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I am submitting herewith a thesis written by Leslie F. Noble entitled "Investigation Of Layering In The Rock Hill Gabbro Pluton, South Carolina." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

Harry Y. McSween, Jr.

Harry Y. McSween, Jr., Major Professor

We have read this thesis
and recommend its acceptance:

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Lawrence A. Taylor

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Accepted for the Council:

CW Minkel

Associate Vice Chancellor and
Dean of The Graduate School

INVESTIGATION OF LAYERING IN THE ROCK HILL GABBRO PLUTON, SOUTH CAROLINA

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Leslie F. Noble

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ABSTRACT

A 400 m.y.-old mafic pluton intrudes the Charlotte Belt at Rock Hill, South Carolina. The pluton is predominantly massive anorthositic gabbro, containing occasional pegmatitic anorthosite lenses. Troctolite comprises less than half of the portion of the pluton studied, and contains discontinuous layering features and anorthosite lenses. Both rock units contain areas of alteration to metagabbro, mostly located along fractures, but the pluton is not otherwise significantly affected by metamorphism. Neither field relationships, petrography, nor mineral chemistry reveal a clearly systematic distribution pattern for the anorthositic gabbro and troctolite units.

Plagioclase compositions analyzed by electron microprobe in samples of either main lithology range from An 64 to An 83. Likewise, the range of olivine compositions analyzed is from Fo 77 to Fo 84. Two distinct pyroxene compositions are found: augite ($En_{42}Fs_{12}Wo_{46}$) and bronzite ($En_{79}Fs_{20}Wo_{1}$). The stratigraphic distribution of lithologies, crystal sizes, and mineral compositions was a focus of this investigation; however, no systematic modal or cryptic layering was discovered.

Textural and modal differences between the units must be explained without classical

fractional crystallization as a major mechanism; models used to explain similar phenomena elsewhere are considered. The Rock Hill pluton probably formed its two modally and texturally distinct units through a mechanism of alternating convection cells and density-currents, as suggested by Irvine (1987) for Skaergaard.

Finally, the association of gabbro and metagabbro is discussed. Based on observations made in this investigation, the metagabbro is thought to have formed along fracture surfaces where water was available. This conclusion differs from previous hypotheses that gabbro and metagabbro represent distinct intrusions of different age.

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1. INTRODUCTION

Problem Defined

The Rock Hill pluton is one of an arcuate chain of 400 m.y.-old gabbro bodies extending from Georgia through the Carolinas (Figure 1). These plutons generally share several characteristics, including the following: mesoscopic or cryptic layering has not been reported from any of the intrusions [except the Rock Hill pluton (Chalcraft, 1970)], and the plutons are usually associated with metagabbro which commonly surrounds the unaltered gabbro (McSween et al., 1984). The apparent restriction of layering to only the Rock Hill pluton out of the numerous intrusions to which it is presumably genetically related is intriguing. Likewise, anorthositic gabbro has not been reported as a predominant lithology in the related plutons, yet is a distinct mappable unit at Rock Hill (Figure 2). The relationship of the ubiquitous metagabbro associated with these plutons has long been problematic. This study investigates both the unique layering and petrology of the Rock Hill pluton and the association of gabbro and metagabbro.

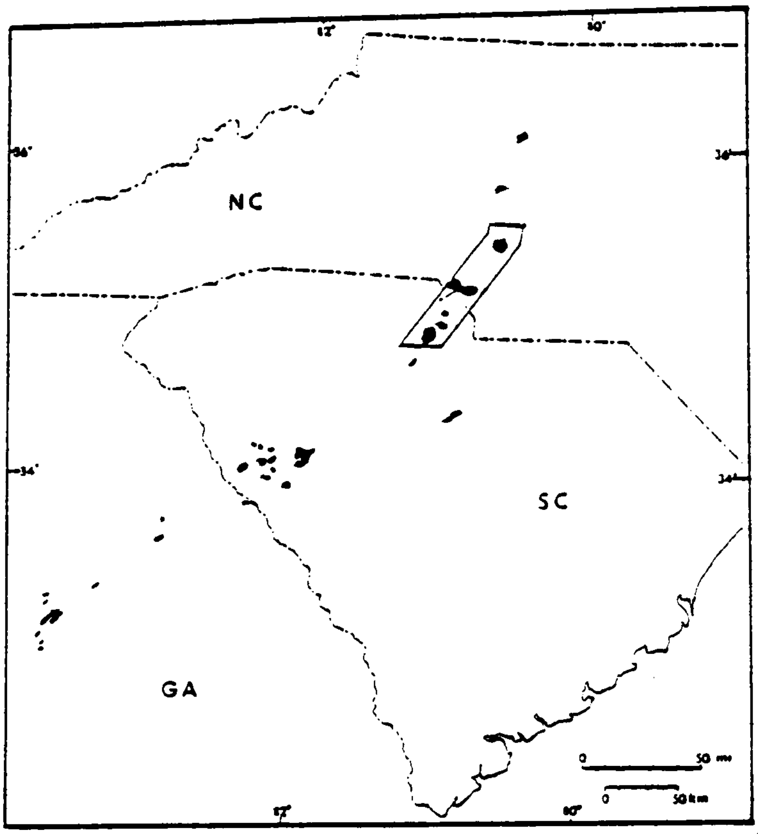
Layering characteristics at Rock Hill are best observed in well-exposed areas. Since the Rock Hill pluton is quarried for crushed stone by Martin Marietta Corporation, an excellent three-dimensional exposure in one portion of the pluton is available.

Figure 1

Rock Hill Pluton in Setting of Related Intrusions.

Regional location map showing outcrops of ~400 m.y.-old gabbroic plutons; Rock Hill and immediately adjacent plutons in the box are enlarged at lower right. The subject of this thesis is the South Rock Hill pluton.

(Adapted from McSween et al., 1984)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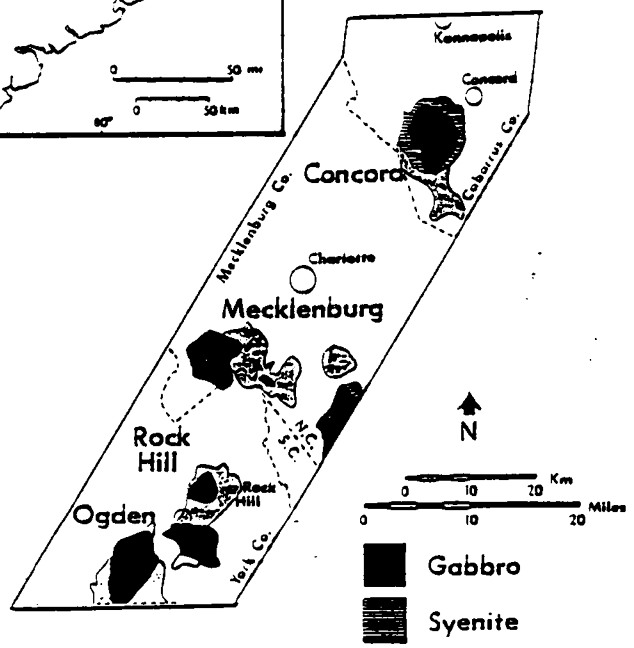
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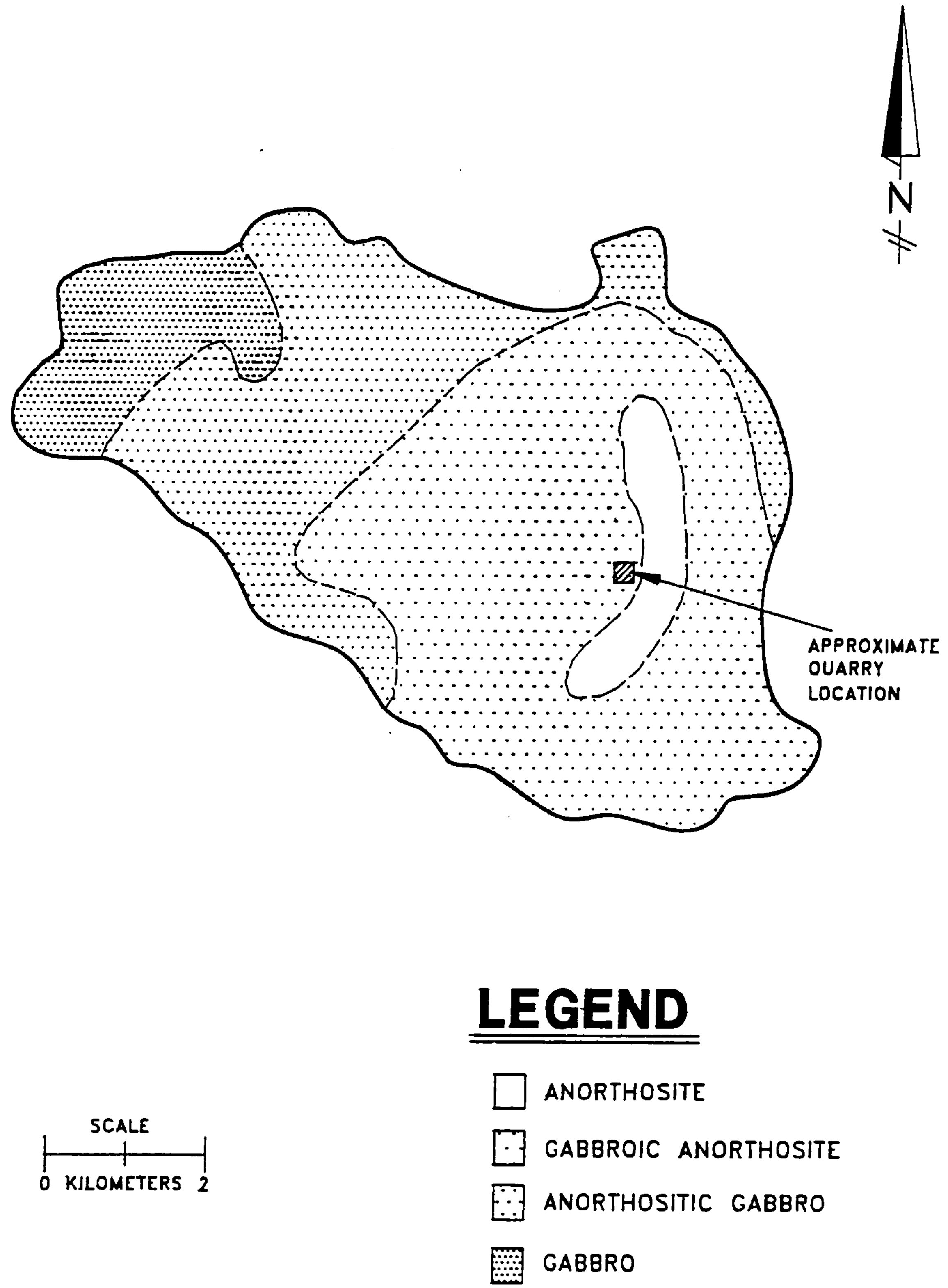
York Co.
N
0
10
20
Km
0
10
20
Miles
Gabbro
Syenite
Metagabbro
Charlotte Belt
Rocks Undivided

Figure 2

Internal Petrography of Rock Hill Pluton (after Chalcraft, 1970).

Geologic map of the Rock Hill gabbro pluton (after Chalcraft, 1970), including location of the subject quarry. The rock types indicated in the legend are those assigned by Chalcraft (1970), and do not necessarily correlate with the nomenclature for rock unit names used in this thesis (see text).


N
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SCALE
0 KILOMETERS 2

The quarry is located in the east-central part of the pluton (Figure 2) immediately adjacent to an area previously mapped as anorthosite (Chalcraft, 1970), perhaps due to the toughness of that lithology for use as aggregate stone. Both in the discarded tailings of the quarry operation and in the weathered boulders elsewhere in the city of Rock Hill, several characteristics suggesting layering are evident. At least three distinct rock types are present: anorthositic gabbro, troctolite, and metagabbro. Along with the outcrop-scale layering noticed in weathered boulders, the occurrence of both anorthositic gabbro and troctolite in the quarry tailings and the distinct lithologic zones identified by Chalcraft (1970) (Figure 2) led to the hypothesis that this pluton may be a layered mafic intrusion (Butler, 1966; Chalcraft, 1970; Wagener, 1974).

The occurrence of metagabbro in the Rock Hill quarry presents an opportunity to solve the problem of the gabbro-metagabbro association which has perplexed workers on this series of intrusions for many years (Butler, 1966; Hermes, 1968; Wagener, 1974; McSween et al., 1984). To investigate the layering features and the gabbro-metagabbro association, permission was obtained from Martin Marietta Corporation to sample extensively within the Rock Hill Quarry. The result is the most thorough study to date of stratigraphic relationships in one of these intrusions.

In this study, petrography and mineral chemistry of the various rock types are examined, compared, and placed in stratigraphic context. Results of electron microprobe analyses of samples from two vertical traverses in the two predominant lithologic units (anorthositic gabbro and troctolite) are presented. Modal data for those specific traverses and for numerous other samples are examined for evidence of graded layering or other subtle changes in lithology. The petrogenetic significance of the observed variations and consistencies is considered. Finally, the metagabbro and its relationship to the other rock types are discussed, resolving the gabbro-metagabbro problem for this pluton and possibly for other genetically related plutons as well, since metagabbro at Rock Hill matches descriptions of metagabbro associated with the other nearby gabbro plutons.

Methods

In order to address the specific areas of interest which are the focus of this study, field work, petrographic analyses, and mineral chemistry analyses were performed. Methods are explained below.

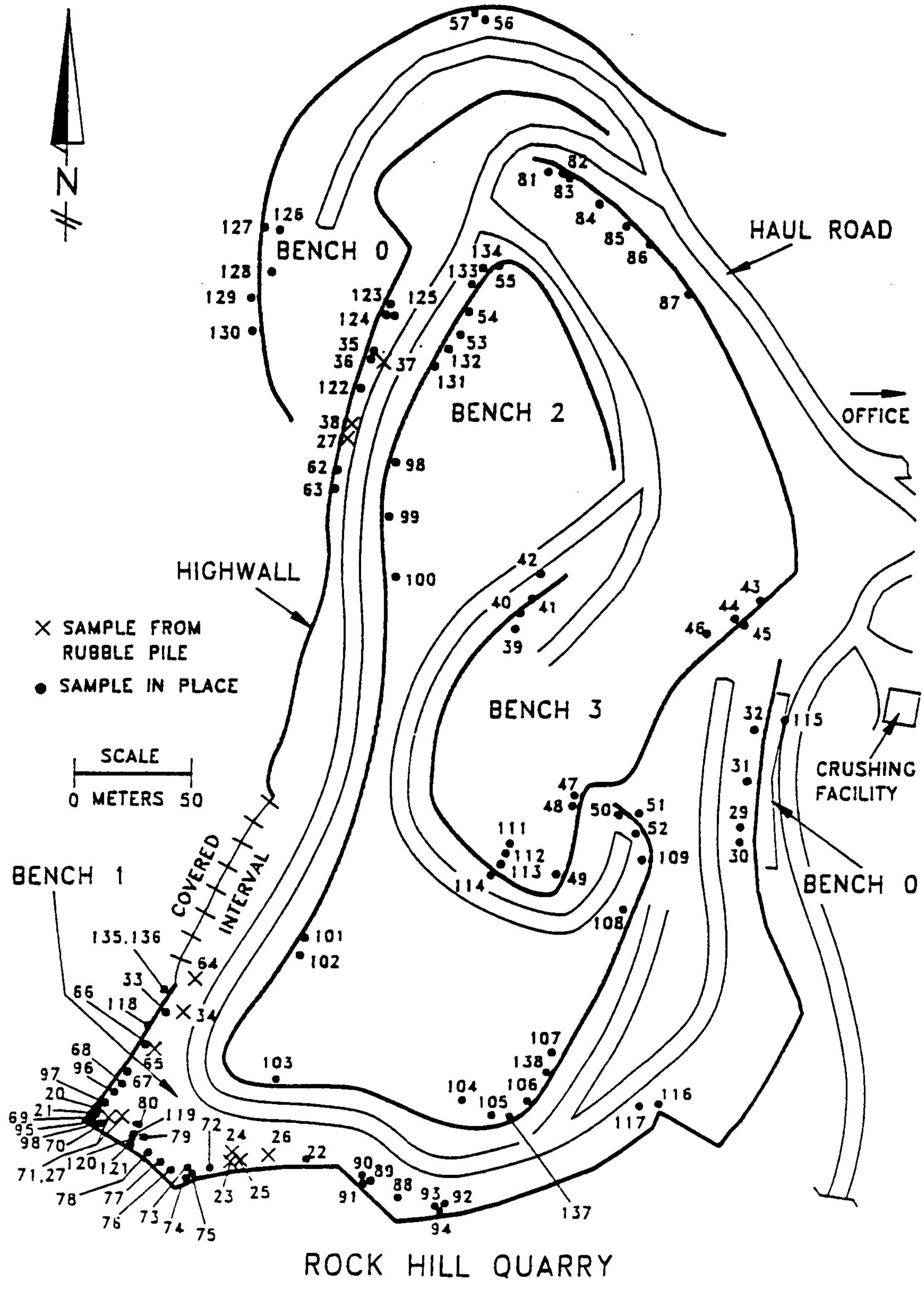
Field Investigation

At the Martin Marietta quarry site, field work consisted of attempting to discern visually and map any layering or other systematic distribution of rock types, and to collect samples accordingly (Figure 3). A vertical sampling strategy was employed in an effort to discover any systematic stratigraphic variations in texture, mode, or

Figure 3

Quarry Map With Sample Locations.

Plan view of Martin Marietta Rock Hill quarry at the time of the field reconnaissance for this study, including sample locations (based on an aerial photograph provided by Martin Marietta Corporation).



ROCK HILL QUARRY

mineral chemistry. Due to ongoing quarry operations and logistical constraints, sampling was concentrated along accessible highwalls. Extensive fracturing in places, as well as faulting of unknown displacement, make the original stratigraphy of parts of the quarry unclear. However, with the exceptionally good exposure, fresh samples of all rock types are available and detailed investigation is possible.

In an effort to sample thoroughly and safely that portion of the pluton exposed at the subject site, a sampling strategy was employed which emphasized vertical sections of given areas of the quarry. Rationale in sample area selection included avoidance of locations of active daily quarry operations, and preference for relatively fresh exposure where fracture zones, faulting, and alteration were minimal. A total of 137 samples were collected and examined. Of those, 125 were collected from known locations within the quarry, with the remainder collected either from quarry stockpiles or other areas of the city of Rock Hill. Two vertical traverses apparently representing continuous stratigraphic sequences were sampled.

Sample Modes and Petrography

From the 137 samples collected during the field investigation, 175 thin-sections were prepared for petrographic descriptions, including 19 polished sections used as microprobe mounts. Of the original 137 samples, 97 samples were point-counted; 82 of those point-counts were transferred to a database for use in this study. The other

15 point counts were of samples collected in areas with no stratigraphic control, i.e. from quarry tailings or from outside of the quarry. Data on the maximum and intermediate dimensions of olivine crystals were measured on 20 samples; maximum and intermediate dimensions of plagioclase crystals were measured on 12 samples.

Modal data are based on 500 points counted per sample in an effort to minimize statistical error; on a few odd-sized thin-sections, or thin-sections containing atypically large minerals, only 400, 300, or even 200 points were counted. The point counts were performed on an automatically advancing stage, preset for each thin-section with a 500-point grid. Spacing of successive points and distance between successive traverses was designed to exceed the diameter of a typical mineral grain within a given thin-section, where possible. Point-count data are included in Appendix A. The error associated with this data, as assessed from the chart of Van der Plas and Tobi (1965), is approximately 3% to 4% relative for the majority of the phases reported.

Mineral Chemistry

Mineral chemistry was analyzed by electron microprobe analysis of 25 samples using a MAC 400S electron microprobe, with a defocussed (5 to 15 μm diameter) beam set at 15 kV, calibrated to appropriate natural and synthetic standards. Data corrections procedures of Bence and Albee (1968) and the data of Albee and Ray

(1970) were utilized in a program which automatically corrects for atomic number, background, absorption, and fluorescence effects. Of the 25 samples probed, 8 anorthositic gabbro unit samples collected in a stratigraphic traverse and 8 troctolite unit samples collected in a stratigraphic traverse are included. Other analyzed samples include anorthositic and pegmatitic lenses and their contacts with enclosing troctolite. Within those 25 samples, a total of 588 points were individually probed for mineral chemistry.

A polished thin section of each sample was prepared on a 2.5 cm circular glass mount. The polished thin-section was then coated with a thin layer (~ 200 Å) of carbon. A reflected light black and white photomicrograph of each polished section was used as a map for locating points to be probed, such as the rim and core of a zoned plagioclase, an interstitial olivine crystal, etc. Samples selected for probing were intended to detect stratigraphic variations in mineral chemistry. Specific points probed were selected in an effort to reveal overall stratigraphic chemical differences, as well as zoning differences, chemical differences between intercumulus versus cumulus minerals, and chemical differences across texturally significant contacts.

2. GEOLOGIC SETTING AND PREVIOUS WORK

The crystalline rocks of the Southern Appalachians, which reach their maximum exposure width of approximately 300 km in North and South Carolina, are generally divided into six northeasterly trending geologic belts. Of these six geologic belts, the Charlotte Belt is the main region dominated by igneous intrusions in the Southeastern Appalachians; indeed, in the Charlotte Belt in northern South Carolina, igneous rocks constitute 75 % of the outcrop area (Butler and Ragland, 1969). Igneous rocks include both granitic and gabbroic intrusions of various ages, and syenite related to one of the gabbro bodies (Olsen et al., 1983). In the context of this investigation, discussion is limited to the series of contemporaneous and genetically related (McSween et al., 1984) gabbroic intrusions (Figure 1).

Tectonic Setting

The age of the Rock Hill pluton is inferred to be approximately 400 m.y., based on its similarity and apparent relationship to other intrusions in this area which have been radiometrically dated (McSween et al., 1984). This age may be compatible with the accretional event for the suspect Avalon or Carolina terrane (Charlotte and Carolina Slate Belts). The Carolina terrane is a late Precambrian to Cambrian volcanic island arc-volcaniclastic sedimentary sequence including early Paleozoic European and African fauna (Hatcher, 1987). The eastern Carolina terrane (Carolina

Slate Belt) is metamorphosed to greenschist facies, while the western portion (Charlotte Belt) is at amphibolite facies (Hatcher, 1987). Emplacement of some of the mafic plutons in the Carolina terrane occurred during convergence and suturing of the exotic terrane to North America, possibly during the Acadian Orogeny (Hatcher, 1987). This activity may have produced an eastward dipping subduction zone resulting in the high grades of metamorphism to the west and the sudden decrease in metamorphic grade within the Carolina terrane east of the central Piedmont suture. This later subduction zone would also have generated plutons. The time of emplacement of the Rock Hill pluton immediately precedes the Acadian (late Devonian). Thus, the Rock Hill pluton emplacement corresponds approximately with the end of the Taconic Orogeny, or between Taconic and Acadian, i.e. Silurian-Devonian transition time. The tectonic history of the Southern and Central Appalachian orogen is still being unraveled. However, evidence indicates that the major metamorphic event in the Charlotte Belt was Acadian. Metagabbro associated with the Rock Hill Gabbro pluton was at one time thought to be Taconic; $^{40}Ar/^{39}Ar$ data now define metamorphism in the area as Acadian.

