# GEOLOGY OF THE LATE PRECAMBRIAN FLAT RIVER COMPLEX AND ASSOCIATED VOLCANIC ROCKS NEAR DURHAM, NORTH CAROLINA

by

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ABSTRACT

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The author wishes to thank Dr. Lynn Glover III, who originally suggested the project, for many thought provoking discussions and constructive criticisms of this study. Special thanks go to Dr. A. K. Sinha for assistance in geochronology, and to Dr. M. C. Gilbert who with assembled the experimental data shown in Figure 10, and assisted in its interpretation.

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# INTRODUCTION

Previous investigations of intrusive complexes in the southeastern Piedmont of the Appalachians have emphasized the petrochemical aspects of these bodies (Wagener, 1973; Medlin and others, 1972; Butler and Ragland, 1969; and Phillips, 1967). Because poor exposure and metamorphism impose severe restrictions on interpretation of the original igneous history of the intrusive bodies, very little is known about the possible genetic relationships between the plutons in the southeastern Piedmont and the surrounding volcanic country rock. Glover and Sinha (1973, p. 241) suggested that the Moriah pluton may have been eruptive, and this study was designed to test that hypothesis.

The Flat River complex (composed of the Moriah pluton and Butner stock) in the low grade Carolina "slate" belt of North Carolina (fig. 1) has been spared the severe deformation accompanying higher grades of metamorphism common to other belts in the Piedmont. It has been metamorphosed to lower greenschist facies, nevertheless it retained much of its original igneous texture. Recent studies of shallow level plutons in the Cascades of Washington (Cater, 1969; Fiske, Hopson, and Waters, 1963; and Tabor and Crowder, 1969), which are unmetamorphosed and better exposed than the Flat River complex, have described the relationships between these plutons and the surrounding volcanic material. With this base of information, the well preserved textures of the Flat River complex provide an excellent opportunity for a similar study in the southern Appalachian Piedmont. Additionally, in

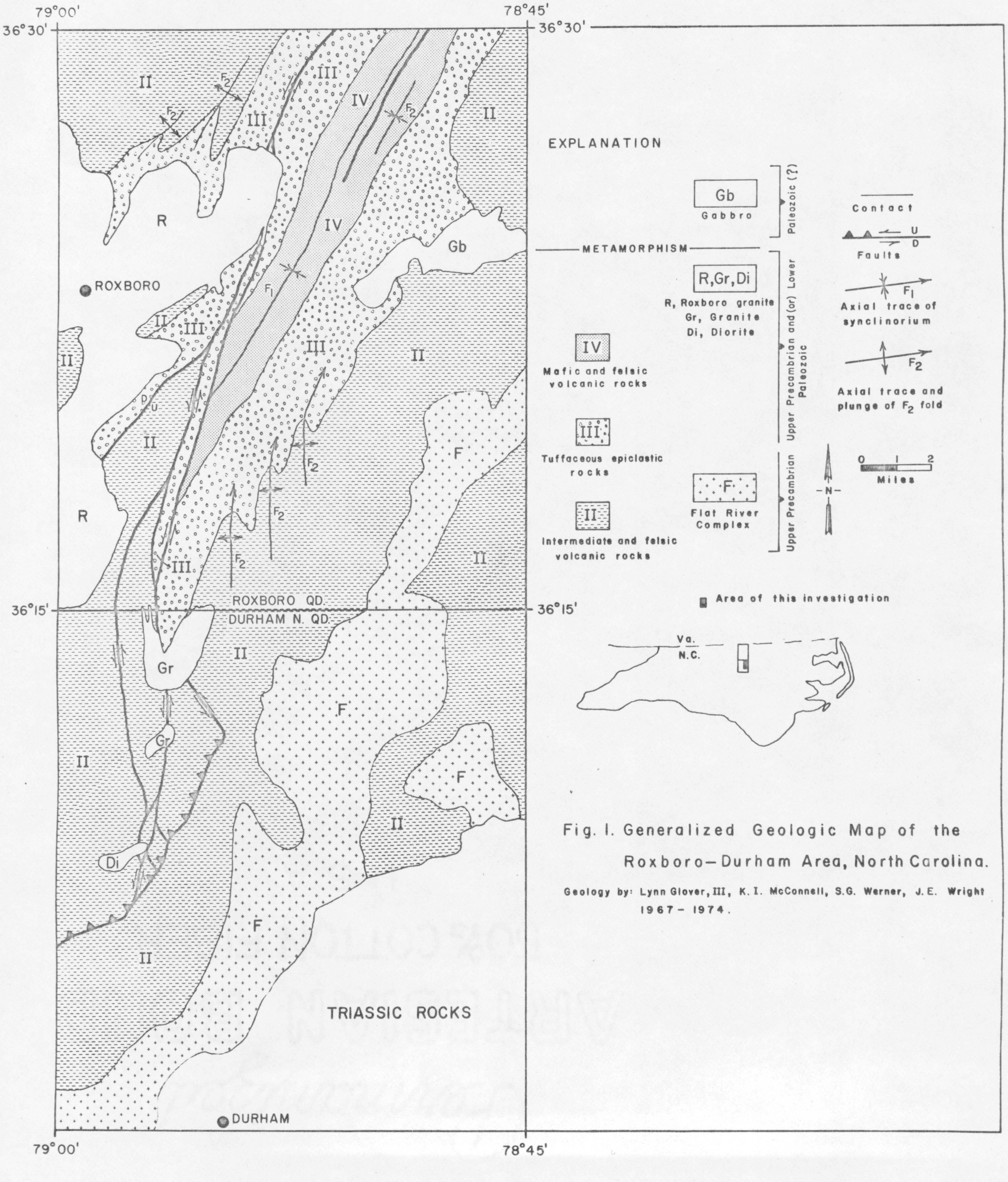

Fig. I. Generalized Geologic Map of the Roxboro–Durham Area, North Carolina.

Geology by: Lynn Glover, III, K. I. McConnell, S.G. Werner, J.E. Wright 1967 - 1974.

this investigation, the techniques of U-Pb isotope studies of zircons provided geochronologic control in relating the intrusive bodies to the volcanic sequence.

# TERMINOLOGY AND METHODS

The igneous classification used in this report is shown in figure 2. Johannsen's classification was used rather than the newer I.U.G.S. (1973) classification in order to allow direct comparison between the intrusive rocks described in this report and the literature of other plutons in the southeastern and western United States. Figure 3 represents modal data from this study classified in the I.U.G.S. system.

Textural nomenclature of igneous rocks follows that given by Williams, Turner, and Gilbert (1954). However, the importance of granophyric texture in this study made it necessary to differentiate between varieties of quartz-feldspar intergrowths. In this report, granophyric texture refers to irregular intergrowths of quartz and potassium-rich feldspar. Two methods of formation of these granophyric intergrowths have been observed: 1) intergrowths resulting from replacement of other minerals preceeding and (or) after the end of crystallization, and 2) intergrowths resulting from the simultaneous crystallization of quartz and potassium-rich feldspar. Both types are described in detail in a later section. However, when the general term "granophyric intergrowths" or "granophyre" are used, it denotes that these intergrowths are believed to result from simultaneous crystallization.

Broad compositional classification of volcanic rocks into mafic, intermediate, and felsic was based on the metamorphic mineralogy, specifically, the relative abundance of chlorite, actinolite and epidote.

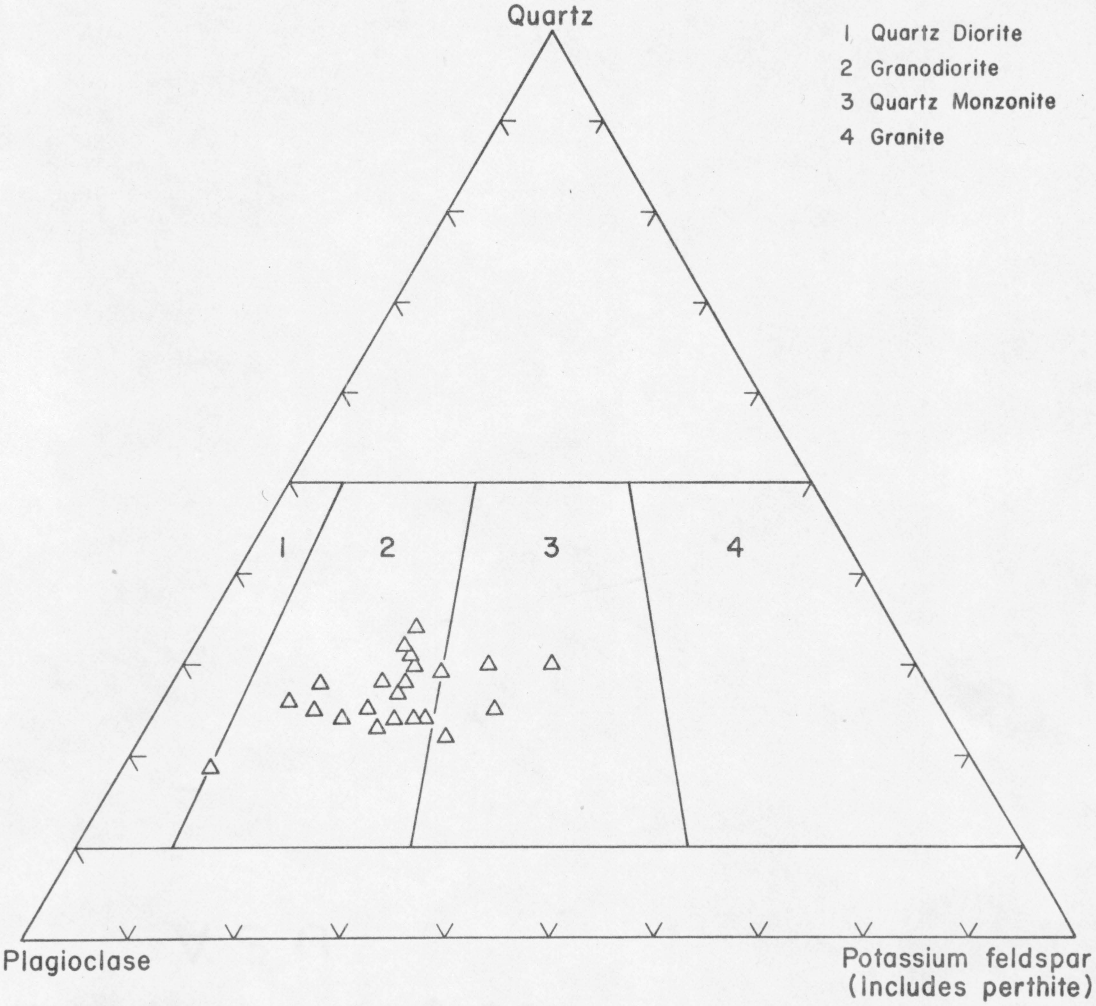

FIGURE 2. GRAPHIC REPRESENTATION OF MODES FROM INTRUSIVE ROCKS OF THE FLAT RIVER COMPLEX. (DIAGRAM MODIFIED AFTER JOHANNSEN, 1931).

