THE PETROLOGY OF SEVERAL LATE TERTIARY GABBROIC PLUGS IN THE SOUTH CARIBOO REGION, BRITISH COLUMBIA

by

ROBIN BRUCE FARQUHARSON

B.Sc., University of British Columbia, 1963

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in the Department
of
GEOLOGY

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

July, 1965

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Geology

The University of British Columbia
Vancouver 8, Canada

Date August 2, 1965

ABSTRACT

Four olivine gabbro plugs crop out on the basaltic plateau in the south Cariboo region of British Columbia. The plugs form elliptical knobs of unaltered gabbro which stand 100 to 200 feet above the plateau surface. They are 300 to 600 feet in greatest diameter, as seen in plan view. Two plugs, Mt. Begbie and Forestry Hill, are described in detail in this thesis.

Alignment of tabular feldspar grains resulting from the upward flow of magma, has produced a foliation in both Mt. Begbie and Forestry Hill plugs. Foliation dips toward the centre at moderate to steep angles in both plugs. Small, scattered lenses of leucogabbro and picritic gabbro lie approximately in the plane of foliation. Marginal foliation is assumed to be roughly parallel to the walls of the plug. Foliation trends indicate that both plugs are funnel-shaped, increasing in diameter toward the surface.

The essential minerals of the plugs are olivine, calcic-augite and plagioclase. They are strongly zoned indicating a disequilibrium environment of crystallization. From a consideration of mineralogical and chemical characteristics it is concluded that the original magma was an alkali basalt magma. Differentiation by fractional crystallization produced small volumes of marginal dolerite and pegmatitic gabbro in the outer portions of Mt. Begbie plug. The trend of differentiation leads

to iron-enrichment in the marginal dolerite, and then to alkali-enrichment in the pegmatitic gabbro.

The four plugs occupy former volcanic vents which, in late Tertiary time, fed lava to the surrounding plateau. The exposed portions of the plugs crystallized possibly within 50 to 150 feet of the surface. General geological relationship, petrological similarity, and the close comparison of fused whole-rock powders suggest a definite kinship of the plugs to the surrounding basaltic lava.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
General Statement	1
Present Study	1
Geologic Setting	3
Location	3
Acknowledgments	4
FIELD CHARACTER	6
Description of the Plugs	6
Mt. Begbie Plug	6
Forestry Hill Plug	8
Lone Butte Plug	8
Tin Cup Mountain Plug	11
Structure	11
Contact Relations at Mt. Begbie	11
Foliation	12
Form of Intrusion	13
PETROGRAPHY	17
General Statement	17
Olivine Gabbro	17
Leucogabbro and Picritic Gabbro	22
Marginal Dolerite	22
Pegmatitic Gabbro	24
Perpendicular Pyroxene Rock	25
Basaltic Chilled Margin	27

Page

PETROGRAPHY - continued

Surrounding Basaltic Lava 27

MINERALOGY 28

General Statement 28

Laboratory Methods 28

Plagioclase 29

Composition 29

Twinning 31

Pyroxene 33

Olivine 35

Iron Ore 38

Silica 39

Zeolite 39

PETROLOGY 40

Composition of the Plugs 40

Mode 40

Chemical Composition 40

Whole-Rock Glass Bead Determinations 44

Specific Gravity 46

Differentiation 47

Nature of the Original Magma 52

History of Crystallization 59

Environment 59

Initial Crystallization 60

Crystallization of Olivine Gabbro 60

Page

History of Crystallization - continued

Crystallization of Marginal Dolerite 64

Crystallization of Pegmatitic Gabbro 64

COMPARISON WITH SIMILAR INTRUSIONS 65

General Statement 65

Skoatl Point Plug 65

Tertiary Dolerite Plugs of North-East Ireland 66

Maiden Island, Oban, W. Scotland 67

Cnoc Rhaonastil, Islay, W. Scotland 67

SUMMARY AND CONCLUSIONS 68

BIBLIOGRAPHY 69

LIST OF ILLUSTRATIONS

Figure		Page
1	Index map	2
2	Location map	5
3	Plan of Mt. Begbie plug	9
4	Plan of Forestry Hill plug	10
5	Section across the zone of perpendicular pyroxenes	12
6	Statistical diagrams of foliation	14
7	Hypothetical cross-section of Mt. Begbie plug . .	15
8	Hypothetical cross-section of Forestry Hill plug .	16
9	Diagram showing composition of pyroxene	34
10	Variation diagram of per cent oxides versus MgO .	48
11	Trend of differentiation of Mt. Begbie plug . . .	49
12	Plot of mafic index versus per cent SiO_2	50
13	FMA diagram showing variation of dolerite pegmatites and their parent rocks	50
14	Differentiation trends of clinopyroxenes in basaltic magmas	54
15	Tetrahedral forsterite - albite - anorthite - diopside diagram	56
16	Differentiation trends on a plot of MgO versus Al_2O_3/SiO_2	58
17	Course of crystallization of olivine gabbro . . .	61

Plate		follows Page
1	Figure 1. View of Mt. Begbie from ½ mile to the south	6

Plate		follows Page
1	Figure 2. View of Lone Butte from ½ mile to the west	6
2	Figure 1. Leucogabbro lens about 12 inches long	7
	Figure 2. Irregular lens of picritic gabbro about 15 inches long	7
3	Figure 1. Contact of marginal dolerite with basaltic chilled margin at Mt. Begbie	11
4	Figure 1. Sub-parallel alignment of feldspars in olivine gabbro	19
	Figure 2. Clinopyroxene replacing olivine . . .	19
5	Figure 1. Rounded olivine inclusions in clinopyroxene	19
	Figure 2. An optically continuous grain of olivine composed of three "agglutinated" individuals	19
6	Figure 1. Large seive-textured pyroxene of Group I	20
	Figure 2. Same as above but with crossed nicols	20
7	Figure 1. Olivine grain surrounded by small anhedral grains of clinopyroxene	21
	Figure 2. Oligoclase rims on tabular plagioclase grains	21
8	Figure 1. Sub-concentric fractures surrounding a skeletal grain of iron ore	21
	Figure 2. Radially fibrous zeolite interstitial to plagioclase	21
9	Figure 1. Granophyric fringe between cristobalite and plagioclase	23
	Figure 2. Olivine sub-ophitically enclosing plagioclase	23
10	Figure 1. Tetragonal crystal of cristobalite in a cavity within marginal dolerite	23
	Figure 2. Thin blades of pseudobrookite in a cavity within marginal dolerite	23

Plate		follows Page
11	Figure 1. Pseudobrookite replacing magnetite/ilmenite grain in marginal dolerite	24
	Figure 2. Skeletal olivine extended in one direction	24
12	Figure 1. Skeletal or "poikilitic" grains of olivine enclosed by large feldspar grain in pegmatitic gabbro	25
	Figure 2. Skeletal iron ore in pegmatitic gabbro	25
13	Figure 1. Fringes of "exsolved" iron ore on grains of pyroxene in pegmatitic gabbro	25
	Figure 2. Elongate, twinned grains of tridymite occupying a miarolytic cavity in pegmatitic gabbro	25
14	Figure 1. "Perpendicular" pyroxene grains disrupting the flow alignment of feldspar . . .	27
	Figure 2. Irregular tridymite-filled cavities in the basaltic chilled margin	27
15	Figure 1. Oscillatory zoning in plagioclase . . .	31
	Figure 2. Baveno twin with close polysynthetic albite twinning	31
16	Figure 1. Agglutination twin of plagioclase composed of several sub-parallel individuals .	32
	Figure 2. Jagged pericline twinning in pegmatitic gabbro	32
17	Figure 1. Lamellar intergrowth of ilmenite and magnetite	39
	Figure 2. Replacement rim of hematite on magnetite	39
18	Figure 1. Hematite replacing magnetite/ilmenite intergrowth along a (111) plane	39

LIST OF TABLES

Table		Page
1	Average Cross-Sections of Common Minerals for Several Rock Types	18
2	Range of Zoning in Plagioclase	29
3	Optical Properties of Pyroxene	34
4	Composition of Olivine	37
5	Modes	41
6	Calculated Chemical Compositions	43
7	Glass Bead Determinations	45
8	Specific Gravity	46
9	Comparison of Chemical Compositions	55

INTRODUCTION

General Statement

Several knobs of olivine gabbro crop out on the basaltic plateau surface in the South Cariboo region of British Columbia. The general aspect of these igneous bodies suggests that they are volcanic plugs[1] filling vents which fed some of the surrounding basaltic flows. Four such plugs are known to the writer and a detailed study has been made of two of these. The object of this thesis is to provide a description of the plugs and to postulate a history of intrusion and crystallization of the original magma.

Present Study

Initial field study of the plugs was done in August, 1964 while the writer was a geological assistant to Dr. H.W. Tipper of the Geological Survey of Canada. Independent study was resumed for several days in October, 1964. The two plugs which have been mapped in detail are designated by the names Mt. Begbie plug and Forestry Hill plug.[2] Two other similar plugs, Lone Butte and Tin Cup Mountain, have been visited by the writer but little description is included.

Data collected in the field include a rough outline of the shapes of the plugs using a chain and compass technique,

---

[1] American Geological Institute Glossary (1962) defines volcanic plug as a neck consisting of a monolithic mass of solidified igneous rock.

[2] Not a formal geographic name.

attitudes of jointing, and measurements of primary foliation.

Data collected in the laboratory include optical descriptions of the component minerals, universal stage determination of mineral compositions, point-counter analysis of mineral percentages, powder camera x-ray identification of some minerals, refractive indices of some minerals, and refractive indices of fused whole-rock glass beads.

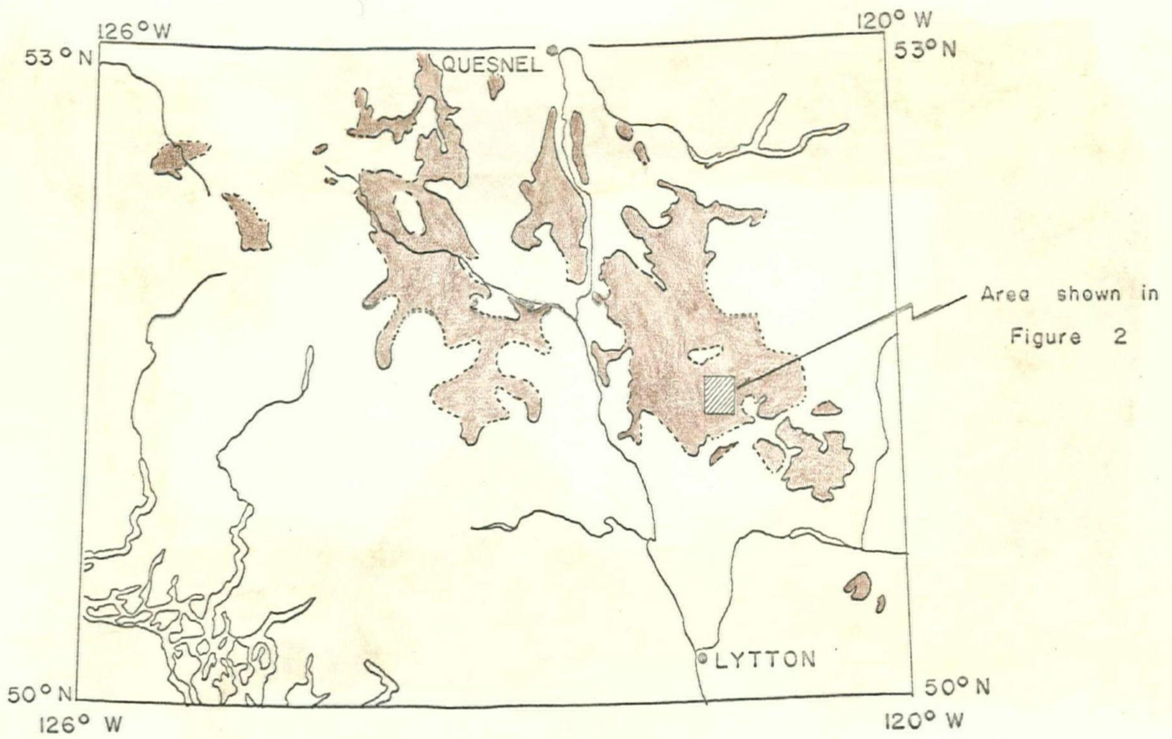

Figure 1. Map showing the distribution of late Tertiary plateau basalts in south-central British Columbia (from Mathews and Rouse, 1963, p. 57). The four plugs are located within the hachured area (see Figure 2).

Geologic Setting

The plugs are situated in a region of widespread late Miocene or early Pliocene volcanism (Mathews and Rouse, 1963, p. 60) where a succession of basaltic flood lavas built an extensive plateau surface. The lavas are essentially undeformed except for broad, regional warping. The succession is typified by a paucity of pyroclastic and epiclastic material and by widespread uniformity of rock type. From limited field observation the writer is able to suggest a two-fold division of the lavas into porphyritic and non-porphyritic, where the former occupies the highest stratigraphic level of the succession. Figure 1 shows the regional distribution of late Tertiary plateau basalts and the area within which the four plugs are located.

Pleistocene glacial deposits 10 to 20 feet thick cover most of the bedrock. Basaltic boulders up to 8 feet in diameter are contained in the drift. Continental ice moved about S. 10° E. near Lone Butte and about S. 27° E. in the vicinity of 83 Mile House (M.A. Smith, 1965, p. 15).

Location

The plugs are situated in the South Cariboo area of British Columbia between 70 Mile House and 100 Mile House. Figure 2 is a map showing the locations of the four plugs. All are within a few minutes walking distance of roads.

Mt. Begbie plug is about 1 1/2 miles north of 83 Mile House and just east of Highway 97. A forestry access road connects with the highway and leads 1/8 mile to the base of

Mt. Begbie. Lone Butte plug is just north of the Bridge Lake road about 1/2 mile east of Lone Butte settlement. Forestry Hill plug is situated about four miles east of Lone Butte along the Bridge Lake road. A forestry access road leads north about 1/4 mile from Bridge Lake road to the top of the knob. Tin Cup Mountain plug is about 10 miles east of 70 Mile House on the road that runs south of Green Lake. The plug lies about 1 mile south of the road and can be partly approached by way of recent logging roads.

Acknowledgments

The writer wishes to thank Dr. H.W. Tipper who suggested a study of the plugs. Mr. K. Domai gave valuable assistance in the field. Mr. A. Davidson provided stimulating and instructive discussion concerning the mineralogy of the plugs. Thin sections were prepared through the courtesy of Mr. E. Montgomery. Thanks are expressed to Dr. K.C. McTaggart and to Dr. W.H. Mathews for their criticism of the manuscript.

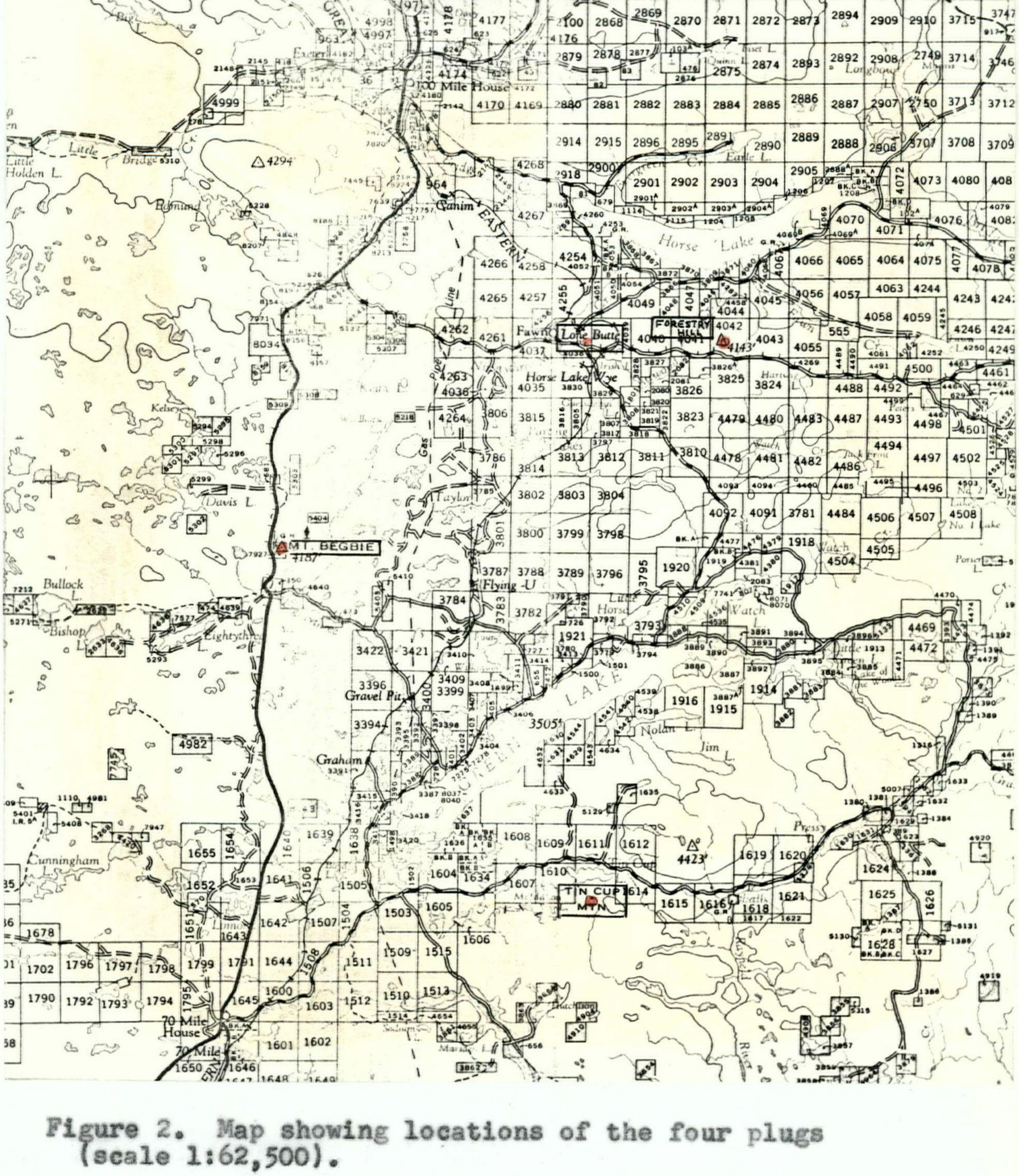

Figure 2. Map showing locations of the four plugs (scale 1:62,500).

FIELD CHARACTER

Description of the Plugs

Mt. Begbie Plug. Mt. Begbie (Plate 1, Figure 1) is an elongate knob of olivine gabbro which rises some 250 feet above the surrounding terrain. The plug is elliptical in plan, the long axis of the ellipse trending about N. 50° W. The fairly flat top is surrounded by cliffs which provide well-exposed sections. The southern flank is eroded to a much lower elevation than is the northern flank. A plan view of the plug is shown in Figure 3. The outline was determined from radial chain and compass traverses. Sample locations and measurements of foliation are shown.

Mt. Begbie plug intrudes the plateau basalts. The contact is visible only at the south-east extremity of the plug where gabbro is adjacent to feldspathic basalt. It is irregular and steeply-dipping and may be slightly inclined towards the plug. A chilled margin 1 to 2 feet thick is composed of black to grey feldspathic basalt.

The main rock type of the plug is olivine gabbro. Other modifications, which occur in minor abundance, include; leucogabbro, picritic gabbro, marginal dolerite and pegmatitic gabbro. Leucogabbro (Plate 2, Figure 1) and picritic gabbro (Plate 2, Figure 2) occur in lenses which are variable in shape and are seldom greater than 1 foot in length. These are scattered sparsely throughout the plug. Marginal dolerite

PLATE 1

Figure 1. View of Mt. Begbie from ½ mile to the south.

Figure 2. View of Lone Butte from ½ mile to the west.

occurs in an irregular, discontinuous zone which separates gabbro from the chilled basaltic margin. The zone is 2 to 3 feet wide and is probably concentric with the contact. Pegmatitic gabbro occurs in irregular lenses near the margin. A large lens (position shown in Figure 3) 15 feet in diameter, is seen in the southern portion of the plug. It is surrounded by olivine gabbro. Elsewhere small pegmatitic lenses, usually less than 6 inches in diameter, occur enclosed by either olivine gabbro or marginal dolerite.

Jointing is typically blocky. Four prominent sets of joints are developed; a vertical radial set, a vertical tangential set, and two shallow- to moderate-dipping conjugate sets. Shallow-dipping joints are frequently closely spaced with intervals as little as 4 inches. Some large joint planes form large, smooth, curving cliff faces. Some vertical joints are coated with a thin mat of feldspar.

Alignment of tabular feldspar grains has produced a foliation in the gabbro. This is best developed near the margin of the plug and becomes less obvious towards the centre.