Gabbro-Metagabbro Complexes

The areal distribution (arcuate chain of outcrops, Figure 1) and petrologic characteristics of this series of plutons suggest a compressional plate boundary as the magmatic source (McSween et al., 1984). Most of the gabbro bodies in this series are closely associated with metagabbro. Some studies of individual plutons have concluded that the gabbro had coincidentally intruded previously formed regionally metamorphosed gabbro (e.g. Hermes, 1968; McSween, 1981). A study of the Rock Hill pluton by Chalcraft (1970) concluded that the irregular distribution of degree of alteration within the pluton suggests that alteration was brought about by penetration of fluids generated from magmatic differentiation. However, such pluton-specific studies did not address the persistent recurrence of similar gabbro and metagabbro throughout this area.

The gabbro-metagabbro complexes as a group have more recently been interpreted as sites of multiple episodes of intrusion. In this hypothesis, heated lithosphere insulates successive pulses of magma resulting in nested intrusions (McSween et al., 1984). This is plausible since calculations on the mechanics of magma ascent (Marsh, 1976; 1978) indicate that the first few bodies of rising magma would crystallize at depth due to decreased velocities and increased viscosities as they rise into cold lithosphere. A combination of consistent tectonic or structural control and re-utilization of preheated magma ascent pathways of earlier intrusions could explain the gabbro-metagabbro association (McSween et al., 1984). However, field relationships demonstrating clear cross-cutting patterns are lacking in these bodies because of very limited exposure. This study considers the possibility that each complex represents one large incompletely metamorphosed intrusion, as suggested for similar occurrences of probable Taconic age in the Alabama Inner Piedmont

(Neilson and Stow, 1980).

Previous Work on the Rock Hill Pluton

The Rock Hill mafic pluton is located within and immediately south of the city of Rock Hill in York County, South Carolina (Figure 1), about 30 miles south of Charlotte, North Carolina. A second gabbro body is located immediately north of the city of Rock Hill, separated from the subject pluton by intervening metagabbro (Figure 1). The pluton typically forms a topographic low, but spheroidally weathered boulders are fairly common in yards, pastures, and undeveloped areas of the city. Thus the pluton is unusually well exposed for a Charlotte Belt intrusion. The exposure allowed several previous workers (Butler, 1966; Wager, 1968; Chalcraft, 1970) to notice layering accentuated by preferential weathering of olivine in some of the boulders (Figure 4a).

Previous work on the Rock Hill pluton is limited. The Rock Hill pluton was specifically mentioned by Overstreet and Bell (1965) and physically described in some detail by Butler (1966). The petrography and geophysics of the Rock Hill pluton were the subject of a Masters thesis by Chalcraft (1969); he subsequently published an article on his work (Chalcraft, 1970).

Figure 4

Photographs (weathered boulder, view of quarry).

(a) Photograph of a weathered boulder along Porter Road near the Rock Hill quarry. Note faint layering defined by weathered olivine crystals.

(b) View of quarry facing north, showing uppermost through lowermost benches, labelled 0 through 3.

(a)

(b)

To date, Chalcraft's work is the most in-depth study of the Rock Hill pluton available. He mapped lithologic areas within the pluton (Figure 2), including detailed lithologic descriptions, as well as interpretations of gravity and magnetic data. The gravity data were plotted as a Bouguer anomaly map intended to reveal the contact between the pluton and its host rock by inflections in isogals caused by density contrasts. Where the Rock Hill pluton is in contact with adamellite or similar rocks, isogal inflections corresponding to the contact are evident. However, the isogal inflections are absent or difficult to discern where surrounding rocks have densities similar to that of the pluton. The magnetic data were plotted as a magnetic anomaly map, which reveals a large anomaly in the southeastern quarter of the pluton. Chalcraft (1970) interpreted this anomaly to represent a variation in shape within the pluton or as a magmatic neck or feeder. In addition, Chalcraft (1970) modelled profiles of gabbroic intrusions of various thicknesses and compared the models to his measured magnetic profiles, resulting in an estimated thickness for this pluton of approximately 10,000 feet.

The lithologic regions mapped by Chalcraft (1970) are suggestive of layering, particularly the central region of "anorthosite" (Figure 2). The four lithologies identified and mapped by Chalcraft (1970) are based on the terminology of Buddington (1939) and thus do not correlate directly to the I.U.G.S.-approved terminology (Streckeisen, 1976) applied more commonly today. Using either scheme of nomenclature, an outcrop pattern of progressively more plagioclase-rich lithologies from the outer margin toward the center of this pluton may be observed (Figure 2). Chalcraft (1970) interpreted the lithologic regions within the pluton as evidence of fractional crystallization and relative movement of crystals and liquid magma, with crystal settling and magmatic flow explaining the layering features. Chalcraft (1970) particularly noticed outcrop-scale layering in the eastern portion of the pluton. Medlin (1966) noticed similar systematic variations in mineral distribution and crystal size at the Buffalo Mafic complex in Union County, South Carolina, located only about 45 miles southwest of the Rock Hill pluton, which he interpreted as evidence of possible large-scale layering.

Given the outcrop pattern of lithologies within the pluton and the unique occurrence of a distinctive "anorthosite" lithology at Rock Hill versus related plutons, a need was perceived for more definitive evidence of layering. Thus, the present work details the petrography and mineral chemistry of a specific portion of the intrusion within Chalcraft's "anorthosite" region (Figure 2) in an effort to determine if layering can be more clearly identified in a stratigraphically controlled setting.

Site Description

With its comparatively good exposure, the surface of the Rock Hill Gabbro Pluton has been mapped in some detail by visiting scattered outcrops (Chalcraft, 1970). However, little stratigraphic control was available in studying the pluton by that means, although Chalcraft (1970) interpreted his map distributions to reflect sampling of gross layers. The area of study selected as the focus of this investigation is the Martin Marietta Rock Hill Quarry. This operation mines the gabbro for use as aggregate, railroad ballast, etc. At the time that field work for this investigation was conducted, the subject site consisted of a quarry extending approximately 60 meters into the ground below surrounding grade, with a width of approximately 305 meters and a length of approximately 730 meters. Three primary benches from the surface to the base of the quarry were created by the quarrying procedure. These are referred to as Bench 1 (upper), Bench 2 (middle) and Bench 3 (lower). In addition, a fourth (uppermost) bench is present on portions of the west and east sides of the quarry. Figures 3 and 4b depict the four benches. By examining outcrops on all four benches, several main rock types were observed which are described in the following section. In addition, fine-grained diabase dikes occasionally occur throughout the pluton, oriented parallel to the main fracture sets observed at the site. The diabase dikes are clearly a later feature (presumably Mesozoic) and were not studied as part of this investigation.

3. PETROGRAPHY AND FIELD RELATIONSHIPS

Major Rock Types Encountered

The Rock Hill pluton consists of several distinct rock types. The classification scheme used by Chalcraft (1970) to subdivide the entire pluton (Figure 2) is based on sample modes, so the resulting rock types are not readily identifiable in hand sample. This report details a portion of the pluton near Chalcraft's anorthosite section (Figure 2), where three different lithologic units have been distinguished in hand specimen: anorthositic gabbro unit, troctolite unit, and metagabbro. These three are easily recognizable in the field based on appearance and texture.

- Anorthositic gabbro unit

Rocks assigned to the anorthositic gabbro unit are purplish-brown to dark gray and have a typical gabbroic mineralogy, including black olivine, pyroxene, and amphibole with a noticeable predominance of dark plagioclase. This rock type is typically massive (Figure 5a) with no spectacular features from the hand-sample to the outcrop (or highwall) level. A notable exception is the occasional occurrence of lenses of coarse-grained (pegmatitic) anorthositic gabbro enclosed in the otherwise massive gabbro. Other less dramatic

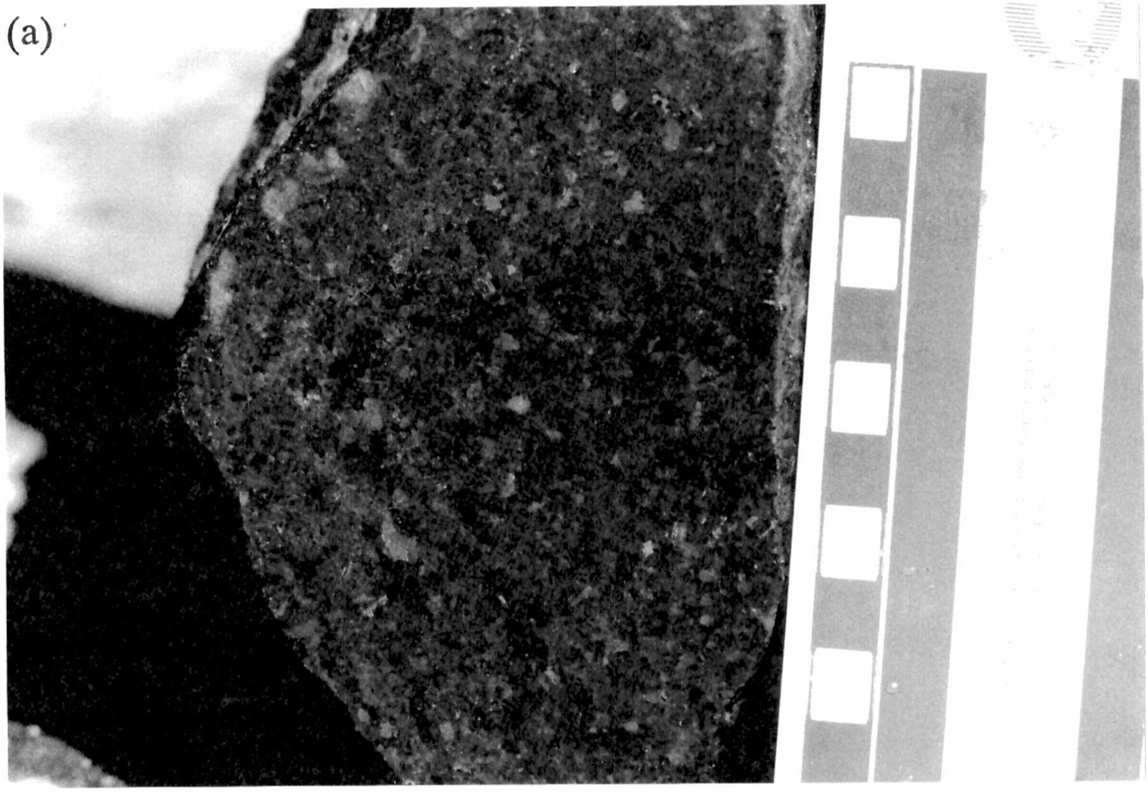
Figure 5

Photographs of hand specimens (typical massive gabbro, typical troctolite).

(a) Typical massive anorthositic gabbro.

(b) Typical troctolite.

(a)



(b)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Grain Size Scale
Avoid incorrect exposures by taking meter readings before placing scale in picture area. Fine-focus on GSA seal
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mineralogical/textural variations are sometimes visible across a single hand-specimen (sample # 92-upper and 92-lower, for example). Preferred orientations of plagioclase crystals are rarely noticeable.

- Troctolite unit

Rocks identified as belonging to the troctolite unit are gray to white stippled with black, and have a distinctly bimodal-appearing mineralogy: plagioclase predominates, with 10% - 50% black olivine crystals giving the rock its stippled appearance. This rock type may be massive at hand-sample scale, but typically displays faint to distinct modal layering at the outcrop scale, a phenomenon often also apparent in hand specimen (Figure 5b). However, layers are seldom traceable more than a few meters. Preferential alignment of plagioclase crystals is visible in some hand samples and in most thin-sections of this lithology. Lenses or blocks of almost (modally) pure plagioclase are present within the troctolite unit. The lenses typically measure from a few tens of centimeters across by 10 to 15 centimeters wide, while the blocks may measure a meter square or greater (Figure 6). No reaction rims are evident around these lenses or blocks. In some cases, the plagioclase-rich lenses appear to grade into the surrounding rock. Conversely, draping of thin layers of olivine crystals over the blocks is apparent at some outcrops,

Figure 6

Photographs of outcrops of troctolitic rock displaying plagioclase lenses.

Photographs of outcrops of troctolitic rock displaying a smaller (a) and larger (b) plagioclase lens with accumulated olivine above. Note safety glasses for scale in both photographs.

(a)

(b)

although distinct evidence for compression of previously deposited layers was not observed.

Lenses of pegmatitic rock are occasionally present within the troctolite unit like those found in the anorthositic gabbro unit, with approximate dimensions matching those of the smaller plagioclase-rich lenses (Figure 7). In one area of the quarry, blocks of anorthositic gabbro were observed enclosed by troctolitic rock, with no obvious sedimentary orientation of the blocks (sample 118 is an example).

- Metagabbro

Metagabbro typically has a white to slightly pink groundmass with green mottling. The mineralogy is predominantly white, clouded plagioclase with fibrous green amphiboles replacing the mafic minerals (Figure 8), with occasional pyrite, and rarely large (up to 15 cm) amphibole crystals. Metagabbro as studied at the subject site resembles metagabbro as described from the other plutons in this series of intrusions. At Rock Hill, this rock type is texturally massive to faintly layered, depending on its protolith. The metagabbro often contains features indicative of one of the other lithologies described, such as plagioclase-rich lenses and pegmatitic lenses, or stippling produced by green alteration minerals replacing olivine in precursor troctolite.

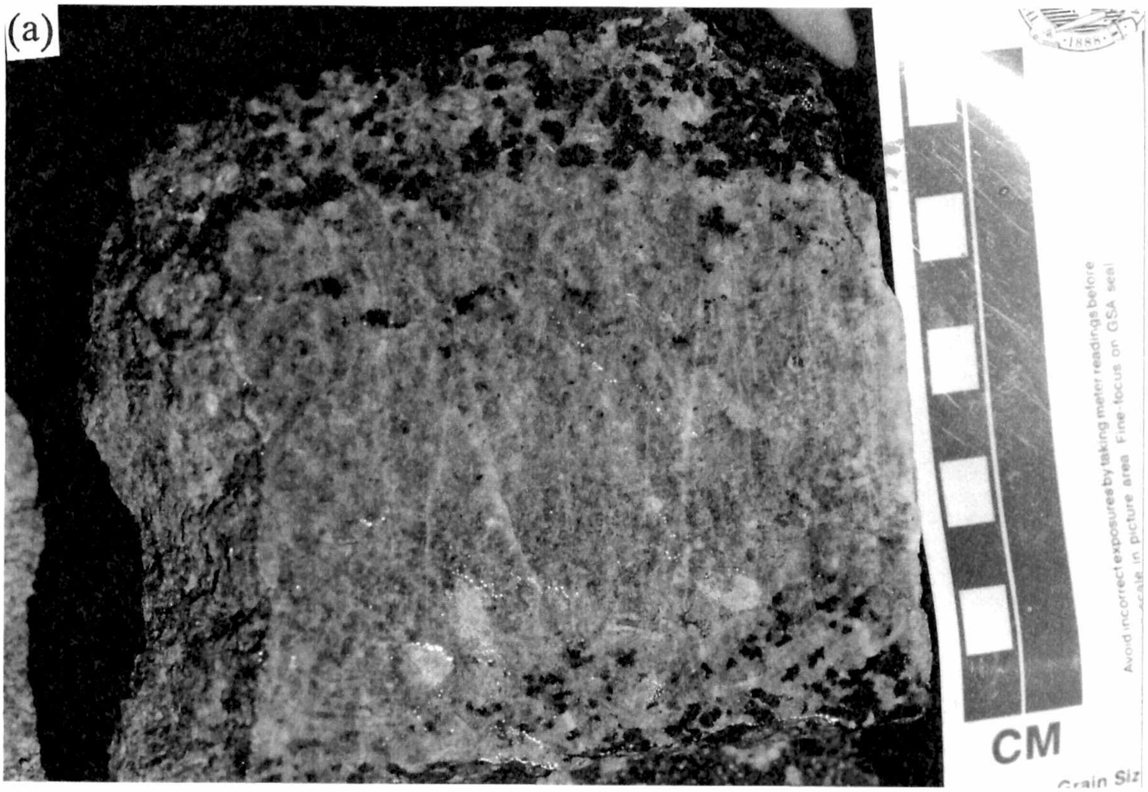
Figure 7

Photographs of hand specimens (plagioclase lens, pegmatitic lens).

(a) Sawed surface of typical plagioclase lens in troctolite.

(b) Sawed surfaces of pegmatitic lens in troctolite.

(a)


1888
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(b)

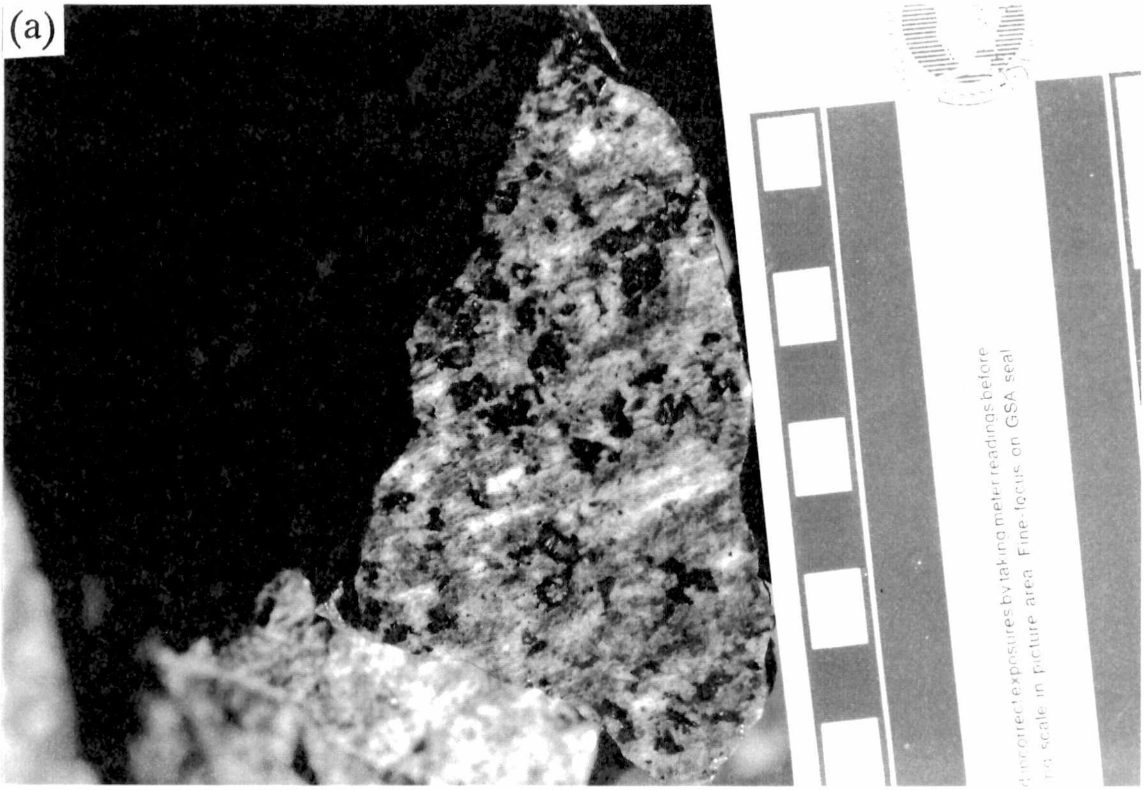
Figure 8

Photographs of hand specimens (typical metagabbro, alteration along small-scale fracture planes).

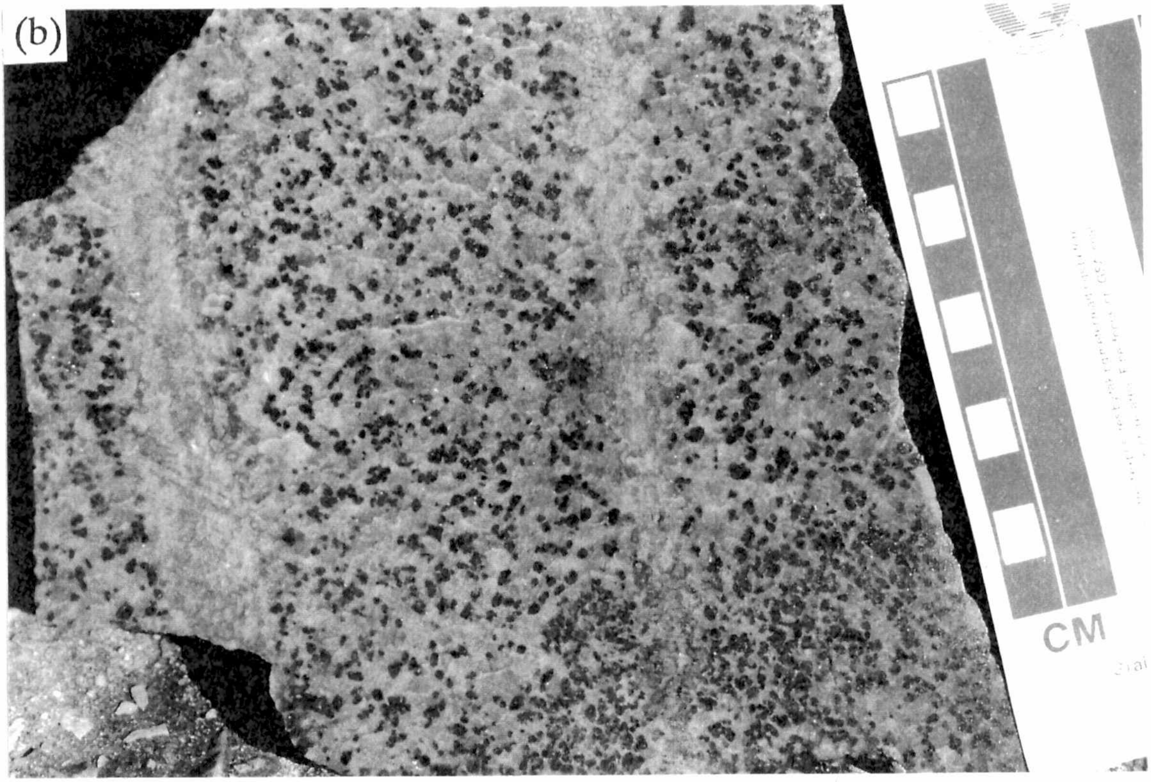
(a) Sawed surface of typical metagabbro.

(b) Sawed surface of troctolite with alteration confined to parallel vertical fractures.

(a)



(b)



Some samples of metagabbro have the appearance of unaltered massive gabbro in the field, and are revealed as metagabbro only after petrographic examination and modal analysis. The plagioclase in these latter samples is typically not clouded. However, alteration of pyroxenes and olivines is advanced or complete.

Each of the two first lithologic units listed above was studied in a vertical traverse designed to detect any petrographic or chemical variations related to stratigraphic position. Details of each of the two main lithologic units are presented in the sections below, including specific information gathered from samples along the two traverses.

