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Mineralogy and petrology of the Dutchmans Creek gabbroic intrusion, South Carolina

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Abstract

The Dutchmans Creek gabbro is a differentiated pluton consisting of olivine gabbro, anorthositic gabbro, pyroxene gabbro, and hornblende–pyroxene gabbro. This sequence of rock types represents advancing differentiation, as indicated by progressive increase in Fe/(Fe+Mg) ratios of coexisting ferromagnesian minerals and decrease in the anorthite component of plagioclase. Modal olivine decreases systematically in the sequence. The parent magma crystallized under conditions of high PH_2O and fO_2, which increased with fractionation, as suggested by modal increase in hydrous minerals and changes in the compositions of opaque minerals. Late-magmatic reactions occurred between many mineral phases and produced a variety of symplectic or replacement textures. Petrologic differences between the Dutchmans Creek gabbro and other neighboring plutons include early precipitation of Fe–Ti oxides, absence of olivine reaction relationships, and systematic areal distribution of olivine within the pluton. These differences may be due to the fact that much of the pluton has barely been unroofed by erosion, and only the upper regions of the magma chamber are visible. Early cumulate rocks are exposed in the pluton interior due to deeper erosion, whereas late differentiates outcrop at higher topographic levels at pluton margins. Water migration to the top of the chamber may have resulted in higher prevailing fO_2 and subsequent lowering of liquidus temperatures in the upper volatile-rich portions of the chamber.

Introduction

More than 30 post-metamorphic (late Paleozoic) gabbro plutons occur in an arcuate chain extending for at least 500 km in the southern Appalachian Piedmont areas of North Carolina, South Carolina, and Georgia. Detailed petrographic descriptions of only two of these bodies, the Mecklenburg, North Carolina pluton (Hermes, 1968, 1970), and the Buffalo, South Carolina pluton (Medlin *et al.*, 1972) are available in the literature. Limited petrographic descriptions have been published for several other plutons (McCauley, 1961; Butler, 1966; Chalcraft, 1968; Mathews, 1969; Medlin, 1969a; McSween, 1970; Waskom and Butler, 1971; Hadley, 1973); other descriptive studies have been submitted as unpublished theses (Morgan, 1963; Mathews, 1967; Myers, 1968; Medlin, 1969b; Cabaup, 1969). This paper presents and interprets results of a detailed mineralogic and petrologic examination of one large, elongate pluton, the Dutchmans Creek gabbro in central South Carolina (McSween, 1972).

The few detailed studies of neighboring Piedmont plutons similar to the Dutchmans Creek gabbro have indicated that systematic relationships between petrographic properties, mineralogy and mineral chemistry, and location within the pluton are poorly defined or nonexistent (Hermes, 1968; Medlin *et al.*, 1972). Moreover, macroscopic layering phenomena are generally not observed, and little if any differentiation has occurred. This paper demonstrates that subtle but clearly discernible differentiation trends, reflected in systematic variations in modal mineralogy, mineral chemistry, and texture, are present in rocks of the Dutchmans Creek pluton. The unique features of this pluton result from crystallization under conditions of high water content and oxygen fugacity, and an unusual erosional exposure pattern.

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Field relationships

A geologic map and preliminary petrologic description of the Dutchmans Creek gabbro were published by McSween (1972). The gabbro was intruded near the contact between the Charlotte and Carolina slate belts in southeastern Fairfield County, South Carolina, and is situated along regional strike between two large circular post-metamorphic batholiths, the Winnsboro quartz monzonite to the southwest and the Liberty Hill granite to the northeast.

The envelope rocks are a sequence of interlayered quartz–muscovite schists, amphibolites, and leucocratic gneisses regionally metamorphosed to the amphibolite facies (Wagener, 1970). Two stratigraphic units can be distinguished in the country rocks. A metavolcanic group, originally an interbedded sequence of volcanic and pyroclastic material, includes felsic, intermediate, and mafic rocks with prominent foliations, and is noted as "fine-grained gneiss and amphibolite" in Figure 1. The leucocratic gneiss unit is a metasedimentary unit comprised mainly of quartzo-feldspathic rocks with massive or porphyroblastic textures.

Preparation of a refined map of the Dutchmans Creek pluton showing more details of the gabbro contracts was undertaken as part of this study (Fig. 1). The irregularly-shaped, elongate intrusion occupies a distinct, topographically low area along Dutchman's Creek, for which the pluton is named. The margin of the gabbro as mapped from outcrops and distinctive soil changes was found to correspond with a prominent break in slope, easily determined on topographic maps and stereoscopic pairs of aerial photographs. The margins of this gabbro, and other Piedmont gabbros, can therefore be delineated directly from the local topography with some accuracy. Steep-sloped prominences occurring within the pluton are large roof pendants or inclusions, and their lithologies are the same as the country-rock strata which that portion of the pluton intrudes (Fig. 1). Topographic elevations for contacts of the gabbro with surrounding country rocks and with the large inclusions are the same, suggesting that the inclusions are roof pendants and that the pluton has barely been unroofed by erosion.

Exposures of gabbro are massive, spheroidal, and have distinctive pitted surfaces from the differential weathering of component minerals. The most common outcrops are large residual boulders from one to several meters in diameter. Though these boulders are not bedrock in the strict sense, they do occur "in place." Bedrock exposures occur in a number of streams, and distinctive brownish-gray gabbro saprolite exposures are common in road cuts and road ditches. Both residual boulder outcrops and bedrock exposures are most abundant near the margins of the pluton or in the vicinity of the roof pendants, but there are large tracts of gabbro terrain where there are no outcrops. No layering was observed in any of the exposures. Pyroxene hornfels was found at several localities along the pluton margins.

The pluton is crosscut by numerous small leucocratic dikes consisting of quartz, muscovite, orthoclase, plagioclase, and chlorite. The planar dikes range from several centimeters up to 3 meters thick and vary from fine- to coarse-grained. They occur in various orientations from near-vertical to almost horizontal, and appear to be confined to the gabbro.

The gabbro margins closely correspond with the outline of a pronounced local gravity high depicted on the map by Popenoe and Bell (1975), as shown in Figure 2. The delineation of this gravity high indicates that at depth the gabbro is elongate and of roughly the same size, shape, and orientation as suggested by its outcrop area at the surface.

Mineralogy and petrography

Modal and textural variations

Gabbro samples consist largely of plagioclase, olivine, clinopyroxene, and orthopyroxene in varying proportions, with lesser amounts of biotite, hornblende, and opaque minerals. Rock types based on the proportions of these major phases can be classified as:

(1) *olivine gabbro,* characterized by significant quantities of euhedral to subhedral olivine (>20 percent) with plagioclase, augite, bronzite, and biotite;

(2) *anorthositic gabbro,* containing >60 percent plagioclase, with augite, hypersthene, opaque minerals, and fairly abundant olivine (~15 percent);

(3) *pyroxene gabbro,* in which augite (16–30 percent) and hypersthene (7–14 percent) are the predominant mafic minerals, with plagioclase and usually abundant biotite (5–15 percent); and

(4) *hornblende–pyroxene gabbro,* composed of >15 percent amphibole with augite, hypersthene, plagioclase, and fairly large concentrations of Fe–Ti oxides (usually 9–10 percent).