To the south-east, leading away from the plug for at least 1/2 mile, is a belt of strewn boulders and blocks of olivine gabbro. The belt is about 75 yards wide and strikes S. 25° E., about parallel to the movement of continental ice (M. Smith, 1965, p. 15). The material is interpreted as a boulder train formed by a glacier plucking rock from Mt. Begbie and depositing it south-eastwards.

PLATE 2

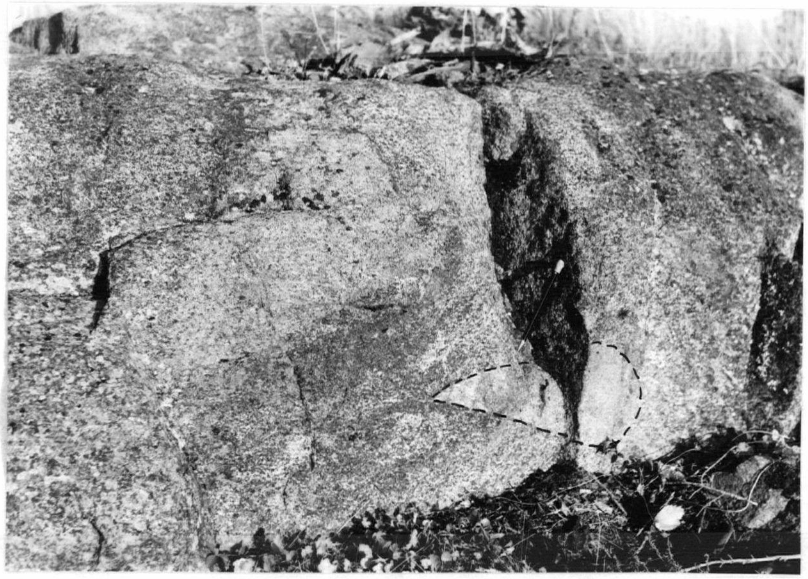

Figure 1. Leucogabbro lens about 12 inches long.

Figure 2. Irregular lens of picritic gabbro about 15 inches long. Large black specks are lichen.

Forestry Hill Plug. Forestry Hill plug is a rounded knob rising about 200 feet above the surrounding plateau. It is elliptical in plan with the long axis trending N. 60° E. Red to black vesicular olivine basalt crops out on the south-west and north-east flanks of the knob but nowhere is the contact exposed. Rock exposure is generally poorer than at Mt. Begbie. Figure 4 is a plan view of the plug derived from chain and compass traverses. Sample locations and foliation trends are shown.

The plug is composed of olivine gabbro similar to that of Mt. Begbie plug. Lenses of leucogabbro and picritic gabbro are scattered throughout but there is no visible marginal dolerite or pegmatitic gabbro. Towards the margin the gabbro contains occasional spherical vesicles lined with a white zeolite.

Jointing is typically blocky with a fairly wide separation of individual joint planes. The topographic form of the plug around the margin is governed largely by a step-like arrangement of vertical and shallow-dipping joint planes. Here, vertical joints tend to occur as conspicuous, continuous planes roughly parallel to the margin of the plug.

As in Mt. Begbie, alignment of tabular feldspar grains has produced a foliation in the gabbro.

Lone Butte Plug. Lone Butte (Plate 1, Figure 2) is a cylindrical knob, almost circular in plan, which projects about 150 feet above the surrounding terrain. The top is very flat and is about 250 feet in diameter. The steep walls of the butte

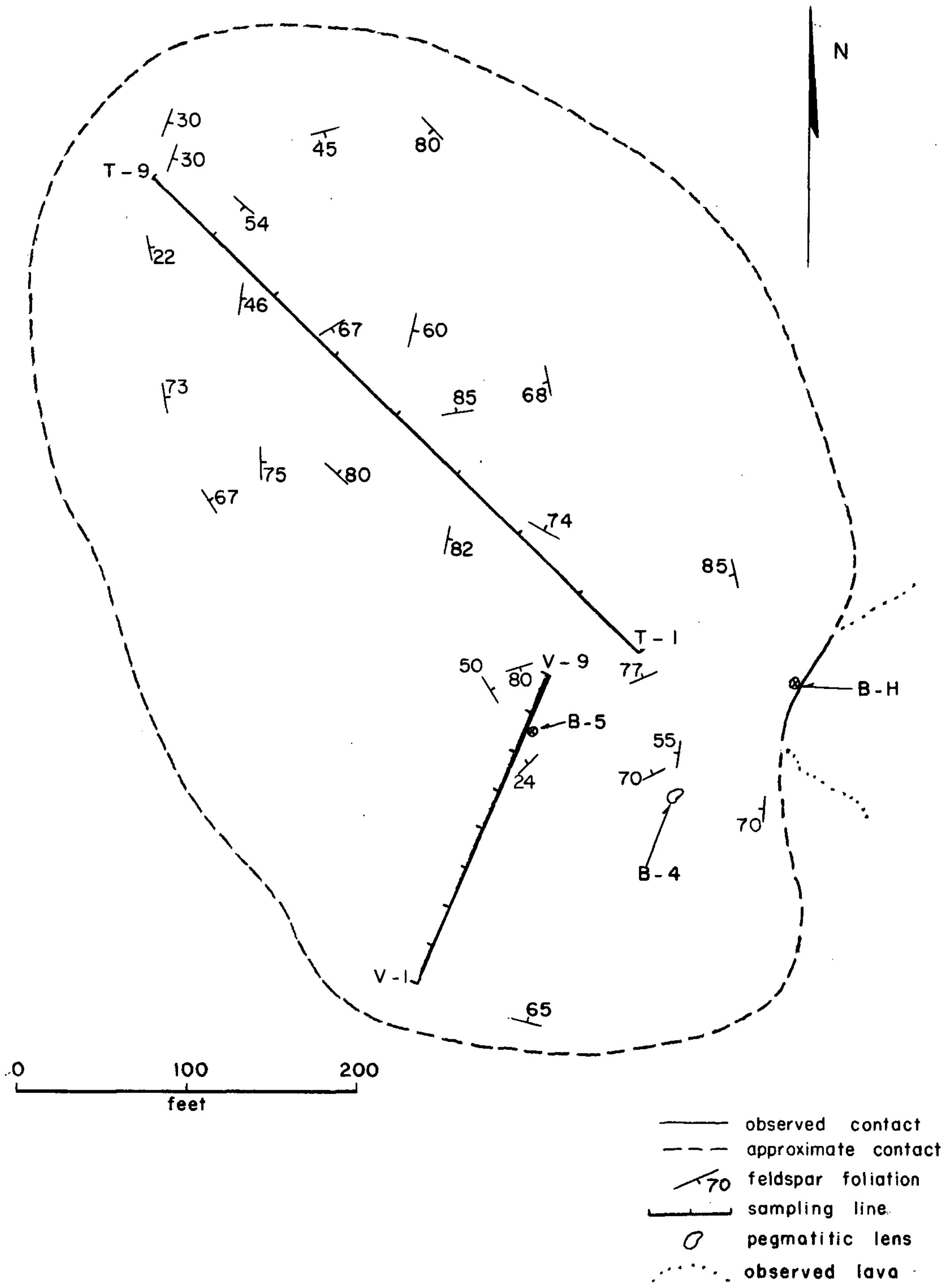

Figure 3. Plan view of Mt. Begbie plug.

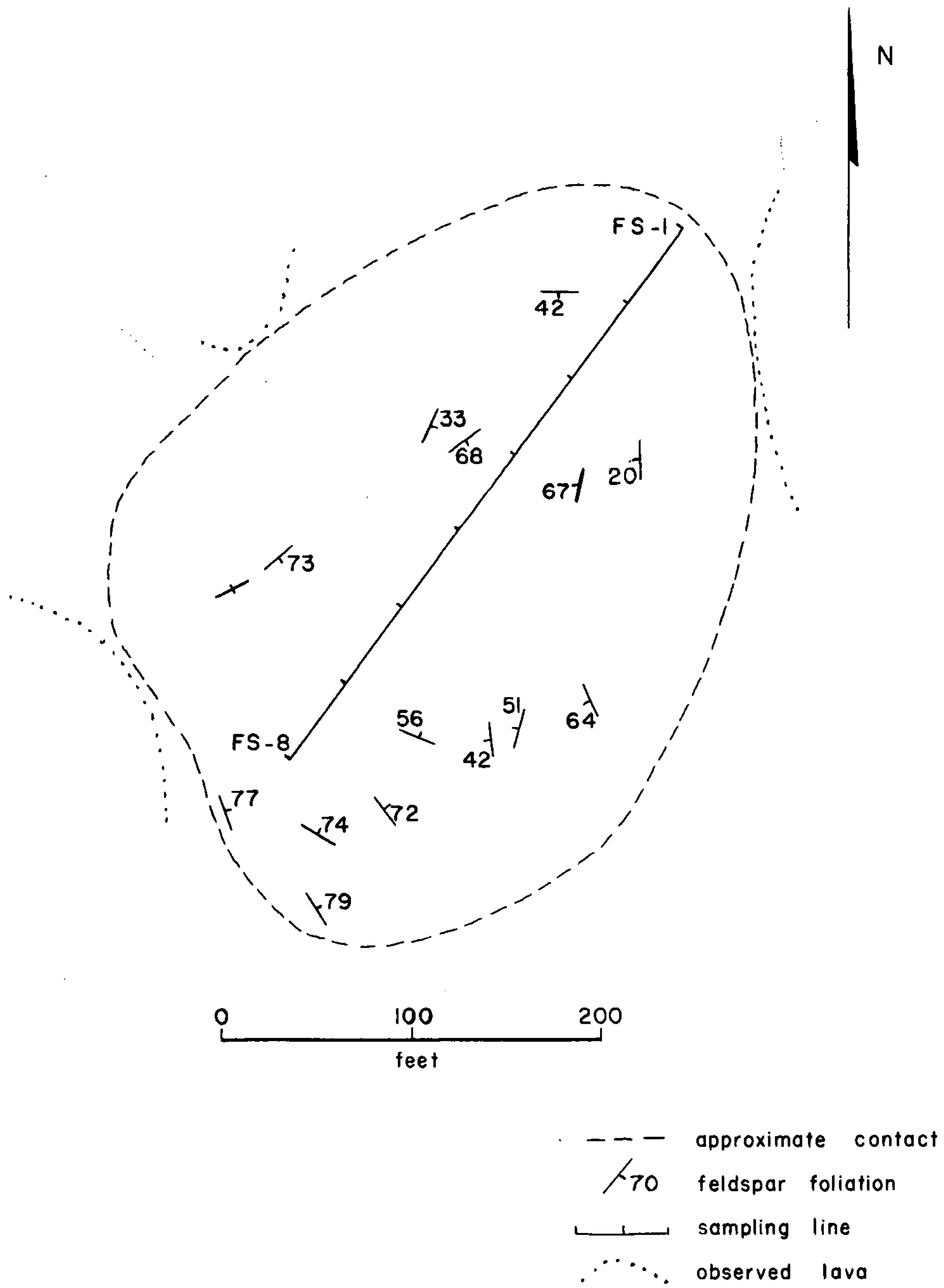

Figure 4. Plan view of Forestry Hill plug.

provide excellent rock exposure. There is no visible contact with the surrounding basalt.

The rock is a dark, fresh olivine gabbro very similar to the previously described plugs. Feldspars are locally aligned but show no particular foliation. There are no leucogabbro or picritic gabbro lenses: the rock is homogeneous.

Tin Cup Mountain Plug. Tin Cup Mountain is the largest of the four plugs but little is known of its shape or dimensions. It was only briefly visited by the writer and no detailed description is presented. The rock is a dark olivine gabbro which is non-foliated. A few spherical vesicles are contained near the margin. No contact with the surrounding basalt was seen.

Structure

Contact Relations at Mt. Begbie. The chilled basaltic margin of the plug is in sharp contact with the surrounding plateau basalt. A sharp contact also exists between the chilled margin and the marginal dolerite. This is shown in Plate 3, Figure 1. As mentioned previously the dolerite is discontinuous so that in places, olivine gabbro is in direct contact with the chilled margin. Otherwise, the contact between marginal dolerite and olivine gabbro of the main mass is gradational.

Where olivine gabbro is in contact with the chilled margin there is only a slight decrease in grain size. Within 6 inches of the contact the grain size is as coarse as that in the middle of the plug. Several modifications of the gabbro appear at the contact. Small lenses of picritic gabbro and

PLATE 3

Figure 1. Contact of marginal dolerite (above) with basaltic chilled margin (below) at Mt. Begbie ($x\frac{1}{2}$). The photograph is about normal to the plane of contact.

leucogabbro 3 to 4 inches thick occur flattened parallel to the contact. In places, a banded zone appears which contains several layers of large elongate pyroxene grains oriented perpendicular to the contact. The layers are parallel to the contact and the pyroxenes appear to have grown inwards. Figure 5 is a diagram of the zone.

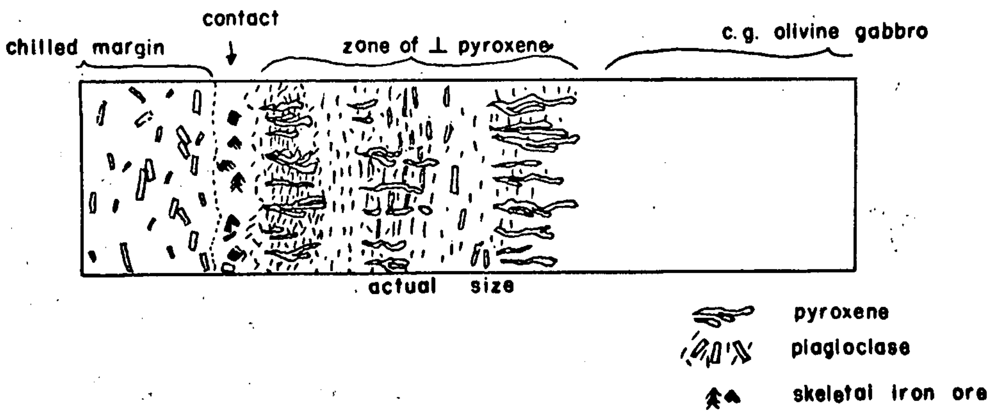

Figure 5. Schematic section across the zone of perpendicular pyroxenes.

<u>Foliation</u>. Alignment of tabular feldspars is interpreted as a flow foliation caused by upward movement of a crystal-charged magma. Twenty-six measurements of foliation were taken from Mt. Begbie plug and fifteen from Forestry Hill plug. These are plotted in Figures 3 and 4, respectively. As mentioned previously foliation is best developed marginally, where it is parallel to the contact, and is virtually non-existent in the central portions. In leucogabbro lenses, which are characteristically

poor in mafics, the foliation is well-developed. In picritic gabbro lenses feldspar alignment is interrupted by the great number of equidimensional mafic grains. In these the foliation is poorly-developed.

The statistical diagrams in Figure 6 show in a quantitative way the degree of foliation determined by plotting poles to (010) planes of feldspars. Sample V-9, a specimen of olivine gabbro, has an average discernible foliation whereas sample B-5, a specimen of leucogabbro, has a well-developed foliation.

In both Mt. Begbie and Forestry Hill plugs the pattern of foliation dips consistently towards the centre at moderate to steep angles. Generally, the foliation is steeper towards the centre indicating that planes of foliation tend to converge with depth. The variations in foliation are probably a result of irregularities in the flow of magma.

Form of Intrusion. Assuming that the marginal foliation is about parallel to the contact of gabbro with wall rock, the plugs constrict downwards (i.e. they are funnel-shaped). The diagrams of A. Rittmann (1962, p. 90-91), illustrating phases of basaltic eruption, show that in vertical cross-section the feeder channels widen as they approach the surface. Likewise, the exposed portions of Mt. Begbie and Forestry Hill plugs are envisaged as being the flared tops of otherwise fairly uniform diameter conduits. Figures 7 and 8 are vertical cross-sections of Mt. Begbie plug and Forestry Hill plug, respectively, showing hypothetical forms of the intrusions.

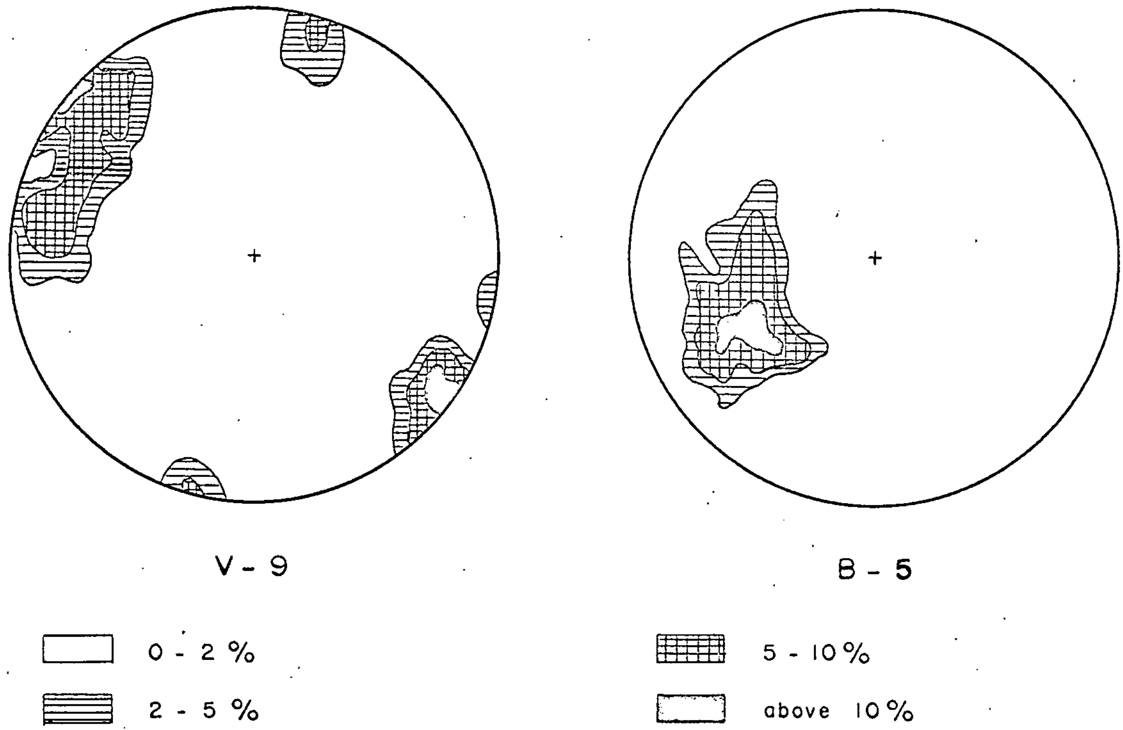

Figure 6. Statistical diagrams illustrating the degree of alignment of feldspar tabulae.

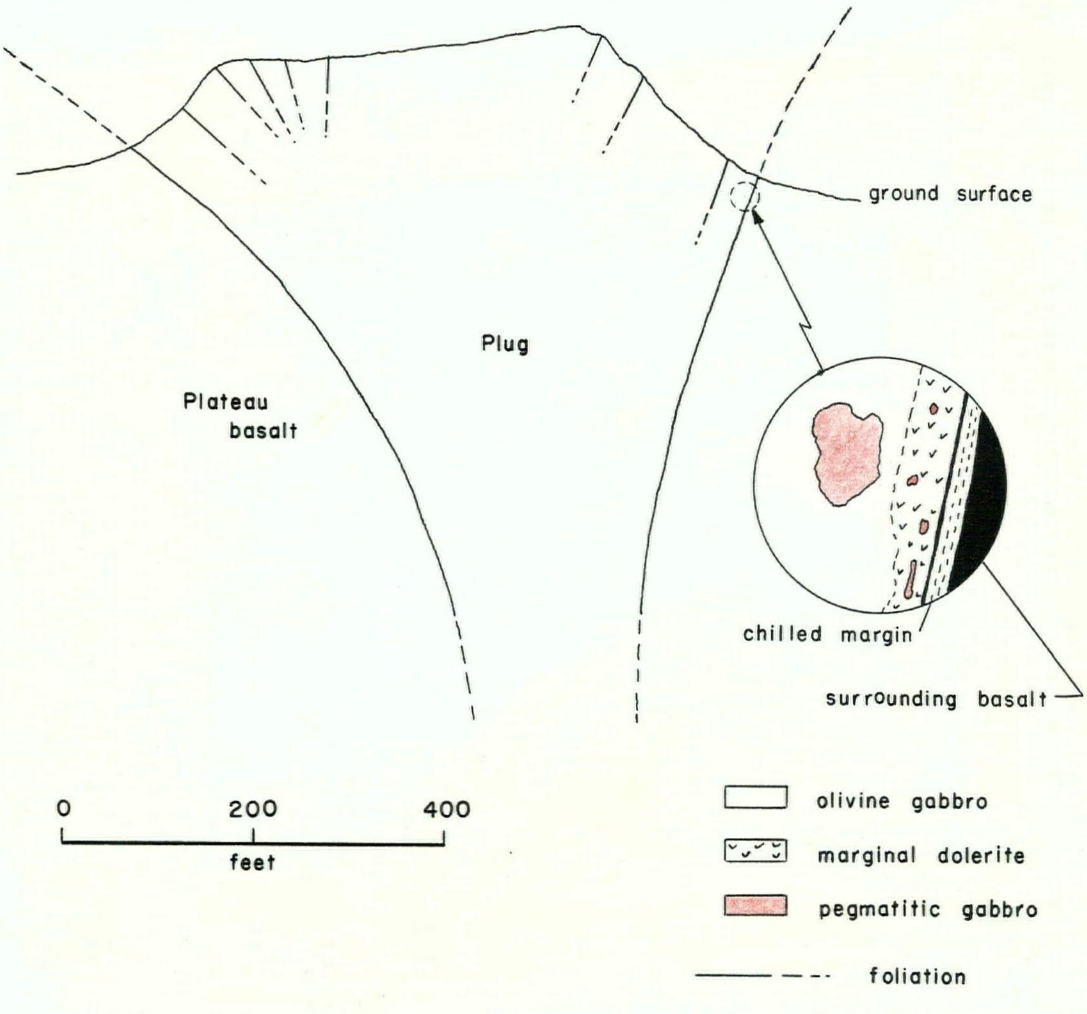

Figure 7. Hypothetical N.W. - S.E. cross-section of Mt. Begbie plug.

