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ABSTRACT

Allen T. Grundy. GEOLOGY AND GEOCHEMISTRY OF THE GRANITIC AND RELATED ROCKS OF THE LITTLETON AND THELMA AREA, EASTERN PIEDMONT, NORTH CAROLINA. (Supervising Professor, Dr. Richard K. Spruill) Department of Geology, April, 1982.

In the Littleton and Thelma area, three granitic rock units (A, B, and C) and a blastomylonite (D) have been recognized on the basis of mapping, petrographic analyses, and chemical analyses (major elements and Rb, Sr, Y, Zr, and Ba). These rocks have a prominent NNE foliation, and they have been subjected to greenschist facies metamorphism and cataclastic deformation. One of the granites (Unit C), a coarse-grained, porphyritic, biotite granite (dated at 292 ± 30 my) is a phase of the Butterwood Creek Pluton (Farrar and others, 1981). The other granites (Units A and B), are fine to medium-grained biotite granite and medium to coarse-grained biotite granite, respectively. All granites in the study area share petrographic and chemical characteristics, and they were probably emplaced during the same intrusive episode. The blastomylonite is fine-grained and leucocratic and its major and trace element chemistry is somewhat dissimilar to results from the other granitic units. On a K_2O-Na_2O-CaO diagram, the granitic rock units plot with Hercynian granites of the Piedmont, and possess similarities in trace element content to these late Paleozoic intrusions.

Elongate blocks of schist derived from the Raleigh belt are dispersed throughout the granitic rocks. Metavolcanic rocks, characteristic of the Carolina slate belt, are found on the eastern side of the study area. Mesozoic (?) subophitic to intergranular diabase dikes cut the

older rocks. These have alkalic affinities based on low SiO_2 and traces of normative nepheline.

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GEOLOGY AND GEOCHEMISTRY OF THE GRANITIC AND
RELATED ROCKS OF THE LITTLETON AND THELMA AREA,
EASTERN PIEDMONT, NORTH CAROLINA

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Allen T. Grundy
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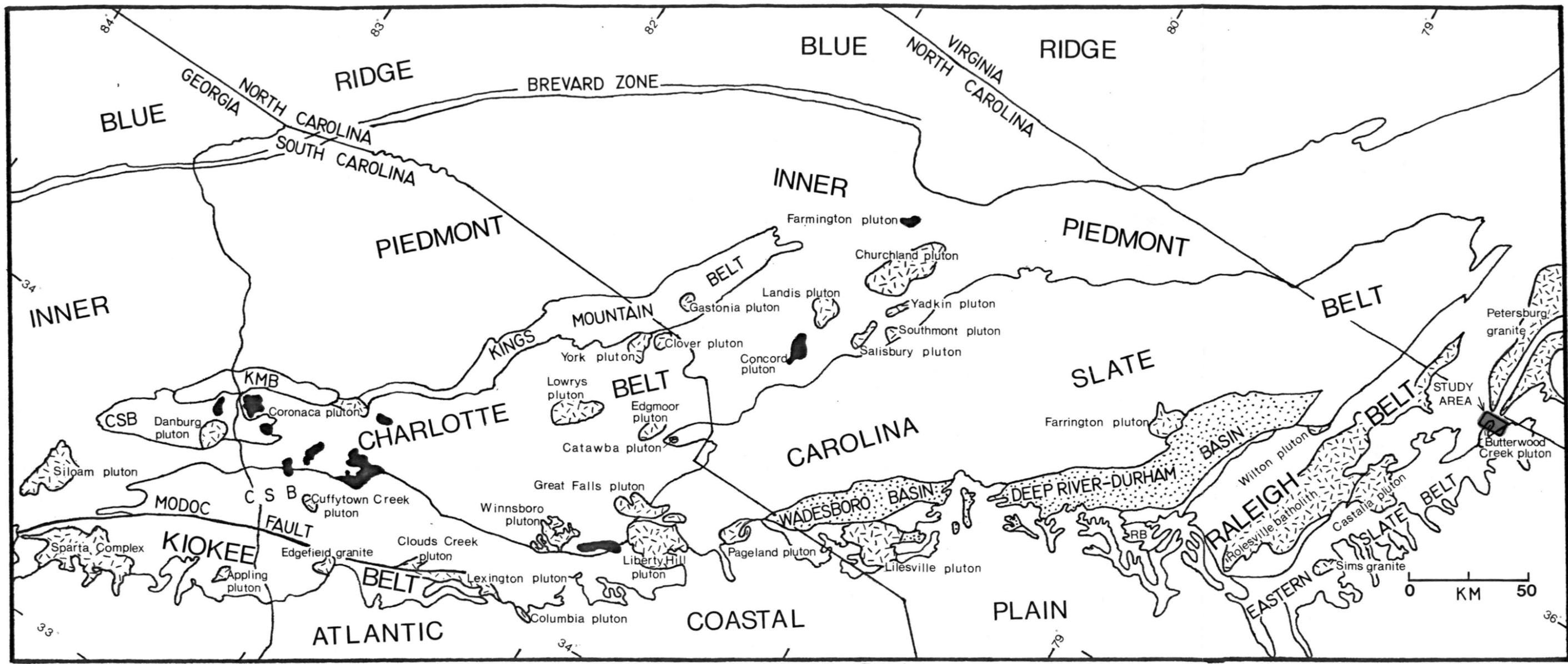
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INTRODUCTION

Littleton and Thelma are located in the eastern portion of the Piedmont in North Carolina (Fig. 1). Structurally, the study area lies in a marginal zone between the Raleigh belt to the west and the eastern Carolina slate belt to the east. Three granitic rock units have been described in the area based on mapping, petrographic analyses, and chemical analyses (major elements and Rb, Sr, Y, Zr, and Ba). These rocks have a prominent NNE foliation, and they have been subjected to greenschist facies metamorphism and cataclastic deformation.

The Butterwood Creek granitic pluton, located immediately south of the study area, includes an undeformed hornblende granite, a foliated, fine-grained biotite granite, and a foliated, coarse-grained porphyritic, biotite granite (Speer and others, 1980). A Rb/Sr whole rock isochron for the pluton yields an age of 292 ± 30 my and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7045 (Farrar and others, 1981). The porphyritic, biotite-bearing phase extends into the study area, and it is one of the three granitic rocks which I investigated in this study. The other granitic rocks in the study area are herein referred to as the Lake Gaston granites.

Mapping and sample collection were conducted during March, April, and May of 1980. A majority of the samples were taken from road cuts and from exposures along Lake Gaston (Fig. 3). In addition, thirteen samples were obtained from drill cores provided by the North Carolina Department of Natural Resources and Community Development-Geological Section. The cores were drilled in 1959 in the north central portion of



Modified from Williams (1978) Tectonic lithofacies map of the Appalachian orogen (1,000,000)

MAFIC ROCKS
 GRANITIC ROCKS

Figure 1. Tectonic Belts and Plutons of the S.E. Appalachian Piedmont.

the study area in what was then an alternate site for Gaston Dam. The core samples provided fresh material for petrographic and chemical analyses.

The basic objective of the study was to delineate and classify the various rock types. The eight rock units defined in this study are shown on the geologic map (Fig. 2). Units A and B are the Lake Gaston granites. Unit C is the porphyritic, biotite-bearing phase of the Butterwood Creek pluton. Unit D is a leucocratic blastomylonite. Unit E rocks are country rock blocks which are dominantly schists and are probably related to the Raleigh belt rocks to the west. Unit F rocks are metavolcanics which are typical of the eastern Carolina slate belt rocks. Unit G includes Mesozoic (?) diabase dikes, and Unit H is Tertiary gravel which covers much of the eastern part of the study area.

Another objective of this study was to relate the granitic rocks of the Littleton and Thelma area to other granitic rocks of the Piedmont, particularly to the Butterwood Creek pluton and to other Hercynian plutons.

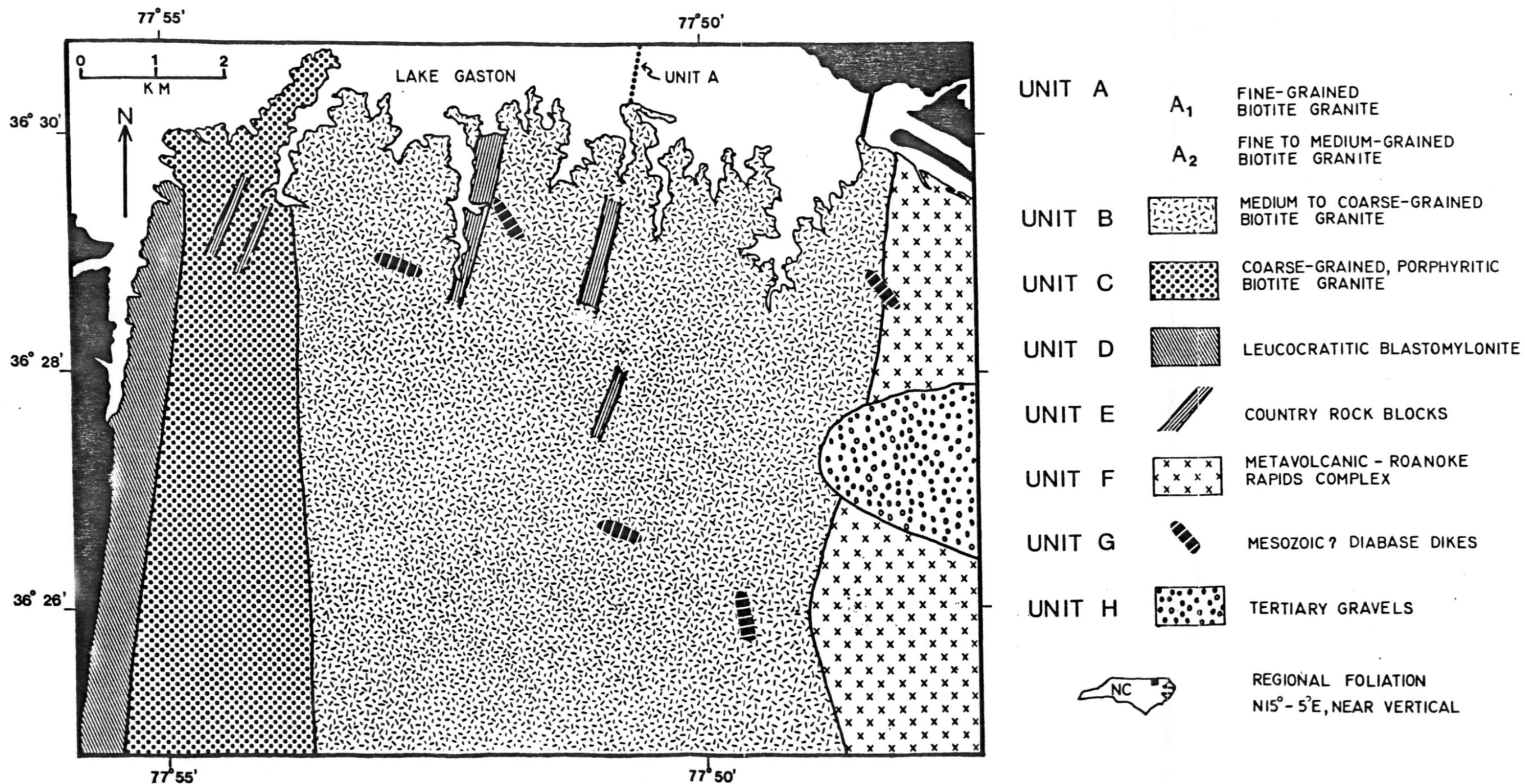


Figure 2. Geologic Map of the Study Area.

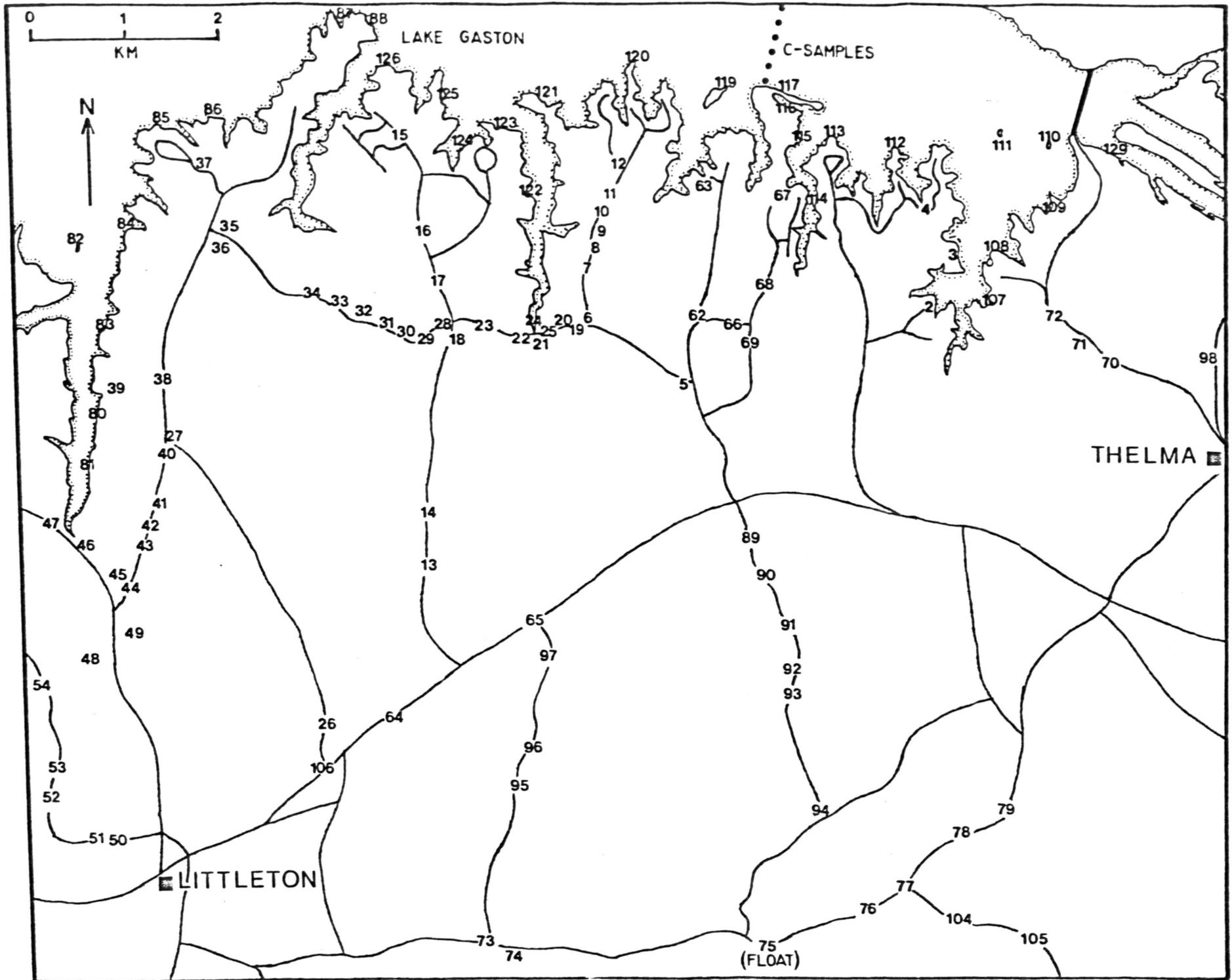


FIGURE 3.