Typical modal analyses are presented in Table 1. The locations of these samples are shown in Figure 2. Figure 3 illustrates variations in the modes of these rock types; the samples in Figure 3 are plotted from top to bottom in the order of increasing Fe/(Fe+Mg)

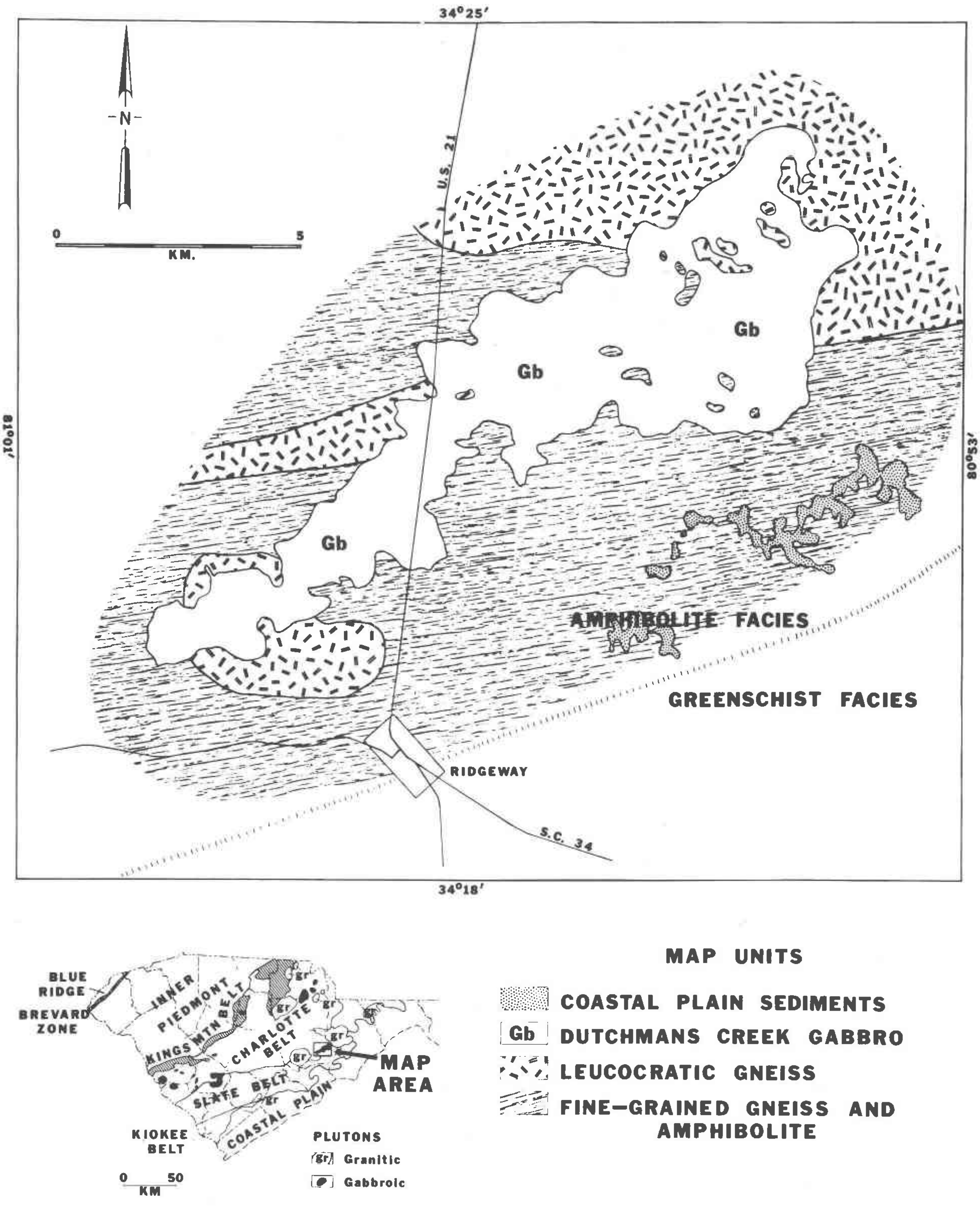

Fig. 1. Geologic map of the Dutchmans Creek gabbro. Inset at lower left shows the position of the study area in the South Carolina Piedmont.

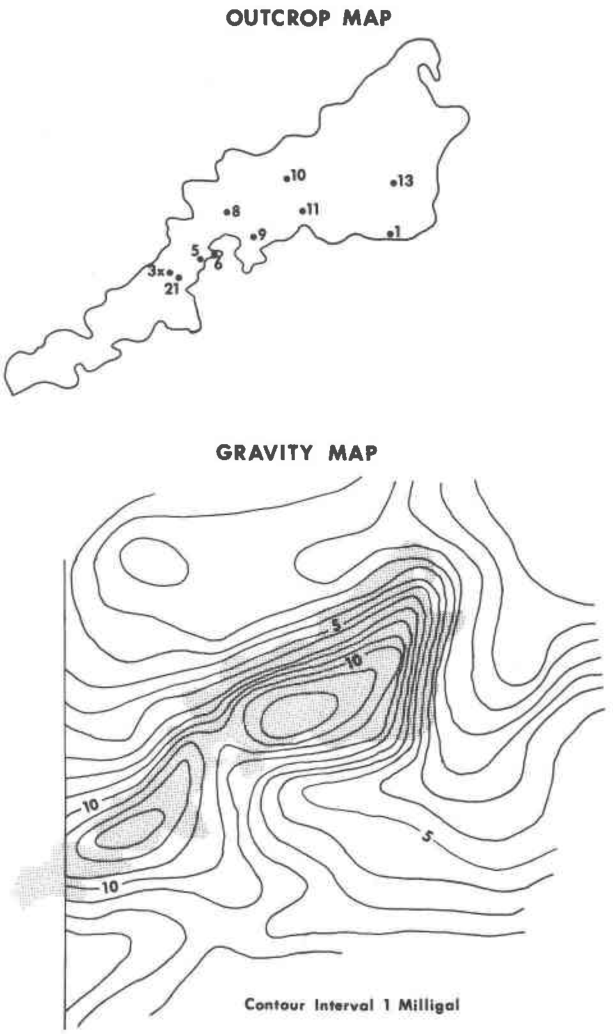

Fig. 2. Sketch maps illustrating the outcrop locations of gabbro samples described in the text (prefix DC is omitted) and the correspondence between the surface outcrop pattern of the pluton and the positive gravity anomaly measured by Popenoe and Bell (1975). The vertical line at the left of the gravity map is the western limit of Popenoe and Bell's study area.

in ferromagnesian minerals (arrow), which is also the order of decreasing modal olivine. As will be demonstrated, this sequence of samples, and the sequence of rock types delineated in the preceding paragraph, represent increasing differentiation. The outcrop distribution of these rock types will also be discussed later.

Accessory minerals vary systematically in the sequence of rock types. Sulfide minerals, especially pyrrhotite, are abundant in olivine gabbro (Table 1), but occur in only minor quantities in other members of the sequence. Pyrite is the predominant sulfide in altered gabbro. Magnetite and ilmenite are ubiquitous accessory minerals, but their abundance is lowest in olivine gabbro and increases in the sequence to hornblende–pyroxene gabbro, which contains 9–10 percent. Traces of hematite are present in pyroxene gabbro and significant quantities occur in hornblende–pyroxene gabbro. Apatite generally occurs only in pyroxene gabbro and hornblende–pyroxene gabbro, along with minor epidote and sericite.

Systematic textural variations occur among the various rock types. Hypidiomorphic granular or cumulate textures characterize olivine gabbro and anorthositic gabbro samples (Fig. 4A, B). In pyroxene gabbro and hornblende–pyroxene gabbro, large pyroxene and amphibole grains poikilitically enclose olivine, plagioclase, and sometimes opaque minerals (Fig. 4C, D). A few pyroxene oikocrysts occur in olivine gabbro and anorthositic gabbro, indicating that the abundance of pyroxene, especially clinopyroxene, determines whether the texture is predominately granular or poikilitic.

Superimposed on these primary textural variations are late-magmatic alterations. Hydrous mineral phases partially replace mafic minerals in some samples, as in Figure 4D where poikilitic pyroxene grains have been largely replaced by hornblende. As hydration and replacement become more pronounced, primary igneous textures are somewhat obscured by a myriad of reaction relationships among various minerals (Fig. 4E). Extensive deuteric alteration produces altered gabbro, readily recognized in hand specimen by coarse-grained textures and the distinctive green (hornblende) and purple to gray (plagioclase) crystals. Both prismatic and fibrous varieties of amphibole occur. Pyroxenes are partially or completely replaced by amphibole and biotite, and olivine is absent. Plagioclase laths are partially sericitized. Common accessory minerals are calcite, pyrite, hematite, and sphene.

Small xenoliths in the gabbro have sharp contacts with the host rocks, often delineated by reddish reaction rims suggesting oxidation of Fe (McSween, 1972). These rocks have fine-grained granular (hornfelsic) textures (Fig. 4F), and consist primarily of olivine, clinopyroxene, plagioclase, and magnetite. They are relatively free of hydrous phases, except for small quantities of biotite.