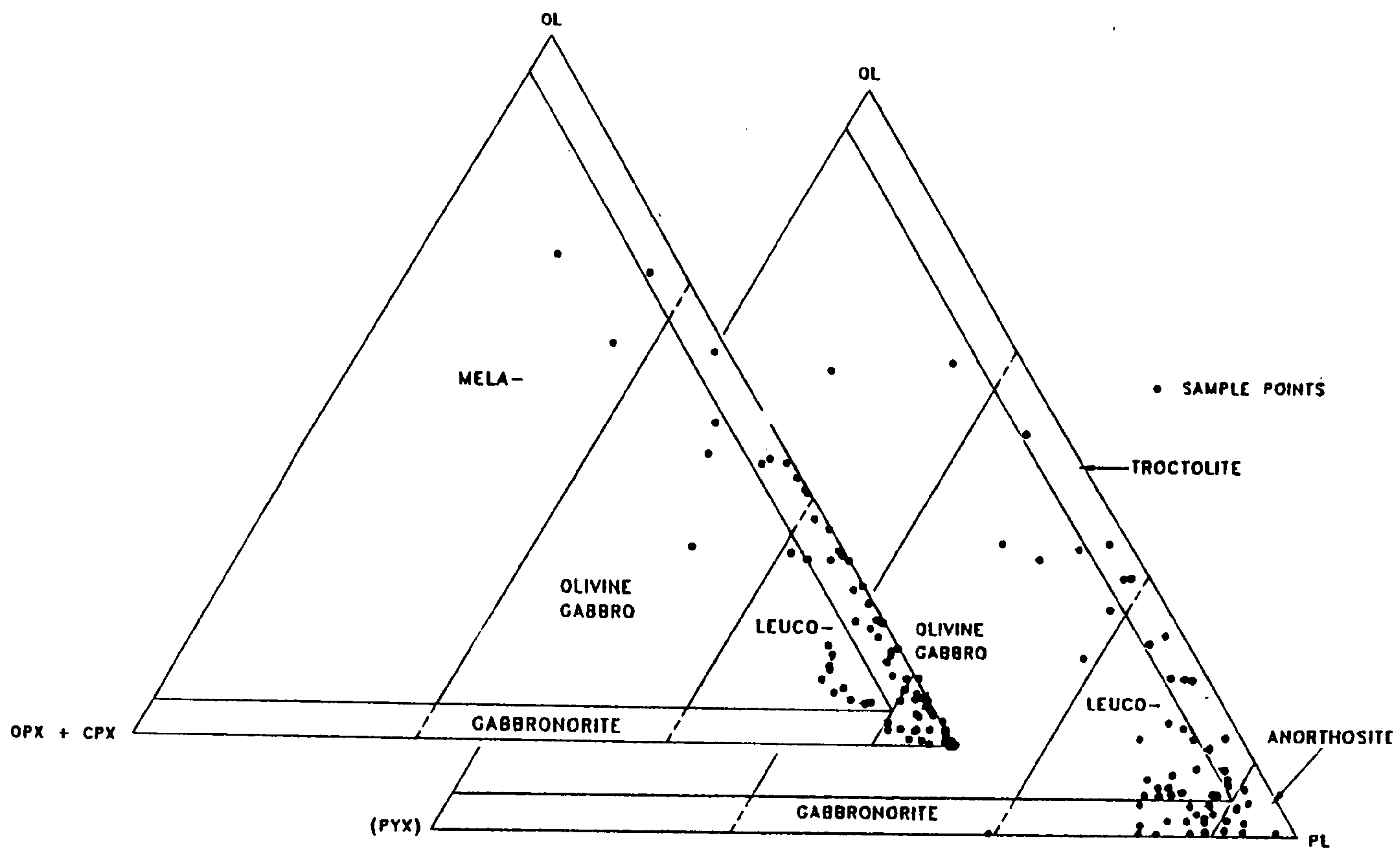
Sample Modes And Crystal Sizes

When sample modes from 82 point-counts (all point counts entered in a computer data-base) are plotted together on a single Streckeisen (1976) triangular diagram (Figure 9), the appropriate names for the rocks encountered at the subject site are revealed. In constructing this Figure, no attempt was made to use different symbols to distinguish the lithologic units as assigned in the field. Therefore, biases based on a given sample's physical appearance are not reflected in Figure 9. The majority of these 82 point-counts are typical examples of the two major lithologies found at the subject site. However, included are a few examples of plagioclase lenses, pegmatitic lenses, olivine-rich layers, and metagabbros. Based on the distribution of modes

Figure 9

Sample modes plotted on a triangular diagram after Streckeisen (1976) (ol - pl - opx + cpx).

Sample modes plotted on a ol - pl - opx + cpx triangular diagram (Streckeisen, 1976). Underlying is a similar diagram replacing opx + cpx with (pyx), where (pyx) = all phases except olivine and plagioclase. All samples in the data-base are plotted (see text), including samples from the 2 traverses. (No samples identified *in the field* as "metagabbro" are included in the database, yet many contained enough alteration minerals to affect these plots). No distinction as to lithologic unit is made, as unit assignments are based on field observations, not sample modes. Some samples are shifted noticeably to the right on the ol - pl - opx + cpx diagram compared to the underlying diagram (where all "other" phases are represented by the left-hand corner), due to preferential alteration of pyroxene, even in relatively unaltered samples (see text).


OL
OL
MELA-
OLIVINE GABBRO
LEUCO-
OLIVINE GABBRO
GABBRONORITE
OPX + CPX
• SAMPLE POINTS
TROCTOLITE
LEUCO-
ANORTHOSITE
GABBRONORITE
(PYX)
PL

within the fields assigned by Streckeisen (1976), the site contains primarily olivine gabbro (including leuco-olivine gabbro and a lesser amount of mela-olivine gabbro), and troctolite (including leuco-troctolite). In addition, the site contains leuco-gabbronorite, a lesser amount of gabbronorite, and anorthosite. The number of points plotted in each field is probably slightly biased towards the anorthosite field due to the deliberate collection and analysis of plagioclase lenses in an effort to discover the origin of these features. Likewise, troctolite may be over-represented by the number of points on this diagram due to the more interesting appearance of these samples in hand specimen, leading to a disproportionate number of them being collected and analyzed. Thus, although the relative abundance of each type is not accurately represented by the ol - pl - opx + cpx portion of Figure 9, the existence at the subject site of each of these rock types is confirmed.

The fields on Figure 9 occupied by the samples analyzed from Rock Hill overlap those of nearby gabbroic plutons Mecklenburg, Ogden, and Concord (Figure 1) (McSween, et al., 1984). However, troctolite is apparently more abundant at Rock Hill, and anorthosite is absent from the other nearby plutons. Further, hornblende is the predominant mafic mineral in some samples from the nearby localities (McSween, et al., 1984) while at the portion of the Rock Hill pluton studied, olivine is consistently more abundant than hornblende.

While modal data were being collected, crystal size data were obtained for many of the samples comprising the two stratigraphic traverses. Data on the maximum and intermediate dimensions of olivine crystals were measured for 20 samples: all 12 samples of the troctolite unit traverse and some "special samples" (in this case, plagioclase lenses) gathered along the traverse, along with all samples of the anorthositic gabbro unit traverse. Maximum and intermediate dimensions of plagioclase crystals were measured for the 12 troctolite unit traverse samples and "special samples".

Field Relationships

Field relationships among the three major rock types at the subject site are not particularly illuminating. In some instances, one rock type seems to grade into another vertically or horizontally over a scale of a few meters to tens of meters. In most instances, contacts are obscured by apparent faulting and by intervening metagabbro along fractured intervals. The degree of alteration in metagabbro varies from completely altered near fracture surfaces to slightly altered with distance from the fracture surface, over distances varying from a few meters to several tens of meters. Along a given highwall, one may identify outcrops of the troctolite unit grading into metagabbro, grading back into troctolite or into anorthositic gabbro over a distance of as much as 100 meters. Covered intervals are problematic in some portions of the quarry. No clearly systematic distribution of rock types, mappable layering features, or genetically revealing field relationships were discerned in the field.

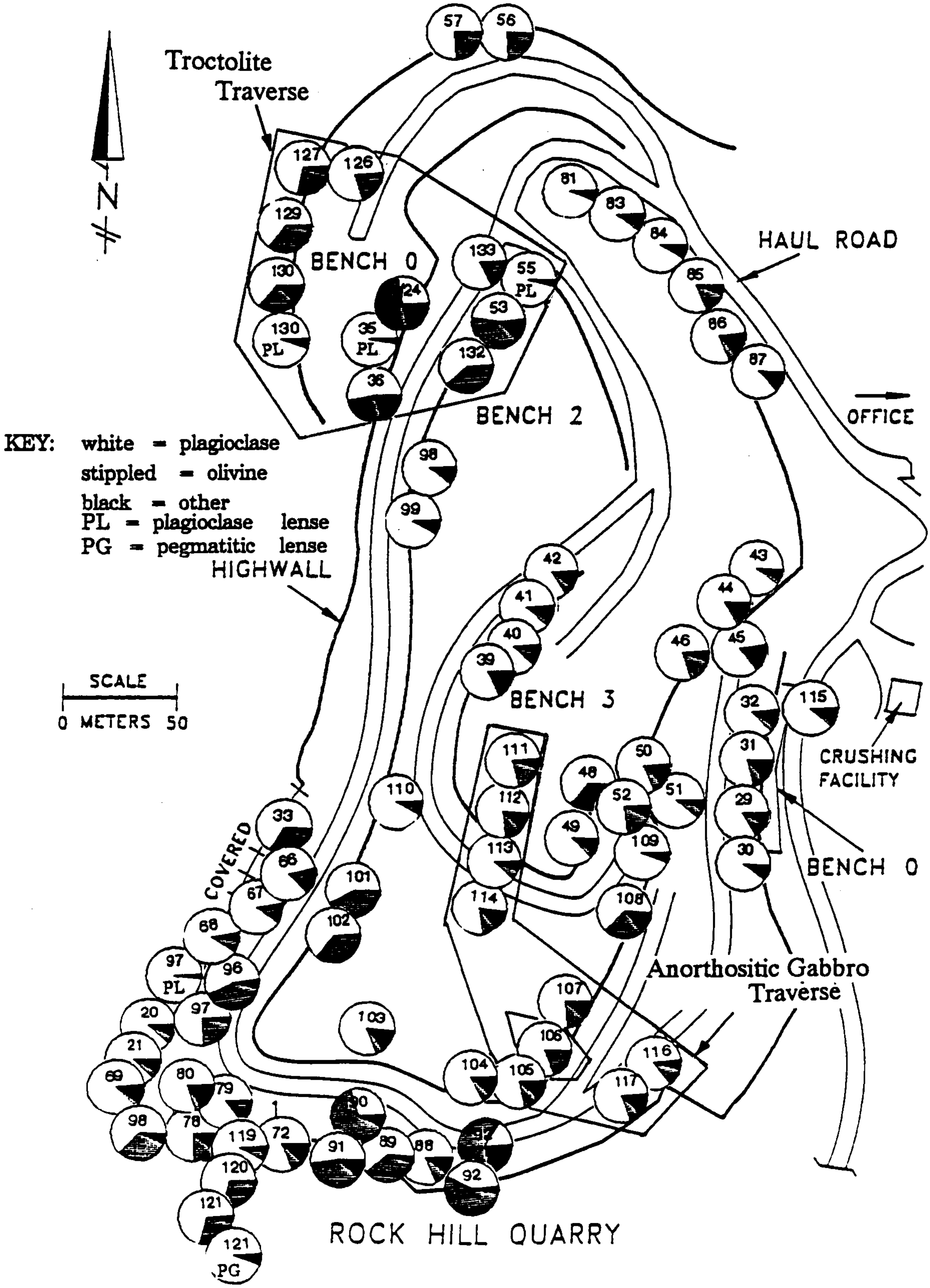
In an effort to delineate field relationships, modal data for 82 samples are presented as pie-diagrams in their approximate relative stratigraphic positions on Figure 10. In constructing this Figure, modal data were subdivided into only three categories: plagioclase, olivine, and other. Included in "other" are pyroxenes, opaque minerals, amphiboles, biotite, and other alteration minerals. At the scale used in Figure 10, none of the minerals united as "other" would constitute an identifiable slice of a pie-diagram if listed individually. The anorthositic gabbro unit traverse and the troctolite unit traverse are identified by boxes containing their respective modal data pie-diagrams. Examination of the relative stratigraphic positions of the modes in Figure 10 does not reveal strong stratigraphic control over modes. In general, the anorthositic gabbro unit comprises much of the quarry exposure, whereas the troctolite unit is located principally in the northwestern uppermost bench, the northwestern and central western parts of bench 1, the northwestern corner of bench 2, and a small portion of bench 1 on the southeast end of the quarry.

One unique sample was collected in an area of the quarry characterized by troctolite unit rocks. This sample (sample # 135) contains troctolite and anorthositic gabbro in contact via an intervening pegmatitic lens. This sample was thin sectioned within the troctolitic portion, within the anorthositic gabbro portion, and within the intervening pegmatitic portion. Modal data gathered for each of these subportions

Figure 10

Modal data on quarry map.

Quarry map with modal data superimposed as pie diagrams.


Troctolite Traverse
N
BENCH 0
BENCH 2
BENCH 3
HAUL ROAD
OFFICE
KEY: white = plagioclase
stippled = olivine
black = other
PL = plagioclase lense
PG = pegmatitic lense
HIGHWALL
SCALE
0 METERS 50
CRUSHING FACILITY
BENCH 0
COVERED
Anorthositic Gabbro Traverse
ROCK HILL QUARRY

of sample # 135 reveal that each subsection is modally typical of other samples of those lithologies available from elsewhere in the quarry. The pegmatitic portion is modally similar to typical massive gabbro (olivine-gabbro per Streckeisen, 1976), whereas the anorthositic gabbro-appearing portion is modally anorthosite. The troctolite-appearing portion is in fact modally troctolite. In the immediate vicinity of where sample # 135 was collected (bench 1 of the west wall), the discovery was made of an apparent contact between the troctolite unit and the massive anorthositic gabbro unit. Unfortunately, the apparent contact could only be traced about one meter before it lost definition. The physical appearances of the two rock units gradationally merged laterally. Further, faulting as well as rubble-piles related to quarry operations obscured the nature of the contact in both directions laterally. Where the contact could be examined, it consisted of a near-horizontal, slightly wavy (wavelengths approximately 20 cm, amplitudes approximately 5 cm), fairly sharp contact with olivine-rich troctolite above and massive anorthositic gabbro below. The apparent contact could not be sampled directly due to the lack of fracturing on that limited section of the highwall.

From the limited amount of field relationship information available, it appears that the two main lithologic units, troctolite and anorthositic gabbro, usually grade into one another, but occasionally have sharp contacts.

Anorthositic Gabbro Unit Traverse

Most of the anorthositic gabbro unit is texturally massive, with the exception of a few texturally/mineralogically varied areas, which are typically not well defined nor laterally (or vertically) continuous. There is some variation in crystal size in the anorthositic gabbro, but it is not noticeably systematic or mappable. In some instances, pods or lenses of pegmatite occur which have the same general modal composition as the majority of the anorthositic gabbro. These lenses are typically a few tens of centimeters across, 10 to 15 centimeters wide, and lensoid in shape. No reaction rims are present between the lenses and enclosing rock.

Anorthositic gabbro samples examined microscopically are adcumulates: they consist predominantly of cumulus subhedral to anhedral twinned plagioclase with faintly defined or no preferred orientation of crystals in most samples (Figure 11a) (although exceptions were found, ie. portions of sample # 114). Some plagioclase zoning occurs, which is optically noticeable in some instances but does not span a large range of composition (see Mineral Chemistry, below). A small percentage of cumulus olivine occurs, but most of the nonplagioclase assemblage is postcumulus. Plagioclase and olivine crystals occur within the postcumulus crystals in some instances.

Figure 11

Photomicrographs (typical anorthositic gabbro, typical troctolite).

(a) Typical anorthositic gabbro, crossed nicols, showing random orientation of plagioclase crystals.

(b) Typical troctolite, crossed nicols, showing preferred orientation of plagioclase crystals.

(a)

1 mm
SCALE

(b)

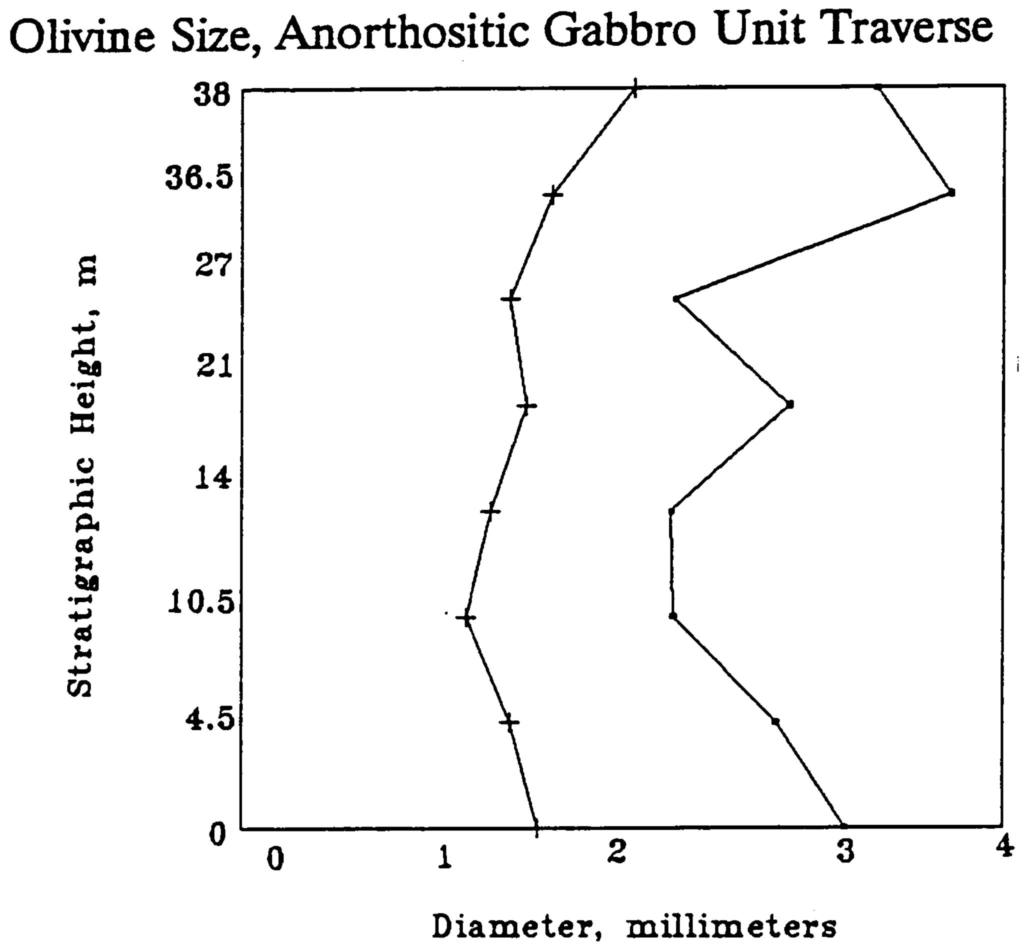
Olivine is the second most abundant phase. Some subophitic plagioclase grains are found partially enclosed in olivine grain margins, and enclosure of other olivine grains at olivine grain margins also occurs. Fractures in olivine grains are typically filled with opaque minerals, creating the black coloration of olivine grains in hand specimen. In a few instances, a finely crystalline alteration mantle, possibly fine-grained serpentine, occurs on the outer edges of olivine crystals. Olivine crystals inthe anorthositic gabbro traverse average 2.84 mm in maximum dimension, and 1.51 mm in the intermediate dimension. A plot of olivine crystal size vs. stratigraphic position is presented in Figure 12. This Figure reveals no consistent stratigraphic control on olivine crystal size in the anorthositic gabbro unit.

Some clinopyroxene occurs interstitially, and poikilitic clinopyroxene is common. These crystals may be large; in at least one sample (sample # 117), almost all of the clinopyroxene in the thin-section is optically continuous. Opaque minerals occur both as inclusions and as interstitial material, and may be euhedral to subhedral, or even anhedral where they conform to interstitial shapes. Some instances of myrmekitic intergrowth of opaque minerals with olivine and biotite occur. A limited amount of biotite is present associated with opaque phases and clinopyroxene. Amphibole is included in anorthositic gabbro in small percentages.

The average sample mode from the anorthositic gabbro unit traverse consists of 80% plagioclase, 10% olivine, 7% pyroxene, and 3% opaque phases (principally sulfides

Figure 12

Olivine size versus stratigraphic height in the anorthositic gabbro unit traverse.



Olivine Size, Anorthositic Gabbro Unit Traverse
Stratigraphic Height, m
38
36.5
27
21
14
10.5
4.5
0
0
1
2
3
4
Diameter, millimeters

and oxides). To enable the reader to identify the particular samples constituting each of the 2 vertical traverses probed, an additional Streckeisen (1976) diagram was prepared (Figure 13) which assigns a unique symbol to each major rock type. The anorthositic gabbro unit traverse rocks plot primarily in the leuco-olivine gabbro field, where the average mode for this traverse plots, and also in the leuco-troctolite and the anorthosite fields of Streckeisen (1976). Modes in this traverse range from 76.4% to 87.6% plagioclase, 7.2% to 16.4% olivine, and 5.8% to 13.4% other phases. Other phases include primarily clinopyroxene (2.4% to 11%) and opaque phases (1% to 2.6%), but also include small percentages of alteration minerals, amphibole, and biotite in some samples.

As noted above, some small-scale textural/mineralogical variation is apparent in the anorthositic gabbro unit in places. A striking example is sample # 92. The hand-sample collected was divided into two parts, upper and lower. A comparison of the modes of these two samples is provided in Figure 14. Although the thin-sections were cut from the sample less than 0.5 meter apart vertically, a rather dramatic difference in mode is found. Indeed, sample # 92-lower plots in the olivine gabbro field, while sample # 92-upper plots in the troctolite field. Yet, the sample was collected in a section of the quarry characterized by massive anorthositic gabbro.

Figure 13

Sample modes for the two traverses probed plotted on a triangular diagram after Streckeisen (1976) (ol - pl - opx + cpx).

Sample modes for probed samples from the anorthositic gabbro unit traverse, the troctolite unit traverse, and "special" (plagioclase lenses, pegmatitic lens, unusually olivine-rich) samples probed plotted on a ol - pl - opx + cpx triangular diagram (Streckeisen, 1976). These points also appear on Figure 9 without the traverse-identifying symbols shown here.

