VITA

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PETROGRAPHY AND PETROLOGY OF SOME
INTRUSIVE BODIES IN THE
SOUTHERN WILLAMETTE VALLEY,
OREGON

by

JOHN HOLMES SHAW

A THESIS

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APPROVED:

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ABSTRACT

Many post-middle Oligocene bodies of intrusive rocks are located in the southern Willamette Valley near Eugene, Oregon. Six of these which form topographic highs, Creswell Butte, Spencer Butte, East Butte, Skinner Butte, Gillespie Butte, and North Butte, are examined in detail.

From outcrop patterns, aerial photos, available literature, and field observations, the author believes the buttes to be sills or sill-like structures, concordant or slightly discordant with the surrounding Eugene Formation. Specifically, Creswell Butte, Spencer Butte, and East Butte are eastward dipping sills; Skinner Butte is a sill-like structure dipping northwest; Gillespie Butte is a phacolith occupying a local synclinal fold plunging to the northwest; North Butte is a small laccolith with a feeder dike below the outcrop.

All six buttes have similar lithological characteristics. They are medium- to fine-grained basalts with an ophitic and in places glomeroporphyritic texture. Plagioclase (labradorite) is the predominant mineral and coexists with lesser amounts of the pyroxenes, hypersthene and ferroaugite. Some samples have trachytic texture. Hypersthene and ferroaugite are present at Creswell,

Spencer, Gillespie, and North Buttes, but only the monoclinic pyroxene is present at East and Skinner Buttes. The ferromagnesium grains are moderately altered to chlorophaeite. This chloritic material appears to have altered from hypersthene mainly, but in some samples it has replaced ferroaugite. Other minerals, in minor quantities, are magnetite, ilmenite, apatite, and zircon.

There is no evidence supporting differentiation within the buttes. The constant Fe^2/Mg^2 ratio suggests the same magma source for all six buttes and thus rules out the possibility of extensive differentiation. There is, however, variation in the pyroxene content, which suggest a temperature variation during intrusion. The two-pyroxene basalts in the thesis area represent higher temperature conditions where the hypersthene was 'frozen' in the rocks and not allowed to undergo a normal inversion to pigeonite. The basalts which contain only ferroaugite indicate a temperature of formation lower than that normal for a two-pyroxene basalt.

INTRODUCTION

Nature and Occurrence of the Intrusive Group

Situated in the southern part of the Willamette River Valley, Oregon, are several prominent outcrops of near surface intrusive igneous rocks. These bodies commonly form topographic highs in the valley and are never larger than 2 square miles in area. Petrographic examinations show the rocks to be medium- to fine-grained basalts. The bodies in this area represent only a small part of the many local intrusions which took place during the post-middle Oligocene throughout the Cascades and Coast Range of Oregon (King, 1959).

General Stratigraphy

Several of these small intrusions are considered sills or "sill-like" structures (Vokes, Snavely, and Myers, 1951) concordant with the Tyee (early Eocene), Spencer (late Eocene), Fisher, and Eugene (early to middle Oligocene) Formations. These four sedimentary units are generally marine sands composed of coarse- to fine-grained highly arkosic and micaceous sandstones, interspersed with layers of mudstone, siltstone, and shale, and lenses of volcanic ash (Vokes, Snavely, and Myers, 1951). The sedimentary formations reflect the gentle eastward dip of the east limb of the Coast Range of which they are a part.

Lying on the tilted and eroded sedimentary formations and the intrusive bodies is an extensive sheet flow of olivine basalt, commonly porphyritic with phenocrysts of olivine and plagioclase feldspar. Baldwin (1959) tentatively correlates these basalt flows with the Columbia River Basalt (middle Miocene) of northwestern Oregon. Peck (1960) states, however, that the local flows may be early Miocene. Field relationships indicate that whatever the age of the basalt flows, they are younger than the intrusions.

<u>Structure and Trends of the Intrusive Group</u>

The intrusive group as mapped by Vokes, Snavely, and Myers (1951) is shown as strictly concordant with the eastward dipping Eugene Formation in the valley and somewhat discordant with the eastward dipping Tyee, Spencer, and Fisher Formations. Snavely (personal communication, 1964) explains the use of the term "sill" as applying to "those intrusive bodies parallel or nearly parallel with the surrounding sedimentary units." The term "sill" will be used in this thesis with special reference to this local application of Snavely.

The north lineation of the intrusive outcrops near Eugene further suggests a concordancy with the sediments of the east limb of the Coast Range geanticline. The truncation of this lineation may be explained by the possible presence of numerous minor faults trending northwest to northeast, as reported by Witt (personal communication, 1964) and Vokes, Snavely, and Myers (1951). Buddington and Callaghan (1936, p. 437) note a similar north alignment of intrusive bodies in the Cascade Range, which they attribute to an axis of a possible continuous batholith at depth. The author does not feel that this reasoning is applicable to the intrusions in the southern Willamette Valley.

Area of Investigation

The author was concerned in this thesis with the following six buttes of the post-middle Oligocene intrusive group concordant within the Eugene Formation: Creswell Butte at Creswell, and Spencer, East,[1] Skinner, Gillespie, and North[1] Buttes at Eugene. The location of these six buttes is in the area encompassed by 44° 06' and 43° 54' North latitude and 123° 06' and 123° 00' West

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[1] Because no name could be found in the literature, East and North Buttes were named by the author.

longitude. Vokes, Snavely, and Myers (1951) map and discuss the regional relationships of these six buttes. Figure 1 shows their location.

Objectives

The main objectives of this research were to study in detail the petrography and mineralogy of all six buttes and with this information determine the relationships of one butte to another and within each butte. These objectives were carried out utilizing modal analyses, cation percentages, and grain sizes of selected samples from the buttes.

Previous Work

Vokes, Snavely, and Myers (1951) made the first detailed geologic map of the southern Willamette Valley area, and Baldwin (1959, p. 45-50) discusses the regional geology.

Much work has been done concerning the petrography and stratigraphy of rocks in areas near the one investigated in this thesis. Bray (1958) discusses the petrology and petrography of the Oligocene intrusives in western Lane County, Oregon. Handley (1931), Buddington and Callaghan (1936), Bogue and Hodge (1940), and Peck (1960) have done extensive work on the rocks of the Cascade Range. Anderson (1963) mapped the northwest one quarter of the Brownsville quadrangle, but fails to differentiate the intrusive rocks from the younger lava flows.

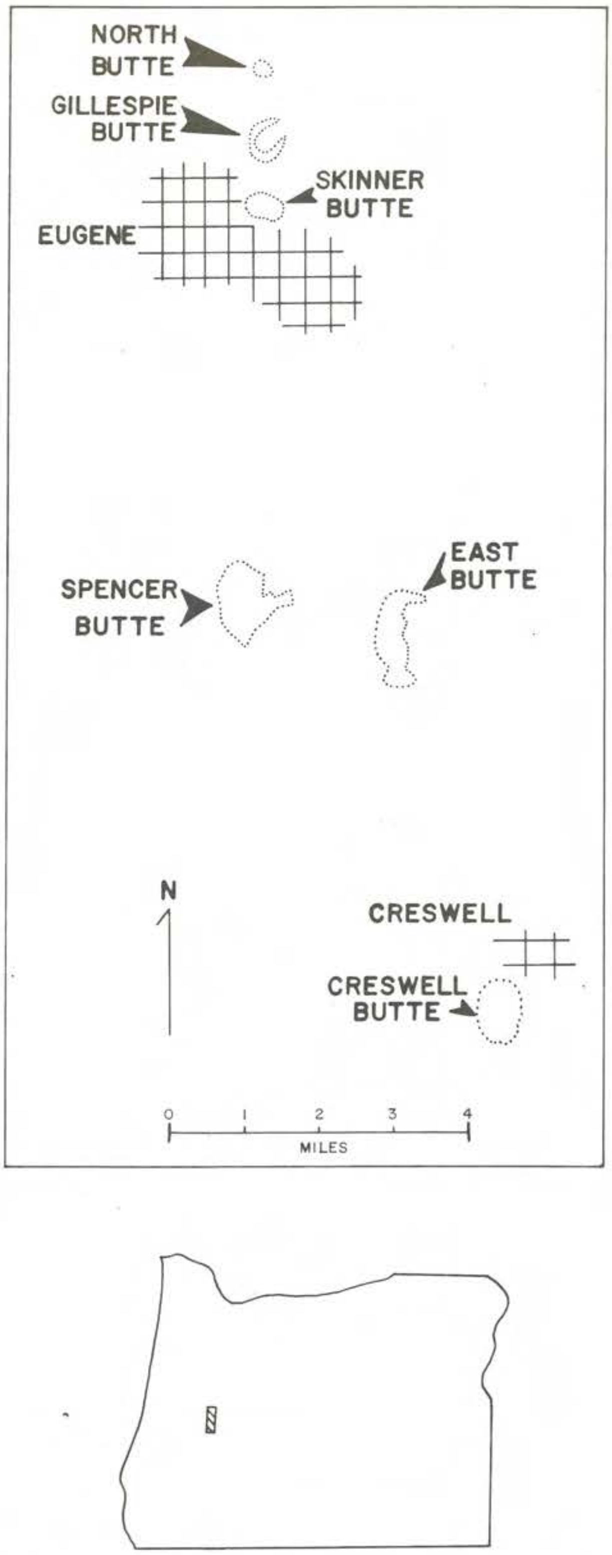


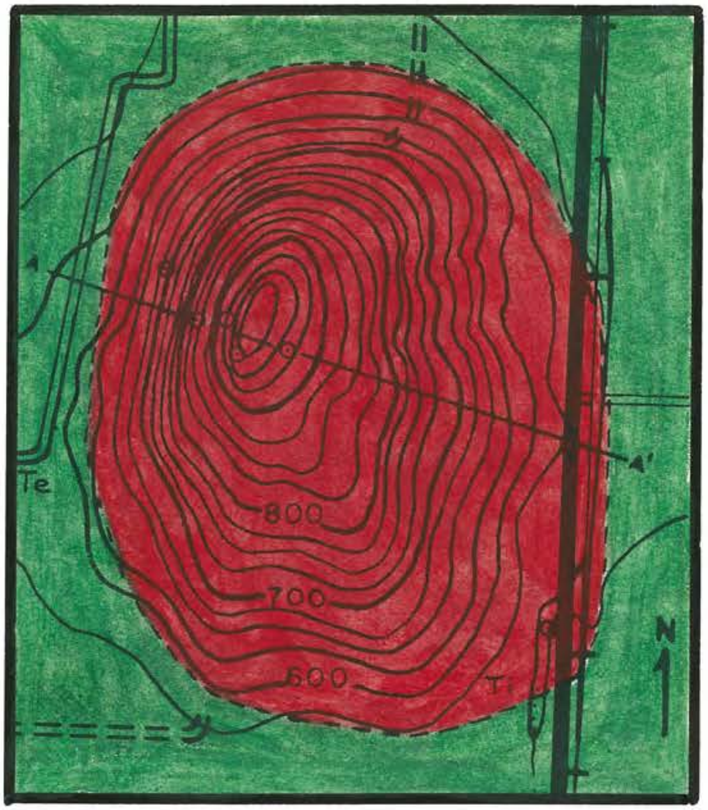
Figure 1. Index map of the thesis area

FIELD INVESTIGATIONS

Outcrop Patterns and Assumed Structures

The contacts between the igneous rocks and the Eugene Formation are obscured by the overburden on all of the buttes and by the dense vegetation on all but East and Gillespie Buttes. Thus, the author studied the aerial photos, maps, and literature pertinent to the area in an effort to determine the structure of the buttes. Creswell, Spencer, and East Buttes show an irregular outcrop pattern which lend themselves to an assumed eastward dipping sill structure. Gillespie Butte, North Butte, and to a certain extent Skinner Butte exhibit unique outcrop patterns and thus require special considerations.

According to Vokes, Snavely, and Myers (1951), Creswell Butte has a sub-elongate outcrop pattern (Figure 2). The gentle southeast and the steep northwest slopes appear to represent the dip and reverse slopes of a sill striking N 17° E and dipping 16° SE. The thickness estimated from geometric analysis of this structure is 950 feet. The shape of the butte appears to be structurally controlled and may be due in part to a series of truncating east trending faults, as reported by Witt (personal communication 1964).



GEOLOGIC MAP OF

CREWELL BUTTE

CRESWELL, OREGON

SCALE 1:15624

CONTOUR INTERVAL 25 FEET

INTRUSIVE ROCK Ti

EUGENE FORMATION Te

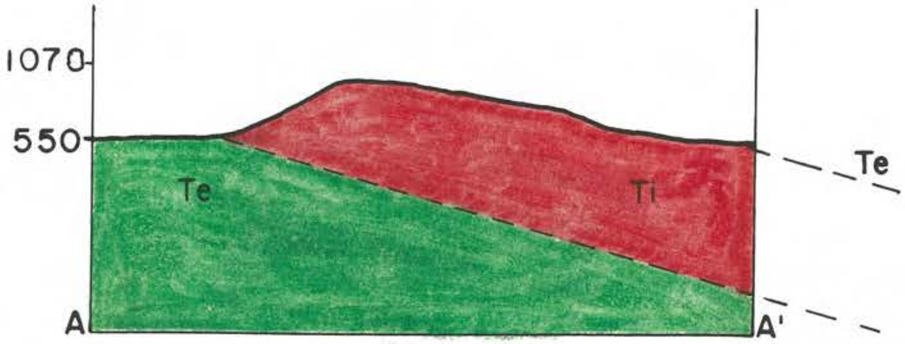
After Vokes, Snavely, and Myers (1951)

Figure 2

Figure 3 shows a cross section of Creswell Butte along a line A - A' of the map view in Figure 2.

A prominent lineation striking northward at Spencer Butte is evident on aerial photos (1 inch equals 660 feet). The lineation is imparted to the outcrop by the crude columnar jointing (Pl. 1) that suggests a sill structure for the butte. Assuming that a theoretical plane drawn perpendicular to the dip of the jointing represents a cooling surface parallel to dip of the sill, there is a general correlation to the structure assumed by Vokes, Snavely, and Myers (1951) in their cross section A - A'. Billings (1954), however, states that the upper layer of a cooling igneous sheet will sag into the middle of the structure and that the geometrical analysis outlined above should be used with extreme caution. This author feels that the lack of other structural evidence at Spencer Butte necessitates the assumption of a strike parallel to the joint planes and a dip perpendicular to the dip of the joint planes. The author assumes a dip of 17° E, as do Vokes, Snavely, and Myers (1951). The estimated thickness of the sill is 1030 feet.