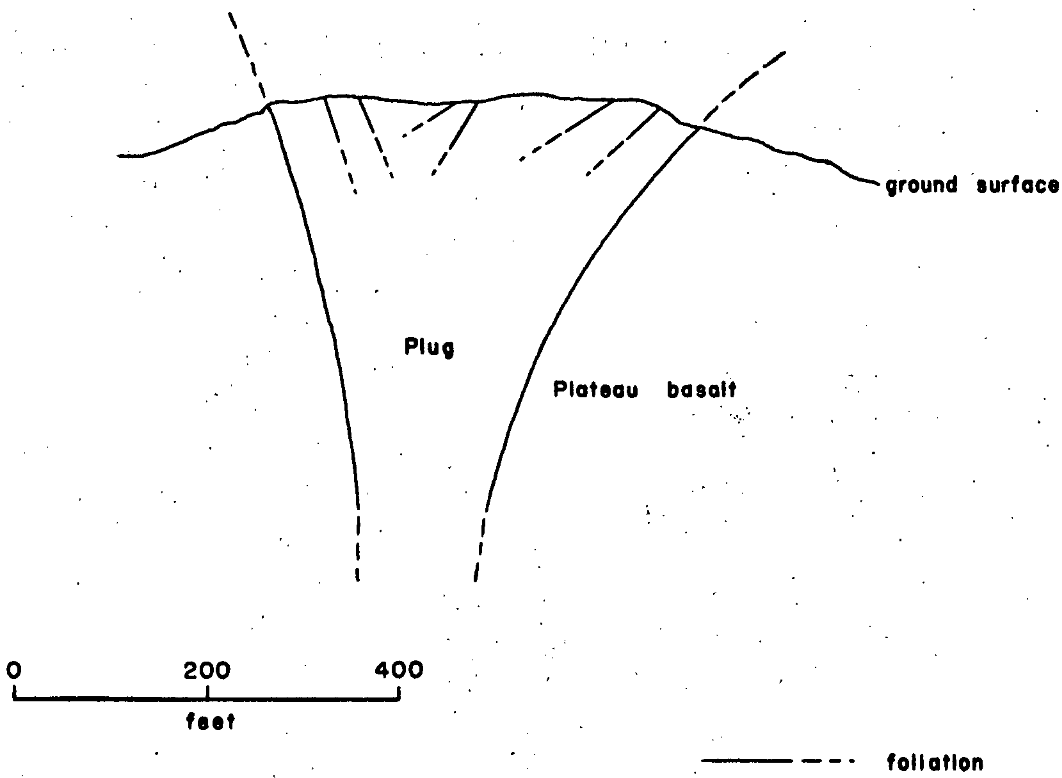

Figure 8. Hypothetical N.E. - S.W. cross-section of Forestry Hill plug.

PETROGRAPHY

General Statement

The four plugs are petrologically very similar. Each is composed mainly of olivine gabbro having almost identical textures and mineralogy. Thus, the description of olivine gabbro applies to all the plugs. The description of leucogabbro and picritic gabbro applies to Mt. Begbie and Forestry Hill plugs.

Olivine Gabbro

Olivine gabbro is a fresh, medium-grained rock composed essentially of olivine, clinopyroxene and plagioclase. Total mafics form about thirty per cent of the rock by volume. Iron ore, apatite and zeolite are the main accessory minerals. The gross texture of olivine gabbro is trachytoid, becoming intergranular where the feldspars are disoriented. Sub-parallel alignment of feldspars is shown in Plate 4, Figure 1. There is a general tendency for mafic minerals to cluster (Plate 4, Figure 1). Grain dimensions of the common minerals are listed in Table 1 for several rock types. Average areal dimensions of grains were obtained from a general survey of several thin sections.

The rock varies from dark greenish-grey to light speckled grey despite the generally uniform mineral composition. The light-coloured variety is notably diktytaxitic with angular cavities up to 2 mm. in diameter, which are bounded by feldspars.

Table 1

Average Cross-Sections (in mm.) of Common Minerals for Several Rock Types

	V - 5	FS - 8	B - 5	B - 4
plagioclase	7.5 x 0.8	9.3 x 0.9	6.1 x 0.8	18.0 x 12.0
olivine	3.6 x 2.4	5.4 x 3.7	2.4 x 1.7	5.2 x 2.2
pyroxene				
Group I	10.6 x 7.7	11.8 x 9.4	-	-
Group II	2.4 x 2.2	2.9 x 2.3	4.0 x 2.1	7.4 x 3.1
Group III (X-section)	0.7 x 0.7	0.6 x 0.6	-	-
iron ore	2.5 x 1.5	3.8 x 2.1	3.1 x 1.9	5.2 x 4.1
apatite (X-section)	0.2 x 0.2	0.2 x 0.2	0.3 x 0.3	0.4 x 0.4

V - 5. Mt. Begbie olivine gabbro
FS - 8. Forestry Hill olivine gabbro
B - 5. leucogabbro
B - 4. pegmatitic gabbro

The dark variety has only a few such cavities and where they become more numerous the rock has a transitional, mottled light and dark colour.

Zoning is seen in plagioclase, pyroxene and olivine. Plagioclase grains show extreme oscillatory zoning, becoming more sodic towards the rims. Pyroxene is zoned with oscillatory zoning apparent in occasional large grains. About twenty-five per cent of olivine grains show normal zoning, becoming more iron-rich towards the rims.

Because of the tendency for mafics to cluster, olivine is intimately associated with pyroxene. Elsewhere it is associated with plagioclase, sometimes in sub-ophitic relationship. Occasionally olivine is interstitial to plagioclase (Plate 4, Figure 2). Olivine occurs as subhedral to euhedral grains except where it is surrounded by pyroxene. Where it is included within pyroxene, olivine appears as anhedral, rounded grains (Plate 5, Figure 1). In many instances olivine appears as composite grains where several individuals have grown together still preserving traces of their original euhedral boundaries. In some of these the individuals maintain near-perfect optical continuity throughout the composite grain (Plate 5, Figure 2) with only slight differences in extinction or slight deflections of cleavage occurring across former grain boundaries.

Pyroxene occurs in three distinct size groups (see Table 1). Group I includes relatively large, generally compound grains which have an overall subhedral development. These

PLATE 4

Figure 1. Sub-parallel alignment of feldspars in olivine gabbro. Note the cluster of mafics on the right (crossed nicols, x10).

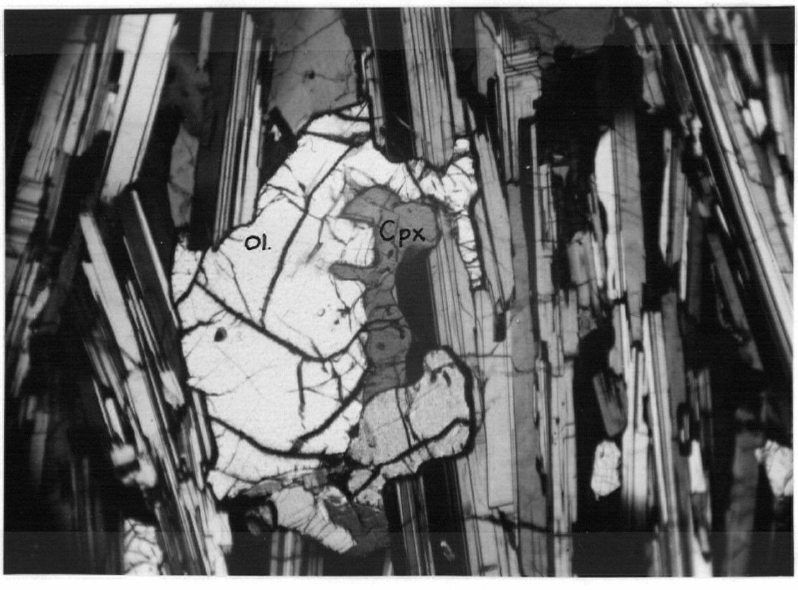

Figure 2. Clinopyroxene (grey) replacing olivine (white). Note extension of olivine grain that is interstitial to plagioclase (crossed nicols, x30).

PLATE 5

Figure 1. Rounded olivine inclusions (Ol.) in clinopyroxene (Cpx). Note the sub-ophitic grains of plagioclase around the margin (crossed nicols, x30).

Figure 2. An optically continuous grain of olivine (Ol.) composed of three "agglutinated" euhedral individuals. Note the two small, euhedral grains of Group III pyroxene (Cpx) (crossed nicols, x30).

grains typically have a pronounced seive texture with inclusions of plagioclase, iron ore and olivine (Plate 6). The inclusions may be arranged in one to several concentric zones. The margins of these pyroxenes generally bear a sub-ophitic relationship towards plagioclase.

Pyroxenes of Group II include the more common anhedral to subhedral grains which form an intersertal texture with plagioclase. They are commonly associated with, and clustered around olivine.

Pyroxenes of Group III are relatively small, generally euhedral prismatic grains which are characteristically interstitial to plagioclase (Plate 5, Figure 2). They are frequently included within interstitial sodic plagioclase.

Pyroxene is commonly seen rimming olivine. Typically, a partial to complete aggregate rim of small anhedral grains, optically disoriented, surrounds olivine (Plate 7, Figure 1). Occasional projection of pyroxene into olivine is interpreted as replacement of olivine by pyroxene (Plate 4, Figure 2).

Plagioclase occurs predominantly as subhedral, tabular grains with an average ratio of length to width of 10 to 1 in cross-section (see Table 1). Twinning is ubiquitous. Where alignment is well-developed it is evident that many grains are composed of several quasi-parallel individuals. Smaller grains of plagioclase are generally seen either in positions length-across the foliation or as inclusions within large grains of plagioclase or pyroxene.

PLATE 6

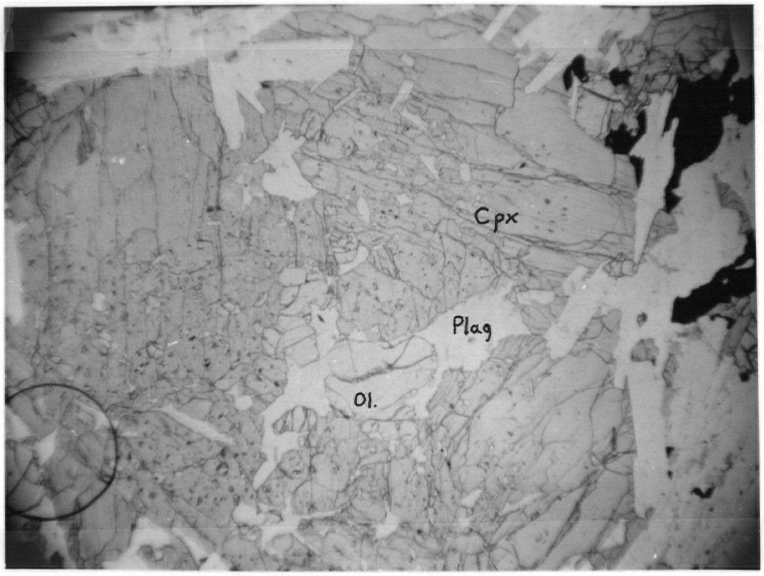

Figure 1. Large, seive-textured pyroxene of Group I (medium-grey) with inclusions of plagioclase (white), olivine (light-grey) and iron ore (black specks) (plane light, x10).

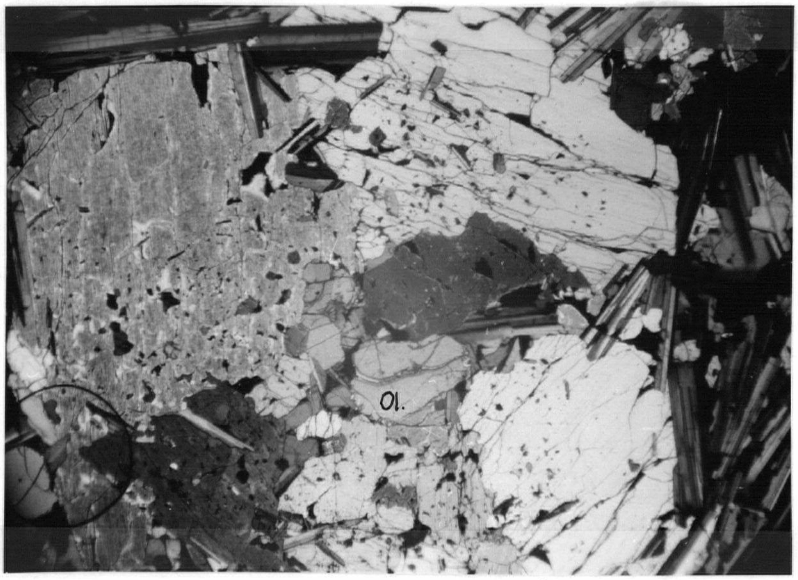

Figure 2. Same as above but with crossed nicols, showing the compound nature of the pyroxene grain (x10).

A distinctly later generation of plagioclase forms irregular rims on earlier-formed plagioclase tabulae (Plate 7, Figure 2). The material is oligoclase and appears to be normally zoned. It is most abundant in the angular interstices provided by disoriented tabulae. Where tabulae are sub-parallel and closely packed, oligoclase rims are thin or absent. Occasional textures are seen which suggest marginal corrosion and replacement of tabular plagioclase by the rim oligoclase.

The accessories, iron ore and apatite, are scattered throughout the rock. Iron ore is generally subhedral, often skeletal, and is associated mainly with olivine and pyroxene. Otherwise it occurs as anhedral, interstitial grains. Occasionally it sub-ophitically encloses feldspar. Where ore is surrounded by plagioclase there is commonly a sub-concentric set of conchoidal fractures developed in the plagioclase (Plate 8, Figure 1). Fractures are most numerous around sharp edges of ore and are usually filled with hematite.

Apatite occurs as euhedral hexagonal prisms associated mainly with plagioclase and interstitial matter. It is seen as inclusions within magnetite, plagioclase, interstitial pyroxene (Group III) and zeolite.

Zeolite occupies some of the diktytaxitic cavities in association with interstitial oligoclase. Plate 8, Figure 2 shows radiating clusters of zeolite. Commonly, a ragged boundary between oligoclase and zeolite is seen, suggesting replacement of oligoclase by zeolite. In Mt. Begbie plug cristobalite is also seen in a few diktytaxitic cavities. It

PLATE 7

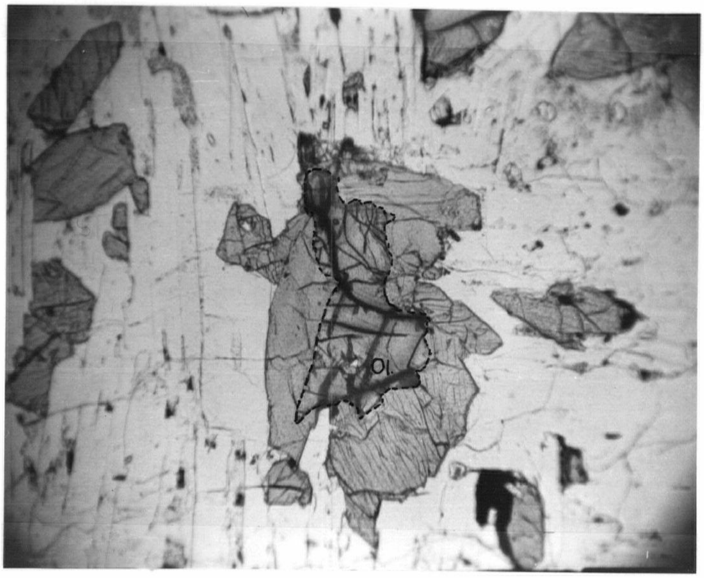

Figure 1. Olivine grain (Ol.) surrounded by small, anhedral grains of clinopyroxene (plane light, x30).

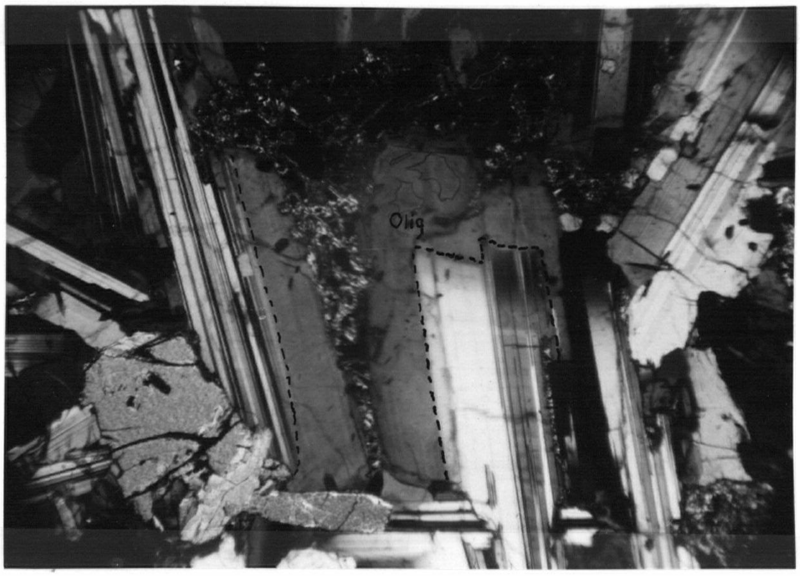

Figure 2. Oligoclase rims (Olig) on tabular plagioclase grains (crossed nicols, x30).

PLATE 8

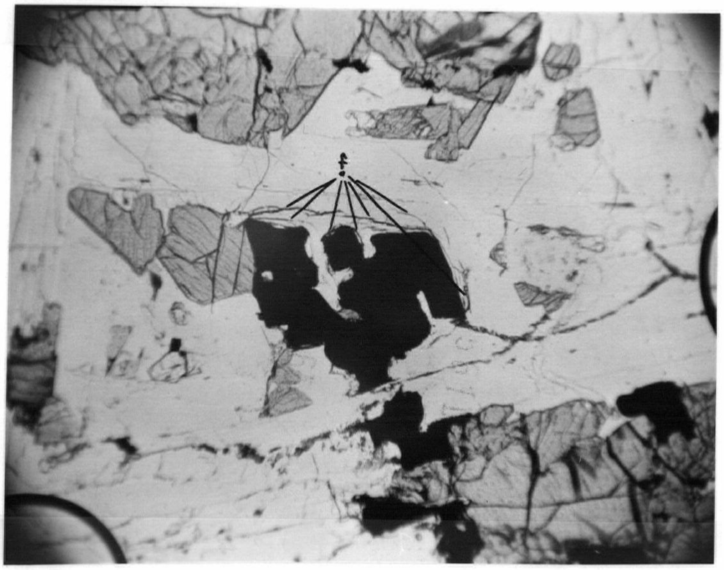

Figure 1. Sub-concentric fractures (f) filled with iron ore, surrounding a skeletal grain of iron ore (plane light, x30).