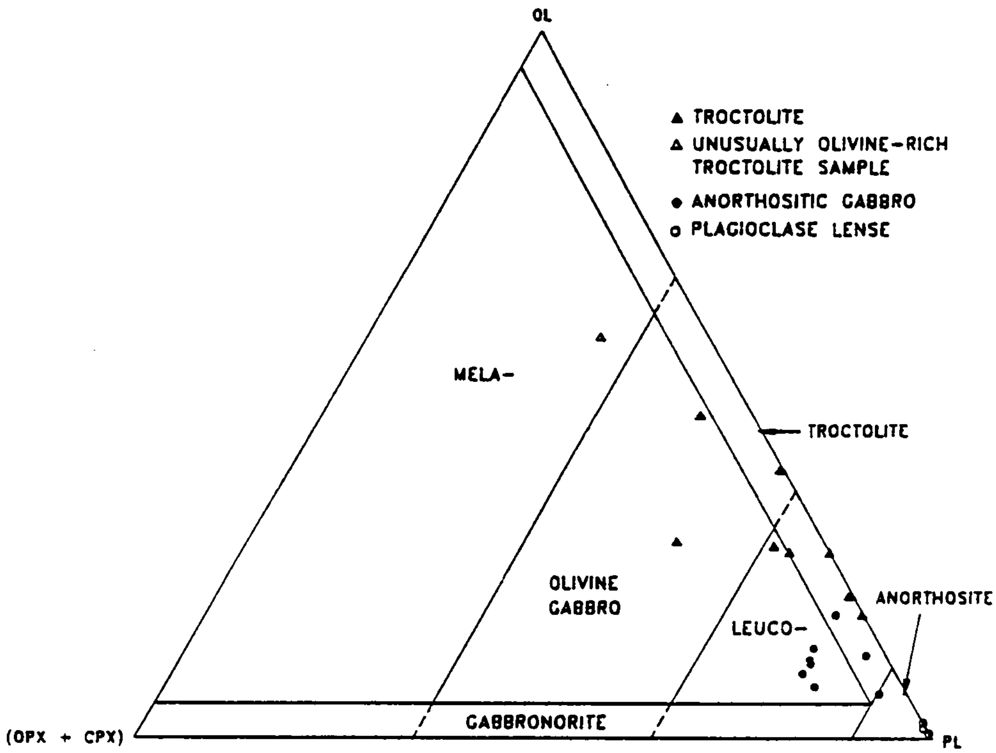
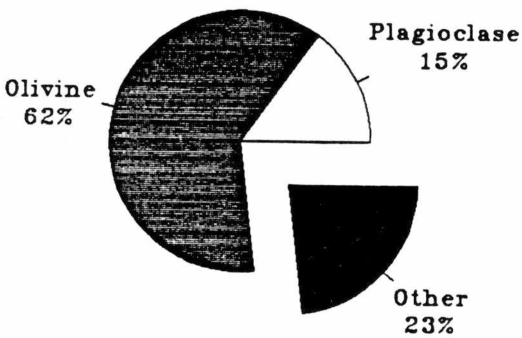

OL
TROCTOLITE
UNUSUALLY OLIVINE-RICH TROCTOLITE SAMPLE
ANORTHOSITIC GABBRO
PLAGIOCLASE LENSE
MELA-
TROCTOLITE
OLIVINE GABBRO
LEUCO-
ANORTHOSITE
GABBRONORITE
(OPX + CPX)
PL

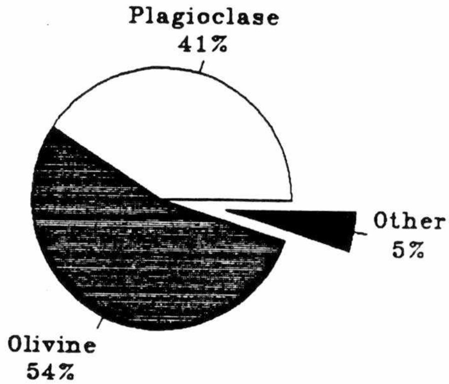
Figure 14

Comparison of modes within sample number 92, upper and lower parts.

Upper



Lower



OTHER FOR
UPPER SAMPLE

Clinopyroxene	13%
Opaque Minerals	6%
Alteration Minerals	4%
Amphibole	<1%

OTHER FOR
LOWER SAMPLE

Clinopyroxene	2%
Opaque Minerals	2%
Alteration Minerals	1%
Amphibole	<1%

Troctolite Unit Traverse

At the Rock Hill quarry, rocks identified in the field as troctolite unit are generally confined to specific areas of the quarry, as previously noted (see Field Relationships). Small-scale layering phenomena, such as olivine-accentuated draping of layers over blocks of anorthosite, provide evidence of a complex crystallization history for this unit. Most of the layering is wispy in nature, and difficult to trace horizontally for more than a few tens of centimeters or perhaps meters. Plagioclase lenses, typically comparable in size and shape to the pegmatitic lenses in the anorthositic gabbro unit, occur in places. These plagioclase-rich zones usually occur in the form of lens-shaped blocks of almost (modally) pure plagioclase. It is these lenses, anywhere from a few centimeters to several meters across, which are the most noticeable sedimentary-like crystal deposition features in the troctolite. Similar lenses or thin layers of dunite were also noted in a few instances. Most of the layering features observed were near-horizontal, with no consistent attitudes observed on those layers displaying slight dips. Chalcraft (1970) reported that layers strike subparallel to the pluton's contacts and dips decrease from near-vertical in the eastern portion of the pluton to approximately 45 degrees in the western portion of the pluton. No such extreme dips could be confirmed at the quarry.

Troctolite unit samples examined microscopically typically display a preferred orientation of plagioclase crystals (Figure 11b) which are present in moderately greater abundance than equant olivine crystals. Plagioclase grains are subhedral to anhedral, twinned, and sometimes zoned in both troctolite unit rocks and enclosed plagioclase lenses (Figure 15a).

As in anorthosite, cumulus olivine crystals (Figure 15b) have fractures typically filled with opaque phases and may be serpentinized at crystal edges. Alteration has preferentially attacked fractures, which cross-cut plagioclase crystals and are radial to the equant olivine crystals. Small plagioclase crystals are enclosed by olivine, and olivine may occur as inclusions in plagioclase grains. Olivine crystals measured for samples in the troctolite unit traverse, including plagioclase lenses, average 2.33 mm in the maximum dimension and 1.54 mm in the intermediate dimension. Plagioclase crystals in the same samples have an average maximum dimension of 2.36 mm and an average intermediate dimension of 1.25 mm. The plagioclase crystals are approximately half as long in the intermediate dimension than in the maximum dimension. Plots of crystal size vs. stratigraphic position are presented in Figure 16a (olivine sizes) and Figure 16b (plagioclase sizes). As in the anorthositic gabbro unit traverse, no consistent stratigraphic control on crystal size is revealed.

As in anorthositic gabbro, pyroxenes occur interstitially in the troctolite unit. Likewise, opaque minerals occur not only in fractures within olivine grains but as subhedral to anhedral, interstitial or included crystals. Amphibole is found in this lithology in somewhat greater percentages than in the anorthositic gabbro unit.

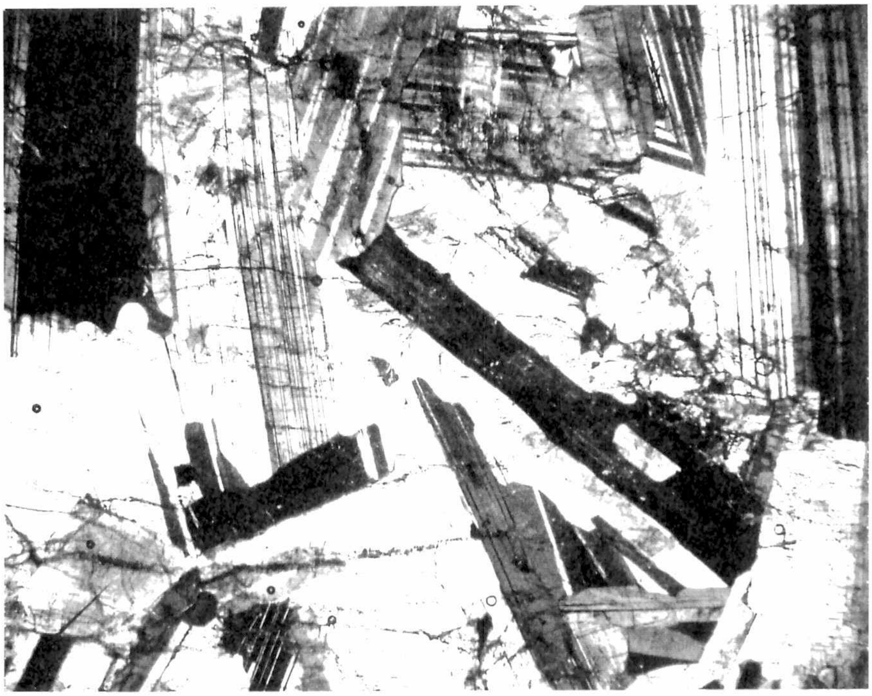
Figure 15

Photomicrographs (typical plagioclase lens, cumulus olivine in troctolite).

(a) Typical plagioclase lens, crossed nicols.

(b) Cumulus olivine in troctolite, crossed nicols.

(a)



(b)

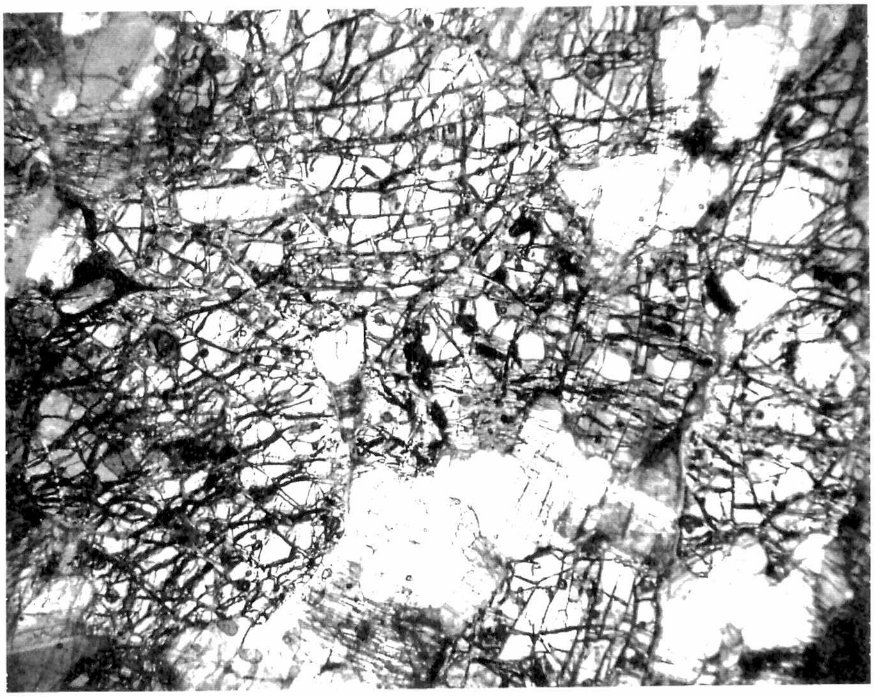


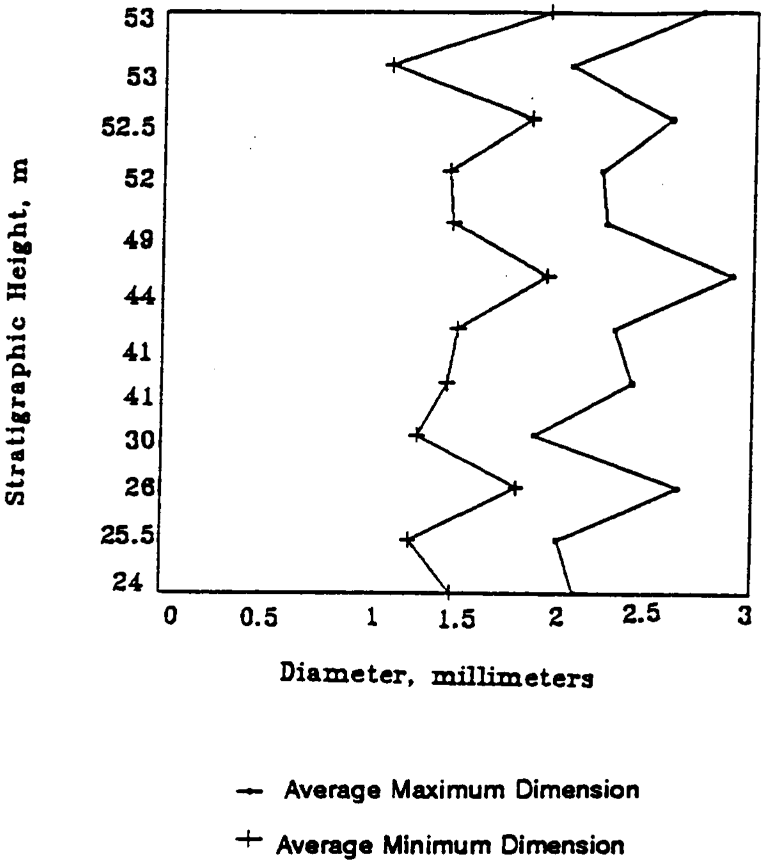
Figure 16

Crystal size versus stratigraphic height in the troctolite unit traverse.

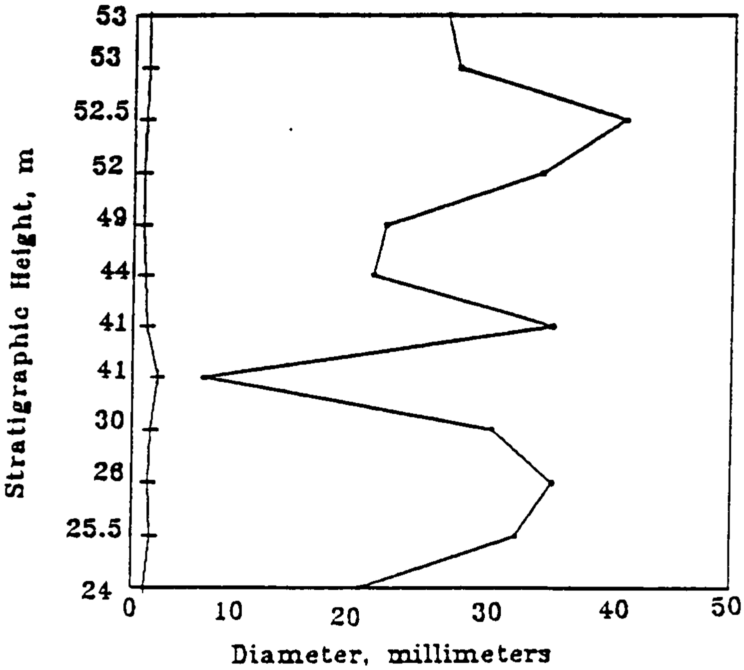
(a) olivine size, and

(b) plagioclase size

(a) Olivine Size, Troctolite Unit Traverse



(b) Plagioclase Size, Troctolite Unit Traverse



Pegmatitic lenses are occasionally found in the troctolite unit (Figure 17a).

The average mode in the troctolite unit traverse consists of 65% plagioclase, 28% olivine, and 7% other phases. The other phases consist on average of 3% clinopyroxene, 0.1% orthopyroxene, 2% opaque phases (principally oxides), 0.1% biotite, and 1% alteration minerals. These averages are based on the 8 samples collected in the troctolite unit vertical traverse which were not "special samples" (ie. those collected due to their unusual appearance, such as plagioclase lenses, unusually olivine-rich layers, etc.). Most of the troctolite unit traverse samples plot in the leuco-troctolite field or near the olivine-plagioclase side of either the olivine gabbro or leuco-olivine gabbro fields on a Streckeisen (1976) triangular diagram (Figure 13). Plagioclase lenses are modally anorthosite, according to the nomenclature of Streckeisen (1976) (Figure 9, Figure 13). Note that some samples which plot as anorthosite in the olivine-plagioclase-pyroxene triangle are actually metagabbro samples, as explained below (see Metagabbro Section).

Comparison Of The Primary Lithologic Units

Some similarities are found in the petrography of rocks of the anorthositic gabbro and troctolite units. However, besides the obvious modal distinction, the most significant differences between the two lithologies are textural. A tendency towards

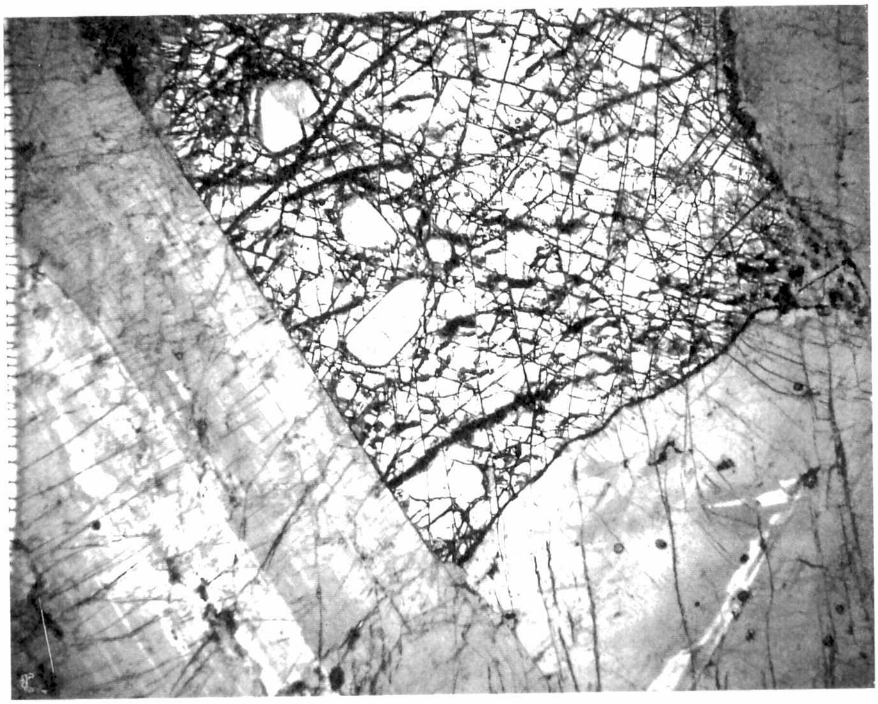
Figure 17

Photomicrographs (typical pegmatitic lens, typical metagabbro).

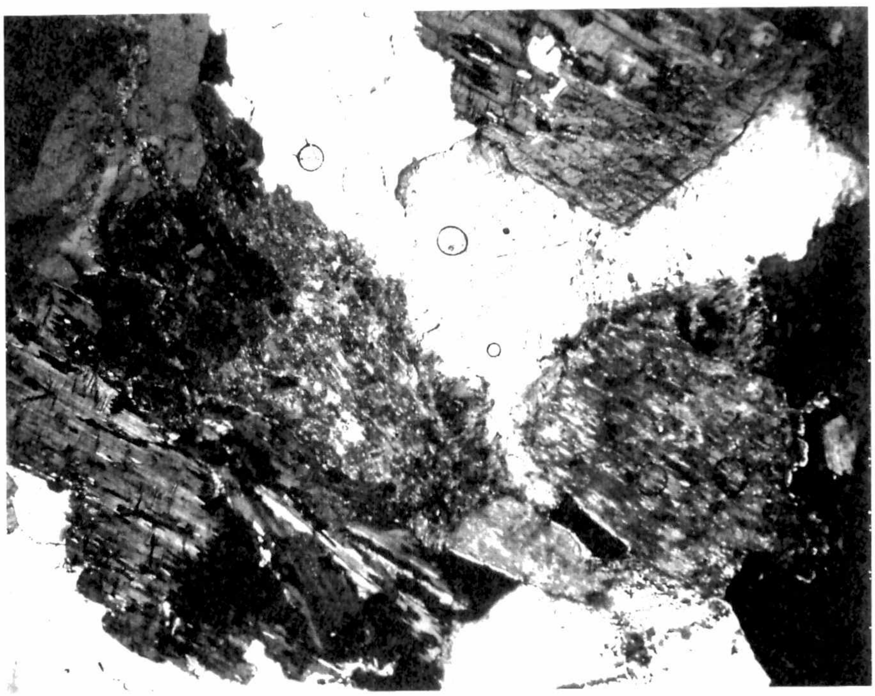
(a) Typical pegmatitic lens (compare crystal sizes to those in Figures 11 and 15, at the same scale), uncrossed nicols, showing cumulus plagioclase, intercumulus olivine, and smaller plagioclase crystals enclosed in olivine.

(b) Typical metagabbro, uncrossed nicols.

(a)



(b)



textural massiveness marks anorthositic gabbro, while troctolite typically displays preferred orientation of elongate crystals as well as small-scale layering features.

Sample modes are divided among three main fields of the Streckeisen (1976) diagram: olivine gabbro, troctolite, and anorthosite. This finding is consistent with the gross lithologies observed in the field. Plots of mode versus stratigraphic height reveal no discernible stratigraphic control on modes in either lithology (Figure 18). However, these plots do graphically display the variation in mode typical of the troctolite unit, and the homogeneity in mode typical of the anorthositic gabbro unit.

Based on the crystal size data gathered, the troctolite unit lithology contains slightly smaller but more equant olivine grains than does the anorthositic gabbro unit lithology. This may be related to the higher olivine content in the troctolite versus anorthositic gabbro. Olivine crystals may have formed slightly earlier in troctolite than in anorthositic gabbro, thereby being less crowded during growth.

Metagabbro

Metagabbro is found throughout the quarry along fracture planes, some of which display evidence of fault movement of an unknown degree. The metagabbro may persist laterally away from the fracture surface for a meter or less, or for many tens

Figure 18

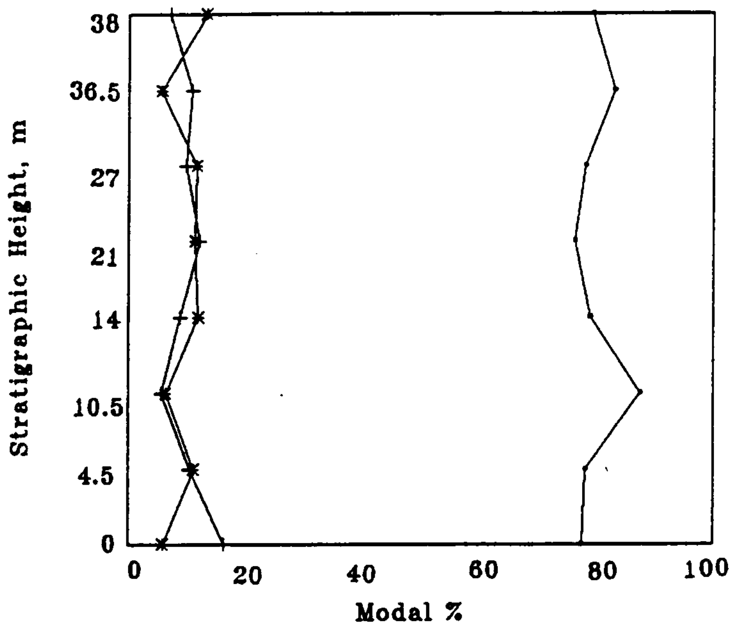
Sample mode versus stratigraphic height in the two traverses.

