PETROLOGY

OF THE

GRANITIC ECHO-POND COMPLEX,

NORTHEAST, VERMONT

by

YASHVIR SINGH NIKHANJ

B.Sc(Hons.), Ranchi University,

Ranchi, India (1967)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF

MASTER OF SCIENCE

AT THE

MASSACHUSETTS INSTITUTE OF

TECHNOLOGY

June, 1970

Signature of Author ____________________

Department of Earth and Planetary Sciences,
(June 4, 1970)

Certified by ____________________

Thesis Supervisor

Accepted by ____________________

Chairman, Departmental Committee on
Graduate Students

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The Echo Pond Complex, emplaced during the Acadian Orogeny, consists of at least two intrusive phases in a mafic to sillicic sequence. This magma suite is characterized by the initial injection of the Calcic gabbroic melt followed by minor diorite and abundant granitic melt and later by pegmatite and quartz veins. As a result of contamination of the granitic melt with the mafic unit hornblende bearing granodiorite is formed along the contact zone of granitic pluton with the mafic pluton. Electron microprobe studies on hornblende from the hornblende bearing granodiorite suggest that the hornblende bearing granodiorite crystallized from a melt. The Echo Pond Complex consists of approximately 80% granitic rocks, 15% gabbro, hornblende and diorite and 4% of hornblende bearing granodiorite and less than 1% of pegmatites and quartz veins. The rest is migmatite formed along the contact zone of granite with the country rock.

Modal analysis plot on plagioclase - K-spar - quartz show a continuous and systematic range of composition of this calc-alkaline trend over most of the area.

The chemistry, minerology and structural features and geological setting of the pluton are compatible with a parent magma developed by mining of sillicic magma from the lower crustal region and mafic magma from the upper mantle. Ultramafic hornblendite present in the mafic unit is derived as a xenolith from the deep crust. The strong zoning in the plagioclase, successive appearance of several mineral phases in most rocks, the sequence of emplacement and the chemical trend of the intrusive suite suggest the operation of fractional crystallization. Differentiation of primary mafic magma produced progressively more granitic magma, which were subsequently emplaced in the upper crust. Partial or complete assimilation of unknown cognate mafic rocks may have been a modifying process. Both assimilation and differentiation appear to have occurred at deeper levels than are now exposed.

Stratigraphic reconstruction suggest batholith emplacement between depths of 10.5 km to 11 km. The roof zone is presently exposed. The rocks of the batholith are directionless, relatively free of inclusions and in sharp contact with the country rock. Emplacement probably occurred due to lateral dilation and uplifting of the roof.

Thesis Supervisor: Richard S. Naylor
Title: Assistant Professor of Geology

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INTRODUCTION

In northern Vermont numerous small granitic plutons intrude the upper part of a 25,000 ft. thick section of Cambrian through Lower Devonian geosynclinal rocks. Two-mica granite and granodiorite are the characteristic rock types of this series of plutons. The granitic rocks are weakly foliated and were apparently emplaced during the Acadian metamorphism and deformation, (Fig. 1).

The Echo Pond Complex (Fig. 2) is a composite pluton, roughly elliptical in plan, about 7 1/2 miles (12 km) long and 6 miles (10 km) wide. The longer axis is nearly perpendicular to the axis of folds in the country rock. As mapped by Goodwin (1963) the major part of the complex is a granitic pluton 25 sq. miles (64 sq. km) in area, joined on the southeast by a smaller mafic body about 10 sq. miles (25 sq. km) in area.

The granitic pluton consists mainly of uniform, medium-grained, two-mica granite with minor granodiorite. Aplite and pegmatite veins are rare except near the contact with the country rock.

The mafic body contains diorite, gabbro, and uralitic ultramafic rocks. Near the contact of the mafic pluton with the granitic pluton, the granite contains abundant hornblende. Most probably the hornblende developed as a result of contamination of the granitic melt with the mafic rocks. Cross cutting relationships indicate that the granitic pluton is younger than the mafic pluton.

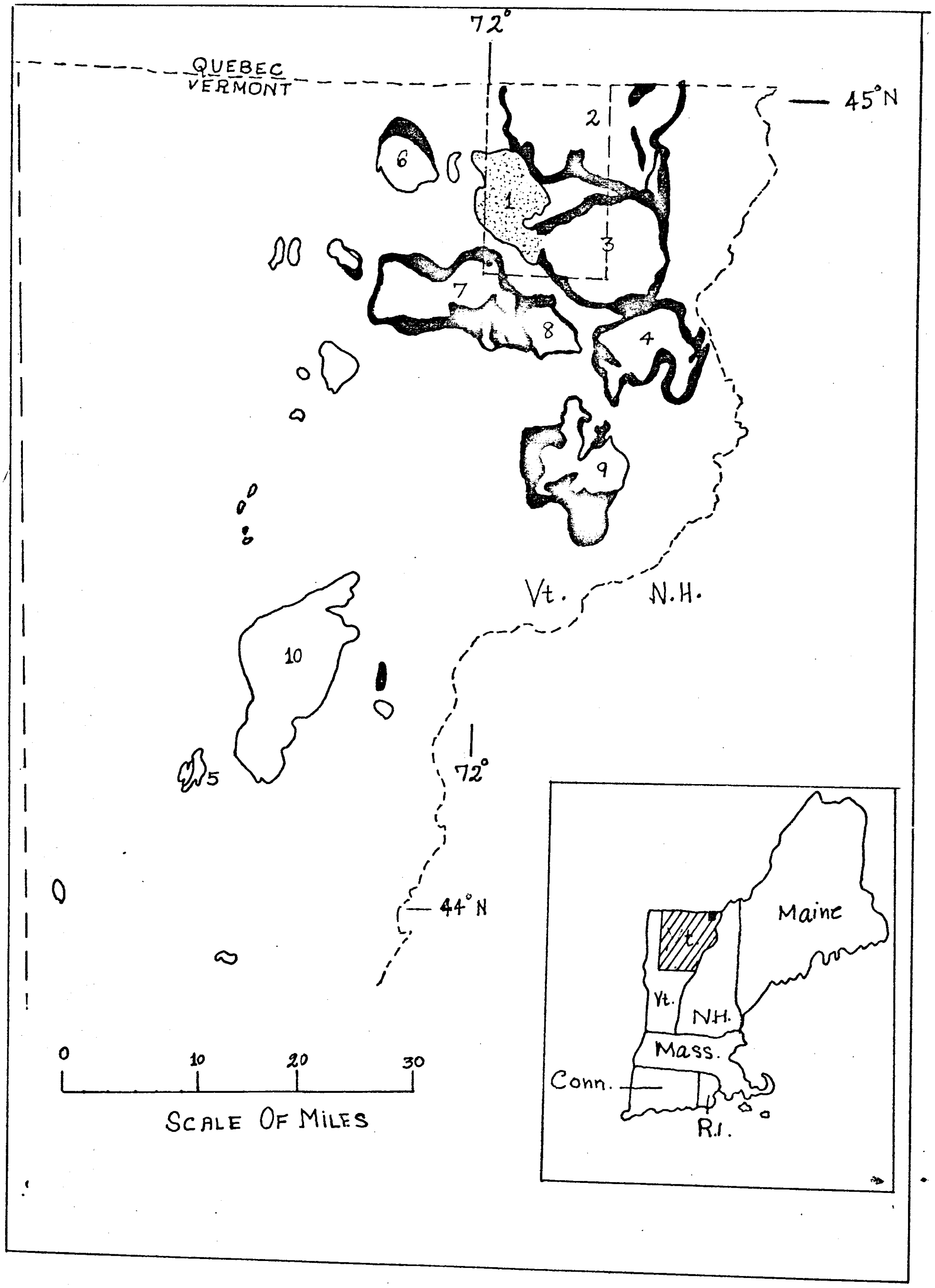
The granitic plutons in northern Vermont intrude calcareous schists of the Devonian Waits River Formation (Doll, Cady, Thompson and Billings, 1961). The country rock was strongly deformed and metamorphosed (staurolite grade regional metamorphism) prior to the emplacement of the plutons.

The plutonic rocks of the Echo Pond Complex are more deeply eroded than the country rock and lie in a poorly exposed basin, whose topography is subdued relative to that of the country rock terrane. The area is densely wooded and locally swampy, but several low hills (for example Bear Hill, Fig. 2) provide good exposures of the granitic rocks. Two weeks were spent in the field to map the area in the summer of 1969.

Fig. 1. Location map showing the distribution of granitic plutons in northeast Vermont. (Compiled from Doll, Cady, Thompson and Billings, 1961).

1. Echo Pond Complex (strippled)
2. Averill Pluton
3. Nulhegan Pluton
4. Maid Stone Pluton
5. Barre-Granite Pluton
6. Derby Pluton
7. Wiloughby Pluton
8. Newark Pluton
9. Victory Pluton
10. Knox Mountain Pluton

Dark area show the Sillimanite Aureole around the granitic plutons. The area marked by a quadrangle shows the location of Island-Pond quadrangle.



72°
QUEBEC
VERMONT
45°N
1
2
3
4
5
6
7
8
9
10
Vt.
N.H.
72°
44°N
0
10
20
30
SCALE OF MILES
Maine
Vt.
Vt.
N.H.
Mass.
Conn.
R.I.

Figure 1.

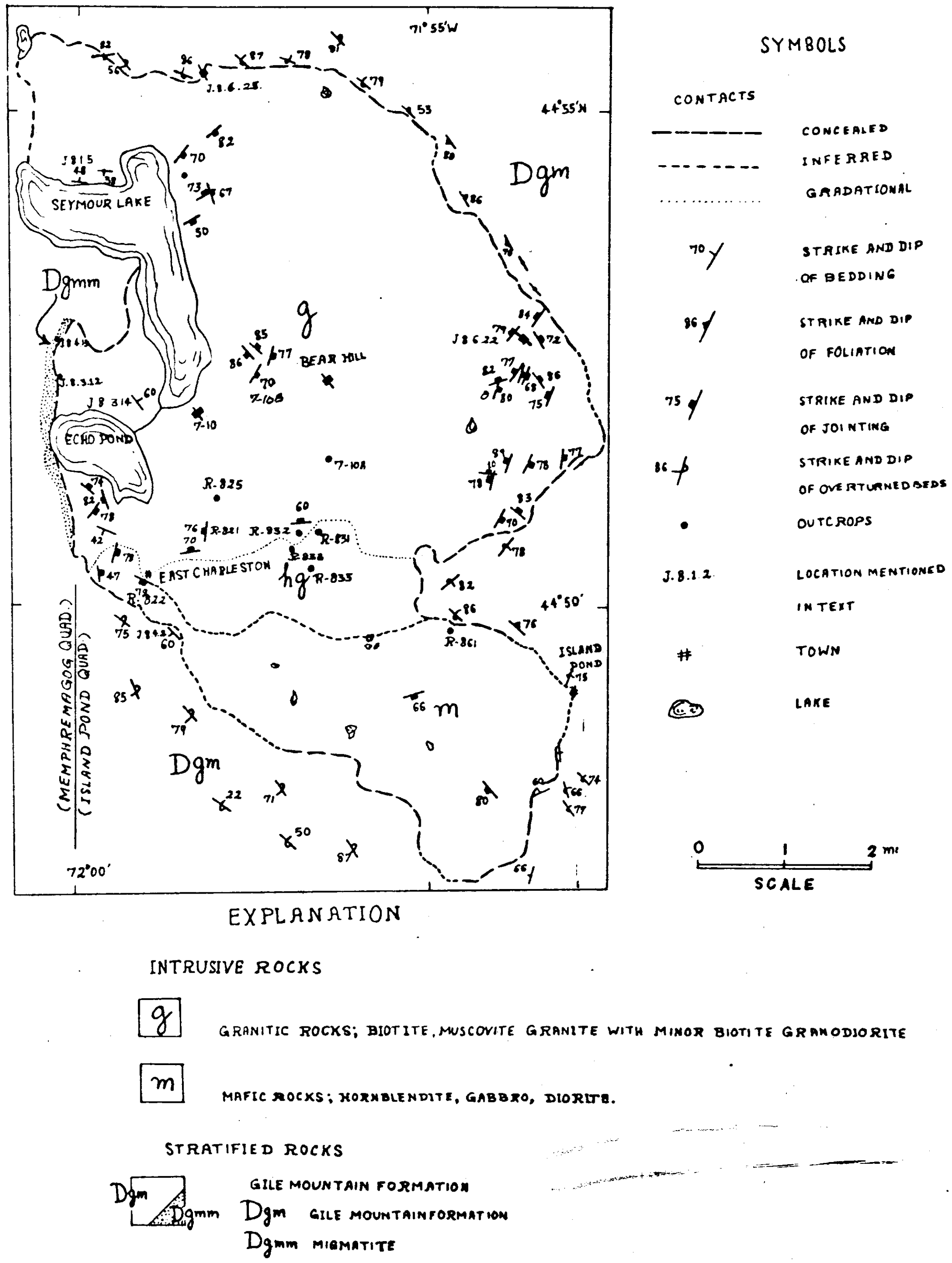


Fig. 2. Geological map of Echo Pond Complex. (After Goodwin, 1963; and Doll, 1951. Modified by Yashvir S. Nikhanj and Betty Recks, 1970).