Mineral chemistry

Minerals in ten thin sections were analyzed using a MAC Model 400 electron microprobe with appropriate synthetic and natural standards. Data were reduced using an iterative routine that corrects for

Table 1. Modal analyses (volume percent)

Mineral	DC 8	DC 9	DC 10	DC 21	DC 13	DC 11	DC 5	DC 6	DC 1	DC 3x
Olivine	29.2	28.9	22.8	14.3	16.4	4.1	1.1*	1.2*	0.9*	12.4
Clinopyroxene	12.3	18.8	7.8	8.2	7.6	27.2	19.5	16.1	19.8	40.2
Orthopyroxene	6.7	2.7	8.6	9.2	9.1	7.5	13.7	7.3	7.7	-
Plagioclase	40.6	39.8	50.8	60.5	62.8	52.8	50.2	53.8	43.1	39.5
Biotite	8.3	7.6	7.8	0.6	0.5	4.5	7.0	15.3	1.9	0.1
Hornblende	0.8	0.7	0.5	1.6	0.1	0.3	4.0	3.5	17.2	-
Magnetite	0.3	0.2	0.5	3.2	2.0	2.0	2.3	1.3	3.4	7.8
Ilmenite	0.3	0.5	0.7	2.1	1.4	1.5	2.1	1.2	6.0+	-
Spinel	tr	-	tr	0.3	tr	tr	tr	-	-	-
Sulfides	1.5	0.8	0.5	tr	0.1	0.1	0.1	0.3	tr	tr
Apatite	-	-	-	-	-	tr	tr	tr	tr	-
No. Points	1547	1523	1547	1576	1500	1512	1512	1525	1560	1000

*olivine + iddingsite in partings

+ilmenite + hematite lamellae

DC 8, DC 9, DC 10 are olivine gabbro; DC 21, DC 13 are anorthositic gabbro; DC 11, DC 5, DC 6 are pyroxene gabbro; DC 1 is hornblende pyroxene gabbro; DC 3x is a granular xenolith.

background, atomic number, absorption, and fluorescence effects.

Mafic minerals in the Dutchmans Creek gabbro exhibit a remarkable compositional uniformity in any particular hand specimen, but systematic variations in Fe contents occur between the ferromagnesian silicates of different samples. Ferromagnesian silicates coexisting in the same analyzed thin section (represented by filled symbols) are connected by solid lines in Figure 5. Coexisting minerals in a granular xenolith

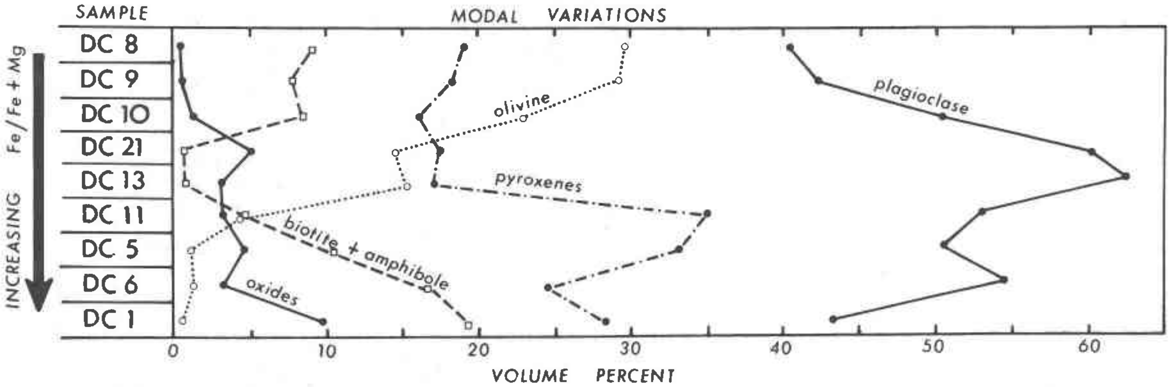

Fig. 3. Modal variations among analyzed gabbro samples (from Table 1). The samples are ordered from top to bottom by increasing Fe/(Fe+Mg) in the ferromagnesian minerals (advancing differentiation). DC 8, DC 9, DC 10 are olivine gabbro; DC 21, DC 13 are anorthositic gabbro; DC 11, DC 5, DC 6 are pyroxene gabbro; DC 1 is hornblende-pyroxene gabbro. Sample locations are shown in Fig. 2.

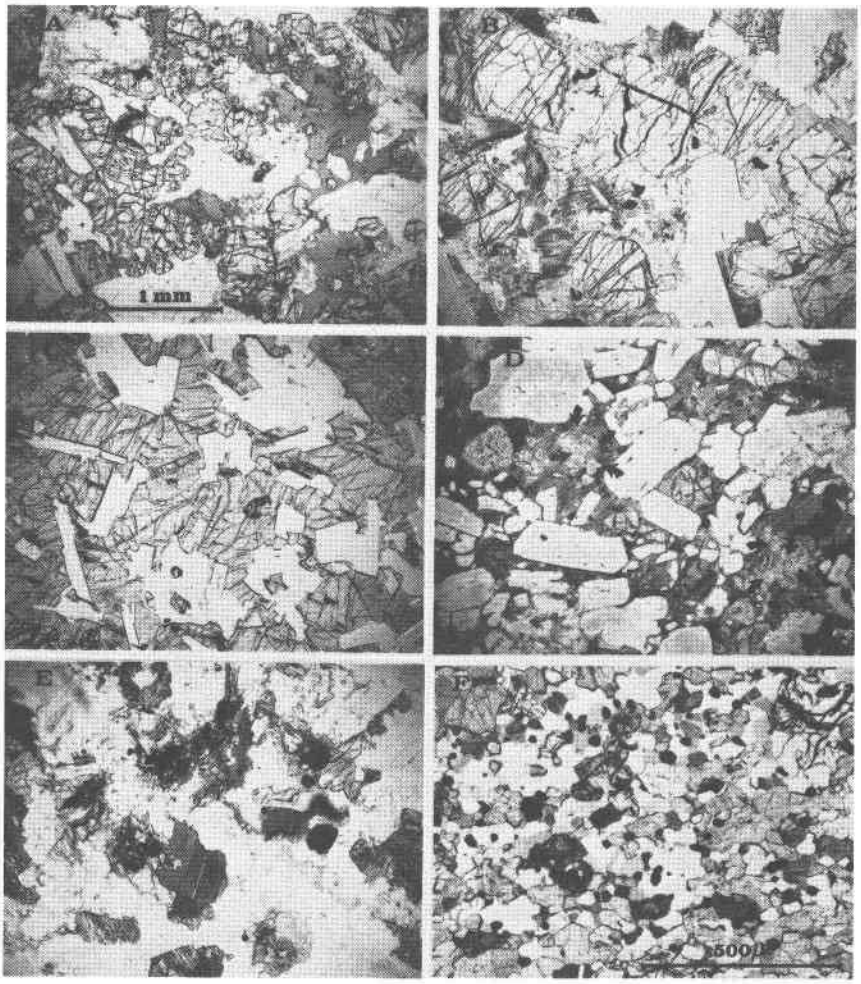

Fig. 4. Textural variations among gabbro samples. All photomicrographs in plane-polarized light to same scale as in (A), except (F). (A) Hypidiomorphic-granular texture in olivine gabbro (DC 8). (B) Cumulate texture formed of large euhedral olivines in olivine gabbro (DC 9). (C) Plagioclase and minor olivine enclosed poikilitically in large, optically-continuous clinopyroxene crystal in pyroxene gabbro (DC 11). (D) Clouded plagioclase, opaque minerals, and altered olivine poikilitically enclosed by hornblende in hornblende-pyroxene gabbro (DC 1). The amphibole is secondary, as evidenced by relict areas of clinopyroxene (arrows). (E) Late magmatic alteration of pyroxene gabbro (DC 5) in the form of biotite growth, replacement of orthopyroxene (Im) in anorthositic gabbro; scale as in (A). (C) Rims of red-brown biotite around magnetite/ilmenite in contact with plagioclase in pyroxene gabbro. (D) Vermicular intergrowths of magnetite with orthopyroxene host in pyroxene gabbro (reflected light). (E) Symplectite of aluminous orthopyroxene and plagioclase in pyroxene gabbro (DC 5) in the form of biotite growth, replacement of orthopyroxene by magnetite, and saussuritization of plagioclase. (F) Granular hornfelsic texture in xenolith (DC 3X) consisting of clinopyroxene, olivine, plagioclase, and magnetite (crossed nicols).

are connected by a dashed line. Complete analyses for pyroxenes and olivines are presented in Table 2 and for hydrous minerals in Table 3.

