1956). Thus their compositions may be a result of "anatectic convergence" accompanying ultrametamorphism. That is, the anatexis of a group of heterogeneous rocks may yield a rock of more uniform composition. The similarity of the average type II composition to that of the granodiorite, which is apparently intrusive into the Packsaddle, also suggests that they may represent lit-par-lit injection of granodioritic material into the Packsaddle Schist during regional metamorphism. That they did not respond simply to P-T variations by recrystallization during metamorphism is suggested by Figures 13 and 14. Although they fall on the mafic end of the curves, they apparently

Table 5. Partial chemical analyses of plagioclases*

Sample No.	Rock Type	% Na	% Ca	% K	ppm Sr	ppm Rb	% Ab
7		6.01	3.94	.58	868	43	68
8a	II	5.34	4.96	.95	1000	30	61
8b	III	4.67	5.96	.73	1030	75	53
9a	II	5.37	4.83	.75	1020	48	61
10b	III	5.85	3.77	.95	770	52	67
13e	I	6.70	3.03	.40	425	19	76
13f	II	5.28	4.73	.94	1100	50	60
13g	II	5.48	5.07	.37	890	98	62
13h	II	5.42	5.11	.37	1000	30	62
13t	II	5.22	4.94	.88	995	62	60
15d	V	6.25	3.39	.72	283	69	71
15e	V	6.12	3.40	.97	691	87	60
57b	VI	5.82	4.03	.79	321	38	66
59b	VI	6.44	2.98	.90	224	114	73

* The data were corrected for quartz by converting % Na, % Ca, and % K to % Ab, % An, and % Or, respectively, and summing to 100%.

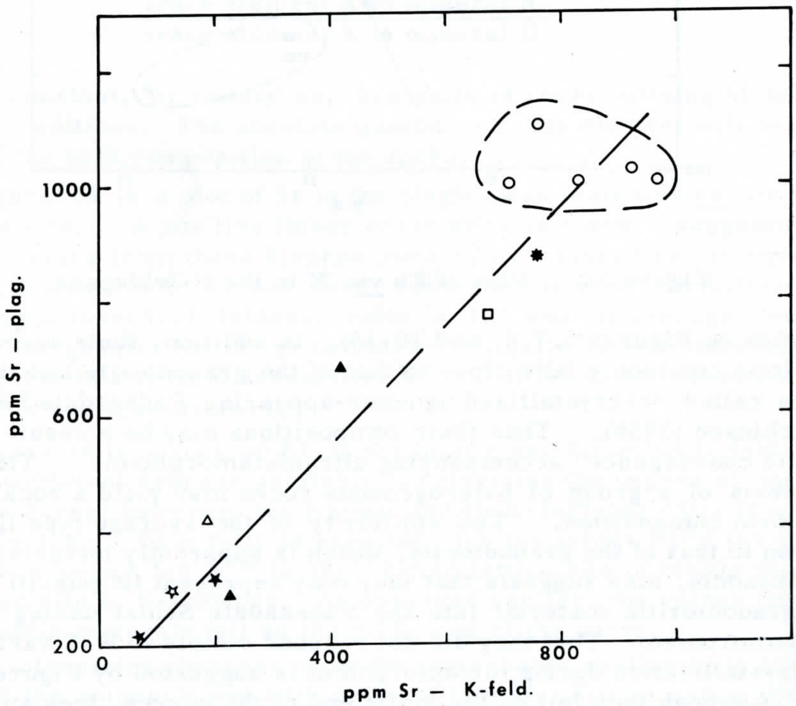

Figure 13. Plot of Sr in coexisting plagioclases and K-feldspars.

Table 6. Analytical methods and precision.