PREVIOUS WORK

Goodwin (1963; Island Pond Quadrangle) and Doll (1951; Memphramagog Quadrangle) have studied the areas around the Echo Pond Complex primarily for their stratigraphic interest. The stratigraphy and structure of adjacent quadrangles have been studied by Myers (1954; Averill Quadrangle), Chapman (1954; Guildhall Quadrangle), Woodland (1966; Burke Quadrangle) and Dennis (1956; Lyndonville Quadrangle).

Woodland (1966) and Albee (1957) studied the petrology of Burke Quadrangle and Hyde-Park Quadrangle respectively. Particular attention to the study of northern Vermont granites has been paid by Murthy (1957; Barre granite, Chayes (1950) and Jahns (1943).

Compilations have been prepared by Cady (1970), Doll and others (1961).

GENERAL GEOLOGY

On a regional scale the Echo Pond plutons show sharp and concordant contact relationships with the country rocks, but locally the contact is discordant or gradational. The metasediments generally dip away from the contact, but locally dip towards the contact. Weakly developed primary foliation and lineation is noted in the granite and granodiorite.

The Lower Devonian Gile Mountain Formation, which surrounds the pluton, consists of argillites, phyllites and schists interbedded with minor quartzite and limestone (Doll, 1951, p. 18). The nature of these rocks has been studied by Doll (1951), Goodwin (1963) and Murthy (1957). The intrusion of granite has left no complete section of Gile Mountain Formation from which an estimate of thickness could be obtained. However Doll (1951, p. 34) estimated a thickness of 4300 ft. in the Memphremagog Quadrangle.

The country rock around the complex shows a strong foliation and a regional staurolite grade metamorphism prior to the emplacement of the pluton. Thermal contact metamorphism around the Echo Pond Complex ranges up to andalusite grade. Along the margins of the granitic pluton inclusions of variable size, shape, and degree of assimilation and recrystallization are found. South of Echo Pond numerous small inclusions of metasedimentary rocks, only a few inches long, are found with a considerable degree of orientation. Some large blocks of Gile Mountain Formation, completely surrounded by granite are found along a road cut near East Charleston. The block is 22 ft. across. Attitude measured on this block is N80°W, strike; and 72° SW, dip, which is perpendicular to the regional trend of the metasedimentary rocks. Smaller, randomly-oriented, brecciated blocks of country rock are also found enveloped by the granite. The intrusive series of plutons ranges in composition from gabbro to granite. The pluton contains about 80% granite and granodiorite, 15% gabbro, hornblendite, and diorite, and nearly 5% contaminated hornblende bearing granodiorite. Most of these rocks are typical of the Calc-alkaline Suite (see Turner and Verhoogen, 1960, p. 369). Along the western margin, the granite emits numerous, small, highly-contorted granitic dikes and quartz veins into partially granitized metasedimentary country rocks. The partially granitized metasedimentary rocks with numerous granitic dikes give an appearence of rock, intermediate in composition and texture to the granite and country rock. This intermediate type of rock is termed "migmatite" in this paper.

MAFIC AND ULTRAMAFIC BODIES

Along a road cut the unit is exposed only in two outcrops. The unit shows gradational contact with the metasedimentary rocks. It has a wide range in chemical composition, mineralogy, and petrology. The rock types included in this unit are ultramafic hornblendite, gabbro and diorite. Only a single, weathered outcrop provides an exposure for the hornblendite. Lack of outcrops in the area makes it difficult to define the representativeness of the rock types exposed in the two outcrops. The rest of the area is mapped on the basis of large float blocks of the gabbro and diorite.

Hornblendite

Mineralogy: Hornblendite contains variable proportions of hornblende, cummingtonite, tremolite-actinolite with minor amounts of calcite, chlorite, talc, pyrite and other opaque iron-oxides (Table 1). Tremolite-actinolite occurs as inclusions in hornblende and cummingtonite.

Hornblende, the main constituent of the rock, occurs in large subhedral to anhedral poikilitic crystals. The crystals are poorly pleochroic (in order of X - light yellow, Y - yellowish brown to Z - pale yellow). An electron microprobe analysis made across the hornblende (Fig. 3) shows a uniform chemical composition with respect to Ca, Mg, and Si, but hetrogeneity is observed across the grain with respect to Fe, Al, and Ti (Fig. 4 and Table 2). No particular zoning sequence is observed within hornblende. Cummingtonite, the next most abundant mineral also occurs as subhedral to anhedral crystals and it locally encloses tremolite-actinolite. Optical study of cummingtonite shows a rather uniform composition, with bands of different birefrengence

TABLE 1

ESTIMATED MODES OF THE MAFIC AND ULTRAMAFIC ROCKS

<table>
<tr><th>SP. No.</th><th>R-831</th><th>R-835</th><th>J.8.4.2</th><th>R-822</th></tr>
<tr><td>Quartz</td><td>2</td><td>1.2</td><td>1.9</td><td>-</td></tr>
<tr><td>Plagioclase</td><td>53.1
(An_{15-18})</td><td>53.9
(An_{18-20})</td><td>38.7
(An_{40})</td><td>39.3
(An_{50})</td></tr>
<tr><td>K-spar</td><td>-</td><td>-</td><td>13.0</td><td>-</td></tr>
<tr><td>Hornblende</td><td>24.02</td><td>23.1</td><td>20.65</td><td>40.9</td></tr>
<tr><td>Biotite</td><td>10.1</td><td>10.6</td><td>4.90</td><td>9.40</td></tr>
<tr><td>Muscovite</td><td>-</td><td>-</td><td>Traces</td><td>-</td></tr>
<tr><td>Sericite</td><td>-</td><td>Traces</td><td>5.75</td><td>-</td></tr>
<tr><td>Magnetite</td><td rowspan="2">9.87</td><td rowspan="2">10.29</td><td>10.60</td><td>0.52</td></tr>
<tr><td>Other minor *Accessories</td><td>14.50</td><td>10.88</td></tr>
</table>

*Accessories include - chlorite, apatite, zircon, epidote, and sphene

R-831 Hornblende bearing granodiorite

R-835 Hornblende bearing granodiorite

J.8.4.2. Diorite

R-822 Gabbro

For locations of the rocks see Fig. 2.

TABLE 2

MICROPROBE ANALYSIS OF HORNBLENDITE MINERALS

MgO	FeO	Al_2O_3	SiO_2	CaO	TiO_2	Na_2O	MnO	K_2O
16.1	6.40	6.00	49.9	11.0	0.40	0.400	0.175	0.065
19.5	4.80	0.90	50.0	11.0	0.130	0.300	0.180	0.053
18.8	5.20	1.58	52.0	11.3	0.071	0.282	0.160	0.037
19.0	4.85	1.18	51.8	11.3	0.043	0.251	0.160	0.034
19.1	4.97	0.92	51.0	11.2	0.064	0.310	0.145	0.035
17.8	6.00	3.20	48.0	11.0	0.195	0.340	0.200	0.036
17.9	6.70	2.90	50.0	9.8	0.199	0.340	0.230	0.033
18.0	6.10	2.80	50.0	11.0	0.145	0.370	0.235	0.042
18.5	7.20	1.45	50.0	8.8	0.126	0.240	0.232	0.032
17.9	6.40	2.80	50.0	10.3	0.120	0.271	0.180	0.044
18.0	6.50	2.60	50.0	10.2	0.110	0.200	0.253	0.036
18.2	6.30	2.45	50.0	10.5	0.140	0.270	0.300	0.050

Analyses are done by probe traverses made on a thin section of hornblendite, sample No. J.8.1.2. Also see Fig. 4. Possible corrections during analyses are described in the Appendix.

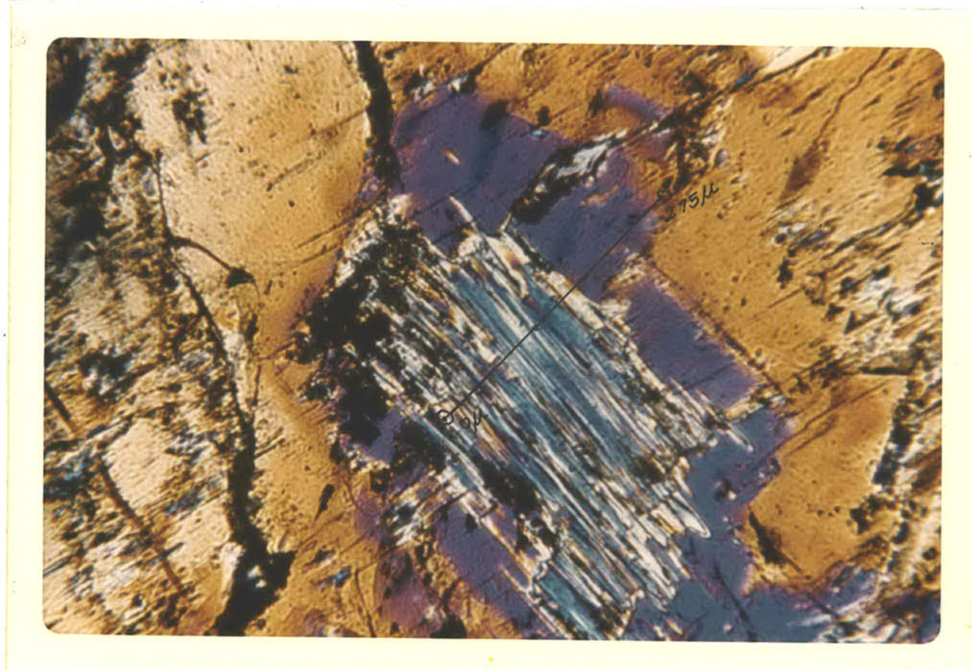


Fig. 3. Photomicrograph of hornblendite (sample No. J.8.1.2). Bar shows location of microprobe traverse. Hornblende enclosing tremolite-actinolite with reaction rim of CaMg-rich hornblende (corssed polars x 130). In the photograph. 0 275μ

Fig. 4. Microprobe traverses across hornblendite sample No. J.8.1.2 shown in Fig. 3. Corrected weight percent oxides plotted as a function of distance along the traverse. Fig. 4 (a), scan #1, CaO, FeO, Al_2O_3; Fig. 4 (b), scan #2, MnO, Na_2O, K_2O; Fig. 10 (c) and (d), scan #3, MgO, TiO_2, and SiO_2.

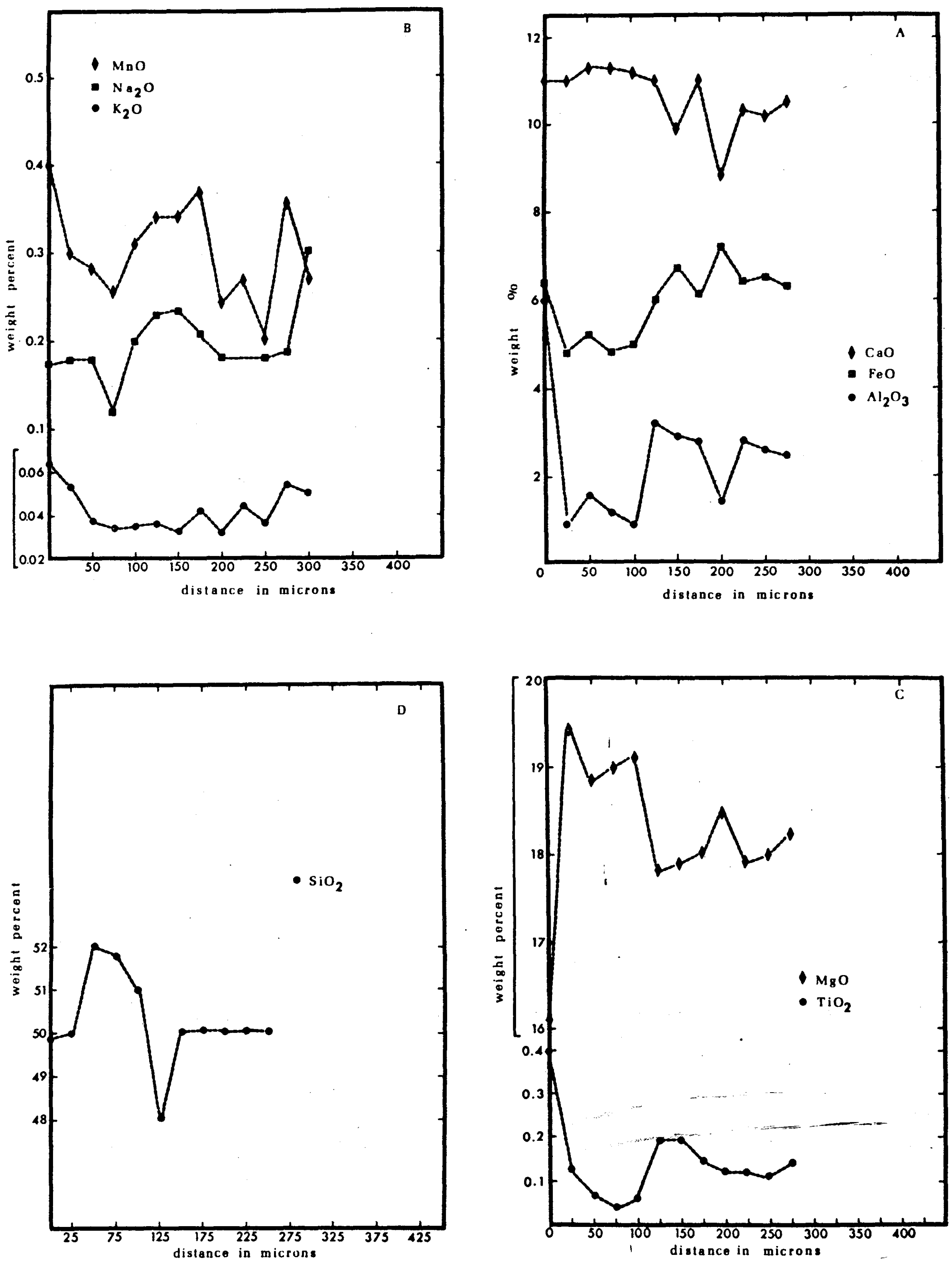

B
MnO
Na2O
K2O
weight percent
0.5
0.4
0.3
0.2
0.1
0.06
0.04
0.02
50 100 150 200 250 300 350 400
distance in microns
A
CaO
FeO
Al2O3
weight %
12
10
8
6
4
2
0 50 100 150 200 250 300 350 400
distance in microns
D
SiO2
weight percent
52
51
50
49
48
25 75 125 175 225 275 325 375 425
distance in microns
C
MgO
TiO2
weight percent
20
19
18
17
16
0.4
0.3
0.2
0.1
0 50 100 150 200 250 300 350 400
distance in microns

Figure 4.

developed along the cleavage and fracture planes. Minerals of the tremolite-actinolite series occur in minor, subrounded to elongated patches inside the hornblende and cummingtonite.