Clinopyroxene and lesser amounts of orthopyroxene are the dominant mafic minerals of most gabbro samples. Clinopyroxene typically occurs as large oikocrysts, although this phase also forms discrete grains in some granular rocks. Clinopyroxenes have a very limited compositional range, and plot in the augite field near the salite boundary on the pyroxene quadrilateral (Fig. 5). Clinopyroxenes in the analyzed hornfelsic xenolith (DC 3x) are more Mg-rich and Ca-poor than the corresponding phase in the enclosing gabbro (Fig. 5).

Orthopyroxene occurs generally as discrete subhedral to anhedral crystals, or less commonly as large oikocrysts enclosing plagioclase and olivine. This mineral is slightly pleochroic from pale pink to pale

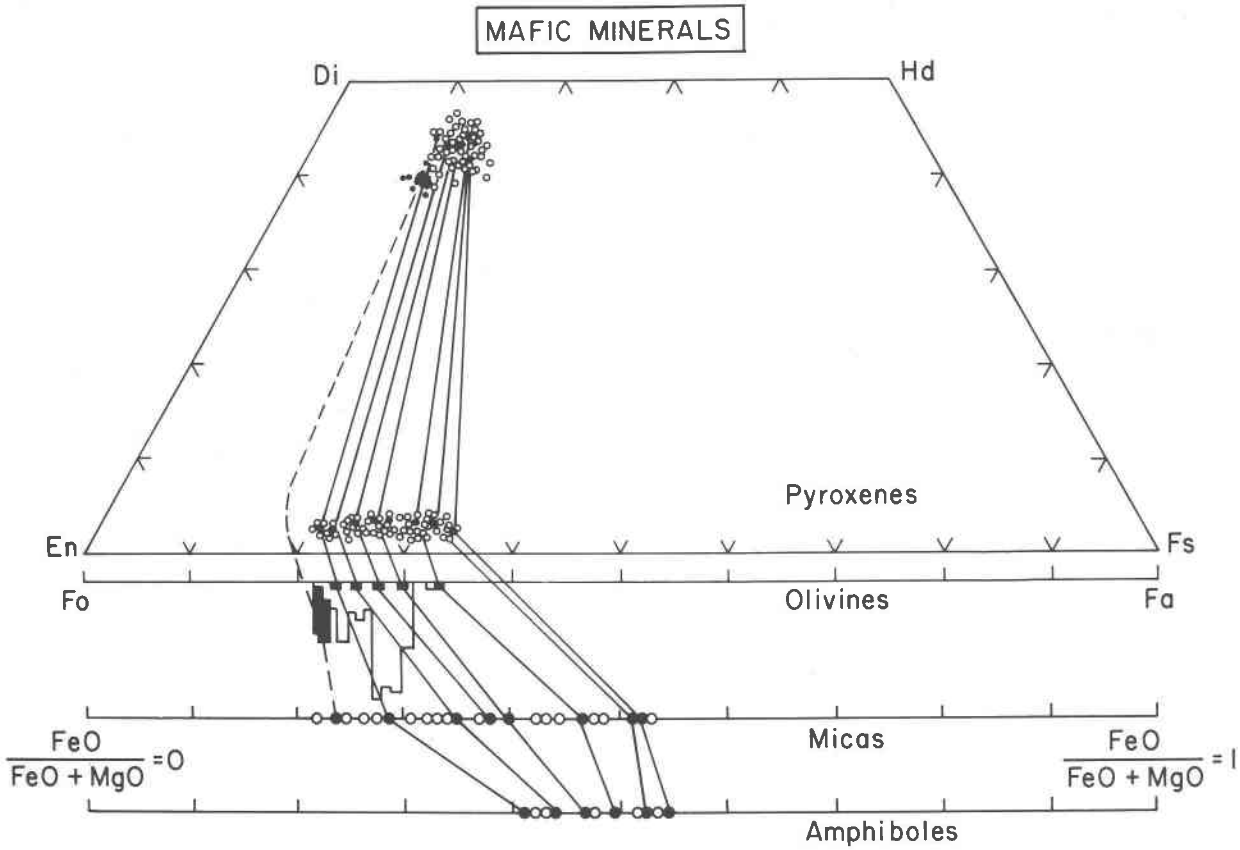

Fig. 5. Compositions of ferromagnesian silicates in gabbro samples. Minerals coexisting in the same sample (filled symbols) are connected by solid tie-lines. Coexisting phases in a granular xenolith are connected by a dashed line. The tie-lines represent the following samples from left to right: DC3x, DC 8, both DC 9 and DC 10, DC 21, DC 13, DC 11, both DC 5 and DC 6, DC 1.

green and often contains exsolution lamellae of clinopyroxene on (100). Orthopyroxenes also demonstrate a limited Fe-enrichment trend (Fig. 5), although hypersthene variations are greater than those in clinopyroxene.

The partitioning of Fe and Mg between coexisting orthopyroxene and clinopyroxene differs from most stratified gabbroic intrusions. K_D ($X_{Fe}^{opx}X_{Mg}^{cpx}/X_{Mg}^{opx}X_{Fe}^{cpx}$) values average 0.97, which is significantly different from the K_D value of 1.4 reported for most other bodies, but is very similar to the 0.94–1.09 range reported for the Jabal Sha'l' intrusion (Coleman *et al.*, 1977).

Minor elements in pyroxenes also show regular variations with increasing fractionation [*i.e.* increasing Fe/(Fe+Mg)]. The trends for Ti, Al, Cr, and Mn in pyroxenes are illustrated in Figure 6. Ti and Mn increase and Cr decreases with increasing Fe content of the pyroxenes (arrows). Clinopyroxenes have substantially lower Mn contents than coexisting orthopyroxenes.

Olivine occurs as large euhedral crystals in cumulate rocks (Fig. 4B), as subhedral to anhedral chadacrysts enclosed by pyroxene in poikilitic rocks (Fig. 4C), or as irregular interstitial grains in granular samples (Fig. 4A). It is characteristically fresh and unaltered in granular and cumulate rocks, but replacement by magnetite and iddingsite along internal partings occurs in pyroxene gabbro and hornblende–pyroxene gabbro. The olivine compositional range measured in all gabbroic rocks is Fo_{66-88}, and Fe-enrichment in olivines varies directly with Fe-enrichment in coexisting pyroxenes (Fig. 5). No compositional zoning in olivines was observed. Although the distribution of Fe and Mg between coexisting olivine and orthopyroxene is relatively insensitive to temperature, such data can be used to assess equilibrium between the two phases. The average K_D (Fe/Mg oliv/Fe/Mg opx) for Dutchmans Creek samples is 1.15, in close agreement with the experimentally-determined distribution coefficient of 1.12 (Medaris, 1969). Olivine in the hornfelsic xenolith (DC 3x) is

Table 2. Chemical analyses of pyroxenes and olivine (weight percent oxides by microprobe)

	Orthopyroxene		Clinopyroxene		Olivine	
	DC 8	DC 11	DC 8	DC 11	DC 8	DC 11
MgO	28.4	26.0	15.4	14.7	37.1	34.9
Al_2O_3	1.98	1.59	3.81	2.76	.34	.00
SiO_2	53.3	54.3	51.3	51.3	40.3	37.9
CaO	1.82	1.34	20.4	20.9	.00	.00
TiO_2	.38	.39	1.49	.77	.07	.04
Cr_2O_3	.18	.03	.07	.03	.00	.00
MnO	.28	.48	.26	.29	.35	.48
FeO	13.4	16.5	7.54	8.95	21.9	26.3
Total	99.74	100.65	100.27	99.70	100.06	99.62
	Atoms/6 Oxygens		Atoms/6 Oxygens		Atoms/4 Oxygens	
Mg	1.52	1.40	.85	.82	1.43	1.38
Al	.08	.07	.17	.12	-	-
Si	1.92	1.96	1.89	1.92	1.04	1.01
Ca	.07	.05	.81	.84	-	-
Ti	.01	.01	.04	.02	-	-
Cr	-	-	-	-	-	-
Mn	.01	.02	.01	.10	.01	.01
Fe	.40	.50	.23	.28	.47	.58
Total	4.01	4.01	4.00	4.01	2.95	2.98

Fo_{87-88}, apparently in equilibrium with the coexisting magnesian clinopyroxene, but not in equilibrium with the adjacent host anorthositic gabbro (DC 21), which contains olivine of Fo_{74-75}.