Site Locations for Rock Samples

REGIONAL GEOLOGY

The Piedmont of the southeastern Appalachians has been divided into tectonic belts (King, 1955; Crickmay, 1952; and Hatcher, 1972). The major belts are briefly described here and are illustrated in Figure 1.

INNER PIEDMONT

Well foliated biotite gneisses, augen gneisses, granite gneisses, and schists of moderate metamorphic grade dominate the Inner Piedmont belt. The Brevard Zone separates the Inner Piedmont from the Blue Ridge province to the northwest. The Henderson gneiss, a major rock unit in the Inner Piedmont, is in contact with the Brevard Zone and shows signs of severe cataclastic deformation near the fault. Early Paleozoic intrusions are common within the Inner Piedmont, but Hercynian intrusions are not found (Sando, 1979).

KINGS MOUNTAIN BELT

The Kings Mountain belt is a sinuous belt extending from Georgia to North Carolina. It is located between the Inner Piedmont and the Charlotte belt (Fig. 1). Metasedimentary and metavolcanic rocks of low-to-medium metamorphic grade dominate the belt; some may be early Paleozoic in age (Overstreet and Bell, 1965; Keith and Sterrett, 1931). The belt is composed of mica schists, amphibolites, quartzites, conglomerates, marbles and calc-silicate rocks (Fullagar and Butler, 1979). Intrusions of both gabbroic and granitic rocks are common.

CHARLOTTE BELT

The Charlotte belt is of medium-metamorphic grade located between two belts of lower metamorphic grade. The rocks of the Charlotte belt include gneisses and schists which may in part be equivalent in age to the metasedimentary and metavolcanic rocks of the adjacent Kings Mountain and Carolina slate belts (Overstreet and Bell, 1965). Intrusive rocks are important in the Charlotte belt and range in composition from felsic to ultramafic.

CAROLINA SLATE BELT

The Carolina slate belt is chiefly composed of clastic sedimentary rocks and volcano-plutonic complexes of a trondhjemitic to tonalitic nature, all of low-metamorphic grade (Whitney and others, 1978; Weisenfluh and Snoke, 1978). The most common rock types are phyllite, argillite, tuff, breccia, and volcanic flows with composite units locally attaining thicknesses greater than 7000 m (Stromquist and Sundelius, 1969). The volcanic compositions range from rhyolitic to basaltic (Fullagar, 1971). The rocks of this belt are considered by St. Jean (1965) to be Cambrian in age. Butler and Ragland (1969) suggest an Ordovician age. Shearing, recrystallization, and replacement by chlorite, sericite, epidote, and other low-grade metamorphic minerals are characteristic of the slate belt rocks. The Carolina slate belt is divided into a larger western portion which is separated from the smaller eastern portion by the Raleigh belt.

RALEIGH BELT

The Raleigh belt is composed of high-grade paragneiss and orthogneiss flanked by high-grade pelitic schists including a graphite schist (Stoddard and others, 1978). In addition to the pelitic schists, some amphibolites and hornblende gneisses flank the belt. The Rolesville granitic pluton intrudes the central part of the belt. The belt is antiformal in structure and it is bordered on both the east and the west by the Carolina slate belt.

KIOKEE BELT

The Kiokee belt, composed of high-grade gneisses and schists, is located in the eastern Piedmont of Georgia and South Carolina. The Kiokee belt is bounded on the northwest by the Modoc fault (Overstreet and Bell, 1965), which separates it from the southern portion of the Carolina slate belt. Rocks of this belt have experienced two episodes of regional metamorphism (Snoke and others, 1980).

PLUTONISM

In the Piedmont of the southeastern Appalachians, there have been three main periods of plutonic activity (Table 1). These periods have been defined by Butler and Ragland (1969) as pre-metamorphic (595-520 my), syn-metamorphic (415-385 my), and post-metamorphic (330-260 my). These terms are used with respect to an inferred period of metamorphism that peaked 420-380 my ago (Fullagar, 1971).

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for most of the plutons are very low, indicating that they were produced from a magma that originated in the mantle or lower crust. A comparison of these ratios with initial ratios of granites from other orogenic areas indicates that the lower crust of the Piedmont from 600-300 my ago had a relatively lower Rb/Sr ratio than the lower crust of other continental regions during this time (Fullagar, 1971).

PRE-METAMORPHIC 595 to 520 my

Five plutons or igneous complexes in this age group are located in the Carolina slate belt, or in the Charlotte belt near its boundary with the Carolina slate belt. Compositions of these plutons range from gabbroic to granitic. Butler and Ragland (1969) suggest that the east stock of the Farrington complex is the intrusive equivalent of the nearby felsic metavolcanic rocks of the Carolina slate belt.

PRE-METAMORPHIC

	M.Y.	References
Hatcher	595±80	Fullagar (1971)
Great Falls	554±63	"
Edgemoor	545±30	"
Sparta	535±25	"
Farrington	519±48	"

SYN-METAMORPHIC

Concord	413±21	Fullagar (1971)
Salisbury	413±4	"
Lowrys	407±4	"
Southmont	390±4	"
Yadkin	386±9	"

POST-METAPHORICEastern Group

Petersburg	330±8	Wright and others (1975)
Lilesville	326±27	Fullagar & Butler (1979)
Catawba	325±27	Fullagar (1971)
Castalia	313±13	Fullagar & Butler (1979)
Clouds Creek	313±2	"
Medoc Mountain	301±6	Anderson & Fullagar (1977)
Winnsboro	301±4	Fullagar (1971)
Liberty Hill	299±15	"
Pageland	296±5	Fullagar & Butler (1979)
Edgefield	293±14	"
Butterwood Creek	292±30	Farrar and others (1981)
Lexington	292±15	Fullagar & Butler (1979)
Sparta	289±2	"
Sims	287±9	Wedemeyer & Spruill (1980)
Wilton	285±10	Fullagar & Butler (1979)
Columbia	285±7	"
Coronaca	278±2	"
Siloam	264±3	Radcliff & Humphrey (1971)

Western Group

York	322±6	Fullagar & Butler (1979)
Clover	-----	"
Gastonia	-----	"
Landis	292±29	"
Churchland	282±6	"

Table 1. List of plutons in the Piedmont of the southeastern Appalachians and their ages.

SYN METAMORPHIC 415 to 385 my

Five igneous intrusions belong to this group (Table 1). These plutons are located in the Charlotte belt, and they lie along a linear northeast-southwest trend. Compositionally, the group ranges from gabbro-diorite, associated with a syenite ring dike at Concord, to homogenous granite at Salisbury. The Salisbury pluton and others of the same differentiation trend are believed to be the intrusive equivalents of some metavolcanic rocks of the Carolina slate belt (Butler and Ragland, 1969).

POST-METAMORPHIC 330 to 260 my

At least twenty-five granitic plutons from this Hercynian group have been recognized (Table 1). Fullagar and Butler (1979) divided them into a western group and an eastern group. They noted that the western group has higher Sr than the eastern group. Sando (1979) confirmed the higher Sr contents and further noted higher Ba, Mg/(Mg+Fe) and V/Fe₂O₃ in the western group. He also recognized that the western group is chemically more homogenous and that the eastern group is more heterogenous. Speer and others (1980) list seventeen post-metamorphic gabbroic plutons that are located in the Piedmont from North Carolina to Georgia. The genetic relationship of these mafic bodies to the granitic plutons is uncertain.

PETROGRAPHIC DESCRIPTIONS OF THE ROCK UNITS

A total of 153 samples were petrographically analyzed. The modal percentages of 82 samples were determined (Appendix I). Averages for each unit are listed in Table 2. The International Union of Geological Sciences (IUGS) Subcommission's recommended plutonic rock classification, as described by Streckeisen (1976), was utilized for classification of the felsic and intermediate rocks. Most of these samples plot in the granite fields, and only a few are granodiorites. Unit A rocks plot as monzogranites. Units B and C plot as monzogranites and Unit D rocks are syenogranites.

UNIT A

Unit A includes nine samples taken from the cores plus one surface sample (117-2), collected in the area of the core holes (Fig. 3). The engineering firm of Stone and Webster described the cores as "weathered granite" (top), "granite to be grouted" (middle) and "sound granite" (bottom). To insure fresh rock, the core samples were collected one meter below the top of the "sound granite".

Unit A has been divided into subunits A₁ and A₂, based on petrographic and chemical parameters. Subunit A₁ has an average grain size of 0.3 mm and contains large (up to 1 cm) potassium feldspar megacrysts (Plate 1). Subunit A₂ has fewer megacrysts and an average grain size of 0.8 mm (Plate 2). The biotite content in subunit A₁ is slightly higher than in subunit A₂, while subunit A₂ is richer in quartz. Aside from these minor differences, the samples of Unit A are similar.

	UNIT	subunits		UNIT	UNIT	UNIT
	A	A ₁	A ₂	B	C	D
Number of samples	10	7	3	36	5	4
Potassium Feldspar	30	30	30	29	35	51
Quartz	27	24	33	30	27	32
Biotite	11	13	7	7	13	1
Muscovite	acc	acc	acc	2	1	1
Oligoclase	30	31	28	33	23	14
Opaques	1	1	1	acc	acc	1
Chlorite	acc	acc	acc	acc	acc	acc
Epidote	acc	acc	acc	acc	acc	---
Sphene	acc	acc	acc	acc	acc	acc
Apatite	acc	acc	acc	acc	acc	acc
Zircon	acc	acc	acc	acc	acc	acc

Table 2. Modal percentages of the silicic rock units. "acc" equals < 1%.

In hand specimen, penetrative foliation or fluxion structure (Higgins, 1971) is prevalent and is due to the parallel alignment of the mica grains. In thin section, the fluxion structure becomes more evident due to the preferred orientation of most elongate mineral grains and quartz stringers.

The oligoclase grains are slightly to moderately altered to sericite. Sericitization follows the cleavage traces. In those plagioclase grains which are zoned, the sericitization has preferentially occurred in the presumably more calcic cores. The potassium feldspar is predominantly microcline. Oligoclase and microcline are found in the matrix and as megacrysts. Bulbous myrmekite is variable in occurrence, and it has the characteristic form of embayments in the potassium feldspar megacrysts. The quartz is commonly found as "flamboyant stringers" (Higgins, 1971). Biotite, muscovite, and chlorite are commonly associated, but also occur as isolated flakes. Mica flakes larger than 2 mm are rare. Zircon is evenly distributed throughout the rock as small euhedral grains. Apatite is present as characteristic prisms rarely over 0.2 mm in diameter. Sphene is found as both euhedral and anhedral grains. Granular sphene commonly surrounds irregular masses of magnetite.

According to Higgins (1971), this rock is a porphyroclastic mylonite gneiss. Due to the high degree of neomineralization-recrystallization, areas of mortar texture are low in abundance. They are generally restricted to the tails of the megacrysts and to thin zones parallel to the foliation.

UNIT B

The rocks of Unit B dominate the field area (Fig. 2). The unit is extremely variable in texture, but it is reasonably consistent compositionally. Megacrysts are present in all but a few samples. They range in size from about 1 mm to 2 cm. Foliation is apparent throughout and it is due predominantly to the alignment of the micaceous minerals (Plate 3). In those samples with low mica contents, the foliation is only observable in thin section, and it is due to the alignment of quartz stringers and mortar zones.

Oligoclase has been moderately to severely altered to sericite. In some grains the cores of the oligoclase grains are filled with coarse muscovite. Twinning is often masked by sericitization; however, albite, pericline, and Carlsbad twinning were identified. Rare bent feldspar twins are present. Oligoclase and microcline are found as megacrysts and both occur in the matrix. Bulbous myrmekite is common throughout the granitic rocks of the Littleton and Thelma area, but is best developed in Unit B. It is found in megacrysts and matrix grains. The quartz commonly occurs as "flamboyant stringers". Some of the isolated quartz grains are megacrysts, but they do not possess the augen shape which is characteristic of the feldspar megacrysts. All quartz grains exhibit a strain-induced subgrained texture. The mica content in Unit B is variable, ranging from about 20% to less than 1%. This mineralogical variation may be one of the main factors controlling the textural variation mentioned previously. Without exception, the mica is aligned parallel to, and thus defines, the foliation (Plate 3). Chlorite and, less commonly, sphene are associated with biotite and muscovite. Sphene is generally

euhedral where it is associated with mica and anhedral where it fills interstitial spaces.

The rocks of Unit B are classified as a porphyroclastic mylonite gneiss (Higgins, 1971). There is a wide range in the extent of neomineralization-recrystallization, and a few rocks of Unit B may be proto-mylonites.

UNIT C

Unit C is restricted to the western side of the study area (Fig. 2), where it typically outcrops as large (several meters in diameter) spheroidally weathered boulders. This rock is quite distinctive. Large megacrysts of microcline and oligoclase make up about 50% of the rock (Plate 4). Some megacrysts have augen shapes but others are subhedral to euhedral. The size of the megacrysts ranges from about 3 cm to less than 0.5 mm. Although a great majority of the feldspar is present as megacrysts, it is found in the matrix as well. Bulbous myrmekite is commonly associated with the potassium feldspar megacrysts. The alkali feldspar is perthitic and dominantly microcline. Sericitization in the oligoclase grains is slight to moderate. Inclusions of nearly every mineral found in the matrix are found in the feldspar megacrysts. The matrix is chiefly composed of quartz and biotite. Quartz is commonly in stringers, and biotite is generally wrapped around the megacrysts and stringers. Spene is unevenly distributed, and it is found in clusters associated with biotite and opaque minerals. Chlorite is present as isolated flakes, but more commonly it is associated with biotite. Apatite and zircon are present in very small amounts.