Fig. 3 shows the photo taken under microscope under crossed polars. It shows the area analyzed by the electron microprobe. Greyish yellow hornblende - the host; bluish green tremolite-actinolite lamellae; and dark reddish blue border zones can be seen clearly on the photograph. Fig. 4 shows the variation in the oxides of nine elements analyzed by electron microprobe. Apparent chemical differences are interpreted as concentration of Mg, Si and Ca in tremolite-actinolite and of Fe, Al, Ti and Mn in the dark blue zone. The differences in chemical composition may have been minimized to some degree by ionic diffusion in solid state.

Texture and Mineral Relationships: In a thin section the rock is texturally heterogeneous. The hornblende and cummingtonite occur independently of each other. From the textural study it seems that none of the minerals in the hornblendite crystallized from magma, i.e. all are secondary. The absence of any plagioclase in the hornblendite suggests a parent pyroxene rich igneous rock from which the hornblendite was derived. The hornblende and cummingtonite appear to have been derived from primary pyroxene as a result of uralitization. And the tremolite-actinolite formed as an alteration product in the hornblende and the cummingtonite during the emplacement of the younger intrusions. Chemically the origin of hornblende can be explained as follows:

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_8} + \underset{\text{Diopside}}{CaMgSi_2O_6} + \underset{\text{Enstatite}}{3MgSiO_3} + H_2O \rightarrow \underset{\text{Hornblendite}}{Ca_2Mg_4Al_2Si_7O_{22}(OH)_2}$$

Gabbro

Mineralogy: The gabbro consists dominantly of plagioclase and hornblende with biotite, secondary chlorite, pyrite, apatite, and minor amounts of zircon (Table 1).

Plagioclase occurs as subhedral crystals twinned on the albite and Carlsbad laws. The composition of the plagioclase ranges from An_{50} to An_{55} (labradorite). No significant zoning is observed in the plagioclase. Some plagioclase laths are enclosed by hornblende.

The hornblende is only weakly pleochroic suggesting that it has a relatively high Mg/Fe ratio.

The biotite shows weak pleochorism. Pleochroic halos are seen around zircon inclusions in the biotite.

Texture and Mineral Relationships: Most of the minerals in the gabbro are probably primary and of magmatic origin. Biotite encloses opaque magnetite, apatite and zircon. Biotite seems to be an early mineral to form, since it is enclosed by hornblende and plagioclase. Plagioclase apparently began to crystallize earlier than the hornblende since it occurs as inclusions in the latter. Chlorite is found scattered sporadically in the hornblende as an alteration product. At some places biotite is also altered to chlorite. The chlorite is colorless, with low relief and wavy extinction.

Diorite

Mineralogy: Diorite is a dark and dense rock. A fresh looking exposure is exposed to the east of East Charleston. The diorite contains plagioclase (oligoclase to labradorite in composition, Table 3) with hornblende, biotite and abundant magnetite. Minor amounts of quartz and some accessory minerals like sericite, chlorite, zircon, apatite and sphene are also present. The hornblende is weakly

TABLE 3

COMPOSITION OF PLAGIOCLASES FROM DIFFERENT ROCKS IN THE ECHO POND COMPLEX

Sp. No.	Ext.on Ab-Twins* in degrees	An-content	Percent of Plag. in the rock	Rock Type
J.8.4.13	29±0.5	An_{50-55}	50	Diorite
J.8.4.2	18-19	An_{40}	55	Diorite
J.8.4.2	8.5±0.35	An_{15}	56.25	Diorite
R-831	9 - 10	An_{15-18}	53.1	Hbld.-granodiorite
R-832	24±2	An_{40}	42.0	Hbld.-granodiorite
R-821	5.5-6	An_{10-12}	48.40	Granodiorite
J.8.1.5	5.5-6	An_{10-12}	46.0	Gabbro
J.8.1.6.	4 - 5	An_{6}	42.0	Granodiorite

*Extinction angles are measured on the albite twins in unzoned plagioclases.

pleochroic and the biotite shows dark brown to colorless pleochroism.

Texture and Mineral Relationships: Most minerals in the diorite are highly altered by later younger intrusions. The plagioclase is clouded with sericite. Hornblende encloses abundant magnetite. The hornblende seems to have been derived from uralitization of primary pyroxene. During uralitization some magnetite is released and calcite is formed by release of Ca from the structure. In the diorite magnetite forms up to 10% of the whole rock (Table 1). Chlorite formed by alteration mostly of hornblende and biotite is colorless, non-pleochroic and it shows wavy extinction.

"GRANITIC" BODY

The northern part of the pluton is underlain by granitic rocks. The nomenclature, granite and granodiorite, is designated on the basis of K-spar content in the rock. Unfortunately the lack of outcrops make it difficult to map these two rock types distinctly. But granite is most abundant and is a good representative of the sialic igneous rocks of Echo Pond Complex (Table 4). Fig. 5 shows a uniform variation in the K-spar and plagioclase content in the granitic rock.

Mineralogy: The granite and granodiorite contain variable amounts of quartz, potash-feldspar, albite-rich plagioclase, and biotite with minor amounts of primary muscovite, sericite, magnetite, apatite, zircon, xenotime, epidote, sphene and some enhedral crystals of garnet. Plagioclases in the granite and granodiorite are generally zoned. The microcline occurs mostly as large poikilitic phenocrysts. The phenocrysts are microperthitic (Table 5). Plagioclase is generally zoned in the range of An_{30} to An_{10}. The plagioclase occurs as euhedral to subhedral crystals. Generally the plagioclase is fractured, without any late fracture fillings, (Fig. 6b), and occurs as segregated clots in the rock. Quartz commonly appears in small grains dispersed throughout the thin section. Biotite shows wide variation in color, pleochrism, and degree of freshenss. At most places in the interior of the pluton, biotite is fresh and does not show any strain effects or alteration, but along the margins of the pluton biotite is highly altered and strained.

Fig. 7 shows plots of variation in Ca, Na, and K content in microprobe traverses across a zoned plagioclase grain (Fig. 6a). Two consecutive runs were made for Ca, Na, and K. One traverse is made

TABLE 4

MODAL ANALYSIS OF GRANITIC ROCKS ON THE BASIS OF 1000 POINT COUNT

Sp. No.*	J.8.6.22	R-833	J.83.14	7-10	7-10A	7-10B	J.8.1.5	J.8.4.13
Quartz	18.2	24	25.8	18.7	33.9	30.8	26.6	12.7
Plagioclase	13.3 (An_{12})	19.5 (An_{9-11})	24.0 (An_{10-11})	24.2 (An_{10-12})	38.3 (An_{8-10})	47.6 (An_{10})	48.4 (An_{10-12})	51.4 (An_{12-15})
K-spar	49.0	47.7	36.2	48.0	18.6	9.0	4.2	12.7
Hornblende	-	-	-	-	-	-	-	-
Biotite	14.0	5.7	6.67	3.6	2.8	7.8	16.3	21.20
Muscovite	1.6	1.2	2.10	2.2	1.6	1.2	1.2	-
Sericite	2.6	0.4	3.96	3.0	0.8	3.50	0.2	-
Other minor accessories	2.3	1.5	1.27	4.3	4.0	0.1	3.30	1.20

*Accessories - includes - chlorite, epidote, apatite, zircon, sphene, garnet, xenotime and magnetite.

TABLE 5

	$2\theta, \bar{2}01^{*}$	Wt. % orth.	Spec. No.
1**	21.2°	69.2	J.8.7.26.
2***	21.1°	82	J.8.4.14.

Wt. percent of orthoclase content in megacrysts of microcline in porphyritic granite. 1 - NW of the pluton

2 - South of Echo Pond

* - value of $\bar{2}01$ taken average of the ones obtained from two scans one at 1/2° per minute and other at 1° per minute rate.

** - felspar homogenized at 800°C under P_{H_2O} = 2kb, for one week.

*** - felspar homogenized at 1000°C under dry conditions for two days.

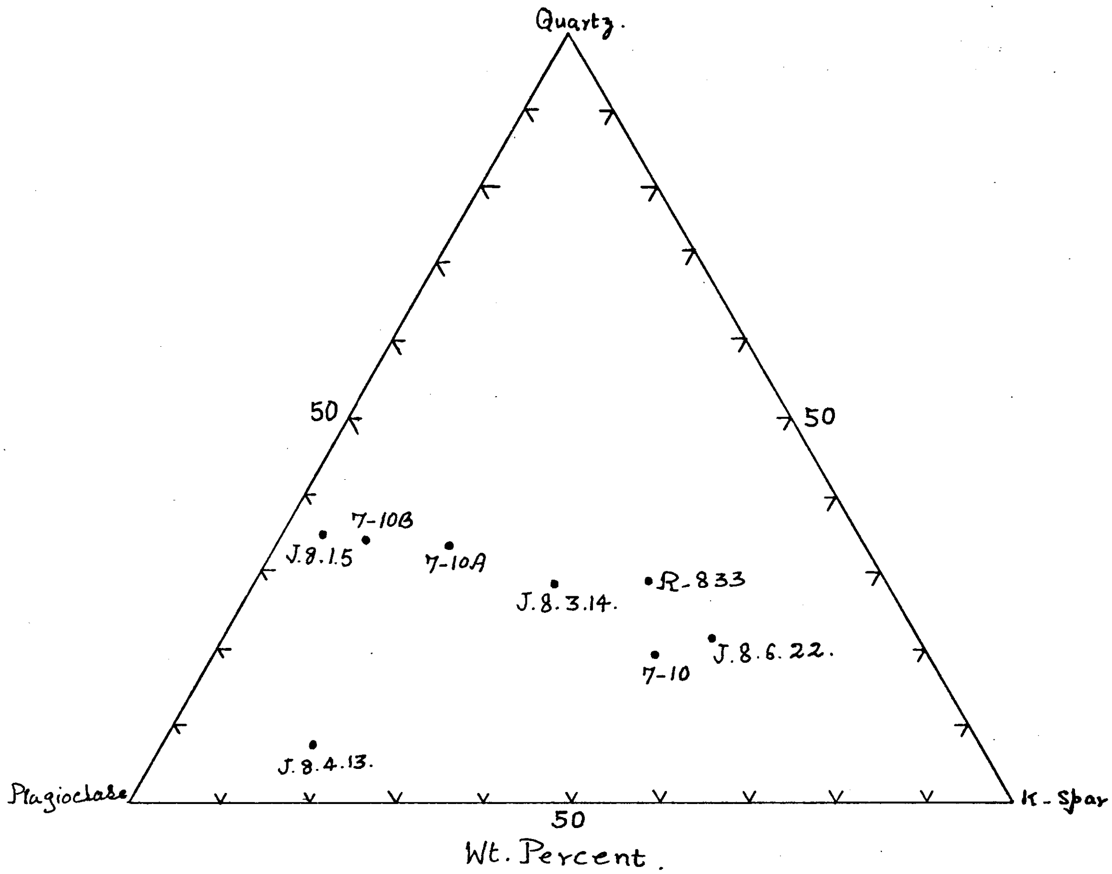


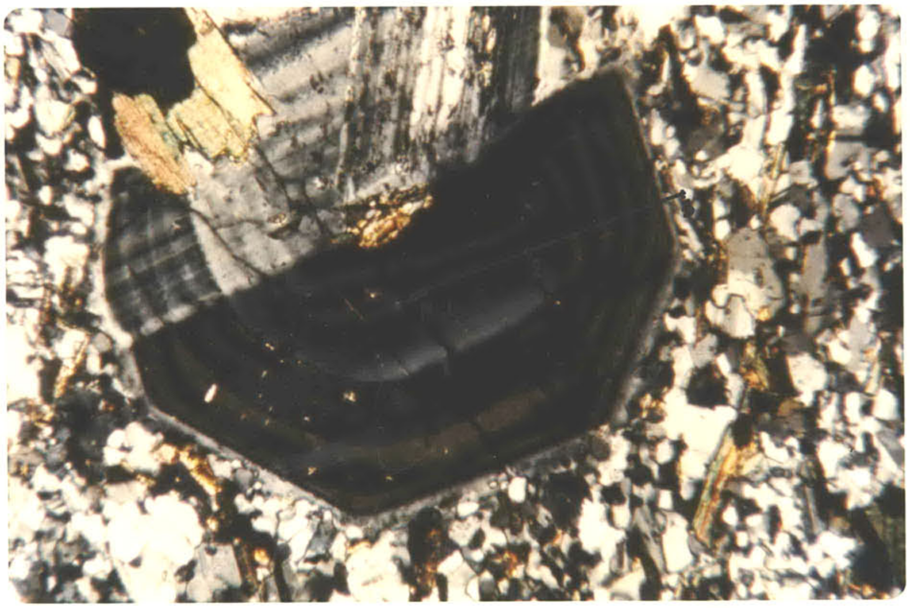
Fig. 5. Modal analysis of granitic rocks from Echo Pond Complex.