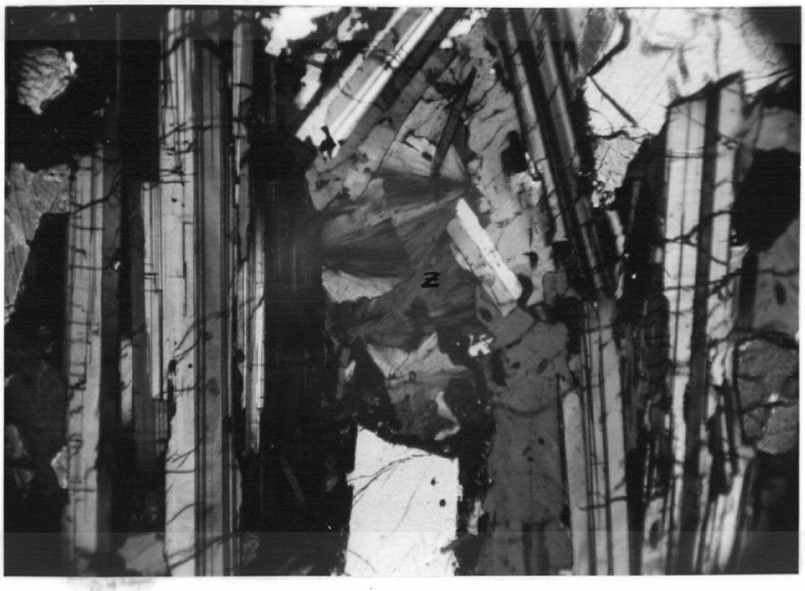

Figure 2. Radially fibrous zeolite (Z) interstitial to plagioclase (crossed nicols, x30).

occurs as twinned grains sometimes in granophyric intergrowth with oligoclase (Plate 9, Figure 1).

Deuteric alteration has produced a small amount of biotite, iddingsite and serpentine. These are the products derived from alteration of olivine. Biotite is occasionally seen as thin rims on iron ore.

Leucogabbro and Picritic Gabbro

Leucogabbro and picritic gabbro are closely related to "normal" olivine gabbro. The textures and mineralogy are identical to those described for olivine gabbro. The prime distinction between leucogabbro and picritic gabbro is the percentage of mafic minerals. Leucogabbro contains little olivine and is generally somewhat poorer in clinopyroxene than the "normal" olivine gabbro. Conversely, picritic gabbro contains much olivine and is somewhat richer in clinopyroxene. Texturally, the degree of alignment of feldspars is a reflection of the percentage of mafic minerals whereby leucogabbro is well-foliated and picritic gabbro is virtually non-foliated.

Marginal Dolerite

Marginal dolerite is a light-grey, medium-grained rock composed essentially of plagioclase and clinopyroxene. The average grain size is 1 to 3 mm. in diameter. The texture is homophanous with plagioclase and pyroxene arranged in sub-ophitic relationship. Olivine is scattered sparsely through the rock, and iron ore and apatite are the main accessories. Zoning of plagioclase, pyroxene and olivine is similar to that described for olivine gabbro.

Olivine occurs as subhedral grains sometimes enclosing plagioclase in sub-ophitic fashion (Plate 9, Figure 2). Pyroxene is the dominant mafic mineral and is typically formed as anhedral to subhedral grains in association with plagioclase. Pyroxene does not rim olivine. There is a slight tendency for mafic minerals to cluster.

Cavities, both diktytaxitic and vesicular, are abundant in parts of the marginal dolerite. They are up to 5 cm. long and contain cristobalite and pseudobrookite.[1] Cristobalite is formed either as single tetragonal dipyramids (Plate 10, Figure 1) or as sub-spherical twinned tetragonal forms. It occasionally occurs as white frosty coatings on cavity walls.

Pseudobrookite occurs as acicular, dark-brown to reddish-brown striated prisms projecting into, or grown against the walls of cavities (Plate 10, Figure 2). In dolerite that contains many cavities pseudobrookite is an abundant accessory. Here, prismatic grains are seen included within plagioclase and replacing iron ore (Plate 11, Figure 1).

"Schlieren-like" structures appear in parts of the dolerite and are oriented roughly parallel to the margin of the plug. The structures are thin, irregular layers up to several feet

---

[1]Pseudobrookite is composed of two end-members; $FeO \cdot 2TiO_2$ and $Fe_2O_3 \cdot TiO_2$.

PLATE 9

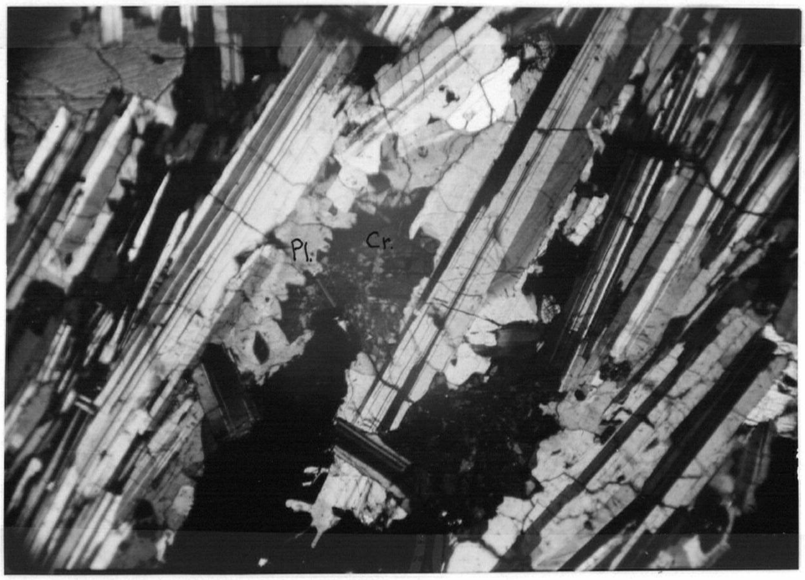

Figure 1. Granophyric fringe between cristobalite (Cr) and plagioclase (Pl.) (crossed nicols, x30).

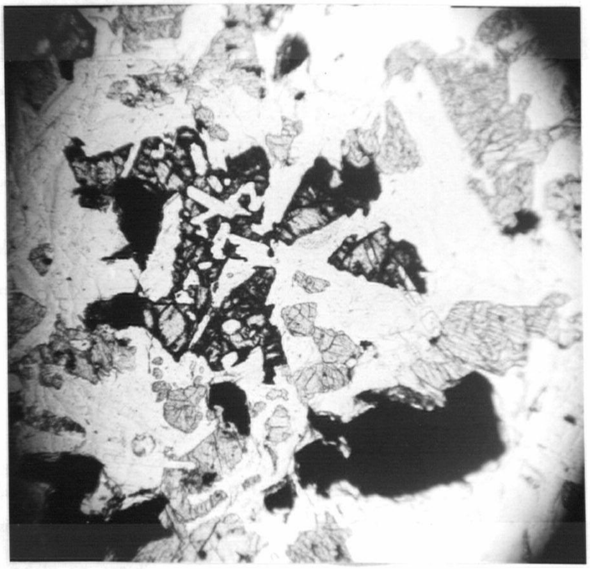

Figure 2. Olivine (dark) sub-ophitically enclosing plagioclase (white) (plane light, x30).

PLATE 10

Figure 1. Tetragonal crystal of cristobalite in a cavity within marginal dolerite (x5).

Figure 2. Thin blades of pseudobrookite lying against the walls of a cavity within marginal dolerite (x5).

long composed of either iron ore-rich material or of finer-grained dolerite. They are interpreted as having formed by infilling of rifts developed at a late stage in the crystallization of marginal dolerite. The infilling material was perhaps fluid, derived by filter pressing of adjacent crystal mush.

Pegmatitic Gabbro

Pegmatitic gabbro is a pinkish, coarse-grained, homophanous rock composed essentially of plagioclase, clinopyroxene and olivine. Iron ore and apatite are accessory minerals. Numerous miarolytic cavities up to 10 mm. in diameter are distributed throughout the rock. Plagioclase, pyroxene and olivine show slight normal zoning. A few grains of pyroxene show strong zoning at the rim to aegerine-augite.

Plagioclase grains are much more equant than those in olivine gabbro. The grains are subhedral with cross-sections ranging from 6 mm. by 4 mm. to 42 mm. by 28 mm. On the average they are much larger than either pyroxene or olivine. Many grains are composite, having formed by agglutination of several grains. Discontinuous albite and pericline twinning is common.

Olivine and pyroxene occur as subhedral grains either associated with, or included within plagioclase. Olivine is commonly skeletal forming groups of individuals attached in optical continuity (Plate 11, Figure 2). It is also seen as poikilitic inclusions within plagioclase (Plate 12, Figure 1). Pyroxene is more abundant than olivine and has a greater average

PLATE 11

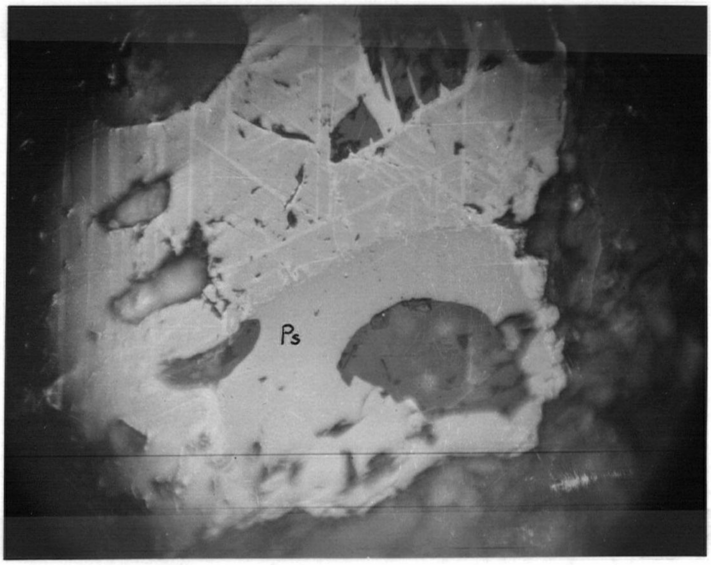

Figure 1. Pseudobrookite (Ps) replacing magnetite (grey)/ ilmenite (white) grain in marginal dolerite (polished section, crossed nicols, x120).

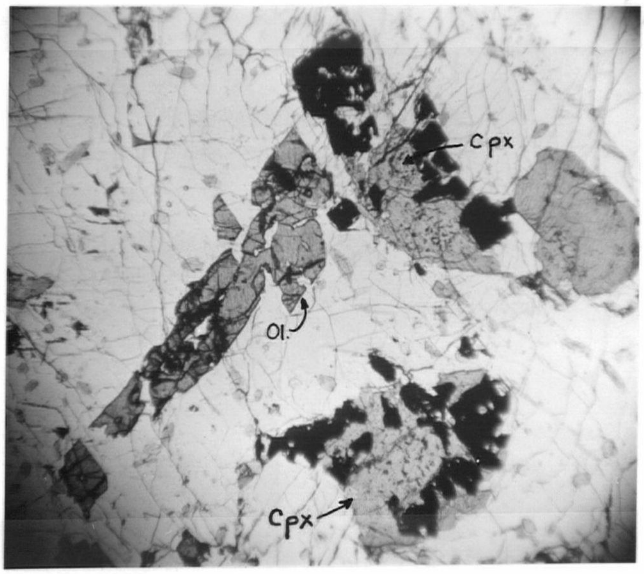

Figure 2. Skeletal olivine grain (Ol.) extended in one direction (towards bottom, left). Clinopyroxene (Cpx) is fringed by iron ore grains, and contains tiny "exsolved" iron ore blebs in the core (plane light, x30).

grain size. It is sometimes seen as poikilitic inclusions within plagioclase.

Iron ore forms relatively large, skeletal grains associated with plagioclase, pyroxene and olivine (Plate 12, Figure 2). It commonly forms a fringe of grains included within the margins of pyroxene grains (Plate 11, Figure 2). Clusters of small, anhedral grains are sometimes seen included within pyroxene (Plate 11, Figure 2). Plate 13, Figure 1 shows pyroxene grains with marginal fringes of small iron ore grains. This texture suggests that iron oxide was exsolved from pyroxene in later stages of crystallization.

Apatite occurs as abundant hexagonal prisms closely associated with, and included within plagioclase. Commonly, hundreds of small grains form a swirled or fan-like pattern within plagioclase.

Miarolytic cavities are bounded predominantly by plagioclase. Within the cavities plagioclase shows a simple pinacoidal termination; pyroxene exhibits the typical prismatic termination; iron occurs as octahedrons, frequently embedded in pyroxene and plagioclase; apatite occurs as very slender prisms projecting from the walls; tridymite is seen as small, elongate twinned grains (Plate 13, Figure 2).

Perpendicular Pyroxene Rock

The zone in which elongate pyroxene grains are arranged parallel to the margin of the plug (see Figure 5), is composed of alternating mafic and feldspathic layers. The pyroxenes are

PLATE 12

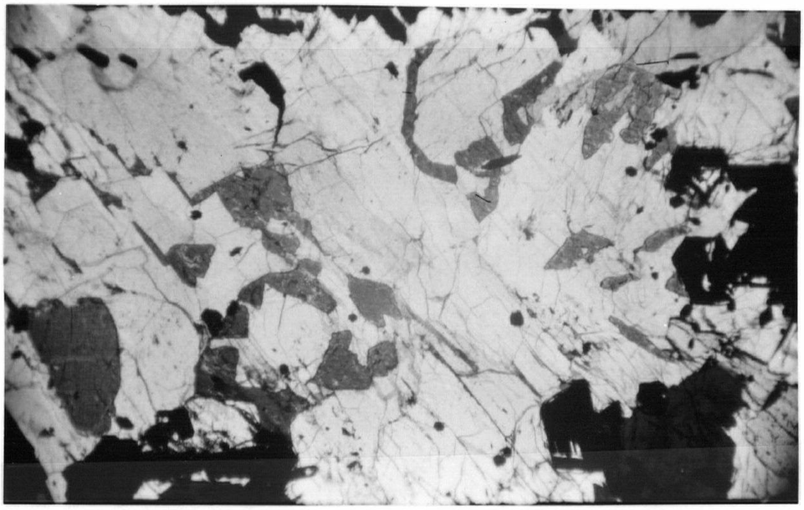

Figure 1. Skeletal or "poikilitic" grains of olivine enclosed by large feldspar grain in pegmatitic gabbro (crossed nicols, x10).

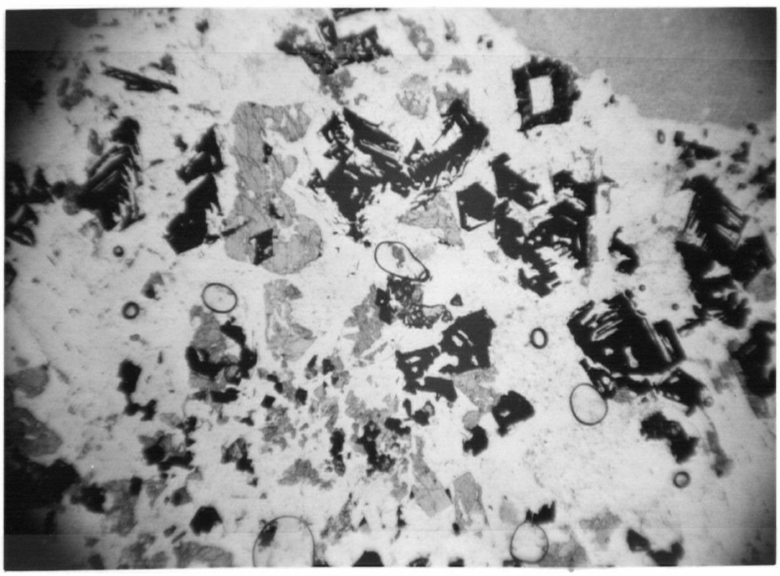

Figure 2. Skeletal iron ore in pegmatitic gabbro (plane light, x10).

PLATE 13

Figure 1. Fringes of "exsolved" iron ore on grains of pyroxene in pegmatitic gabbro (polished section, plane light, x120).

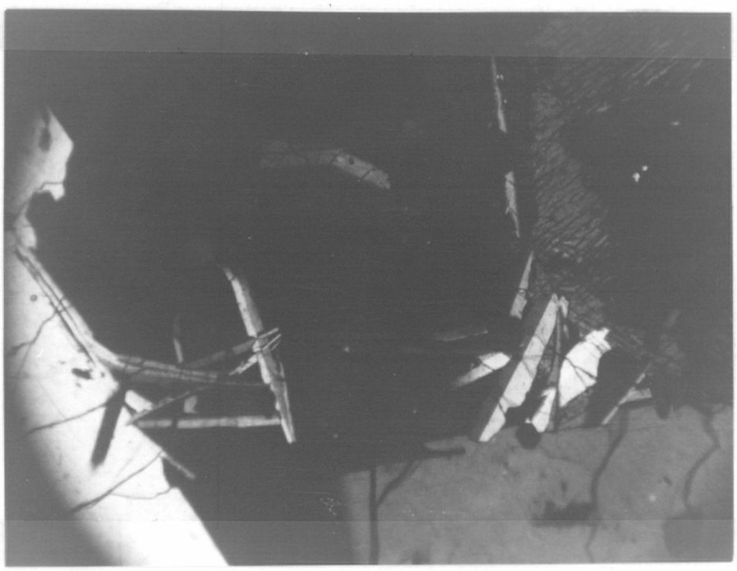

Figure 2. Elongate, twinned grains of tridymite occupying a miarolitic cavity in pegmatitic gabbro (crossed nicols, x30).

curved, branching grains up to 2 cm. long and are set in a matrix of olivine and plagioclase grains 1 to 3 mm. in diameter. They show a sub-ophitic relationship with plagioclase and progressive inward growth has interrupted the well-developed feldspar foliation (Plate 14, Figure 1).

Commenting on the origin of feldspar grains oriented perpendicular to the margin of the Skaergaard intrusion, Wager and Deer (1939, p. 147) state:

> ... they can only have assumed their present disposition by inward growth of appropriately oriented felspars attached to the already solidified, outer material. ... In order that large acicular crystals of this kind may grow, diffusion, aided perhaps by circulation of the liquid, must keep the growing crystals supplied with material appropriate to their composition, and this free diffusion and circulation must take place so effectively that new centres of crystallization are not started in the liquid ahead of the growing crystals. ... It seems likely that ... lower viscosity and freer diffusion than is usual in basic magmas, were responsible for the production of the perpendicular felspar rock.

They also state (p. 151) that:

> The large pyroxenes sometimes extend into wavy masses set roughly at right-angles to the wall of the intrusion and these are thought to have an origin similar to that of the perpendicular felspar crystals.

Taubeneck and Poldervaart (1960, p. 1316) suggest that similar layered rocks: "... originate through undercooling combined with intermittent convective and turbulent currents in the magma." They state (p. 1317) that:

> The orientation of the crystals with their longer dimensions nearly at right angles to the banding and the highly elongated, curved, branching or feathery forms of the crystals can have resulted only from unusually rapid crystallization on cool surfaces, such as would occur with undercooling.

Such conditions of undercooling in Mt. Begbie plug were discontinued after a layered zone 3 to 4 inches thick had formed.

Basaltic Chilled Margin

The chilled margin is black to grey, porphyritic basalt. Plagioclase phenocrysts averaging 5 mm. in length and olivine phenocrysts up to 2 mm. in diameter are set in a fine-grained, microlitic groundmass of plagioclase and clinopyroxene. Phenocrysts of clinopyroxene up to 5 mm. in diameter are occasionally seen. Plagioclase phenocrysts are sub-parallel to the margin of the plug. Fine grains of iron ore are scattered evenly throughout the rock.

Numerous irregular vesicles up to 2 cm. in diameter are scattered throughout the chilled margin. Many of them are filled with fine-grained, granular tridymite (Plate 14, Figure 2). The presence of abundant vesicles in rapidly chilled basalt suggests that the wall rock may have been wet thereby supplying water to the intrusive material.

Surrounding Basaltic Lava

The surrounding basaltic lava bears a distinct similarity to the basaltic chilled margin. The rock is porphyritic consisting of phenocrysts of plagioclase and olivine in a microlitic groundmass of plagioclase and clinopyroxene. A few phenocrysts of clinopyroxene are scattered throughout. Plagioclase phenocrysts generally show some flow alignment. Where they compose more than fifty per cent of the rock there is no flow alignment

PLATE 14

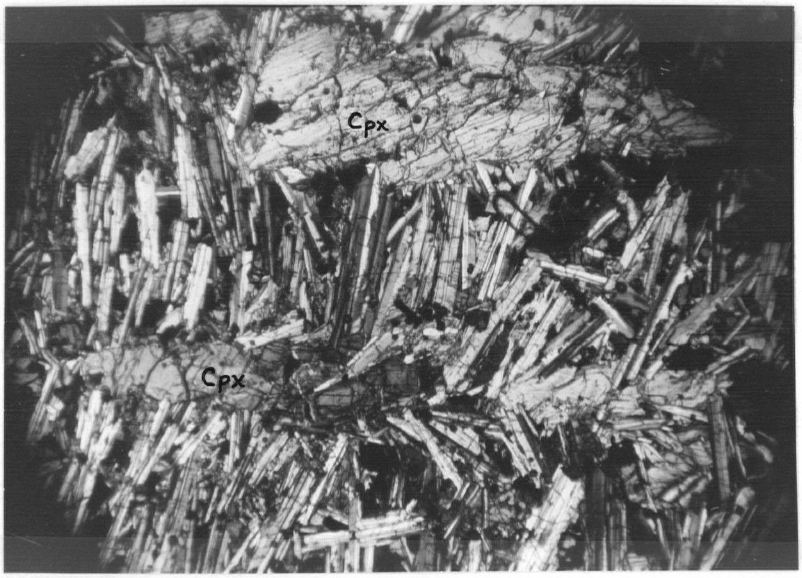

Figure 1. "Perpendicular" pyroxene grains (Cpx) disrupting the flow alignment of feldspars (crossed nicols, x10).