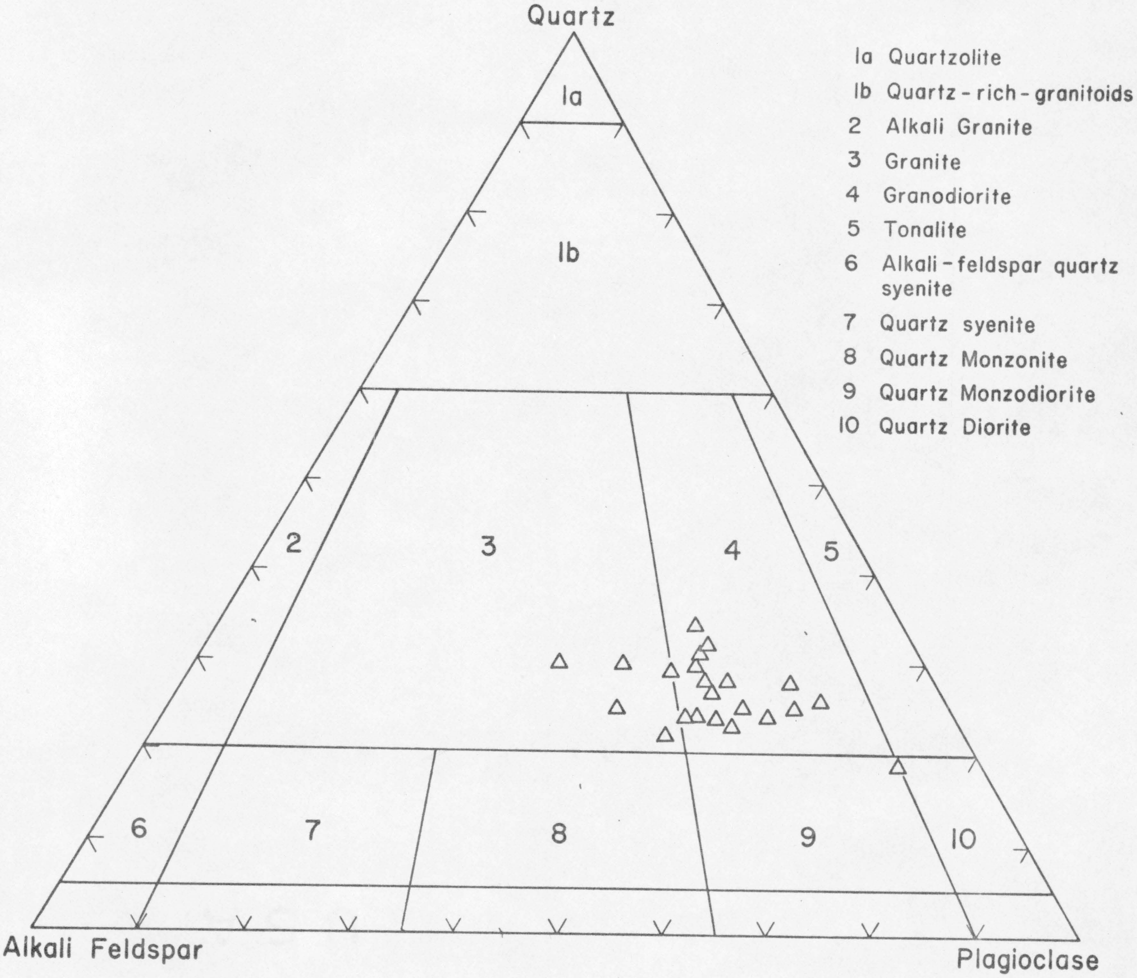

FIGURE 3. GRAPHIC REPRESENTATION OF MODES FROM INTRUSIVE ROCKS OF THE FLAT RIVER COMPLEX. (DIAGRAM AFTER I.U.G.S. SUB-COMMISSION ON THE SYSTEMATICS OF IGNEOUS ROCKS, 1973).

Textural terminology used to describe pyroclastic rocks was based on the report of Fisher (1966). Figure 4 is a diagramatic representation of this classification.

## Thin Section Methods

Systematic sampling of the rock types in the study area was partially precluded by poor exposure. However, representative samples of both the volcanic members and intrusive bodies were collected. Thin sections of these rocks were stained according to methods prescribed by Bailey and Stevens (1960) with one exception. The final wash after the amaranth solution was applied to the slide was performed with alcohol rather than water. This was done to prevent the amaranth from dissolving.

Thirty-eight thin sections from the intrusive rocks were examined. Of these, twenty-four were point counted to determine modes. The rocks were point counted so as to approximate the original mineralogy rather than the present mineralogy. In this method, epidote and white mica were counted as plagioclase when it could be discerned that they were alteration products of plagioclase. Also, since all plagioclase now has an anorthite content of less than $An_5$ as a result of metamorphism, any mineral that could be identified as plagioclase was counted as plagioclase. Five hundred counts were taken on each slide at 1 mm x 1 mm intervals. To approximate the mineralogy of the last liquid to crystallize, point counts were also made of the granophyric groundmass of six samples. In each slide, four different areas of granophyric intergrowths were counted at intervals of .5 mm x .5 mm for 50 counts.

FIGURE 4. MIXTURE TERMS AND END-MEMBER TERMS USED FOR PYROCLASTIC FRAGMENTS (FISHER, 1966)

Several thin sections from each volcanic member were examined for mineralogy and texture, but a binocular microscope examination of rock slabs produced the best results.

### Electron Microprobe Methods

Electron microprobe analysis of feldspar compositions of three samples from the intrusive rocks of the Flat River complex was performed by David Briggs.

Plagioclase phenocrysts, plagioclase grains in the groundmass and in one slide, a perthitic grain were analyzed for Na, Ca, and K. Aluminum and silicon were added stoichiometrically in proper proportions. Analyses were performed on an ARL electron microprobe and data were reduced by use of the EMPAR VII program of Rucklidge and Gasparrini (1969). A more detailed discussion of the procedures used can be obtained from Briggs (1974).

### Isotopic Dating Methods

Isotopic analysis for uranium and lead was performed on zircons separated from three samples of the intrusive phases within the Flat River complex. Approximately 75 lb. of each sample was crushed and processed through the standard Wilfley table, magnetic separator, and heavy liquid separation processes. All samples were acid washed twice, before and after handpicking, for thirty minutes in 7N nitric acid. This rendered the zircon concentrate >99 percent pure.

One sample was split into non-magnetic and magnetic concentrates and both the splits and the combination were analyzed. Zircons in samples K-39 and K-40 are uniformly small (<1 mm), well faceted, commonly have overgrowths and opaque inclusions. Sample LGO-43 has a somewhat more diverse zircon population with some zircons >1 mm. Zircons in this sample are also well faceted and have overgrowths.

Zircons from each sample were then dissolved and processed through ion exchange columns in accordance with procedures described by Krogh (1972). Lead concentrate was loaded onto a rhenium filament by the silica gel-phosphoric acid method of Cameron and others (1969). Uranium concentrate was loaded onto a rhenium filament by the titanium oxide-phosphoric acid method of Krogh (1972). Analysis for lead and uranium was performed on a 34 cm solid-source Avco mass spectrometer with an in line PDP-11 minicomputer in the Isotope Geology Laboratory of Virginia Polytechnic Institute and State University.

# STRATIGRAPHY

## General Statement

Volcanic rocks exposed in the northeast quadrant of the Durham North quadrangle probably represent the lower part (unit II) of the Carolina "slate" belt volcanic sequence as described by Glover and Sinha (1973) in the adjacent Roxboro quadrangle (fig. 1). East of the Flat River complex (fig. 5), these rocks are herein divided on the basis of sedimentary structure and texture into three members: X, Y, and Z. Unit $A_1$ (Wright, 1974) west of the Flat River complex cannot be directly related to units on the east. In the area of figure 5, unit $A_1$ has been mapped only in reconnaissance.

The lack of sedimentary structural data and exposed sedimentary contact relations in member Z precludes the possibility of defining the succession of stratigraphic units in the study area. However, sedimentary structural data found in member Y and exposed contact relations between members Y and X suggest an interpretation of these relations.

The present structural data and contact relations suggest that units Y and X form a homoclinal structure dipping to the southeast and may represent the southeastern limb of an anticlinorium adjacent to the Virgilina synclinorium (Glover and Sinha, 1973) to the northwest. In the Oxford area, to the northeast, Hadley (1973) shows a regional anticlinorium that can be extended into the study area. However, members X and Y seem to have a somewhat more easterly trend than volcanic rock units to the west and north (fig. 1) which may indicate that they have been rotated during the intrusion of the Moriah pluton. A possible fault contact relation between members Z and Y, discussed in a later section, prohibits relating structure found in member Y to member Z.