with 50μ steps and the other with 10μ steps, covering the early part of the first traverse. The runs were made in moving inside to outside of the grain with 1, 2 and 3 as reference points (Fig. 6a). Significant oscillatory zoning is seen on the 50μ step run, ranging in composition from An_{35} to An_{25}. Minor small variation in composition is noticed on the 10μ run (Fig. 7, c and e). This probably accounts for the lamellae thickness effect. In both, 10μ and 50μ step runs, some points with significantly high potassium content are noticed. The high potassium content is probably due to the presence of sericite developed along the plagioclase cleavage planes.

The oscillatory zoning in the plagioclase is of reverse type. Low to moderate anorthite content in the plagioclase shows that the plagioclases are crystallized from primary granitic magma. And it rules out the possibility of plagioclases being xenocrysts left after the partial melting of a more basic parent rock to produce granitic magma.

Well developed pleochroic halos occur around zircon inclusions in biotite. Fresh euhedral primary muscovite forms up to 2% of the whole rock (Table 4). Some secondary muscovite and sericite is also found along the plagioclase cleavage planes, developed as a result of late magmatic metasomatic effects. Some primary magnetite is associated with the biotite.

Texture and Mineral Relationships: The granite is a dark to light gray, porphyritic, medium to coarse-grained rock. Most of the minerals in the granite and granodiorite are fresh and do not show extensive alteration. The microcline occurs as large, euhedral megacrysts. It has a poikilitic texture and encloses the grains of quartz and



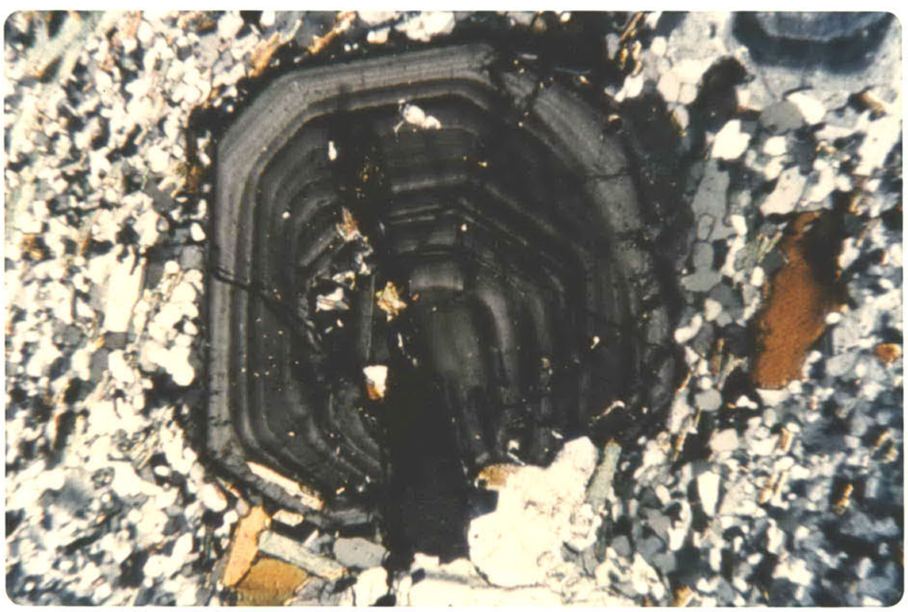


Fig. 6. (a) Photomicrograph of zoned plagioclase sample No. J.8.3.12. (crossed polars x 130). Bar shows location of microprobe traverse with reference points 1, 2, and 3.

(b) Photomicrograph of zoned plagioclase sample No. J.8.3.12.

Fig. 7. Microprobe traverse across zoned plagioclase sample J.8.3.12. shown in Fig. 6 (a). Corrected weight percent oxides plotted as a function of distance along the traverse. Fig. 7 (a) and (b) scan #1 shows the plot with 50μ steps analysis. Fig. 7 (c) shows the plot made with 10μ steps traverse, covering the early part of the 50μ steps run, and Fig. 7 (d) and (e) show the variation in albite, anorthite, and orthoclase for 50μ and 10μ traverse respectively.

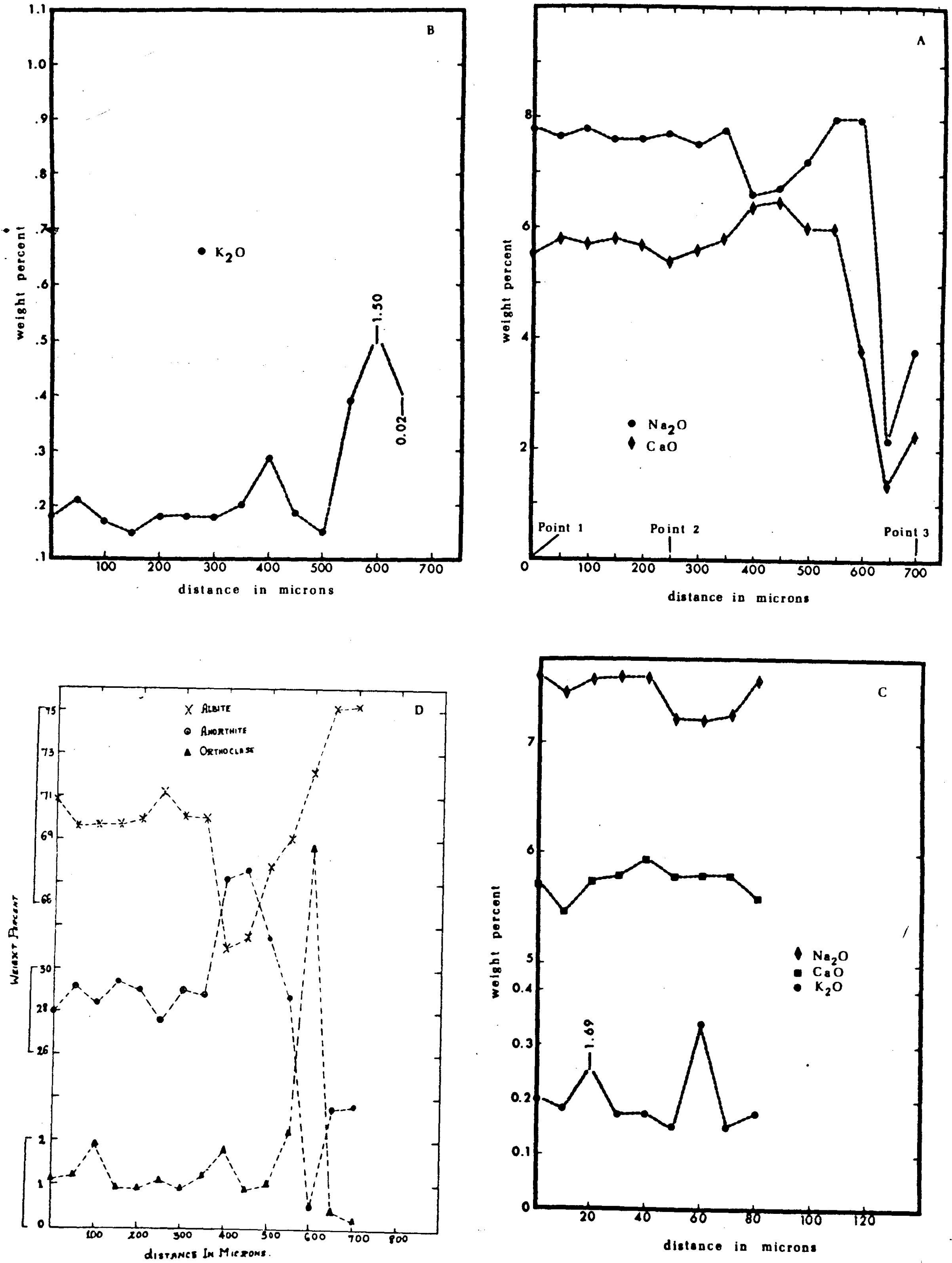

B
weight percent
K2O
1.50
0.02
distance in microns
A
Na2O
CaO
Point 1
Point 2
Point 3
D
Albite
Anorthite
Orthoclase
Weight Percent
distance in Microns
C
Na2O
CaO
K2O
1.69

Figure 7.

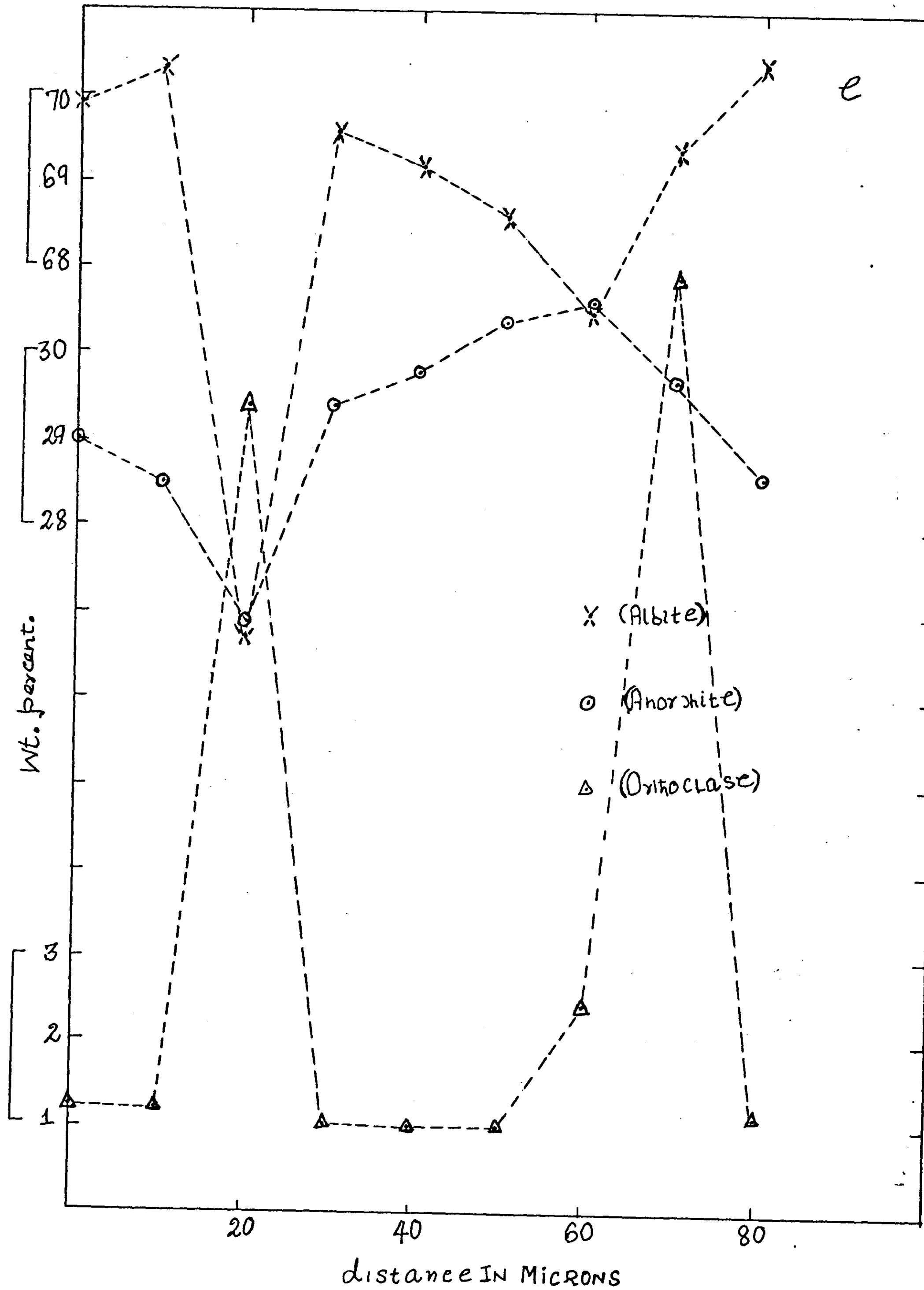

e
70
69
68
30
29
28
3
2
1
Wt. percent.
X (Albite)
⊙ (Anorthite)
△ (Orthoclase)
20
40
60
80
distance IN MICRONS

Figure 7 (e).

plagioclase. Micropegmatite and myrmekite are common in the granite and granodiorite. The myrmekite texture is developed along the contacts of adjacent grains of K-spar and plagioclase. The myrmekite projects into or borders the plagioclase.