Biotite forms large irregular sheaths often intergrown with opaque minerals. This phase is highly pleochroic from cream or light tan to deep reddish-brown. The total Fe/(Fe+Mg) ratios of biotites vary sympathetically with the Fe contents of other ferromagnesian minerals (Fig. 5). Whether this variation in total Fe reflects progressive change in the oxidation state of Fe is not known. Assuming full octahedral-site occupancy, charge balance constraints from the reaction $Ti^{4+} + \square \rightleftarrows 2Fe^{2+}$ indicate the presence of some Fe^{3+} in all analyzed biotites, but no inference can be made from available microprobe data on the relative proportions of Fe^{2+} and Fe^{3+}. Biotites have high TiO_2 contents (4.2–5.0 weight percent, Table 3). The Na content of biotites decreases with increasing Fe/(Fe+Mg) (Table 3); Na in more highly differentiated rocks is incorporated into hornblende and plagioclase rather than biotite.

Amphibole occurs in most gabbro samples as small brownish-green crystals in reaction relationship with clinopyroxene. In more highly differentiated samples it has greater modal abundance, sometimes almost completely replacing clinopyroxene. Typical amphibole analyses are presented in Table 3. The total Fe content of the amphibole increases as the Fe content of other minerals (Fig. 5). A plot of (Na+K) *vs.* Si in amphiboles indicates that all are hornblendes intermediate in composition between the pargasite and edenite series (Fig. 7). Ti/Al ratios in hornblendes apparently increase with Fe/(Fe+Mg), as illustrated in Figure 7, lower diagram.

Plagioclase occurs as euhedral laths enclosed poikilitically by pyroxene or as larger more equant grains in granular or cumulate rocks. Many plagioclase crystals are clouded with abundant oriented needles of opaque inclusions. Individual grains are normally zoned, and plagioclase in hornblende–pyroxene gabbro is partially altered to sericite, epidote, and calcite. The measured compositional range for plagioclase in all gabbroic rocks analyzed is An_{41-76}, but plagioclase in any one specimen has a more restricted compositional range which varies with Fe content of the coexisting mafic minerals. For example, olivine gabbro sample DC 8, which has the most magnesian mafic phases observed in Figure 5, contains Ca-rich plagioclase of An_{61-76}; hornblende–pyroxene gabbro DC 1, containing the most Fe-rich mafic phases in Figure 5, has plagioclase compositions of An_{41-63}

Table 3. Chemical analyses of hydrous mineral phases (weight percent oxides by microprobe)

	Amphibole		Biotite	
	DC 8	DC 1	DC 8	DC 1
Na_2O	2.74	1.32	.85	.00
K_2O	1.38	.94	9.01	9.75
CaO	11.8	11.8	.01	.00
MgO	14.6	12.3	18.7	14.6
FeO	9.99	13.7	8.92	15.0
MnO	.09	.19	.03	.06
TiO_2	.45	3.50	5.39	5.19
Cr_2O_3	.11	.03	.01	.04
Al_2O_3	12.5	10.9	16.0	14.6
SiO_2	43.5	44.2	39.2	38.7
Total	97.16	98.88	98.12	97.94
FeO/FeO+MgO	.41	.53	.32	.51
	Atoms/24 (O,OH,F)		Atoms/12 (O,OH,F)	
Na	.78	.37	.12	.00
K	.26	.18	.81	.91
Ca	1.85	1.84	.00	.00
Mg	3.20	2.68	1.96	1.58
Fe	1.23	1.67	.52	.91
Mn	.01	.02	.00	.00
Ti	.05	.38	.29	.28
Cr	.01	.00	.00	.00
Al	2.17	1.88	1.32	1.25
Si	6.41	6.46	2.75	2.81
	15.97	15.48	7.77	7.74

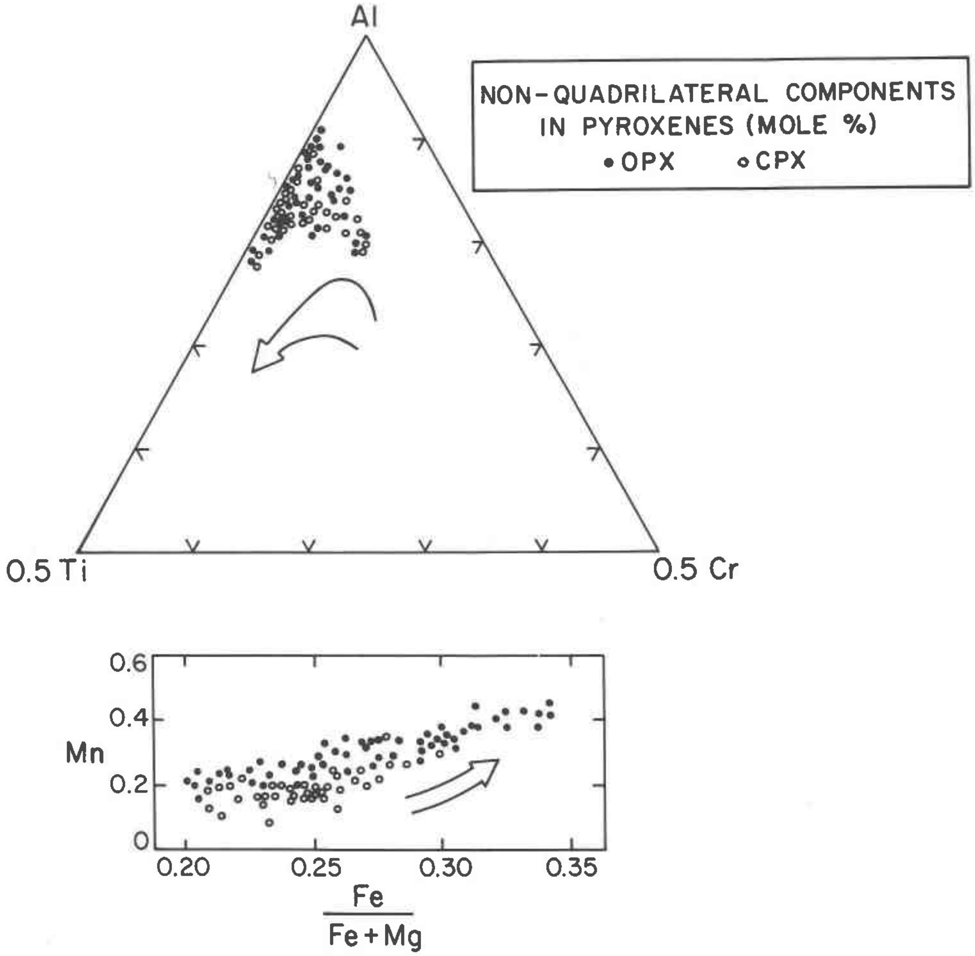

Fig. 6. Minor element variations in orthopyroxenes and clinopyroxenes. Top: Cr decreases and Ti increases with increasing Fe/(Fe+Mg) (arrow). Bottom: Mn varies sympathetically with Fe/(Fe+Mg); orthopyroxenes have consistently higher Mn contents than clinopyroxenes.