Element	Sample	Analytical Method	Precision*
Na_2O	bulk rock	flame photometry	4%
K_2O	bulk rock	flame photometry	4%
CaO	bulk rock	EDTA titration	7%
MgO	bulk rock	EDTA titration	15%
Ca	biotite	atomic absorption spectro-photometry	2%
Mg	biotite	atomic absorption spectro-photometry	1%
Fe	biotite	atomic absorption spectro-photometry	1%
K	biotite	atomic absorption spectro-photometry	1%
Rb	biotite	atomic absorption spectro-photometry	1%
Na	biotite	atomic absorption spectro-photometry	2%
Ni	biotite	atomic absorption spectro-photometry	7%
Co	biotite	atomic absorption spectro-photometry	7%
Na	plag. & K-feld.	atomic absorption spectro-photometry	1.5%
Ca	plag. & K-feld.	atomic absorption spectro-photometry	4%
K	plag. & K-feld.	atomic absorption spectro-photometry	5%
Sr	plag. & K-feld.	atomic absorption spectro-photometry	1.5%
Rb	plag. & K-feld.	atomic absorption spectro-photometry	1.5%

* The precision quoted is the average of the relative deviations from the mean of each set of duplicate analyses. Approximately 10% of the samples were analyzed in duplicate.

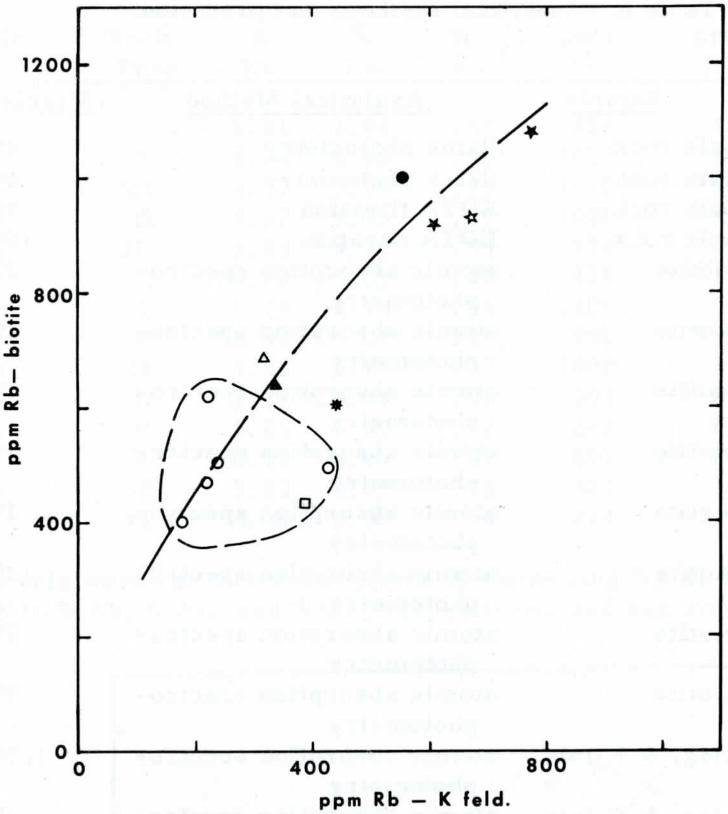

Figure 14. Plot of Rb in coexisting biotites and K-feldspars.

exhibit no covariance. Field evidence does not point to forceful injection. Thus they are probably a result of fusion in place.

Additional evidence may be offered for the possible anatectic nature of the type II gneisses. Figure 15 is a ternary plot of coexisting feldspars in the Ab-Or-An system. The general parallelism of the tie lines between the coexisting feldspars on Figure 15 is suggestive of their being formed at rather uniform P-T conditons. Yoder et. al. (1957, p. 206-214) have demonstrated that the slope and position of the tie lines connecting data points of these coexisting minerals on an Ab-Or-An plot is a function of the P-T conditions during crystallization. Their experiments were performed at 2000 and 5000 bars. Assuming $P_{total} = P_{H_2O}$ and that the feldspars crystallized in equilibrim, one can predict whether the temperatures were sufficiently high in these rocks for at least partial anatexis. Larger angles between tie lines and the Ab-Or join are indicative of higher temperatures and lower pressures of crystallization (Yoder et. al., 1957, Figure 44, p. 212).

Table 7. Modal analyses of Valley Spring Gneiss rocks from the northern profile.[1]

Sample No.	% quartz	% plagioclase	% K-feldspar	% biotite	% hornblende	% muscovite	% dark opaques	% minor accessories
15b	25.8	37.9	27.6	6.9	0.7	tr.[2]	1.1	tr.
15d	24.9	32.6	26.2	10.0	2.7	tr.	3.0	0.6
15e	28.7	39.3	27.4	2.6	1.8	tr.	0.2	tr.
15f	23.8	46.5	15.3	8.7	4.5	tr.	0.9	0.3
15g	38.1	29.6	29.5	0.2	---	0.9	1.7	tr.
15h	37.6	29.2	29.4	0.2	---	2.4	1.2	tr.