VARIATIONS WITHIN THE PLUTON

The granitic pluton shows variations in both texture and composition. Two texturally distinct rock types can be identified easily in the field. One is porphyritic, coarse-grained granite and the other is medium to coarse-grained granodiorite and granite. With respect to the representativeness, porphyritic granite represents only a small area. It covers the areas south of Echo Pond and in the northwest part of the pluton. Most of the area is underlain by the medium to coarse-grained granite and granodiorite. Compositionally, most area of the pluton is covered by granite. Due to the lack of outcrops it is difficult to get an exact estimate of the areas covered individually by the two rock types. It is also difficult to draw a boundary between texturally distinct rocks. The granodiorite is commonly localized to the border zones of the pluton. It contains some very well zoned plagioclase megacrysts. Figure 5 shows the plot of the modal compositions of the granite and the granodiorite. The compositional variation within the pluton can be explained as follows: During the final period of emplacement of the granitic melt, a temperature gradient was set up between the melt and the relatively cooler country rock. Volatile pressure in the melt is directly proportional to the temperature. The difference in temperature between the country rock and the melt builds up a volatile pressure gradient and the volatiles (mainly H_2O) at higher pressures in the melt tend to escape through the country rock. The volatiles at high temperature and pressure act as a good transporting agent for the lighter alkali ions (Na and K). Leaking of alkaline ions from the melt along the margins make the melt locally deficient in K-content and develops granodiorite from the parent granitic melt.

This phenomenon holds true in most areas around the pluton, except to the northwest part of the pluton, where porphyritic granite with K-spar megacrysts is exposed, near the contact with the country rock.

HORNBLENDE BEARING GRANODIORITE

The contact zone between the granitic and mafic pluton is occupied by the hornblende bearing granodiorite. The zone of hornblende bearing granodiorite varies considerably in width. Only three outcrops are seen in the field. The rest of the area is mapped on the basis of float blocks of hornblende bearing granodiorite.

Minerology: Hornblende bearing granodiorite contains abundant plagioclase, hornblende and biotite, with minor quartz and traces of magnetite, chlorite and apatite (Table 1). The plagioclase has An_{35} to An_{40} composition and is commonly albite twinned. Hornblende occurs as elongated needles, enclosing chlorite, magnetite and biotite. The hornblende is weakly pleochroic. The biotite is generally brown in color and is highly pleochroic. The biotite in the ground mass is altered and strained. Electron microprobe analysis is done on two biotite grains and the hornblende (Fig. 8 a and b). The probe results are tabulated in Tables 6, 7 and 8.

Texture and Mineral Relationships: The hornblende in the hornblende bearing granodiorite occurs as long needles without any specific orientation. The hornblende encloses biotite, which suggests that the biotite probably crystallized earlier than the hornblende. Plagioclase crystallized later than the hornblende. Plagioclase grows around the hornblende and biotite. Abundant sericite is developed along the cleavage planes of the plagioclase. Abundant chlorite is also seen, formed by the alteration of hornblende and some biotite.

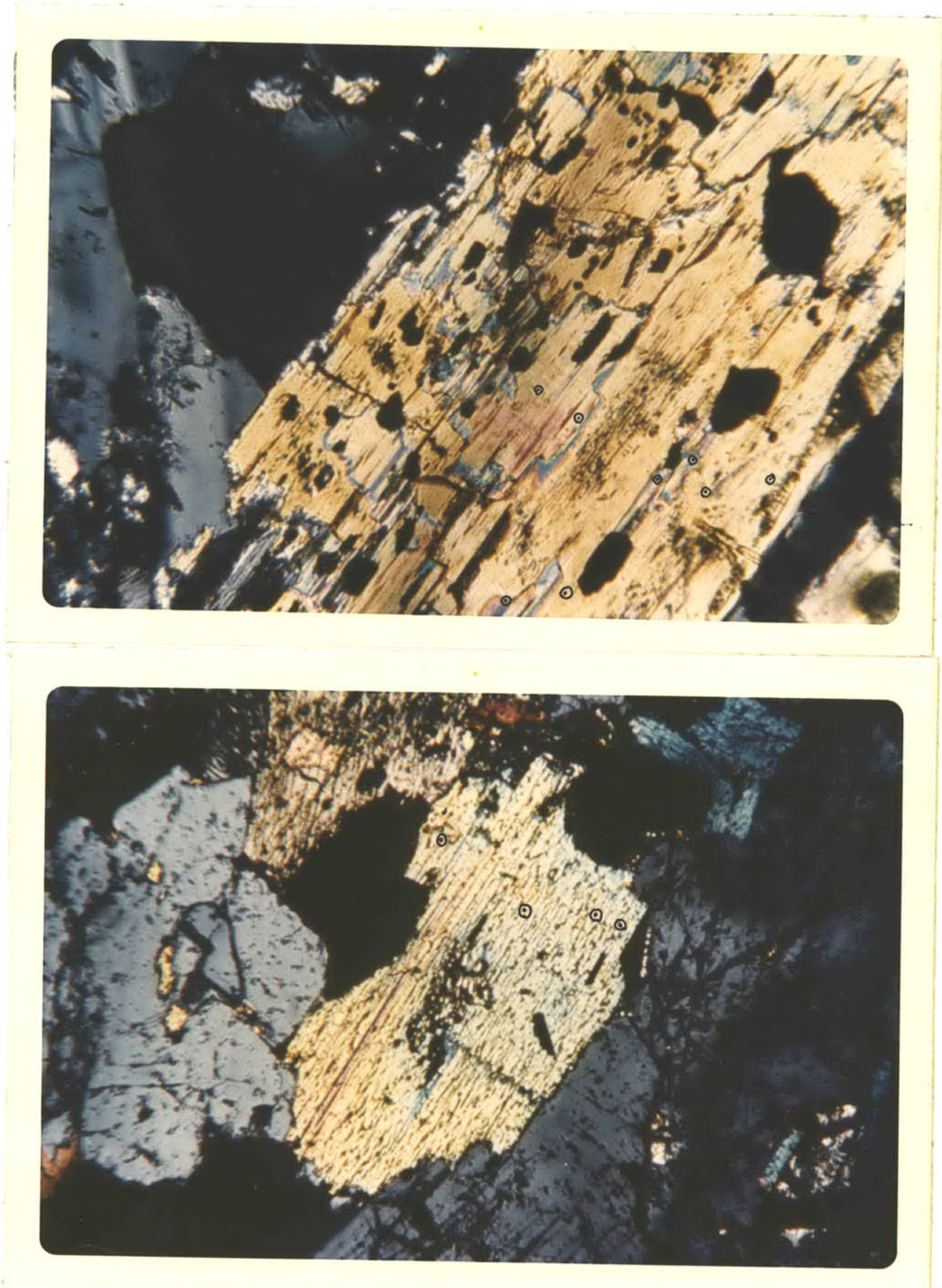


Fig. 8. (a) Photomicrograph of hornblende sample no. R-831 (crossed polars x 130). Notice the reddish biotite enclosed by hornblende.

(b) Photomicrograph of biotite sample no. R-831 (crossed polars x 80). This biotite is from the groundmass.

The circled points mark the locations analysed by electron microprobe.

TABLE 6

HORNBLENDE ANALYSIS, FROM HORNBLENDE BEARING GRANODIORITE

(Sample R-831)

Oxides	Wt. % Oxides	Ratios Element to Fe	Ratio Values
SiO_2	45.8350	Mg/Fe	1.59883
TiO_2	1.1846	Ca/Fe	1.12429
Al_2O_3	11.8071	Ti/Fe	0.07827
FeO⊛	13.6451	Cr/Fe	0
MnO	0.19776	Mn/Fe	0.01137
MgO	12.1554	Zn/Fe	0
BaO	-	Mg/Mg+Fe	0.61339
CaO	11.9682	Mg/Den.*	0.42641
Cr_2O_3	-	Ca/Den.*	0.30114
Na_2O	1.2848	Mn/Den.*	0.00393
K_2O	0.6020	Fe/Den.*	0.26850
H_2O^+	1.3914		
Total	100.0713		

*Den. (denominator) = Mg + Ca + Mn + Fe

Also see Fig. 14.

⊛ Total Fe analysed as Fe^{+2}.

TABLE 7

HORNBLENDE ANALYSIS

(Sample No. R-831, See Fig. 15)

Cell volume	904.20	
Space Group	$C_{2/}m$	
Unit Cell Contents		
Si	6.65	
Al^{IV}	1.35	
$Fe^{+3\ IV}$	-	
Ti^{IV}	-	
Tetrahedral	8.00	100 Mg/(Mg+Fe+Mn)::59.23
Al^{VI}	0.67	
Mg	2.64	
Fe^{+3} / Fe^{+2}	1.65	
Mn	0.03	
Ti	0.12	
Octahedral	5.11	
Ca	1.86	
Na	0.36	
K	0.11	
Larger Cations	2.33	

Analysis made on the basis of total anhydrous oxygen = 23

Total Fe as Fe^{+2}.

TABLE 8

BIOTITE ANALYSIS (Sample No. R-831)

	1*	2*	Element Ratios	1*	2*
SiO_2	38.0779	38.1523	Mg/ Fe	1.4439	1.6345
TiO_2	2.4732	2.1440	Ca/ Fe	0.00452	0.00369
Al_2O_3	16.3322	16.7530	Ti/ Fe	0.13522	0.11917
FeO	16.4583	0.0489	Mn/ Fe	0.00438	0.00323
MnO	0.0712	13.7420	Mg/Mg+ Fe	0.59071	0.61982
BaO	-	-	Mg/Den!	0.58856	0.61792
CaO	0.0582	0.0593	Ca/Den!	0.00184	0.00186
Cr_2O_3	-	-	Mn/Den!	0.00178	0.00122
Na_2O	0.1589	0.1223	Fe/Den!	0.40781	0.37899
K_2O	9.3126	9.4473			
H_2O	4.0121	4.2138	Den! = Mg + Ca + Mn + Fe		
			Total Fe as Fe^{+2}		
Total	100.0823	100.0641			

NO. OF IONS ON THE BASIS OF 11 (O)

	1*		2*	
Si	2.82	4.00	2.80	4
Al	1.18		1.20	
Al	0.24		0.30	
Fe	1.02		0.95	
Ti	0.14	2.904	0.11	2.863
Mg	1.50		1.50	
Mn	0.004		0.003	
Na	0.020		0.017	
Ca	0.005	0.905	0.005	0.922
K	0.880		0.900	
Ba	-			
(o)	1.480	1.480	2.080	2.080

*1 - Biotite analysed from the one enclosed by hornblende (see Fig. 8a)

*2 - Biotite analysed from the groundmass (see Fig. 8(b)).

VEIN ROCKS

General Occurrences and Relationships

Veins are interpreted as late stage offshoots of granite. No mafic veins are found cutting the granite. The granite and pegmatite veins range in thickness from a few centimeters to several feet. For example, the pegmatite vein east of East Charleston is found to be 7 ft. in thickness. Two stages of emplacement of the veins are noticed on the basis of cross cutting relations. Older veins have been displaced by a younger cross cutting vein (Fig. 10). The veins cutting the country rock are rare and less abundant as compared to the ones around the Nulhegan quartz monzonite pluton, southeast of the Echo Pond Complex.

Veins Cutting Diorite

Diorite, the least basic member of the mafic pluton to the east of East Charleston, is cut by numerous small, granitic veins. The presence of 2 in. to 6 in. wide granitic veins give a banded appearance to the dark massive diorite. Beside these small veins a massive pegmatite 7 ft. thick is also seen cutting across the diorite. All of these veins are bordered by secondary dark acicular hornblende (Fig. 10). The granitic veins show a significant effect on the minerology of diorite around the veins. The plagioclase is highly sericitized and the hornblende encloses a large amount of opaque dark magnetite. No mafic dikes or veins cut the diorite.