Figure 2. Irregular tridymite-filled cavities in the basaltic chilled margin, south portion of Mt. Begbie (width of area in photograph is 2 feet).

and the texture is diktytaxitic. Vesicles are common and are generally devoid of amygdaloidal material.

MINERALOGY

General Statement

Mineral compositions are approximately the same for olivine gabbro, leucogabbro, picritic gabbro and marginal dolerite. Thus, the following description of minerals does not differentiate between these rock types. The major silicate minerals in pegmatitic gabbro differ in composition from those of the other rock types. These are discussed at the end of each relevant section.

Laboratory Methods

Approximate compositions of plagioclase, pyroxene and olivine were determined by optical methods. Minerals that were not identified in thin section or polished section were determined by x-ray powder photographs.

A Leitz four-axis universal stage was used to measure 2V of olivine, pyroxene and plagioclase; $Z \wedge c$ of pyroxene; and to determine the anorthite content of plagioclase. The oil immersion technique was used to measure the beta-refractive index of crushed pyroxene grains. Oils which bracketed the index of the mineral were mixed in various proportions until a match was obtained. The index of the matching oil was measured with an Abbe refractometer using monochromatic sodium light. X-ray powder photographs were taken of olivine samples to determine the composition. The curve of Jambor and Smith (1964, p. 736), relating the spacing of d_{174} back-reflection to forsterite content, was used. Corrections were applied for film shrinkage.

Plagioclase

Composition. Plagioclase composition was determined on a universal stage using the determinative curves of F.J. Turner (1947). The most frequently used curves were those for albite, carlsbad, and carlsbad-albite twins. Other determinations were made on the plane stage using the carlsbad-albite method. The two methods are in good agreement within the limits of accuracy which is, according to Turner (p. 397), ±3% An.

Table 2

Range of Zoning in Plagioclase*

	core	margin
Mt. Begbie plug	72	23
Forestry Hill plug	68	22
Porphyritic lava	71	58

*An-content

The range of zoning thus derived is shown in Table 2 for each of Mt. Begbie plug, Forestry Hill plug, and the porphyritic lava surrounding Mt. Begbie. Note the corresponding composition of the cores of feldspars in the plugs and the cores of feldspar phenocrysts in the lava.

In many sections of the [010] zone feldspars appear to be zoned in a normal progressive manner. However, in much broader sections perpendicular to (010), zoning is seen to be oscillatory (Plate 15, Figure 1) with many reversals, each differing in composition by only a slight amount. In general, the tabular grains are zoned to about An_{35} at the margin. The interstitial and rim oligoclase is zoned to An_{22}. Apparently little or no gap in composition exists between margins of the tabulae and the enclosing outer rims.

The nature and composition of the outer plagioclase rims is not easily resolved by optical means. Measurements of 2V are in the range of 60 to 70 degrees (-), indicative of some degree of internal lattice disorder resulting from a high temperature of crystallization. The method of Rittmann and Essam (1961, p. 43) was used to ascertain whether the plagioclase is of a high or low temperature type. Measurements plot between the two curves suggesting that the feldspar is intermediate between high and low temperature type.

The presence of K-feldspar in solid-solution is certain to have an effect on lowering the 2V (anorthoclase has a 2V of about 55° or less). According to Turner and Verhoogen (1960, p. 112), oligoclase can accommodate 15 to 20 per cent of the

K-feldspar molecule in solid-solution depending on the water pressure in the system. The interstitial plagioclase would likely contain most of the potassia present in the original magma since it is the residual material and would incorporate the characteristically residual potassia.

Plagioclase in the pegmatitic gabbro is sodic andesine. The range of zoning is much reduced. A few measurements give the range of zoning as An_{40} in the core progressing outwards to An_{31}. The method of Turner (1947) found only restricted use because of a paucity of well-defined twinning. However, it is assumed that the measurements obtained roughly cover the total range of zoning.

Twinning. Plagioclase exhibits many normal, parallel, and interpenetration twin types. A general survey taken during the course of feldspar determinations indicates that albite, carlsbad-albite, carlsbad, pericline and manebach (in order of decreasing abundance) are the most common twin types. Baveno twins are occasionally seen, always combined with albite twinning (Plate 15, Figure 2).

Most conspicuous of the twinning textures are the combination (J.V. Ross, 1957) or agglutination twins (K.E. Seifert, 1964) (see Plate 16, Figure 1). These are twins which have formed by the growing-together of two or more grains, most commonly combined on the (010) face. Ross states (1957, p. 654) that: "Twin laws which most frequently govern combination of

PLATE 15

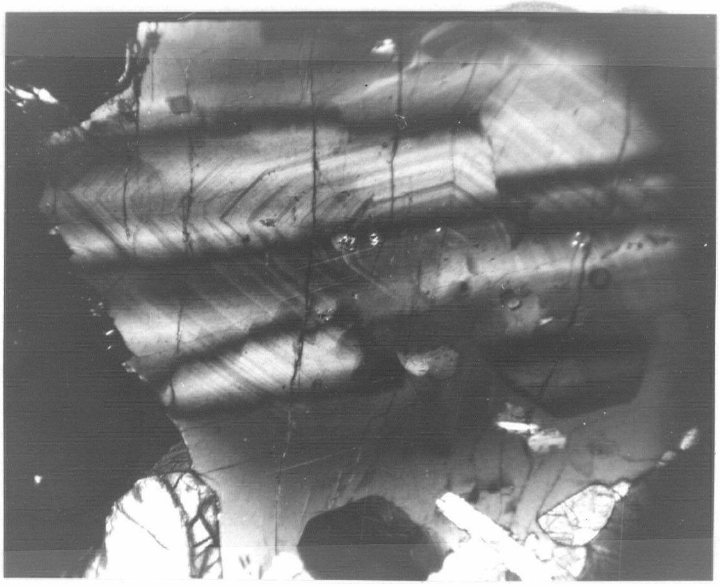

Figure 1. Oscillatory zoning in plagioclase. Fine lines represent zoning; broad bands are twin planes (crossed nicols, x30).

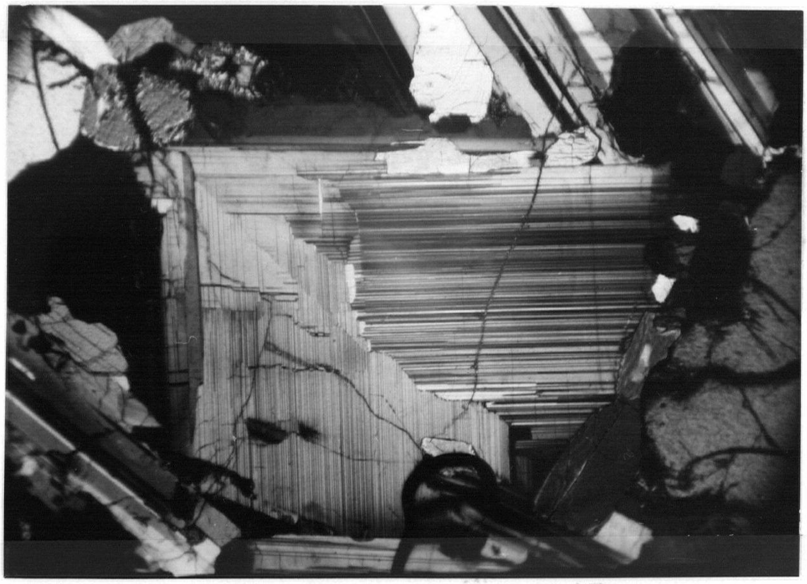

Figure 2. Baveno twin with close polysynthetic albite twinning (crossed nicols, x30).

plagioclase feldspars are the Albite-Carlsbad and Carlsbad laws."

Seifert suggests (1964, p. 317) that:

> Agglutination twins are formed when two or more essentially grown crystals make contact and adhere in a twinned orientation. Agglutination twins only form in environments allowing crystals some freedom of movement and such an environment must be at least partially fluid. Normally these twins might be expected to be more prevalent in an environment where the fluid has movement, such as normally occurs in an extrusive igneous environment.

Upward movement of magma in a conduit, inducing flow-parallelism, would provide excellent opportunity for plagioclase grains to grow together.

Pericline twinning is of minor importance. However, in several cases, plagioclase assumes the appearance of having a microcline twinning texture. The combination of pericline and albite twinning produces a very fine "tartan" appearance.

In the pegmatitic gabbro, twinning is generally indicative of a stress environment. Discontinuous sets of albite twinning occur in most grains as well as a jagged type of pericline twinning (Plate 16, Figure 2). According to Seifert (1964) the latter type is particularly indicative of a stress environment. Seifert states (p. 309) that:

> Petrographic characteristics of jagged pericline twinning indicates it formed in a solid rock by stresses acting over a minimum of several crystal diameters. The two most obvious characteristics of this twin, jagged edges and en echelon pattern, suggest shearing stresses operating in a confined space. The consistent association of this twin with other rock deformation features implies a common origin and indicates that the granite must have been essentially solid in order to transmit stresses over the required several crystal diameters to produce this association.

PLATE 16

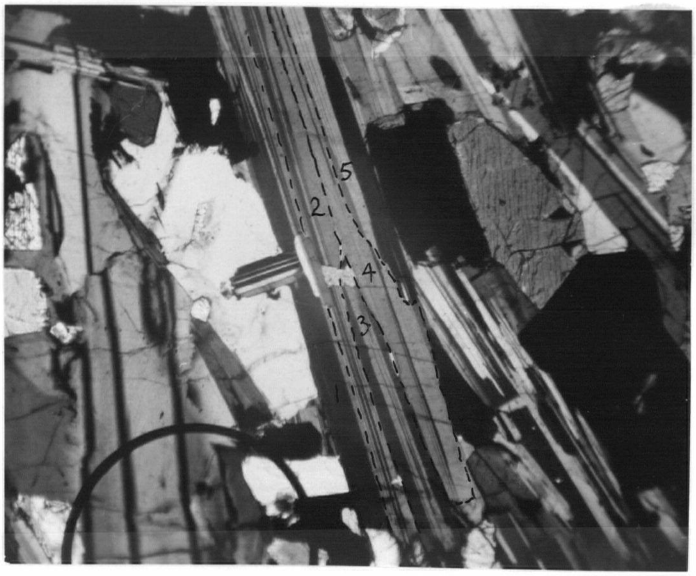

Figure 1. Agglutination twin of plagioclase composed several sub-parallel individuals (crossed nicols, x30).

Figure 2. Jagged pericline twinning in pegmatitic gabbro (crossed nicols, x10).

Pyroxene

Optical data derived for pyroxene are shown in Table 3. Thirty to forty grains were measured for 2V (double axis measurements). The diagram of Hess (1949) using 2V versus n_β indicates that the pyroxene is a salite. It is zoned in an oscillatory fashion from $Ca_{50}Mg_{36}Fe_{14}$ in the core to $Ca_{42}Mg_{37}Fe_{21}$ at the rim. The trend of zoning is shown in Figure 9.

Refractive indices could not be ascertained for the core or rim of an individual grain. Instead, a range of refractive index was established from measurement of many grains. The accuracy of the averaged results is about ± 0.002 and the range of refractive index is 0.005. The results of J.F.G. Wilkinson (1957, p. 125) in his investigation of clinopyroxenes, indicate that during zoning, an increase in refractive index is accompanied by a decrease in 2V. The data are arranged accordingly (Table 3) and are consistent with the hypothesis that zoning is normal (Wilkinson, 1957, p. 126).

The method of Hess (1949), using grains twinned on (010), was followed in measuring $Z \wedge c$. Only those grains requiring angles of tilt less than about 40 degrees were considered. The reported figure is an average of ten determinations.

The three end members Ca-Mg-Fe serve to indicate the rough composition of pyroxene and to illustrate the trend of crystallization. Other components; Al_2O_3, Fe_2O_3, TiO_2, and Na_2O; are generally present in minor abundance. LeBas (1962) has shown that the ratio of alumina to titania present in clinopyroxenes is about 5 to 1. A modified Ca-Mg-Fe triangular

Table 3

Optical Properties of Pyroxene

2V	57_{core}	-	51_{rim}
n_β	1.691_{core}	-	1.696_{rim}
$Z \wedge c$		$45\frac{1}{2}$	
Color	brown; brown with a mauve tint in the pegmatitic gabbro; green in the marginal dolerite		
Pleochroism	faint		

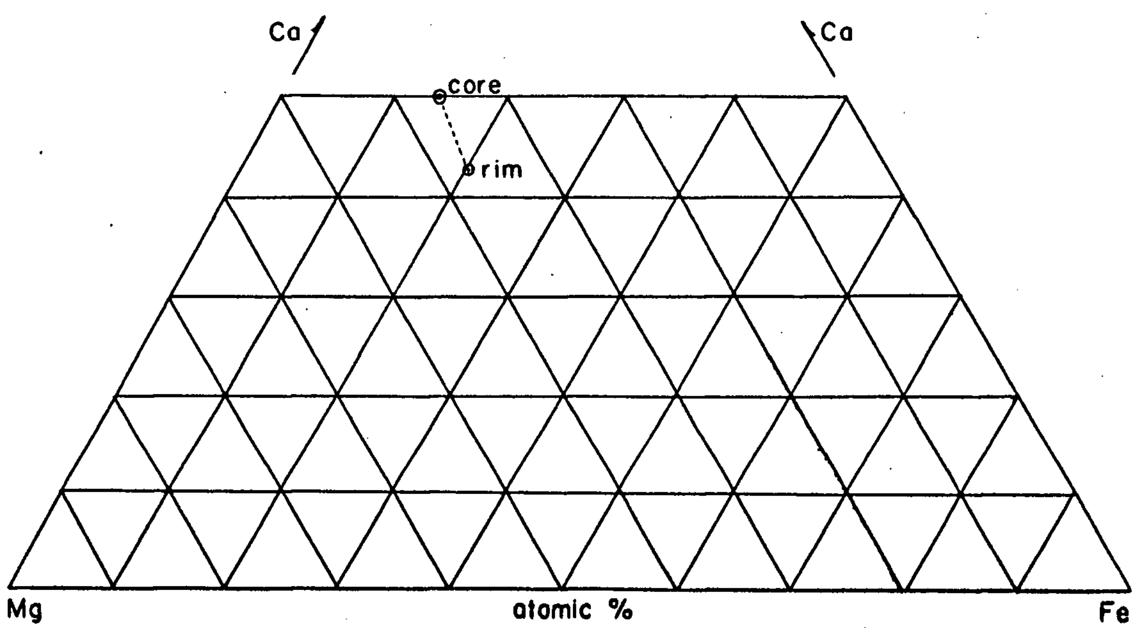

Figure 9. Composition of pyroxene (from H. Hess, 1949, p. 634)

diagram contoured for atomic per cent aluminum in pyroxenes (M.J. LeBas, 1962, p. 278), shows that the salite likely contains 5 to 10 per cent aluminum. A general plot of aluminum versus weight per cent TiO_2 (ibid, p. 280), shows the corresponding TiO_2 values to be roughly 1 to 2 per cent. Soda appears mainly as the acmite molecule (M.J. LeBas, 1962, p. 280).

In the pegmatitic gabbro aegerine-augite is present as thin, strongly-zoned rims on salite. Measurements of 2V for several grains show that the pyroxene is zoned from a 2V of 58 degrees in the core decreasing outwards to 56 degrees and thence in the rim increasing from 64 degrees to 88 degrees. The curve of Deer, Howie, and Zussmann (vol. 2, p. 87), relating 2V to ferric iron content in aegerine-augite, indicates a progressive increase from 0.2 to 0.4 Fe^{+3} ions per formula unit. This is roughly equivalent to an increase from 20 to 40 mol. per cent of aegerine in diopside.

<u>Olivine</u>

Olivine is zoned from Fa_{35} at the core to Fa_{56} at the rim. Single axis measurements of 2V were made and the Fa-content was read from the curve of Deer, Howie, and Zussmann (vol. 1, p. 22). Grains in which the X and Y crystallographic axes lie at slight angles to the plane of the thin section gave the most favourable results. During the course of 2V determinations it was found that even in the same thin section results differed by as much as 10 degrees. The range of 2V measurements varied from 68° (-) to 90°, certainly much greater than a feasible range of zoning. Sections through different zones in different grains would account for some variation but certainly not for the degree of variation encountered. Procedural error and error owing to effects of dispersion account for some variation. It is also possible that the olivines are of different generations and therefore differ in composition.

As a check on the range of composition, x-ray powder photographs were taken and the compositions read from the curve of Jambor and Smith. Since the olivines are zoned, the observed reflections were not well-defined. Reflections varied from a fairly dark, sharp line to a light, broad, diffuse line depending on whether or not the original grain was strongly zoned. For all determinations only those which gave results differing by no more than 5 per cent Fo between the curve of Jambor and Smith and that of Yoder and Sahama (1957, p. 475) (for d_{130}) were considered. The range of 95 per cent confidence is ±2 per cent Fo. The x-ray determinations provide only a rough check, in that they generally fall within the range of zoning indicated by 2V determinations. The results of the two methods are shown in Table 4.

With regard to determining composition of olivines, other people have expressed difficulties corresponding to those encountered by the writer. Concerning measurements of 2V, Wilkinson (1956, p. 444) remarks: "It can be seen that 2V determinations of the olivines in a particular slice may show variations of 7 to 8 degrees." He further states (p. 443) that

2V accuracy on any single grain is ±2 degrees. Wilkinson notes also (p. 444) that:

> In the Breven dolerite dyke, Krokstrom (1932 pp. 256-8) found variations in the optic axial angles of olivines whose densities appeared to be constant. In one slice nine crystals showed a range in 2V of 75 to 88 degrees.

Table 4

Composition of Olivine

Sample	$2V_\gamma$		Fa		d_{174}	Fa
	core	rim	core	rim		
Mt. Begbie						
V-1	102	109	39	53	1.0302	46
V-5	104	110	44	57	1.0291	42
T-9	104	110	44	57	1.0311	49
Forestry Hill						
FS-4	107	109	49	53	-	-
FS-6	-	-	-	-	1.0288	41
FS-2a	99	109	33	53	1.0271	35
FS-2	104	110	44	57	1.0288	41
Average range	Fa_{35} - Fa_{56}				Range	Fa_{35} - Fa_{49}

The range of zoning in Mt. Begbie and Forestry Hill plugs compares almost equally with that found in the Black Jack sill (J.F.G. Wilkinson, 1956) and in the British Carboniferous-Permian teshenites and essexites (S.I. Tomkieff, 1939). In the former the average range of zoning in any one part of the sill is about 20 per cent Fa. In the latter, zoning ranges from 15 to 17½ molecular per cent Fa. In agreement with Wilkinson's observations (1956, p. 454) is the fact that only about 25 per cent of olivine grains show zoning.

Olivine in the pegmatitic gabbro is the most fayalitic olivine encountered in the plugs. Measurements of $2V_\gamma$ range from 112 degrees to 114 degrees giving a range of zoning of Fa_{58} (core) to Fa_{62} (rim). In this rock the range of zoning of olivines is much reduced compared with those in the other rock-types.

Iron Ore

As observed in polished section, iron ore occurs as five distinct phases; magnetite, ulvospinel, ilmenite, hematite and pseudobrookite. Lamellar magnetite/ilmenite intergrowths are very common (Plate 17, Figure 1). Ilmenite lamellae are interpreted as having formed by exsolution along (111) crystallographic planes of magnetite. They are frequently enlarged and irregular where additional replacement of magnetite has occurred.

A cloth-textured magnetite/ulvospinel intergrowth is seen in grains under very high magnification. This apparently reflects the condition in which the two phases are present in the same amount. It has recently been considered (A. Davidson, personal communication) that exsolution of ilmenite is caused by oxidation of ulvospinel in solution with magnetite, and not from a solution of magnetite and ilmenite. Therefore, it is thought that many magnetite/ilmenite intergrowths were originally solid-solutions or exsolved intergrowths of ulvospinel and magnetite. Oxidation of ulvospinel produces ilmenite and magnetite according to the equation: $3Fe_2TiO_4 + O = Fe_3O_4 + 3FeTiO_3$ (A. Davidson, personal communication).