Unit C is classified as a porphyroclastic protomylonite (Higgins, 1971). The degree of cataclasis is fairly consistent within Unit C, although one sample, 75-1, has been sheared to a much greater degree than other samples from the unit (Plate 4).

UNIT D

Unit D is confined to the extreme western portion of the study area (Fig. 2); it is a mappable stratigraphic unit which can be traced for at least 20 km (Stoddard and McDaniel, 1979). The rocks of Unit D are very fine grained. The largest grains are about 0.2 mm in diameter. Due to the low mica content, the foliation is not as pronounced as it is in the other rocks of the study area. Where the foliation is observable in hand specimen, it is apparent as bands of slightly different tint (Plate 6). The alternation of these bands is not regular nor are their thicknesses consistent. The bands range from about 2 mm to 8 mm in thickness. The grain size within any particular band is very consistent; however, the grain size changes from one band to another. These bands are remarkably linear in some locations and can be traced for several meters. In other locations the bands are irregular and wavy. The only noticeable compositional difference between bands is that some have higher concentrations of magnetite than others. In addition, parallel alignment of elongate mineral grains and quartz stringers contribute to the foliation. Bulbous myrmekite is rare, possibly due to the low plagioclase content. Sericitization is moderate in Unit D and is confined to oligoclase grains. Most grains are slightly rounded and uniform in character. Quartz occurs as isolated grains which are evenly distributed throughout

the rock. Quartz also occurs as stringers. Magnetite dominates the opaque minerals and is evenly distributed throughout the rock. Sphene and apatite occur in accessory amounts.

UNIT E

Unit E includes schist, meta-rhyolite and meta-diorite. No detailed petrographic studies were made on this unit. These rocks are grouped together because they occur in various isolated, elongate blocks completely enclosed by the granitic rocks (Fig. 2). The foliation is parallel to the direction of elongation of the blocks, and it is concordant with the regional NNE foliation.

Schists composed of muscovite, biotite, quartz, and garnet dominate Unit E. Some chlorite grains cross the schistosity. In nearly one half of the schist samples a small scale ($\lambda = 1-3$ cm) folding is present. Quartz veins are common. Garnet porphyroblasts contain micaceous inclusions that lack a preferred orientation.

Three other rocks have been found within these isolated blocks. One is a meta-rhyolite which has been recrystallized to the extent that the original texture is partially obscured. The grain size averages less than 1 mm. A few clusters of strained quartz grains, about 2 mm in diameter, suggest recrystallization of original quartz-filled amygdules. The second rock type is composed of quartz and fine-grained white mica, which are believed to be products of intense alteration. The third is a porphyroclastic meta-diorite (?). The major minerals are quartz, plagioclase, biotite, potassium feldspar, epidote, and sphene. This rock has a cataclastic foliation, broken and bent feldspar twins, and some bulbous myrmekite.

UNIT F

Unit F is composed of a section of rocks referred to as the Roanoke Rapids complex (Farrar, in press). Unit F is found in the extreme eastern edge of the study area (Fig. 2), and the contact marks the eastern extent of the Lake Gaston granites. The Roanoke Rapids complex extends 15 km farther to the east, and only a small portion of it is in the study area. Farrar (in press) interprets the contact as a nearly vertical normal fault. No field evidence was found in the study area to support this interpretation. However, small folds ($\lambda = 1$ meter) were observed in the contact area, where comminuted granite, pegmatite veins, and thin micaceous layers were folded. The fold axes are nearly vertical and the axial planes trend parallel to the NNE regional foliation. The folding is attributed to the same episode of mechanical deformation that produced the cataclastic textures in the other rocks of the area (Plate 8).

Several different rock types from the Roanoke Rapids complex were collected. Four of the most distinctive types are described below:

- a) One of the rock types is composed of tremolite-actinolite, chlorite, and opaque minerals. It is well foliated. The chlorite flakes wrap around the amphibole grains in such a manner as to suggest a cataclastic texture. It is probable that this rock is derived from an ultramafic protolith because the only constituents are Fe- and Mg-bearing minerals.
- b) Another rock type from Unit F was probably a mafic volcanic rock. This is suggested by remnant plagioclase laths and by vesicles which are now filled with strained quartz. Quartz,

microcline, and plagioclase are the major mineral phases and there is evidence of hydrothermal alternation.

- c) A brecciated rock with a matrix of very fine-grained quartz is another member of Unit F. The size of the quartz matrix approaches the limit of resolution of a petrographic microscope. A weathered, limonitic appearance is typical of the 1-3 cm fragments in this rock.
- d) A compositionally layered rock with a strong foliation, accentuated by quartz stringers and parallel alignment of the mica grains, is common along the shore of the Roanoke River just downstream from the Gaston Dam. Bent and broken feldspar twins are common. Mineralogically, it is composed of plagioclase, microcline, quartz, chlorite, muscovite, apatite, zircon, magnetite, and pyrite.

UNIT G

The diabase rocks of the study area comprise Unit G. Sample C-11a was taken from one of the core holes and the others were sampled from numerous dikes outcropping throughout the area (Fig. 2). Usually, the diabase is found as spheroidally weathered cobbles in the saprolite.

Subophitic to intergranular texture is common in all samples. Some dikes are amygdaloidal with calcite and chlorite in-fillings, while others are completely devoid of amygdules. Phenocrysts of olivine are common, and augite phenocrysts are less common. Olivine and augite are altered to iddingsite, limonite, and magnetite in some samples. Antigorite may be the alternation mineral in the fractures of some olivine

grains. A poikilitic texture (augite includes labrodorite) is present in one sample.

Evidence of two cooling episodes of differing rates exists, exhibited by the two sizes of plagioclase laths and by smaller projections on the smaller laths (Plate 9). The larger laths are presumed to have formed during the first and slower cooling episode. Most of the magma must have crystallized during this episode because a great majority of the feldspar occurs as large laths. Thin projections extend from the terminal ends of the smaller laths, which presumably crystallized during a more rapid cooling rate. The origin of these projections has been described as a quenching phenomenon (Lofgren, 1971).

UNIT H

The Tertiary gravels consist of well rounded quartz pebbles and cobbles supported in a sandy clay matrix. The gravels are found only in the eastern portion of the study area (Fig. 2), although they may have previously blanketed the entire region.

GEOCHEMISTRY OF THE SIALIC ROCK UNITS

Geochemical analyses for major and trace elements were performed on 32 samples. Individual analyses are listed in Appendix II and average analyses for the sialic rock units appear in Table 3. Concentrations of Na_2O and MgO were determined using a Perkin Elmer model 303 Atomic Absorption Spectrophotometer with a Spectrum 1320 AA concentration digitizer. Concentrations of Al_2O_3 , SiO_2 , K_2O , CaO , TiO_2 , MnO , $\text{Fe}_2\text{O}_3^{\text{T}}$ (total iron as Fe_2O_3), Rb , Sr , Y , Zr , and Ba were determined by X-ray fluorescence utilizing a General Electric XRD-6, SPG-3 Vacuum Spectrometer. Trace element concentrations (Rb , Sr , Y , and Zr) were measured using the method of Drez (1977) modified after Wilband (1975). This method utilizes the Mo Compton ($\text{Mo}_{\text{K}\alpha\text{c}}$) scattering peak as an indicator of background and mass absorption (Reynolds, 1967). Instrumental data, along with accuracy and precision values are given in Appendix II.

The objectives of the geochemical analyses were threefold: 1) to chemically describe and characterize the rock units; 2) to use the chemical data to support the petrographic and field division of the rocks into their respective rock units; and 3) to use the chemical data to compare these rocks to other granites in the Piedmont.

CHEMICAL WEATHERING OF THE GEOCHEMICAL SAMPLES

Twenty-one of the geochemical samples are from surface outcrops. Although an effort was made to collect fresh samples, a more direct measure of the degree of weathering is desirable. Two methods to estimate weathering effects were applied to the data for the surface samples.

	UNIT	subunits		UNIT	UNIT	UNIT
	A	A ₁	A ₂	B	C	D
Number of samples	10	7	3	9	3	3
SiO ₂	65.15	64.54	66.56	70.61	65.60	72.72
Al ₂ O ₃	15.06	14.95	15.31	15.99	15.44	15.66
TiO ₂	0.71	0.81	0.49	0.20	0.63	0.30
Fe ₂ O ₃ ^T	3.40	3.80	2.45	1.02	3.84	1.55
MgO	0.63	0.69	0.49	0.45	0.69	0.46
MnO	0.05	0.06	0.03	0.03	0.08	0.02
CaO	1.99	2.14	1.64	1.07	2.33	0.38
K ₂ O	4.95	4.92	5.02	5.98	4.60	7.74
Na ₂ O	3.89	3.84	4.01	3.26	3.65	1.54
Volatiles(LOI)	0.52	0.47	0.42	0.95	0.80	1.00
Rb	178	184	165	237	181	209
Sr	786	859	555	222	379	90
Y	30	36	17	5	25	38
Zr	362	387	304	124	233	288
Ba	1463	1524	1319	718	1034	1171
K/Rb	2334	2245	2541	2185	2147	3173
K/Sr	561	479	753	4588	1024	8485
K/Ba	282	268	316	843	378	556
Ca/Y	498	400	725	1684	647	78
Ti/Zr	11.8	12.6	9.9	10.9	16.5	6.1
Rb/Sr	0.24	0.21	0.30	1.08	0.5	2.6
Ba/Sr	1.96	1.78	2.38	3.23	2.71	15.8
K ₂ O/Na ₂ O	1.27	1.28	1.25	1.83	1.26	5.03

Table 3. Chemical analyses of the sialic rock units. Major elements in wt%, trace elements in ppm, volatiles are in wt%.

The twelve samples taken from the core holes are unquestionably fresh, and these were used as references to gauge the validity of the methods.

One method (Chesworth, 1977) utilizes a $\text{CaO}+\text{MgO}$, $\text{Na}_2\text{O}+\text{K}_2\text{O}$, $\text{SiO}_2+\text{Fe}_2\text{O}_3^{\text{T}}+\text{Al}_2\text{O}_3$ triangular diagram (Fig. 4). The basic assumption of the method is that as a rock weathers, it loses the alkali and alkaline earths preferentially, resulting in an enrichment of SiO_2 , $\text{Fe}_2\text{O}_3^{\text{T}}$, and Al_2O_3 . As weathering proceeds, the points will define a trend toward the $\text{SiO}_2+\text{Fe}_2\text{O}_3^{\text{T}}+\text{Al}_2\text{O}_3$ apex. Therefore, when measuring samples of an uncertain original composition, the method gives a relative degree of weathering which is useful in comparing rocks with assumed similar original compositions. The geochemical samples are plotted in Figure 4 and are listed in order of least to most weathered in Table 4.

A second method (Parker, 1970) implies that the strength of the cation-to-oxygen bond is the key to weathering susceptibility. Parker's index (I_p) is defined by the following expression:

$$\frac{\text{Moles of Na}}{0.35} + \frac{\text{Moles of K}}{0.25} + \frac{\text{Moles of Ca}}{0.7} + \frac{\text{Moles of Mg}}{0.9} \times 100 = I_p.$$

The values in the demoninators are the bond strengths of the X-O (Nicholls, 1963). Parker applied this index to several weathering profiles of different igneous rocks. Table 5 lists the I_p for all geochemical samples. For comparison, averages from Parker's profiles for granites are also listed.

The order of least to most weathered as determined by Chesworth's method is similar to the order determined by Parker's method. These results also agree with visual estimates indicating that those samples (126-1, 76-1, 97-1) which plot closest to the $\text{SiO}_2+\text{Fe}_2\text{O}_3^{\text{T}}+\text{Al}_2\text{O}_3$ apex in

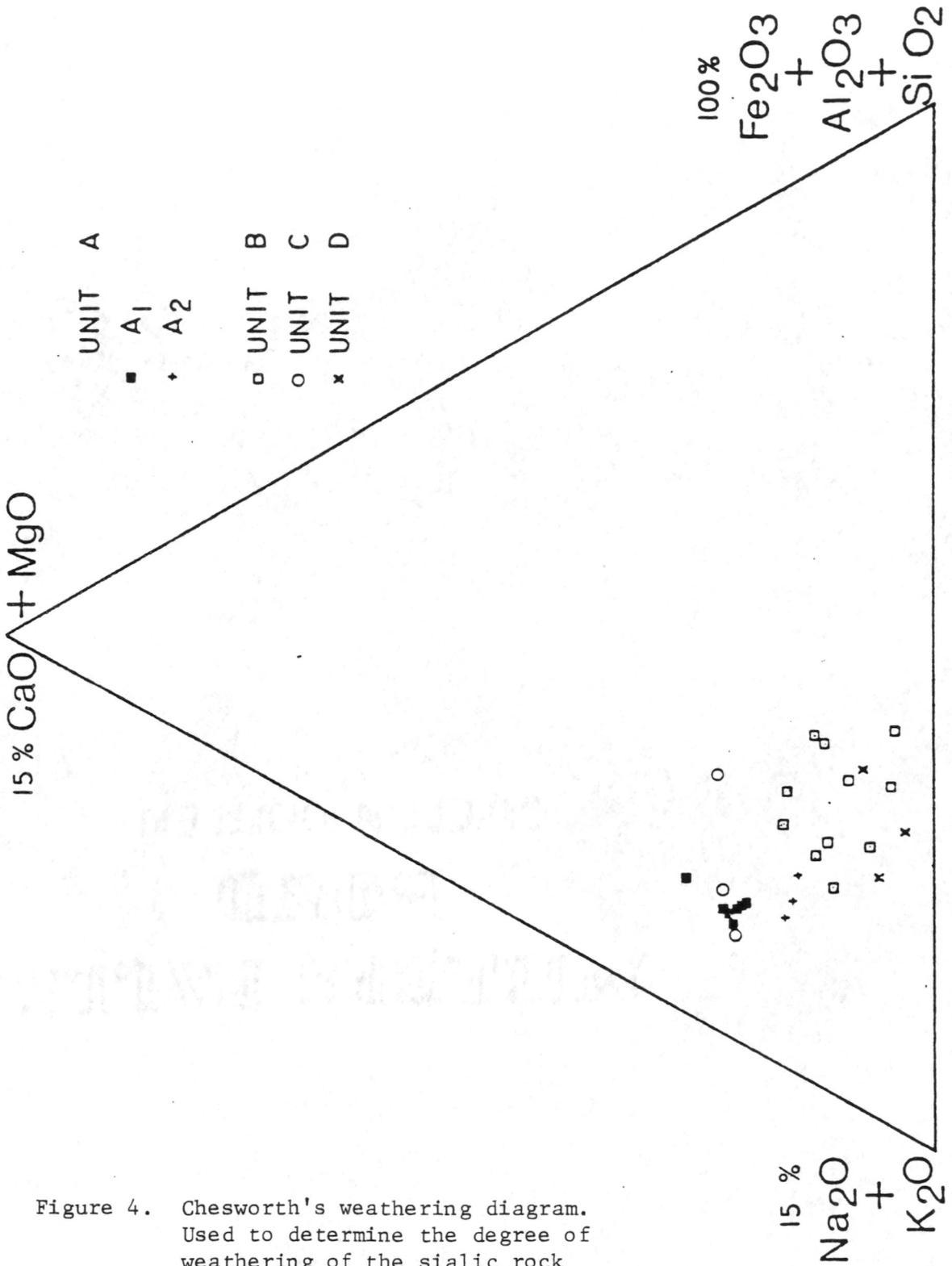


Figure 4. Chesworth's weathering diagram. Used to determine the degree of weathering of the silicic rock units. After Chesworth (1977).