(Fig. 8). The K_2O content of plagioclase, expressed as mole percent orthoclase, is very low but increases slightly with increasing albite component (Fig. 8).

Fe–Ti oxides are present in all gabbroic rocks, either as discrete crystals or connected grains with sharp, straight boundaries (Fig. 9A). The magnetite–ilmenite pairs analyzed ($Mt_{99}Usp_1$ and $Ilm_{94-86}Hm_{6-14}$) have undergone subsolidus reequilibration and do not define an oxygen fugacity or temperature of crystallization. Most ilmenite grains contain considerable Mg, with formulae approximately corresponding to $Fe_{0.9}Mg_{0.1}TiO_3$. Both oxide phases occur as individual homogeneous grains in olivine gabbro and anorthositic gabbro. Minor oxidation of ilmenite to hematite occurs in pyroxene gabbro samples, and thick, subparallel lamellae of hematite are present within ilmenite in hornblende–pyroxene gabbro (Fig. 9A). Minor amounts of green hercynitic spinel occur in association with Fe–Ti oxides in all rock types except hornblende–pyroxene gabbro. The green spinel, which commonly occurs at the boundary between magnetite and ilmenite (Fig. 9B), has compositions which vary from about $(Mg_{0.65}Fe_{0.35})Al_2O_4$ in olivine gabbro and anorthositic gabbro to $(Mg_{0.55}Fe_{0.45})(Fe_{0.1}Al_{1.9})O_4$ in pyroxene gabbro.

Sulfide minerals occur as rounded blebs in all rock types except hornblende–pyroxene gabbro, but are especially abundant in olivine gabbro. The blebs consist predominantly of pyrrhotite with lesser amounts of pyrite, chalcopyrite, and pentlandite.

Apatite forms large euhedral crystals in pyroxene gabbro and hornblende–pyroxene gabbro. Other accessory minerals in these two rock types include epidote and sericite as alteration products of plagioclase.

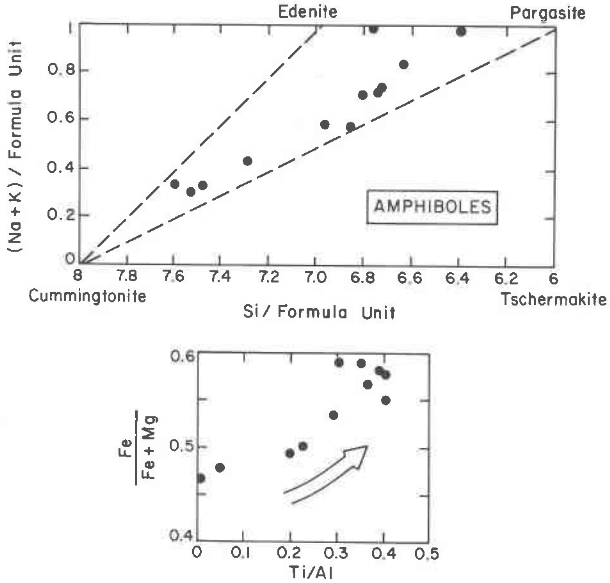

Fig. 7. Compositional variations of amphiboles based on 24 (O,OH,F). Top: hornblendes fall between pargasite and edenite series. Bottom: Ti/Al ratio increases with Fe/(Fe+Mg).

Mineral reactions and the crystallization sequence

The order of crystallization for most minerals can be determined from a synthesis of modal, textural, and chemical data. The progressive sequence of Fe-enrichment in coexisting ferromagnesian minerals presumably represents increasing differentiation. Modal mineralogy, and consequently rock type, vary systematically with increasing Fe/(Fe+Mg) ratios in the silicates. Modal variations in the rock samples ordered by increasing ferromagnesian silicate Fe contents (Fig. 3) suggest the following primary crystallization model: early crystallization and accumulation of olivine, followed closely by Fe–Ti oxides and plagioclase (olivine gabbro); steady depletion of olivine with increasing crystallization of magnetite/ilmenite and plagioclase (anorthositic gabbro); continued precipitation of opaque minerals, with further reduction of plagioclase crystallization and near exhaustion of olivine, formation of large quantities of pyroxene (pyroxene gabbro); continued crystallization of magnetite/ilmenite, pyroxenes, and some plagioclase, stabilization of amphibole relative to clinopyroxene (hornblende–pyroxene gabbro). This proposed sequence is consistent with the progressive change in plagioclase toward more sodic compositions in the series. It is also supported by textural constraints, such as the euhedral shapes of olivine and opaque minerals in early cumulate rocks, the enclosing of olivine, plagioclase, and opaque minerals by pyroxenes, *etc.*

The presence of rounded sulfide blebs of uniform mineralogy in early-crystallized rocks suggests that these represent immiscible globules suspended in the crystallizing magma, analogous to sulfide blebs observed in Hawaiian tholeiitic lava lakes (Skinner and Peck, 1969). These dense globules may have settled with cumulate phases in early differentiates. The rounded shapes of some blebs have been modified by growing silicate crystals abutting or impinging on the globules.

This sequence of primary crystallization is complicated by a complex assortment of late-magmatic reaction relationships between coexisting minerals. Among different samples the pervasiveness of these mineral reactions increases with increasing fractionation, *i.e.* increasing Fe/(Fe+Mg) ratios of the ferromagnesian silicates. Examples of the following reaction relationships can be found in almost all of the gabbroic rocks, but they are especially well developed in pyroxene gabbro and hornblende–pyroxene gabbro. Most of the mineral reactions observed are similar to those described in other Piedmont gabbros (Hermes, 1968; Medlin *et al.*, 1972) with one notable exception: complex reaction coronas of pyroxenes and hornblende around olivine grains in rocks from other plutons are absent in Dutchmans Creek samples.

Biotite is almost invariably associated with opaque minerals, characteristically forming rims around the magnetite and ilmenite, especially where these are in contact with plagioclase (Fig. 9C). Spectacular reaction relationships between orthopyroxene and magnetite are illustrated by vermicular intergrowths of magnetite in hypersthene (Fig. 9D). Goode (1974)

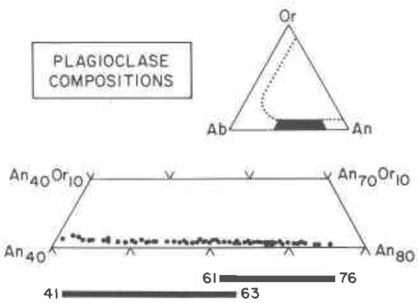

Fig. 8. Plagioclase compositions fall within black area of the triangular inset. Analyses from all samples indicate a range of An_{41-76}. However, each individual sample has a more restricted range which varies with compositions of the mafic minerals. Sample DC 8 contains plagioclase in the range An_{61-76} (upper bar); plagioclase in DC 1 has An_{41-63} (lower bar).