Figure 4 shows the outcrop pattern of Spencer Butte. It is essentially the same as that of Vokes, Snavely, and Myers (1951), with the exception of the northeast quarter,



GEOLOGIC CROSS SECTION OF

CRESWELL BUTTE

ALONG LINE A-A'

SCALE 1:15624

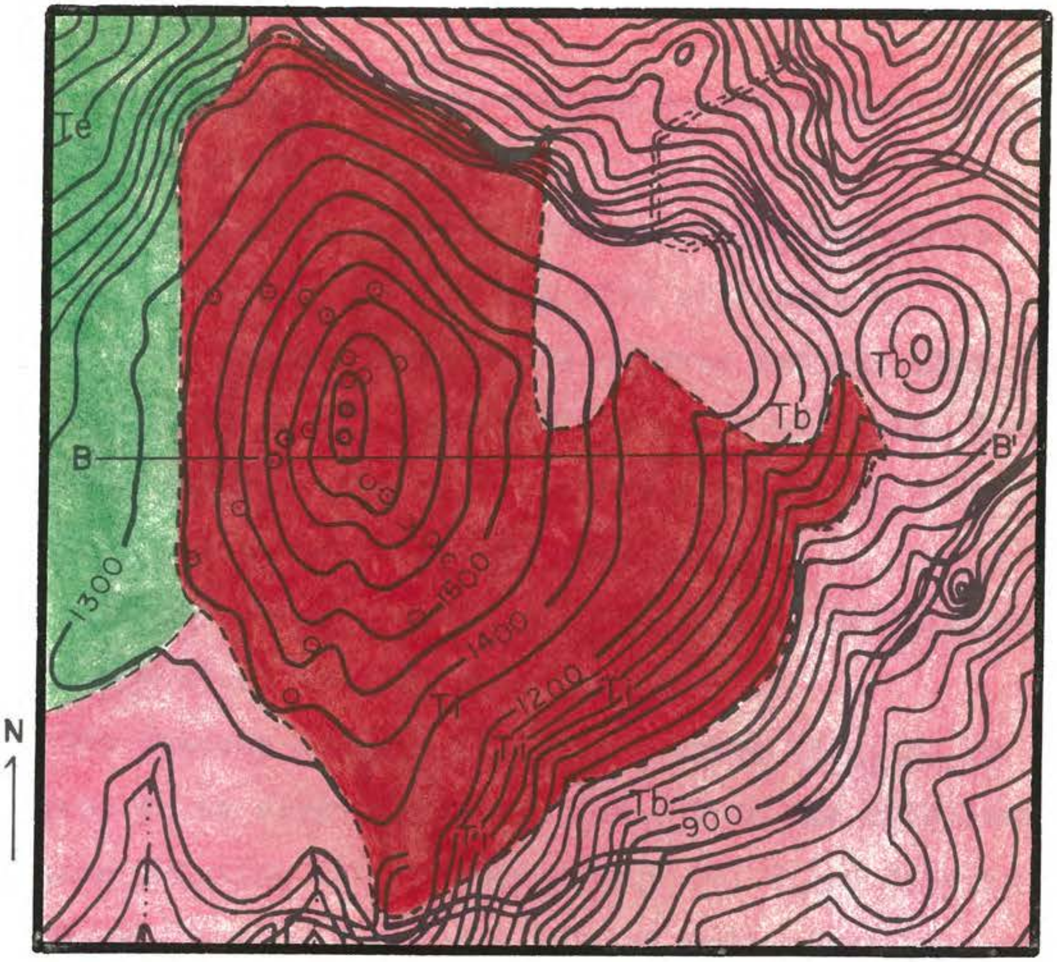
INTRUSIVE ROCKS Ti
EUGENE FORMATION Te

Figure 3

PLATE 1

View looking south on summit of Spencer Butte showing crude columnar jointing.

CRUDE COLUMNAR JOINTING AT SPENCER BUTTE



GEOLOGIC MAP OF
SPENCER BUTTE
EUGENE, OREGON
SCALE 1:15624
CONTOUR INTERVAL 25 & 100 FEET
CHANGING ON THE 1200 FOOT CONTOUR

FLOW BASALT	Tb
INTRUSIVE ROCKS	Ti
EUGENE FORMATION	Te

After Vokes, Snavely,
and Myers (1951)
Figure 4

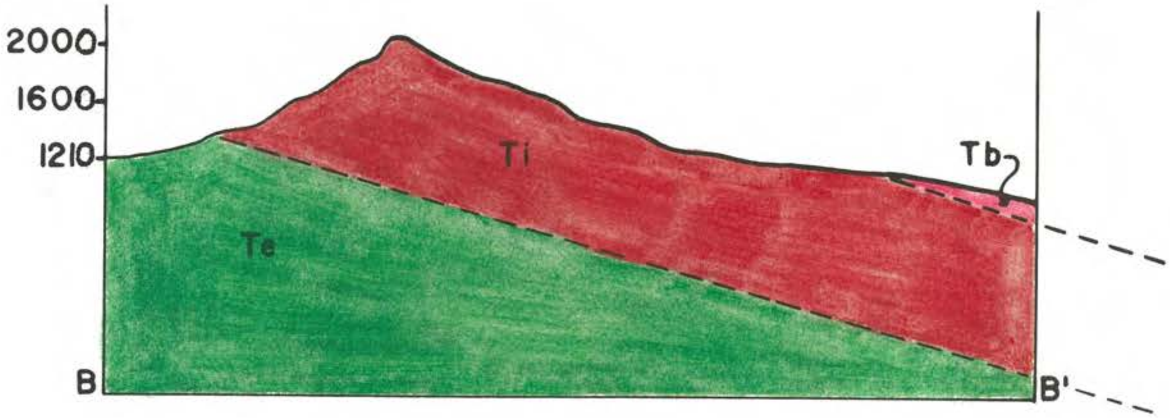
which was remapped by Kays and the author during field investigations in July, 1963.

Figure 5 shows a cross section of Spencer Butte along a line B - B' of the map view of Figure 4.

East Butte has an elongate outcrop pattern (Fig. 6) which typifies a sill structure as drawn by Vokes, Snavely, and Myers (1951). The sill strikes N 16° E and dips 14° SE and is estimated to be 580 feet thick.

Figure 7 shows a cross section of East Butte along a line C - C' of the map view in Figure 6.

The outcrop pattern of Skinner Butte (Fig. 8) is subelongate in an east-west direction. From the excellent columnar jointing (Pl. 2) striking N 76° W and dipping 20° SW, the author deduced a sill structure striking in the same direction and dipping 20° NE. Bearing in mind, however, Billings's (1954) statement of the validity of columnar jointing as a criterion for dip and strike of a sill, the author realizes that the structure at Skinner Butte may be closer to a pod or laccolith-like intrusion, as suggested by Lund (1964, personal communication). He was compelled, however, to choose the less substantiated term "sill" to facilitate a later study of differentiation. Thus, Figure 9 shows an idealized cross section of the Skinner Butte "sill" of the map view in Figure 8. The estimated thickness is 560 feet.



GEOLOGIC CROSS SECTION OF

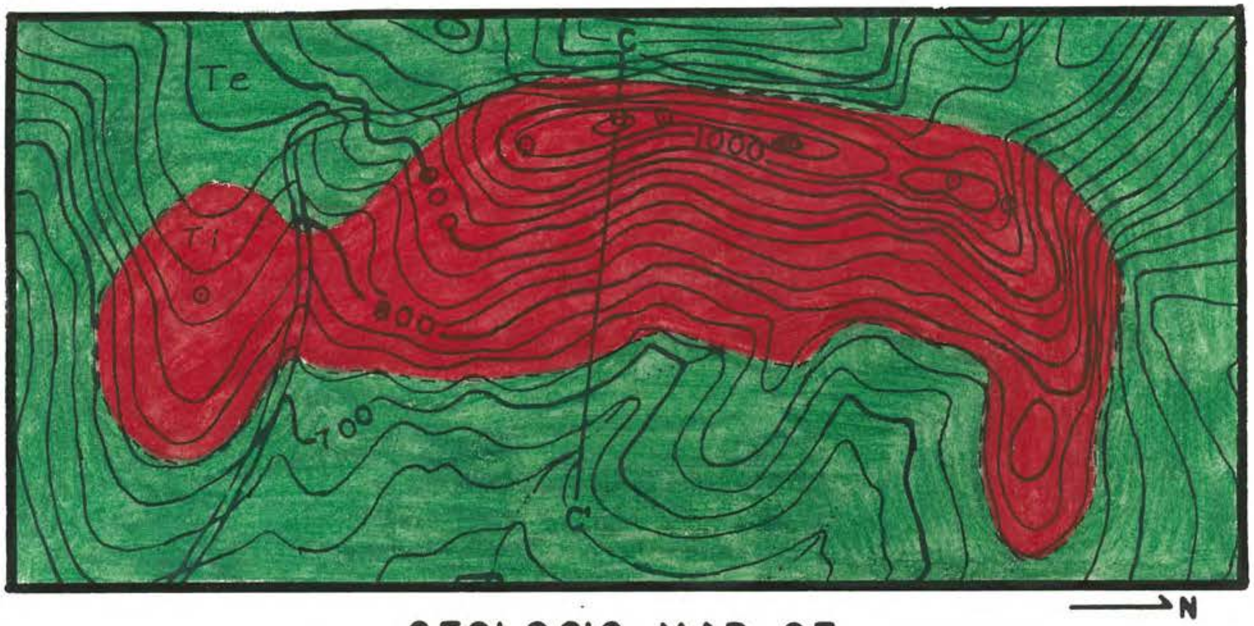
SPENCER BUTTE

ALONG LINE B–B'

SCALE 1:15624

FLOW BASALT	Tb
INTRUSIVE ROCKS	Ti
EUGENE FORMATION	Te

Figure 5



GEOLOGIC MAP OF

EAST BUTTE

EUGENE, OREGON

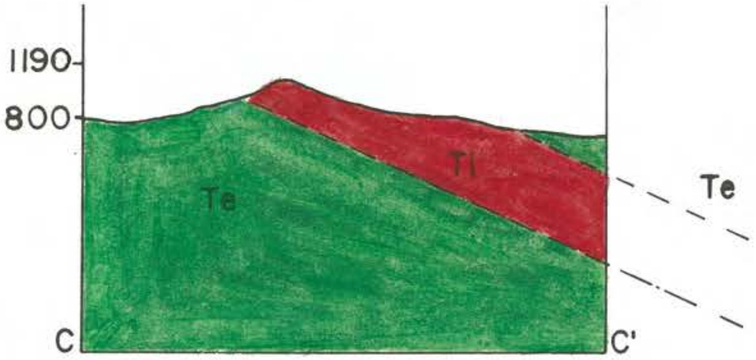
SCALE 1:15624

CONTOUR INTERVAL 25 FEET

FLOW BASALT Tb
INTRUSIVE ROCKS Ti
EUGENE FORMATION Te

Figure 6

After Vokes, Snavely,
and Myers (1951)



GEOLOGIC CROSS SECTION OF
EAST BUTTE
ALONG LINE C–C'
SCALE 1:15624

FLOW BASALT Tb
INTRUSIVE ROCKS Ti
EUGENE FORMATION Te

Figure 7

GEOLOGIC MAP OF

SKINNER BUTTE

EUGENE, OREGON

SCALE 1:7812

CONTOUR INTERVAL 5 & 25 FEET
CHANGING ON THE 450 FOOT CONTOUR

INTRUSIVE ROCKS Ti
EUGENE FORMATION Te

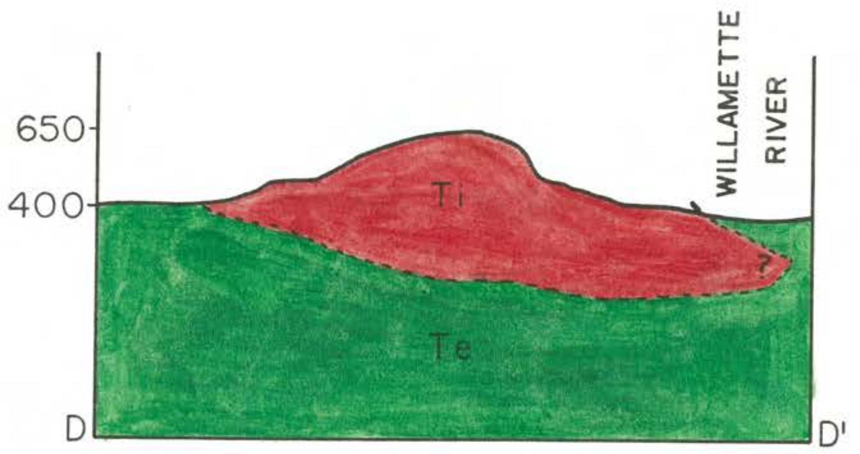
After Vokes, Snavely,
and Myers (1951)

Figure 8

PLATE 2

View looking east into the quarry at Skinner Butte
showing well-developed columnar jointing.

WELL-DEVELOPED COLUMNAR JOINTING AT SKINNER BUTTE



GEOLOGIC CROSS SECTION OF

SKINNER BUTTE

ALONG LINE D-D'

SCALE 1:7812

INTRUSIVE ROCKS	Ti
EUGENE FORMATION	Te

Figure 9

The intrusion at Gillespie Butte is a U-shaped body on a topographic high (Fig. 10). This configuration suggests a small phacolith with an estimated maximum thickness of 145 feet occupying a local synclinal fold in the Eugene Formation (Figs. 11, 12, and 13). The plunge of the fold is northwest and is approximately equal in magnitude to the dip component of Skinner Butte half a mile to the south.

The outcrop pattern of North Butte (Fig. 14) is very nearly round and suggests a small laccolith structure (Baldwin, 1959) as shown in cross section (Fig. 15), with an assumed maximum thickness of more than 125 feet. The feeder dike for the laccolith could not be located in the field and is assumed to lie beneath the structure. This hypothesis might be substantiated by gravity surveys across the butte.