<u>UNIT A</u>		<u>UNIT B</u>	<u>UNIT C</u>	<u>UNIT D</u>
<u>SUBUNIT A₁</u>	<u>SUBUNIT A₂</u>	<u>LEAST WEATHERED</u>		
Ch - Pk	Ch - Pk	Ch - Pk	Ch - Pk	Ch - Pk
C-29 - C-22	C-19 - C-19	22-2 - 22-2	27-1 - 27-1	39-6 - 39-6
C-A - C-23	C-C - C-C	C-E - C-E	84-1 - 84-1	35-4 - 35-4
C-23 - C-29	117-2 - 117-2	C-11 - 83-2	75-1 - 75-1	80-1 - 80-1
C-22 - C-21		73-1 - C-11		
C-25 - C-A		83-2 - 73-1		
C-21 - C-20		C-13 - 110-1		
C-20 - C-25		112-1 - 105-3		
		105-3 - C-13		
		110-1 - 112-1		
		126-1 - 97-1		
		97-1 - 76-1		
		76-1 - 126-1		

MOST WEATHERED

Table 4. Comparison of Chesworth's (Ch) and Parker's (Pk) methods of determining the degree of weathering.

Figure 4 and have low I_p values are also those samples that were thought to be of questionable freshness. These three samples were not used in the geochemical interpretations which follow.

UNIT A

The chemical designations felsic and intermediate refer to rocks with silica contents of over 66 wt % and between 52 and 66 wt %, respectively. The designation peraluminous refers to rocks in which Al_2O_3 is greater than the sum of Na_2O , K_2O , and CaO on a mole basis.

The SiO_2 contents of the ten samples of Unit A average 65.15 wt % (intermediate range) and three samples from subunit A_2 average 66.56 wt% (felsic range).

Unit A rocks are peraluminous, and they are characterized by high concentrations of Sr, Zr, and Ba. The division of Unit A into two subunits is supported by the concentrations of SiO_2 , MgO, CaO, MnO, $Fe_2O_3^T$, TiO_2 , Sr, Y, and Ba. This division is clearly illustrated in the Harker diagrams of these elements (Fig. 5).

UNIT B

Chemically the rocks of Unit B are quite variable as indicated by the scatter on variation diagrams. The three samples determined to be significantly altered by weathering (126-1, 76-1, 97-1) belong to this unit, and they are not plotted in any diagrams other than the Harker diagrams. The "not significantly weathered" Unit B samples are felsic, and they are peraluminous. Unit B is characterized by its chemical

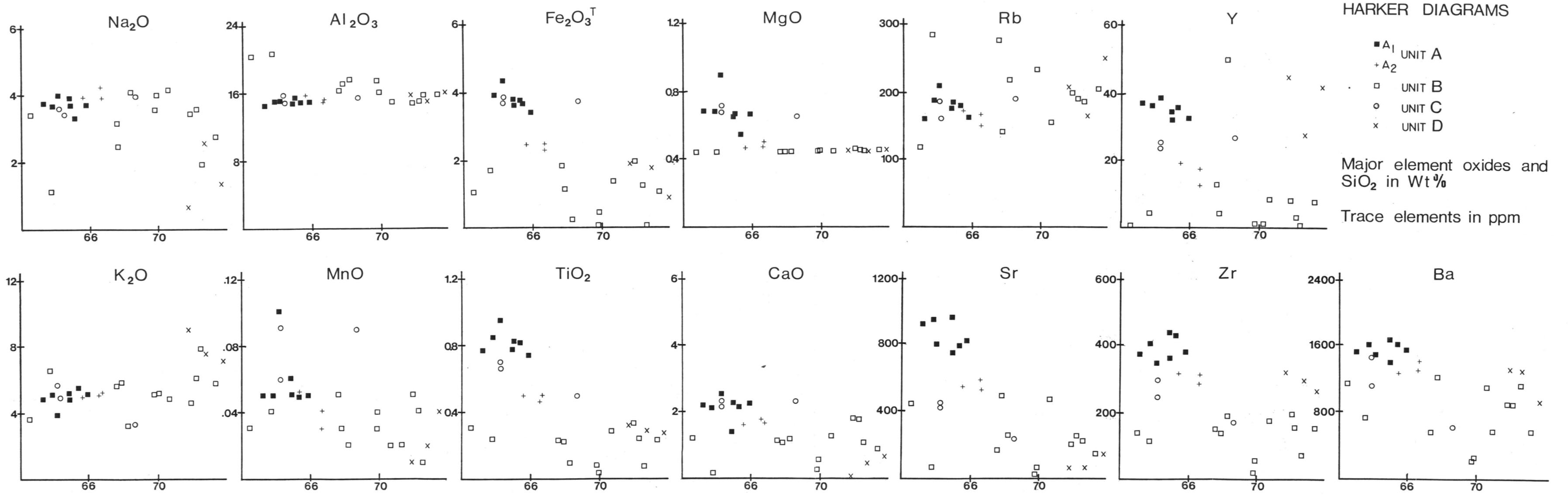


Figure 5. Harker diagrams of the sialic rock units.

heterogeneity, by low Y contents, and by Rb/Sr ratios greater than one. All other units in the study area have $Rb/Sr < 1$.

UNIT C

Of the three Unit C samples that were analyzed (27-1, 75-1, 84-1), one (75-1) is felsic, and the other two are intermediate, although there is only a 4 wt % variation in SiO_2 among the samples. Unit C is characterized by high Ba contents (Table 3).

UNIT D

The rocks comprising Unit D have previously been described as sedimentary or as igneous in origin (Stoddard, personal commun.) Unit D samples are felsic and peraluminous. Unit D is characterized by high K_2O and Ba, and low Na_2O , CaO, and Ca/Y.

CHEMICAL RELATIONSHIPS OF UNITS A, B, C, AND D

The trend on the AFM diagram of Units A, B, C, and D may be the alkalic portion of a calc-alkalic trend (Fig. 6). Subunit A_1 and Unit C plot together near the alkalic-poor and less siliceous part of this trend, while subunit A_2 and Units B and C plot toward the more evolved portion of the trend. The K_2O - Na_2O -CaO diagram (Fig. 7) shows that Units A, B, and C plot generally within the field of Hercynian granites of the Piedmont.

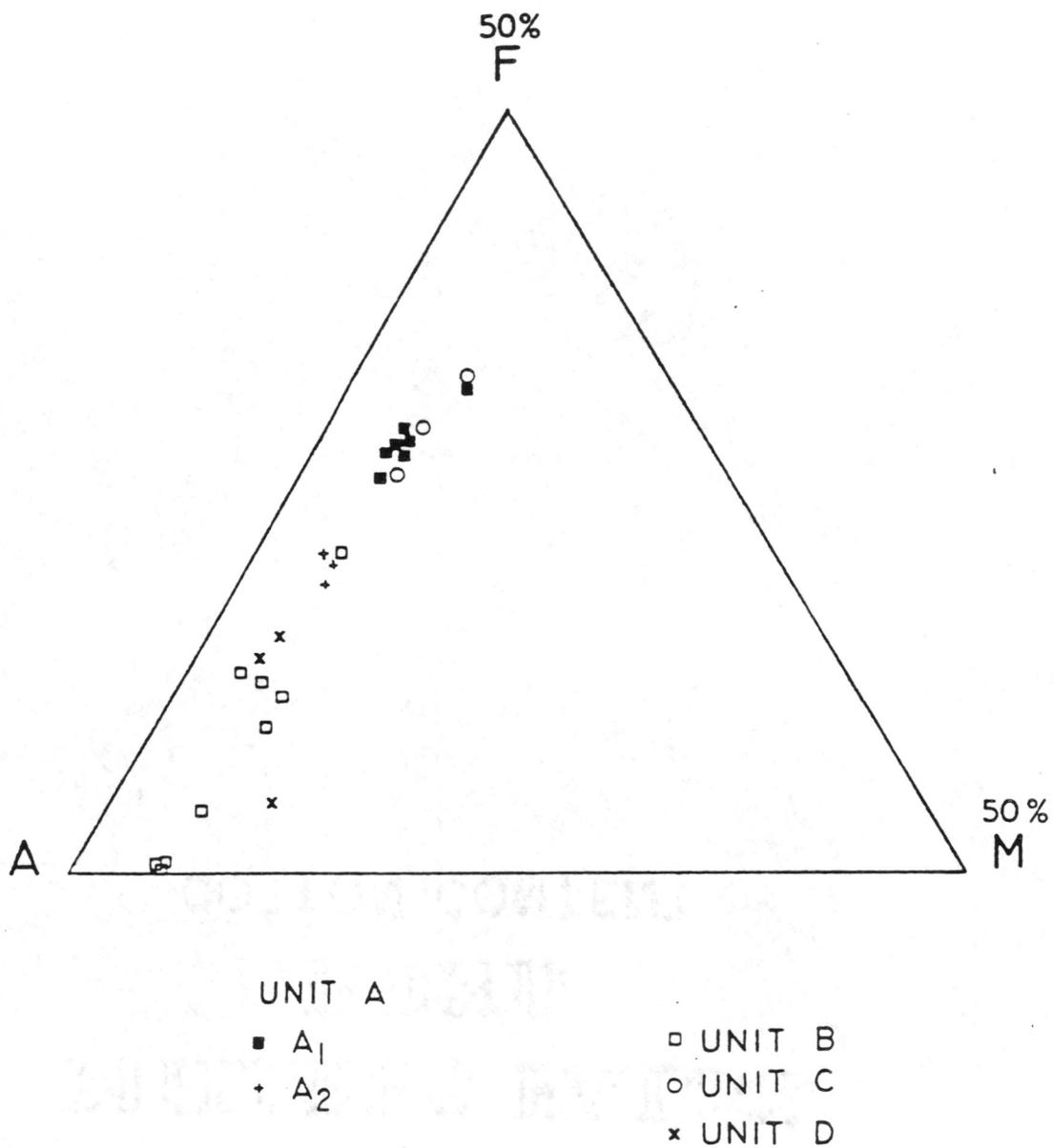


Figure 6. AFM diagram of the sialic rock units.

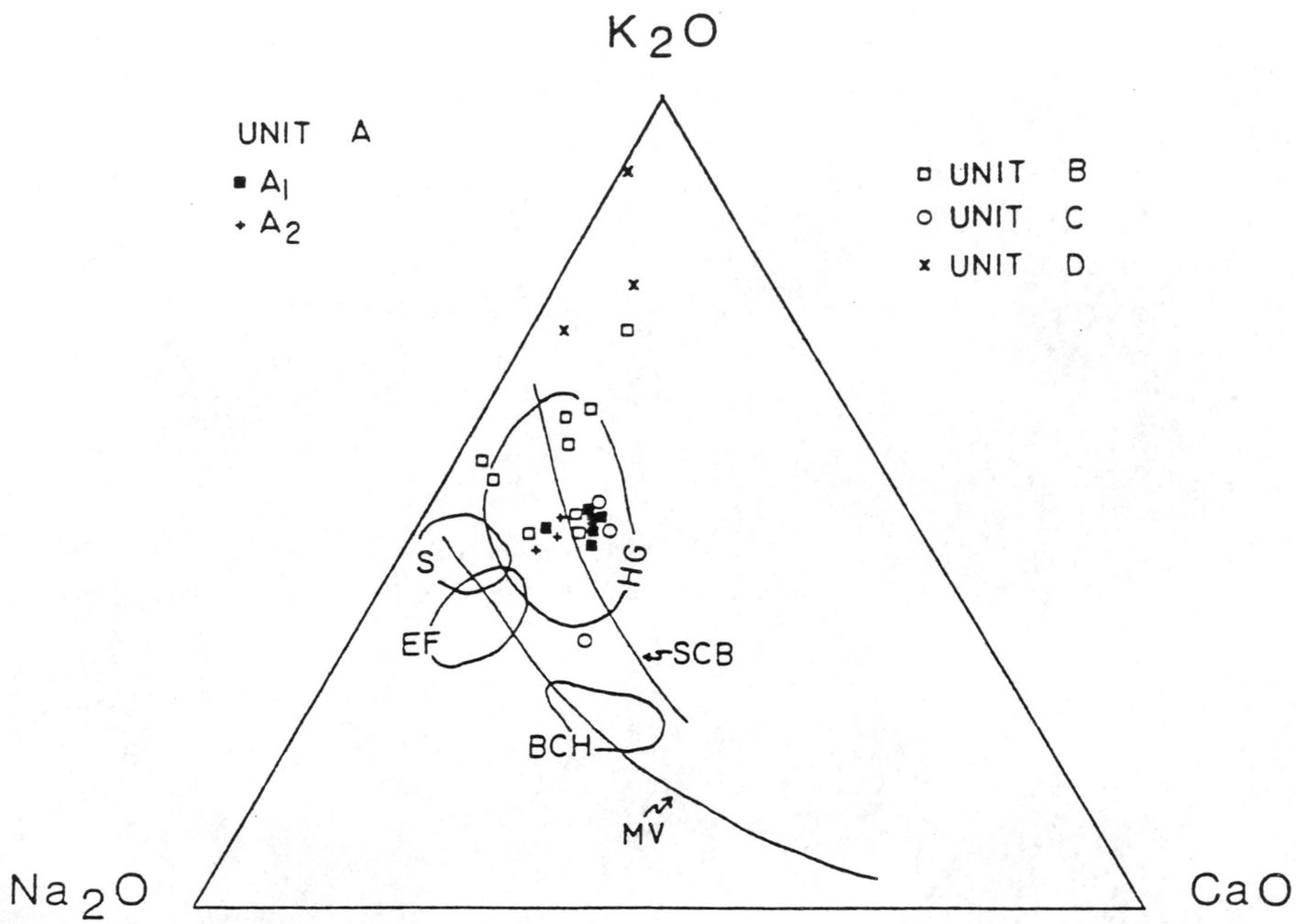


Figure 7. K₂O-Na₂O-CaO diagram of sialic rock units.