Sample mode versus stratigraphic height for

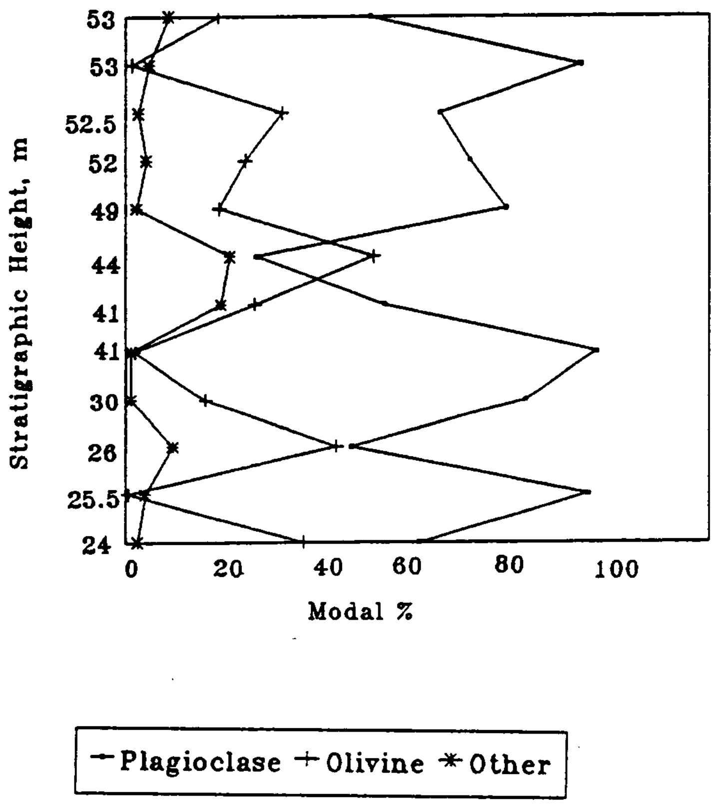
(a) anorthositic gabbro unit traverse, and

(b) troctolite unit traverse.

(a) Mode vs. Height, Anorthositic Gabbro Unit Traverse



(b) Mode vs. Height, Troctolite Unit Traverse



of meters. The most texturally distinctive feature observed in the metagabbro specimens is the occasional instance of exaggerated growth of amphibole crystals. Preferential enlargement of amphibole, which in the parent-rock is a relatively minor constituent, is interpreted as evidence of the abundant presence of water in the alteration process. No critical assemblages are present in the metagabbro for thermometry or barometry.

Metagabbro samples examined microscopically display clouded to relatively fresh, subhedral to anhedral, twinned and zoned plagioclase crystals, with the majority of other original interstitial phases replaced by green clots of fibrous to platy minerals, including chlorite (Figure 17b). Subhedral to anhedral opaque minerals are present interstitially and within other phases. Olivine is absent. In some instances, unusually large (up to 15 cm) amphibole crystals are included in metagabbro samples.

Modally, metagabbro consists of approximately 80% plagioclase, 5% to 14% unidentified alteration minerals, 0% to 1% amphibole, and typically less than 1% opaque phases. These samples tend to plot in the anorthosite corner of the olivine-plagioclase-pyroxene triangle of Streckeisen (1976) (Figure 9). However, it should be noted that this is a distortion of the original lithology, due to preferential alteration of olivine and pyroxene. This effect skews the mode towards the plagioclase corner. If the triangular diagram is modified to depict all other phases besides olivine and plagioclase in the pyroxene corner (Figure 9), the result is a more balanced diagram reflecting fewer anorthosite samples and more gabbro and troctolite samples. Thus, a comparison of the two portions of Figure 9 reveals that the majority of metagabbro samples examined from the quarry had protoliths of troctolite, anorthositic gabbro, or anorthosite.

4. MINERAL CHEMISTRY

With the exception of small-scale features within the troctolite unit, no distinct modal layering phenomena were observed. Therefore, the possibility of cryptic layering was investigated by chemical analysis of individual crystals within samples collected in stratigraphic traverses of both the anorthositic gabbro unit and the troctolite unit. Metagabbro was not probed for mineral chemistry since alteration is likely to have modified the original chemistry of plagioclase, the only surviving parent rock phase.

Analysis of microprobe data indicates no apparent systematic differences in mineral chemistry. The variations in An-contents of plagioclase and Fo-contents of olivine within a given sample are as great as the variations within either vertical traverse or between the two traverses. In both rock types, two distinct pyroxenes are found. These are similar enough from one rock type to the other to be considered the same two minerals: orthopyroxene of the composition $En_{80}Fs_{19}Wo_1$ (bronzite) and clinopyroxene of the composition $En_{43}Fs_{10}Wo_{47}$ (augite) in the troctolite traverse; orthopyroxene of the composition $En_{75}Fs_{24}Wo_1$ (bronzite) and clinopyroxene of the composition $En_{42}Fs_{12}Wo_{46}$ (augite) in the anorthositic gabbro traverse.

Data from all samples probed are included in Appendix B.

Anorthositic Gabbro Unit Traverse

A stratigraphic traverse of one section of anorthositic gabbro unit rocks resulted in 8 samples analyzed.

Plagioclase

The complete range of An compositions in the anorthositic gabbro traverse varies from An 69 (labradorite) to An 86 (bytownite) (Figure 19). The strongest normal zoning from rim to core within a single plagioclase grain ranges from An 69 to An 81 (sample 117). The same sample also contained the only significant example found of reversed zoning, from An 74 to An 69. Strong zoning is not typical, based on rim/core analyses of 28 crystals in 7 samples (Appendix B): the average An composition of rims in this traverse is An 74 (s = 3.8), and the average An composition of cores in this traverse is An 76 (s = 3.6).

In one sample (sample # 105) an included plagioclase within a pyroxene was probed; no significant difference was found in An content between the included crystal and the other plagioclase crystals probed in that sample. In the same sample (sample # 105), two examples of plagioclase crystals enclosed in olivine were analyzed. One of the enclosed plagioclase crystals displayed a composition differing from the average An content of other crystals in the same sample (An 64 rim, An 65 core, vs. an

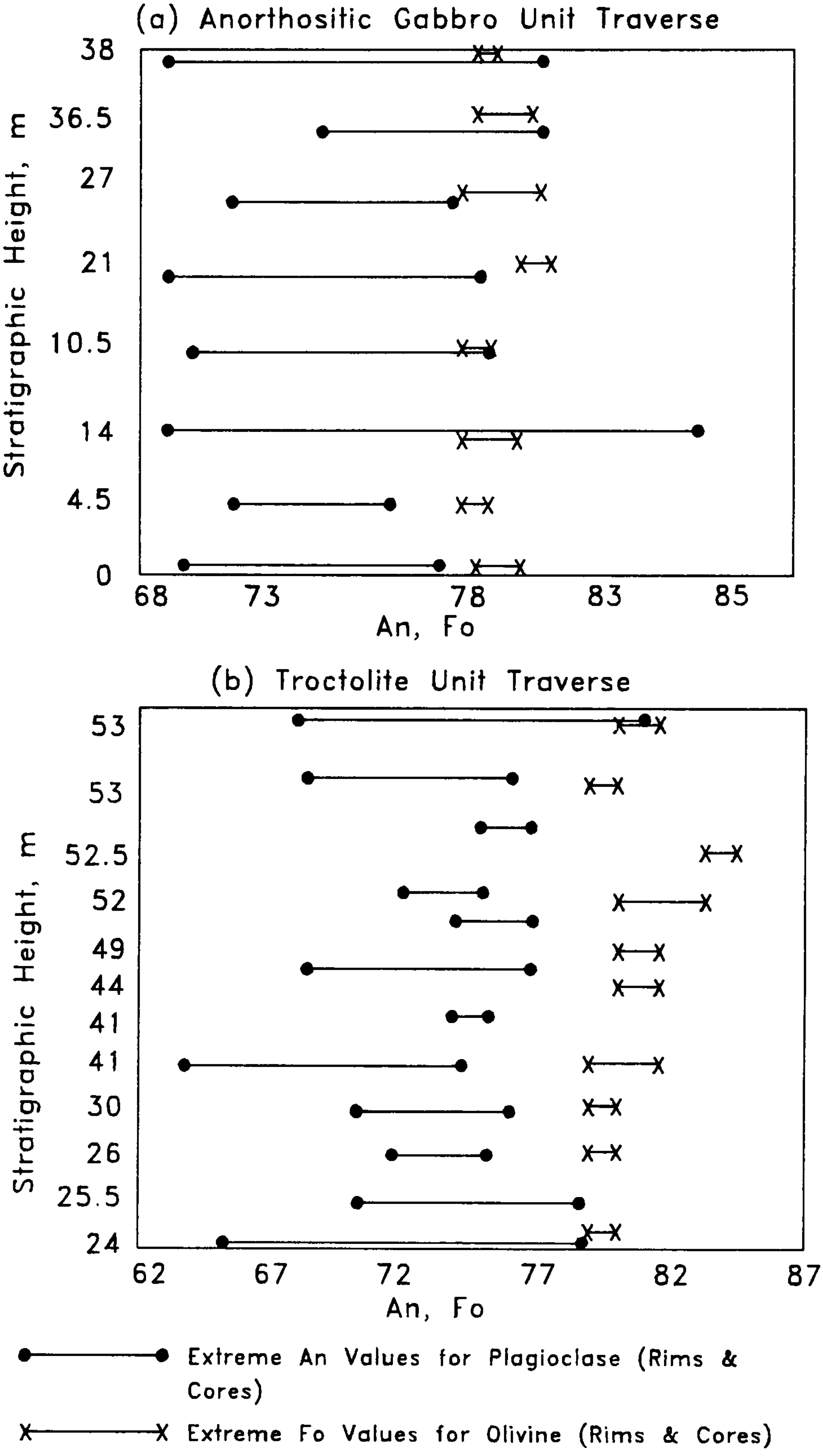
Figure 19

Range of An compositions of plagioclase and Fo compositions of olivine versus stratigraphic height in the two traverses.

Range of values of An composition of plagioclase and Fo composition of olivine versus stratigraphic height in

(a) the anorthositic gabbro unit traverse and

(b) the troctolite unit traverse.


(a) Anorthositic Gabbro Unit Traverse
Stratigraphic Height, m
38
36.5
27
21
10.5
14
4.5
0
68
73
78
83
85
An, Fo
(b) Troctolite Unit Traverse
Stratigraphic Height, m
53
53
52.5
52
49
44
41
41
30
26
25.5
24
62
67
72
77
82
87
An, Fo
Extreme An Values for Plagioclase (Rims & Cores)
Extreme Fo Values for Olivine (Rims & Cores)

average of An 75 in this sample overall). In the other instance of a plagioclase crystal enclosed in an olivine crystal within the same thin section, no significant difference in An content was found between the enclosed grain and other plagioclase grains in that sample (An 76 rim, An 77 core, vs. an average of An 75 in this sample overall).

Stratigraphic position has no evident control over plagioclase composition, as revealed by Figure 20a.

Olivine

The complete range of olivine compositions found within the anorthositic gabbro traverse is from Fo 77 to Fo 81 (Figure 19). With 12 rim/core pairs analyzed in 5 different samples, virtually no olivine zoning was discovered: maximum Fo-content differences between rim/core pairs are typically less than one unit, ie. Fo 79.5 to Fo 80. Stratigraphic position does not appear to exert any discernible control over olivine composition, as revealed by Figure 20a.

Pyroxenes

Two pyroxenes are found within the anorthositic gabbro traverse. Orthopyroxene has the composition $En_{76}Fs_{21}Wo_1$ (bronzite), whereas clinopyroxene has the composition $En_{42}Fs_{12}Wo_{46}$ (augite) (Figure 21). Of the 8 samples whose pyroxenes were analyzed,

Figure 20

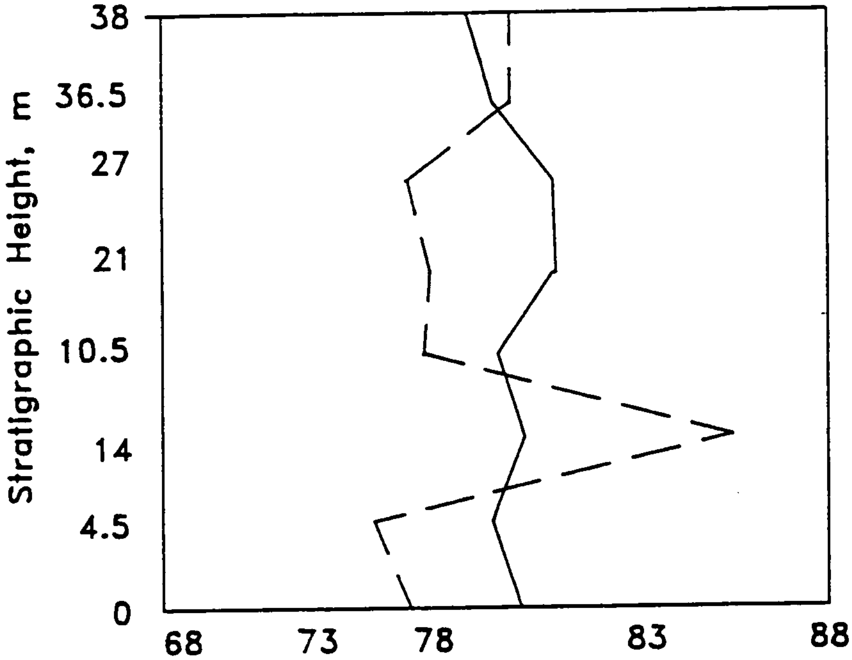
Core An compositions of plagioclase and core Fo compositions of olivine versus stratigraphic height in the two traverses.

Core An compositions in plagioclase and core Fo compositions for olivine versus stratigraphic height in

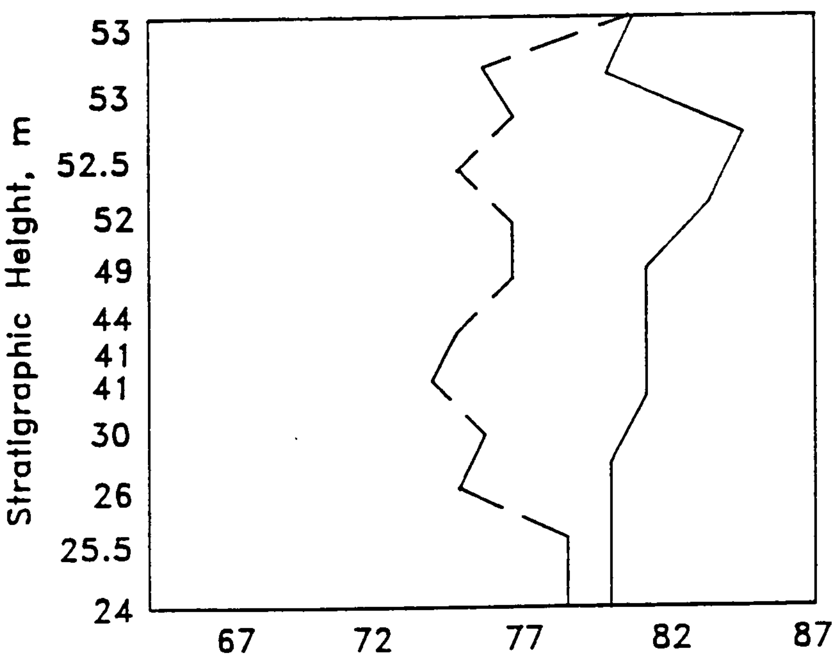
(a) the anorthositic gabbro unit traverse and

(b) the troctolite unit traverse.

(a) Core An Values for Plagioclase and Core Fo Values for Olivine Anorthositic Gabbro Unit Traverse



(b) Core An Values for Plagioclase and Core Fo Values for Olivine Troctolite Unit Traverse



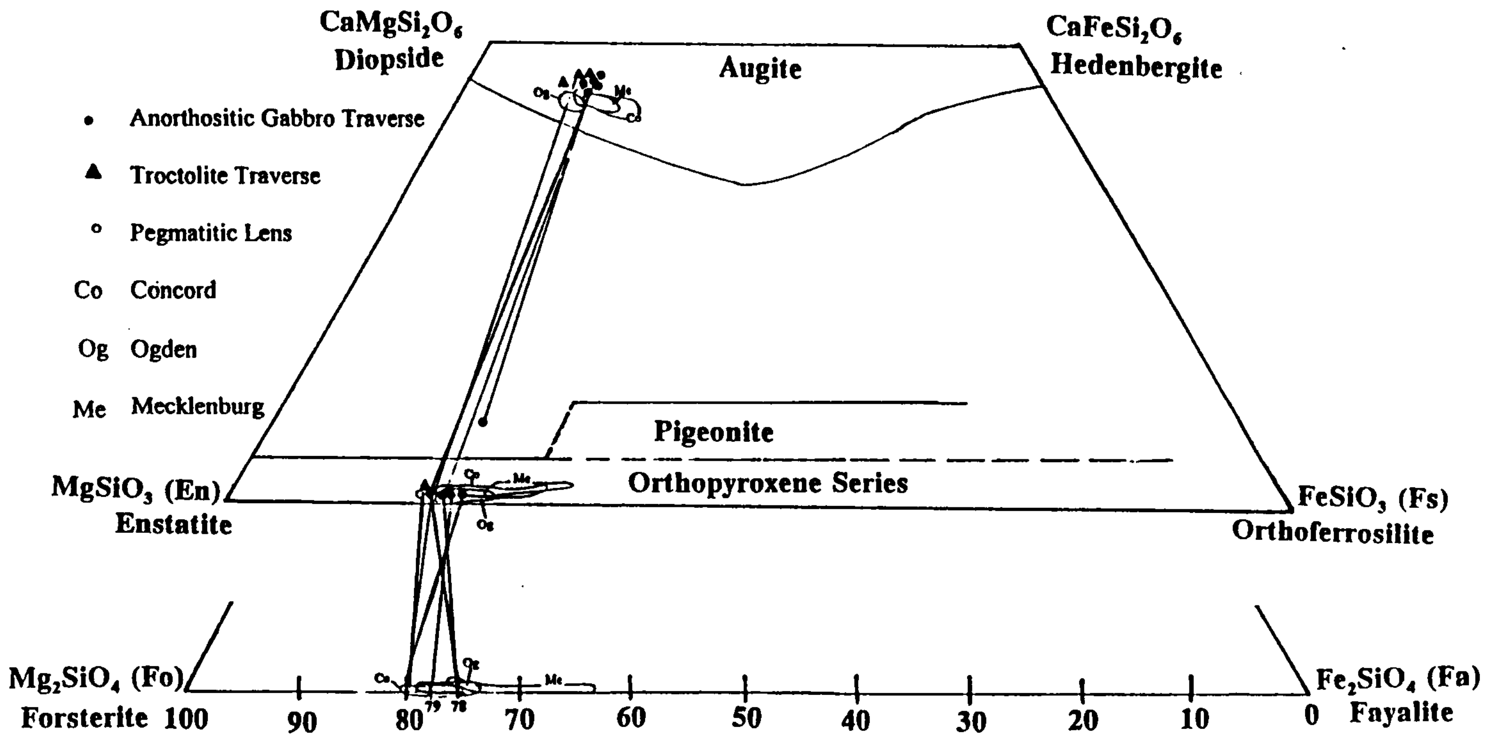
— — — An Values for Plagioclase

——— Fo Values for Olivine

Figure 21

Pyroxene compositions with tie-lines to corresponding olivine compositions.

Pyroxene compositions plotted on a triangular diagram with tie-lines to corresponding olivine compositions, where available. (Data from Concord, Ogden, and Mecklenburg adapted from McSween et al., 1984).


CaMgSi₂O₆
Diopside
Augite
CaFeSi₂O₆
Hedenbergite
• Anorthositic Gabbro Traverse
▲ Troctolite Traverse
○ Pegmatitic Lens
Co Concord
Og Ogden
Me Mecklenburg
Pigeonite
Orthopyroxene Series
MgSiO₃ (En)
Enstatite
FeSiO₃ (Fs)
Orthoferrosilite
Mg₂SiO₄ (Fo)
Forsterite
Fe₂SiO₄ (Fa)
Fayalite
100
90
80
79
78
70
60
50
40
30
20
10
0

both orthopyroxene and clinopyroxene were found in two of those samples (sample # 111 and sample # 112). More pyroxenes analyzed proved to be clinopyroxene than orthopyroxene (18 points in 6 samples for clinopyroxene; 6 points in 4 samples for orthopyroxene). The two samples with both pyroxenes were perhaps coincidentally both collected from Bench 3 (lowermost part) of the quarry. Although the distribution of data suggests that clinopyroxene is more abundant than orthopyroxene, the data are too limited to conclude that some samples lack orthopyroxene.

Other Minerals

Amphibole compositions at 8 points in 4 samples were obtained for the anorthositic gabbro unit traverse; these appear to be hornblende. Likewise, biotite compositions were obtained at three points in two samples. Data are listed in Appendix B.

Troctolite Unit Traverse

A stratigraphic traverse of one section of troctolite unit rocks resulted in 18 analyzed samples, including the following "special samples": 2 plagioclase lenses, 4 pegmatitic lenses (2 from sample # 135 discussed above, and 2 from sample # 101, a pegmatite found in troctolite instead of the usual gabbro) and an anorthositic gabbro block within enclosing troctolitic rock. The "special samples" are examples of petrographically unusual items which were collected either within the troctolite unit traverse or elsewhere within troctolite unit rocks. Data from all samples probed are included in Appendix B.

Plagioclase

The complete range of An compositions in the troctolite traverse is from An 64 (labradorite) to An 83 (bytownite) (Figure 19). The strongest zoning from rim to core within a single plagioclase grain ranges from An 68 to An 81 (sample 130), about the same magnitude as the strongest zoning in a single grain in the anorthositic gabbro unit traverse. Strong zoning is not typical, based on rim/core analyses of 28 crystals in nine samples (Appendix B): the average composition of rims in this traverse is An 73 (s = 3.3), and the average composition of cores in this traverse is An 74 (s = 4.2).

In two samples (sample # 132 and # 133), examples of plagioclase crystals enclosed in olivine were probed. One of the enclosed plagioclase crystals (in sample # 132) displayed strong zoning (An 66 to An 74), but the average An composition did not differ from the average An content of other crystals in the same sample (An 70 rim, An 71 core in this sample overall). In the other instance of a plagioclase crystal enclosed in an olivine crystal (sample # 133), only slightly stronger zoning was found in the enclosed crystal (An 73 to An 76 vs. An 75 to An 76 in this sample overall).

Stratigraphic position has no evident control over plagioclase composition, as revealed by Figure 20b.

Olivine

The complete range of olivine compositions found in the troctolite traverse is from Fo 79 to Fo 84. With 8 rim/core pairs analyzed in 5 different samples, virtually no olivine zoning was discovered (ie. the maximum difference in Fo content is typically less than one Fo unit).

Stratigraphic position does not appear to exert any discernible control over olivine composition, as revealed by Figure 20b.