Method of Sample Collection

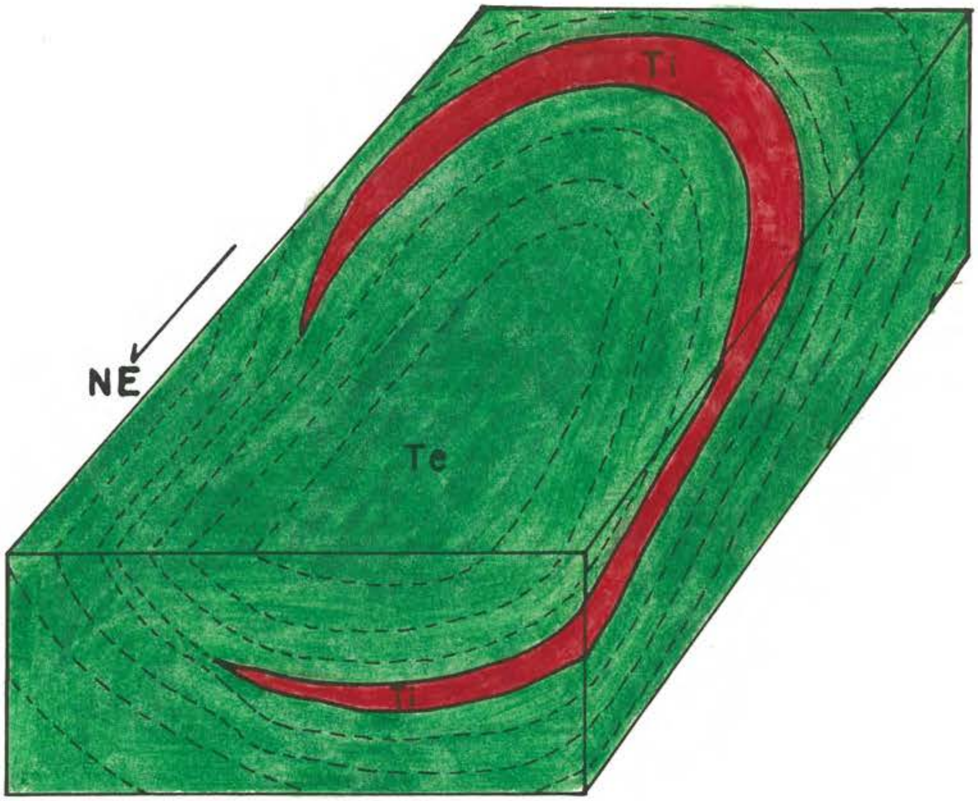
In order to facilitate determination of the extent of differentiation within each body, a series of traverses were chosen for sampling purposes. In most cases these traverses are nearly perpendicular and parallel to the strike of the assumed structure. On some of the buttes the number and amount of exposures are limited; thus, it was necessary in the field to alter slightly the plan of

GEOLOGIC MAP OF
GILLESPIE BUTTE
EUGENE, OREGON

SCALE 1:7812
CONTOUR INTERVAL 5 & 25 FEET
CHANGING ON THE 450 FOOT CONTOUR

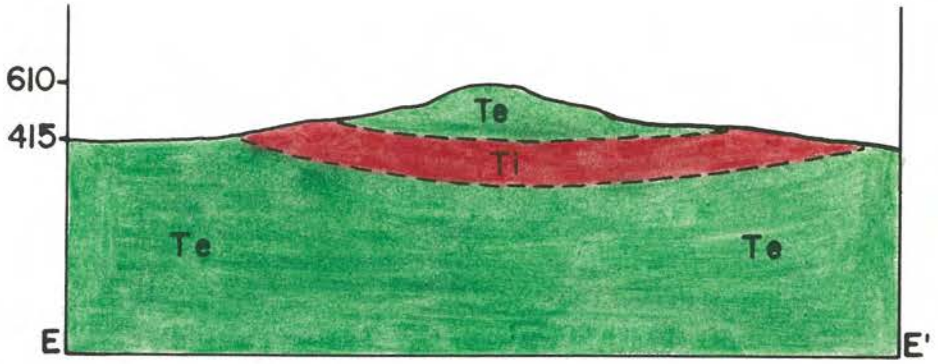
INTRUSIVE ROCKS Ti
EUGENE FORMATION Te

After Vokes, Snavely,
and Myers (1951)
Figure 10



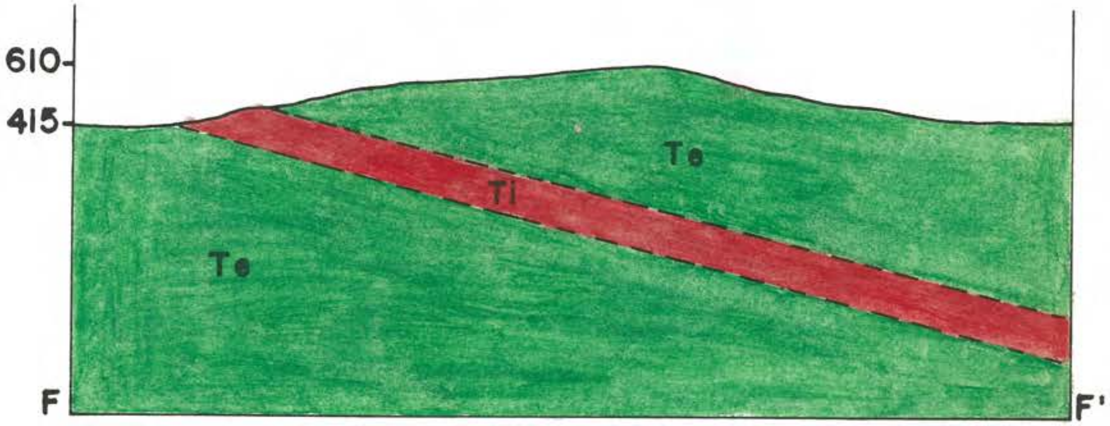
SCHEMATIC BLOCK DIAGRAM OF
GILLESPIE BUTTE
SCALE (APPROX.) 1:7500

INTRUSIVE ROCKS 🟥 Ti
EUGENE FORMATION 🟩 Te



GEOLOGIC CROSS SECTION OF
GILLESPIE BUTTE
ALONG LINE E–E'
SCALE 1:7812
INTRUSIVE ROCKS Ti
EUGENE FORMATION Te

Figure 12



GEOLOGIC CROSS SECTION OF

GILLESPIE BUTTE

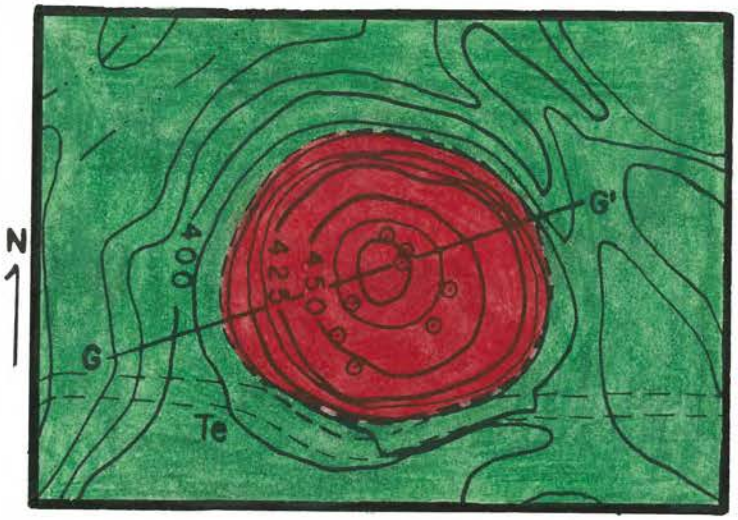
ALONG LINE F–F'

SCALE 1:7812

INTRUSIVE ROCKS Ti

EUGENE FORMATION Te

Figure 13



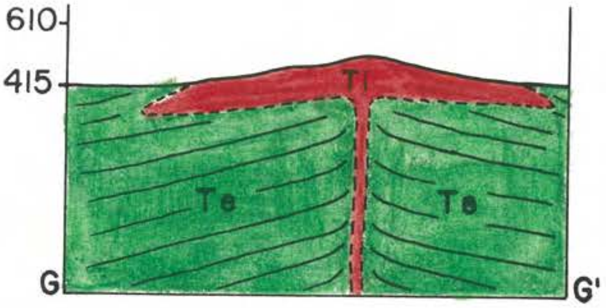
GEOLOGIC MAP OF
NORTH BUTTE
EUGENE, OREGON
SCALE 1:7812

CONTOUR INTERVAL 5 & 25 FEET
CHANGING ON THE 425 FOOT CONTOUR

INTRUSIVE ROCKS 🟥 Ti
EUGENE FORMTION 🟩 Te

After Vokes, Snavely,
and Myers (1951)

Figure 14



GEOLOGIC CROSS SECTION OF
NORTH BUTTE
ALONG LINE G–G'
SCALE 1:7812

INTRUSIVE ROCKS Ti
EUGENE FORMATION Te

Figure 15

collection to include the number of samples needed to make the petrographic study.[1] A total of 53 samples were collected from the six buttes. Overlays for sampling stations at each butte show both the sample number and its location (overlays for Figures 2, 4, 6, 8, 10, and 14 in folder).

Megascopic Description

The intrusive rocks from the thesis area are, in general, medium- to fine-grained massive basalts, ranging in color from N7[2] to N3, all light gray. The weathered portions are all dark yellowish brown, 10 YR 4. The rocks contain small but significant amounts of magnetite, which causes a local declination of up to 50° at Spencer Butte. Some of the samples appear porphyritic; no flow structure is apparent in hand specimen.

Vokes, Snavely, and Myers (1951) report that the larger feeder dikes in the southern Willamette Valley are generally the same composition as the buttes that were investigated. The more numerous smaller dikes are of normal basalt composition.

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[1] The field work was done between July and September, 1963.

[2] Color designations are taken from the Rock-Color Chart, distributed by the Geological Society of America (1951).

PETROGRAPHY

Mineralogical Determinations

Plagioclase Feldspar-- A thin section was made of each of the 53 samples collected. Using the petrographic microscope and the universal stage, the maximum extinction angles for the albite twinning of the plagioclase feldspars were determined for each slide. Because there were always ample feldspar crystals in the section with albite twins cut perpendicular to the {010}, the statistical method by Michel-Lèvy (Kerr, 1959) was used to determine the anorthite content of the plagioclase. The average composition was distinctly in the labradorite range, consistent with the observations of Vokes, Snavely, and Myers (1951), although there were some grains in the neighboring andesine and bytownite range. The range of accuracy of the derived anorthite content is within 3 percent assuming an accuracy of the extinction angle within 2 degrees as stated by Winchell and Winchell (1959, p. 284).

Clinopyroxene-- An average chemical composition for the monoclinic pyroxene was determined by first measuring 2E by the petrographic microscopic and converting it to 2V using Mallard's constant method as outlined by Kerr (1959) and Stoiber (1959). The data and results of these determinations are reported in Table 1. The most consistent 2V obtained (2V=32°) was plotted against an estimated value for the index of refraction of the β vibration direction ($n_\beta = 1.710$) on the diagrams of Hess (1949, Pl. I. p. 634) and Poldervaart and Hess (1951, Fig. 1, p. 474) redrawn in Figures 16, 17, and 18. The resulting average chemical composition for the monoclinic pyroxene is $Wo_{25}En_{34}Fs_{41}$ indicating percent wollastonite, clinoenstatite, and ferrosilite respectively. This composition is termed ferroaugite by Poldervaart and Hess (1951) and is plotted in Figure 18 along with two other monoclinic pyroxenes from associated areas. According to Bray (1958, Table 2, p. 16) the range of accuracy using the above method is between 0.3 percent and 0.2 percent in the ratio of Wo/En+Fs and about 5 percent in the ratio of En/Fs.

Hess (1941a, p. 519-525) reports that ferroaugite is not a common pyroxene. He discusses the apparent gap that exists in the frequency of the optic angles between 30° and 40°. He does, however, acknowledge that ferroaugites are found in the final pyroxene differentiate zone of the Palisade sill, New Jersey. Bray (1958) also reports ferroaugite from the intrusives of western Lane County.

Orthopyroxene--Ferroaugite is easily distinguished

SAMPLE NUMBER	8-5-3	8-27-2	8-20-7	8-20-8	8-20-4	8-27-5	8-20-2	8-27-7	8-5-1
DISTANCE TO LOWER CONTACT (FEET)	957	873	858	838	713	479	364	104	68
ANORTHITE CONTENT	54.0	58.0	61.0	58.0	61.0	58.0	62.0	64.0	53.0
MODAL ANALYSIS (%) :									
Plagioclase	67.5	59.6	65.6	65.3	63.0	46.7	60.8	67.1	52.5
Ferroaugite	17.2	28.0	18.8	20.8	19.4	25.6	20.7	21.0	19.1
Hypersthene	2.2	2.0	2.8	1.6	4.6	6.6	2.6	1.2	13.0
Chlorophaeite	4.2	2.0	3.4	4.0	4.0	16.6	7.6	4.8	6.8
Magnetite	7.6	7.6	8.8	7.4	8.6	5.4	7.6	5.8	8.4
Apatite	0.8	0.8	0.6	0.4	0.4	–	0.4	0.2	Trace
Zircon	0.6	–	–	0.6	–	–	0.2	–	Trace
Adularia	–	–	–	–	–	–	–	–	–
CATION PERCENTS :									
Si^{4}	37.6	44.3	44.6	44.5	43.3	46.4	43.4	44.6	44.5
Al^{3}	16.5	17.6	21.0	19.3	18.8	13.2	18.1	20.8	15.2
Fe^{3}	5.4	6.3	8.0	6.2	7.2	4.4	6.3	4.8	6.8
Fe^{2}	6.9	9.6	10.0	8.8	9.7	13.2	9.8	8.2	12.3
Ca^{2}	8.2	10.5	11.3	10.1	10.0	8.1	9.8	11.0	7.6
K^{1}	–	–	–	–	–	–	–	–	–
Na^{1}	4.9	4.7	4.3	5.2	4.5	3.6	4.2	4.4	4.5
Mg^{2}	18.1	6.7	0.6	6.0	6.3	11.1	6.9	6.0	9.2
P^{5}	2.1	0.3	0.2	0.2	0.2	–	1.6	0.1	–
Zr^{4}	0.8	–	–	0.1	–	–	0.1	–	–
$\mathrm{Fe}^{2}/\mathrm{Mg}^{2}$ RATIO	0.4	1.4	16.7	1.5	1.5	1.2	1.4	1.4	1.3

Table 4. Modal analyses and cation percents of Spencer Butte samples.

Sample	2D	D	n	K	Sin V	V	2V
8-15-2 (Creswell Butte)	1.0	0.5	1.710	1.048	.278	16°	32°
8-27-2 (Spencer Butte)	1.0	0.5	1.710	1.048	.278	16°	32°
8-27-4 (Spencer Butte)	1.0	0.5	1.710	1.048	.278	16°	32°
8-21-4 (East Butte)	1.0	0.5	1.710	1.048	.278	16°	32°
8-12-2 (Skinner Butte)	1.1	.55	1.710	1.048	.306	18°	36°
8-16-2 (Gillespie Butte)	0.9	.45	1.710	1.048	.251	15°	30°
8-16-9 (North Butte)	1.2	0.6	1.710	1.048	.334	20°	40°

Table 1. 2V determination using Mallard's constant.

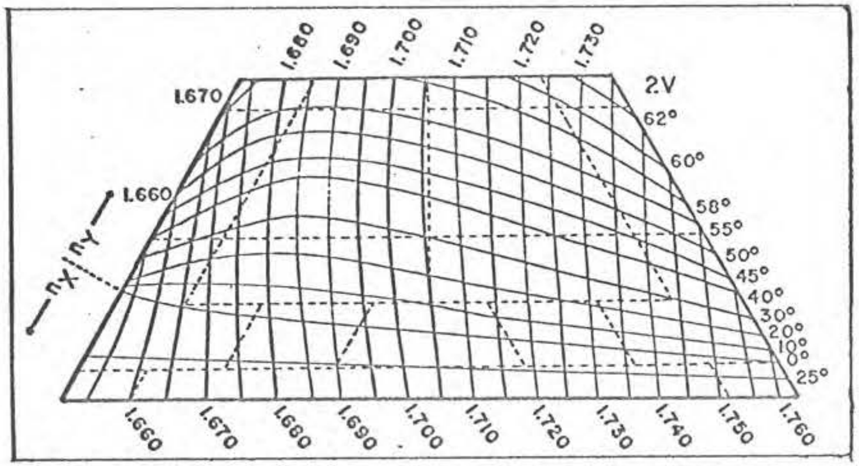

Figure 16. Pyroxene 2V and index of refraction (after Hess, 1949, Pl. I, p. 634).