HG=Hercynian granites; S=Salisbury pluton; EF=East Farrington pluton; BGH=Bacon Quarry and Chapel Hill pluton; MV=Metavolcanic trend of rocks in the Carolina slate belt; SCB=trend indicated by the Southern California Batholiths. The fields in the diagram are from Butler and Ragland (1969).

The concentrations of Rb in Units A, B, C, and D are fairly consistent and are typical of most rocks of granitic composition (Condie, 1976). Those samples of Units A, B, and C with high Sr contents also have high Ba concentrations (Fig. 8). No correlations between K_2O and Sr, K_2O and Ba, or CaO and Y are indicated. However, interpretations involving Y are questionable because of the low precision of the Y analyses (Appendix II). Titanium and Zr exhibit a positive correlation (Fig. 9). In addition, a plot of TiO_2 vs. Zr clearly shows that Units A, B, C, and D are distinct geochemical groups which support the petrographic and field divisions of the units in the study area.

El Bouseily and El Sokkary (1975) discuss the ternary relationship involving Rb, Ba, and Sr. Briefly, they conclude that a normal crystallization trend, beginning with dioritic compositions, would start near the Sr apex on a Rb-Ba-Sr diagram (Fig. 10). The trend would be directed toward the Ba apex, without an increase in Rb, as it passes through a field typical of "granodiorites" and "quartz diorites". This part of the trend is explained by a loss of the potential Sr substitution sites in plagioclase along with the addition of the potential Ba substitution sites in alkali feldspar. The trend reaches a maximum relative concentration of Ba near the Ba apex in a field typical of "normal granites". Later, as enrichment of Rb occurs, the trend is directed toward the Rb apex where it terminates in a field of "strongly differentiated granites". The relative enrichment of Rb is reportedly due to the increase in modal potassium feldspar as differentiation proceeds beyond "normal granites".

According to Figure 10, subunit A_1 is the least differentiated and it is followed by subunit A_2 , Unit C, most samples of Unit B, Unit D,

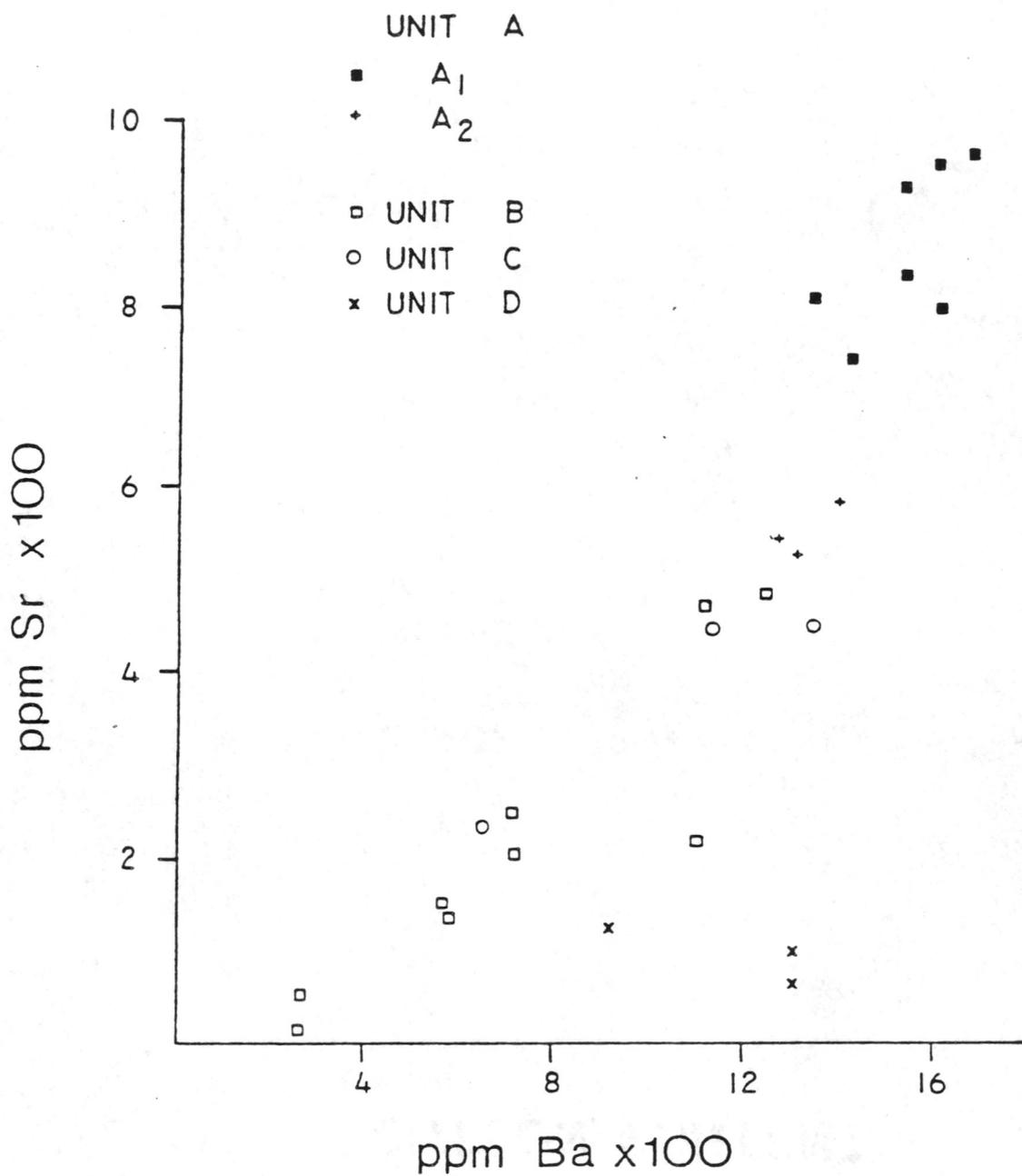


Figure 8. ppm Sr versus ppm Ba. A positive correlation is illustrated by Sr and Ba in the silicic rock units.

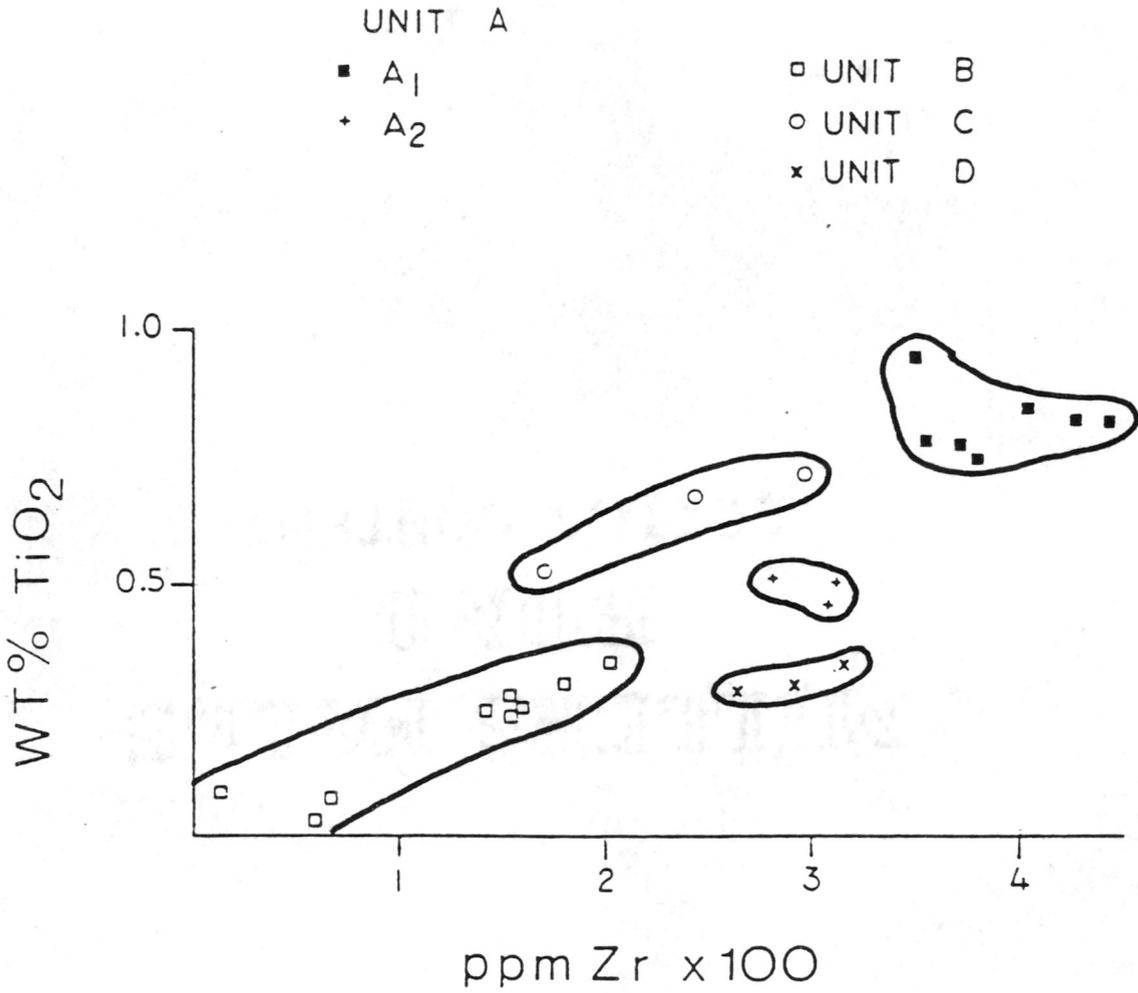


Figure 9. Wt.% TiO₂ versus ppm Zr. A positive correlation is illustrated by TiO₂ and Zr in the sialic rock units. This plot clearly separates the sialic rock units.

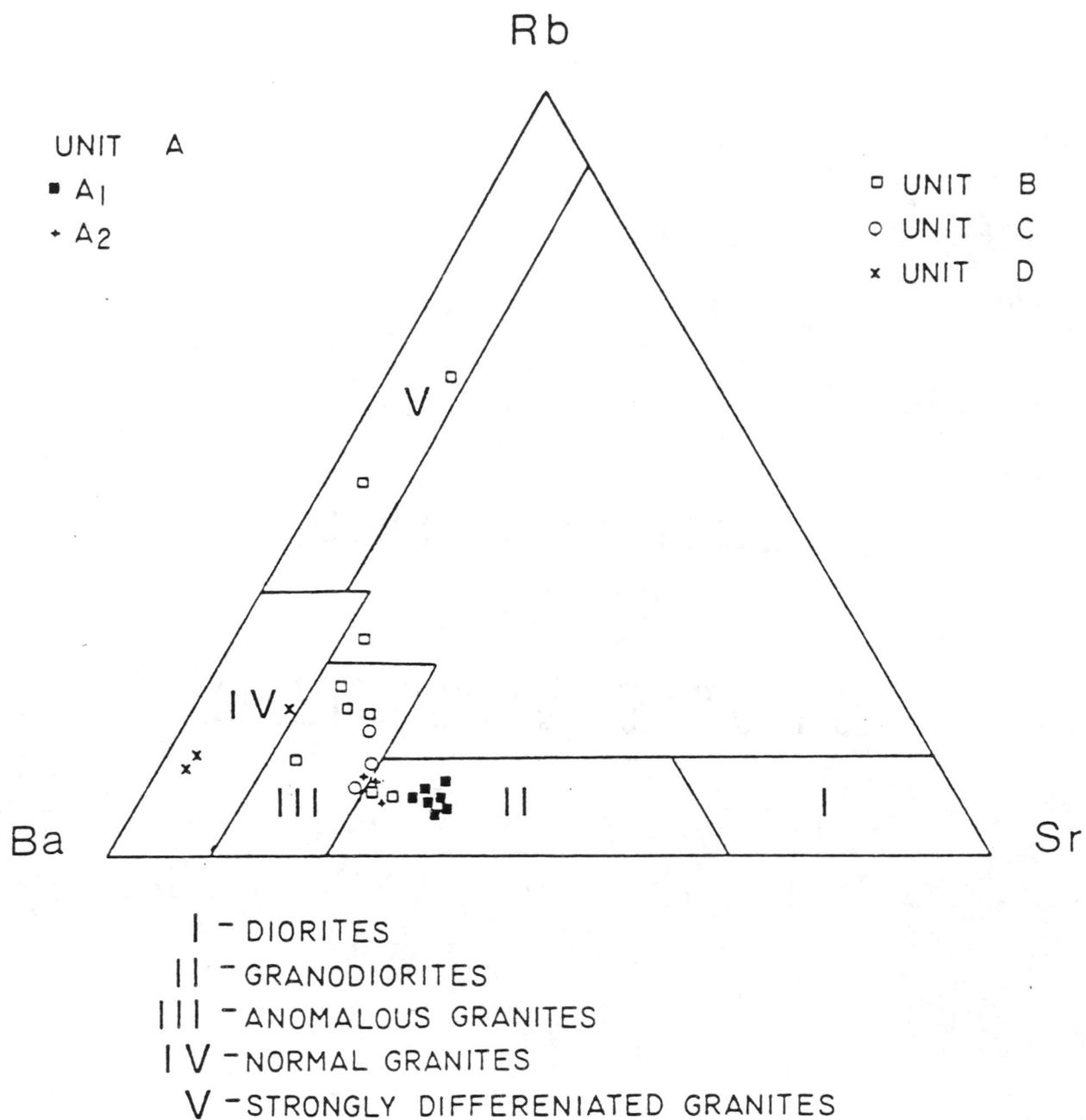


Figure 10. Rb-Ba-Sr diagram. The relationships of Rb, Ba, and Sr are illustrated for the sialic rock units. The fields on the diagram are from El Bouseily and El Sökkary (1975).

and finally, two samples of Unit B (110-1, 83-2). This order of differentiation is essentially the same as that which is indicated by the AFM diagram (Fig. 6). Rocks in the field of "anomalous granites" may simply represent a differentiation state that is transitional between "granodiorite" and "normal granites".