The stratigraphic sequence also includes post-metamorphic rocks of Triassic age. These occur in a basin part of which is shown in fig. 5.

## Member Z

Member Z is a thick sequence of predominantly felsic pyroclastic rocks that lies along the eastern border of the Moriah pluton shown in fig. 5. Glover (Glover and Sinha, 1973) found that unit II, on the western limb of the Virgilina synclinorium, is about 4900 m (16,000 ft) thick.

At the western margin of member Z, the volcanic rocks are in contact with an almost continuous chilled margin (porphyritic dacite) of the Moriah pluton. The intrusion of the Moriah pluton into the rocks of member Z was semi-concordant. The irregularity of the contact, the presence of a chilled margin, and the lack of any erosional effects at the contact between member Z and the Moriah pluton eliminates the possibility of a nonconformity. The southern contact of member Z with member Y has not been observed in outcrop. The contact is indicated by the change from primarily coarse pyroclastic material to finely bedded and laminated tuffs. The change can be seen in float over an approximate distance of fifty feet. The abrupt change in rock type and the presence near the contact of cleavage that is not conformable with the regional trend suggest that the contact is a fault.

Member Z is dominated by vitric fragments of lapilli and ash size (Fisher, 1966) over similar lithic fragments. Large amounts of pumiceous debris also occur locally.

In the northeast part of the member, only vitric and pumiceous material were observed. Vitric fragments range in size from medium lapilli (16 mm) to fine ash (.25 mm). Lapilli fragments make up approximately 15 percent of the rock, whereas fine ash represents as much as 45 percent. Pumice fragments occur locally as partially collapsed round bubble pumice drawn out into wispy stringers. Pumice commonly makes up from 20 to 25 percent of the vitric tuffs. Rounded and broken plagioclase crystals make up 15 percent of the tuffs.

Spherulites are found in both the groundmass and lapilli size fragmental material of at least one sample from the northeast part of the member. Spherulites in the southeastern part of unit II in the Roxboro quadrangle have also been reported by Glover (Glover and Sinha, 1973).

To the southwest, member Z becomes coarser, and lithic fragments comprise as much as 20 percent of the rock. Lapilli ranging in size to as much as 45 mm and coarser ash (.25 - 2 mm) make up 45 to 50 percent of the rock and fine ash makes up 35 to 40 percent. Pumice, much less abundant in this part of member Z, occurs in a less collapsed form than that found to the northeast. Lithic fragments are predominantly fine bedded ash with some fine grained vesicular fragments present. Plagioclase crystals amount to 10 to 15 percent of the rock.

Vitric tuffs similar to those found in the northeast also occur in the southwest part of member Z. These are characterized by eutaxitic texture probably formed as a result of the complete collapse of pumice during welding (Ross and Smith, 1961). Also present in the southwestern part of the member is an outcrop of massive, round-bubble pumice along the northern border of Lake Michie. This rock type was not mapped because it could not be adequately identified in the weathered outcrops.

Mid-Paleozoic greenschist facies metamorphism (Glover and Sinha, 1973) has recrystallized these rocks, rendering them difficult to classify as andesites, dacites, etc. without chemical analyses. Quartz is common in the groundmass and in lapilli size fragments. Sodic plagioclase (determined by extinction angles) is abundant and commonly shows broken and bent twin lamellae. The plagioclase crystals have been albitized, saussaritized, and sericiticized during metamorphism. The dominant mafic mineral present is chlorite. Chlorite is usually seen as small flakes possibly in part a replacement of biotite, but is in some cases associated with magnetite and epidote as a possible replacement of amphibole or pyroxene. Chlorite commonly makes up less than 10 percent of the rocks.

Rocks containing very little primary quartz and large amounts of actinolite and chlorite are not uncommon in member Z. They are, however, subordinate to the more felsic material.

Secondary minerals present in small amounts are; calcite, white mica, epidote, pyrite and stilpnomelane (?). Primary accessory minerals present are magnetite and apatite.

Textural features found within member Z are indicative of subareal or, in part, possibly marine pyroclastic deposition. Features such as spherulites, eutaxitic texture and abundant pumice, common to this member, are characteristic of ash flow tuffs deposited subareally (Ross and Smith, 1961), while the absence of these features in parts of member Z may imply a marine environment. Volcanism contemporaneous with deposition is indicated by the presence of large pumice and angular pyroclastic fragments in member Z. It is unlikely that pumice can be eroded from a volcanic terrain and redeposited, because of its fragile nature (Fiske, 1969).

The major textural variation is from vitric to less vitric tuffs in a southwest direction. The vitric nature, the presence of spherulites in the groundmass and fragmental material, and the presence of collapsed pumice suggest that the northeast part of member Z was probably deposited subareally.

Within the southwestern part of this member, the disappearance of pumice and spherulitic structures may indicate that the environment of deposition had changed in the southwest to a subaqueous one. This change could also take place vertically in the member, but the true attitude of the member is not known and this relation could not be established. However, the parts of southwestern member Z just north of Lake Michie (fig. 5) that have eutaxitic texture and large amounts of pumiceous debris were probably deposited subareally.

## Unit $A_1$

Unit $A_1$ occurs along the western border of the Moriah pluton and has been described in detail by Wright (1974). This unit may be correlative with member Z if the Moriah pluton cores an anticlinorium adjacent to the Virgilina synclinorium, but textural and compositional differences seem to discount any direct correlation between the two units.

The contact between unit $A_1$ and the Moriah pluton is sharp. Porphyritic dacite, common to the eastern border of the Moriah pluton, is absent at this contact. Somewhat finer-grained intrusive and minor sulfide mineralization and shearing in the volcanic rock are evident at the contact.

The thickness of this unit has been estimated to be a minimum of 2500 m (8100 ft) (Wright, 1974).

In this area, unit $A_1$ is a heterogeneous mixture of poorly sorted andesitic pyroclastic rocks, andesitic lavas and minor amounts of dactic pyroclastic rocks (Wright, 1974). Andesitic lapilli tuff predominates in the unit, but varying amounts of tuff breccia, crystal tuff and lava are also present. Interbedded with these rocks is well-sorted, bedded fine tuff that commonly shows graded bedding with small scale cross bedding and soft sediment faulting and slumping.

Subaqueous depositional features such as pull apart structures in the tuff breccias and quench brecciation of the lavas, have been observed in unit $A_1$. Both of these features are present in the lobe of volcanic rocks extending into the Moriah pluton from the west (fig. 5). The presence of the above mentioned factors and interbedded fine tuff that shows graded bedding indicate that unit $A_1$, in the study area, was probably deposited in a subaqueous environment.

## Member Y

Member Y is a unit of fine-grained volcaniclastic rocks that commonly show graded bedding or laminations. Member Y is adjacent to the coarser lapilli tuff of member Z, but the contact between the two has not been observed in outcrop. Cleavage developed in the northeastern part of member Y, just south of the dam on Lake Michie, that diverges from the normal north-northeast trend suggests that a fault may be present between members Z and Y. A fault is also suggested by the abrupt change from coarse pyroclastic rocks to finely bedded and laminated tuffs. Injections of fine-grained material, similar to that in member Y, are present in fractures in the basal lavas of member X. This may represent upward movement of the water-rich fine tuff into quench fractured and brecciated lava. Intrusive contacts occur at the east and west borders of member Y. Fig. 5 shows that the Moriah pluton and the Butner stock, described in a later section, have been intruded discordantly into member Y. Contact zones are usually narrow with minor sulfide mineralization.

Minimum thickness of member Y is 1600 m (5200 ft). However, the true structural relations of this member are unknown and the thickness may be larger.

Member Y is composed primarily of very fine and well sorted volcaniclastic material. Also present are small amounts of lapilli tuff and a zone of interbedded quartz and iron oxides. The greatest proportion of the volcaniclastic material is fine ash (<.1 mm) although grains range in size to as much as .5 mm in the coarser beds. Graded bedding is commonly present and is expressed by thin basal layers of crystals and recrystallized glass fragments overlain by ash that grades vertically into finer sizes.

Current indications such as scour channels, crossbedding, and ripple marks were not observed. Soft sediment deformation is present, however, and is usually expressed by local high angle reverse or normal faults that die out vertically.

Continuous exposure of bedded iron oxide in float and outcrop has provided a marker unit and shows a general east-northeasterly trend for member Y. The bedded iron oxides are seen along strike for approximately 4150 m (15,800 ft) and have been deformed by soft sediment faulting and folding. This zone of iron-oxides occurs interbedded with the volcaniclastic material and can be observed on the power lines just south of the dam on Lake Michie. The thickness of this zone is approximately 300 m (1150 ft).

X-ray powder diffraction patterns of this rock indicates that hematite, quartz and magnetite are present. Microscopic examination shows that rare muscovite is also present.

The iron oxide grains commonly have crystal faces and make up 50 percent of some samples. Iron oxide layers generally occur in 2 to 5 mm laminations, but have been observed to be up to 10 cm. Polygonal quartz grains are present within the iron oxide layers and commonly form individual layers interbedded with the iron oxide.

The depositional environment implied by characteristics of member Y show a marked change from the subareal environment interpreted for member Z. Graded bedding and sorting are good indications that member Y was subaqueously deposited. Interbedded lapilli tuff and beds of small euhedral plagioclase crystals are indicative of a volcaniclastic source for most of member Y, while the absence of volcaniclastic material from the bedded hematite suggests that parts of member Y were deposited during a period of volcanic inactivity. From these factors it seems safe to assume that member Y was deposited in a basin during the waning stages of volcanic activity.