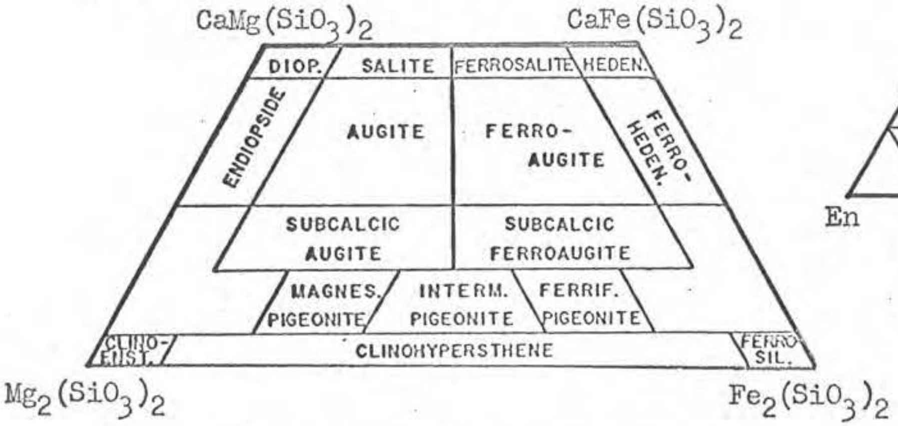

Figure 17. Pyroxene classification (after Poldervaart and Hess, 1951, Fig. 1, p. 474).

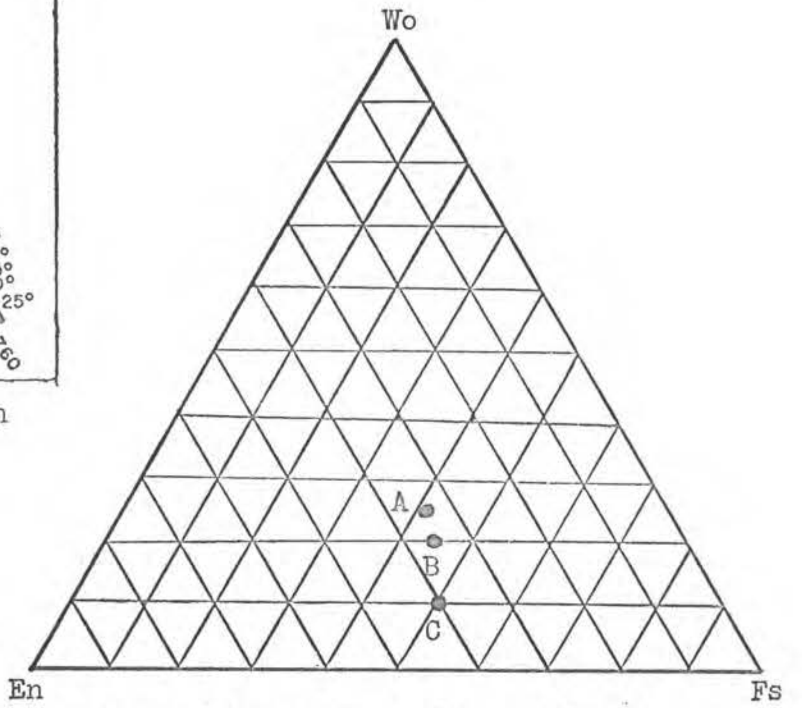

Figure 18. Pyroxene composition of southern Willamette Valley rocks and Cascade Range rocks.

A. $Wo_{25}En_{34}Fs_{41}$ of Willamette Valley intrusive group.

B. $Wo_{20}En_{35}Fs_{45}$ of Cascade Range (Peck, 1960, No. 8, Table 12).

C. $Wo_{10}En_{40}Fs_{50}$ of Cascade Range (Peck, 1960, No. 4, Table 12).

from the orthorhombic pyroxene, hypersthene, by the latter's parallel extinction angle (z=c) and pink to green pleochroism. X-ray diffraction patterns were made in an effort to determine the chemical composition of the hypersthene, but no suitable curves are available relating the data to composition. Thus, an average composition of $(Fe_{0.4}, Mg_{0.6}) SiO_3$ was determined using Kerr's (1959) interference color chart in conjunction with Winchell's (1923) diagram for physical and optical properties versus chemical composition.

Magnetite and ilmenite-- Magnetite is readily identified and separated from a crushed sample[1] by means of a hand magnet. The remaining opaque mineral was separated from the same sample by the Franz Isodynamic Separator and identified as ilmenite by means of X-ray diffraction patterns. Magnetite and ilmenite cannot be differentiated in thin section and therefore are referred to hereafter as iron oxide.

Apatite and Zircon-- Apatite and zircon are identified in thin section by their optical properties according to Kerr (1959). The former is characterized by low relief and birefringence, the latter by high relief and birefringence, and parallel extinction.

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[1] Sample 8-16-8 from North Butte.

Chlorophaeite-- A green to brown chloritic alteration product is observed in the rocks. Bray (1958) describes a mineral derived from glass in the intrusive group of western Lane County and calls it palagonite based on its isotropic nature. This author notes some anisotropic margins on the grains and tentatively identifies it as chlorophaeite as described by Buddington and Callaghan (1936) and Heinrich (1956, p. 82).

Zeolites-- The zeolites analcite, chabacite, and natrolite are identified by their indices of refraction in immersion oils.

Petrographic Calculations

Modal Analysis-- Those samples which are most closely aligned to a traverse parallel or perpendicular to the strike of a sill are selected for modal analysis. Five hundred point counts per slide are made with the petrographic microscope by means of the point counting stage. A volume percent of the actual minerals (with the exception of ilmenite) is obtained by dividing the total counts (500) into the number of counts per mineral. Because the iron oxides cannot be distinguished in thin section both are grouped under the heading magnetite.

Cation Percentages-- The cation percentages are obtained using Barth's (1952) method. Conversion to cation percentages is made by using idealized mineral formulas (Table 2) supplemented by the mineralogical determinations discussed in the previous section. It is understood that the clinopyroxenes contain moderate amounts of titanium (Hess, 1941a, p. 516). These smaller fractions are not, however, considered in the cation percentage calculations. The alteration product chlorophaeite is calculated as hypersthene because it exhibits relic 010 and 100 cleavages from the original orthorhombic pyroxene in some samples. Chlorophaeite after ferromagnesium hypersthene is common in the Columbia River Basalt, as reported by Buddington and Callaghan (1936).

Average Grain Size-- For each modal analysis a corresponding grain size analysis is made; twenty grains of each mineral (chlorophaeite excepted) are measured by means of a calibrated micrometer eyepiece. Wherever possible, the direction of measurement coincides with the direction of elongation. Measurements in millimeters for each mineral are then divided by the number of measurements for that slide yielding an average grainsize. Because of its very irregular shape, the average grainsize of chlorophaeite is virtually impossible to determine.

Petrography of Creswell Butte

Megascopic Description-- The rock of Creswell Butte is

	OXIDE PERCENT[1]									
	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	K_2O	Na_2O	MgO	P_2O_5	ZrO_2
Albite $NaAlSi_3O_8$	68.7	19.5					11.8			
Anorthite $CaAl_2Si_2O_8$	43.2	36.7			20.1					
Ferroaugite $(Ca_{.25},Mg_{.34},Fe_{.41})SiO_3$	52.0			22.4	12.0			13.6		
Hypersthene $(Fe_{.4},Mg_{.6})SiO_3$	51.7			31.1				17.2		
Magnetite Fe_3O_4			69.0	31.0						
Apatite $Ca_5(PO_4)_3$					56.8				43.2	
Zircon $ZrSiO_4$	67.2									32.8
Adularia $KAlSi_3O_8$	64.7	18.4					16.9			

Table 2. Idealized mineral formulas and oxide percents.

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[1] Modified from Wahlstrom, 1947, p. 238.

massive, light gray (N7), medium-grained basalt and is slightly zeolitized. Plagioclase and pyroxene may be identified with a hand lens. The samples collected from the top part of the sill have a slightly larger grain size than those collected at the base. The author believes that the grain size is generally too small to classify the rock as a gabbro.

Microscopic Description-- Plagioclase is the dominant mineral in the rock. It ranges in composition from An_{50} to An_{56}, averaging $An_{52.5}$, normal for the plagioclase composition in a diabase according to Turner and Verhoogen (1960, p. 211). The plagioclase is subhedral and has an average grainsize of 0.32 mm in the elongate direction. Most of the larger grains are zoned. Simple Carlsbad and albite twins are common.

Two pyroxene minerals are present. The most abundant of these, the clinopyroxene, is rarely in phenocrysts or ophitic. It is usually anhedral and many grains have pinacoidal twinning on the $\{100\}$ plane. The average grain size is 0.28 mm. The other pyroxene present, the orthopyroxene hypersthene, is subhedral where in phenocrysts in the groundmass and anhedral in the ophitic parts of the rock. The hypersthene is not twinned and has an average grainsize of 0.61 mm.

Iron oxide is present in very minor amounts, never exceeding 4 percent. Moorehouse (1959, p. 168-169) reports that the iron ores are very common accessory minerals of diabases. The magnetite is commonly found in the interstices of the plagioclase in the groundmass and in minute separations along the cleavage planes of the pyroxenes. The average grainsize for the opaque iron oxide is 0.13 mm.

Chlorophaeite altered from hypersthene is dispersed in the interstices of the unaltered plagioclase laths throughout the samples.

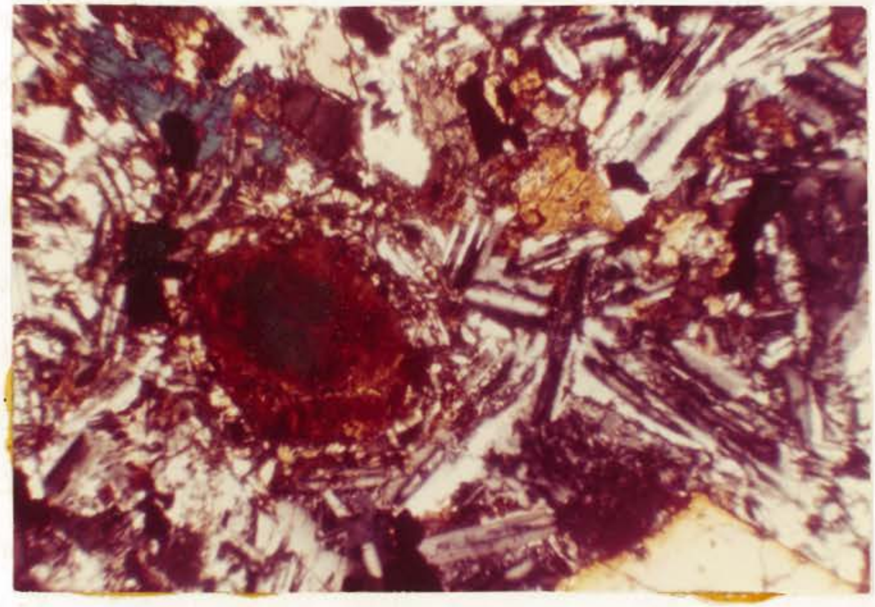
All samples contained a trace of fine-grained interstitial quartz, but not enough to effect their classification. A trace of zircon (0.03 mm) is present in one sample (9-5-3) included in a larger grain of ferroaugite. Minor amounts of unaltered vein feldspar, adularia, are present in one sample (8-15-3). There is no flow structure apparent in the rock.

On the basis of their mineral composition, the rock at Creswell Butte is classified according to the Johannsen's (1939) classification as basalt (2312 A).

Plate 3 shows a representative section of the mineral associations and characteristic textures of the rock from Creswell Butte.

Modal Analyses and Cation Percentages--Listed in Table 3 are the modal analyses and cation percentages for

PLATE 3



Elongate and zoned plagioclase, intergranular ferroaugite, and hypersthene phenocryst, magnetite. Nicols crossed (sample 8-15-1)

PHOTOMICROGRAPH OF CRESWELL BUTTE BASALT

SAMPLE NUMBER	9-5-3	8-15-1	8-15-3	8-15-5
DISTANCE TO LOWER CONTACT (FEET)	946	722	545	213
ANORTHITE CONTENT	51.0	50.0	52.0	56.0
MODAL ANALYSIS (%) :				
Plagioclase	69.8	77.0	68.0	64.6
Ferroaugite	26.8	14.2	20.4	22.8
Hypersthene	-	2.4	1.4	3.8
Chlorophaeite	1.0	3.0	4.0	5.8
Magnetite	2.2	3.4	4.0	3.0
Apatite	-	-	-	-
Zircon	0.2	-	-	-
Adularia	-	-	2.2	-
CATION PERCENTS :				
Si^{4}	48.3	49.4	47.8	47.6
Al^{3}	20.1	21.3	20.1	19.3
Fe^{3}	1.9	2.9	3.4	2.5
Fe^{2}	6.5	5.6	7.0	8.3
Ca^{2}	10.3	9.0	9.2	9.9
K^{1}	-	-	0.3	-
Na^{1}	6.6	7.2	6.5	5.5
Mg^{2}	6.1	4.6	5.7	7.3
P^{5}	-	-	-	-
Zr^{4}	0.4	-	-	-
Fe^{2}/Mg^{2} RATIO	1.1	1.2	1.2	1.1

Table 3. Modal analyses and cation percents of Creswell Butte samples.

four of the five samples collected at Creswell Butte.

Petrography of Spencer Butte

Megascopic Description-- The rock of Spencer Butte is uniform in physical appearance. It is massive, medium gray (N5), fine-grained basalt which rarely has porphyritic or ophitic texture in hand specimen. Some crude columnar jointing is evident at the summit (Pl. 1), but no other structure which can be interpreted as a cooling phenomenon is reflected in the hand specimen. The rock is highly weathered near the surface and varies in color from light brownish gray (5 YR 6/1) in the core to moderate brown (5 YR 4/4) in the iron oxide veneer.

Microscopic Description-- Microlites of plagioclase (0.26 mm) dominate the rock and range in composition from An_{51} to An_{65}, averaging An_{59} (labradorite). This composition range is slightly higher than that which Turner and Verhoogen (1960, p. 211) attribute to an ordinary basalt. The plagioclase is subhedral, twinned according to the albite and Carlsbad twin laws, and commonly zoned.