Units A, B, and C are interpreted as plutonic igneous intrusions that may be genetically related. Unit D is geochemically distinct and is of uncertain origin.

CHEMICAL COMPARISON OF THE LAKE GASTON GRANITES
WITH THE BUTTERWOOD CREEK PLUTON

The only chemical data available for the Butterwood Creek pluton is that of Unit C. The chemistry of the Lake Gaston granites (Units A and B) is similar to that of the porphyritic, biotite-bearing phase of the Butterwood Creek pluton (Unit C); however, the greatest similarities are exhibited by Units A and C.

Two of the Unit C samples are quite similar, while the other, (75-1) is slightly different with respect to SiO_2 , K_2O , TiO_2 , Sr, and Ba (Appendix II). Sample 75-1 has been deformed by cataclasis to a much greater degree than the other samples and the observed chemical differences may be due to the effects of this cataclasis. Therefore, the original chemical composition of Unit C is probably best estimated by samples 27-1 and 84-1.

Eleven of the Harker diagrams (all except Sr and Y) illustrate the similarities between Units A and C. These two units plot in close proximity on the AFM and $\text{K}_2\text{O}-\text{Na}_2\text{O}-\text{CaO}$ diagrams. In addition, the similarities between these two units are well illustrated by the relationships between $\text{K}_2\text{O}-\text{Ba}$, $\text{K}_2\text{O}-\text{Rb}$, and Sr-Ba.

CHEMICAL COMPARISON OF UNITS A, B, AND C WITH
HERCYNIAN GRANITES OF THE PIEDMONT

A chemical comparison of Units A, B, and C with Hercynian granites of the Piedmont reveals that Units A, B, and C display chemical characteristics similar to both the eastern and western Hercynian granitic groups. The major element chemistry of the two Hercynian granitic groups does not differ greatly. The K_2O contents of the eastern group are slightly higher than those of the western group (Fullagar and Butler, 1979; Sando, 1979; and Butler and Ragland, 1969).

The trend illustrated by Units A, B, and C on the AFM diagram (Fig. 6) approximates the calc-alkaline trend exhibited by the eastern group of Hercynian granites. All but one sample of Units A, B, and C plot within the field characteristic of the Hercynian granites (Fig. 7).

Fullagar and Butler (1979) report an average Sr content of 138 ppm for the eastern group and an average of 636 ppm Sr for the western group. A comparison of the Sr concentrations of Units A, B, and C indicates that subunit A_1 is about one third richer in Sr than the average western group. The Sr content of subunit A_2 is similar to the average Sr content of the western group. Strontium in Unit B is similar to the average for the eastern group and Sr in Unit C is intermediate between the Sr concentrations of the two Hercynian groups. The high Ba contents of Units A and C are comparable to those of the western group, while Ba in Unit B is more comparable to that of the eastern group.

In summary, Units A and C have affinities for the western Hercynian granites and Unit B more closely resembles the eastern Hercynian granites on the basis of selected trace elements.

GEOCHEMISTRY OF UNIT G

Four diabase samples were analyzed for major elements and trace elements (Rb, Sr, Y, Zr, and Ba) utilizing the same methods as described for the sialic rock samples. Parker's weathering index (Ip) indicates that these samples are not significantly weathered.

MAJOR ELEMENTS

The four diabase samples contain similar, but low concentrations of SiO_2 (44-45 wt %) when compared to other diabase rocks (Condie, 1976; Weigand and Ragland, 1970). On an alkali-silica diagram (Fig. 11), they lie on or near the boundary between alkaline and subalkaline basalts.

Unit G samples were classified using a normative Di-Hy-Ol-Ne-Qz diagram (Fig. 12) modified by Weigand and Ragland (1970). This diagram is a projection from plagioclase in the Di-Qz-Ol-Pg tetrahedron (Yoder and Tilley, 1962). Figure 12 illustrates Unit G samples and shows two fields of diabasites defined by Weigand and Ragland (1970) for rocks from Nova Scotia to Alabama. Unit G samples are transitional between olivine tholeiites and alkali olivine basalts (Fig. 12).

TRACE ELEMENTS

A comparison of the trace element concentrations of Unit G with average trace element concentrations of basalts from various tectonic settings (Condie, 1976) indicates that Unit G samples more closely resemble continental rift tholeiites than continental rift alkali

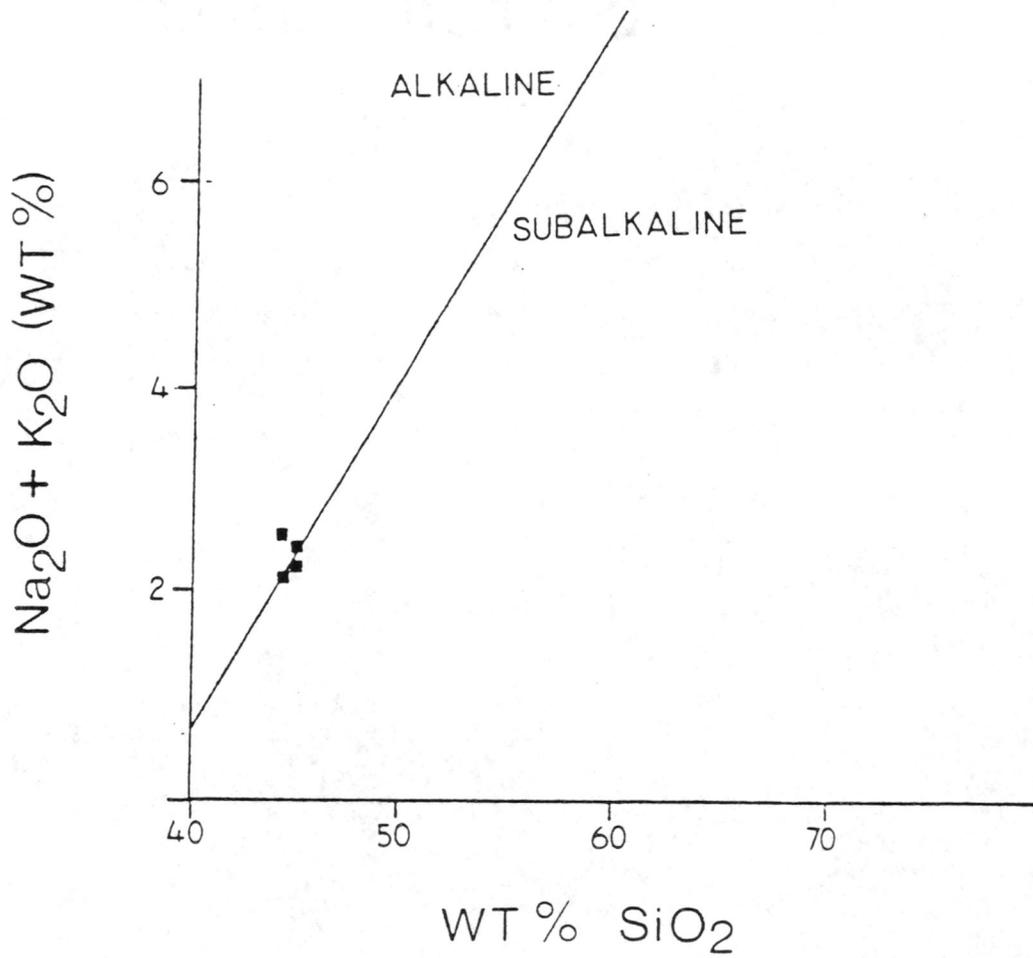


Figure 11. Alkali-Silica diagram of Unit G samples. Alkaline-subalkaline boundary from MacDonald (1968).

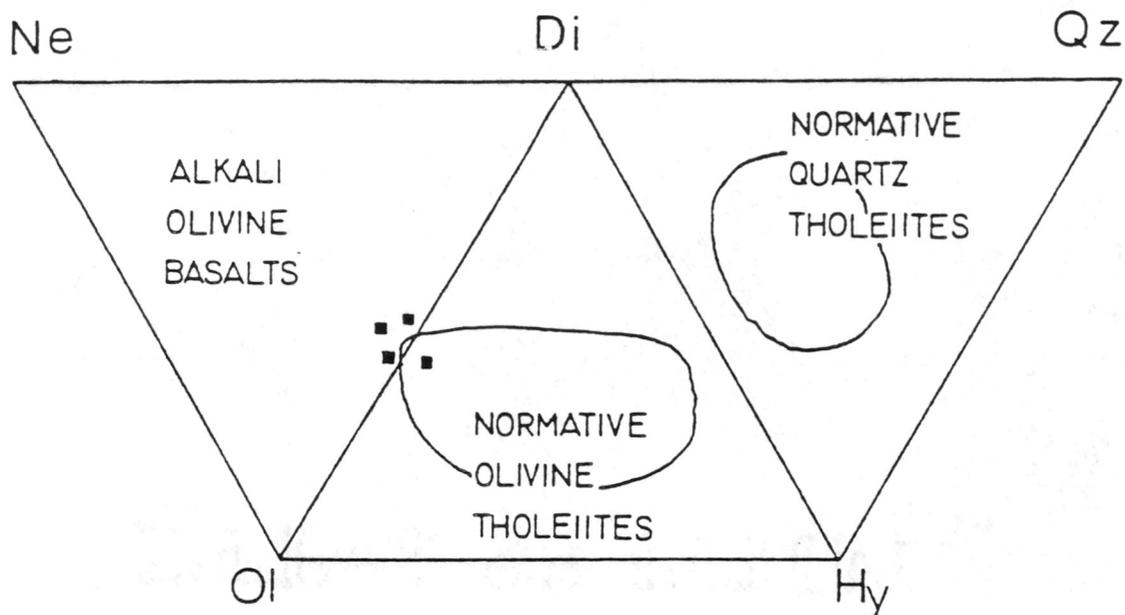


Figure 12. Di-Hy-Ol-Ne-Qz diagram. This is a projection from plagioclase in a Di-Qz-Ol-Pg tetrahedron (Yoder and Tilley, 1962). Unit G samples plot on the boundary of Alkali Olivine Basalts and Normative Olivine Tholeiites. The circled fields indicate the two compositions typical of diabase rocks from Nova Scotia to Alabama (Weigand and Ragland, 1970).

basalts. This classification is based on the overall low concentrations of all trace elements analyzed. Rubidium and Y are below detection limits in all samples except C-11a, and Sr and Zr contents are lower than those in most basalts regardless of their tectonic setting. Barium concentrations (Table 6) are more typical of continental tholeiites (Condie, 1976).

SiO ₂	44.64	K/Rb	13698*
Al ₂ O ₃	14.17	K/Sr	169
TiO ₂ ^T	0.66	K/Ba	118
Fe ₂ O ₃ ^T	14.48	Ca/Y	4521*
MgO	11.12	Ti/Zr	64
MnO	0.17	Rb/Sr	0.01
CaO	10.31	Ba/Sr	1.46
K ₂ O	0.23	Fe ₂ O ₃ ^T /Fe ₂ O ₃ ^T +MgO =	0.57
Na ₂ O	2.11		
Volatiles(LOI)	1.86		
Rb	1		
Sr	113		
Y	4		
Zr	65		
Ba	157		

Table 6. Chemical analyses of Unit G. The major elements are in wt%, and trace elements are in ppm. The values are based on four samples.

* Based on C-11a, the only sample with Rb and Y above detection limits.

DISCUSSION

The petrographic and chemical differences between Units A and B are not sufficient to conclude that these units are the result of two different magma bodies. The heterogeneity of many granitic bodies, particularly those of the eastern Piedmont, is great enough to suggest that these two units may be the result of internal variations within a single intrusion. However, the petrographically distinct nature of Unit C suggests that it is the result of crystallization of a magma body separate from that which produced Units A and B.

Differences in the degree of cataclasis and neomineralization-recrystallization has had a great effect on the development of textural differences between Units A and B and the intraunit textural variations of Unit B. Evidence for neomineralization-recrystallization of differing degrees is particularly evident throughout Unit B.

The Hollister mylonite zone can be traced through the study area and is attributed to extreme attenuation in the limb area of a fold (Farrar and others, 1981). Hatcher and others (1977) described the extent of many faults in the eastern Piedmont and concluded that the eastern Piedmont fault system is most likely a set of faults initiated by attenuation of ductile material along the limbs of major folds. The inconsistency in the intensity of shearing throughout the body might be explained by the fact that rocks of different mineral compositions will take up the shear strain differentially during folding. Due to the layered structure of the micas, these minerals tend to easily deform cataclastically. Higgins (1971) constructed a "cataclastic reaction series" where micas, quartz, feldspars, and garnets are increasingly

more resistant to shear stress. The reverse order gives the increasing tendency of these minerals to form porphyroblasts. Based on this concept, rocks with greater mica contents have probably been more intensely sheared, and rocks with lesser mica contents and greater feldspar contents have probably undergone less shearing and more recrystallization. This process produces a variation in grain size and a conspicuous variation in the prominence of foliation (fluxion structure).

The effects of cataclasis and neomineralization-recrystallization dominate the texture of Unit D and obscure all original texture. Based on the composition of Unit D and its location between the pelitic country rocks to the west and the granitic rocks of the study area (Fig. 2), this unit could be interpreted as older country rock associated with the Raleigh belt, or as an intrusive rock associated with the Lake Gaston granites. If the unit was part of the Raleigh belt, the composition indicates that the protolith was an arkosic sandstone or a rhyolite. An association with the Raleigh belt rocks is suggested by the migmatitic appearance of Unit D in some outcrops (Plate 7). This migmatitic appearance is an unlikely result of the greenschist facies metamorphic event experienced by the Lake Gaston granites. It would most likely be a result of a more complex metamorphic history as experienced by the Raleigh belt.

There is some evidence to suggest that Unit D is younger than Unit C. Plate 6 is a photograph of the contact between Units C and D. The protrusion of a megacryst of Unit C into Unit D suggests that Unit D intruded Unit C. The foliation of Unit D clearly wraps around the protruding megacryst indicating that the developing texture of Unit D conformed to the edges of the megacryst. If Unit D did intrude Unit C,

it was probably associated with the same igneous activity which produced the other granites of the study area.

An aplitic dike origin has been suggested by Spruill (personal commun., 1981). The low Ca/Y ratio and somewhat high Y content suggest that Unit D is highly differentiated. However, it is exposed over a large area indicating that it was a large tabular body with a thickness approaching one kilometer. The absence of pneumatolytic minerals and the large areal extent of Unit D make the aplite interpretation less likely.