Relationships with Granite Body

All of the granitic veins and pegmatites found in the area seem to be related to the granitic pluton. The veins and pegmatites are interpreted as late stage offshoots of the residual volatile rich melt

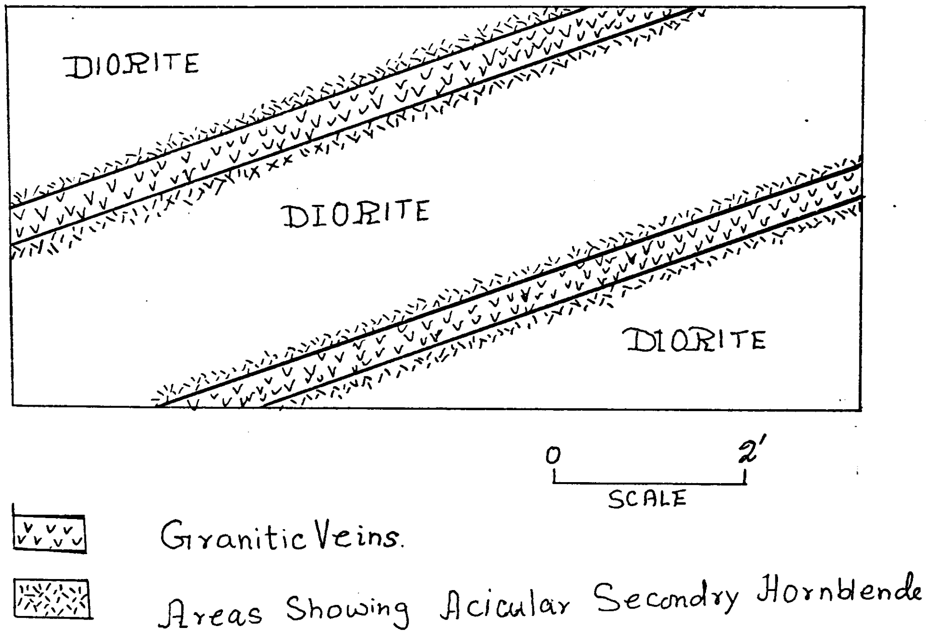


Fig. 10. Diagram illustrating the banding present in the diorite due to granitic veins.

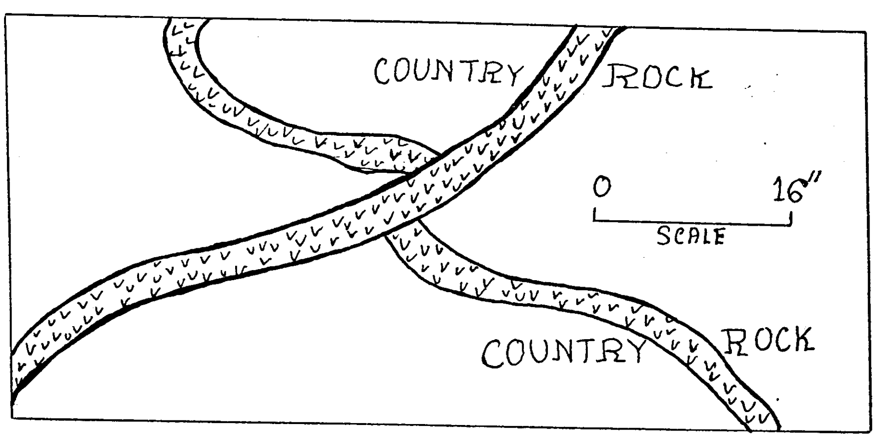


Fig. 10. Diagram illustrating the two stages of emplacement of granitic veins.

left after the crystallization of the granite and granodiorite in the area. The emplacement of the granitic and pegmatitic veins took place due to the escape of volatiles along the fissures and zones of weakness. Most of the granite veins including the pegmatites are found to be potassium-rich and peraluminous. The appearance of large K-spar megacrysts south of Echo Pond also suggest a parent potassium-rich granitic melt.

COUNTRY ROCK

The Gile Mountain Formation consists of dominantly phyllite, argillites and schists regionally metamorphosed to staurolite grade. The brown-colored fine-grained schists and finely foliated phyllites are common. At some places calc-sillicate beds are interspersed in the Gile Mountain Formation (Goodwin, 1963, p. 25).

Around the Echo Pond Complex some granite and pegmatite veins are found cutting the Gile Mountain Formation. The pegmatite veins contain microcline, plagioclase, quartz, muscovite, and biotite as dominant minerals. The pegmatites are potassium-rich and peraluminous. No significant change in minerology of the country rock, or of the pegmatitic veins cutting the country rock is noticed. The country rock is strongly deformed and shows banding and flow structure (Fig. 11). At some places the country rock is partially granitized by the intruded granitic veins.

Migmatites

On the west margin of the granitic pluton numerous small granitic veins are found cutting across the country rock. This intermixing of the country rock with the granite veins has produced a rock intermediate in composition and texture to the country rock and the granite. Such a rock is termed as "migmatite". A migmatite zone over 100 m. wide is noticed along the west margin of the granitic pluton. Within the migmatite zone highly altered biotite and sericitized plagioclase are found in the granitic veins cutting the country rock. Among other minerals in the migmatite zone, a mineral assemblage of andalusite, biotite, muscovite, garnet, and quartz, is found. The metamorhpic mineral assemblage around the pluton is discussed later.

Fig. 11. Photograph of a migmatite taken in the field west of the granitic pluton. Notice the development of ptymatic folds by granitic veins cutting the country rock. (Left margin of the picture) For references, an inch scale lies along the outcrop, and arrow points to north.

Metamorphism of Country Rock

Low to moderate temperature effects are noticed on the country rock. Schist and phyllite around the Echo Pond Complex has been thermally metamorphosed to andalusite grade. The high grade metamorphic rocks near the Echo Pond Complex contain staurolite, andalusite, biotite, quartz and kyanite; andalusite, biotite, quartz, and K-spar mineral assemblages (both reported from the west side of the pluton). Kyanite with some staurolite and andalusite is also observed from the east side of the granitic pluton. It seems that during the thermal metamorphism, temperature, pressure conditions stayed around the kyanite-andalusite region but temperature never got high enough to form the polymorph sillimanite.

Sillimanite is found only in one thin section studied from the rock specimens collected from north of the pluton. Sillimanite is also reported from that area by previous workers (Goodwin, 1963; and Doll, 1951). According to my interpretation, the sillimanite aureole between the Averill pluton and the Echo Pond Complex is primarily due to the emplacement of the Averill pluton, which is wholly surrounded by a sillimanite aureole.

Petrography of the Pelitic Rocks: Biotite, associated with some muscovite, is the most common and widely distributed mineral in the metasediments around the Echo Pond Complex. Fine-grained quartz is always present and is less commonly associated with K-spar. Among the opaque minerals are magnetite, pyrite, some graphite dust, and minor amounts of other opaque iron oxides. Chlorite is invariably a common constituent, formed mainly by alteration of biotite.

The following mineral assemblages associated with some other minerals have been observed in the Echo Pond area:

1. Andalusite + biotite + muscovite + quartz
2. Staurolite + garnet + biotite + quartz + K-spar + muscovite
3. Kyanite + staurolite + biotite + quartz + plagioclase + sphene
4. Kyanite + andalusite + biotite + quartz + muscovite

Similar metamorphic mineral assemblage is reported by Woodland (1966) from Burke Quadrangle.

The Mineral Paragenesis: Adjacent to the granitic pluton (in the western region) there is petrographic evidence of metasomatism and greater activity of fluids, by the appearance of larger general grain size and the appearance of large xenoblasts of plagioclase (1.2 -1.6 mm., Location No. 12, Map No. 2). The alteration of staurolite and andalusite to white mica and local granitization of the country rock is also in favor of metasomatism.

Thompson's projection is used for the system Al_2O_3 - FeO - MgO - K_2O to represent the muscovite bearing assemblage (Fig. 12). In the projection quartz is considered in excess and activity of H_2O is determined externally. Composition of different minerals is studied by optical methods.

The assemblage of staurolite with kyanite and andalusite is common, as noted in the thin section studies. Staurolite is laced with quartz inclusions. Suziki (1930) suggested that staurolite is generally limited to certain rocks of limited chemical composition and they have a limited temperature range (Turner and Verhoogen, 1951). Harker (1939) suggested reactions for the formation of staurolite involving chloritoid. But no chloritoid is observed in the Echo Pond area.

Texture and Mineral Relationships: The detailed petrographic study shows the development of staurolite from the biotite.

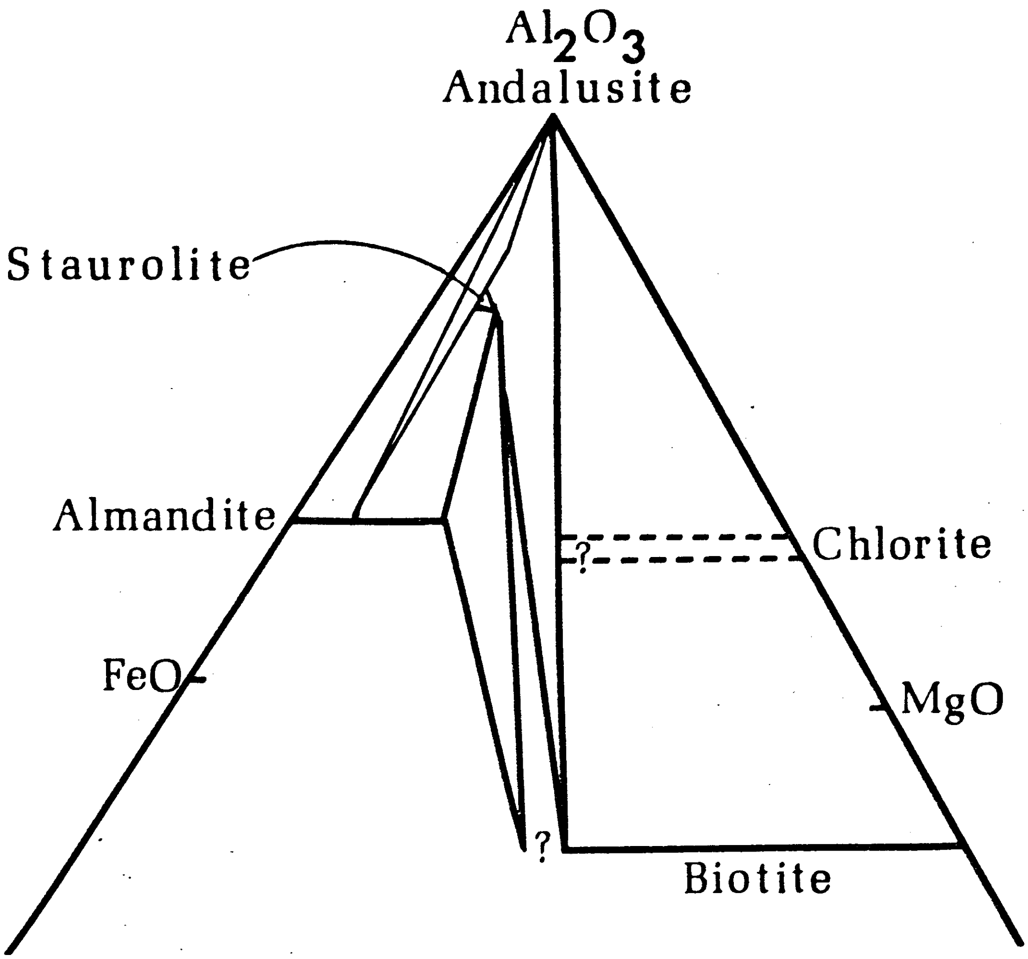


Fig.II2 Projection of the SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O system showing phases stable with Quartz, Muscovite and Plagioclase.

Andalusite seems to be later than staurolite, formed at higher temperatures probably by the reaction:

Staurolite + muscovite + quartz ⟶ andalusite + orthoclase + water

whereas the appearance of the reaction:

muscovite + quartz ⟶ andalusite + orthoclase + water

(after Turner and Verhoogan, 1951) also seems possible.

DISCUSSION

Magmatic Origin of Rocks

In the mafic pluton, gabbro and diorite appear to be primarily of magmatic origin. Presence of zoned plagioclases and the crystalline nature of most of the minerals suggest that the rocks crystallized from a melt. Crystallization of the gabbro and diorite must have taken place at a much deeper level than the present level of exposure. Hornblendite, which appears to be secondary in origin, most probably is the result of uralitization from pyroxene-rich parent igneous rock. Because of the tremendously high temperatures it is hard to speculate the melt of hornblendite composition at depths of the granitic melts.

In discussing the origin of granite, one always ends up with the following questions:

1. Was granite ever a melt? If so how was it emplaced to its present level of exposure?

2. What was the original composition of the melt?

3. How much and what type of assimilation took place during the emplacement?

To support the magmatic origin of granite one can interpret from the petrological as well as structural evidences.

Petrographically, the granite and granodiorite contain well zoned plagioclase crystals, and the nucleation effects during crystallization are also noticed in the thin section studies. For example, xenotime is nucleated by epidote, followed by biotite and later by muscovite. These features suggest that the granite and granodiorite crystallized from a melt.

Structurally some large rotated blocks of the country rock are found enveloped in granite. These possibly are the blocks broken from the roof during the emplacement of the granite and caught up in the melt.

The above discussion supports very well the magmatic origin of the granitic rocks. To consider the emplacement of the melt to present level of exposure one can proceed as follows:

Along most of its contact the country rock dips away from the pluton, except at a few places, toward it. On a regional scale the granitic pluton is concordant with the country rock but is discordant on close examination. Generally speaking during emplacement, room has to be provided for concordant bodies by flexing or spreading apart of the country rock. But in the case of Echo Pond pluton because its discordant room has to be provided either by forceful injection or magmatic stopping. The forceful injection can work its way up for granitic melt and stopping can solve the room problem. But the absence of marginal faults and fracture zones in the adjacent country rock (none reported by Doll, 1951; Goodwin, 1963; or Billings, 1951) suggest a stopping phenomenon.