Anhedral ferroaugite (0.18 mm) is commonly present in the interstices of the plagioclase in an intergranular texture. Some samples[1] have an excellent glomeroporphyritic

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[1] Samples 8-27-5 and 8-20-7 from Spencer Butte.

texture which is not apparent in the hand specimens. The ferroaugite in these aggregates has well developed pinicoidal twinning on the {100} plane, but polysynthetic twinning on the {001} plane is uncommon. The paragenesis of the plagioclase and ferroaugite at Spencer Butte is clearly indicated by the common embayment and inclusion of the former in the latter in the ophitic parts of the rock.

Hypersthene (0.37 mm) is present at Spencer Butte as phenocrysts and in ophitic intergrowths with the plagioclase in the groundmass. In contrast to the ferroaugite, the hypersthene is not twinned and is in noticeably smaller amounts.

Chlorophaeite appears to have resulted from an alteration of both pyroxenes in these rocks (Pl. 4, Fig. 1). It is common in the interstices of the plagioclase laths, around the ophitic hypersthene, and in the glomeroporphyritic aggregates of ferroaugite.

Iron oxide in amounts averaging 7.4 percent and 0.1 mm in grain size is usually located in the interstices of the groundmass. Less commonly it is in the minute separations along the cleavage planes of the pyroxenes and as small crystalline aggregates. Ferroaugite inclusions in the iron oxide grains are common in some samples (Pl. 4, Fig. 2).

PLATE 4

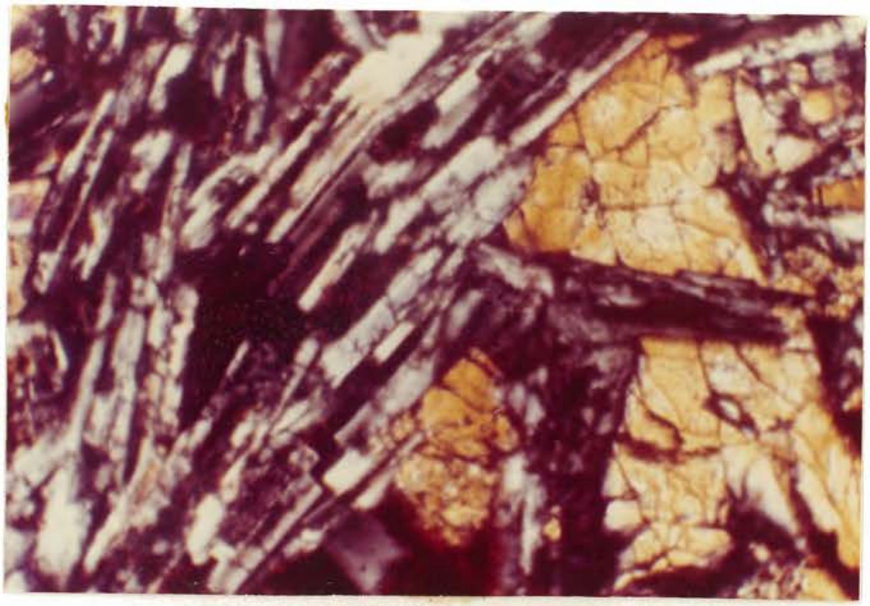

Figure 1. Ophitic and trachytic textures. Nicols crossed (sample 8-27-5)

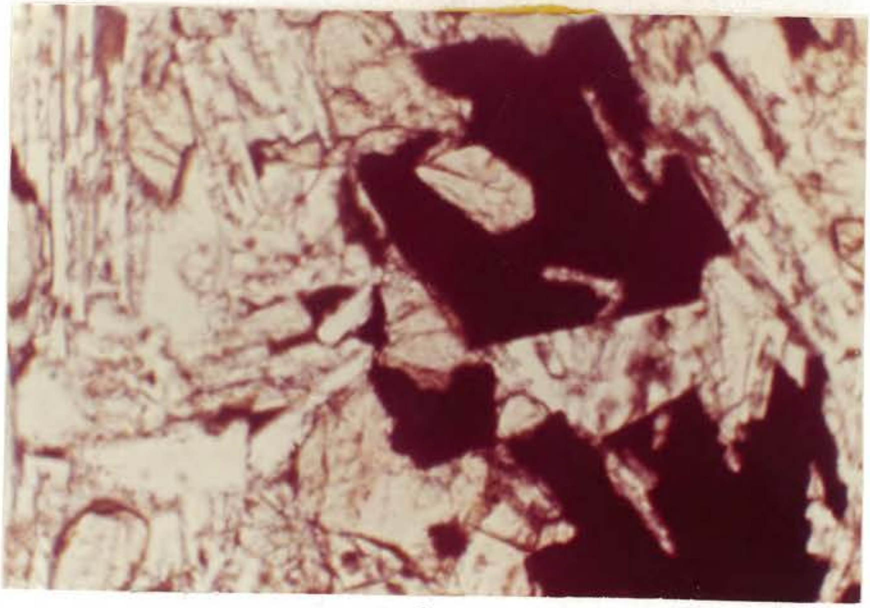

Figure 2. Ferroaugite inclusion in octahedral magnetite grain. Nicols not crossed (sample 8-20-10)

PHOTOMICROGRAPHS OF SPENCER BUTTE BASALT

Apatite and zircon are present in minor amounts with apatite predominating. Both average 0.02 mm in grain size.

On the basis of Johannsen's (1939) classification, the rock at Spencer Butte is termed basalt (2312 A).

Figure 1 of Plate 5 shows a trachytic flow structure, evident in only some parts of the rock. Figure 2 of Plate 5 shows more typical textures and mineral associations of the rock at Spencer Butte.

Modal Analyses and Cation Percentages-- The modal analyses and cation percentages of nine of the 24 samples collected at Spencer Butte are listed in Table 4.

Petrography of East Butte

Megascopic Description-- The rock at East Butte is massive, medium gray (N5), porphyritic basalt that is slightly zeolitized.[1] The phenocrysts appear to be highly weathered grains of ferroaugite, averaging about 2 mm in diameter. Very few crystal outlines can be identified with a hand lens which suggested to the author that the phenocrysts are actually aggregates of the clinopyroxene. One sample (8-21-1) contains a grain which cannot be identified with certainty, but appears to be a large (1 mm),

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[1] Sample 8-21-1 from East Butte.

PLATE 5

Figure 1. Well-developed trachytic texture of the plagioclase in the groundmass. Nicols crossed (sample 8-20-12)

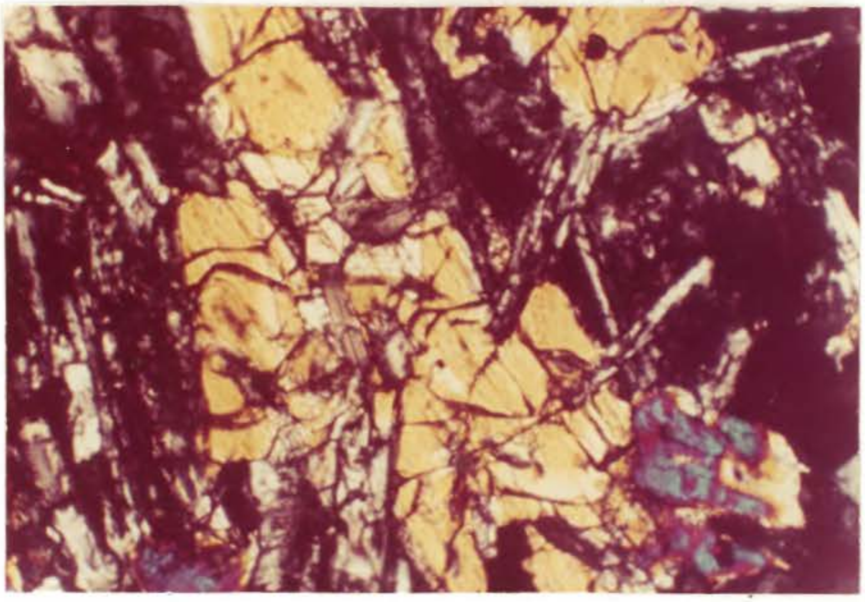

Figure 2. Intergranular, ophitic, and crude trachytic textures. Nicols crossed (sample 8-20-12)

PHOTOMICROGRAPHS OF SPENCER BUTTE BASALT dark gray, high-calcic plagioclase grain with well developed albite twinning striations. Some large grains of magnetite can also be seen in the samples.

Microscopic Description-- Plagioclase feldspar is the predominant mineral. It ranges in composition from An_{56} to An_{70}, averaging An_{61}; the average grain size is 0.22 mm. Sample 8-21-1 has the highest anorthite content, which may substantiate the identification of the large grain described above. No single plagioclase grain of that size is found in the thin section, however. The plagioclase microlites in the groundmass are aligned in a trachytic texture in some parts of the rock. It is subhedral and has well-developed albite and Carlsbad twinning. Pericline twinning is present,[1] but not common. Some of the larger grains are zoned.

Ferroaugite in the phenocrysts occurs as glomeroporphyritic aggregates of smaller anhedral grains averaging 0.39 mm in size. It is commonly twinned and basal sections have good prismatic cleavage. The ferroaugite is also common in the interstices of the plagioclase laths in an intergranular relationship. Some minute plagioclase grains are included in the clinopyroxene.

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[1] Sample 8-21-7 from East Butte.

One ferroaugite grain observed is zoned (Pl. 6). Moorehouse (1959, p. 166) reports that a progression from the inner part of a zoned clinopyroxene to the outer shell should be enriched in divalent iron at the expense of magnesium. The orientation of this grain does not allow accurate 2V determinations and thus, this trend cannot be substantiated.

The rock at East Butte is noticeably lacking in hypersthene and abundant in chlorophaeite. The latter is concentrated in the interstitial ferroaugite.

Iron oxide is present averaging 4.1 percent in amount and 0.25 mm in grainsize. A few samples with large aggregates of the iron oxide have minute inclusions of both ferroaugite and plagioclase (Pl. 7, Fig. 1).

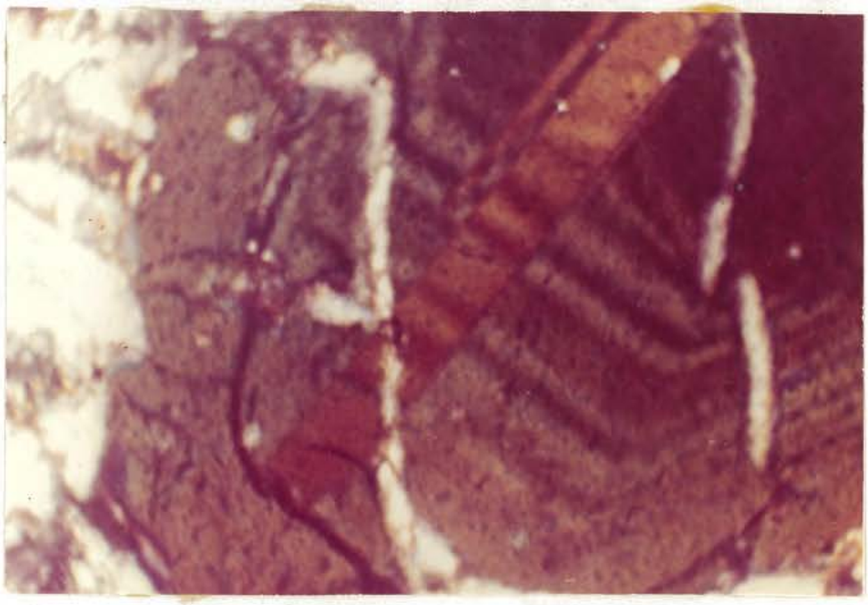
None of the common accessory minerals are present with the exception of a trace of zircon (0.07 mm) in sample 8-21-5.

The rock is classified as basalt (2312 A) according to Johannsen's (1939) classification.

Plate 7, Figure 2 shows the typical mineral associations and textures of the rock from East Butte.

Modal Analyses and Cation Percentages-- Listed in Table 5 are the modal analyses and cation percentages for four of the seven samples collected at East Butte.

PLATE 6



0.2 mm

Zoned and twinned ferroaugite phenocryst.
Nicols crossed (sample 8-21-6)

PHOTOMICROGRAPH OF EAST BUTTE BASALT

PLATE 7

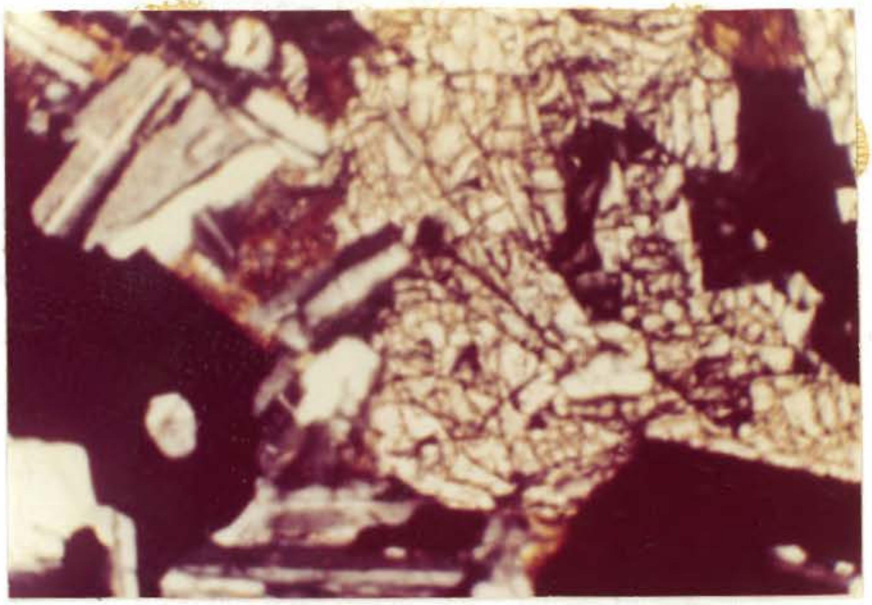


Figure 1. Plagioclase inclusion and embayment in basal section of ferroaugite. Note ferroaugite cluster and plagioclase inclusion in magnetite. Nicols crossed (sample 8-21-2)

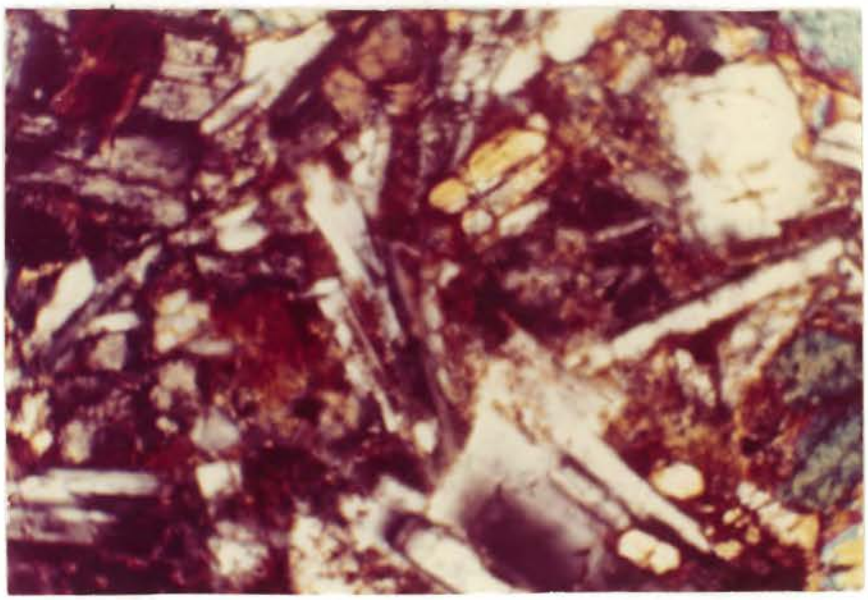


Figure 2. Typical ophitic texture. Nicols crossed (sample 8-21-7)

PHOTOMICROGRAPHS OF EAST BUTTE BASALT

SAMPLE NUMBER	8-21-1	8-21-7	8-21-5	8-21-3
DISTANCE TO LOWER CONTACT (FEET)	596	239	208	172
ANORTHITE CONTENT	70.0	56.0	58.0	60.0
MODAL ANALYSIS (%) :				
Plagioclase	41.7	60.2	57.0	52.8
Ferroaugite	28.0	25.7	26.8	29.8
Hypersthene	1.0	0.6	-	Trace
Chlorophaeite	24.7	9.4	11.6	14.0
Magnetite	4.4	4.0	4.6	3.2
Apatite	-	-	-	-
Zircon	-	-	-	-
Adularia	-	-	-	-
CATION PERCENTS :				
Si^{4}	46.0	46.2	46.8	47.0
Al^{3}	12.9	19.2	16.4	15.8
Fe^{3}	3.6	3.7	3.8	2.6
Fe^{2}	14.0	7.7	10.2	10.8
Ca^{2}	8.7	10.7	9.6	9.7
K^{1}	-	-	-	-
Na^{1}	2.4	6.2	4.8	4.0
Mg^{2}	12.4	6.3	8.5	9.9
P^{5}	-	-	-	-
Zr^{4}	-	-	-	-
Fe^{2}/Mg^{2} RATIO	1.1	1.2	1.2	1.1

Table 5. Modal analyses and cation percents of East Butte samples.