Magnetite and ilmenite also occur separately as homogeneous grains with no exsolved or intergrown material. Hematite occurs as rims on (Plate 17, Figure 2), or as crude lamellar intergrowths (Plate 18) with the titaniferous magnetite grains. It is also present as homogeneous, separate grains. Pseudobrookite is seen replacing intergrowths of magnetite and ilmenite (see Plate 11, Figure 1). It was identified by x-ray powder photograph.

Silica

Silica is present in three forms; cristobalite, tridymite, and α- quartz. These were each identified by x-ray powder camera photographs. Both cristobalite and tridymite probably formed metastably. According to Deer, Howie, and Zussmann (vol. 4, p. 194) the two persist metastably as α- forms under atmospheric conditions provided that sufficient aluminum and sodium are contained in the structure.

Zeolite

A zeolite was shown by x-ray powder photograph to be close to either a Na-harmotome ($NaAl_2Si_6O_{16}\ \ 6H_2O$) or a member of the Phillipsite group. The mineral has parallel extinction, an average refractive index of 1.514, and a measured 2V of 86 degrees (+).

PLATE 17

Figure 1. Lamellar intergrowth of ilmenite (light and dark grey) and magnetite (medium grey). The coarse, irregular blades of ilmenite (light grey) formed by replacement of magnetite along pre-existing, fine ilmenite lamellae (polished section, crossed nicols, x30).

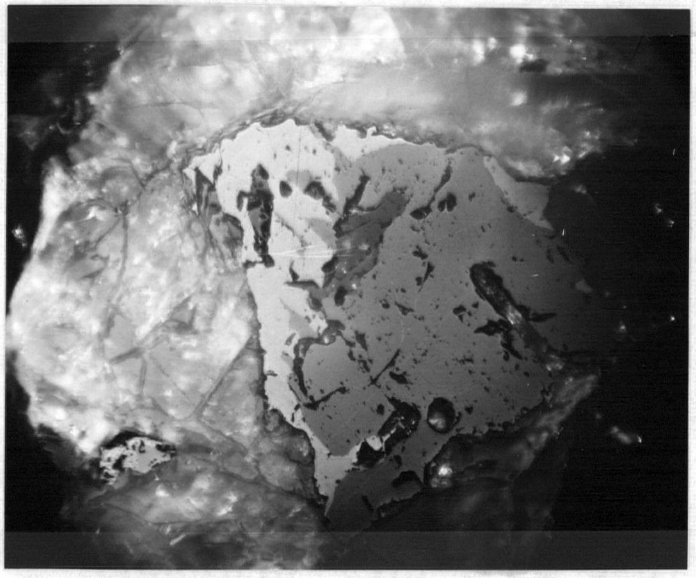

Figure 2. Replacement rim of hematite on magnetite (polished section, crossed nicols, x30).

PLATE 18

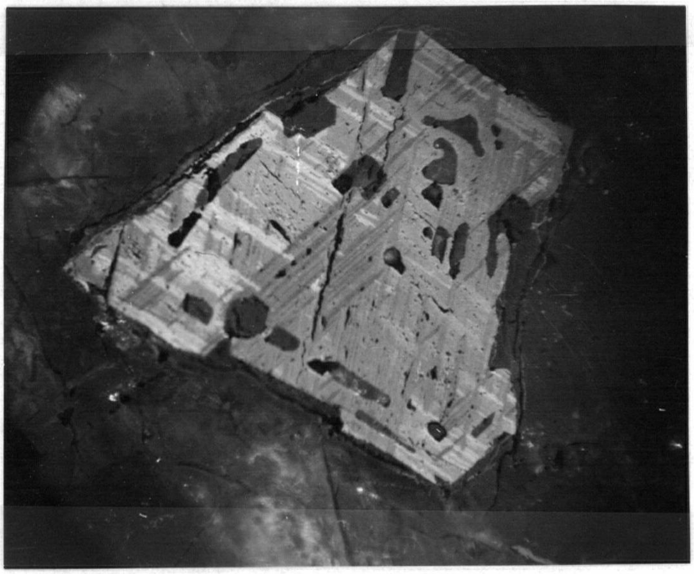

Figure 1. Hematite (white) replacing magnetite/ilmenite intergrowth along a (111) plane (polished section, crossed nicols, x30).

PETROLOGY

Composition of the Plugs

Mode. Modal volume percentages were calculated by the standard point-counter method. Traverses of 1500 to 2000 points per thin-section were made giving an accuracy of about ±4 per cent of the major minerals present. The percentage of minerals of minor abundance is accurate only to about ±1 per cent of the mode. Because of coarse grain size, the mode of pegmatitic gabbro is somewhat less accurate than the modes of other rock types. Because of heterogeneity in grain size and composition (e.g. scattered occurrence of cristobalite and pseudobrookite), the mode for marginal dolerite is not truly representative.

The results of modal analysis are shown in Table 5. Only the principal rock-forming minerals are included since silica, pseudobrookite, etc., are generally absent. Alteration minerals are counted as olivine, the only mineral that is altered, because they form much less than 1 per cent of the rock. The modes for Mt. Begbie and Forestry Hill plugs are an average of six thin-section analyses. The remainder were derived from analyses of one thin-section, each.

Chemical Composition. Chemical compositions calculated from the modes have been derived in order that comparisons can be made with other intrusions of a similar nature. Such compositions

Table 5

Modes

	A	B	C	D
olivine	15.0	14.1	11.2	15.7
pyroxene	18.2	18.2	19.2	15.9
plagioclase	60.0	58.8	61.3	62.1
iron ore	4.3	5.0	4.9	4.0
apatite	1.3	1.5	2.2	1.3
zeolite	1.2	2.4	1.2	1.0

	E	F	G	H
olivine	34.0	3.0	1.0	3.1
pyroxene	18.8	10.3	36.2	13.3
plagioclase	42.9	77.8	52.7	71.9
iron ore	3.9	4.6	9.5	8.9
apatite	0.5	1.2	0.5	2.8
zeolite	-	3.1	-	-

A. Mt. Begbie plug
B. Forestry Hill plug
C. Lone Butte plug
D. Tin Cup Mountain plug
E. picritic gabbro
F. leucogabbro
G. marginal dolerite
H. pegmatitic gabbro

must be considered approximate. For a qualitative discussion, however, it is felt that calculated chemical compositions are useful.

Three major factors lead to inaccuracies in the calculated chemical compositions. First, the sources of error in the modes are carried over into the calculated compositions. Secondly, whereas it is difficult enough to determine accurately the compositions of olivine, pyroxene and feldspar by optical methods, the difficulty is compounded when all three are zoned. Therefore, the average mineral compositions used in calculating chemical compositions are arbitrary. Thirdly, conversion of volume per cent to weight per cent was done without a precise knowledge of densities of the minerals. Approximate densities were assigned to each mineral in accord with its composition.

The following provisions were made for calculating chemical compositions in terms of weight per cent oxides:

1. The average feldspar composition was set at An_{50} (density 2.69).
2. The average olivine composition was set at Fa_{46}. The density of Fa_{46} (from Deer, Howie, and Zussmann, vol. 1, p. 22) is 3.7.
3. The composition of pyroxene was taken from Johannsen's table for augite. A density of 3.36 was taken from the curve relating density to per cent iron in diopside (H. Hess, 1949, p. 641).

4. Iron ore was taken as being two-thirds magnetite and one-third ilmenite, by volume. Density was taken as 5.0.

5. Zeolite was calculated as feldspar because of the similarity in chemical composition.

6. In the pegmatitic gabbro, the average feldspar composition is An_{35} (density 2.67); the average olivine composition is Fa_{60} (density 3.9).

Chemical compositions are listed in Table 6 for olivine gabbro of Mt. Begbie and Forestry Hill plugs, and for marginal dolerite and pegmatitic gabbro. Olivine gabbro represents the approximate bulk composition of each plug.

Table 6

Calculated Chemical Compositions

	A	B	C	D
SiO_2	46.7	47.2	44.6	46.5
Al_2O_3	16.8	16.8	15.7	17.3
Fe_2O_3	3.7	3.3	8.1	7.5
FeO	9.6	9.3	8.2	7.7
MgO	8.2	8.4	5.3	3.1
CaO	10.2	10.5	13.0	9.2
Na_2O (+K_2O)	3.2	3.2	2.6	4.9
TiO_2	1.1	0.9	2.4	2.6
P_2O_5	0.4	0.5	0.2	1.2

A. Mt. Begbie olivine gabbro
B. Forestry Hill olivine gabbro
C. marginal dolerite
D. pegmatitic gabbro

Whole-Rock Glass Bead Determinations. The refractive indices of fused whole-rock powders were determined using the method of W.H. Mathews (1951, p. 99). The purpose of this was to provide a partial check on the calculated chemical compositions of the plugs, and to show whether or not the surrounding plateau lavas bear any petrologic relationship to the plugs.

Preparation of the glass beads involved the following procedure. A rock chip weighing about 100 grams was crushed on a steel plate. The comminuted material was taken up completely as a sample. Random samples of about 1 gram weight were taken, avoiding any of the larger particle fraction. These samples were ground to -200 mesh in an agate mortar. After drying in air, 10 to 20 milligrams of the sample was transferred to a small cup carved in the tip of a carbon electrode. The sample was fused in a carbon arc.

The glass beads were then crushed and their refractive indices measured by the method of matching calibrated oils. The indices thus obtained are accurate to ±0.003. Two glass beads were made from each sample and three samples were prepared from each rock specimen. Therefore, the results for each specimen are an average of six determinations. These are shown in Table 7.

Determinative curves of refractive index versus per cent silica are provided by several writers. A diagram compiling several curves is shown by Mathews (1951, p. 97). The curve of Curtis and Slemmons, for Pliocene to Recent rocks from Mt. Lassen, gives a silica content of 48 per cent for both Mt. Begbie plug and the surrounding lava. The curve of L.R. Kittleman, Jr. (1963, p. 1408), derived from a suite of volcanic rocks from the Owyhee Plateau, Oregon, gives a silica content of 46 ±2 per cent. Callaghan and Sun (1956, p. 762) have derived a curve from some volcanic rocks of New Mexico which gives a silica content of 46.5 per cent. They (1956, p. 763) have also derived a set of curves relating percentage of MgO, CaO, and FeO + Fe_2O_3 to refractive index. The results are shown in Table 7.

Table 7

Glass Bead Determinations

	R.I.		SiO_2	MgO	CaO	FeO + Fe_2O_3
T-3 (Mt. Begbie)	1.608	A.	48.0			
		B.	46±2			
		C.	46.5	8.3	10.1	11.9
Surrounding Lava	1.609	A.	48.0			
		B.	46±2			
		C.	46.5	8.3	10.2	11.9

A. Curtis and Slemmons curve
B. L.R. Kittleman curve
C. Callaghan and Sun curve

The average silica content is 46 to 47 per cent. The results indicate a good correspondence between the silica content derived from glass bead determinations and that derived from calculated chemical analyses. The results show that Mt.

Begbie plug and the surrounding lava contain the same amount of silica.

<u>Specific Gravity</u>. The specific gravity of the olivine gabbro of Mt. Begbie and Forestry plugs, and that of the porphyritic lava surrounding Mt. Begbie are shown in Table 8. Measurements of specific gravity were made using powdered samples and a powder density bottle. The method is accurate to about ±0.02 grams/$cm.^3$ It was used because the rock contains an abundance of small cavities which would otherwise trap air if specific gravity was determined on solid samples.

Table 8

Specific Gravity

	S.G.
Mt. Begbie plug	3.01
Forestry Hill plug	2.99
porphyritic lava	2.93

Differentiation

Fractional crystallization resulting from zoning of minerals, has produced differentiation in Mt. Begbie plug. Marginal dolerite and pegmatitic gabbro are differentiates of the olivine gabbro. Figure 10 is a variation diagram with per cent oxides plotted against per cent MgO. The MgO-content is seen to decrease from olivine gabbro through marginal dolerite to pegmatitic gabbro. There is a marked increase of Fe_2O_3 in marginal dolerite and pegmatitic gabbro, corresponding to an increase in magnetite-content. Marginal dolerite has the greatest percentage of total iron oxides. Pegmatitic gabbro is enriched in alkalis.

The trend of differentiation is shown in Figure 11. Marginal dolerite is the intermediate, iron-enriched phase and pegmatitic gabbro is the final, alkali-rich phase. The trend is compared with trends for Cnoc Rhaonastil, an alkali dolerite plug (see later section on Comparisons), and the Palisade diabase, New Jersey (both taken from Walker and Patterson, 1959, p. 150).

Figure 12 is a plot of mafic index versus per cent SiO_2. The trend of differentiation of Mt. Begbie plug is roughly parallel to the trend of the Skaergaard magma (taken from E.F. Osborn, 1959, p. 634). Other trends are shown for comparison.

Figure 13 is an FMA diagram (taken from Walker and Poldervaart, 1949, p. 662) illustrating the variation of dolerite pegmatites and the parent rocks from which they were derived.

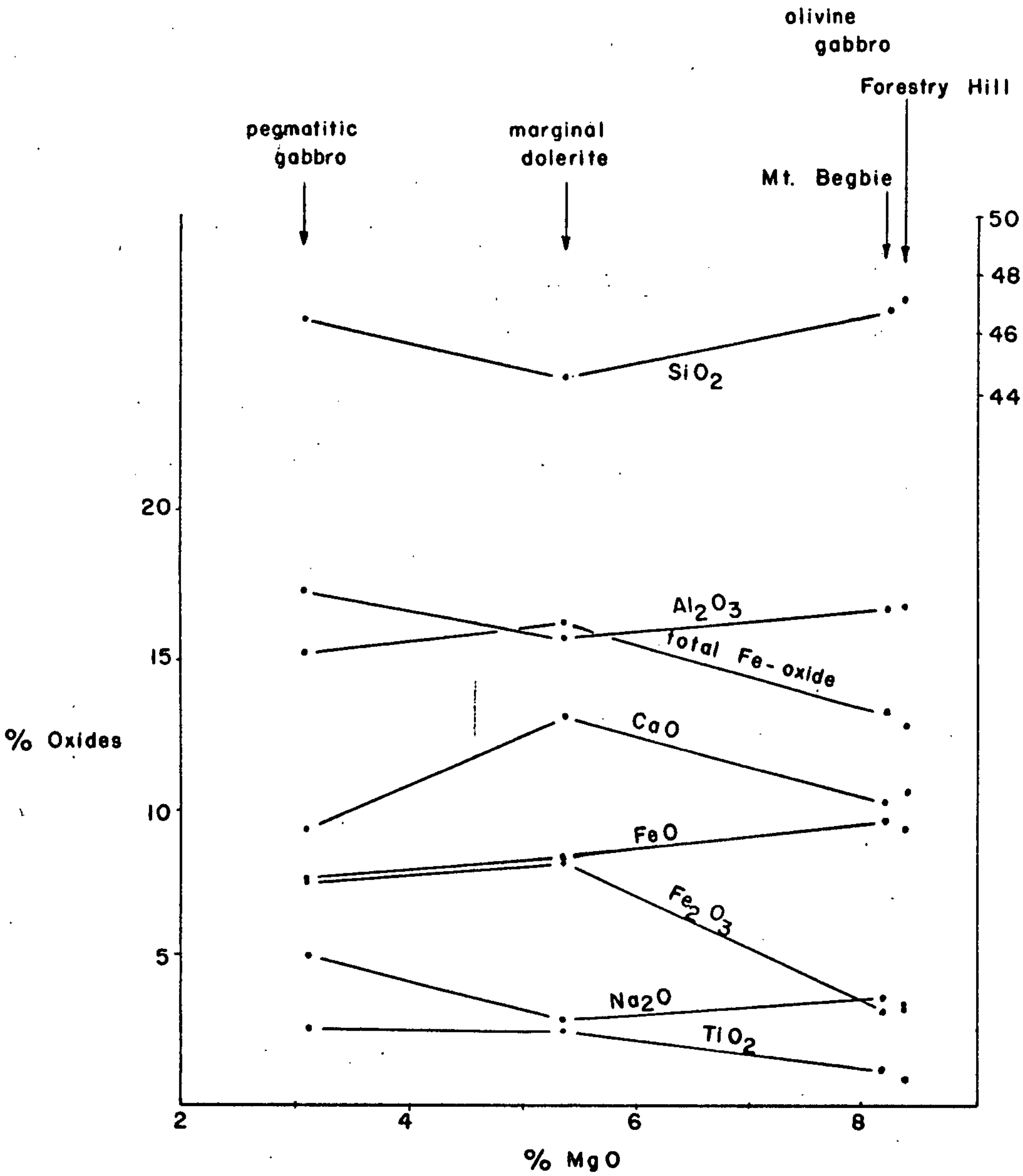

Figure 10. Variation diagram.

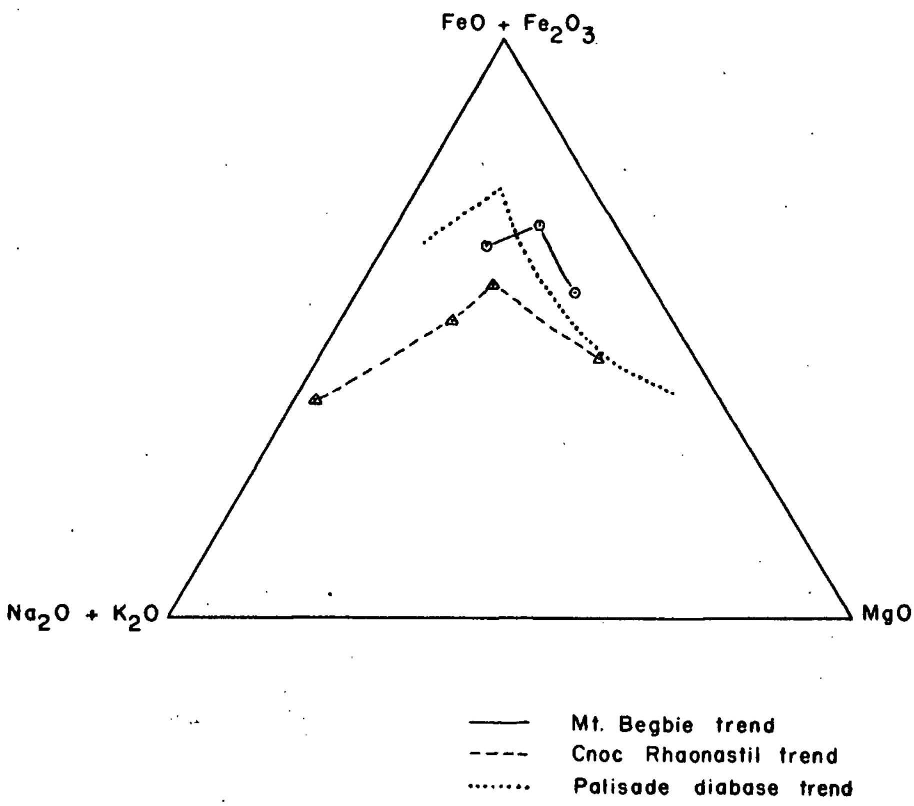

Figure 11. Trend of differentiation of Mt. Begbie plug compared with that for Cnoc Rhaonastil, an alkali dolerite and the Palisade intrusion, a tholeiitic diabase (from Walker and Patterson, 1959).

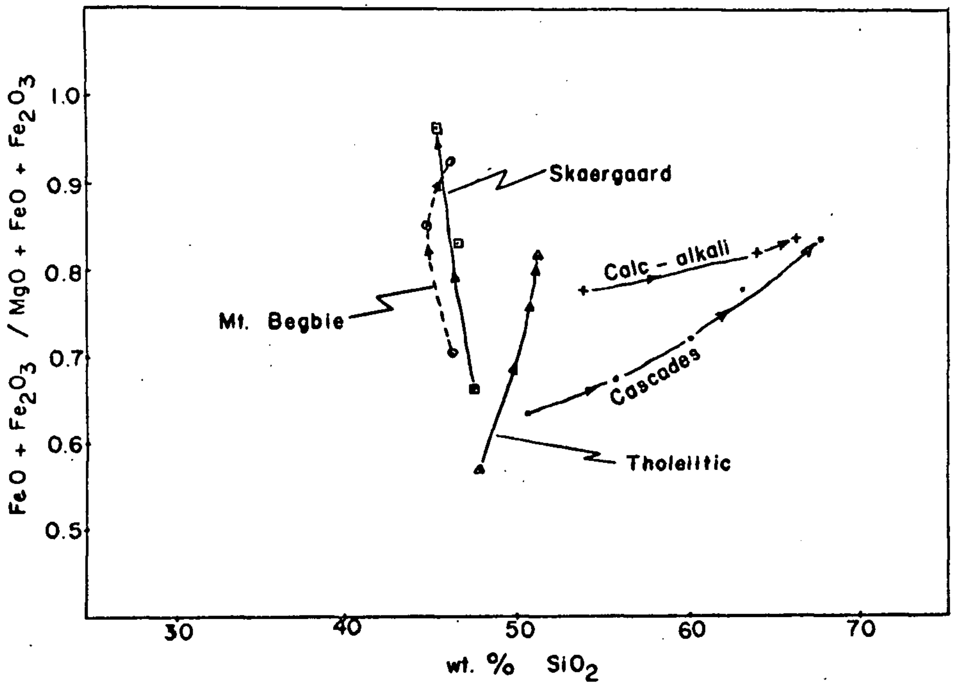

Figure 12. Plot of mafic index versus SiO_2 with trends for Mt. Begbie, Skaergaard, Calc-alkali series, Tholeiitic series and Cascade series (from Osborn, 1959).