Protoclastic deformation of a granitic intrusion could also produce the textural and compositional characteristics of Unit D. Cataclastic deformation in Unit D was more intense than in the other units, an observation which is contradictory to the assumption that the more micaceous rocks would be more highly sheared. The average mica content of Unit D is only 2.6%. Rocks from this study with up to seven times more mica show less evidence of shearing than do the samples of Unit D. This anomaly suggests that Unit D was exceptionally ductile during cataclasis. Shearing of Unit D while it was only partially crystallized could have reduced grain size by crushing and by enhancing nucleation sites.

The isolated blocks of muscovite schists of Unit E are interpreted as xenolithic blocks derived from the Raleigh belt schists to the west of the study area. Stoddard and McDaniels (1979) have suggested that the country rock schist has undergone two episodes of regional prograde metamorphism based partly on zoning in garnets. The isolated blocks of schist in the study area are characterized by the same high grade of metamorphism of the Raleigh belt schists. Chlorite in the isolated

schist blocks cuts the schistosity, indicating either retrograde metamorphism or a later episode of metamorphism under late greenschist facies conditions. Due to the high mica content of these blocks, they probably would have taken up a great deal of the shearing strain, and therefore, their elongate shapes may be due to cataclasis.

AGES OF THE LAKE GASTON GRANITES
AND THE BUTTERWOOD CREEK PLUTON

The absolute ages of the Lake Gaston granites are not known. The Rb/Sr whole rock date (292 ± 30 my) of Farrar and others (1981) for the Butterwood Creek pluton utilized samples from the Brinkleyville-Aurelia Springs area (immediately south of the study area) and samples from a drill core in the vicinity of Littleton (Farrar, 1980, personal commun.). The samples from the Brinkleyville-Aurelia Springs area are described as undeformed hornblende granite. Rocks of this composition were not found in the study area. The Littleton core material is of the same lithology as Unit C of this study.

The geographic proximity and the close chemical affinities of the Lake Gaston granites to the Butterwood Creek pluton and other Hercynian granites of the Piedmont is supportive but not conclusive evidence of a Hercynian age for the Lake Gaston granites. Therefore, radiometric age dating is suggested for future investigation of the Littleton and Thelma area.

Farrar and others (1981) document the age of the ductile deformation along the Hollister mylonite zone to be post-290 my. It is possible that the Lake Gaston granites and Unit C were emplaced prior to the deformation, and that the undeformed phase of the Butterwood Creek pluton was emplaced after the deformation. If the protoclastic interpretation of Unit D is correct, the time of emplacement would post-date the Lake Gaston granites and Unit C, pre-date the undeformed hornblende granite, and therefore accurately date the age of mechanical deformation in the Hollister mylonite zone.

CONCLUSIONS

- 1) The Lake Gaston granites (Units A and B) possess chemical similarities with the porphyritic, biotite-bearing granite of the Butterwood Creek pluton (Unit C). This similarity is especially evident in Units A and C.
- 2) Units A, B, and C are similar in major and trace element chemistry to Hercynian granites of the Piedmont.
- 3) Units A and C possess chemical characteristics that more closely resemble the western Hercynian granites, and Unit B more closely resembles the eastern Hercynian granites.
- 4) Units A, B, and C are believed to be related in origin and time of emplacement.
- 5) Cataclasis has affected all of the pre-Mesozoic rock units in the Littleton and Thelma area.
- 6) Greenschist facies metamorphism probably accompanied the cataclasis, giving rise to the bulbous myrmekite, perthite, chlorite, epidote, and the magnetite-sphene association found throughout the granitic rock units.
- 7) The isolated blocks (Unit E) within the granites are interpreted as xenolithic blocks derived from the Raleigh belt schists to the west of the study area.

8) The diabases of Unit G have alkalic affinities based on their major element chemistry; however, their trace element chemistry resembles that of continental rift tholeiitic basalts.

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APPENDIX I

Modal Percentages of Rock Samples. Acc Equals
Less Than One Percent

<u>Sample</u>	<u>K-spar</u>	<u>Qtz</u>	<u>Bio</u>	<u>Musc</u>	<u>Oligo</u>	<u>Op</u>	<u>Ch</u>	<u>Ep</u>	<u>Sp</u>	<u>Ap</u>	<u>Zir</u>
UNIT A - subunit A ₁											
C-A	34	27	13	acc	24	acc	acc	acc	acc	acc	acc
C-20	25	23	13	acc	36	1	acc	acc	acc	1	acc
C-21	30	25	15	1	27	1	acc	acc	1	1	acc
C-22	30	20	11	1	35	acc	1	acc	acc	2	acc
C-23	35	20	12	acc	30	acc	1	acc	1	1	acc
C-24	24	24	13	acc	36	1	acc	acc	acc	2	acc
C-29	28	28	12	acc	30	1	acc	acc	acc	1	acc
subunit A ₂											
C-C	30	36	7	acc	25	1	acc	acc	1	1	acc
C-19	31	29	9	1	29	1	acc	acc	1	acc	acc
117-2	29	34	12	1	24	1	acc	acc	acc	acc	acc
UNIT B											
C-E	34	32	1	2	30	acc	acc	acc	acc	acc	acc
C-11	34	27	5	3	31	acc	acc	acc	acc	acc	acc
C-13	30	36	7	2	25	acc	acc	acc	acc	acc	acc
2-1	20	29	9	2	40	acc	acc	acc	acc	acc	acc
12-1	12	27	7	acc	55	acc	acc	acc	acc	acc	acc
15-1	28	27	4	acc	40	acc	acc	acc	acc	acc	acc
15-2	27	23	7	acc	44	1	acc	acc	acc	acc	acc
17-1	29	11	9	acc	51	acc	acc	acc	acc	acc	acc
20-2	22	30	7	2	40	acc	acc	acc	acc	acc	acc
20-3	28	26	9	2	36	acc	acc	acc	acc	acc	acc
20-4	24	30	7	1	39	acc	acc	acc	acc	acc	acc
21-9	31	37	4	2	27	1	acc	acc	acc	acc	acc
22-2	45	36	3	acc	16	1	acc	acc	acc	acc	acc
22-4	29	29	6	1	36	acc	acc	acc	acc	acc	acc
29-1	22	32	9	acc	37	1	acc	acc	acc	acc	acc
31-3	28	38	6	1	28	acc	acc	acc	acc	acc	acc
32-1	18	40	9	1	33	acc	acc	acc	acc	acc	acc
35-14	26	43	acc	1	29	2	acc	acc	acc	acc	acc
45-2	51	23	2	1	24	1	acc	acc	acc	acc	acc
63-10	46	25	5	4	21	acc	acc	acc	acc	acc	acc
64-1	23	25	17	2	39	acc	acc	acc	acc	acc	acc
66-3	43	26	2	acc	29	acc	acc	acc	acc	acc	acc
71-1	26	29	12	4	30	acc	acc	acc	acc	acc	acc
73-1	33	29	5	5	27	acc	acc	acc	acc	acc	acc
76-1	34	31	2	9	25	acc	acc	acc	acc	acc	acc
83-2	44	30	2	acc	24	acc	acc	acc	acc	acc	acc
89-2	30	33	5	3	30	acc	acc	acc	acc	acc	acc
95-1	39	35	5	1	20	1	acc	acc	acc	acc	acc
97-1	24	39	1	1	35	acc	acc	acc	acc	acc	acc

APPENDIX I (continued)

<u>Sample</u>	<u>K-spar</u>	<u>Qtz</u>	<u>Bio</u>	<u>Musc</u>	<u>Oligo</u>	<u>Op</u>	<u>Ch</u>	<u>Ep</u>	<u>Sp</u>	<u>Ap</u>	<u>Zir</u>
105-5	25	28	21	2	23	1	acc	1	1	acc	acc
111-2	20	32	6	2	40	acc	acc	acc	acc	acc	acc
112-1	37	33	4	3	25	acc	acc	acc	acc	acc	acc
120-1	21	29	8	1	42	acc	acc	acc	acc	acc	acc
126-1	22	33	4	1	41	acc	acc	acc	acc	acc	acc

UNIT C

27-1	29	29	21	1	21	1	acc	acc	acc	acc	acc
33-1	33	29	15	acc	24	acc	acc	acc	acc	acc	acc
33-4	45	28	6	acc	23	acc	acc	acc	acc	acc	acc
35-2	26	33	12	1	26	acc	1	acc	2	acc	acc
84-1	44	24	9	1	23	acc	acc	acc	acc	acc	acc

UNIT D

35-4	50	32	1	2	15	1	acc	---	acc	acc	acc
39-3	55	28	3	acc	14	1	acc	---	acc	acc	acc
39-6	55	26	acc	acc	17	2	acc	---	acc	acc	acc
80-1	44	42	1	3	10	1	acc	---	acc	acc	acc

<u>Sample</u>	<u>Labradorite</u>	<u>Olivine</u>	<u>Augite</u>	<u>Chlorite</u>	<u>Opaque</u>
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UNIT G

7-1	48	5	42	4	3
8-1	62	18	19	acc	2
29-2	51	1	44	1	3
70-5	55	17	26	1	1

APPENDIX II

A. Chemical Analyses of the Geochemical Samples

UNIT A - subunit A₁

	<u>C-A</u>	<u>C-20</u>	<u>C-21</u>	<u>C-22</u>	<u>C-23</u>	<u>C-25</u>	<u>C-29</u>
SiO ₂	63.21	64.85	65.25	65.80	64.87	64.06	63.78
Al ₂ O ₃	14.44	15.08	14.94	15.10	15.30	14.97	14.85
TiO ₂	0.76	0.77	0.81	0.73	0.81	0.94	0.84
Fe ₂ O ₃ ^T	3.79	3.65	3.68	3.42	3.77	4.34	3.94
MgO	0.70	0.66	0.56	0.65	0.68	0.91	0.69
MnO	0.05	0.06	0.05	0.05	0.05	0.10	0.05
CaO	2.19	1.43	2.11	2.25	2.28	2.59	2.14
K ₂ O	4.86	4.83	5.47	5.13	5.10	3.94	5.13
Na ₂ O	3.83	4.06	3.43	3.80	3.82	4.12	3.81
Volatiles	0.47	0.33	0.38	0.55	0.63	0.51	0.43
Rb	164	188	183	168	181	214	190
Sr	925	743	793	833	959	809	949
Y	38	33	36	33	35	40	37
Zr	396	356	425	376	438	345	402
Ba	1529	1395	1606	1533	1673	1333	1600

Major elements and Volatiles(LOI) in Weight Percent (wt%).

Trace elements in Parts per Million (ppm).

APPENDIX II (continued)

	UNIT A - subunit A ₂ /				UNIT B			
	<u>C-19</u>	<u>C-C</u>	<u>117-2/</u>	<u>C-E</u>	<u>C-11</u>	<u>C-13</u>	<u>22-2</u>	<u>73-1</u>
SiO ₂	66.56	66.63	65.52	70.60	72.21	71.90	72.47	67.57
Al ₂ O ₃	15.15	15.00	15.79	14.93	15.14	14.78	15.82	16.40
TiO ₂	0.46	0.50	0.50	0.28	0.25	0.33	0.07	0.25
Fe ₂ O ₃ ^T	2.33	2.54	2.48	1.39	1.24	1.98	0.05	1.83
MgO	0.51	0.48	0.47	0.45	0.46	0.47	0.45	0.45
MnO	0.03	0.04	0.03	0.02	0.04	0.05	0.01	0.05
CaO	1.72	1.64	1.57	1.28	1.74	1.79	1.04	1.07
K ₂ O	5.00	5.19	4.88	4.77	4.97	4.50	7.68	5.61
Na ₂ O	4.25	3.90	3.87	4.17	3.59	3.46	1.93	3.18
Volatiles	0.36	0.29	0.60	0.45	0.36	0.38	0.72	1.12
Rb	166	152	177	157	193	199	187	282
Sr	587	529	548	474	244	202	222	154
Y	18	13	19	8	3	8	---	13
Zr	307	274	308	177	155	199	64	156
Ba	1397	1300	1261	1100	706	717	1096	562

Major elements and Volatiles(LOI) in Weight Percent (wt%).

Trace elements in Parts per Million (ppm).

APPENDIX II (continued)

	UNIT B (cont.)						
	<u>76-1</u>	<u>83-2</u>	<u>97-1</u>	<u>105-3</u>	<u>110-1</u>	<u>112-1</u>	<u>126-1</u>
SiO ₂	63.72	69.90	68.19	73.29	69.80	67.79	62.49
Al ₂ O ₃	20.95	16.06	17.77	15.88	17.56	17.32	20.65
TiO ₂	0.24	0.03	0.09	0.24	0.08	0.24	0.30
Fe ₂ O ₃ ^T	1.74	---	0.25	1.05	0.46	1.16	1.09
MgO	0.45	0.46	0.45	0.45	0.45	0.45	0.45
MnO	0.04	0.04	0.02	0.02	0.03	0.03	0.03
CaO	0.15	0.52	1.18	0.84	0.27	1.05	1.19
K ₂ O	6.46	5.04	3.17	5.63	4.93	5.72	3.69
Na ₂ O	1.15	4.02	4.17	2.77	3.59	2.50	3.41
Volatiles	2.19	1.00	1.10	1.36	1.43	1.74	3.90
Rb	292	525	225	207	236	145	123
Sr	61	58	247	140	21	486	441
Y	4	---	50	8	---	4	---
Zr	118	58	191	152	16	140	136
Ba	733	247	340	573	225	1232	1154

Major elements and Volatiles(LOI) in Weight Percent (wt%).

Trace elements in Parts per Million (ppm).

APPENDIX II (continued)

	UNIT C			UNIT D		
	<u>27-1</u>	<u>75-1</u>	<u>84-1</u>	<u>35-1</u>	<u>39-6</u>	<u>80-1</u>
SiO ₂	64.08	68.61	64.10	71.75	72.67	73.74
Al ₂ O ₃	15.92	15.39	15.00	15.95	14.74	16.29
TiO ₂	0.67	0.51	0.71	0.33	0.29	0.27
Fe ₂ O ₃ ^T	3.81	3.85	3.86	1.96	1.79	0.91
MgO	0.73	0.66	0.69	0.45	0.46	0.46
MnO	0.06	0.09	0.09	0.01	0.02	0.04
CaO	2.15	2.56	2.28	0.03	0.44	0.67
K ₂ O	5.61	3.23	4.95	8.83	7.35	7.03
Na ₂ O	3.57	3.96	3.42	0.68	2.54	1.39
Volatiles	0.73	0.95	0.71	1.42	0.43	1.16
Rb	163	190	189	209	165	252
Sr	454	240	442	61	65	144
Y	24	27	25	45	27	42
Zr	243	164	293	312	290	263
Ba	1336	632	1135	1301	1292	920

Major elements and Volatiles(LOI) in Weight Percent (wt%).