Petrography of Skinner Butte

Megascopic Description-- The rock of Skinner Butte is massive, dark gray (N3), fine-grained basalt. It is slightly porphyritic with phenocrysts of ferroaugite averaging 1 mm in size. Excellent columnar jointing (Pl. 2) is present at Skinner Butte.

Microscopic Description-- Subhedral plagioclase (0.17 mm) forms the groundmass of the rock and is the dominant mineral. The feldspar ranges in composition from An_{55} to An_{60}, averaging An_{58}. This composition is consistent with the average for basalt stated by Turner and Verhoogen (1960, p. 211). One sample[1] has local trachytic texture of the plagioclase. Some large grains are zoned.

The ferroaugite is common both as subhedral and anhedral grains. The former occurs primarily in the phenocrysts; the latter occurs as small glomeroporphyritic aggregates in the groundmass. The average grainsize, 0.15 mm, is misleading because the large grains in the phenocrysts are less abundant than the small grains in the groundmass.

---

[1] Sample 8-12-2 from Skinner Butte.

Because no hypersthene is apparent in the rock, chlorophaeite must have originated from ferroaugite. Plate 8, Figure 1 shows relic prismatic cleavage from a ferroaugite phenocryst present in a chlorophaeite grain.

Iron oxide occur as small (0.07 mm) disseminated anhedral grains, as high as 6.0 percent in amount,[1] but averaging only 3.6 percent.

No accessory minerals are apparent in the rock.

According to Johannsen's (1939) classification, the rock is termed basalt (2312 A).

Plate 8, Figure 2 shows a typical section of the rock from Skinner Butte.

Modal Analyses and Cation Percentages-- The modal analyses and cation percentages for all five of the samples collected at Skinner Butte are listed in Table 6.

Petrography of Gillespie Butte

Megascopic Description-- The intrusive body at Gillespie Butte is composed of massive, medium light gray (N6), fine-grained rock. In hand specimen it appears to be a diabase. One sample[2] has highly weathered ferroaugite

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[1] Sample 8-12-1 from Skinner Butte.

[2] Sample 8-16-3 from Gillespie Butte.

PLATE 8

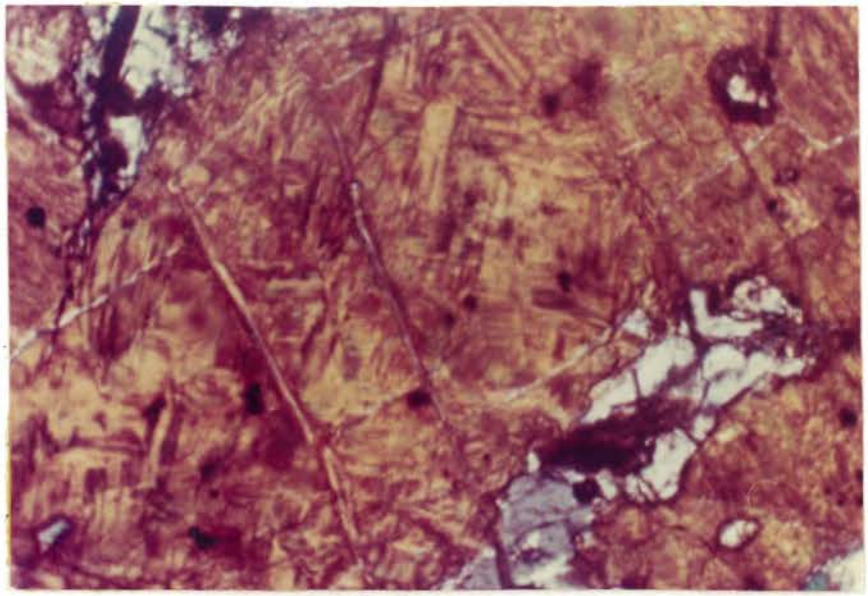

Figure 1. Chlorophaeite after ferroaugite. Note relic prismatic cleavage. Nicols crossed (sample 8-12-1)

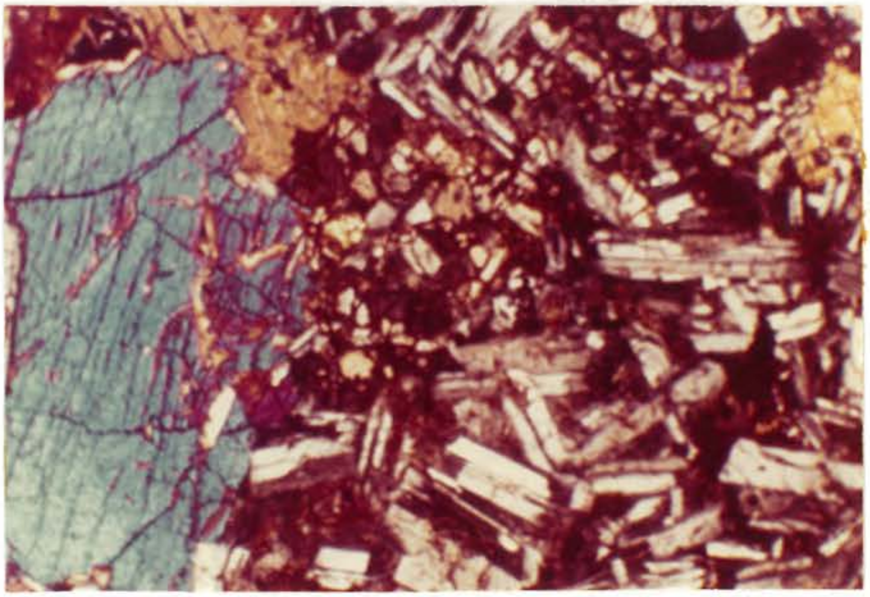

Figure 2. Euhedral ferroaugite, chlorophaeite after ferroaugite, and trachytic textures of the plagioclase. Nicols crossed (sample 8-12-2)

PHOTOMICROGRAPHS OF SKINNER BUTTE BASALT

SAMPLE NUMBER	8-12-3	8-16-1	8-12-4	8-12-2	8-12-1
DISTANCE TO LOWER CONTACT (FEET)	484	379	374	338	228
ANORTHITE CONTENT	59.0	56.0	55.0	60.0	60.0
MODAL ANALYSIS (%) :					
Plagioclase	54.8	57.7	56.2	52.5	63.3
Ferroaugite	31.4	29.7	28.2	31.6	24.8
Hypersthene	–	Trace	–	–	–
Chlorophaeite	10.4	9.6	12.4	13.2	6.0
Magnetite	3.4	2.6	3.2	2.6	6.0
Apatite	–	–	–	–	–
Zircon	–	–	–	–	–
Adularia	–	–	–	–	–
CATION PERCENTS :					
Si ^{4}	45.7	47.8	47.3	47.4	44.4
Al ^{3}	24.0	16.8	16.8	15.5	18.8
Fe ^{3}	2.8	2.2	2.7	2.1	5.0
Fe ^{2}	4.2	9.5	9.7	10.8	8.8
Ca ^{2}	10.1	10.0	9.8	10.0	11.3
K ^{1}	–	–	–	–	–
Na ^{1}	4.1	4.7	4.8	4.0	4.8
Mg ^{2}	9.1	8.8	8.7	10.1	6.7
P ^{5}	–	–	–	–	–
Zr ^{4}	–	–	–	–	–
Fe ^{2}/ Mg ^{2} RATIO	1.1	1.1	1.1	1.1	1.3

Table 6. Modal analyses and cation percents of Skinner Butte samples.

phenocrysts, and all samples are slightly zeolitized.

Microscopic Description-- Microlites of subhedral plagioclase (0.19 mm) in the groundmass are the main constituents of the rock. They range in composition from An_{40} to $An_{49.5}$, (upper andesine), which clearly places the rock in the andesite rock range according to Heinrich (1956). The author feels that this low anorthite content is attributed to a lack of adequate plagioclase grains in the samples available for the Michel-Lèvy statistical determination, and thus, does not represent a typical composition of the feldspar. A few grains have pericline as well as albite and Carlsbad twinning. The larger feldspar crystals, within a groundmass of smaller grains, are commonly zoned. One sample[1] has trachytic texture in the plagioclase microlites in the groundmass.

Anhedral ferroaugite (0.19 mm) usually occurs as small interstitial grains within the groundmass. A few glomeroporphyritic aggregates of ferroaugite have large subhedral to euhedral grains with good prismatic cleavage (Pl. 9, Fig. 1) and simple pinacoidal twinning on the $\{100\}$ plane.

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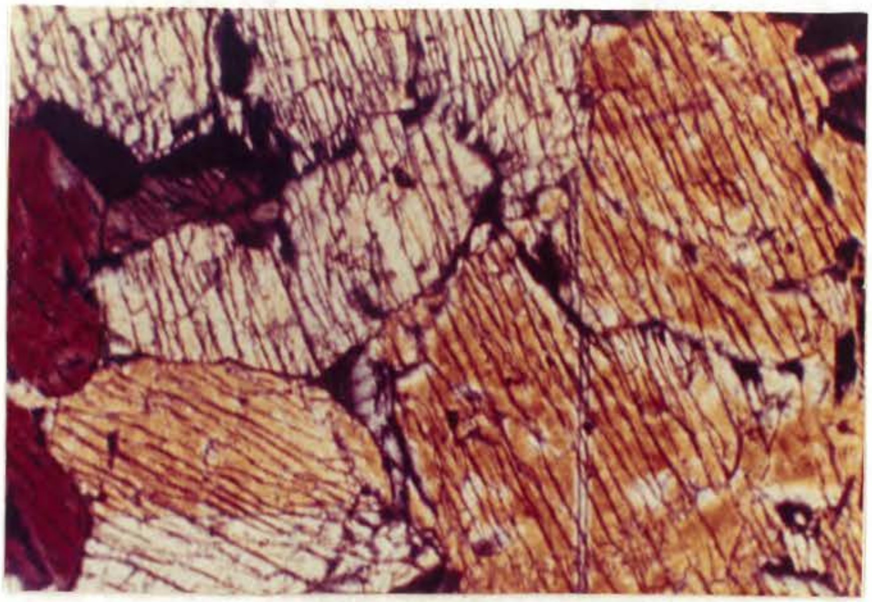
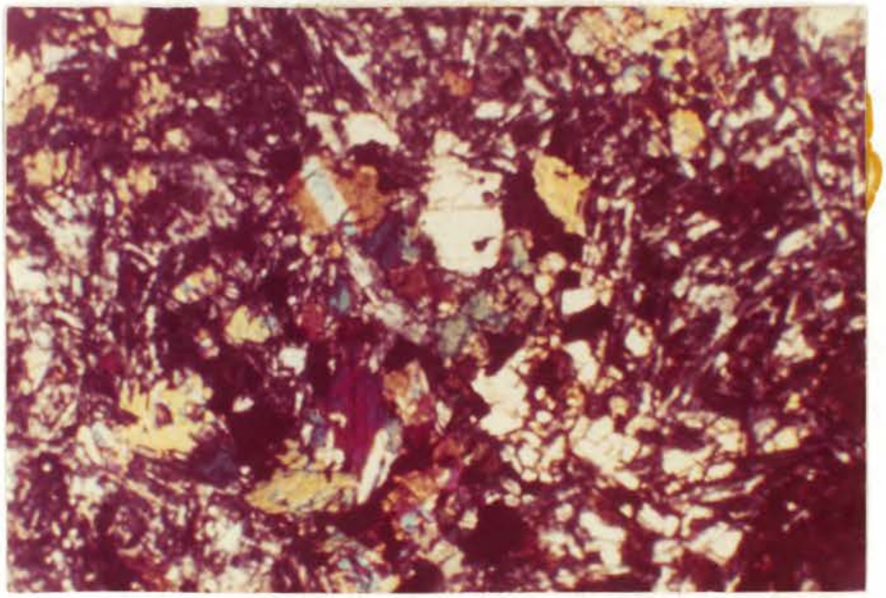
[1] Sample 8-16-3 from Gillespie Butte.

PLATE 9



0.2 mm

Figure 1. Clustered ferroaugite phenocrysts. Note prismatic cleavage and simple pinacoidal twinning. Nicols crossed (sample 8-16-2)



0.6 mm

Figure 2. Typical textures. Note plagioclase microlites, clustered and intergranular ferroaugite, and ophitic intergrowth. Nicols crossed (sample 8-16-2)

PHOTOMICROGRAPHS OF GILLESPIE BUTTE BASALT

Hypersthene is present in small amounts in the rock and occurs as large (0.41 mm) anhedral grains in an ophitic association with the feldspar in the groundmass.

Small quantities of chlorophaeite are present as disseminated grains throughout the groundmass. The mineral appears to be concentrated near the ophitic hypersthene grains, which suggests that it is an alteration product from that pyroxene rather than from the ferroaugite.