Pyroxenes

Two pyroxenes are found within the troctolite unit traverse (Figure 21). Only one example of orthopyroxene was probed on the traverse (excluding "special samples"). This orthopyroxene has the composition $En_{80}Fs_{18}Wo_2$ (bronzite, sample #130). The clinopyroxene in this traverse has the composition $En_{42}Fs_{12}Wo_{46}$ (augite). Of the four traverse samples whose pyroxenes were probed, orthopyroxene was found in one sample without another pyroxene present in the probe mount, although the modal data reflect clinopyroxene only for this sample (sample # 130). Clinopyroxene alone was found in 3 traverse samples. More pyroxenes probed in this traverse proved to be clinopyroxene than orthopyroxene (6 points in 3 samples for clinopyroxene; 1 point in 1 sample for orthopyroxene). Although the distribution of data suggests that clinopyroxene is more abundant than orthopyroxene, the amount of data is too limited to conclude that some samples lack either pyroxene. Modally, the percentage of pyroxene in troctolite unit rocks is smaller than in anorthosite unit rocks, thus the more limited amount of mineral chemistry data is not surprising.

Other Minerals

Amphibole compositions at 14 points in 6 samples were obtained for the troctolite unit traverse; these are hornblende. One biotite composition (sample # 127) was obtained. Data are listed in Appendix B.

Comparison Of Both Traverses

Results of mineral chemistry analyses are summarized on several variation diagrams in Figures 19 through 21. In general, these Figures reveal a somewhat broader range of An content in plagioclase crystals in troctolite samples versus anorthositic gabbro samples, and a slightly broader range of Fo content in olivine crystals in troctolite samples versus anorthositic gabbro samples (Figure 19). There is no apparent stratigraphic control on core An or core Fo content in either lithology (Figure 20).

Plots of most calcic plagioclase versus most magnesian olivine for both traverses (Figure 22) reveal randomly scattered points within a narrow range of An and Fo values. No linear correlations are apparent.

Pyroxenes probed in samples from both traverses are plotted on a pyroxene quadrilateral in Figure 21, along with corresponding olivine compositions and appropriate tie-lines. Inspection of this figure reveals that although anorthositic gabbro unit traverse samples tend to plot slightly to the more Fe-rich side of troctolite unit samples, the mineral compositions of all of the samples are clumped in the augite, bronzite, and forsterite regions. Crossing tie-lines are present, and no progression of Fe-enrichment is evident from this diagram.

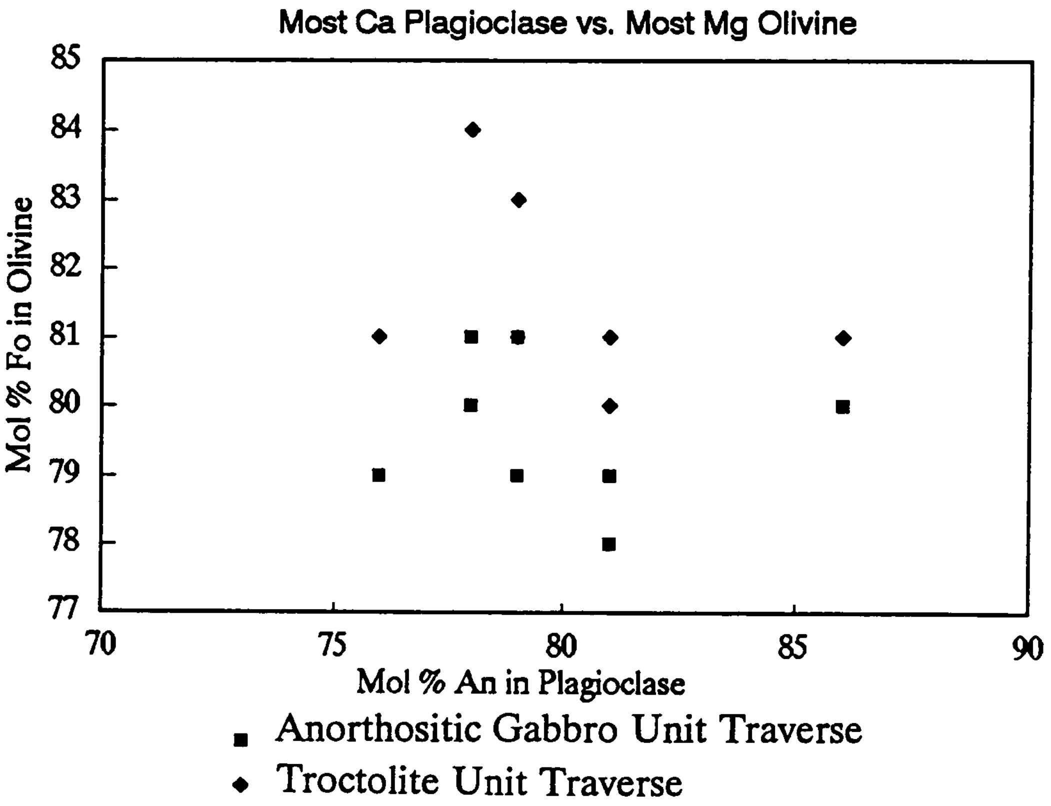
In summary, significant differences between the mineral chemistries of the two units are not apparent.

Comparison With Related Plutons

Just as no significant differences in mineral chemistry were discovered between the two units at the subject site, significant differences between mineral chemistry at Rock Hill and other nearby, presumably cogenetic gabbroic plutons are not apparent. Pyroxene and olivine data from Ogden, the closest gabbroic pluton to Rock Hill (Figure 1), are included in the indicated fields in Figure 21. Likewise, fields are

Figure 22

Most calcic plagioclase versus most magnesian olivine in the two traverses.


Most Ca Plagioclase vs. Most Mg Olivine
85
84
83
82
81
80
79
78
77
Mol % Fo in Olivine
70
75
80
85
90
Mol % An in Plagioclase
Anorthositic Gabbro Unit Traverse
Troctolite Unit Traverse

indicated for pyroxene and olivine data from Concord and Mecklenburg (Figure 1) on Figure 21. Similar results are observed from Farmington, Barber, and Buffalo, although to avoid crowding, only the fields from the three nearest plutons with available data are shown on Figure 21. Data from Buffalo, the furthest from Rock Hill of any of the nearby plutons mentioned in this paper, displays the greatest deviations from the Rock Hill data. However, these are also more widely distributed across a plot such as Figure 21, with some data points agreeing closely with the Rock Hill data. Overall, while some minor variation occurs in the mineral chemistries of these plutons, no major differences are found. Therefore, the presence of anorthosite and of layering features at Rock Hill, and the lack of anorthosite or noticeable layering features at the other nearby plutons, is apparently not related to some intrinsic difference in the chemistry of the Rock Hill pluton versus the nearby plutons.

Special Samples

One unique sample was collected in an area of the quarry characterized by troctolite unit rocks. This sample (sample # 135, also discussed in the petrography section, above) contains troctolite and anorthositic gabbro in contact via an intervening pegmatitic lens. Due to its unique juxtaposition of lithologies, this sample was analyzed in some detail as 4 samples, designated 135A (troctolite), 135B (anorthositic gabbro), 135A-Pegmatite (pegmatitic lens at contact with troctolite), and 135B-

Pegmatite (pegmatitic lens at contact with anorthositic gabbro). Mineral chemistry for this sample is presented with the "Special Samples" in Appendix B, which also includes another pegmatitic lens (sample # 101, a pegmatitic lens enclosed in troctolite), plagioclase lenses (sample # 55 and # 130), and a sample from an anorthositic gabbro block found enclosed in troctolite (sample # 118).

No significant differences in An content of plagioclase or Fo content of olivine were discovered in any of the subportions of sample # 135 vs. each other or any other probed samples typical of the main lithologies. Data on clinopyroxene chemistry was available only for the troctolite portion of sample # 135; it is virtually the same as clinopyroxene found in all other samples of both troctolite and anorthositic gabbro probed. Likewise, orthopyroxene chemistry from both the troctolite and pegmatite portion of sample # 135 are essentially indistinguishable from any other orthopyroxene probed. The chemistry of amphibole in all 4 subportions of sample # 135 is virtually identical.

The other pegmatitic lens probed (besides that in sample # 135) was a rare pegmatite lens in the troctolite unit, sample # 101. Most pegmatite lenses were observed in anorthositic gabbro, as stated earlier. The An composition in sample # 101 was very similar to the An compositions in the troctolite unit traverse as a whole in the anorthositic gabbro unit traverse. Likewise, the composition of olivine in sample # 101 very closely matches the olivine composition of the troctolite unit traverse, and the olivine composition of the anorthositic gabbro unit traverse. An orthopyroxene analysis in sample # 101 does not differ significantly from those in any of the other samples probed. Amphibole composition in sample # 101 is within the range of compositions found in all other samples probed.

The findings were essentially the same for sample # 118, a block of massive anorthositic gabbro found enclosed in troctolite. No significant differences in mineral chemistry were discovered between it and any other samples probed.

Three plagioclase lenses were probed: sample # 35, sample # 130 p.l. and sample # 55. Despite distinct modal differences, no significant differences in mineral chemistry were discovered in any of the phases probed as compared to other samples probed from both traverses.

5. PETROGENESIS

Textural observations suggest that plagioclase and olivine were the earliest crystallizing phases at Rock Hill, as for the other nearby gabbroic intrusions (e.g. Olsen et al., 1983). Fe-enrichment trends are limited for the samples analyzed from Rock Hill (Figure 21). The limited extent of Fe-enrichment trends observed at the nearby plutons was suggested by McSween et al. (1984) as evidence supporting the hypothesis that these gabbroic plutons may have been emplaced as crystal mushes. Yet fractional crystallization must have occurred to produce the cumulate plagioclase and olivine units found at Rock Hill and the nearby plutons. Thus, a mechanism must be invoked for producing cumulate rocks with the textural features observed at Rock Hill without relying on crystal settling alone. Crystal mushes may be one part of the explanation for Rock Hill.

In the absence of distinct vertical variations in mineral chemistry as revealed by microprobe analyses of traverses of both anorthositic gabbro and troctolite, the occurrence of 2 distinct lithologic units (in terms of mode and texture) must be explained by a mechanism other than simple crystal settling accompanied by fractional crystallization. First, possible flaws in the sampling strategy are considered to assess the validity of the observation that stratigraphic variations do not occur. Next, explanations applied to similar observations at other layered intrusions are discussed and compared to findings at Rock Hill. Finally, a possible explanation for the relationship between gabbro and metagabbro at the Rock Hill pluton is discussed.

Possible Sampling Biases

An examination of the data gathered in this study reveals that differences in mineral chemistry between the two main lithologies investigated are not dramatic. As described earlier, sampling within the quarry was limited to some extent by active quarry operations. Perhaps if the two traverses had been separated further, or if a broader band of each rock type had been sampled, a more distinct difference in mineral chemistry between anorthositic gabbro and troctolite may have been revealed. In this possible scenario, the troctolite and gabbro do represent two distinct layers, but the chemical differences between them are slight near their contacts, with the quarry having coincidentally intercepted a contact. Such a coincidence seems somewhat improbable; a more likely possibility is that these two lithologies occur together over a large area of the pluton, and/or have been brought into fault contact with each other in many areas, such that the quarry intercepts a relatively representative section near Chalcraft's "anorthosite region". If so, the problem of the lack of clear chemical distinction between the two lithologies remains open.

The data available in this study also do not reveal significant differences within vertical traverses of a single rock type. Limitations in the vertical dimension exposed by the quarry may provide an explanation. Chalcraft (1970) estimated through modelling magnetic data obtained in his study that the Rock Hill pluton is approximately 10,000 feet (3,048 meters) thick. Thus, the maximum vertical sequence available to sample within the quarry (approximately 60 meters) represents only about 2 % of the presumed thickness of the pluton. It is quite possible that a distinct progression in mineral chemistry occurs within the Rock Hill pluton over a much broader vertical scale than that represented by this study. The scale of layering may be on the order of hundreds of meters, consistent with the lithologic regions mapped by Chalcraft (1970) (Figure 2).

The effect of possible errors in the analysis of mineral chemistry of the samples should be minimized by the total number of individual points analyzed. This possibility is not thought to have contributed any meaningful bias to the analytical results.

A fourth, less attractive possibility remains. The Rock Hill pluton, on a gross scale, may be quite chemically homogenous throughout. The subject quarry may be as representative as any other possible sampling locality anywhere in the pluton. This possibility could be investigated by additional sampling elsewhere in the city of Rock Hill. However, the availability of "in-place" outcrops is limited, and the weathered condition of boulders would make collection of "fresh" samples much more difficult than it is within the quarry. Chalcraft (1970) carried out such a sampling program, but did not include mineral chemistry in his investigation. If one could obtain sufficient samples representative of each of Chalcraft's lithologic regions (Figure 2), it is possible that more distinctive chemical variation would be revealed, and may be found to be consistent with the gross layering suggested by the outcrop pattern identified by Chalcraft (1970).

Origin Of The Layering

Given the homogeneity of mineral chemistry found within a given stratigraphic traverse at the subject site, and also between the two traverses, outcrop-scale layering features observed at Rock Hill must be explained without reliance on fractional crystallization through concurrent crystal settling as an important mechanism. "The tuning of convection, crystallization kinetics, and phase equilibria ... can produce a variety of textures and layering but not a diversity of compositions" (Marsh, 1988). The subjects of magmatic convection, crystal settling dynamics, and the formation of layered intrusions in general are beyond the scope of this thesis. The body of literature on these subjects is vast, with excellent examples and intriguing hypotheses cited by numerous authors. Without attempting to extrapolate too liberally, the mechanics of the formation of features observed at Rock Hill are considered. Hypotheses suggested for similar occurrences are outlined below, since some of the specific outcrop-scale features found at Rock Hill are apparently similar to those described from some better-known plutons. Site-specific factors for Rock Hill are compared to those at the more thoroughly studied sites in an effort to arrive at an explanation for the features observed at Rock Hill.

Comparison With Similar Occurrences Elsewhere

Discussion of similar occurrences is presented in this Section with comparisons to Rock Hill in an attempt to explain the layering in troctolite at Rock Hill, with emphasis on: 1) the formation of plagioclase lenses; and 2) the co-occurrence of the two lithologies, including the lack of layering features in the anorthositic gabbro lithology.

1) Formation of Plagioclase Lenses

Plagioclase flotation and later foundering of blocks may have provided the mechanism for formation of plagioclase lenses at Rock Hill. In the Skaergaard intrusion (Irvine, 1987), subrounded to angular blocks and fragments of anorthositic gabbro and gabbroic anorthosite apparently stoped from a part of the upper border series. These blocks are interpreted by Irvine (1987) as concentrations of plagioclase originally accumulated by flotation: density differences as small as 0.1 g/cm^3 can theoretically result in plagioclase flotation or settling. At Rock Hill, the lensoid shape of the plagioclase-rich pods and layer-parallel alignment suggest movement of plagioclase lenses as discreet units through a moving liquid to their ultimate resting places.

2) Lack of Layering Features in Anorthositic Gabbro and Co-occurrence of the Two Main Lithologies

At some of the more well-documented layered intrusions, diagenetic recrystallization is believed to have obliterated some of the original layering features. Some mechanism must be invoked to explain the inconsistent occurrence of layering features at the Rock Hill site. However, diagenetic recrystallization as a mechanism for the formation of the two different lithologies at Rock Hill was considered and rejected. Rejection of that mechanism is based on the clear examples available at the subject site of altered rock (metagabbro), which differ significantly in appearance and mineralogy from the massive anorthositic gabbro lithology.

At Skaergaard, areas displaying "trough layering" are found (Irvine, 1987). These are areas where massive and layered lithologies are found side by side, the layered part in troughs between massive areas. The troughs may divide or join upward; Irvine's schematic gives the troughs the appearance of migrating patch reefs in cross-section. Irvine (1987) suggests that the massive rock was formed *in situ* by convection cells which resulted in thorough mixing and prevented effective crystal settling. Meanwhile, density currents produced the intervening layered troughs. At Rock Hill, there was insufficient exposure of contacts between the massive lithology and the layered lithology to assess the applicability of this hypothesis. However, the one contact observed, as mentioned previously, displayed a sharp, slightly undulose contact surface, suggestive of contact while both lithologies were in a semi-liquid state. At least the troctolite portion was apparently in a semi-liquid state when this contact was formed, while the anorthositic gabbro portion may have been in the form of a crystal mush, as suggested for the other plutons in this series to explain their general lack of layering features (McSween, 1984). Blocks of anorthositic gabbro in troctolite (i.e. sample # 118; mentioned previously) may have their origin in the ripping up and incorporation of more viscous, semisolidified gabbro into still fluid and circulating troctolitic magma. Plagioclase lenses may also have become incorporated into the circulating troctolite by partial ripping up of a semi-solidified plagioclase-rich floatation crust.

The close proximity in the Rock Hill quarry of two distinct lithologic units should be explained by some mechanism, preferably one which explains the lithologic differences in genetic terms. The homogeneity of mineral chemistry between the two lithologies makes coincidental reintrusion by separate pulses of magma less probable (unless the magma pulses were compositionally almost identical). Therefore, a mechanism like that suggested by Irvine (1987) for the trough layering at Skaergaard may have operated at the subject site as well. Its effects may not be well exposed due to subsequent faulting. As discussed above, similar lithologies and field relationships from other more thoroughly investigated plutons provide hypothetical models which may apply to the Rock Hill pluton.

<u>Site-specific Factors</u>

The lack of definitive contacts at the subject site is the most troublesome aspect of an attempt to tie the two main lithologies into a coherent genetic scenario. Massive anorthositic gabbro grades into, or more typically comes into fault contact with, layered troctolite. With a few minor exceptions, mineral chemistries are virtually identical between the two lithologies, and between samples in vertical traverses in each lithology. The close proximity in the quarry of the two lithologic units, assuming fault displacements are small, leads to the supposition that they formed close together, and that the one example of a definitive contact found at the subject site is not unique. The occurrence in at least one area of the subject site of anorthositic gabbro blocks in troctolite (i.e. sample # 118) indicates that anorthositic gabbro in at least a semi-consolidated state formed before solidification of troctolite.

Layering features within the troctolite unit are intriguing, and may suggest that a variety of crystal settling, crystal flotation, and convective processes influenced the final petrography and gross appearance of the lithology. Likewise, the general lack of layering features in the anorthositic gabbro unit requires a genetic explanation consistent with the occurrence of layering features in its companion (and chemically equivalent) troctolite lithology.

Plagioclase lenses are arguably the most interesting gross feature at the subject site. They are a feature which draws the eye, and makes olivine-rich layers appear more pronounced. The explanation provided by Irvine (1987) for plagioclase flotation and subsequent sinking leading to plagioclase lenses and blocks at Skaergaard is embraced for the subject site. The similarity in gross appearance of the plagioclase lenses, including draping layers in enclosing rock, and apparent flow direction-parallel alignment of the lenses, as well as the similarity of rock types involved is compelling.

The modal differences between the anorthositic gabbro unit and the troctolite unit are accounted for most readily in the context of a genetic explanation for the difference in massive versus layered lithologies crystallizing from the same magma. Here, the hypothesis applied to the Skaergaard by Irvine (1987) (convection cells and intervening density currents, as discussed above) is suggested for the Rock Hill site. Though impossible to demonstrate empirically for the subject site within the scope of this investigation, this hypothesis suggests a mechanism for producing massive rock adjacent to layered rock, differing only in modal distribution. Thus, the hypothesis fits the observed features at the Rock Hill site.

The question of why layering is found at Rock Hill and not at other plutons in this series remains open. The answer may simply involve the quality and quantity of the exposure at Rock Hill versus the other plutons. Preferred orientation of plagioclase grains is reported from other plutons in this series. Perhaps that is an indication that more pronounced modal layering lies undiscovered in some of the related intrusions. After all, massive gabbro constitutes most of the outcrop area of the Rock Hill pluton, where good overall exposure (and excellent exposure in the quarry) have fortuitously allowed the presence of layering features to be discovered in the troctolite lithology, which is not the predominant lithology present in terms of area of exposure.

Origin Of The Gabbro-Metagabbro Association

The co-occurrence of gabbro and metagabbro at the Rock Hill site appears to be an artifact of fracturing of the pluton and availability of water. The metagabbro lithology occurs along and near fracture planes and fault surfaces, and grades into less altered rock over scales varying from a few centimeters to many tens of meters. Due to the extensive faulting and fracturing present, metagabbro is intimately mixed with the relatively unaltered rock typical of the main portion of the pluton, and is not restricted to the margins of the pluton as previously mapped (Butler, 1966, Chalcraft, 1970). Previous mapping indicates that larger masses of metagabbro are present near the edges of the pluton; this is where fracturing would have been more pervasive. Indeed, the North Rock Hill pluton, separated from the subject pluton by a maximum outcrop width of approximately 2.4 km of metagabbro (based on the map of Butler, 1966), may be a fault slice of the subject pluton, or may be connected to the subject pluton below the ground surface: a potentially interesting problem for another investigator.

The Rock Hill pluton is one in a series of cogenetic gabbroic bodies, most of which are closely associated with metagabbro. The descriptions of what has been mapped as "metagabbro" at the other intrusions in this series match the description of metagabbro at Rock Hill. Some studies of individual plutons concluded that the gabbro had coincidentally intruded previously formed regionally metamorphosed gabbro (e.g. Hermes, 1968; McSween, 1981). Since the areal distribution (Figure 1) and petrologic characteristics of these plutons are indicative of a compressional plate boundary as the magmatic source (McSween et al., 1984), the gabbro-metagabbro complexes have been interpreted as sites of multiple episodes of intrusion. As previously stated, this hypothesis suggests that each new pulse of magma utilizes heated lithosphere along previous magma ascent pathways (McSween, 1984). The resulting nested intrusions are differentially metamorphosed due to their age differences (i.e. later plutons metamorphosed earlier ones). A combination of consistent tectonic or structural control and re-utilization of preheated magma ascent pathways of earlier intrusions could explain the gabbro-metagabbro association (McSween et al., 1984). Cross-cutting relationships between metagabbro and gabbro would help decide if this hypothesis applies to the subject site. However, limited exposure has not permitted the establishment of field relationships demonstrating clear cross-cutting patterns, until the present study.

Based on the irregular distribution of altered gabbro and the apparently random degree of alteration within the Rock Hill pluton, Chalcraft (1970) concluded that penetration of fluids generated by magmatic differentiation caused the alteration to metagabbro. Findings of this study indicate that the Rock Hill gabbro/metagabbro complex represents one large incompletely metamorphosed intrusion, most altered where fluids were most accessible: along fracture surfaces, which are probably more numerous near the margins of the pluton. Medlin (1966) reached a similar conclusion at the Buffalo Mafic complex in Union County, South Carolina (probably not part of this series of intrusions, but located only about 45 miles southwest of the Rock Hill pluton). At Mecklenburg (Figure 1) Hermes (1968), reached the same conclusion about the availability of fluids affecting degree of metamorphism, but concluded that the metagabbro represented an older intrusion.

Fronabarger (1984) considered two hypotheses for formation of the gabbro-metagabbro association in this series of plutons in light of isotopic age data, bulk rock chemistry, and textural data. One is the multiple intrusive event hypothesis suggested by McSween et al. (1984), and the other a single intrusive event hypothesis, which fit the data Fronabarger obtained, as well as data from some other plutons in this series. Fronabarger found that available data from some of the plutons fit the multiple-intrusion hypothesis, while data from others fit a single-intrusion hypothesis. Fronabarger concluded that if all of the gabbro-metagabbro complexes in this series formed by one mechanism, then more information was needed. Specifically, direct views of gabbro-metagabbro contacts to establish the existence or absence of cross-cutting relationships. Direct views of gabbro-metagabbro contacts have now been documented at Rock Hill, as described above.