Trace elements in Parts per Million (ppm).

APPENDIX II (continued)

	UNIT G			
	<u>8-1</u>	<u>29-2</u>	<u>70-5</u>	<u>C-11a</u>
SiO ₂	44.23	44.60	44.91	44.82
Al ₂ O ₃	14.65	15.26	14.47	12.31
TiO ₃	0.51	0.41	0.58	1.15
Fe ₂ O ₃ ^T	15.81	13.97	13.83	14.32
MgO	11.24	11.16	12.33	9.75
MnO	0.24	0.18	0.05	0.20
CaO	10.47	10.41	10.23	10.12
K ₂ O	0.18	0.14	0.25	0.33
Na ₂ O	2.37	2.00	1.93	2.14
Volatiles	1.74	0.95	0.92	3.69
Rb	----	----	----	2
Sr	98	108	84	163
Y	----	----	----	16
Zr	38	38	76	106
Ba	157	98	182	191

Major elements and Volatiles(LOI) in Weight Percent (wt%).

Trace elements in Parts per Million (ppm).

APPENDIX II (continued)

B. XRF Instrument Settings

	<u>Tube</u>	<u>Detector</u>	<u>Xtall</u>	<u>2θ</u>	<u>Vacuum</u>	<u>HV</u>	<u>mA</u>	<u>KV</u>
SiO ₂	Cr	Gas Prop.	PET	108.70	Yes	173x1	20	45
Al ₂ O ₃	Cr	Gas Prop.	PET	144.80	Yes	173x1	20	45
TiO ₂	Cr	Gas Prop.	200 LiF	86.35	Yes	165x1	15	45
Fe ₂ O ₃ ^T	W	Gas Prop.	200 LiF	57.65	No	140x16	5	45
MnO	W	Gas Prop.	200 LiF	63.10	Yes	163x1	20	45
CaO low conc.	Cr	Gas Prop.	200 LiF	113.25	Yes	168x1	3	45
CaO high conc.	Cr	Gas Prop.	200 LiF	113.25	Yes	168x1	1.5	45

	<u>Tube</u>	<u>Detector</u>	<u>Xtall</u>	<u>2θ</u>	<u>Vacuum</u>	<u>Gas HV</u>	<u>Scint. HV</u>	<u>mA</u>	<u>KV</u>
Rb	Mo	Gas & Scint.	220 LiF	38.00	No	125x16	65x16	40	45
Sr	Mo	Gas & Scint.	220 LiF	35.85	No	125x16	65x16	40	45
Y	Mo	Gas & Scint.	220 LiF	33.90	No	125x16	65x16	40	45
Zr	Mo	Gas & Scint.	220 LiF	32.10	No	125x16	65x16	40	45
Ba	Mo	Gas & Scint.	220 LiF	115.40	Yes	138x16	78x16	46	45

APPENDIX II (continued)

C. AA Instrument Settings

	<u>Vis</u>	<u>Slit</u>	<u>Source Current</u>
MgO	286.6	4	10
Na ₂ O	295.3	4	8

D. Precision and Accuracy Values of
Geochemical Analyses

ANALYSES	PRECISION		ACCURACY		CORRELATION COEFFICIENT OF CALIBRATION CURVE
	Diff. in wt % or ppm	% Diff	Diff. in wt % or ppm	% Diff	
SiO ₂	0.09*	0.2**	1.24	2.4	0.983
Al ₂ O ₃	0.08	0.8	0.50	3.4	0.991
TiO ₂	<0.01	0.8	0.20	14.5	0.997
Fe ₂ O ₃	0.04	0.4	0.43	6.5	0.994
MgO	0.08	1.9	0.62	21.6	0.983
MnO	0.09	31.3	<0.01	4.5	0.995
CaO low conc.	0.01	0.8	0.04	5.2	0.999
CaO high conc.	0.03	0.3	0.06	6.5	0.999
K ₂ O	0.04	0.8	0.10	3.2	0.999
Na ₂ O	0.09	2.9	0.39	13.7	0.941
Rb	14	8.9	9	9.6	0.997
Sr	8	5.6	16	11.2	0.998
Y	5	27.7	11.8	32.8	0.952
Zr	10	8.7	25.5	13.7	0.967
Ba	43	8.1	50	9.4	0.996

APPENDIX II (continued)

- Precision - All standards and 20% of the rock samples were analyzed twice. Differences in wt % = the average difference in wt % between the first run and the second run.
- % Difference = the average percent difference between the first run and the second run of those which were run twice.
- Accuracy - Difference in wt % = the average wt % differences between the literature concentration values of the standards used and the concentration values determined from the calibration curves used in the analyses.
- % Difference = the average percent differences between the literature concentration values of the standards used and the concentration values determined from the calibration curves used in the analyses.
- * Average wt % difference between 18 successive runs and the average of these 18 successive runs attained from AGV-1 (Average for the successive runs equals 58.59 wt%).
- ** Average percent of 58.59 of which the successive runs differed from the average of the successive runs.



Plate 1. Hand specimens of subunit A₁.

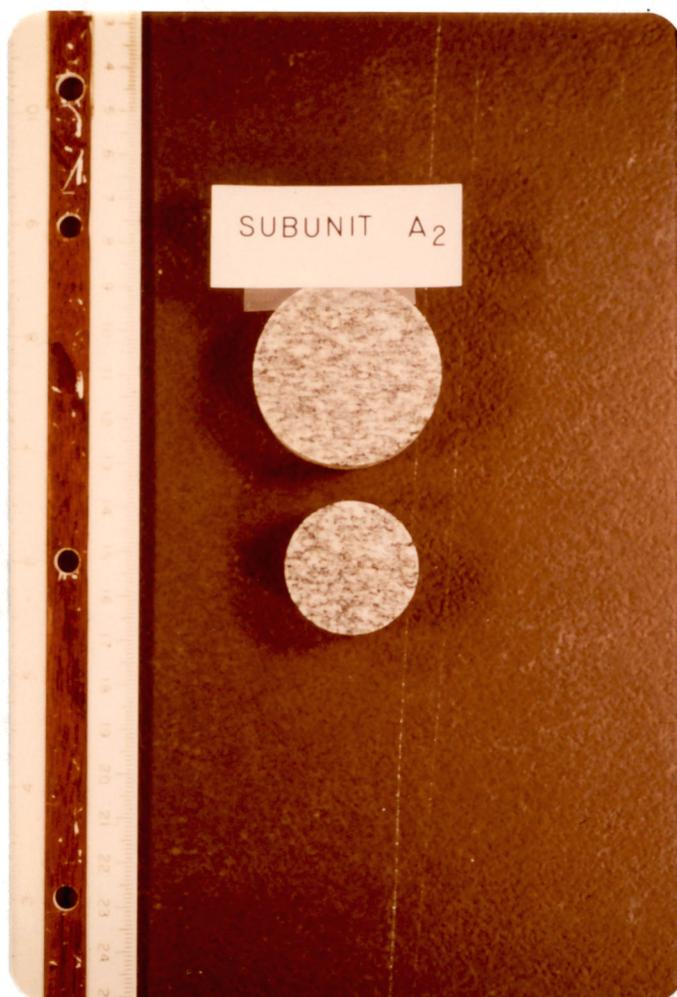


Plate 2. Hand specimens of subunit A₂.

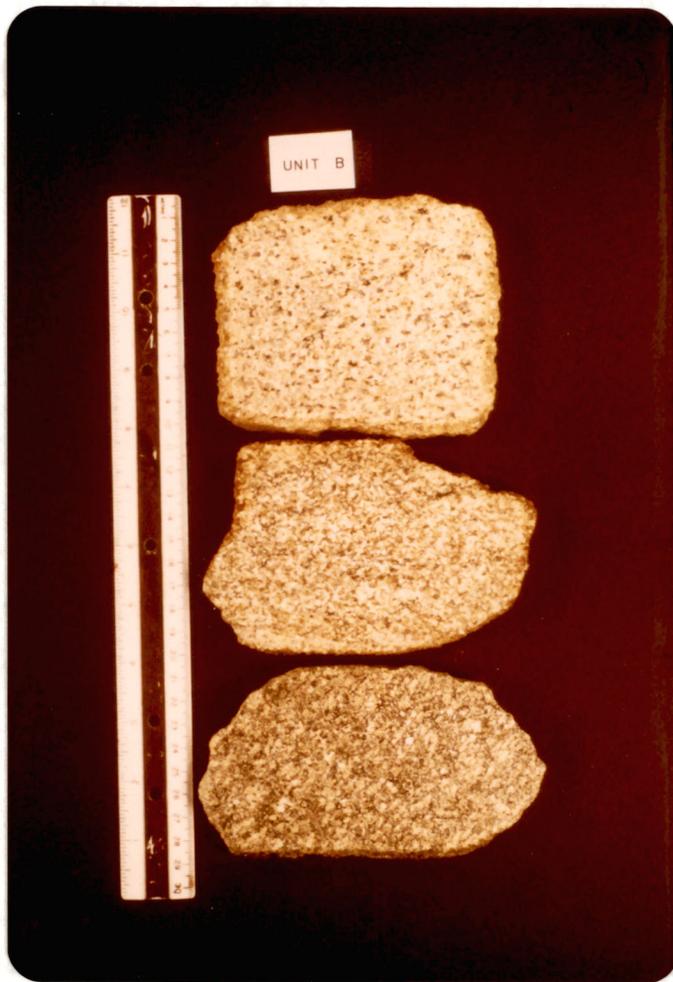
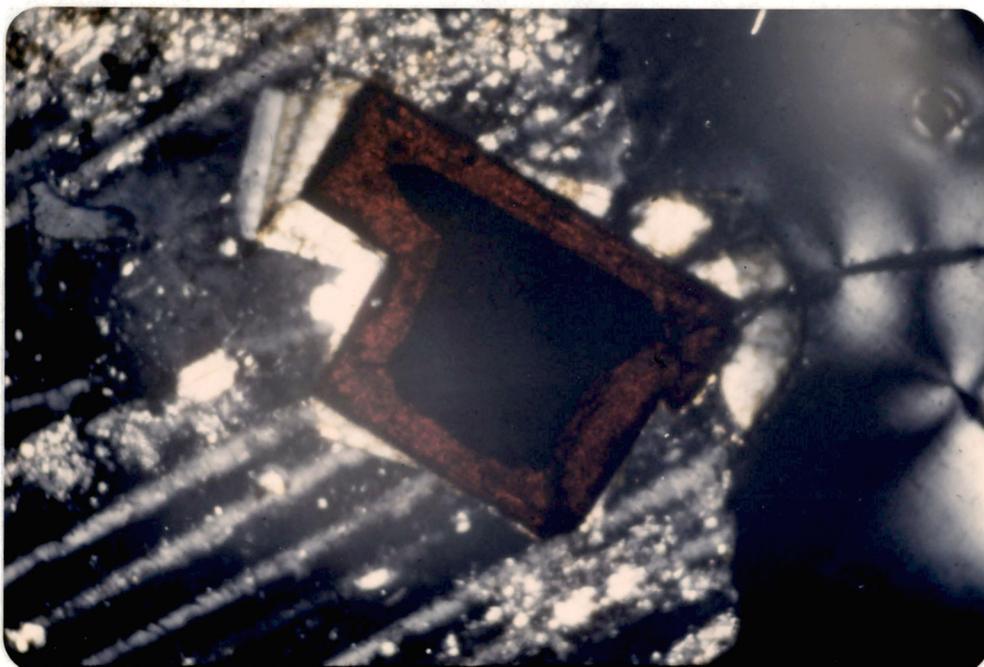


Plate 3. Hand specimens of Unit B.



Plate 4. Hand specimens of Unit C. Sample on the left (75-1) has been deformed by cataclasis to a much greater degree than other Unit C samples.



1 mm

Plate 5. Pressure fringe within Unit C. The more rigid pyrite (?) grain is an inclusion of oligoclase.



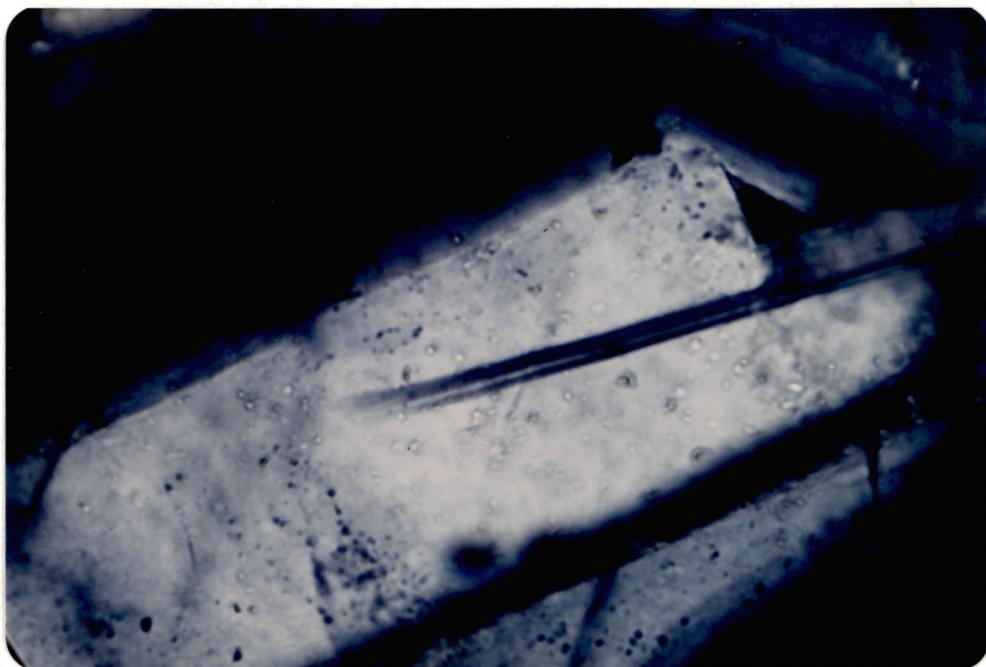
Plate 6. Hand specimens of Unit D.



Plate 7. Unit D outcrop. Note the migmatitic appearance.



Plate 8. Folds in the contact area of Units B and F.



0.2 mm

Plate 9. Plagioclase grains in Unit G. Note the thin projections at the terminal end of the smaller lath.



Plate 10. Schlieren in Unit B.