Iron oxide averages 6.6 percent in amount and occurs commonly as small (0.09 mm) grains, many of which have an octahedral crystal outline.

Only one sample[1] has traces of the accessory minerals apatite (0.02 mm) and zircon (0.01 mm). The same sample also has some adularia (0.49 mm) concentrated in a veinlet.

According to Johannsen's (1939) classification, the rock at Gillespie Butte is an andesite (2212 A). The author believes that if a sufficient number of fresh plagioclase grains were available for the application of the statistical Michel-Lèvy method, the rock would prove to be a basalt.

Plate 9, figure 2 shows the typical mineral associations and textures of the rock at Gillespie Butte.

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[1] Sample 8-16-4 from Gillespie Butte.

Modal Analyses and Cation Percentages-- Listed in Table 7 are the modal analyses and cation percentages for all three of the samples collected at Gillespie Butte.

Petrography of North Butte

Megascopic Description-- The rock at North Butte is massive, medium dark gray (N4), fine-grained basalt. Some parts are slightly porphyritic with phenocrysts of ferroaugite. The rock is generally highly weathered to a very light gray (N8), and one sample[1] shows spheroidal weathering into little knobs averaging 0.75 inches in diameter.

Microscopic Description-- Plagioclase feldspar, ranging from An_{52} to $An_{60.5}$ and averaging $An_{56.4}$, is the dominant mineral. It occurs as small (0.25 mm) subhedral microlites forming the groundmass of the rock. The larger crystals are commonly zoned.

Anhedral ferroaugite (0.24 mm) is common in the interstices of the plagioclase groundmass. Subhedral ferroaugite (0.6 mm) is common both as phenocrysts and aggregates. The larger subhedral grains have simple pinacoidal twinning on the $\{100\}$ plane and well-developed prismatic cleavage (Pl. 10, Fig. 1).

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[1] Sample 8-16-4 from North Butte.

SAMPLE NUMBER	8-16-2	8-16-4	8-16-3
DISTANCE TO LOWER CONTACT (FEET)	102	42	20
ANORTHITE CONTENT	49.5	44.0	40.0
MODAL ANALYSIS (%) :			
Plagioclase	63.5	61.6	60.0
Ferroaugite	22.4	17.5	28.4
Hypersthene	4.2	8.6	1.6
Chlorophaeite	3.0	9.3	4.2
Magnetite	6.8	7.1	5.8
Apatite	–	Trace	–
Zircon	–	Trace	–
Adularia	–	3.0	–
CATION PERCENTS :			
Si^4	46.0	47.1	47.4
Al^3	17.9	17.2	15.9
Fe^3	5.6	5.8	4.8
Fe^2	9.0	9.1	9.4
Ca^2	8.6	7.1	8.1
K^1	–	0.2	–
Na^1	6.3	7.0	6.8
Mg^2	6.5	6.5	7.6
P^5	–	–	–
Zr^4	–	–	–
Fe^2/ Mg^2 RATIO	1.4	1.4	1.2

Table 7. Modal analyses and cation percents of Gillespie Butte samples.

PLATE 10

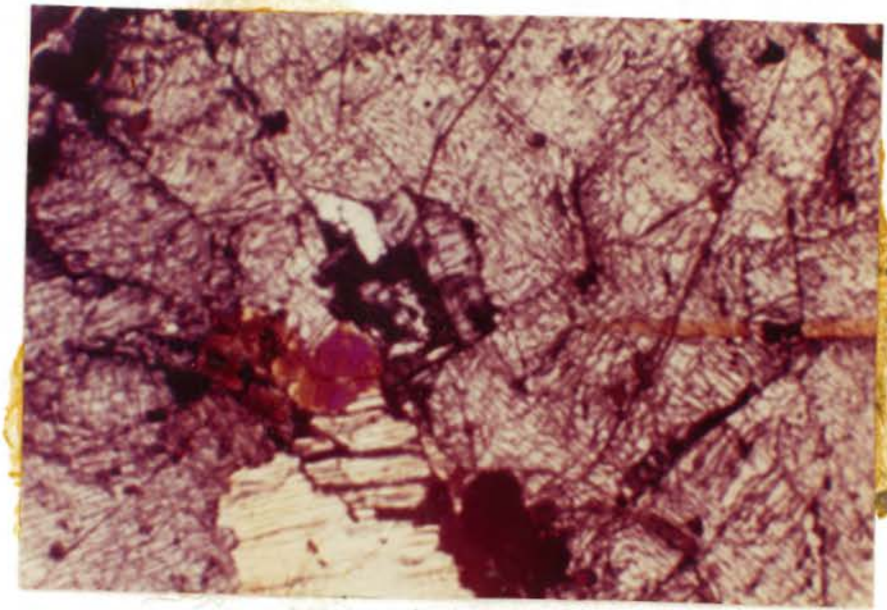

Figure 1. Prismatic cleavage in clustered ferroaugite, Nicols crossed (sample 8-16-8)

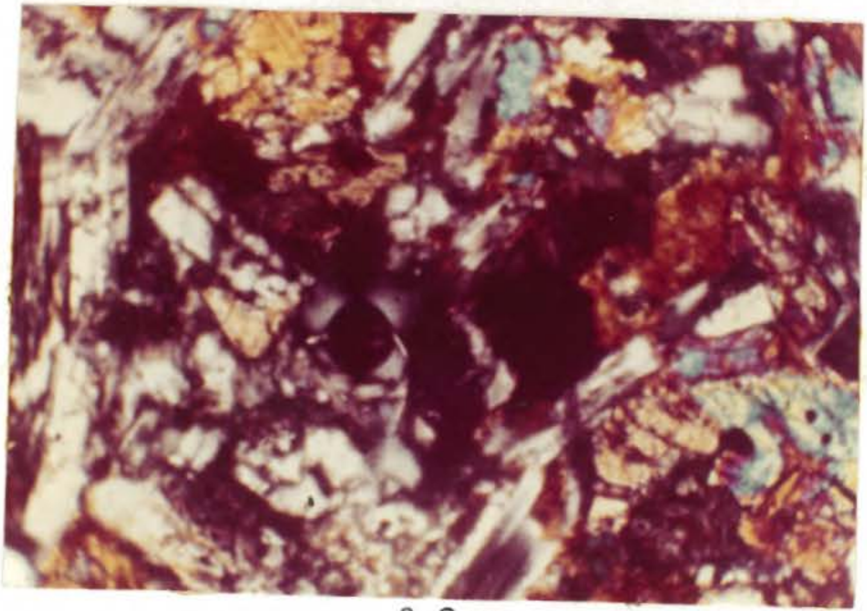

Figure 2. Typical intergranular texture. Note microlites of plagioclase, disseminated magnetite, and chlorophaeite after clustered and interstitial ferroaugite. Nicols crossed (sample 8-16-6)

PHOTOMICROGRAPHS OF NORTH BUTTE BASALTS

Anhedral hypersthene (0.5 mm) is present in varying amounts throughout the rock in an ophitic association with the feldspar in the groundmass.

The chlorophaeite appears to have resulted mainly from an alteration of the ferroaugite. It is equally distributed throughout the rock in both the glomeroporphyritic and intergranular clinopyroxene. Only a few grains of hypersthene altering to chlorophaeite are apparent.

Iron oxide is present in amounts averaging 5.4 percent. It is dispersed throughout the rock usually occupying interstitial positions in the groundmass.

No accessory minerals are apparent with the exception of one sample,[1] which has a trace of apatite.

The rock is termed basalt (2312 A) according to Johannsen's (1939) classification.

Plate 10, Figure 2 shows the typical mineral associations and textures of the rock at North Butte.

<u>Modal Analyses and Cation Percentages</u>-- Listed in Table 8 are the modal analyses and cation percentages for four of the eight[2] samples collected at North Butte.

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[1] Sample 8-16-7 from North Butte.

[2] Sample 8-16-12 was discarded after laboratory investigations proved it was not a typical sample from North Butte.

SAMPLE NUMBER	8-16-7	8-16-8	8-16-9	8-16-10
DISTANCE TO LOWER CONTACT (FEET)	(All distances are equal.)			
ANORTHITE CONTENT	52.0	60.5	58.0	56.0
MODAL ANALYSIS (%) :				
Plagioclase	59.4	52.7	61.4	54.6
Ferroaugite	20.0	28.2	24.0	29.4
Hypersthene	7.0	7.2	1.8	2.2
Chlorophaeite	8.0	5.4	8.6	7.6
Magnetite	5.4	6.0	4.2	6.0
Apatite	0.2	-	-	-
Zircon	-	-	-	-
Adularia	-	-	-	-
CATION PERCENTS :				
Si^{4}	46.4	45.3	51.2	45.8
Al^{3}	16.8	15.6	17.4	15.3
Fe^{3}	4.5	5.1	3.8	4.9
Fe^{2}	10.1	11.3	3.7	10.9
Ca^{2}	8.5	9.6	8.6	9.4
K^{1}	-	-	-	-
Na^{1}	5.3	3.9	7.1	4.4
Mg^{2}	8.3	9.3	8.2	9.0
P^{5}	-	-	-	-
Zr^{4}	-	-	-	-
Fe^{2}/Mg^{2} RATIO	1.2	1.2	0.4	1.2

Table 8. Modal analyses and cation percents of North Butte samples.

PETROLOGIC AND PETROCHEMICAL COMPARISONS

Mineralogy and Texture

The rocks from the six buttes are uniform in their mineralogy. Plagioclase is the dominant mineral, occurring mainly as microlites in the groundmass and in minor amounts as large zoned grains. Anhedral ferroaugite is always present, commonly in the interstices of the plagioclase and less commonly in aggregates in the glomeroporphyritic parts of the rocks. Anhedral magnetite (and ilmenite) is present in minor amounts not exceeding 9 percent, both as microcrystals and as exsolution traces in the pyroxenes.

The remaining minerals vary in concentration from butte to butte. Interstitial quartz is present in the rock at Creswell Butte, but only in trace amounts. Anhedral to subhedral hypersthene is present in significant amounts at Creswell, Spencer, Gillespie, and North Buttes and in trace amounts at East and Skinner Buttes. Chlorophaeite is present in all of the rocks and appears to have resulted from an alteration of either or both of the pyroxenes. The accessory minerals, apatite and zircon, are common at Spencer Butte, less common at Creswell, Gillespie, and North Buttes, and not apparent at East and Skinner Buttes. Anhedral adularia is present in veinlets at Gillespie Butte, and samples from Creswell, East, and Gillespie Buttes are slightly zeolitized.

The textures of all the samples are uniform. The plagioclase microlites and interstitial ferroaugite and magnetite average less than 0.25 mm in size. Some samples which appear porphyritic in hand specimen are actually composed of ferroaugite clusters. Hypersthene, averaging 0.4 mm in grain size, is found both as phenocrysts and in an ophitic intergrowth with the feldspar in the groundmass. Some evidence of flow structure is noted in the rocks.

On the basis of mineral composition, the rocks are all termed medium- to fine-grained basalts according to Johannsen's (1939) igneous rock classification. On the combined bases of minerals and texture all of the rocks are termed diabases according to Heinrich (1956). Some of the rocks are glomeroporphyritic.

Paragenesis

Zircon-- Euhedral zircon, characteristic of high temperatures according to Ford (1949), probably crystallized out of the magma first. It is present only in very minor amounts.

Plagioclase Feldspar-- Euhedral untwinned zoned plagioclase grains are present only in minor amounts. The author believes they represent the short period of crystallization between the zircon and the normal twinned plagioclase formation stages. The microlites of plagioclase should, according to Barth (1936), show a slight (less than 7 percent) concentration of alkali feldspar. The author observed no other stage of feldspar crystallization (with the exception of veinlets of hydrothermal adularia), which indicates that the plagioclase crystallized along line Q-R in Barth's (1936, p. 325) diagram (Fig. 19) where the two phase boundary is not reached.

Pyroxenes-- The continuous series of plagioclase along line Q-R and the discontinuous series of the pyroxenes give an account of the essential crystallization process of a basaltic magma. Barth (1936, p. 329) shows the schematic relationship of these mineral groups in a typical basalt, which is redrawn in Figure 20. Line A-B represents the continuous series from diopsidic to hypersthenic pyroxene. If the composition of the original basaltic magma lies to the left or right of the boundary O-P, crystallization of either plagioclase or pyroxene respectively will result until the boundary is reached. At the boundary simultaneous crystallization of both

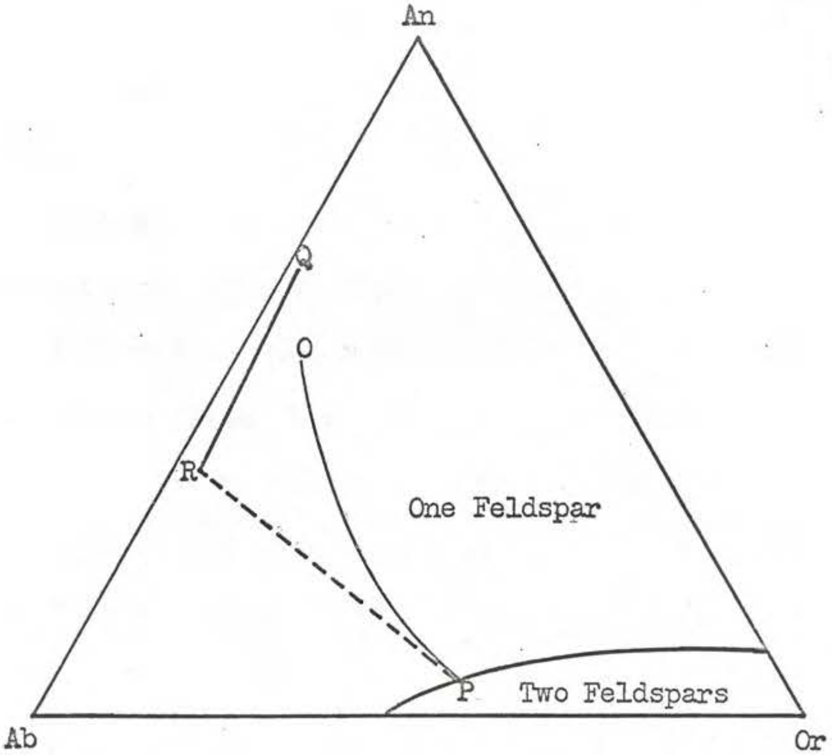

Figure 19. Plagioclase crystallization in basaltic magma (after Barth, 1936, Fig. 1, p. 325).