Several characteristics of the basinal environment can be ascertained. First, the lack of current features indicates that member Y could have been deposited in a lake or in a marine environment below wave base. Second, the hematite interbedded with member Y is similar to iron formation deposits of Precambrian and possibly Paleozoic age (O'Rourke, 1961), in that both are thinly bedded and laminated and that both are composed primarily of iron oxides and silica. Iron formation has been defined by James (1954) as "... a chemical sediment, typically thin-bedded or laminated, containing 15 percent or more iron of sedimentary origin, commonly but not necessarily containing layers of chert." Chemical precipitation of the iron oxide parts of member Y is suggested by the lack of any epiclastic or pyroclastic material.

The major environmental condition necessary for the development of iron formation is a restricted basin (Park and MacDiarmid, 1970, p. 400). Therefore, member Y may have been deposited in a lake restricted to open flow of water or in an enclosed submarine basin.

### Member X

Lavas that are known to overlie the thin-bedded tuffs of member Y have been grouped together into member Z. The lower contact has been observed in float southwest of the dam on Lake Michie. It shows fine-grained material similar to unbedded parts of member Y injected into fractures in member X. These fractures may have resulted from rapid chilling of the lava when it came in contact with water or by continued movement after the base of the lava flow had solidified. After fracturing took place, the waterladen fine tuff may have moved upward into the fractures in response to the weight of the overlying lava. The upper contact and the presumed intrusive contact with the Moriah pluton are not exposed because of a covering of Triassic rocks to the south. The contact with the Butner stock appears intrusive because of its discordancy to the northeasterly trend of member X, but was not observed.

The minimum thickness for member X is 800 m (2600 ft). True thickness could not be ascertained because of the Triassic covering.

Variation in color in the lavas ranges from light green to black depending on the magnetite and chlorite content. The lavas are commonly porphyritic with intergranular to intersertal groundmass. Parts of member X appear to be fragmental because of color mottling. Lighter areas result from increased vesiculation of parts of the rock and subsequent filling of the vesicles with lighter minerals (quartz). The lighter areas do have distinct boundaries, however, and may be fragmental in the sense that they represent pieces (cinders) of the lava flow that had already been solidified and then reincorporated into the lava.

Amygdules are common to all parts of member X and in some cases make up as much as 35 percent of the rock. Vesicles have been filled by various minerals, most commonly quartz, calcite, epidote, and chlorite, and less commonly pyrite, magnetite, prehnite and garnet. Amygdule diameters generally range up to 1 cm although filled cavities larger than 1 cm have been observed.

Mineralogy of the lavas of this member has been altered by mid-Paleozoic metamorphism. In the groundmass, mafic minerals are now chlorite, epidote and minor actinolite. Chlorite commonly occurs in large amounts (60-70 percent) in the fine-grained material occupying the interstices between vesicles and crystals. Some chlorite, presumably Mg-rich because it is colorless in plain light, is associated with epidote and may be pseudomorphic after pyroxene. Epidote and calcite are common in the groundmass and make up 15 to 20 percent of the rock. Plagioclase occurs as highly saussaritized and seritized phenocrysts as well as small lath-like crystals that show little alteration. Plagioclase ($An_8$, determined by extinction angles) makes up approximately 15 percent of the rocks. Quartz occurs only as vesicle fillings. Primary accessory minerals present are apatite and magnetite.

The highly vesicular nature of parts of member X, some rocks containing 30 percent vesicles, and the presence of large (1 cm) filled vesicles implies that member X was extruded at very shallow water depths or possibly subareally. The 1 cm size of amygdules at the contact with member Y (southwest of Lake Michie) limits the depth of water present in the basin at the time of extrusion to less than 500 m (Moore, 1965).

# INTRUSIVE ROCKS

## General Statement

A large area of the northeastern quadrant of the Durham North quadrangle is occupied by intrusive rocks (Fig. 5). The pluton shown in the southeastern part of the area is herein named the Butner stock for an adjacent small community. The large pluton transecting the western part of the mapped area has been termed the Moriah pluton in this paper for the small community of Moriah in the southeastern part of the Roxboro quadrangle. The proximity of the two intrusive bodies and the fact that they both intrude the same units at the same stratigraphic level suggests that they may be related. Intrusive apophyses piercing the volcanic strip separating the two bodies and interpretation of magnetic anomalies in the area from an aeromagnetic map (U.S.G.S. Geophysical Investigations Map GP-883) support the relation and suggest that the intrusives may be connected at depth. Therefore, the Moriah pluton and the Butner stock have been combined with related hypabyssal rocks (dacite porphyry) into the Flat River complex.

Other intrusive rocks to the east and northeast in the Oxford area (Hadley, 1973) were believed to have been comagmatic with those in the Flat River complex until isotopic dating, presented in this report, showed that at least part of Hadley's complex is much younger.

Pre-metamorphic mafic dikes and post-metamorphic diabase dikes of probable Triassic age are common in all parts of the field area.

## Flat River Complex

The Flat River complex was described by Glover (Glover and Sinha, 1973) in his study of the Virgilina deformation in the Roxboro quadrangle. Subsequent mapping to the south and southwest (Wright, 1974; and this report) has extended the known outcrop of the Flat River complex to the southwestern border of the Durham North quadrangle. The complex is, therefore, exposed for a distance of at least 40 km.

Facies within the Flat River complex have been distinguished on the basis of both mineralogy and texture. The predominant facies is a felsic, medium-grained intrusive rock. This facies forms the core of the Moriah pluton and is present in the eastern part of the Butner stock (fig. 5). It is composed predominantly of porphyritic granodiorite with subordinate amounts of porphyritic quartz monzonite, equigranular granodiorite and equigranular quartz monzonite.

The second facies is also felsic, but was separated from the felsic medium-grained facies on the basis of its finer-grained groundmass. This facies is dacite and probably represents a chilled margin of the Flat River complex. It has been observed along the borders of the complex in the Roxboro quadrangle (Glover and Sinha, 1973) and in the study area. Wright (1974) also found dacite in what may be the roof of the complex in the southwestern part of the Durham North quadrangle.

The third facies is intermediate to mafic. This facies is medium-grained, commonly porphyritic, and composed of both quartz diorite and gabbro. These rock types were not treated individually because the proportion of the two varied widely. In both the Roxboro and Durham North quadrangles, the intermediate to mafic facies occurs along the borders of the complex.

Poor exposure and little vertical relief hinders detailed examination of contact zones. However, three types of contact zones can be defined.

The most common type of contact is found along the eastern border of the Moriah pluton in the northeast quadrant of the Durham North quadrangle and appears to result from the chilling of the margin of the granodioritic core. The contact usually contains porphyritic dacite that in some cases shows evidence of shearing. Porphyritic dacite in the margins of the Moriah pluton to the southwest of the study area is generally autoclastic and associated with intrusive breccia (Wright, 1974).

The second type of contact zone occurs along the northwest and southeast borders of the Moriah. Here, the contact is very sharp with the pluton margin being only slightly finer grained and the volcanic rocks showing sulfide mineralization and shearing.

The third type of contact zone occurs only along the northeastern border of the lobe of volcanic rock (unit $A_1$) that enters the mapped area from the west (fig. 5). This contact is characterized by the presence of abundant vein quartz and rock that appears to have been altered by hydrothermal fluids. The altered rock has lost all of its original texture and now consists of a mass of quartz and feldspar.

### Felsic medium-grained facies

The felsic medium-grained intrusive rocks are a combination of granodiorite and quartz monzonite (fig. 2) which are undifferentiated because of the difficulty in estimating feldspar percentages in the field. Granodiorite is by far the most common intrusive rock type in the study area. Idiomorphic plagioclase phenocrysts are surrounded by an hypidiomorphic groundmass of quartz, plagioclase, potassium-rich feldspar and minor amounts of mafic minerals.

Intergrowths of quartz and potassium-rich feldspar occur in 70 percent of the samples, commonly making up 50 percent of the groundmass of the rocks. Some of the intergrowths surround and embay the plagioclase phenocrysts suggesting replacement of the phenocrysts by potassium feldspar and quartz. Tabor and Crowder (1969) have described similar arrangements of micropegmatite around plagioclase in the Cloudy Pass batholith. They believe that the plagioclase had been replaced by micropegmatite and attribute its formation to the prevalence of residual solutions. Osterwald (1953) has observed myrmekitic intergrowths between plagioclase and potash feldspar in the granites of the Big Horn Mountains of Wyoming and attributes its formation to the replacement of plagioclase by potassium feldspar through introduction of silica during metamorphism. Either of these mechanisms could have produced the alteration seen in the phenocrysts of the Flat River complex, however, the presence of resorbed quartz crystals in some of the intrusive rocks may indicate that replacement of the plagioclase phenocrysts may have occurred before the end of crystallization in a reaction with the remaining magmatic liquid.

Much more common in these rocks are intergrowths that are unrelated to plagioclase phenocrysts and do not appear to be the result of replacement of any other mineral. These intergrowths are commonly micrographic, but are usually irregular (Fig. 6). They are believed to result from simultaneous crystallization of quartz and potassium feldspar (Deer, Howie, and Zussman, 1963).

Another texture common to both the quartz monzonite and the granodiorites, is formed by the incorporation of slightly more mafic autoliths. These autoliths are finer-grained than the host and generally consist of highly altered plagioclase laths surrounded by quartz and minor potassium feldspar and mafic material. It is suggested that these autoliths represent portions of a chilled margin or roof that has been reintruded and partially assimilated by the coarser phase. A large roof pendant similar to the smaller autoliths in mineralogy and texture occurs east of the Flat River near the N.C. State Forestry field camp. Large plagioclase phenocrysts and other coarser parts of the fine-grained autoliths indicate that it was probably partially crystalline before being chilled. The contact zone between the two phases is sharp, but granophyric intergrowths in the groundmass of the coarser phase commonly embay the finer phase. Granophyric intergrowths also seem to be more common near the contact.