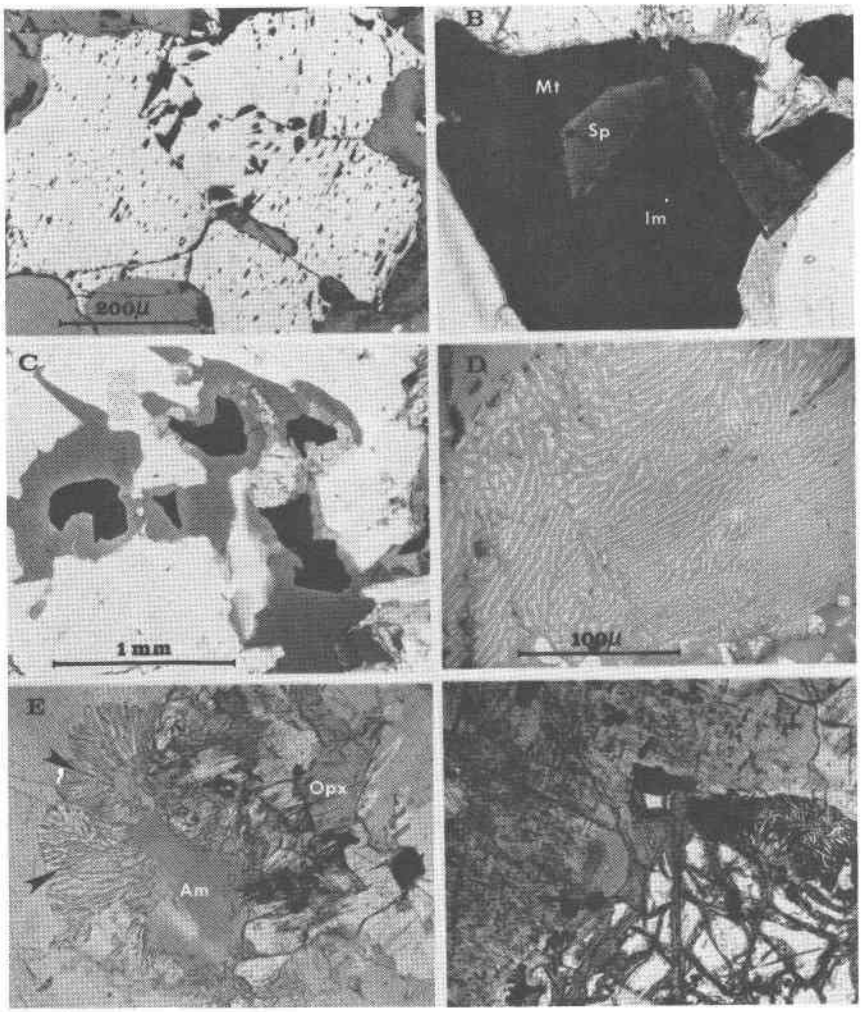

Fig. 9. Mineral reactions in gabbro samples. (A) Euhedral magnetite crystal (center) surrounded by ilmenite grains in hornblende–pyroxene gabbro (reflected light). White subparallel lamellae in ilmenite are hematite formed by subsolidus oxidation. (B) Intergrowth of green spinel (Sp) with magnetite (Mt) and ilmenite (Im) in anorthositic gabbro; scale as in (A). (C) Rims of red-brown biotite around magnetite/ilmenite in contact with plagioclase in pyroxene gabbro. (D) Vermicular intergrowths of magnetite with orthopyroxene host in pyroxene gabbro (reflected light). (E) Symplectite of aluminous orthopyroxene and plagioclase in pyroxene gabbro (arrows). The intergrowth abuts amphibole (Am) and orthopyroxene (Opx) being replaced by magnetite; scale as in (A). (F) Olivine grain (lower right) in pyroxene gabbro replaced by iddingsite along internal partings. The olivine is enclosed poikilitically by pyroxene, which has reacted to form magnetite and minor amphibole (dark spots perpendicular to Bushveld-type to exsolution lamellae). Scale as in (A).

has explained similar orthopyroxene–magnetite symplectites as resulting from subsolidus oxidation of olivine in the compositional range Fo_{63-75}. This corresponds to the range of olivine compositions (Fo_{71-75}) in which symplectic intergrowths occur in the Dutchmans Creek samples. Symplectic intergrowths of aluminous orthopyroxene and calcic plagioclase (Fig. 9E) are also common in pyroxene gabbro samples. These symplectic pyroxenes have Fe/(Fe+Mg) ratios identical to other orthopyroxenes in the host rock, but higher Al_2O_3 contents (3.4–3.8 weight percent). Associated plagioclase is more Ca-rich (An_{79}) than adjacent plagioclase grains ($\sim An_{50}$). These intergrowths may represent early-settling glomerocrysts that have partially reacted. Although reaction rims of pyroxene and hornblende around olivine are not observed, the rare olivine grains in pyroxene gabbro and hornblende–pyroxene gabbro are replaced along partings by iddingsite and/or magnetite (Fig. 9F). Hornblende commonly replaces clinopyroxene along grain boundaries. In hornblende–pyroxene gabbro, hornblende completely replaces large poikilitic clinopyroxene crystals except for a few small relict areas, with only minor alteration of the textures of the enclosed plagioclase and magnetite (Fig. 4D). Few olivine grains or relicts are contained in these oikocrysts, indicating that olivine was practically exhausted as a liquidus phase before this melt crystallized.

The mineral reactions described in the preceding paragraph are apparently late-magmatic changes produced by local equilibrium between early crystallizing phases and residual volatile-rich melt. A summary of the combined crystallization and reaction sequence inferred from petrographic observation of Dutchmans Creek rocks is as follows:

(1) *early magmatic*—separation of immiscible sulfide blebs from the silicate melt; olivine, plagioclase, and primary magnetite and ilmenite crystallize from the melt; settling of early-crystallizing phases to produce some cumulate rocks and fractionated liquid;

(2) *intermediate magmatic*—crystallization of orthopyroxene and clinopyroxene, enclosing pre-existing grains poikilitically; crystallization of apatite and continued crystallization of plagioclase and opaque minerals;

(3) *late magmatic*—reactions between residual melt and (a) orthopyroxene to form magnetite, (b) magnetite and ilmenite to stabilize biotite, (c) clinopyroxene to form hornblende; recrystallization of opaque minerals, reaction between mgnetite and ilmenite to form green spinel, and subsolidus oxidation of ilmenite to form hematite.

This third (late-magmatic) stage of reaction is well developed only in more highly differentiated rocks, such as pyroxene gabbro and hornblende–pyroxene gabbro. All samples, however, exhibit some late-magmatic mineral reactions. The proposed crystallization model is similar to the sequence advocated by Hermes (1968) for the Mecklenburg gabbro, although the early magmatic crystallization of Fe–Ti oxides and the lack of late-magmatic development of olivine coronas distinguish the Dutchmans Creek rocks. Similarly, there is little evidence that significant quantities of opaque minerals ever precipitated directly from the melt at any time during the crystallization of the Buffalo pluton (Medlin *et al.*, 1972), and olivine coronas are well developed in these rocks as well. Medlin *et al.* also indicated that clinopyroxene, along with olivine and plagioclase, were early-crystallizing minerals.

Areal variations within the pluton

The two previously-published detailed studies of Piedmont gabbros (Hermes, 1968; Medlin *et al.*, 1972) found few systematic variations in petrographic properties or mineral chemistry that correlated with location within the plutons. Hermes did report that rocks with poikilitic textures occurred near Mecklenburg pluton margins, while granular rocks containing more hydrous phases were common in the interior portions. The Dutchmans Creek gabbro is an irregularly-shaped, elongate intrusion (Fig. 1), in contrast to the more circular outlines of the other plutons. This irregularity in shape makes a clear definition of areal variations within the body extremely difficult. The locations of the gabbro samples analyzed in detail (Fig. 2) suggest that rocks from the pluton interior (olivine gabbro, anorthositic gabbro) have cumulate or granular textures and are less differentiated than the poikilitic rocks near pluton margins (pyroxene gabbro, hornblende–pyroxene gabbro), but such a conclusion is tenuous because of the limited number of samples. However, the analyzed samples indicate one readily-observable index of differentiation in these rocks: the modal content of olivine. The proportion of olivine decreases regularly with increasing differentiation, as is clearly indicated in Figure 3. We have estimated olivine contents in a representative number (43) of thin sections from other parts of the pluton, and find that rocks bearing appreciable quantities of olivine ($\geq$10 percent) appear to be concentrated only in the pluton interior (Fig. 10). We therefore suggest that the Dutchmans Creek pluton exhibits a regular areal variation in rock types (and therefore mineral chemistry, since the two are linked) caused by differentiation.