Rather than the metagabbro representing an earlier intrusion, it is suggested that the metagabbro is the metamorphosed equivalent of other lithologies in this intrusion. The metagabbro often contains features indicative of the lithology of the parent rock, such as plagioclase-rich lenses and pegmatitic lenses. Similar occurrences of co-mingled mafic intrusions and metamorphosed equivalents in the Alabama Inner Piedmont have been explained as instances of incomplete metamorphosis of single large gabbroic plutons, wherein some of the parent rock remained relatively unaltered (Neilson and Stow, 1980). The fluids causing alteration may have been in part derived from magmatic differentiation, as Chalcraft (1970) suggested. However, field relationships noted in this study suggest that most of the alteration to metagabbro took place after solidification of the magma, based on the extent to which fracturing controls metagabbro distribution at the subject site. Given the similarities between Rock Hill and the other plutons in this series, the origin of the gabbro/metagabbro association for the entire series may be the same as that suggested for Rock Hill.

6. SUMMARY

A 400 m.y.-old gabbroic pluton intrudes the Charlotte Belt at Rock Hill, South Carolina, and is one of an arcuate series of cogenetic plutons of similar lithology (Figure 1). The area of the pluton studied is within the Martin Marietta Rock Hill quarry, located near the anorthosite region as mapped by others (Figure 2, Chalcraft, 1970). That portion of the pluton studied consists predominantly of massive anorthositic gabbro, with occasional pegmatitic anorthosite lenses. Troctolitic areas make up less than half of the portion of the pluton studied, and contain discontinuous layering features and plagioclase lenses. Both rock types contain areas of alteration to metagabbro found along the pervasive fractures throughout the area studied. Beyond fracturing and localized alteration to metagabbro, the site is not significantly affected by metamorphism.

Neither field relationships, petrography, nor mineral chemistry reveal a clearly systematic distribution pattern of the anorthositic gabbro and troctolite unit rocks at the subject site.

Sample modes reveal that the site contains primarily olivine gabbro and troctolite, with some gabbronorite and anorthosite. Stratigraphic position does not appear to control sample mode or crystal size. The two lithologic units typically grade into each other, or contacts are not identifiable due to fracturing and faulting. At least one instance of a sharp contact between the two lithologies was observed.

The stratigraphic distribution of mineral chemistry was the focus of this investigation; however, no distinct cryptic layering was discovered. Chemical variations are relatively small; vertical variations in traverses in both the anorthositic gabbro and troctolite are no greater than the range of mineral chemistries found within a single sample. The complete range of plagioclase compositions analyzed by electron microprobe in samples of either main lithology is from An 64 to An 83. Likewise, the complete range of olivine compositions analyzed is from Fo 77 to Fo 84. Two distinct pyroxene compositions are found: augite (En42Fs12Wo46) and bronzite (En79Fs20Wo1). Chemical variations do not correlate systematically with stratigraphic level.

Due to the homogeneity of mineral chemistry, textural and modal differences must be explained without classical fractional crystallization accompanied by crystal settling as a major mechanism. Models used to explain similar phenomena elsewhere were considered. The co-occurrence of the two lithologies may be explained by convection cells producing massive anorthositic gabbro with intervening density current deposition producing the (modally) layered troctolite and plagioclase-rich lenses in an otherwise chemically homogenous magma.

The occurrence of metagabbro along fracture surfaces and the types of mineral assemblages found in the metagabbro are taken as evidence that metagabbro was formed where water was available to promote metamorphism.

LIST OF REFERENCES

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Albee, A.L., and Ray, L., 1970, Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates, and sulfates: Anal. Chem. 42, p. 1408-1444.

Bence A. E., and Albee, A.L., 1968, Empirical correction factors for the electron microanalysis of silicates and oxides: J. Geol. 76, p. 382-403.

Buddington, A. F., 1939, Adirondack igneous rocks and their metamorphism: Geol. Soc. Amer. Mem. 7, 354 p.

Butler, J. R., 1966, Geology and mineral resources of York County, South Carolina: South Carolina State Devel. Board, Bull. 33.

Butler, J. R. and Ragland, P. C., 1969, A petrochemical survey of plutonic intrusions in the Piedmont, Southern Appalachians, U.S.A.: Contr. Mineral. Petrol., v. 24, p. 164-190.

Chalcraft, R. G., ms, 1969, Petrography and geophysics of the Rock Hill gabbro pluton, York County, South Carolina: M.S. thesis, Univ. of North Carolina, Chapel Hill.

__________, 1970, Petrography and geophysics of the Rock Hill gabbro pluton, York County, South Carolina: Southeastern Geol., v. 11, p. 153-171.

Fronabarger, A. K., ms, 1984, Petrogenesis of the Mt. Carmel and Greenwood Complexes, South Carolina, and modelling of heat transfer in gabbro: Ph.D. dissertation, Univ. of Tennessee at Knoxville.

Hatcher, Robert D., 1987, Tectonics of the Southern and Central Appalachian internides: Ann. Rev. Earth Planet. Sci., v. 15, p. 337-362.

Hermes, O. D., 1968, Petrology of the Mecklenburg gabbro-metagabbro complex, North Carolina: Contr. Mineral. Petrol., v. 18, p. 270-294.

Irvine, T. N., Layering and related structures in the Duke Island and Skaergaard intrusions, in Parsons, Ian, ed., 1987, Origins of Igneous Layering, D. Reidel Publishing Co., Boston.

Marsh, B. D., 1976, Some Aleutian andesites: their nature and source: Jour. Geol., v. 84, p.27-45.

__________, 1978, On the cooling of ascending andesitic magma: Philos. Trans. R. Soc. London, v. 288, p. 611-625.

________, 1988, Crystal capture, sorting, and retention in convecting magma: Geol. Soc. Amer. Bull., v. 100, p. 1720-1737.

McSween, H. Y., Jr., 1981a, Petrology of the Ogden gabbroic intrusion, York County, South Carolina: South Carolina Geol., v. 25, p. 91-100.

____________, 1981b, Gabbro-metagabbro complexes: a mechanism for magma ascent?: Geol. Soc. Amer. Abs. with Programs, v. 13, p. 508.

McSween, Harry Y., Sando, Thomas W., Clark, Stephen R., Harden, James T., and Strange, E. Allison, 1984, The gabbro-metagabbro association of the southern Appalachian Piedmont: Amer. Jour. Sci., v. 84, p. 437-461.

Medlin, J. H., 1972, Petrology of the mafic igneous complexes in the Southeastern U.S. Piedmont: II, the Buffalo mafic igneous complex, Union County, South Carolina: Southeastern Geol., v. 14, p. 73-106.

Neilson, Michael J., and Brockman, George F., 1977, The error associated with point-counting: Am. Mineral., v. 62, p. 1238-1244.

Neilson, M. J., and Stow, S. H., 1986, Geology and Geochemistry of the mafic and ultramafic intrusive rocks, Dadeville belt, Alabama: Geol. Soc. Amer. Bull., v. 97, p.

296-304.

Olsen, B. A., McSween, H. Y., and Sando, T. W., 1983, Petrogenesis of the Concord gabbro-syenite complex, North Carolina: Am. Mineral., v. 68, p. 315-333.

Overstreet, W. C. and Bell, H., 1965: The crystalline rocks of South Carolina: U. S. Geol. Survey Bull. 1183, 126 p.

Streckeisen, A. L., 1976, To each plutonic rock its proper name: Earth Sci. Rev., v. 12, p. 1-33.

Van der Plas, L., and Tobi, A. C., 1965, A chart for judging the reliability of point counting results: Am. J. Sci., 263, p. 87-90.

Wagener, H. D., 1974, The York-Chester gabbro-metagabbro-amphibolite complex: Geologic Notes, S.C. Div. of Geology, v. 18, p. 1-3.

APPENDICES

APPENDIX A - MODAL DATA

POINT COUNT DATA

SAMPLE NUMBER	PHASE				OTHER SPECIFIED						
	PLAGIOCLASE	OLIVINE	OTHER	TOTAL	CLINOPYROXENE	ORTHOPYROXENE	OPAQUE MINERALS	BIOTITE	ALTERATION MINERALS	AMPHIBOLE	TOTAL
33	334	145	21	500	1	1	3	0	15	1	21
66	418	60	24	502	3	6	6	4	3	2	24
67	433	45	22	500	3	4	6	4	0	4	21
72	407	34	59	500	5	0	11	1	42	0	59
78	375	66	59	500	42	0	8	0	2	7	59
79	424	66	10	500	3	0	2	1	1	3	10
115	438	12	50	500	22	4	4	0	3	17	50
29	416	47	37	500	14	0	10	1	10	2	37
30	452	21	27	500	10	1	3	0	12	1	27
57	380	106	14	500	0	4	4	2	3	1	14
56	382	107	11	500	0	3	5	1	1	1	11
81	467	0	33	500	0	0	1	0	25	7	33
68	437	35	28	500	1	5	4	3	10	5	28
96	276	192	32	500	3	17	1	0	3	8	32
97	485	3	12	500	0	0	3	0	9	0	12
97	226	64	12	302	5	0	3	0	0	4	12
80	399	21	80	500	3	0	4	3	57	13	80
89	311	173	16	500	6	0	4	0	6	0	16
88	405	42	53	500	0	0	3	0	49	1	53
90	140	319	41	500	21	0	14	0	6	0	41
31	396	38	66	500	41	5	7	0	2	11	66
32	429	20	51	500	13	0	5	0	33	0	51
87	437	2	61	500	10	5	9	0	36	1	61
86	398	27	75	500	32	0	3	0	38	2	75
83	441	10	49	500	3	15	7	0	17	7	49
20	436	27	37	500	0	2	3	1	31	0	37
21	439	21	40	500	2	0	12	6	16	4	40
69	430	11	59	500	32	1	1	0	5	20	59
98	316	151	31	498	4	1	1	0	2	23	31
91	260	185	55	500	5	7	9	2	32	0	55
92	75	311	114	500	65	0	30	0	18	1	114
92	207	270	23	500	7	0	10	0	4	2	23
106	406	88	6	500	3	0	0	0	2	1	6
85	407	65	28	500	0	6	9	1	12	0	28
84	455	4	41	500	15	2	9	0	13	2	41
108	319	117	64	500	5	5	12	0	41	1	64
109	466	3	31	500	2	3	9	1	16	0	31
53	234	195	71	500	35	10	9	0	4	13	71
50	402	32	66	500	31	14	2	0	3	16	66
51	445	32	24	501	1	7	8	2	5	1	24
52	386	77	37	500	4	7	11	1	4	10	37

POINT COUNT DATA

SAMPLE NUMBER	PHASE				OTHER SPECIFIED						
	PLAGIOCLASE	OLIVINE	OTHER	TOTAL	CLINOPYROXENE	ORTHOPYROXENE	OPAQUE MINERALS	BIOTITE	ALTERATION MINERALS	AMPHIBOLE	TOTAL
104	412	28	60	500	37	0	2	3	6	12	60
103	409	25	66	500	41	0	2	0	12	11	66
43	453	12	35	500	8	8	7	2	6	4	35
44	420	10	70	500	0	1	12	3	52	2	70
45	417	0	83	500	0	2	9	3	69	0	83
46	398	72	30	500	7	3	13	0	7	0	30
98	444	4	52	500	18	7	2	0	4	21	52
99	454	19	27	500	2	1	7	2	14	1	27
101	292	195	13	500	0	2	3	2	2	4	13
102	315	172	13	500	0	1	5	2	1	4	13
48	323	0	177	500	0	0	5	1	171	0	177
49	441	15	44	500	3	30	2	0	4	5	44
110	457	24	19	500	0	1	5	7	2	4	19
119	451	31	18	500	0	0	2	4	6	6	18
130	355	134	11	500	0	4	4	0	2	1	11
121	350	129	21	500	0	2	5	3	6	5	21
121	461	10	29	500	13	0	1	0	2	8	24
39	409	0	91	500	0	0	7	1	75	8	91
40	430	38	22	490	9	1	2	0	10	0	22
41	433	15	52	500	0	0	9	2	38	3	52
42	416	30	54	500	1	2	5	2	44	0	54
130	252	96	45	393	8	0	10	9	2	16	45
130	468	7	25	500	0	0	0	5	0	20	25
129	324	162	14	500	0	0	0	10	0	4	14
127	354	124	22	500	0	0	0	17	0	5	22
126	391	97	12	500	2	0	0	3	0	7	12
124	136	256	108	500	60	0	0	18	0	30	108
36	267	134	99	500	90	0	0	7	0	2	99
35	484	10	6	500	0	0	0	5	0	1	6
133	411	83	6	500	1	1	3	1	0	1	7
53	233	218	49	500	32	0	0	15	1	1	49
55	476	3	21	500	0	0	0	3	0	18	21
132	211	128	9	348	0	2	0	3	0	4	9
117	397	36	67	500	52	0	0	10	0	5	67
116	416	55	29	500	12	0	0	13	0	4	29
105	391	50	59	500	49	0	0	6	0	4	59
107	382	61	57	500	40	0	0	8	1	8	57
114	395	45	60	500	55	0	0	5	0	0	60
113	438	29	33	500	15	0	0	12	0	6	33
112	391	53	56	500	47	0	0	9	0	0	56
111	388	82	30	500	17	0	0	12	0	1	30

APPENDIX B - MICROPROBE DATA

AVERAGED PLAGIOCLASE ANALYSES
Anorthositic Gabbro Unit Traverse

oxide	sample number [# of points analyzed]								
	117[12]	116[10]	105[11]	107[10]	114[6]	113[10]	112[7]	111[11]	Average
Al_2O_3	32.2(1)	31.3(7)	31.6(7)	32.2(8)	32.3(7)	32.2(10)	32.2(4)	31.3(5)	31.9(4)
Na_2O	2.8(1)	2.7(1)	3.40	2.7(3)	2.8(4)	2.5(9)	2.9(3)	2.9(3)	2.9(3)
SiO_2	48.4(2)	48.5(1)	48.80	48.7(7)	48.6(1)	47.9(14)	49.0(6)	48.9(8)	48.6(3)
CaO	15.4(9)	15.5(7)	15.00	15.3(7)	15.5(7)	15.7(10)	15.4(5)	15.2(6)	15.4(2)
K_2O	0.2(1)	0.2(1)	0.2(1)	0.2(1)	0.2(1)	0.2(1)	0.2(9)	0.2(1)	0.2(1)
FeO	0.8(1)	1.0(1)	0.9(2)	1.0(2)	0.7(2)	0.8(1)	0.9(1)	1.0(1)	0.9(1)
Total	99.77	99.26	100.11	100.09	100.09	99.24	100.49	99.49	99.82
	Cations/8 Oxygens								
	117	116	105	107	114	113	112	111	
Al	1.779	1.723	1.703	1.770	1.671	1.730	1.735	1.714	
Na	0.227	0.240	0.286	0.245	0.305	0.279	0.253	0.253	
Si	2.203	2.242	2.273	2.221	2.302	2.246	2.235	2.246	
Ca	0.784	0.767	0.720	0.759	0.707	0.737	0.763	0.769	
K	0.010	0.007	0.010	0.007	0.008	0.012	0.011	0.010	
Fe	0.023	0.041	0.032	0.029	0.024	0.030	0.033	0.036	
Total	5.026	5.020	5.024	5.013	5.018	5.034	5.029	5.028	
Range of An Compositions	69-81	72-81	71-78	69-79	70-79	69-86	70-77	70-78	74-77
# of r/c pairs	6, max. zoning = 69-81	3, max. zoning = 72-77	5, max. zoning = 71-78	0	3, max. zoning = 70-76	5, max. zoning = 69-77	3, max. zoning = 70-77	3, no zoning	

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited

# of r/c pairs = number of rim/core pairs included in analyses
max. zoning = maximum An difference in a single rim/core pair

Anorthositic Gabbro Unit Traverse
Average An Composition in Plagioclase
in Rim/Core Pairs

Sample #	An Rim	An Core	Avg. An Rims	Avg. An Cores
117	77	76	74(1)	76(1)
	74	74		
	69	81		
	79	78		
	69	78		
	74	69		
116	72	74	74(5)	77(5)
	78	81		
	72	77		
105	64*	65	72(9)	74(3)
	71	78		
	76	75		
	72	76		
	76*	77		
114	70	76	74(6)	77(5)
	77	77		
	75	79		
113	82	86	75(8)	78(4)
	73	76		
	69	77		
	77	77		
	74	75		
112	75	76	73(6)	76(6)
	70	77		
	74	76		
111	76	77	76(1)	77(5)
	77	78		
	75	75		
Average	74(8)	76(6)	74(3)	76(3)

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited
* = Crystal enclosed in olivine.

AVERAGED OLIVINE ANALYSES
Anorthositic Gabbro Unit Traverse

oxide	sample number [# of points analyzed]								
	117[4]	116[10]	105[5]	107[4]	114[4]	113[3]	112[5]	111[7]	Average
MgO	41.2(4)	41.5(5)	42.3(2)	42.5(5)	41.9(6)	42.3(6)	42.3(5)	41.2(7)	41.9(6)
SiO_2	38.4(5)	38.8(4)	38.4(4)	38.9(1)	39.3(9)	38.6(4)	39.1(4)	38.9(3)	38.8(3)
FeO	20.9(3)	20.5(6)	19.5(1)	18.7(2)	20.6(2)	19.9(1)	20.6(5)	20.8(8)	20.2(8)
MnO	0.4(1)	0.5(1)	0.5(1)	0.5(1)	0.4(1)	0.5(1)	0.5(1)	0.5(1)	0.5(1)
Total	100.8	101.2	100.6	100.6	102.3	101.4	102.4	101.3	101.3
	Cations/4 Oxygens								
	117	116	105	107	114	113	112	111	
Mg	1.564	1.587	1.655	1.633	1.608	1.596	1.602	1.551	
Si	0.990	0.954	0.973	0.983	0.969	0.976	0.978	0.989	
Fe	0.447	0.434	0.390	0.391	0.444	0.441	0.433	0.460	
Mn	0.009	0.011	0.010	0.009	0.011	0.012	0.009	0.011	
Total	3.010	3.016	3.027	3.016	3.032	3.024	3.022	3.011	
Range of Fo Composition	77-78	77-79	78-81	80-81	78-79	78-80	78-79	77-80	78-80
# of r/c pairs	2	4	2	0	1	0	0	3	

Note: Virtually no zoning
numbers in parentheses represent one standard deviation in terms of least units cited
# of r/c pairs = number of rim/core pairs included in analyses

AVERAGED CLINOPYROXENE ANALYSES
Anorthositic Gabbro Unit Traverse

oxide	sample number [# of points analyzed]						
	117[4]	116[2]	105[4]	114[3]	112[4]	111[1]	Average
Al_2O_3	4.7(6)	3.7(2)	4.6(5)	4.5(6)	4.8(4)	3.4	4.2(0.5)
MgO	14.4(9)	14.4(3)	14.3(9)	14.2(6)	14.7(6)	13.8	14.3(0.3)
Na_2O	0.6(1)	0.4(1)	0.5(1)	0.5(2)	0.5(6)	0.5	0.5(0.1)
SiO_2	49.6(4)	50.5(2)	49.7(8)	50.2(4)	50.2(9)	51.2	50.2(0.6)
TiO_2	1.3(2)	0.9(1)	1.4(3)	1.2(2)	1.2(2)	0.9	1.2(0.2)
FeO	7.6(8)	7.4(6)	7.6(5)	7.4(1)	7.5(7)	7.4	7.5(0.1)
MnO	0.4(2)	0.3(1)	0.4(2)	0.4(1)	0.3(1)	0.3	0.4(0.1)
CaO	21.3(9)	22.2(4)	21.6(1)	21.7(7)	22.3(7)	22.5	21.9(0.5)
Total	100.1	99.8	99.9	100.1	100.7	100.1	100.1
En Composition	$En_{43}Fs_{13.5}Wo_{43.5}$	$En_{44.5}Fs_{11.5}Wo_{44}$	$En_{43}Fs_{13}Wo_{44}$	$En_{43}Fs_{13}Wo_{44}$	$En_{45}Fs_{11}Wo_{44}$	$En_{44}Fs_{12}Wo_{44}$	$En_{44}Fs_{12}Wo_{44}$

	Cations/6 Oxygens					
	117	116	105	114	112	111
Al	0.167	0.173	0.206	0.198	0.192	0.152
Mg	0.945	0.832	0.746	0.747	0.642	0.761
Na	0.027	0.016	0.040	0.033	0.039	0.034
Si	1.872	1.865	1.850	1.866	1.864	1.901
Ti	0.0.0	0.021	0.046	0.038	0.030	0.026
Fe	0.275	0.217	0.237	0.228	0.187	0.233
Mn	0.010	0.008	0.021	0.016	0.007	0.011
Ca	0.702	0.904	0.874	0.888	0.867	0.897
Total	4.028	4.035	4.020	4.013	4.029	4.014

Notes: numbers in parentheses represent one standard deviation in terms of least units cited

AVERAGED ORTHOPYROXENE ANALYSES
Anorthositic Gabbro Unit Traverse

oxide	sample number (# of points analyzed)				
	107(3)	113(1)	112(1)	111(1)	Average
Al_2O_3	1.8(1)	2.2	5.5	2.1	2.9(8)
MgO	28.8(2)	29.4	25.4	29.5	28.3(9)
Na_2O	0.0(1)	0.0	0.8	0.0	0.2(4)
SiO_2	54.2(5)	53.5	49.7	54.3	52.9(2)
TiO_2	0.3(1)	0.4	0.8	0.4	0.5(2)
FeO	14.4(4)	14.0	12.7	13.5	13.6(7)
MnO	0.5(1)	0.5	0.4	0.4	0.4(1)
CaO	0.9(1)	0.8	4.5	0.3	1.6(9)
Total	100.8	100.8	99.8	100.4	100.4
En Composition	$En_{77}Fs_{22}Wo_{1}$	$En_{75}Fs_{24}Wo_{1}$	$En_{71}Fs_{20}Wo_{9}$	$En_{78}Fs_{22}Wo_{1}$	$En_{75}Fs_{24}Wo_{1}$

	Cations/6 Oxygens			
	107	113	112	111
Al	0.082	0.090	0.236	0.089
Mg	1.547	1.564	1.378	1.561
Na	0.001	0.000	0.050	0.000
Si	1.926	1.907	1.812	1.930
Ti	0.010	0.012	0.020	0.010
Fe	0.409	0.416	0.387	0.400
Mn	0.015	0.16	0.012	0.011
Ca	0.032	0.032	0.173	0.013
Total	4.023	4.036	4.079	4.015

Notes: numbers in parentheses represent one standard deviation in terms of least units cited