In discussing the second question, it can apparently be considered that the granite in the granitic pluton has retained its composition to a large extent. There are some minor granitic veins, offshoots from the granite. And the latter does not show any significant chemical reaction with the inclusions of the country rock. The granite of the complex seems to have retained most of its original composition and possibly is a good representative of the parent granitic melt. It is difficult to answer the third question, on how much and what kind of assimilation could have taken place during the emplacement of the granitic melt. There is not enough thermodynamic data available to answer this question.

The hornblende bearing granodiorite also shows a magmatic origin. The electron microprobe study on the hornblende from the rock supports the magmatic origin very well. Due to the lack of outcrops in the field no other evidence could be seen to support the magmatic origin of the hornblende bearing granodiorite.

Sequence of Crystallization in Granitic Melt

By looking at the textural relationships between constituent minerals of the granite and granodiorite the sequence of crystallization may be established as discussed below.

Biotite and plagioclase appear to be the first minerals to crystallize, in as much as both of them are enclosed by other minerals in the rock. The color and pleochroism of biotite and minor traces of magnetite in the rock suggest that the biotite crystallized under fairly high P_{H_2O} conditions because higher P_{H_2O} favors Fe into the biotite. Presence of minor amount of primary magnetite with the biotite seems to show that during the crystallization of biotite P_{O_2} conditions were also high. The presence of primary muscovite which crystallized after the biotite, shows that during crystallization of muscovite the minimum P_{H_2O} should have been about 3.5 kb (Fig. 13) (Evans, 1965).

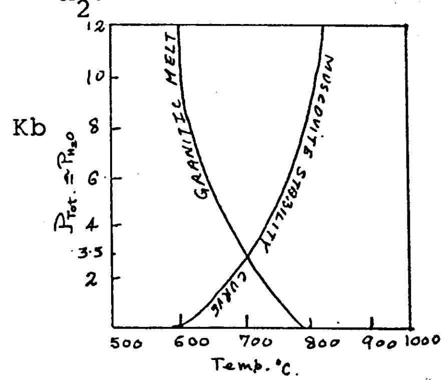


Fig. 13.

Some euhedral crystals of garnet are also identified in the thin section studies of the granite. The garnets formed are probably due to the reaction:

$$(OH)_2KFe_3AlSi_3O_{10} + (OH)_2KAl_3Si_3O_{10} + 3SiO_2 \longrightarrow 2KAlSi_3O_8\text{(melt)}$$

$$Fe_3Al_2Si_3O_{12} + 2H_2O$$

Biotite Muscovite Almandite

In thin section studies, the garnets occur independent of muscovite and biotite. Such texture suggests that the above reaction is buffered by muscovite and biotite from the country rock.

As the crystallization continued along with the uprise of the magma, the melt became relatively more and more enriched in water, due to the tendency of water to stay in the melt. And during the final stages of emplacement, the melt seems to have had large volume of water which made the melt mobile enough to produce large phenocrysts of K-spar. The perthitic nature of the K-spar suggests that the crystallization of alkali-feldspar took place in the sub-solvus region (Table 5).

Some of the accessory minerals like zircon, apatite, xenotime, sphene, sphalerite, allanite and rutile are possibly the earliest primary magmatic minerals to crystallize in the melt.

The myrmekite texture in granitic rocks can be explained by the following reaction:

$$2NaAlSi_3O_8 + CaO \longrightarrow CaAl_2Si_2O_8 + Na_2O + 4SiO_2.$$

The silica released during the reaction intergrows with more Ca-rich plagioclase. The quartz does not show any consistent optical orientation with plagioclase.

The myrmekite texture is common among the granodiorite where the source of calcium is probably the country rock.

The Development of Zoning in Plagioclase

Several workers have attempted to explain the zoning in plagioclases. Turner and Verhoogen (1951) tried to explain the zoning in plagioclase due to changes in water pressure. But it seems difficult to visualize the fluctuations in water pressure so significantly and intermittently to affect the crystal growth in a deep-seated pluton. The responsible mechanics for such changes are hard to speculate.

Jackson, Uhlman and Hunt (1966) have tried to apply the theory of interface motion to the first order (liquid-solid) phase transformation. Jackson (1958) in his theory of interface roughness qualitatively predicts the crystal growth morphology. Most of the quantitative data still seems questionable and unreliable.

The basic concept that lies in the mechanics of crystal growth theory is that the different faces of a growing crystal can have different surface energy. Growth anisotropy is developed due to the differences in the surface energy. The growth anisotropy is well exhibited by the zoned plagioclase shown in Fig. 6 b. In other words, different faces of a crystal can grow at different rates at a given under cooling. The crystal growth isotropy results when such differences are small and crystal grows uniformly.

In this solid-liquid interface model, Jackson in 1958 obtained an expression for the change in free energy on adding molecules to a fraction X of the N-possible sites on an initially plane face at equilibrium temperature Te. $\frac{\Delta F}{NKT_E} = \alpha X(1-X) + X\ln X + (1-X)\ln(1-X)$

where, $\alpha = \frac{L}{RT_E} \cdot \xi$.

where $\mathcal{L}$ = Latent heat of fusion

ξ = Fraction of the total binding energy which binds a molecule in a layer parallel to the plane face to the other molecules in the layer. ξ is always < 1.

This relationship is plotted in Fig. 14 (from Journal of Crystal Growth, 1966, p. 3). Similar plots were obtained during the crystallization of compounds (personal communication with Uhlman, 1970).

It is interesting to note in the figure that for melts with $L_{f}/RT_{E} < 2$ even the most closely packed interface planes should be rough and the initiation of new layers in growth should be easier. And for the melts with $L_{f}/RT_{E} > 4$, the most closely packed faces should be smooth and the initiation of new layers should be difficult.

To interpret the zoning in plagioclases it is apparent that the L_{f}/RT_{E} - value stayed greater than four since the crystallization of a zone of certain chemical composition started. The growth of the zone continued till the L_{f}/RT_{E} - value dropped below two. Then the growth of the new zone started with a composition such that the L_{f}/RT_{E} - value for that zone is greater than four. This way the growth of zones one after another continues until the crystallization in the melt is seized. It is to be noted that the L_{f}/RT_{E} - value is directly a function of the composition of the interface exposed to the melt.

The change in composition in different zones of a plagioclase crystal is controlled primarily by the rate of supply of Al^{+3} - cations to the site of crystal growth in the melt. Rather a uniform supply of aluminium to the growing crystal will form an unzoned plagioclase of uniform composition. In other words, $Al^{+3}:Si^{+4}$ ratio in the structure

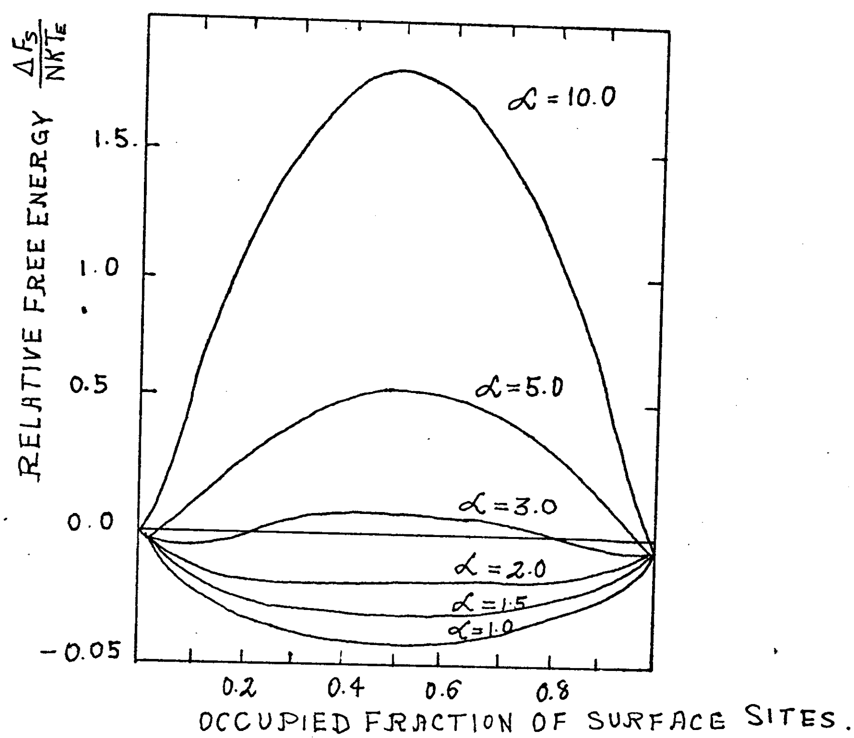


Fig. 14. Free Energy of an Interface Vs. Occupied Fraction of Surface Sites.

of the growing crystal determines the possible ways of accomodating either Ca^{+2} or Na^{+} cations. For example, the $Al^{+3}:Si^{+4}$ ratio of 2:2 will prefer Ca^{+2} into the structure to form an anorthite molecule, where $Ca^{+2}:Al^{+3}:Si^{+4}::1:2:2$. On the other hand a ratio of $Al^{+3}:Si^{+4}::$ 1:3 will prefer Na^{+} into the structure to maintain the charge balance and will form an albite molecule, where $Na^{+}:Al^{+3}:Si^{+4}::1:1:3$. Again the question arises how is the Al^{+3} and Si^{+4} distribution related to temperature and pressure. Higher temperatures and lower pressures prefer lower coordination and more of the available Al^{+3} will tend to the tetrahedral site along with Si^{+4} in the plagioclase structure. This explains the formation of anorthite rich plagioclases at higher temperatures.

But a lack in the supply of aluminium will tend to form the albite molecule even at a higher temperature, thus explaining the reverse type of zoning. And a hetrogeneous supply of aluminium explains oscillatory type of zoning.

As a whole, the zoning in plagioclases is controlled by the temperature and evidently by the supply of Al^{+3} cations to the site of crystallization. Fig. 3 (b) shows a picture of a zoned plagioclase (under crossed nicols) from granodiorite of the Echo Pond Complex.

The nature of zoning as studied by electron-microprobe is oscillatory and reverse. The complex nature of growth of the plagioclase crystal seems to show a wide hetrogeneity during the crystallization of the melt. It is interesting to notice the discontinuity of inner zoned lamellae to the left side of the crystal where they terminate against the next outer lamelie, which is almost continuous around the crystal. This suggests enhancement in the growth of the crystal before the crystallization of the continuous lamellae started. In other words, different steps may be explained as follows:

1. Continuous growth of plagioclase crystals to the last inner lamellae.

2. Partial resorption of the crystal, during which the left part of the inner lamellae were corroded.

3. Again, the continuous growth of the outer lamellae.

The zoned plagioclase crystal is fractured. Displacement of the zoned lamellie along the fractures is also noticed.

D. Development of Tremolite-Actinolite in Hornblendite

Fig. 4 shows the plots of microprobe traverses made across the hornblende enclosing tremolite-actinolite (Fig. 3). The hornblende shows a uniform Si-content on the tetrahedral site in the amphibole structure. The uniform content of Si on the tetrahedral site seems to show that the alterations in the amphiboles took place at low temperatures and probably low pressures. Most of Al^{+3}-ion exchange during the alteration of hornblende took place on octahedral site. Significant variation in the Ti content suggests that Ti has been largely affected due to addition or removal of cations at the octahedral site. It can be seen from the crystal chemistry of amphiboles that Ca with some Na and K on the larger M_4 and A cation sites will suffer the alteration effects on a significant scale. Because the lower energy is involved in the replacement of Ca, Na and K ions in the structure. This fact is well observed in Fig. 4 where variations in Ca, Na and K in a traverse across the grain are plotted.

Discussion of the Probe Results on Hornblende and Biotite from Hornblende Bearing Granodiorite

An estimate of temperature of crystallization of the hornblende can be made by considering the number of Al^{+3} ions present on the tetrahedral site in the unit cell, considering that the Z group represents all the tetrahedral cations and the Y group the octrahedral cations in the structure of hornblende. In my analysis, the results are:

the Z group Si 6.6
Al 1.4

and Y group - with Al - 0.67

These numerical values fall close to the values obtained by Nockolds and Mitchell (1948) on primary hornblende analysis from the diorites and trondhjemites. According to the crystal field effects, aluminum with coodination number 4 and 6 tends to enter in both tetrahedral and octrahedral sites. High temperature and the low pressure favors low coordination, and low temperature and high pressure favors the high coordination (Mason, 1966). At higher coordination the space is more economical. Thus at higher temperatures more Al^{+3} tends to tetrahedral sites, replacing more silica in the amphibole structure, whereas at low temperatures it tends to enter the octahedral site replacing more and more Si in the hornblende structure. The presence of relatively moderate amount of aluminum in the tetrahedral site in the hornblende from the hornblende bearing granodiorite suggest that it crystallized from a melt at relatively moderate temperatures.