At face value, this areal variation in rock types suggests that fractional crystallization has proceeded from the interior outwards to the pluton margins. However, this appearance may result from erosional exposure of the pluton to different levels. The interior portions of the pluton represent lower topographic levels than the pluton margins because of erosion to deeper levels. Olivine gabbro and anorthositic gabbro, both of which are probably cumulates, have been collected from topographic levels of 230–300 feet, whereas pyroxene gabbro and hornblende–pyroxene gabbro have been collected from the 270–400-foot contour interval. Therefore, it is more likely that the pluton may have crystallized from different batches of magma successively invading the chamber minerals, and the higher portions of the chamber were predominantly the residual liquid. Butler and Ragland (1969) indicated that layering in other gabbro plutons in the Piedmont is rarely well-defined, and the few occurrences noted were suggested to result from flowage rather than gravitational crystal

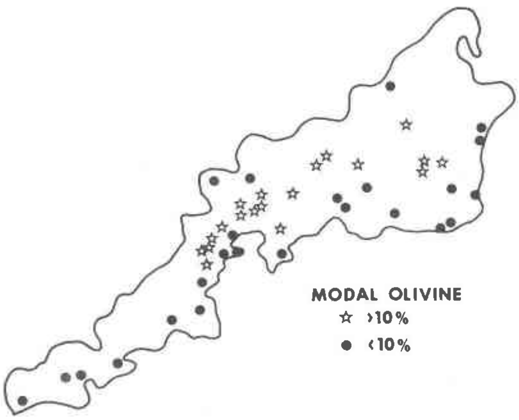

Fig. 10. Distribution of rocks containing >10 percent and <10 percent modal olivine in the Dutchmans Creek gabbro. Rocks containing appreciable olivine outcrop in the interior portions of the pluton.

settling. It is possible, however, that the scale of layering in these plutons is too great to be seen in boulders or small outcrops.

The possibility that different stratigraphic levels of the pluton may have crystallized from different batches of magma successively invading the chamber (Coleman *et al.*, 1977) cannot be excluded. However, such a complex model does not seem to be necessary for this pluton.

The influence of water

From the abundance of hydrated phases in all samples of the Dutchmans Creek gabbro, it is evident that this magma contained an appreciable quantity of water, although a quantitative statement cannot be made. The high dissolved water content is responsible for many of the petrographic features observed in these rocks. Hermes (1968) noted that the Mecklenburg gabbro also crystallized at high PH_2O, and the following discussion may apply to other Piedmont plutons as well.

Ca-rich pyroxenes in the Dutchmans Creek gabbro, as well as the Buffalo and the Mecklenburg gabbros, exhibit a very restricted Fe-enrichment trend (Fig. 5) similar to pyroxenes from other hydrous gabbroic intrusions, such as the Marangudzi ring complex, Rhodesia (Hossain, 1977), the Guadalupe complex, California (Best and Mercy, 1967), and the Jabal Sha'l' gabbro, Saudi Arabia (Coleman *et al.*, 1977). Fe-enrichment in clinopyroxenes crystallized from hydrous magmas may be prevented because clinopyroxene is a stable liquidus phase for only a short crystallization interval, after which biotite and hornblende become stable phases (Best and Mercy, 1967).

The early crystallization of some magnetite with magnesian olivine in the Dutchmans Creek pluton is likely a result of relatively high water content and the high concomitant fO_2 values (Kennedy, 1955; Osborn, 1962; Hamilton *et al.*, 1964). During fractional crystallization at high fO_2, magnetite and olivine coprecipitate and the residual liquid is enriched in silica (the Bowen trend), whereas at low fO_2, Fe-rich olivine crystallizes without magnetite and the residual melt is more Fe-rich (the Fenner trend). The leucocratic dikes which crosscut the pluton are especially abundant in more highly differentiated marginal rocks and may represent a late-stage, silica-enriched melt. The observed early precipitation of magnetite in the Dutchmans Creek magma conflicts with the interpretation of Butler and Ragland (1969) that opaque minerals in Piedmont gabbros were late in the crystallization sequence because of solidification under conditions of lower fO_2. However, it should be noted that although there is some cumulate magnetite in early differentiates of the Dutchmans Creek pluton, much of the magnetite appears later in the crystallization sequence (Fig. 3). Euhedral cumulate olivine has not been reported in other post-metamorphic gabbros of the Piedmont (Hermes, 1968; Medlin *et al.*, 1972).

The water was probably dissolved in the magma prior to emplacement, rather than being absorbed by diffusion from the surrounding country rocks after intrusion. Shaw (1974) has argued that hydration of a magma by diffusion is probably limited to within several tens of meters of the pluton contacts, and isotope systematics indicate that water circulating near the margins of intrusions is mostly absorbed only after significant crystallization has occurred (Taylor, 1974; Taylor and Forester, 1971, 1973; Sheppard *et al.*, 1977).

Comparison with other plutons

The problem

The Dutchmans Creek pluton is similar to other post-metamorphic gabbro intrusions in the southern Appalachian Piedmont, such as the Buffalo and Mecklenburg gabbros. However, a detailed comparison suggests that the Dutchmans Creek gabbro has been differentiated, and *systematic,* albeit subtle, variations occur, whereas the other two plutons are largely undifferentiated, and variations are *unsystematic* (Hermes, 1968; Medlin *et al.*, 1972). The distribution of modal olivine, which varies regularly enough to be an index of differentiation in the Dutchmans Creek pluton, is random in other plutons. This major difference, together with the presence of early-crystallizing Fe–Ti oxides and absence of olivine coronas in Dutchmans Creek rocks, suggests that the crystallization history of this pluton was somehow different from other plutons with which it has been compared in this study.

A possible solution

It was previously noted that the close correspondence between topography and the pluton margins and included roof pendants indicates that much of the Dutchmans Creek pluton has been barely unroofed by erosion. An increase in temperature and confining pressure with depth in a magma chamber could result in a tendency for dissolved water to concentrate in the uppermost portions of the chamber (Kennedy, 1955), especially if it separates as a distinct aqueous phase (Burnham, 1967). This concentration of water would result in higher oxygen fugacities during crystallization. This difference may explain the early crystallization of Fe–Ti oxides, and later subsolidus oxidation of ilmenite to hematite. Other bodies, such as the Mecklenburg and Buffalo complexes, may represent deeper levels exposed by erosion. It is possible that the upper portions of these magma chambers were similar to the Dutchmans Creek pluton as now exposed, and that deeper levels of the Dutchmans Creek pluton are characterized by lower water contents and oxygen fugacities. The increased water content in magma at the roof of the chamber may also have resulted in (1) lower liquidus temperatures and therefore later crystallization, and (2) more pervasive late-magmatic mineral reactions.

Vertical inhomogeneity of the pluton in terms of water content is more likely than horizontal variation. Migration of water to the contacts of the pluton (the Soret effect) is minimal because of the negative temperature-dependence of water solubility in magma and slow diffusion rate of water or its ionic products (Burnham, 1967). However, a separated aqueous phase could rise due to gravity effects.

Such a vertical structure in Piedmont gabbro plutons may also be suggested by the presence of hornfelsic, largely anhydrous xenoliths. Xenoliths in the Dutchmans Creek pluton contain highly magnesian olivines that are larger than the other granular mineral grains and may be partially resorbed phenocrysts. The mineral chemistries of the xenoliths are obviously more primitive (less Fe-rich) than the enclosing gabbro (DC 3x, Fig. 5). We suggest that these mineral segregations may represent early-crystallized magma, possibly rafted upward from below during magma intrusion. These xenoliths crystallized at lower PH_2O (evidenced by general lack of hydrous minerals) and fO_2 (suggested by red oxidized reaction rims on the xenoliths) than the enclosing gabbro. Alternatively, the xenoliths could be formed by sinking of pieces of the upper chilled margin which crystallized before significant quantities of water could migrate upward. Medlin *et al.* (1972) described similar granular xenoliths in the Buffalo pluton as "segregated mineral clusters," and these may have originated in a similar manner.

Conclusions

The Dutchmans Creek intrusion crystallized under conditions of relatively high PH_2O and fO_2. Although similar in many respects to other post-metamorphic gabbros in the Piedmont, the Dutchmans Creek pluton has several unique characteristics which may result from the fact that the intrusion has barely been unroofed by erosion and only the uppermost regions of the magma chamber are visible. Topographically lower portions of the pluton appear to have crystallized before more differentiated roof rocks, possibly as a result of crystal settling and water migration to the top of the chamber with subsequent lowering of liquidus temperatures in the volatile-rich portions of the chamber. Early crystallization of olivine and magnetite prevented significant Fe-enrichment trends in ferromagnesian minerals. The high dissolved water content facilitated diffusion and augmented a series of late-magmatic mineral reactions, which are especially well developed in more highly differentiated marginal samples.

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