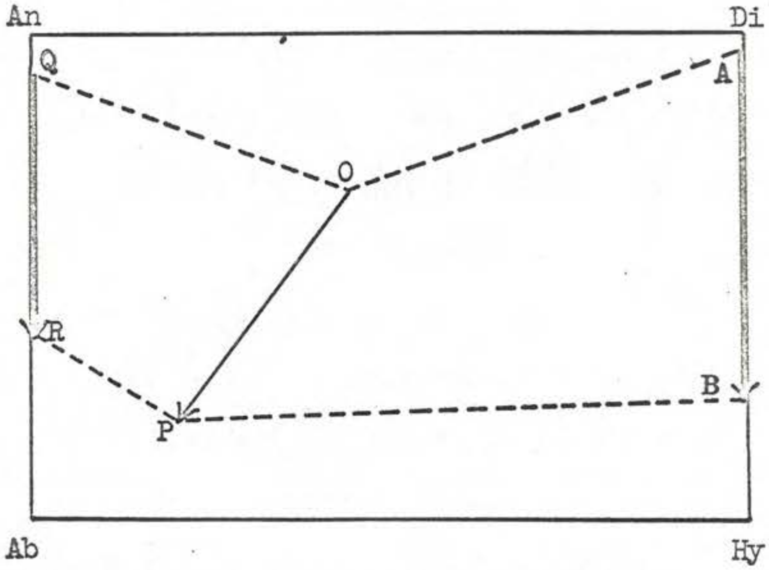

Figure 20. Crystallization process in basaltic magma (after Barth, 1936, Fig. 3, p. 329).

mineral groups takes place.

Inclusions of the plagioclase in the pyroxenes, the ophitic and intergranular relationship of the two mineral groups, and the high plagioclase percentages in the modal analyses all indicate conclusively that the original composition of the magma lies to the left of the O-P boundary. According to Barth's (1936) normative calculations, most basalts lie in this plagioclase field.

In an undersaturated magma, such as the samples apparently represent, high temperature olivines are commonly associated with the ferromagnesium pyroxenes. The absence of olivine and any relic structure of that mineral in later pyroxenes indicates a lower initial temperature of formation and the direct crystallization of hypersthene following plagioclase (Fenner, 1929).

Consistent with the fact that basalts normally contain two pyroxene minerals (Poldervaart and Hess, 1951), hypersthene is always associated with ferroaugite in the samples. The petrology of this particular relationship warrants special consideration. Hess (1941b, Fig. 12, p. 586) shows that the augite-ferroaugite series crystallizes independently of the orthopyroxene (hypersthene) -pigeonite series (Fig. 21). With decreasing temperature, augite, common in two-pyroxene basalts proceeds toward ferroaugite, common in one pyroxene basalts.

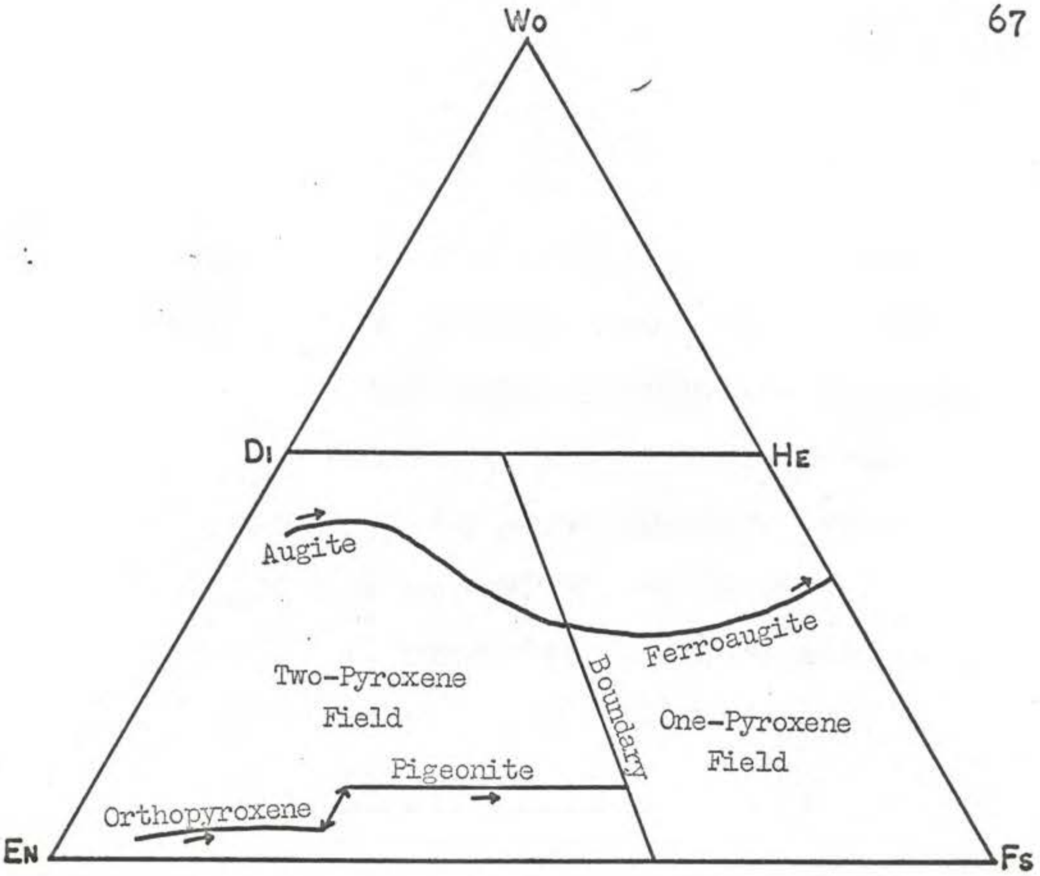

Figure 21. Pyroxene crystallization in basaltic magma (after Hess, 1941, Fig. 12, p. 586).

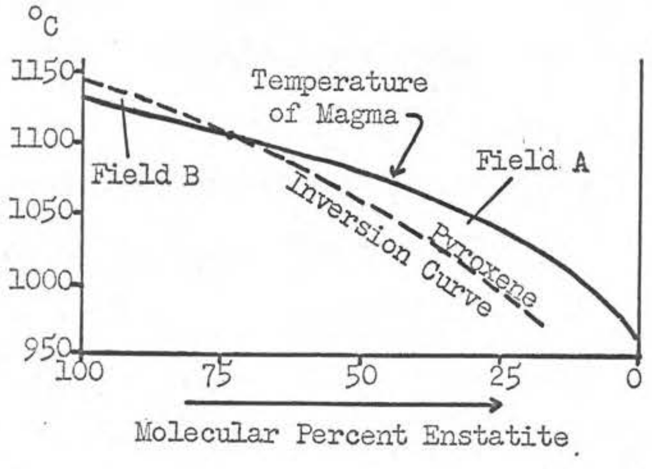

Figure 22. Cooling curve for basaltic magma and pyroxene inversion curve (after Hess, 1941, Fig. 9, p. 583).

In the orthopyroxene-pigeonite series, however, the hypersthene crystallizes at a higher temperature and inverts to pigeonite as the magma cools. Figure 22 (Hess, 1941a, Fig. 9, p. 583) shows the relationship of the temperature of the magma and the orthopyroxene (hypersthene)-clinopyroxene (pigeonite) inversion curve. If the temperature of the magma is above the inversion temperature for a given composition (Field A), the original orthorhombic pyroxene will invert to pigeonite as the temperature is decreased. If the temperature of the magma is below the inversion temperature (Field B), the orthorhombic pyroxene will not be permitted to invert to pigeonite and will be 'frozen' in the rocks.

The samples from Creswell, Spencer, Gillespie, and North Buttes, all of which show both ferroaugite and hypersthene with no pigeonite, indicate the higher temperature conditions of field B.

The nature of the one-pyroxene basalt field in figure 21 is not clear. From Poldervaart and Hess's diagram (1951, Fig. 6, p. 480), which is redrawn in Figure 23, it may be inferred that either a member of the orthopyroxene-pigeonite series or the augite-ferroaugite series may continue to form at decreasing temperatures below the two-pyroxene boundary. Hess (1941a) (Fig. 21), however, shows a termination of the orthopyroxene-pigeonite series at the

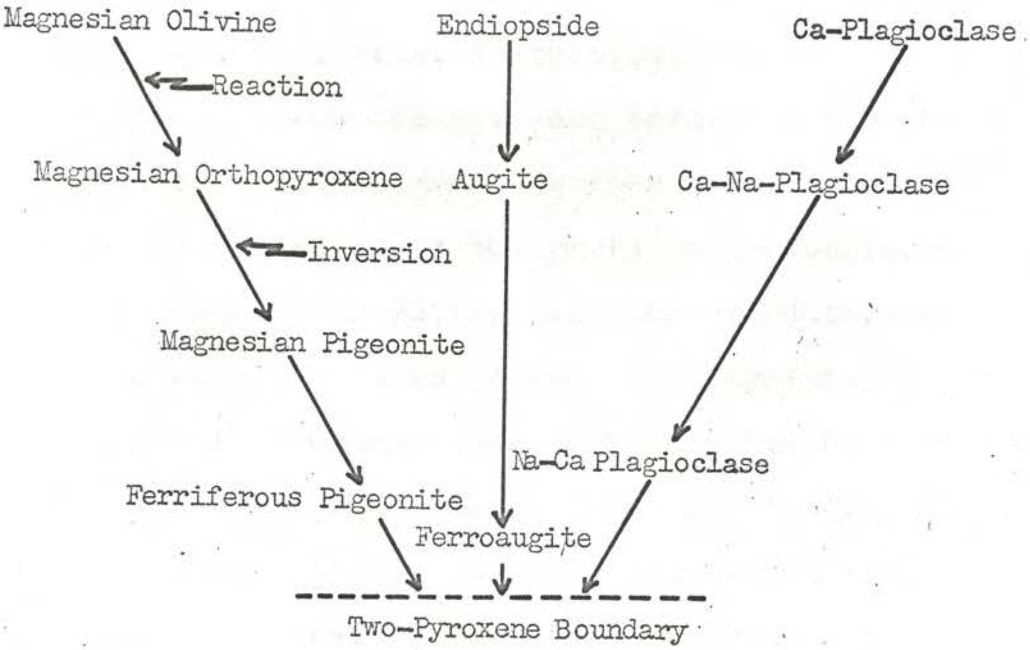

Figure 23. Principle reaction series in a basaltic magma (after Poldervaart and Hess, 1951, Fig. 6, p. 480).

boundary and includes ferroaugite as the most likely constituent of a one-pyroxene basalt.

The rocks from East and Skinner Buttes have only iron-rich clinopyroxene, ferroaugite, with no associated hypersthene. These one-pyroxene basalts could represent a late iron-rich differentiate from the same magma which lead to the formation of the rocks at Creswell, Spencer, Gillespie, and North Buttes, but the constant ratio of Fe^2/Mg^2 in all the rocks (about 1.2) suggests that the composition of the magma was virtually the same at all the buttes (Fenner, 1929). Thus, the rocks from East and Skinner Buttes probably indicate a temperature of formation lower than that indicated by the two-pyroxene boundary in Figures 22 and 23.

Iron Oxide-- The microcrystalline iron oxides present in all samples probably represent the last stage of magmatic crystallization, as defined by Chayes (1950, p. 36), following the last formation of iron-rich pyroxene. The anhedral magnetite in the intergrain zones and along the microbreaks of the ferroaugite cleavage represents an exsolution of the two minerals at decreasing temperatures.

Chlorophaeite-- The alteration product, chlorophaeite, followed magnetite in the sequence. It is found extensively associated with the ferromagnesium minerals in the rocks. According to Peacock and Fuller (1928, p. 369), chlorophaeite is:

> ...probably due to hydrothermal (post-magmatic according to Chayes, 1950) action on ferromagnesium minerals and on the basic constituents...resulting in a fluid product which permeates the rock...

The rocks from Creswell and Gillespie Buttes have chlorophaeite after hyperathene in particular. Peacock and Fuller (1928, p. 363) report the same association in the Columbia River Basalt flows:

> Rhombic pyroxenes such as hypersthene are particularly unresistant to alteration, and the inference that the chlorophaeite pseudomorphs represent completely altered rhombic pyroxenes is fully in accord with the forms of the pseudomorphs and with the chemical composition.

Adularia and Zeolites-- The vein feldspar and amygdaloidal zeolites are products of local hydrothermal action concentrated in the open fractures of the rocks.

Apatite-- According to Tollman and Rogers (Kerr, 1959, p. 231), apatite is mainly a late-magmatic mineral. The author believes that it is not necessarily typical of any temperature range or field of composition. Thus, he cannot accurately place it in this paragenetic scheme.

Extent of Differentiation

Inter-butte Differentiation-- The low silicon content and the Fe^2/Mg^2 ratio (see cation percentages for each sample) constant throughout the samples indicates a uniform magma composition at all the buttes. Thus, mechanical differentiation processes as outlined by Barth (1952) do not appear to be a contributing factor to any variation in compositions within this intrusive group.

The rocks may be crystallization products from a residual liquid which has differentiated from a parent magma. Barth (1936, p. 349) explains that if at depth the pigeonite crystallizes in excess of the stoichiometric ratio and does not react with the residual liquid, then that liquid will be undersaturated with respect to silica. The intrusive rocks of the Cascade Range, as described by Bogue and Hodge (1940) and Peck (1960), and the Coast Range, as described by Bray (1958), have a high concentration of sub-calcic clinopyroxene (namely pigeonite) and may represent such a parent magma. There is, unfortunately, no proof that this process of initial differentiation lead to the undersaturation of the rocks investigated in the southern Willamette Valley.

It appears that given an undersaturated magma with a constant Fe^2/Mg^2 ratio, the only feasible explanation for a petrographic variation lies in a varying temperature of crystallization. None of the samples contain olivine, a common constituent of undersaturated rocks, which indicates that the temperature at all the buttes was below that allowing olivine to form. Creswell, Spencer, Gillespie, and North Buttes show two pyroxenes and, thus, represent the highest temperature of crystallization of the six buttes. At lower temperatures and, thus, probably later than the previous four, the rocks of East and Skinner Buttes formed. They have only ferroaugite, which crystallizes below the temperature necessary for a two-pyroxene basalt.

The plagioclase, relatively constant in composition for the six buttes, has apparently crystallized at slightly higher temperatures and does not reflect the varying temperature conditions significant in the pyroxene mineral group. Trachytic structure evident at many of the buttes indicates that perhaps the plagioclase could have crystallized at these higher temperatures before emplacement, been carried to their present position by the melt, and followed by pyroxene crystallization with decreasing temperature.

Intra-butte Differentiation-- Within each of the six buttes there is no conclusive evidence of magmatic differentiation. Examination of selected samples from traverses parallel and perpendicular to the strike and dip of the assumed structures shows that no two samples from any one butte are exactly alike, nor are there any groupings of similar mineral compositions.

The anorthite content of the plagioclase ranges from An_{40} (Gillespie Butte) to An_{70} (East Butte) and varies throughout all of the buttes, which reflects the idea of a pre-intrusion crystallization of the feldspar and its resulting random emplacement by the melt in the present structures.

The ophitic association of hypersthene and plagioclase, the intergranular and clustered ferroaugite, and the microcrystals of iron oxide, are disseminated throughout the rock at each butte. They apparently crystallized where the openings occurred in the groundmass, and show no evidence of differentiation.

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