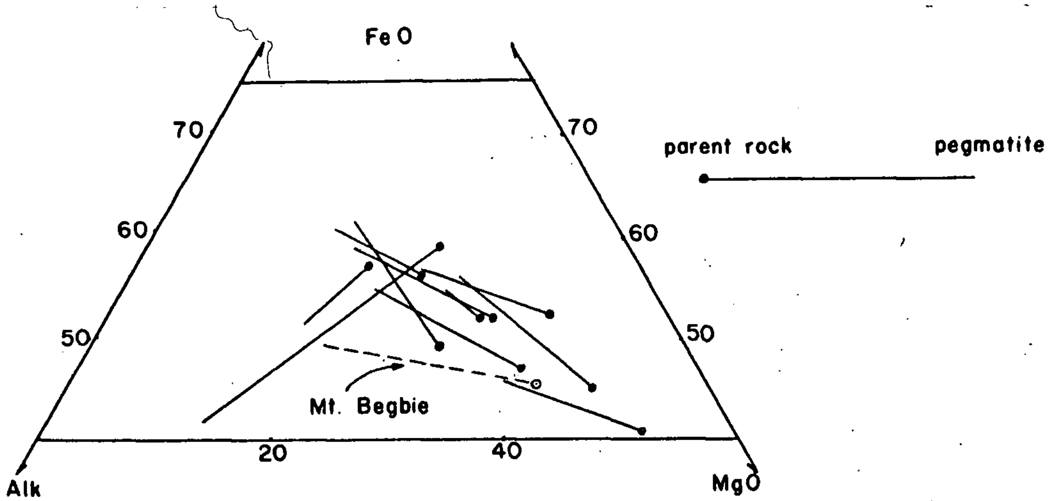

Figure 13. FMA diagram (from Walker and Poldervaart, 1949) showing variation of dolerite pegmatites and their parent rocks.

Concerning dolerite pegmatites of the Karroo intrusions, Walker and Poldervaart (1949, p. 663) comment:

> All the dolerite pegmatites have a higher Fe_2O_3:FeO ratio than their parent rocks. If cooling was slow and if at least 60 - 80 per cent of the main mass was solid when the pegmatite phase crystallized, this relatively high proportion of ferric oxide agrees with the conclusions reached by Phemister (1934, p. 41) on theoretical grounds. The oxidized state of the iron in the dolerite pegmatite prevented much of it from forming pyroxene and thereby led to the crystallization of considerable amounts of quartz and iron ore.

They also state (1949, p. 662) that:

> Tomkieff (1929, p. 117) regarded the dolerite pegmatite of the Whin Sill as a heteromorphic variety of the normal rock, but it is shown ... that where chemical data are available the pegmatitic phase belongs to a later stage in the differentiation series than that reached by the parent rock.

A consideration of differentiation leads to the conclusion that the marginal dolerite and pegmatitic gabbro started crystallizing later than the olivine gabbro. Although the margin is necessarily the coolest portion of the plug (promoting rapid crystallization), the magma there contains the greatest weight-percentage of water (G.C. Kennedy, 1955, p. 493). This results in lowering of liquidus temperatures thereby counteracting the influence of lower temperature. Thus, it is feasible that the marginal phases crystallized later.

A possible mechanism for separating the rock phases is filter-pressing of liquid from a crystal mush. The margin of the plug may have been a locus of rifting caused by movement of the crystallizing magma. Movement, resulting in compaction of crystals, would drive some interstitial fluid toward the rift zone (i.e. the margin). The fluid would be deficient in MgO and rich in FeO because of fractionation through zoning of olivine.

The pegmatitic phase may have developed by trapping residual magma in a growing crystal framework (Walker and Patterson, 1959, p. 148). Volatile-rich fluids concentrated in the residual magma would promote the growth of large crystals and would be enriched in alkalis as a result of zoning of plagioclase and clinopyroxene.

The trend of differentiation resulting from fractional crystallization is, according to E.F. Osborn (1959, p. 642), dependent on the constancy of bulk composition of the magma and of partial pressure of oxygen (p_{O_2}). Where the bulk composition is constant, p_{O_2} decreases and the trend of differentiation is that of the Skaergaard magma (see Figure 12). Lower temperatures at the margin, causing a decrease in dissociation of water (ibid., p. 643), may account for the decrease in p_{O_2}.

Nature of the Original Magma

Several characteristics of the mineral and chemical composition of the plugs indicate the nature of the original magma. According to many investigators, tholeiitic and alkali basalt magmas are the fundamental magma-types (Yoder and Tilley, 1962).

Mineralogically, the characteristics of the plugs are those of alkali basalt. With regard to ferromagnesian minerals of tholeiitic versus alkali olivine-basalt magmas, Poldervaart and Hess (1951, p. 479) state that a reaction relation exists between pyroxene and olivine in tholeiitic rocks whereas none exists in alkali olivine basalts. There is no such reaction relation in the plugs. In further discussion, J.F.G. Wilkinson (1956, p. 737) states:

> The olivines in tholeiitic rocks are unzoned or rarely show slight zoning, indicating the readiness with which this mineral reacts with the magma, compared with the associated clinopyroxene or plagioclase which may be strongly zoned. Widespread normal zoning is a feature of the olivines of alkali olivine-basalt derivatives.

Strong normal zoning is a feature of olivine in Mt. Begbie and Forestry Hill plugs.

The ferromagnesian assemblage includes calcic-augite (salite) and olivine. Wilkinson observes (1956, p. 740) that:

> In alkali olivine-basalt magma, the ferromagnesian assemblage consists of diopsidic clinopyroxene and olivine. In the initial stages, the early separation of forsteritic olivine greatly increases the normative Wo content of the magma (Kennedy, 1933, p. 252). In the absence of possible localized crystal accumulation the failure of the reaction relation results in a moderately low near-constant amount of clinopyroxene. With decreasing temperature, the bulk of Fe/Mg enrichment is borne by an ever-diminishing quantity of olivine, which becomes more fayalitic (and in many instances, more strongly zoned). Exsolution lamellae are uncommon in alkali olivine-basalt clinopyroxenes.

A plot of the trend of zoning of clinopyroxenes from Mt. Begbie and Forestry Hill plugs is compared in Figure 14 with the differentiation trends of tholeiitic and alkali basalt clinopyroxenes. Pyroxene of the plugs plots within the field of alkali basalt pyroxenes.

The chemical composition of the plugs shows affinities to alkali basalt magma. The characteristics of tholeiitic and

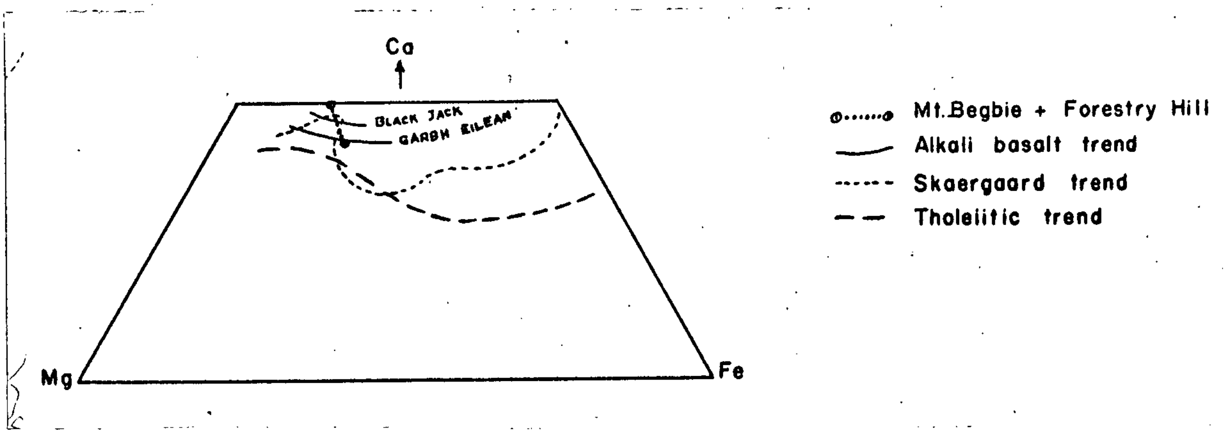

Figure 14. Trend of clinopyroxenes in basaltic magmas. Black Jack sill and Garbh Eilean sill represent alkali basalt trends. (from Wilkinson, 1956, p. 735)

alkali basalt magmas are summarized by Turner and Verhoogen (1960, p. 207) as follows: "there is a tendency for SiO_2 to be higher and for Na_2O, K_2O, and MgO to be lower in tholeiites than in alkaline olivine basalts." Examination of Table 9 shows that the compositions of Mt. Begbie and Forestry Hill plugs compare much more closely with alkali basalt magmas than with tholeiitic magmas. The SiO_2, Al_2O_3 and alkali percentages are close to those of the Tertiary dolerite plugs of Ireland and contrast with those of the tholeiitic Tasmanian dolerites. Similarity to the average Japanese alkali basalt (versus the average Japanese tholeiite) is also seen.

Figure 15 is a tetrahedral diagram showing the major mineral components of an iron-free system (modified from Yoder and Tilley, 1962, p. 352). The plane of olivine - plagioclase - clinopyroxene is the plane of critical saturation. Since these are the major components of the olivine gabbro, the composition

Table 9

Comparison of Chemical Compositions

	A	B	C	D
SiO_2	46.7	47.2	48.0	48.01
Al_2O_3	16.8	16.8	16.7	19.11
Fe_2O_3	3.7	3.3	2.0	1.20
FeO	9.6	9.3	8.8	8.44
MgO	8.2	8.4	8.9	7.72
CaO	10.2	10.5	11.3	10.33
Alkalis	3.2	3.2	2.7	2.51
TiO_2	1.1	0.9	1.2	1.51
P_2O_5	0.4	0.9	0.1	0.07
other	-	-	0.3	1.35

	E	F	G	H
SiO_2	53.18	49.78	50.19	48.11
Al_2O_3	15.37	15.69	17.58	15.55
Fe_2O_3	0.76	2.73	2.84	2.99
FeO	8.33	9.20	7.19	7.19
MgO	6.71	7.79	7.39	9.31
CaO	11.04	11.93	10.50	10.43
Alkalis	3.68	1.50	3.15	3.98
TiO_2	0.65	0.68	0.75	1.72
P_2O_5	0.08	0.07	0.14	0.56
other	1.27	0.64	0.25	0.16

A. Mt. Begbie olivine gabbro
B. Forestry Hill olivine gabbro
C. Average of Tertiary dolerites of N.E. Ireland (Patterson and Swaine, 1957, p. 325)
D. Chilled margin of Skaergaard intrusion (Wager and Deer, 1939, p. 140)
E. Average chilled margin of Tasmanian dolerites (MacDougall, 1962, p. 294)
F. Average tholeiite of Japan (Kushiro and Kuno, 1963, p. 77)
G. Average high-alumina basalt of Japan (ibid.)
H. Average alkali olivine basalt of Japan(ibid.)

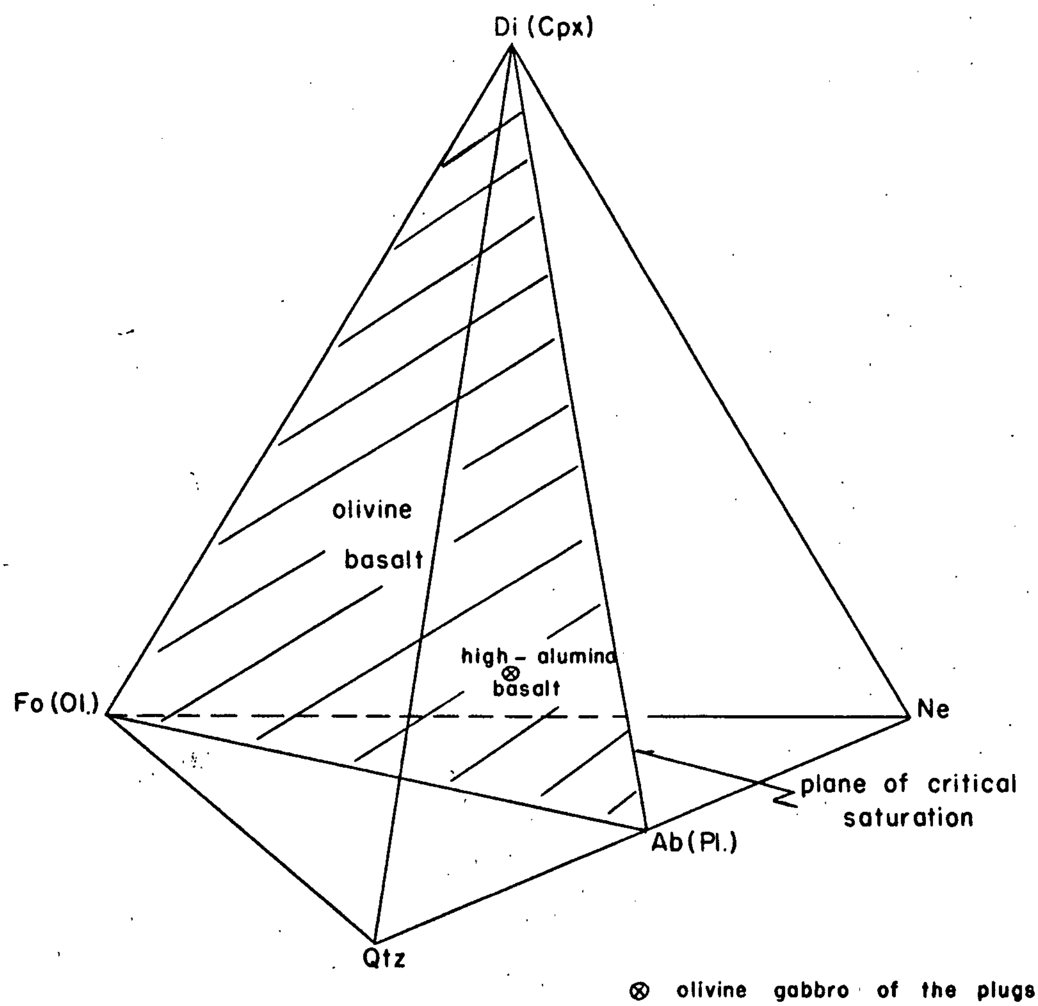

Figure 15. Tetrahedral diagram showing the composition of olivine gabbro close to the high-alumina region of the critical plane of saturation (modified from Yoder and Tilley, 1962).

of the plugs lies close to the plane of critical saturation. The modal composition plots within the region of high-alumina basalt.

The chemical composition of Mt. Begbie and Forestry Hill plugs shows a fairly high percentage of Al_2O_3; a reflection of the high percentage of plagioclase. In H. Kuno's classification of fundamental magma-types (1960) the plugs would qualify as high-alumina type. Shown for comparison in Table 9 is the composition of the Skaergaard chilled margin; a high alumina type. Yoder and Tilley (1962) maintain that high-alumina basalt is not a fundamental magma-type. They state (1962, p. 420) that: "Whatever process brings forth a high-alumina basalt probably involves for the most part a concentration of the plagioclase components." They conclude (ibid.) that: "For critically undersaturated basalts, the alumina content would, therefore, be expected to be high in the normal course of fractionation."

A plot of MgO versus Al_2O_3/SiO_2, devised by Murata (1960) to illustrate differentiation trends, is shown in Figure 16. The diagram is taken from Yoder and Tilley (1962, p. 414) and shows the differentiation trends of magmas of both the tholeiitic and alkali series. The trend of Mt. Begbie plug falls close to the alkali series.

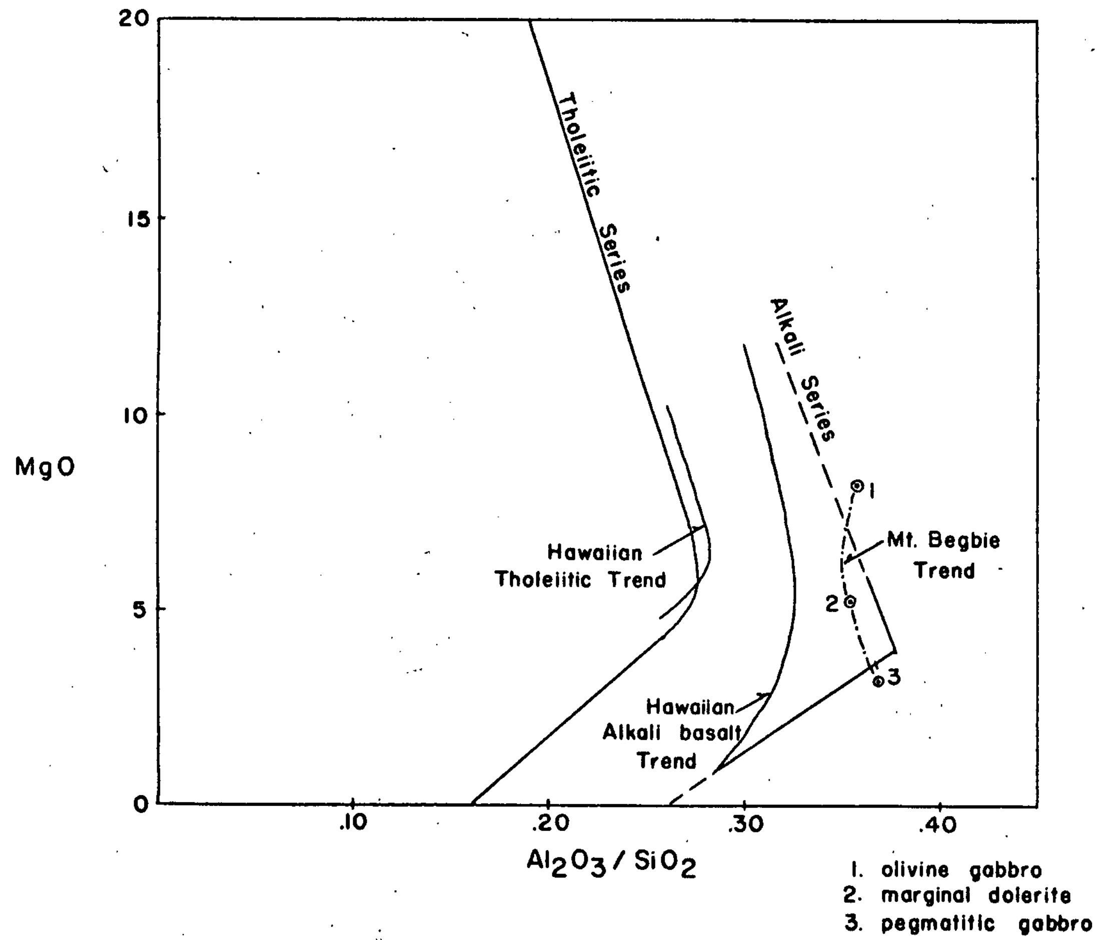

Figure 16. Diagram showing Mt. Begbie trend of differentiation with respect to the tholeiitic and alkali series (from Yoder and Tilley, 1962).

History of Crystallization

Environment. The plugs formed in a very high-level, hypabyssal environment. The depth of erosion of the southern Cariboo plateau surface from late Miocene - early Pliocene to the present is measurable in hundreds of feet (W.H. Mathews, personal communication). The highest exposed parts of the plugs possibly crystallized within 50 to 150 feet of the original surface. From this high level the conduits must certainly have reached the surface supplying lava for basaltic extrusion.

The environment of crystallization of the exposed parts of the plugs was one of non-steady state conditions. The rate of cooling was probably moderate, allowing relatively coarse grains to form. The magma that formed the plugs was emplaced in surroundings that were heated during the interval of extrusion. The chilled margin plus the hot basaltic wall rocks may have provided insulation against rapid heat loss. As evidence for this, fairly coarse olivine gabbro is found in contact with the chilled margin.