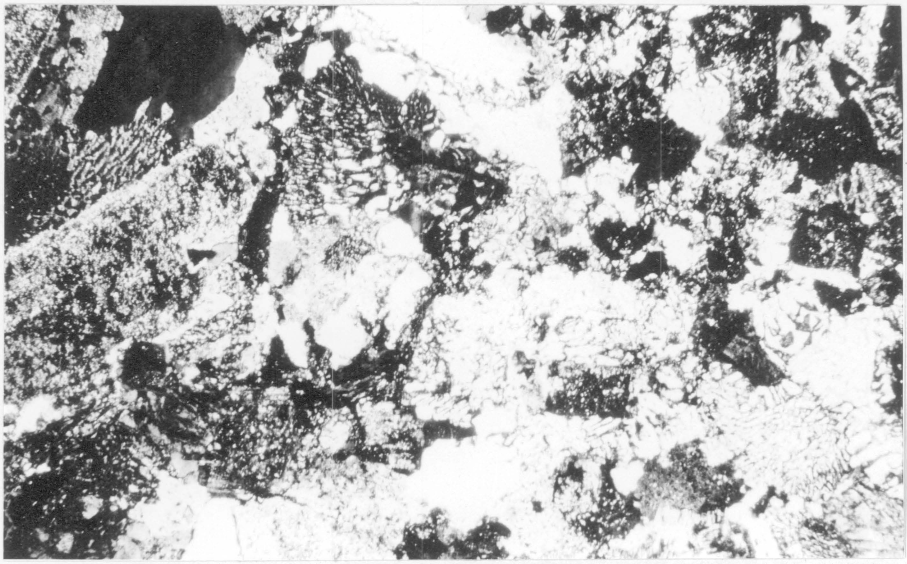

Figure 6. Granophyric Texture in the Felsic Medium-Grained Facies of the Flat River Complex

Spherulite-like texture is also seen in at least one sample of the felsic medium-grained intrusives near the contact with the surrounding volcanic rocks. Radiating crystallites of intergrown quartz and feldspar (fig. 7) are developed in an otherwise medium-grained rock. The spherulitic texture found in the medium grained intrusives does not resemble spherulites from known examples of recrystallized glass, nevertheless, it may indicate that minor amounts of glass were present in the medium-grained intrusives near the contacts.

The mineralogy of the felsic medium-grained intrusive phases of the Moriah pluton does not vary to any great extent. Modes (500 counts) from these rocks are plotted in fig. 2. The main difference between the quartz monzonite and the granodiorite is a 5 to 10 percent increase in the potassium feldspar content and a corresponding decrease in the plagioclase content. Most quartz monzonite (adamellite) in epizonal plutons in the western United States is found in the top of the chamber overlying a core of granodiorite (Tabor and Crowder, 1969; and Fiske, Hopson and Waters, 1963). This location makes them more accessible to hydrothermal fluids and alteration. Tabor and Crowder (1969) found adamellite in the top of the Cloudy Pass batholith and have attributed its position to crystal settling of mafic minerals from the top of the magma chamber. Neither of these processes appears to have produced the quartz monzonites in the Flat River complex. Both alteration and mafic mineral content are similar in the quartz monzonites and granodiorites.

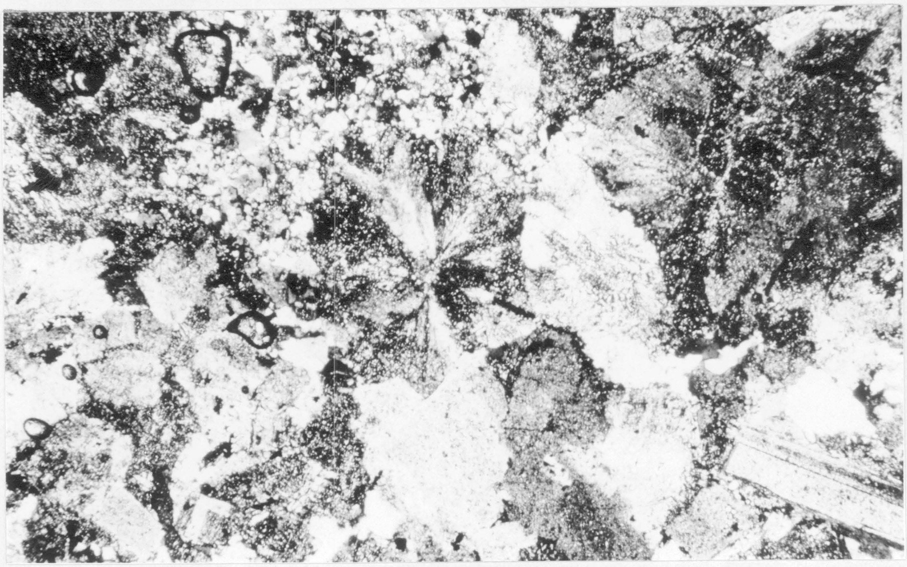

Figure 7. Spherulitic Texture in the Felsic Medium-Grained Facies of the Flat River Complex

The mineralogy has been altered by metamorphism and hydrothermal activity. Plagioclase phenocrysts commonly make up from 30 to 40 percent of the granodiorite and from 18 to 30 percent of the quartz monzonite. The phenocrysts are usually altered to varying amounts of epidote and white mica. Alteration also occurs along the margins of the phenocrysts where plagioclase is replaced by quartz and potassium-rich feldspar intergrowths. Relict zoning in the plagioclase phenocrysts (fig. 8) is shown by calcic replacement products decreasing in size and abundance away from the cores of the phenocrysts. All of the plagioclase phenocrysts have been recrystallized to albite during metamorphism.

The groundmass consists of anhedral grains of quartz and perthite, subhedral grains of plagioclase and micrographic to irregular intergrowths of quartz and potassium-rich feldspar. Plagioclase in the groundmass of the granodiorite makes up from 7 to 24 percent of the rock and in the quartz monzonite 11 to 27 percent of the rock. The grains are subhedral to euhedral and altered to epidote and white mica. Quartz in the granodiorite and quartz monzonite occurs as individual grains and with potassium-rich feldspar in irregular to graphic intergrowths. Quartz makes up approximately 21 to 31 percent of the granodiorite and 22 to 27 percent of the quartz monzonite. It commonly shows undulose extinction, and is rarely polygonal. Potassium-rich feldspar in the felsic medium-grained intrusive rocks occurs as individual grains and in intergrowths with quartz. Individual grains are

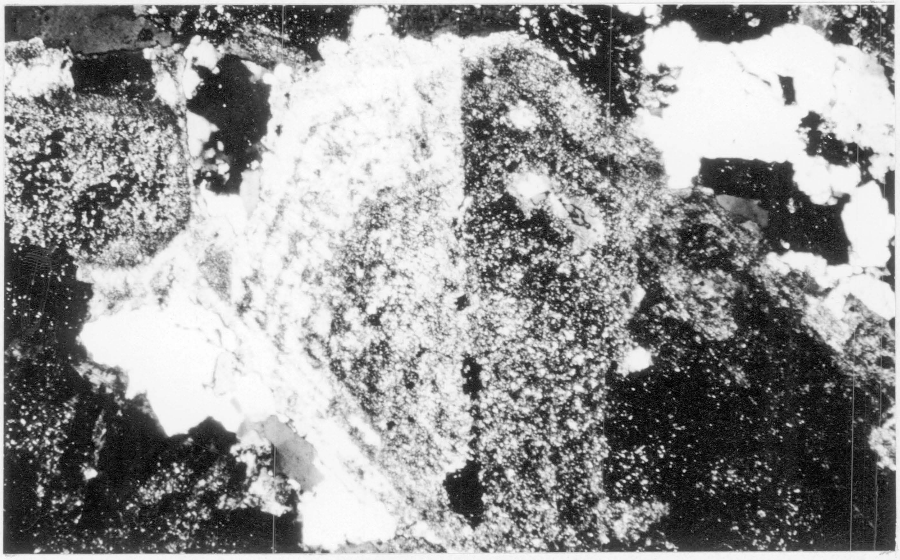

Figure 8. Relict zoning in a Plagioclase Phenocryst from the Felsic Medium-Grained Facies of the Flat River Complex

usually perthitic and commonly show cross-hatched twinning characteristic of microcline. In the intergrowths with quartz, the potassium-rich feldspar is in some cases perthitic, but in others is not. Potassium-rich feldspar makes up 7 to 24 percent of the granodiorite and 28 percent of the quartz monzonite.

Mafic material in the felsic medium-grained intrusive rocks is represented by biotite altered to chlorite, and hornblende altered to epidote, magnetite and chlorite. Biotite, hornblende and their alteration products commonly make up 10 percent of both the granodiorite and quartz monzonite. Accessory minerals present are zircon, pyrite, sphene, apatite, magnetite and (or) ilmenite. Secondary accessory minerals present include calcite, epidote, and white mica.

Paragenesis indicates at least three different rates of cooling. Amphibole now replaced by chlorite, epidote and opaque minerals, appears to have been the first major mineral to crystallize. Plagioclase, when in contact with the replaced amphibole, usually has crystallized around the relict euhedral form of the amphibole. Plagioclase, as large 1 cm grains, began to crystallize either during or after amphibole. During crystallization of plagioclase, the cooling rate changed and the size of the plagioclase crystals became somewhat smaller (1 - 2 mm).

The relation between quartz and plagioclase is difficult to determine. Resorption and recrystallization, common to rocks of the Flat River Complex, was accompanied by replacement of plagioclase by quartz and potassium-rich feldspar. However, several samples where quartz either appeared to be embayed or surrounded by small grains of plagioclase, may indicate that the crystallization histories of these two minerals overlapped to a certain extent.