[1]Modal analyses based upon a count of 1000-1500 points per thin section. Precision is adjudged at $\pm$ 7% of measured value.

[2]tr.-trace, less than 0.1%.

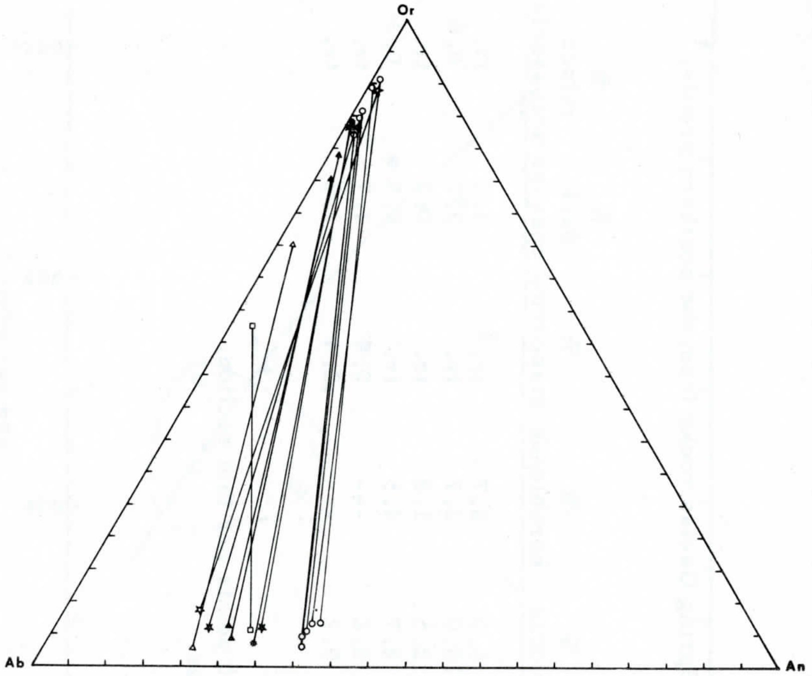

Figure 15. Ternary plot of Or-Ab-An showing tie lines connecting data points for coexisting feldspars.

Since these rocks are of amphiobolite facies, they probably formed under total pressures of 6000-8000 bars and, excluding the higher temperatures associated with the intrusion of the granite, temperatures of 500-600° C. Yoder's tie line between coexisting synthetic feldspars at 770° C and 5000 bars corresponds quite closely to the tie lines between the type II feldspars on Figure 15. At total pressures of 6000-8000 bars granitic material will begin melting at approximately 650° C. Even though these rocks were probably metamorphosed at pressures in excess of 5000 bars, the intrusion of the granitic batholith probably added sufficient heat to at least partially remobilize the Packsaddle rocks.

CONCLUSIONS

1. The sampled wall rocks around the Enchanted Rock batholith may be divided into six types, based upon their compositions, lithologies, and spatial relationships.

2. An ion deficiency in the 12-fold lattice site of the biotites may be a result of deuteric alteration or weathering.

3. Relatively high K/Rb, Mg/Fe, and Ni/Co ratios in the biotites of the Packsaddle Schist, as compared to those of the Valley Spring Gneiss, are probably a function of the pre-metamorphic mafic character of the Packsaddle rocks.

4. The lower Ca/Sr and higher K/Rb ratios in the K-feldspars are probably also due to the more mafic nature of the Packsaddle rocks.

5. Compositions of minerals from rocks of types I, III, and IV have not been noticeably affected by contact metasomatism associated with the intrusion of the granite.

6. Several lines of evidence suggest that the gneisses of type II have been at least partially fused.

7. The xenoliths (type VI) have apparently been granitized, whereas the bulk chemical and mineralogical data indicate that the gneisses of type V have been "basified".

8. With the exception of the Na/K ratio in the K-feldspars, interpretations of the geochemical data are in accord with field and petrographic observations.

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