Recurrent, almost periodic release of volatiles resulting from recurrent rifting of the crystallizing magma is thought to have caused the oscillatory zoning in plagioclase and pyroxene. J.A. Vance believes (1962, p. 746) that oscillatory zoning forms: "in response to recurrent supersaturation in anorthite adjacent to individual crystals." The writer considers it likely that repeated loss of volatiles is a feasible and simple mechanism which would cause oscillatory zoning. An abrupt change from oscillatory zoning in the tabular plagioclase grains to normal zoning in the rim or interstitial plagioclase is seen in the plugs. The change is probably a reflection of late-stage saturation of the residual melt in volatiles (Vance, 1962, p. 746).

Initial Crystallization. Initial crystallization of the magma began prior to, or during the upward transport of magma. Evidence for this is seen in the basaltic chilled margin. The chilled margin contains abundant phenocrysts of plagioclase and olivine and relatively few pyroxene phenocrysts. Thus, it is assumed that plagioclase and olivine started crystallizing together, with pyroxene appearing as the temperature decreased. Experimental results of Yoder and Tilley (1962, p. 451-452) for high-alumina and alkali basalts show the same relative sequence at low water pressures. Plagioclase and olivine begin to separate from the magma almost simultaneously. After a decrease of about 50° C. pyroxene begins to form and the three minerals crystallize together.

Crystallization of Olivine Gabbro. The course of crystallization of olivine gabbro is shown in Figure 17. This is the fundamental basalt tetrahedron including the principal phases of critically undersaturated basalt, plagioclase, clinopyroxene and olivine. The system shown is a simple iron-free one where the components are diopside - forsterite - albite - anorthite. The course of crystallization starts on, or close to the Fo + Pl plane. With continued subtraction of olivine and plagioclase from the magma

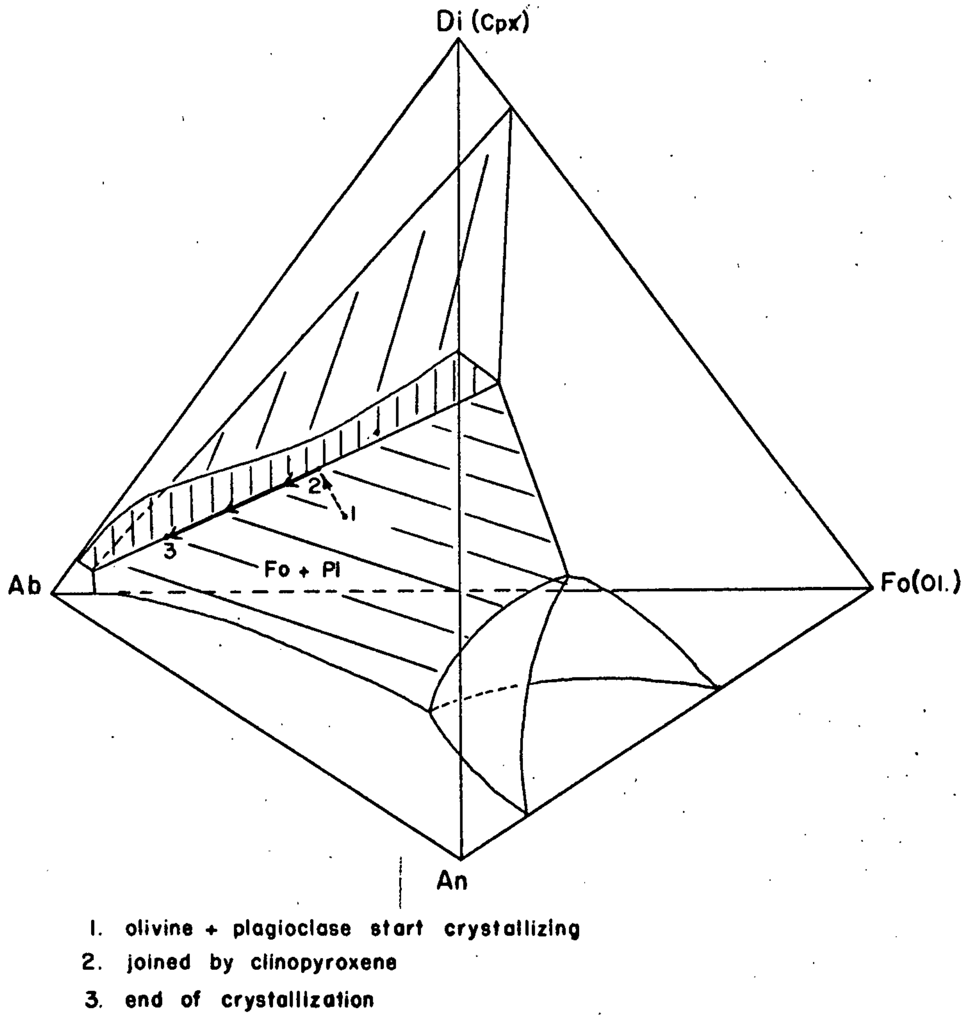

Figure 17. Course of crystallization shown on a tetrahedral Ab - An - Di - Fo diagram (from Yoder and Tilley, 1962).

the liquid trends toward the four-phase curve where clinopyroxene (Di) starts crystallizing. Yoder and Tilley (1962, p. 397) observed experimentally that basalts, in general, reach the four-phase curve at about the same temperature, 1155° to 1170° C. With continued crystallization the composition of the liquid proceeds along the four-phase curve. Crystallization of the magma was completed at the point where plagioclase of composition An_{20} solidified. Yoder and Tilley (1962, p. 450) observe that for high-alumina basalts the range of crystallization for plagioclase is broad, approximately 100° to 175°.

The order of crystallization of the three groups of pyroxenes can be determined from textures. The large, seive-textured pyroxenes of Group I formed early enclosing small grains of plagioclase, olivine and iron ore. A strong tendency for pyroxene to cluster is shown by the great number of large, compound grains. The pyroxenes of Group II formed later as the greater volume of crystals in the magma destroyed the freedom to cluster. Thus, they occur in intergranular relationship with plagioclase. Walker and Poldervaart note (1949, p. 673) that augite has low powers of spontaneous crystallization. Where pyroxene occurs rimming olivine, the olivine grains probably served as nucleii. The interstitial, euhedral pyroxenes of Group III formed in association with interstitial oligoclase at a stage when the magma was saturated with volatiles.

In discussing the crystallization of pyroxenes from undersaturated basaltic magmas Poldervaart and Hess (1951, p. 487) suggest a possible control on the composition of clinopyroxenes:

> Olivine appears as early phenocrysts and continues to crystallize for a considerable interval before a clinopyroxene separates. The early crystallization of a calcium-free olivine phase increases the normative Wo content of the magma with respect to En and Fs, ... When clinopyroxene does appear, it is commonly a member of the diopside-hedenbergite series rather than augite.

Zoning in olivine is much more extreme than it is in clinopyroxene. In this regard, Wilkinson (1957, p. 132) suggests that:

> Clinopyroxene, which remains relatively unchanged in composition, exerts a control on composition of olivine that forms in that MgO is depleted by pyroxene much more than FeO. Thus olivine becomes more fayalitic as crystallization proceeds.

Iron ore probably crystallized quite early in the sequence. Several generations of ore are registered in the textural observations. Early ore is that which is composed of magnetite-ulvospinel intergrowths (now seen as magnetite-ilmenite intergrowths). Later generations of ore are indicated by homogeneous magnetite or ilmenite grains. The latest generations include hematite grains and ore that is exsolved from ferromagnesian silicates. Thus, the formation of iron ore spanned a considerable amount of the crystallization interval.

Late stage residual solutions deposited zeolite and cristobalite in cavities and effected a partial alteration of olivine to biotite, iddingsite and serpentinous material.

Crystallization of Marginal Dolerite. Marginal dolerite started crystallizing somewhat later than the adjacent olivine gabbro. The absence of flow foliation is in accord with the hypothesis that the magma was derived from the liquid fraction of olivine gabbro. Crystallization of the static liquid resulted in a homophanous texture. Most of the rock was formed by simultaneous crystallization of clinopyroxene, plagioclase and iron ore.

Cristobalite and pseudobrookite formed in the late stages of crystallization. The replacement of magnetite/ilmenite grains by pseudobrookite is attributed to a late stage enrichment in TiO_2. Both cristobalite and pseudobrookite were deposited in cavities by volatile material.

Crystallization of Pegmatitic Gabbro. Pegmatitic gabbro formed late in the crystallization history of the plugs. Large, skeletal crystals of pyroxene, olivine and iron ore indicate fairly rapid growth of grains in the presence of volatiles. All of the main minerals crystallized together. Tridymite was deposited in cavities by volatile fluids. Its presence may indicate that the pegmatitic volatiles were cooler than those which deposited cristobalite elsewhere.

COMPARISON WITH SIMILAR INTRUSIONS

General Statement

The Tertiary dolerite plugs of north-east Ireland and western Scotland show great similarity, both in form and petrology, to the plugs of the present study. Some of these are described below. Very few doleritic or gabbroic plugs from North America have been well-documented.

Skoatl Point Plug

The report on the area of the Kamloops map-sheet by G.M. Dawson (1894) includes a description of Skoatl Point, a Tertiary plug of basaltic composition situated on Kuk-waus' Plateau east of the area shown in Figure 2. In Dawson's words (p. 223):

> Skoatl rises very abruptly, with a steep conical form - somewhat narrower in its north-and-south than its east-and-west diameter ... It is composed of a somewhat coarse-textured, dark grey olivine basalt, with a finely-developed columnar structure. The columns average about a yard in diameter, and are curved in several directions, but with a general tendency to meet toward the apex of the hill. Those on the west side run from base to summit with a gentle sweep. There is every reason to believe that Skoatl represents the plug of an old vent, from which much of the basaltic material of the vicinity may have flowed out.
>
> ... In the hand specimen this is a dark greenish-grey, rather fine-grained porphyritic rock ... Phenocrysts of plagioclase, olivine and augite, are embedded in a fine-grained groundmass composed of lath-shaped sections of plagioclase and granules of augite, olivine and magnetite together with some glassy interstitial matter.
>
> "Flow-structure" is sometimes well brought out by the arrangement of the small plagioclase crystals in the rock.

Tertiary Dolerite Plugs of North-East Ireland

Patterson and Swaine (1957) include a general description of the form of Tertiary dolerite plugs of north-east Ireland. They state (p. 321):

> Appreciation of the three-dimensional form of the plugs is naturally limited by restricted vertical exposures. The wall contacts appear to be steep, and the general impression which the observer gains is of a flattened cylinder, presumably emanating in depth from a hidden magma chamber. This conception is undoubtedly oversimplified, and, in plan, the form of the Carrickarade plug is irregular, while the Corkey Rocks plug has been shown by Walker to incline towards a sill.
>
> Evidence for the nature of the upward extension of the plugs is equally indirect. None of them is seen to terminate upwards and they have been presumed to be the feeders of lava flows which are now removed by erosion, although no direct connection has been traced between a plug and a flow. The contact alteration produced by some of the plugs strongly suggests that the conduits must have carried magma for considerable periods of time.

One of the plugs (Tieveragh) documented by Tomkieff (1940) is described as follows:

> Tieveragh is a picturesque conical hill half a mile N. W. of Cushendall. It was recognized by McHenry to be a volcanic neck infilled with dolerite. It is slightly elliptical in cross-section, with an average diameter of 600 feet. It breaks through tuffaceous sandstone and conglomerate of Old Red Sandstone age. The centre of the plug is composed of olivine dolerite similar to other Irish dolerites of Tertiary age. The exposures are not good and in the samples studied the olivine is completely serpentinized, although labradorite and poikilophitic purplish augite are quite fresh. Iron-ore is usually moulded on plagioclase and the mesostasis consists of chlorite and fibrous zeolite. The dolerite is coarse right up to the margin of the plug. Two or three feet from the contact a small exposure of dolerite displays a remarkably coarse rock very rich in olivine. According to its granularity this rock should be classed as gabbro. The olivine is fresh and it occurs in the form of large irregular crystals. As measured on the Fedorov stage its optic axial angle varies from 90° to 86°, and therefore its composition varies from Fo_{87} to Fo_{77} (Mol. per cent). It is only slightly zoned. The plagioclase is a zoned labradorite. The ophitic pyroxene with 2V = 56 and γ:c = 41, appears to be a normal augite. A rather abundant mesostasis consists of radial and tufted chloritic aggregates.

Towards the margin of the plug this olivine-rich rock passes rapidly into an almost olivine-free fine-grained dolerite. The feldspar of the marginal dolerite is also labradorite but strongly zoned to oligoclase. The greatest change, however, is shown by the pyroxene which occurs in the form of idiomorphic and herring-bone structure.

Maiden Island, Oban, W. Scotland

The description of the geology of Maiden Island (F. Walker, 1939), an intrusion of olivine dolerite, includes the following chief points of interest (p. 475):

1. The occurrence of an unusually large mass of olivine-dolerite in the form of an elongated boss (400 yds. by 125 yds.).
2. The differentiation of this olivine-dolerite into bands of varying texture, but uniform mineralogical composition.
3. The development of a series of later segregation veins and patches in the olivine-dolerite.
4. The local occurrence of a thin band of picrite along the contact - a phenomenon apparently unique in the British Tertiary Province, and one which provides an interesting problem in differentiation.

The composition of plagioclase is An_{60}, zoned to An_{30} at the margin. The pyroxene is a pale purplish-brown to colourless clinopyroxene with 2V about 60^{o} and $Z \wedge c = 38^{o}$. Olivine has a 2V about 90^{o}.

Cnoc Rhaonastil, Islay, W. Scotland

Cnoc Rhaonastil is a boss of leucodolerite which has differentiated into several rock types (Walker and Patterson, 1959). Dolerite pegmatite, olivine-rich dolerite, and anorthositic bands are associated with leucodolerite. Commenting on the anorthositic bands Walker and Patterson (1959, p. 143) state that: "The constituent minerals are these of the leucodolerite but the mafic minerals are even scarcer."

SUMMARY AND CONCLUSIONS

The four plugs; Mt. Begbie, Forestry Hill, Lone Butte and Tin Cup Mountain originated by crystallization of basaltic magma, possibly within 50 to 150 feet of the surface. The bulk composition of the plugs is olivine gabbro in which olivine, calcic-augite and plagioclase are the essential minerals. Extreme zoning of the minerals indicates a disequilibrium environment of crystallization. From a consideration of mineralogical and chemical characteristics it is concluded that the original magma was an alkali basalt magma. Differentiation by fractional crystallization produced small volumes of marginal dolerite and pegmatitic gabbro in the outer portions of Mt. Begbie plug. The trend of differentiation leads to iron-enrichment in the marginal dolerite, and then to alkali-enrichment in the pegmatitic gabbro.

Foliation in Mt. Begbie and Forestry Hill plugs dips toward the centre at moderate to steep angles. Marginal foliation is assumed to be roughly parallel to the walls of the plug. Foliation trends indicate that both plugs are funnel-shaped, increasing in diameter toward the surface.

The four plugs occupy former volcanic vents which, in late Tertiary time, fed lava to the surrounding plateau. General geological relationship, petrological similarity, and the close comparison of fused whole-rock powders suggest a definite kinship of the plugs to the surrounding basaltic lava.

BIBLIOGRAPHY

Callaghan, E., and Sun, M.S., 1956, Correlation of some igneous rocks of New Mexico by the fusion method: Am. Geophys. Union Trans., v. 74, p. 1405-1410.

Dawson, G.M., 1894, Report on the area of the Kamloops map-sheet: Geological Survey of Canada Annual Report, v. 7, p. 1B-427B.

Deer, W.A., Howie, R.A., and Zussmann, J., 1962, Rock-forming minerals, v. 1, 2 and 4.

Hess, H.H., 1949, Chemical composition and optical properties of common clinopyroxenes, part 1: Am. Mineralogist, v. 34, p. 621-666.

Jambor, J.L., and Smith, C.H., 1964, Olivine composition determination with small-diameter x-ray powder cameras: Mineralog. Mag., v. 33, p. 730-741.

Johannsen, A., 1939, A descriptive petrography of the igneous rocks, v. I: Univ. Chicago Press, 318 p.

Kennedy, G.C., 1955, Some aspects of the role of water in rock melts, in Poldervaart, A., ed., Crust of the earth: Geol. Soc. America Spec. Paper 62, p. 489-503.

Kittleman, Jr., L.R., 1963, Glass-bead silica determination for a suite of rocks from the Owyhee Plateau, Oregon: Geol. Soc. America Bull., v. 74, p. 1405-1410.

Kuno, H., 1960, High-alumina basalt: Jour. Petrology, v.1, p. 121-145.

Kushiro, I., and Kuno, H., 1963, Origin of basalt magmas and classification of basaltic rocks: Jour. Petrology, v. 4, p. 75-89.

LeBas, M.J., 1962, The role of aluminum in igneous clinopyroxenes with relation to their parentage: Am. Jour. Sci., v. 260, p. 267-288.

MacDougall, I., 1962, Differentiation of the Tasmanian dolerites: Geol. Soc. America Bull., v. 73, p. 279-316.

Mathews, W.H., 1951, A useful method for determining approximate composition of fine-grained igneous rocks: Am. Mineralogist, v. 36, p. 92-101.

________, and Rouse, G.E., 1963, Late Tertiary volcanic rocks and plant-bearing deposits in British Columbia: Geol. Soc. America Bull., v. 74, p. 55-60.

Murata, K.J., 1960, A new method of plotting chemical analyses of basaltic rocks: Am. Jour. Sci., v. 258-A, p. 247-252.

Osborn, E.F., 1959, Role of oxygen pressure in the crystallization and differentiation of basaltic magma: Am. Jour. Sci., v. 257, p. 609-647.

Patterson, E.M., and Swaine, D.J., 1957, The Tertiary dolerite plugs of N.E. Ireland - A survey of their geology and geochemistry: Royal Soc. Edinburgh Trans., v. 63, p. 317-331.

Poldervaart, A., and Hess, H.H., 1951, Pyroxenes in the crystallization of basaltic magma: Jour. Geol., v. 59, p. 472-489.

Rittmann, A., 1962, Volcanoes and their activity: New York, John Wiley and Sons, 305 p.

Ross, J.V., 1957, Combination twinning in plagioclase feldspars: Am. Jour. Sci., v. 255, p. 650-656.

Seifert, K.E., 1964, Genesis of plagioclase twinning in Nonewaug granite: Am. Mineralog., v. 49, p. 297-320.

Smith, M., 1965, Continental glaciation in the Bonaparte River and Quesnel Lake map-sheets, British Columbia, Canada: unpublished B. Sc. Thesis, University of British Columbia.

Taubeneck, W.H., and Poldervaart, A., 1960, Geology of the Elkhorn mountains, northeastern Oregon: Part 2, Willow Lake intrusion: Geol. Soc. America Bull., v. 71, p. 1295-1322.

Tomkieff, S.I., 1939, Zoned olivines and their petrogenetic significance: Mineralog. Mag., v. 25, p. 229-251.

________, 1940, The dolerite plugs of Tieveragh and Tievebulliagh near Cushendall, Co. Antrim, with a note on buchite: Geol. Mag., v. 77, p. 54-64.

Turner, F.J., 1947, Determination of plagioclase with the four-axis universal stage: Am. Mineralog., v. 32, p. 389-410.

________, and Verhoogen, J., 1960, Igneous and metamorphic petrology: New York, McGraw-Hill Book Co., 602 p.

Vance, J.A., 1962, Zoning in igneous plagioclase: normal and oscillatory zoning: Am. Jour. Sci., v. 260, p. 746-760.

Wager, L.R., and Deer, W.A., 1939, The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland: Meddr. om Grønland, Bd. 105, no. 4, 352 p.

Walker, F., 1939, The geology of Maiden Island, Oban: Edinburgh Geol. Soc. Trans., v. 13, p. 475-482.

________, 1940, Differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., v. 51, p. 1059-1106.

________, and Patterson, E.M., 1959, A differentiated boss of alkali dolerite from Cnoc Rhaonastil, Islay: Mineralog. Mag., v. 32, p. 140-152.

________, and Poldervaart, A., 1949, Karroo dolerites of the Union of South Africa: Geol. Soc. America Bull., v. 60, p. 591-706.

Wilkinson, J.F.G., 1956, Clinopyroxenes of alkali olivine-basalt magma: Am. Mineralog., v. 41, p. 724-743.

________, 1957, The clinopyroxenes of a differentiated teshenite sill near Gunnedah, New South Wales: Geol. Mag., v. 94, p. 127-134.

________, 1957, The olivines of a differentiated sill near Gunnedah, New South Wales: Geol. Mag., v. 93, p. 441-455.

Yoder, H.S., and Sahama, Th. G., 1957, Olivine x-ray determinative curve: Am. Mineralog., v. 42, p. 475-491.

Yoder, H.S., and Tilley, C.E., 1962, Origin of basalt magmas: Jour. Petrology, v. 3, p. 342-532.