Perthite is generally found to have surrounded, embayed or replaced plagioclase. The reverse was never observed and it is reasonable to assume that perthite began to crystallize after crystallization of plagioclase had ended. Crystallization of perthite instead of two individual feldspars may indicate that a hypersolvus relationship (Tuttle and Bowen, 1958) existed at the time of its crystallization in the more fractionated parts of the magma.

Quartz and potassium-rich feldspar not related to the replacement of plagioclase are commonly observed as irregular and regular intergrowths on the 1 to 2 mm scale and appear to have crystallized together. Either a rapid drop in temperature or a rapid rise in the solidus, caused possibly by a change in water pressure, is indicated by crystallization of quartz and potassium-rich feldspar in micrographic intergrowths.

To determine the age of the Flat River complex, zircons were separated from two samples of the felsic medium-grained intrusive rocks. Sample localities are given in table 1 and plotted in fig. 5. Results of U-Pb isotopic analysis of the zircon separates are given in table 1. Figure 9 is a concordia diagram of the four samples analyzed. It can be seen that the samples are discordant and define a linear regression best fit chord with an upper

### Table 1

### Isotopic Analysis of Zircons and NBS 983 Pb Standard

| | ppm | | Observed Ratios | | | Atomic Ratios | | | Apparent Age (m.y.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample # | u | Pb | $\frac{Pb^{206}}{Pb^{204}}$ | $\frac{Pb^{207}}{Pb^{206}}$ | $\frac{Pb^{208}}{Pb^{206}}$ | $\frac{Pb^{206*}}{U^{238}}$ | $\frac{Pb^{207*}}{U^{235}}$ | $\frac{Pb^{207*}}{Pb^{206*}}$ | $\frac{Pb^{206*}}{U^{238}}$ | $\frac{Pb^{207*}}{U^{235}}$ | $\frac{Pb^{207*}}{Pb^{206*}}$ |
| K-40<br>combined | 492<br>±1 | 33.7<br>±.46 | 1158<br>±23 | .07461<br>±.00036 | .19373<br>±.00131 | .06186 | .52672 | .06183 | 387 | 430 | 668 |
| K-40<br>magnetic | 888<br>±11 | 36.1<br>±.06 | 1335<br>±27 | .07180<br>±.00017 | .17615<br>±.00028 | .03738 | .31115 | .06044 | 237 | 275 | 620 |
| K-40<br>non-magnetic | 386<br>±7 | 29.3<br>±.01 | 2474<br>±49 | .06659<br>±.00012 | .16905<br>±.00024 | .07079 | .59087 | .06061 | 441 | 471 | 626 |
| K-39 | 361<br>±3 | 37.0<br>±.10 | 457<br>±9 | .09359<br>±.00036 | .25709<br>±.00070 | .08483 | .71459 | .06120 | 525 | 548 | 646 |
| LGO-43 | 533<br>±1 | 49.0<br>±.12 | 1756<br>±35 | .06633<br>±.00012 | .23412<br>±.00059 | .08128 | .64768 | .05786 | 504 | 507 | 524 |
| NBS 983 | | | 2688<br>±53 | .07128<br>±.00006 | .01366<br>±.00002 | | | | | | |
| NBS 983 | | | 2731<br>±55 | .07116<br>±.00014 | .01364<br>±.00011 | | | | | | |
| NBS 983 | | | 2695 | .07120<br>±.00004 | .01362<br>±.00002 | Absolute values (Catanzaro and others, 1968) | | | | | |

Common Pb Corrections: 600 m.y. - $Pb^{206}/Pb^{204} = 17.5639$, $Pb^{207}/Pb^{204} = 15.8776$, $Pb^{208}/Pb^{204} = 36.467$

500 m.y. - $Pb^{206}/Pb^{204} = 17.7142$, $Pb^{207}/Pb^{204} = 15.8886$, $Pb^{208}/Pb^{204} = 36.627$

$U^{238}/U^{235} = 137.88$

Decay Constants: $U^{235} = .98485 \times 10^{-9}\ yr^{-1}$; $U^{238} = 1.55130 \times 10^{-9}\ yr^{-1}$ (Jaffey et al., 1971)

Sample Locations:

K-40

K-40 magnetic 4 1/2 km southeast of Bahama, N.C., Durham North Quadrangle.

K-40 non-magnetic

K-39 1-1/2 km east of Bahama, N.C., Durham North Quadrangle.

LGO-43 Active quarry on north side of Tar River in northwestern Creedmore, N.C. Quadrangle.

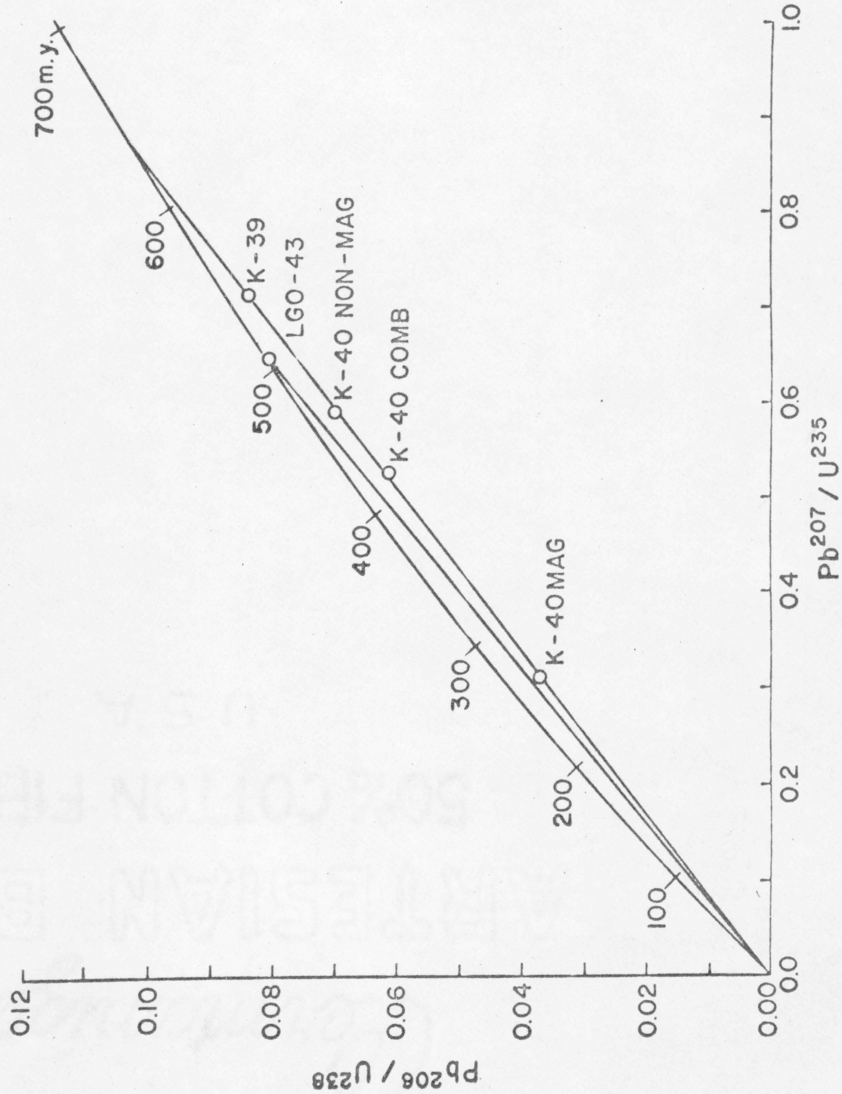

Figure 9. Concordia Diagram for Zircons from the Moriah Pluton

intercept with the concordia of 650 ± 30 m.y.

Other isotopic analyses indicate that the top of unit II, which the Flat River Complex intrudes, is 620 ± 20 m.y. (Glover and Sinha, 1973). Within error limits of the ages of the Flat River Complex and unit II, it is possible to have had nearly contemporaneous deposition of unit II, with intrusion and final crystallization of the Flat River Complex.

Regionally, the age determined for the Flat River Complex probably coincides with Fullagar's (1971) 595 - 520 m.y. belt of intrusive rocks that occur in or near the Carolina "slate" belt. The age obtained for the Flat River Complex (650 m.y.) coupled with the ages of the top of unit II (620 m.y.) and the Roxboro pluton (575 m.y.) (Glover and Sinha, 1973) extends the range of this 520 m.y. to 595 m.y. intrusive period to 520 to 650 m.y.

### Dacite

Dacite occurs in an almost continuous band along the eastern border of the Moriah pluton in the study area. It was not observed in the Butner stock.

Dacite weathers to a pale buff to red color and is commonly porphyritic with large (1 cm) phenocrysts of quartz and plagioclase. It shows some evidence of protoclastic deformation, but is in contrast to the dacite along the southwestern boundary of the Flat River Complex (Wright, 1974) which shows intense deformational affects. The dacite is considered to be intrusive on the basis of the lack of fragmental texture.

Plagioclase and quartz occur as euhedral to subhedral grains that make up approximately 20 percent of the dacite. Plagioclase phenocrysts are in some cases broken and rounded. Quartz phenocrysts commonly show resorbtion. Mid-Paleozoic metamorphism has saussaritized and seriticized the plagioclase and altered the composition to albite (determined by extinction angles).

The groundmass in the dacite is composed of a fine-grained xenomorphic aggregate of quartz, feldspar, chlorite and white mica. Epidote occurs as a secondary accessory mineral. Magnetite and (or) ilmenite is also present.

The dacite in the study area probably represents a chilled margin of the felsic medium-grained facies of the Moriah pluton and is, therefore, comparable in age to the medium-grained facies.