It is difficult to assign the site distribution for Ca, Na and K among 'M_4' and 'A' sites in the amphibole structure. Probably most of the Ca occupied the 'M_4' site and the Na and K occupied 'A', the larger cation site in the structure. Among biotites, the general chemical formula can be written as:

$X_1Y_{2-3}Z_4O_{10}(OH)_2$ where, X is mainly Ca, Na and K

Y is mainly Al, Mg, and Fe but also Mn, Ti, etc.

Z is mainly Si and Al, may be also Fe^{+3} and Ti.

Probe analysis on biotites (Table 8) shows that the number of cations on the Y site is 5, but not exactly six to call it a triochrahedral mica.

Based on the probe results the following structural formulas for hornblende and biotite are calculated:

$$(K_{0.90}\,Na_{0.02}Ca_{0.005})(Mg_{1.5}Fe^{+2}_{0.95})(Al_{0.3}Ti_{0.11})(Al_{1.2}Si_{2.8}O_{10})(O,OH)_2 .$$

- biotite from the groundmass. (Fig. 8 b).

and

$$(K_{0.88}\,Na_{0.2}Ca_{0.005})(Mg_{1.5}Fe^{+2}_{1.0})(Fe^{+2}_{0.02}Al_{0.2}Ti_{0.14})(Si_{2.8}Al_{1.2}O_{10})(O,OH)_2.$$

- biotite enclosed by the hornblende (Fig. 8 a).

and

$$(Na_{0.4}K_{0.1}Mn_{0.3})(Ca_{1.9})(Mg_{2.6}Fe^{+2}_{1.6}Al_{0.6}Ti_{o.12})(Si_{6.6}Al_{1.4})O_{22}(O.OH)_2$$

- hornblende (Fig. 8 a) where 100 Mg:$(Mg+Fe^{+2}+Fe^{+3}+Mn)$::59.23.

The probe results are tabulated in Tables 6,7 and 8. From the structural formulas calculated above, the biotite enclosed by hornblende shows a higher Fe and Ti content. The apparent chemical difference in Fe and Ti content can be explained due to difference in temperature of crystallization of two biotites. Apparently the biotite enclosed by hornblende, crystallized earlier in the melt at higher temperatures. At higher temperatures it is easier for biotite to accomodate more of Fe^{+3} and Ti into the structure. This explains why there is higher Fe and Ti content in the biotite enclosed by the hornblende.

Discussion of the P-T Diagram for Al_2SiO_5 Polymorphs, found Around the Echo Pond Complex

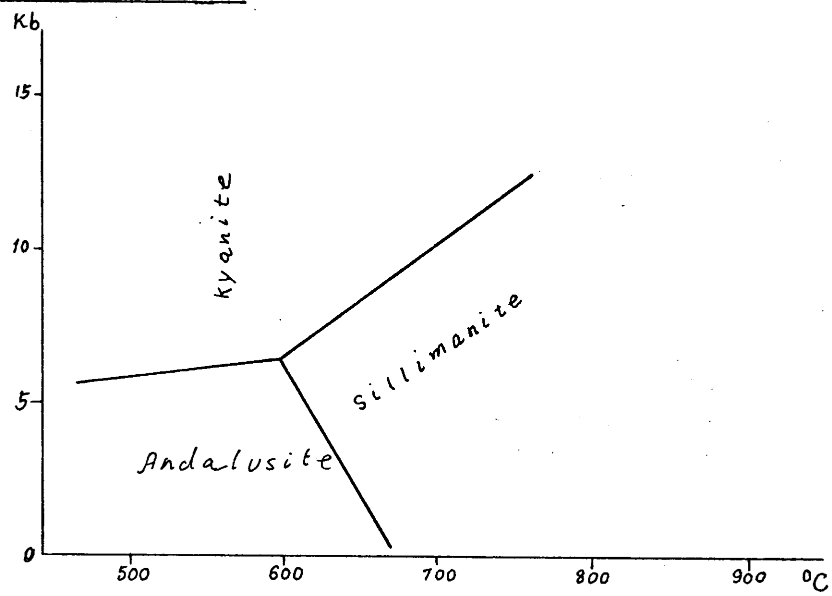


Fig. 15 Diagram showing the phase boundaries and the triple point. The triple point coordinates are P=6.5 kb and T=595°C (after Althaus, 1967).

The study of the polymorphs of Al_2SiO_5 found in the metasediments surrounding the granitic plutons in New England has been used as a key note to approximate the relative pressure and temperature conditions of emplacement of the plutons. As discussed before, the Echo Pond Complex shows an assemblage of metamorphic minerals which carries andalusite as a thermal metamorphic index mineral and kyanite, which is probably the result of regional grade metamorphism.

The presence of only andalusite and kyanite polymorphs in the vicinity of the pluton suggests that the temperature and pressure conditions were not high enough to form sillimanite. Although, the pressure and temperatures might or might not have been high enough to form metastable sillimanite phase. Considering the former interpretation, it can be considered that the P and T conditions in the country rock during the emplacement of the granitic melt were around the triple point (Fig. 15) (P=6.5 kb and T=595°C). These are the approximate upper limits of $P_{H_2O} = P_{Tot.} = 6.5$ kb and T = 595°c that can be assigned to the country rock. And to heat the country rock from 500 to 600°C the melt has to be around 800 to 1000°C. Pressure and temperature gradients could have also been developed between the relatively colder margins and the hotter interior regions of the pluton.

Taking into account the above arguments the upper limits of pressure and temperature of emplacement of the granitic melt can be estimated about T = 900 to 1000°C and $P_{H_2O} = P_{Tot.} = 6.5 \pm 0.5$ kb.

Origin of Magmas

The magmas of Echo Pond Complex originated at depth significantly greater than the present level of exposure. To form and crystallize the magma in situ, it requires much higher temperatures than noticed on the surrounding country rocks. The andalusite and staurolite present in the country rock suggest an optimum temperature of emplacement for the granitic melts. Also, no high temperature effects are noticed around the mafic pluton, suggesting that the mafic unit never attained its complete molten state while in contact with the country rock. These factors show that the magma must have been originated at deeper levels and emplaced to the present level in a partially molten state.

The mafic magmas possibly originated in the upper mantle at fairly high temperatures. The composition of the parent magma was most likely the gabbroic. The intrusion of gabbroic magma acted as a source of heat for the fusion of crustal material for form granitic magma. But the hornblendite in the mafic unit is certainly a uralitized product of a parent pyroxene rich igneous rock. The latter might have been caught up in the gabbroic melt working its way up and uralitized to its present texture and minerology.

In the granitic rocks, the presence of muscovite and garnet are consistent with the per-aluminous nature of the granite and also are consistent with the partial or complete fusion of the crustal material. Probably the radioactivity and convection currents from the mantle would not have been high enough to melt the crustal material to form granitic magma. Most probably the origin of the parent calc-alkaline magma for the Echo Pond Complex have resulted from the hybridization of the mantle derived gabbroic magma and the crustal granodioritic magma, and crystallization differentiation superimposed on the evolutionary process.

The origin of the parent magma for Echo Pond Complex can be visualized in three different ways:

1. Primary andesitic magmas developed by partial or complete fusion of the upper mantle or deep crust (Ringwood and Green, 1966; Hamilton, 1964; O'Hara, 1965; Metsumoto, 1965; Dikenson, 1962).

2. Mining of silicic and mafic magmas from the lower crust and upper mantle respectively (Holmes, 1932; Kuno, 1959; and Coats, 1962).

3. Derived from basaltic parent magma by some process of fractionation (Waters, 1962).

The second process seems to be the most probable one for the origin of the parent magma of the Echo Pond Complex, though it is difficult to completely rule out the third possibility, because one could argue that the differentiated denser mafic residue from the parent basaltic magma never reached the surface and was left to an unseen depth. But this possibility is ruled out due to the presence of the mafic pluton associated with the Echo Pond Complex.

Mode and Level of Emplacement

The structural character of the pluton and textural features suggest that successive magmas were forcefully emplaced in the upper crustal region.

The roof of the batholith is presently exposed. Several pendants of country rock indicate an irregular roof. The relationship between the structure of the wall rock and the pendant blocks is not well understood. The strike and dip of the pendant blocks is almost opposite to the regional strike and dip of the country rock.

The youngest rocks invaded in the Complex are granitic igneous rocks. The exact thickness of these preserved rocks is not known. Kyanite is found in the country rock up to far distances from the pluton, which suggest that there must have been a 15 km overburden or more. The plutons are somewhat younger than kyanite but there may not have been much stripping by the time they were emplaced. To crystallize primary muscovite in the granitic melt a minimum of 10.5 km to 11 km of overburden is required (where $P_{H_2O} = P_{Tot.} = 3.5$ kb., after Evans, 1965). To crystallize muscovite after the emplacement of the granitic melt, the minimum depth of emplacement can be considered to be about 10 to 12 km.

The presence of trace minerals like xenotime, zircon, and euhedral apatite and garnet suggest that the granite was once in a completely molten state. Deep brown color and highly pleochroic nature of biotite shows a high P_{H_2O} and at the same time, the presence of minor primary magnetite with the biotite seems to show that P_{O_2} was also high to oxidize some of the iron to magnetite.

The electron microprobe results show a maximum of An_{35} content in the primary plagioclases. To get the plagioclase of this composition in the melt the temperature of the melt has to be around 800°C, with the possible corrections due to water pressure and the other components in the melt. Again this could be the lower limit of temperature of the granitic melt.

These are the approximate values of pressure and temperature during the history of the granitic melt.

SUMMARY AND GEOLOGICAL HISTORY

The Echo Pond Complex intrudes the Lower Devonian Gile Mountain Formation. The Complex lies in the west part of the Island Pond Quadrangle. The country rock around the pluton shows a regional staurolite grade metamorphism prior to the emplacement of the pluton. Andalusite grade contact thermal metamorphism is observed around the granitic pluton. Relatively lower temperature of emplacement of the Echo Pond Complex, compared with other plutons in northeast Vermont, is explained due to the absence of sillimanite aureole around it. Sillimanite aureole surrounds most of the granitic plutons in northeast Vermont (Fig. 1).

The Complex intruded forcefully in a mafic to silicic sequence, at a much deeper level than the present level of exposure. As a result of emplacement of younger granitic melt against the partially solidified mafic unit, the hornblende bearing granodiorite formed along the contact zone of the granitic pluton with the mafic pluton. The electron microprobe analysis on hornblende and biotites from hornblende bearing granodiorite suggest that it crystallized from a melt.

Absence of high temperature effects on the country rock around the mafic pluton reveals the fact that the mafic unit never atained its complete molten state while in contact with the country rock. An outcrop of a single block of hornblendite in the mafic unit is possibly a xenolith from the deep crust which was carried up to the present level by the melt.

Approximate temperature and pressure of emplacement of the granitic melt were $P_{Tot.} = P_{H_2O} \simeq 6.5 \pm 0.5$ Kb; and $T \simeq 900 \pm 100°C$. The granitic melt during its initial stages should have been at higher temperatures

With the uprise of the magma and continued crystallization the water pressure gradually went up, with the tendency of water to stay in the melt. And probably reached its maximum (6-7 Kb) during the emplacement.

APPENDIX

The electron microprobe analysis was done at California Institute of Technology, under the supervision of A. A. Chodos and Prof. A.L. Albee. The samples studied in this research were polished rock thin sections mounted in epoxy. All samples were carbon coated. Both the traverse and single point analysis were made on the samples. Brief description is also given of the samples used for the probe analysis:

J.8.3.12. Well zoned plagioclase chosen from the granodiorite. No twinning is noticed in the plagioclase crystal and it has some sericite developed along its cleavage planes. The analysis was carried out by two consecutive probe traverses across the crystal.

J.8.1.2. Hornblendite sample which shows hornblende enclosing tremolite-actinolite with a reaction rim surrounding the tremolite-actinolite inclusion. The sample was found a good representative of the general texture of the rock. Probe traverses were made, for nine elements, across the sample.

R - 831 Biotite enclosed by a hornblende crystal, a typical texture of the rock, and a biotite grain from the groundmass were chosen for single point probe analysis. The biotite crystal from the groundmass was chosen to be the least altered and with no visible optical zoning.

The biotite enclosed by hornblende is fresh and unaltered. Whole mineral analysis was carried out on two biotite samples and a hornblende crystal.

In order to avoid repetition the author likes to refer the reader to a paper by Bence, A.E., and Albee, A.L. (1958).

. This paper deals with the correction techniques and the standards used for the analysis reported in this paper.

The raw data counts were fed directly into the computer. The computer gave the single point analysis results and made plots on a semilog scale for the traverses made across the samples. The plots were made with K-values (defined as the background corrected intensity of a characteristic radiation line of an element in the compound relative to that of the pure element) on the log scale against distance in microns. The analyses were made against oxide standards (personal communication with Prof. Albee, 1970). So, the K-values obtained were directly proportional to the weight percent of oxides in the sample. The K-values taken from the semilog plots are plotted on a simple graph, against the distance.

It is important to point out here that in all of the analysis total Fe was calculated as Fe^{+2}. The oxidation state of iron in some cases is approximated by considering the charge balance technique, in calculating the structure formula of biotite and hornblende.

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