AVERAGED AMPHIBOLE ANALYSES
Anorthositic Gabbro Unit Traverse

oxide	sample number (# of points analyzed)				
	107(1)	114(2)	112(4)	111(2)	Average
Al_2O_3	12.5	13.6(6)	13.8(1)	13.5(3)	13.3(6)
MgO	14.5	15.6(1)	15.8(3)	15.5(4)	15.3(6)
Na_2O	2.4	2.2(1)	2.2(1)	2.2(1)	2.2(1)
SiO_2	42.3	42.7(1)	42.5(3)	42.5(2)	42.5(2)
TiO_2	2.8	1.6(1)	1.4(3)	1.9(3)	1.9(6)
FeO	10.7	9.4(1)	9.2(4)	9.2(1)	9.6(7)
MnO	0.4	0.2(1)	0.2(1)	0.2(1)	0.3(1)
CaO	12.2	12.0(2)	12.0(1)	12.0(1)	12.1(1)
K_2O	1.2	---	0.9(1)	0.9(1)	1.0(1)
Total	98.9	97.3	98.1	98.0	98.3

	Cations/23 (O,OH,F)			
	107	114	112	111
Al	2.045	0.682	2.250	2.187
Mg	3.008	2.956	3.190	3.161
Na	0.655	0.095	0.614	0.600
Si	5.893	6.888	5.902	5.910
Ti	0.295	0.096	0.173	0.180
Fe	1.244	0.703	1.042	1.156
Mn	0.052	0.028	0.025	0.036
Ca	1.822	3.265	1.815	1.800
K	0.206	0.016	0.160	0.171
Total	15.219	14.729	15.187	15.201

Notes: numbers in parentheses represent one standard deviation in terms of least units cited

AVERAGED BIOTITE ANALYSES
Anorthositic Gabbro Unit Traverse

oxide	Sample # [# of points analyzed]		
	113[2]	111[1]	Average
Al_2O_3	8.1(7)	16.5	12.3(9)
MgO	20.0(5)	21.1	20.5(8)
Na_2O	0.2(1)	0.4	0.3(2)
SiO_2	41.3(5)	37.6	39.5(6)
TiO_2	1.8(4)	3.1	2.5(9)
FeO	14.7(1)	6.5	10.6(7)
MnO	0.2(1)	0.3	0.2(1)
CaO	0.7(8)	0.2	0.5(3)
K_2O	5.1(2)	9.3	7.2(2)
Total	92.0	95.0	93.5

	Cations/12(O,OH,F)	
	113	111
Al	2.715	2.906
Mg	3.987	4.720
Na	0.046	0.087
Si	5.391	5.207
Ti	0.393	0.354
Fe	1.358	0.945
Mn	0.023	0.016
Ca	0.016	0.084
K	1.902	1.418
Total	15.831	15.737

Notes: numbers in parentheses represent one standard deviation in terms of least units cited

TROCTOLITE UNIT TRAVERSE

Averaged Plagioclase Analyses

	Sample # (# of points analyzed)									
Oxides	130[13]	129[7]	127[11]	126[9]	124[10]	36[4]	33[7]	132[12]	133[7]	Average
Al_2O_3	31.6(7)	32.0(6)	32.6(4)	32.5(4)	31.9(5)	31.4(5)	31.0(9)	31.9(6)	32.5(4)	31.9(5)
Na_2O	2.8(4)	2.7(2)	2.9(1)	2.7(1)	2.9(4)	3.3(7)	2.9(1)	3.3(4)	2.9(2)	3.0(2)
SiO_2	48.6(2)	47.0(9)	48.0(2)	47.9(5)	48.5(9)	48.9(4)	48.5(5)	48.8(8)	48.4(7)	48.6(6)
CaO	14.9(8)	15.7(5)	15.5(5)	15.6(4)	15.4(7)	14.5(2)	15.1(2)	14.6(8)	15.5(4)	15.1(5)
K_2O	0.2(1)	0.2(1)	0.1(1)	0.2(1)	0.2(1)	0.2(1)	0.2(1)	0.1(1)	0.2(1)	0.2(1)
FeO	1.0(5)	1.1(3)	0.8(1)	1.0(5)	0.9(3)	1.1(3)	1.0(1)	0.9(5)	0.9(6)	1.0(1)
Total	99.2	99.4	100.6	99.8	99.7	99.3	99.46	99.5	100.4	99.7
	Cations/8 Oxygens									
	130	129	127	126	124	36	33	132	133	
Al	1.732	1.762	1.757	1.757	1.754	1.712	1.739	1.709	1.757	
Na	0.291	0.234	0.253	0.251	0.238	0.332	0.241	0.334	0.250	
Si	2.250	2.209	2.242	2.216	2.217	2.272	2.241	2.279	2.222	
Ca	0.720	0.787	0.745	0.767	0.781	0.685	0.749	0.680	0.764	
K	0.013	0.010	0.011	0.009	0.015	0.009	0.011	0.007	0.013	
Fe	0.030	0.030	0.033	0.036	0.027	0.034	0.05	0.027	0.025	
Total	5.036	5.032	5.021	5.036	5.032	5.044	5.015	5.036	5.031	
An Composition	74(8)	76(6)	75(9)	76(9)	75(4)	71(6)	74(1.5)	71(7)	75(2)	74(2)
# of Rim/Core Pairs	6	5	4	2	5	1	2	3	2	37
Strongest Zoning	68-81		73-76 Rev.	78-76 Rev.	69-77	67-64 Rev.	-	66-74 * 70-67 Rev.	73-76 *	-

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited

* = Crystal enclosed in olivine.

Rev. = Reversed Zoning

Troctolite Unit Traverse
Average An Composition in Rim/Core Pairs

Sample #	An Rim	An Core	Avg. An Rims	Avg. An Cores
130	74	71	73(6)	76(9)
	75	83		
	74	73		
	75	74		
	73	73		
	68	81		
129	78	77	77(1)	77(6)
	76	77		
	77	76		
127	75	74	75(1)	74(8)
	76	73		
	76*	75		
	74*	74		
126	75	75	76(2)	76(7)
	78	76		
124	69	77	72(4)	77(7)
	69	77		
	74	77		
	73	78		
	77	76		
36	67	76	67	64
53	75*	75	76(7)	75(7)
	76	74		
132	70	67	70(5)	71(5)
	66*	74		
	73	71		
133	73*	76	75(1)	76(7)
	76	77		

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited
* = Crystal enclosed in olivine.

TROCTOLITE UNIT TRAVERSE

Averaged Plagioclase Analyses

Special Samples

	Sample # [# of points analysed]								
Oxides	130PL[14]	5PL[15]	5[20]	135A[4]	135B[9]	101[23]	110[8] +	135B[10]	135A[7]
Al_2O_3	32.20(0.80)	31.80(0.64)	31.16(0.51)	32.49(0.77)	31.76(0.23)	32.21(0.80)	31.04(0.40)	32.02(0.63)	32.09(0.63)
Na_2O	2.93(0.29)	3.01(0.13)	3.20(0.34)	3.02(0.30)	3.10(0.32)	2.95(0.30)	3.21(0.22)	3.03(0.30)	2.94(0.34)
SiO_2	48.20(0.91)	48.88(0.82)	49.80(0.72)	48.06(0.80)	49.00(0.80)	48.76(1.23)	49.06(0.40)	48.20(0.94)	48.63(0.94)
CaO	15.24(0.61)	15.22(0.30)	14.80(0.64)	15.10(0.90)	14.01(0.67)	15.23(0.90)	14.79(0.41)	14.97(0.67)	15.00(0.00)
K_2O	0.11(0.02)	0.22(0.03)	0.27(0.03)	0.10(0.02)	0.16(0.04)	0.15(0.03)	0.13(0.04)	0.13(0.04)	0.12(0.04)
FeO	1.21(0.34)	1.00(0.12)	1.03(0.14)	0.99(0.41)	0.99(0.40)	1.13(0.37)	1.00(0.71)	1.03(0.32)	0.82(0.22)
Total	99.96	99.30	100.15	99.04	99.90	100.43	100.05	99.01	99.60
Avg. An Composition	74(2.4)	75(3)	72(3.1)	74(3)	72(3)	74(3)	72(2)	73(3)	74(3)
# of Rim/Core Pairs	4	6	9	2	4	9	2	3	2
Strongest Zoning	69-77	72-78 76-71 Rev.	64-75	67-76 78-74 Rev.	70-77 75-70 Rev.	84-73 Rev.	72-74	73-76	73-71 Rev.

	Cations/8 Oxygens								
	130PL	5PL	5	135A*	135B**	101	110	135B***	135A****
Al	1.730	1.730	1.680	1.734	1.731	1.746	1.729	1.667	1.708
Na	0.233	0.242	0.311	0.260	0.265	0.260	0.272	0.341	0.223
Si	2.213	2.215	2.293	2.219	2.242	2.222	2.240	2.309	2.193
Ca	0.736	0.762	0.692	0.731	0.734	0.735	0.737	0.664	0.706
K	0.011	0.013	0.017	0.006	0.013	0.008	0.009	0.005	0.009
Fe	0.070	0.041	0.035	0.042	0.025	0.047	0.051	0.043	0.026
Total	5.0.3	5.033	5.029	5.043	5.031	5.038	5.027	5.029	5.027

Notes:

Numbers in parentheses represent one standard deviation in terms of least units cited

PL = plagioclase lense

+ = anorthositic gabbro block in troctolite

Rev. = Reversed Zoning

* Pegmatitic Lense Adj. Troctolite

** Pegmatitic Lense Adj. to Gabbro

*** Anorth. Gabbro

**** Troctolite

Troctolite Unit Traverse
Average An Composition in Rim/Core Pairs
Special Samples

Sample #	An Rim	An Core	Avg. An Rims	Avg. An Cores
130 Plag. Lense	77	77	72(7)	75(1)
	74	73		
	69	77		
	70	74		
55 Plag. Lense	73	71	75(8)	75(7)
	75	78		
	76	73		
	72**	78		
	76	71		
	80	79		
35 Plag. Lense	68**	69	70(9)	83(1)
	71	69		
	64	75		
	71**	73		
	75	77		
	70	74		
	70	75		
	71	69		
	71	75		
135A Peg. Lense	78	74	72(8)	75(4)
	67	76		
135B Peg. Lense	71	74	72(2)	74(9)
	75	70		
	72**	73		
	70	77		
101 Peg. Lense	84	73	75(1)	74(5)
	80	74		
	80	75		
	66	65		
	68	72		
	77	76		
	71	75		
	76	76		
	71	76		
118 +	73	73	72(7)	74(7)
	72	74		
135B Anorthositic Gabbro	73 ++	76	74(1)	73(3)
	75	73		
	74	70		
135A Troctolite	78	78	76(5)	74(9)
	73	71		

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited
Plag. Lense = Plagioclase Lense
Peg. Lense = Pegmatitic Lense
\+ = Anorthositic gabbro block in troctolite.
++ = Optically zoned crystal.
* = Crystal enclosed in olivine.
** = Crystal adjacent to or within ilmenite.

TROCTOLITE UNIT TRAVERSE
Averaged Olivine Compositions

	Sample # (# of points analyzed)									
Oxides	130[6]	129[5]	127[9]	126[6]	124(6]	36[5]	33(5]	132(9]	133(7]	Average
MgO	42.3(6)	42.3(6)	44.5(7)	43.4(4)	43.5(5)	42.6(5)	42.8(4)	41.7(8)	42.1(4)	43.1(2)
SiO_2	38.2(4)	40.1(4)	39.8(4)	39.1(4)	39.5(3)	38.9(2)	38.7(4)	39.1(3)	39.4(4)	39.2(6)
FeO	18.6(2)	15.8(2)	18.0(7)	18.8(3)	18.9(4)	18.9(3)	18.9(2)	18.7(2)	19.3(3)	18.4(1)
MnO	0.4(1)	0.4(1)	0.4(1)	0.4(1)	0.5(1)	0.5(1)	0.5(1)	0.5(1)	0.5(1)	0.5(1)
Total	99.5	101.7	102.5	101.6	102.1	100.7	100.8	99.9	101.2	101.1
	Cations/4 Oxygens									
	130	129	127	126	124	36	33	132	133	
Mg	1.578	1.678	1.644	1.641	1.620	1.623	1.602	1.584	1.589	
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Si	1.000	0.992	0.988	0.978	0.985	0.989	0.994	1.002	0.996	
Fe	0.413	0.327	0.369	0.392	0.403	0.389	0.398	0.402	0.410	
Mn	0.010	0.010	0.010	0.010	0.008	0.011	0.011	0.011	0.009	
Total	3.001	3.007	3.011	3.021	3.016	3.012	3.005	2.999	3.004	
Fo Composition	80(4)	84(8)	82(9)	80(6)	80(5)	80(1)	80(5)	80(5)	79(5)	80.5(5)
# of Rim/Core Pairs	0	1	3	1	0	1	2	0	0	
Strongest Zoning	-	-	83-81 Rev.	-	-	79-81 Rev.	-	-	-	

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited

Rev. = Reversed Zoning

TROCTOLITE UNIT TRAVERSE
Averaged Olivine Compositions
Special Samples

	Sample # (# of points analysed)						
Oxides	130 PL(7)	135A(5)	135B(6)	101(11)	110(5)	135B(5)	135A(6)
MgO	41.3(6)	40.3(2)	40.6(8)	41.9(3)	42.0(7)	40.4(6)	41.6(3)
SiO_2	39.1(3)	39.0(3)	39.1(6)	39.5(4)	39.3(3)	39.2(5)	39.2(4)
FeO	19.2(4)	19.8(4)	19.7(2)	18.6(1)	19.0(8)	19.2(8)	18.4(6)
MnO	0.5(1)	0.4(1)	0.5(1)	0.4(1)	0.4(1)	0.5(1)	0.4(1)
Total	100.2	99.6	99.9	100.5	100.6	99.3	99.6
	Cations/4 Oxygens						
	130PL	135A*	135B**	101	110	135B***	135A****
Mg	1.577	1.536	1.536	1.580	1.567	1.533	1.584
Si	0.999	1.016	0.995	1.001	0.999	1.009	1.002
Fe	0.413	0.421	0.441	0.390	0.423	0.417	0.405
Mn	0.010	0.011	0.015	0.011	0.012	0.011	0.007
Total	3.001	2.984	3.005	2.999	3.001	2.990	2.998
Fo Composition	79(0.3)	78(6)	78(4)	80(6)	80(8)	79(1)	80(4)
# of Rim/Core Pairs	0	2	1	0	0	1	1
Strongest Zoning	-	-	80-78 Rev.	-	-	79-80	-

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited
Rev. = Reversed Zoning
* Pegmatitic lense adj. troctolite
** Pegmatitic lense adj. gabbro
*** Anorthositic gabbro
**** Troctolite

TROCTOLITE UNIT TRAVERSE

Averaged Clinopyroxene Compositions

	Sample # [# of points analyzed]		
Oxides	127[1]	126[3]	124[3]
Al_2O_3	3.9	4.5(2)	4.5(4)
MgO	16.0	14.3(2)	15.4(1)
Na_2O	0.4	0.5(1)	0.6(1)
SiO_2	51.6	49.1(6)	50.5(9)
TiO_2	1.0	1.5(2)	1.1(2)
FeO	5.8	6.4(3)	6.6(2)
MnO	0.3	0.4(1)	0.3(1)
CaO	22.7	22.2(6)	20.8(1)
Total	101.7	98.9	99.7
Range of En Composition	En[illegible] Fs_9 Wo[illegible]	En[illegible] Fs_{11} Wo[illegible]	
	Cations/6 Oxygens		
	127	126	124
Al	0.168	0.198	0.207
Mg	0.867	0.781	0.841
Na	0.027	0.034	0.043
Si	1.872	1.845	1.859
Ti	0.028	0.048	0.033
Fe	0.177	0.200	0.208
Mn	0.010	0.014	0.009
Ca	0.881	0.906	0.826
Total	4.030	4.025	4.026

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited

TROCTOLITE UNIT TRAVERSE
Averaged Clinopyroxene Compositions
Special Samples

	Sample # [# of points analyzed]	
Oxides	135A Troctolite [1]	118[4]
Al_2O_3	4.4	4.5(6)
MgO	14.7	14.6(2)
Na_2O	0.4	0.5(1)
SiO_2	50.4	50.2(5)
TiO_2	1.0	1.0(1)
FeO	6.1	6.4(6)
MnO	0.4	0.4(1)
CaO	22.1	21.9(4)
Total	99.5	99.4
En Composition	$En_{[illegible]}Fs_{10}Wo_{47}$	$En_{[illegible]}Fs_{11}Wo_{[illegible]}$

	Cations/6 Oxygens	
	135A Troctolite	118
Al	0.193	0.165
Mg	0.813	0.820
Na	0.030	0.035
Si	1.871	1.884
Ti	0.027	0.027
Fe	0.191	0.221
Mn	0.012	0.012
Ca	0.880	0.861
Total	4.017	4.025

Notes: Numbers in parentheses represent one standard deviation in terms of least unit cited

TROCTOLITE UNIT TRAVERSE

Averaged Orthopyroxene Compositions

	Sample # [# of points analyzed]
Oxides	130[1]
Al_2O_3	2.1
MgO	30.2
Na_2O	0.0
SiO_2	52.8
TiO_2	0.3
FeO	12.4
MnO	0.6
CaO	0.8
Total	99.2
En Composition	En[illegible]Fs[illegible]Wo[illegible]
	Cations/6 Oxygens
	130
Al	0.089
Mg	1.623
Na	0.001
Si	1.902
Ti	0.009
Fe	0.374
Mn	0.017
Ca	0.030
Total	4.045

TROCTOLITE UNIT TRAVERSE

Averaged Orthopyroxene Compositions

Special Samples

	Sample # [# of points analyzed]		
Oxides	135A[2] Troctolite	135B[2] Pegmatite	101[2] Pegmatite
Al_2O_3	2.3(2)	2.2(4)	2.7
MgO	28.9(0)	28.7(1)	30.0
Na_2O	0	0.0(1)	0
SiO_2	53.4(1)	53.3(8)	53.7
TiO_2	0.3(2)	0.3(1)	0.3
FeO	12.8(3)	13.7(1)	12.1
MnO	0.4(1)	0.4(1)	0.4
CaO	0.5(1)	0.7(1)	0.6
Total	98.6	99.3	99.9
Range of En Composition	$En_{79}Fs_{19}Wo_{01}$	$En_{78}Fs_{21}Wo_{01}$	$En_{80}Fs_{18}Wo_{01}$

	Cations/6 Oxygens		
	135A Troctolite	135B Pegmatitie	101 Pegmatite
Al	0.102	0.081	0.080
Mg	1.556	1.549	1.544
Na	0.000	0.000	0.001
Si	1.931	1.933	1.938
Ti	0.006	0.006	0.005
Fe	0.381	0.416	0.413
Mn	0.014	0.014	0.013
Ca	0.020	0.022	0.023
Total	4.010	4.021	4.017

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited

Sample #101 is a pegmatite lense in troctolite.

TROCTOLITE UNIT TRAVERSE
Averaged Amphibole Compositions

Oxides	Sample # (# of points analysed)						
	130(2)	127(1)	124(1)	53(2)	36(1)	132(2)	133(3)
Al_2O_3	12.3(1)	14.3	12.8	13.7(8)	14.0	12.9(7)	14.0(8)
MgO	16.37(2)	16.4	15.3	15.1(4)	15.5	15.4(2)	14.2(5)
Na_2O	2.6(1)	2.1	2.1	2.2(1)	2.2	2.1(3)	1.7(6)
SiO_2	40.6(1)	42.6	41.2	41.8(3)	41.6	40.7(4)	43.2(1)
TiO_2	2.8(4)	0.7	2.4	3.4(1)	2.2	2.3(6)	1.3(2)
FeO	8.7(4)	8.6	8.7	8.9(5)	8.6	8.3(5)	8.8(1)
MnO	0.2(1)	0.4	0.1	0.3(1)	0.2	0.2(1)	0.2(1)
CaO	11.1(1)	11.9	12.5	11.8(3)	13.2	11.8(4)	14.0(4)
K_2O	0.8(1)	N/A	1.1	1.1(1)	1.3	0.8(4)	1.2(1)
Total	99.6	96.96	96.1	97.5	97.7	94.4	97.7

	Cations/23(O,OH,F)					
	130	124	53	36	132	133
Al	2.136	2.137	2.205	2.341	2.271	2.178
Mg	3.215	3.238	3.221	3.196	3.326	3.243
Na	0.584	0.568	0.610	0.592	0.517	0.618
Si	5.972	5.853	5.720	5.806	5.893	5.900
Ti	0.183	0.259	0.372	0.226	0.153	0.150
Fe	1.055	1.033	1.009	0.988	0.999	1.009
Mn	0.026	0.015	0.041	0.021	0.018	0.027
Ca	1.791	1.897	1.745	1.808	1.798	1.825
K	0.214	0.208	0.191	0.208	0.203	0.207
Total	15.176	15.202	15.204	15.206	15.178	15.255

Notes: numbers in parentheses represent one standard deviation in terms of least units cited

TROCTOLITE UNIT TRAVERSE

Averaged Biotite Compositions

	Sample #[# of points analyzed]
Oxides	127[1]
Al_2O_3	16.84
MgO	23.00
Na_2O	0.37
SiO_2	37.60
TiO_2	1.74
FeO	5.28
MnO	0.22
CaO	0.07
K_2O	9.4
Total	94.53
	Cations/12(O,OH,F)
	127
Al	2.856
Mg	4.932
Na	0.104
Si	5.409
Ti	0.189
Fe	0.636
Mn	0.026
Ca	0.011
K	1.724
Total	15.887

TROCTOLITE UNIT TRAVERSE
Averaged Biotite Compositions
Special Samples

	Sample # [# of points analyzed]		
Oxides	101[1]	35PL[3]	135B[1] *
Al_2O_3	17.05	17.79(1.45)	16.27
MgO	23.05	16.27(4.11)	20.09
Na_2O	0.25	0.12(0.03)	0.44
SiO_2	36.47	35.06(1.84)	36.46
TiO_2	1.99	2.99(1.02)	3.42
FeO	5.69	13.42(5.73)	6.62
MnO	0.26	0.26(0.04)	0.17
CaO	0	0.39(0.24)	0.06
K_2O	9.17	7.76(1.55)	9.28
Total	93.94	94.05	92.82

	Cations/12(O,OH,F)		
	101	35PL	135B*
Al	2.918	3.358	2.834
Mg	4.989	2.584	4.425
Na	0.071	0.025	0.126
Si	5.295	5.337	5.388
Ti	0.217	0.211	0.380
Fe	0.691	2.457	0.818
Mn	0.031	0.017	0.022
Ca	0.000	0.049	0.009
K	1.699	1.492	1.749
Total	15.911	15.530	15.751

Notes: Numbers in parentheses represent one standard deviation in terms of least units cited

PL = Plagioclase lense

* = Pegmatitic lense

VITA

Leslie Foley Noble was born on August 19, 1964 in Huntsville, Alabama. She attended schools in the Birmingham, Alabama area, and received a Bachelor of Science degree from the University of Alabama at Birmingham with a major in Geology in June, 1987. Ms. Noble entered the University of Tennessee, Knoxville in August, 1987, and received a Master of Science degree in Geology in December, 1993.

Ms. Noble was married in July, 1987 to Robert Benjamin Noble of Birmingham, Alabama, who is also a geologist. They have one child, Samantha Louise Noble, born October 28, 1990. Ms. Noble is presently employed as a project geologist in an engineering and environmental consulting firm in Birmingham, Alabama.