### Intermediate to mafic facies

Intermediate to mafic rocks of the Flat River Complex occur along the eastern margins of both the eastern and western plutons in the study area (fig. 5). Quartz diorite is the most common rock type and is associated with minor amounts of gabbro. No major occurrences of gabbro were found in the mapped area, but large bodies of gabbro have been noted to the north in the Flat River Complex by Glover (Glover and Sinha, 1973).

The quartz diorite is commonly a medium-grained porphyritic to equigranular rock with large subhedral crystals of plagioclase and amphibole comprising as much as 90 percent of the rock.

Alteration by late-stage fluids and metamorphism has been almost complete in the quartz diorite. Plagioclase crystals, some with untwinned and unaltered rims, are covered by a coarse aggregate of clinozoisite, calcite and white mica. Minor amounts of potassium feldspar is found surrounding plagioclase in some cases.

Primary hornblende shows yellowish-brown pleochroism, but is more commonly altered to blades, or tablets of actinolite or to an aggregate of chlorite, epidote and magnetite.

Quartz in the quartz diorite makes up from 7 to 16 percent of the rock. Quartz occurs as anhedral grains with sharp grain boundaries and undulose extinction. Much of the quartz does not appear to be recrystallized.

Other minerals present in the quartz diorite result mainly from alteration. Chlorite, calcite, white mica, and epidote group minerals occur as alteration products of plagioclase and amphibole. Sphene is present as alteration rims around magnetite. Apatite is also present in minor amounts. Opaque minerals present, other than magnetite, are pyrite and possibly ilmenite.

Only one body of gabbro occurs as a small outcrop near the border between the felsic medium-grained facies and the intermediate facies of the Moriah pluton and may be a more mafic differentiate of the quartz diorite.

As with other intrusive rocks in the Flat River Complex, metamorphism has caused complete reequilibration of the original mineralogy. Plagioclase occurs as highly saussaritized and seriticized phenocrysts that range in size up to 1.2 cm and make up approximately 25 to 30 percent of the rock.

Mafic material is represented by pseudomorphic grains of pyroxene and olivine. The pyroxene has been uralitized, but still retains oblique extinction and herringbone twinning indicative of augite. Olivine has been replaced by brownish-green chlorite and magnetite.

Replacement products present are chlorite, epidote group minerals, white mica and actinolite. Sphene is also present as alteration rims around magnetite.

A chilled margin of porphyritic dacite is present between the intermediate to mafic facies and the felsic medium-grained facies in the southwest (fig. 5). This dacite suggests that the felsic medium-grained facies was chilled along the border with the intermediate facies and that the intermediate to mafic facies was emplaced prior to the emplacement of the felsic facies.

### Emplacement

In this study, two sources of data were available for obtaining insight into the level of emplacement of the Flat River Complex. They are; 1) the field relations of the Flat River Complex referenced to other studies where the level of emplacement has been ascertained, and 2) petrographic relations references to studies of the mineralogy of granites and granodiorites as a function of depth of emplacement.

A first approximation to the level of emplacement can be obtained from the characteristics given by Buddington (1959) for epizonal, mesozonal and catazonal intrusions. Characteristics of the Flat River Complex such as: sharp contacts, associated volcanic rocks, discordancy to the regional trends, and the presence of granophyre, indicate that the Flat River Complex was emplaced in the epizone (1 - 10 km). However, other field relations provide better definition.

Isotopic data have shown that the age of the top of unit II, which the Flat River Complex intrudes, is 620 ± 20 m.y. (Glover and Sinha, 1973). Ages given in this report indicate that the Flat River is 650 ± 30 m.y. old. With this knowledge, it is possible to estimate the thickness of the volcanic pile present during the final emplacement of the Flat River Complex. If the deposition of unit II and the final emplacement of the Flat River are assumed to be contemporaneous, then the maximum thickness of the volcanic pile (unit II) of 4800 m (16,000 ft) would be an upper limit. However, the difference in ages implies that they are not exactly contemporaneous and that the covering of volcanic material was much smaller.

To take this one step further, other field data indicate that the Flat River may have been surface-breaking. Vent breccias characteristic of surface-breaking plutons (Fiske, Hopson and Waters, 1963; and Cater, 1969) are present in the Flat River Complex. Wright (1974) has linked these vent breccias, which cut the Flat River Complex, with the surrounding volcanic stratigraphy. These vents consist of comminuted volcanic and intrusive material with only minor amounts of intergranular magmatic material. This explosive brecciation of both volcanic rocks and pluton implies a very shallow level of emplacement, shallow enough to allow rapid escape of volatiles to the surface. Protoclastic dacites are also characteristic of surface-breaking plutons (Cater, 1969) near their borders. Protoclastic hypabyssal rocks (porphyritic dacite) are common to the Flat River Complex southwest of the study area (Wright, 1974).

The most applicable petrologic study to the level of emplacement is the work done by Tuttle and Bowen (1958) on the Qtz-Ab-Or system. However, two basic requirements are necessary to apply petrography from intrusive bodies to this study: 1) that the magma was granitic in composition, and 2) that the magma was saturated with respect to water during crystallization. In the case of the granodioritic Flat River Complex, the first requirement is not met exactly. However, since the granophyric groundmass represents the last liquid crystallized, modal analyses of the granophyric groundmass should most closely fit the granitic requirement.

The second requirement is also difficult to meet in the case of the Flat River Complex because sharp contacts, lack of pegmatitic or aplitic material, and paragenesis indicate that the Flat River crystallized, at least in part, as an undersaturated or nearly dry magma. The presence of granophyre and spherulitic granophyre in the Flat River Complex and felsic extrusives associated with the Flat River, implies a possible hypersolvus granite-granophyre-rhyolite association as described by Tuttle and others (1964). However, a vapor phase was probably developed during the last stages of crystallization as is indicated by the position of the plots of modal analyses of the granophyric groundmass on a Qtz-Ab-Or diagram (fig. 10). These modal analyses were recalculated to weight percent by the use of electron microprobe derived phase data. Significant error is inherent in the diagram as a result of difficulty in distinguishing albite and potassium-rich feldspar in the fine-grained granophyric intergrowths. However, this error should not affect the interpretation because the quartz content is relatively certain. It can be seen from this diagram that the modes are consistant with the low pressure saturated curves rather than the unsaturated curves. Gibbon and Wyllie (1969) state that the West Farrington granodiorite, which is similar to the Flat River, probably did not develop a vapor phase until the last stages of crystallization during the formation of the granophyric groundmass. The plot also indicates that the groundmass was formed at low pressures and correspondingly shallow depths (<1 km).

Therefore, both field and petrologic data from the Flat River Complex indicate that it was intruded at very shallow and probably surface-breaking levels.

Only minor amounts of xenolithic material were found in the complex. One roof pendant was observed in the northwest and

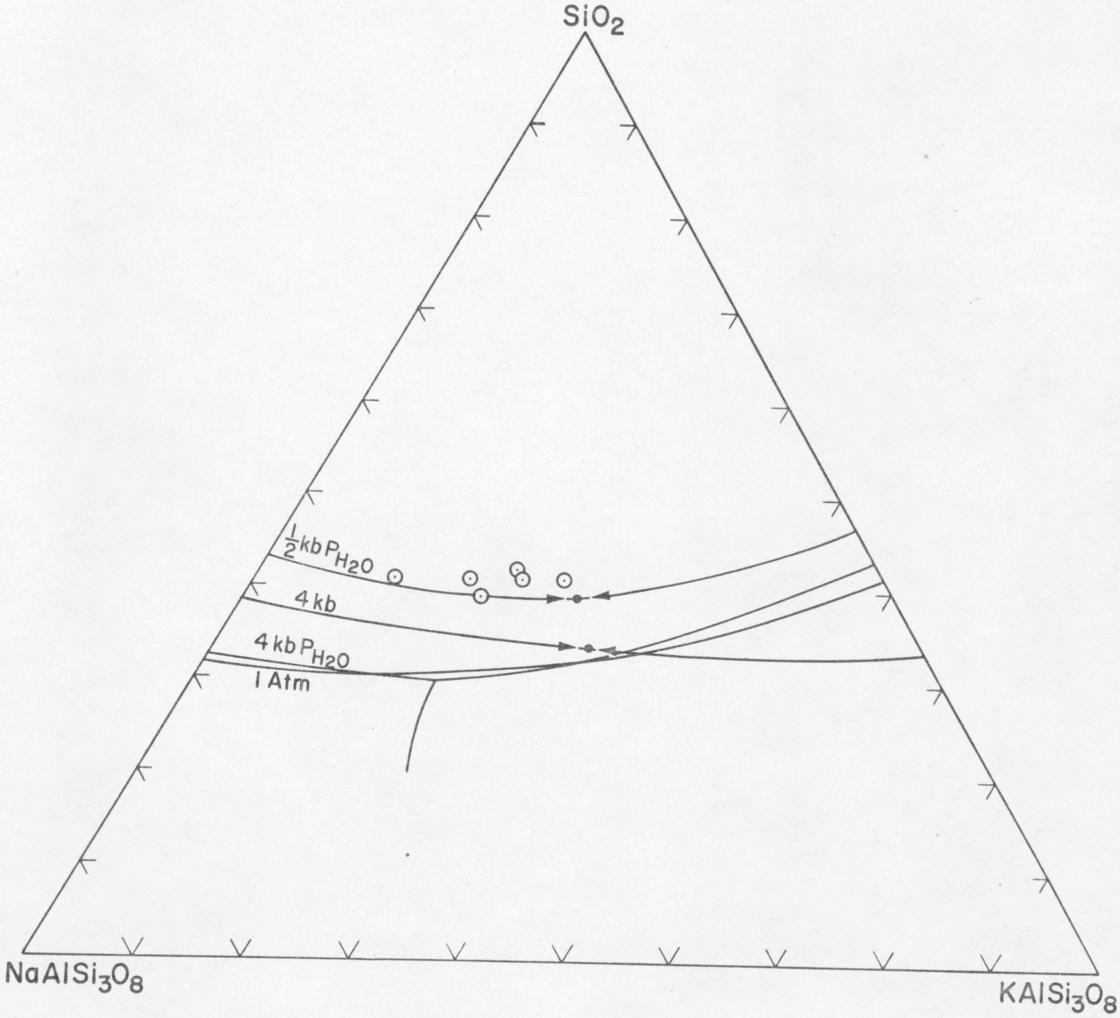

FIGURE 10. $NaAlSi_3O_8$- $KAlSi_3O_8$- $SiO_2$ PLOT: GRANOPHYRIC COMPOSITIONS DETERMINED BY MODAL ANALYSIS. —kb $P_{H_2O}$ CURVE (TUTTLE AND BOWEN 1958), 1 atm CURVE (SCHAIRER, 1950), 4 kb AND 4 kb $P_{H_2O}$ CURVES (STEINER et. al., 1974).

smaller fragments of volcanic rock were observed in the dacite to the southwest (Wright, 1974). This material shows no sign of assimilation or recrystallization by the pluton. For these reasons, stoping and assimilation are not believed to have been a major factor in final emplacement of the Flat River Complex.

The lack of intense deformation in the contact zones or large scale disruption of the regional trend of the country rock seems to indicate that forceful intrusion was not dominant during intrusion.

Hopson et. al. (1970) state that emplacement of shallow level batholiths is not explained by either shouldering aside or stoping and that shallowly emplaced batholiths such as the Cloudy Pass, Snoqualmie, and Tatoosh have spread out under a thin covering of volcanic material. The lack of features suggesting other methods of emplacement and the presence of a chilled margin in the Flat River similar to that present in the Cloudy Pass suggests that the Flat River Complex was emplaced in a similar manner as the Cloudy Pass.

## Early Cambrian Intrusive Rocks

Early Cambrian intrusive rocks occur just east of the study area (fig. 1). Compositionally the rocks are similar to those in the Flat River Complex, but mineral age data indicate that they are much younger. Hadley (1973) mapped intrusives to the north of the Early Cambrian rocks that may be correlative with them.

One zircon sample from this younger rock, a hornblende gabbro-diorite, was isotopically analyzed for uranium and lead. Originally, it was believed that this analysis would provide a point that would lie on the chord already established for the Flat River Complex (fig. 9). However, the data defines a nearly concordant point at 520 m.y. and indicates that this age may represent the true age of the rock or an episodic lead loss at 520 m.y. Since metamorphism is believed to have reached its peak in this area at approximately 425 to 385 m.y. ago (Fullagar, 1971), it is unlikely that this area represents an episodic lead loss.

Considering the Roxboro metagranite to the northwest with an age of 575 ± 20 m.y., and the age of the top of Unit II at 620 ± 20 m.y. (Glover and Sinha , 1973), the age of the Flat River Complex at 650 ± 30 m.y., and this early Cambrian pluton of 520 m.y. to the northeast of the study area, a 130 m.y. period of semi-continuous intrusion and eruption existed in the southern Appalachians during the late Precambrian to early Cambrian.

## Pre-metamorphic Intrusive Rocks of Uncertain Age

Greenstone dikes, possible meta-lamprophyres or meta-basalts, are common in the study area. The dikes have been observed in all members of the volcanic sequence in the area and in the Flat River Complex. The greenstone dikes are usually deeply weathered and commonly exhibit a metamorphic foliation that is consistent with the north-northeast regional trend (Glover and Sinha, 1973; Tobisch and Glover, 1971). Mineralogically, the dikes are composed of actinolite, chlorite, plagioclase, epidote and minor white mica and carbonate material. The age of the dikes is uncertain, but they are known by intrusive relations to younger than 575 m.y., the age of the Roxboro pluton (Glover and Sinha, 1973) which is cut by the greenstone dikes (Glover, pers. communication, 1974). The dikes are older than the mid-Paleozoic metamorphic episode determined by Fullagar (1971) to be 425 to 385 m.y. old and could be any age between the limits of 575 and 385 m.y.

## Post-metamorphic Igneous and Sedimentary Rocks

Post-metamorphic igneous and sedimentary rocks of probable Triassic age are present. The post-metamorphic igneous rocks are diabase dikes and sills (?) which are common throughout the study area. They are generally less than several meters thick, but have been observed to be as much as 200 ft. thick (Prouty, 1931). Compositionally, the diabasic dikes and sills (?) are composed of calcic plagioclase $An_{48-50}$ (determined by extinction angles), pigeonite (very low 2V), and minor olivine. Magnetite is also present. Textures range from subophitic to ophitic.

Arkosic sandstones and conglomerates are present in the southern part of the study area. This area encompasses part of the western border of the Deep River Triassic basin. The contact between the

Precambrian crystalline rocks and the Triassic sediments is a nonconformity.

Arkoses in the study area are cross-bedded and contain fossilized wood. Prouty (1931) has described the stratigraphy of the Deep River basin in detail.

## METAMORPHISM AND DEFORMATION

Structural aspects of the study area can be related to four deformational events in the Piedmont. Glover and Sinha (1973) and Tobisch and Glover (1971) have determined the sequence, effects and age relations for the deformational events in this part of the Carolina "slate" belt during the late Precambrian through Paleozoic. They found that three events have occurred, namely: 1) pre-metamorphic large-scale and small-scale fold development, 2) synmetamorphic cleavage formation with further fold development, and 3) local development of folds related to slip cleavage. Events 1 and 2 were originally believed to be distinct but overlapping events and were combined into the Virgilina-Halifax fold generation. However, more recent isotopic dating (Glover and Sinha, 1973) has shown that the interval of time separating events 1 and 2 is a great deal larger than first believed, being on the order of 200 m.y. Therefore, event 1 was renamed the Virgilina deformation (Glover and Sinha, 1973) and found to be 620 to 575 m.y. old. Event 2 is the Virgilina-Halifax (mid-Paleozoic) generation. Event 3 corresponds to the Milton-Hagers Mountain fold generation. The fourth deformational event in the study area is evidenced by the presence of Triassic sedimentary rocks unconformably overlying late Precambrian igneous rocks at the border with the Triassic basin to the south.

Evidence for the late Precambrian to early Cambrian Virgilina deformation (Glover and Sinha, 1973) is suggested in the study area, where structural measurements recorded on the mid-Paleozoic slaty cleavage do not conform to the regional trend of the late Precambrian to early Cambrian axis of the Virgilina synclinorium ($F_1$). In the Roxboro quadrangle to the north, the Flat River Complex is present on the eastern limb of the Virgilina synclinorium (Glover and Sinha, 1973). The Moriah pluton and volcanic rocks of the study area could, therefore, represent a cross-sectional view through the magma chamber and volcanic pile of the Flat River Complex. However, this relation should be evidenced in the textural characteristics related to the depth of crystallization in the Moriah. No indication of a change in depth of crystallization is seen in the textures of the Moriah across its outcrop area. Hence, it is more likely that the Moriah was merely buckled during the Virgilina deformation and now occupies the core of an anticlinorium adjacent to the Virgilina synclinorium. Hadley (1973) has suggested a regional anticlinorium to the north that, if extended to the south, would approximate the axis of the outcrop area of the Flat River Complex.

### Mid-Paleozoic event

Slaty cleavage ($S_1$) and metamorphic mineral assemblages indicative of low-grade metamorphism are present in the study area and postdate the Virgilina deformation.

Slaty cleavage, present commonly throughout the mapped area, and schistosity, mostly common to the hydrothermally altered areas, generally has a north-south trend and steep dips. $F_2$ folds related to this cleavage have not been observed in the field area, but to the north in the Roxboro quadrangle, $F_2$ folds (event 2, Virgilina-Halifax fold generation) with axial planar cleavage have been recognized (Glover and Sinha, 1973). Glover (Glover and Sinha, 1973) has determined that the axial plane cleavage trends due south in the southern part of this area. The similarities in trends of cleavage between the two adjacent areas suggests that both are related to the same deformational event.

Glover (Glover and Sinha, 1973) has also shown that regional metamorphism accompanied the formation of slaty cleavage and schistosity. Mineral assemblages and mineral compositions present in the Flat River Complex indicate that this area has undergone low-grade metamorphism. Electron microprobe analysis of plagioclase in the Morian pluton shows that they are albitic (table 2). Albite coexists with quartz, epidote, actinolite, chlorite and stilpnomelane (?). This assemblage is characteristic of the lower greenschist facies of metamorphism.

Age limits for this period of metamorphism can be interpreted from isotopic determinations now available. Age determinations given in this report indicate that metamorphism must have occurred after 520 m.y. ago. Other age determinations by Fullagar (1971) provide an upper limit for metamorphism of 380 m.y. bp.

## Triassic Deformation

Triassic deformation is represented solely by the development of the Deep River Triassic basin, part of which occurs in the southern part of the mapped area. Deformational structures related to the formation of this basin are localized along the border between the crystalline rocks of late Precambrian age and the sedimentary rocks of Triassic age. Only minor deformation is observed and it consists of minor shearing in some of the crystalline rocks.

Table 2. Electron microprobe analyses of feldspars from intrusive rocks of the Moriah Pluton for Or, An, Ab. All results in mole %. (Analyst David Briggs)

| Sample no. | Site | Or | An | Ab |
|---|---|---|---|---|
| A. Plagioclase | | | | |
| K-74 | Phenocryst | .36 | 1.05 | 98.41 |
| | Groundmass | .32 | 1.32 | 98.35 |
| K-54 | Phenocryst | .46 | 1.25 | 98.29 |
| | Groundmass | .43 | 1.11 | 98.45 |
| K-35 | Phenocryst | .44 | .91 | 98.63 |
| | Groundmass | .44 | .99 | 98.56 |
| B. Microcline penthite | | | | |
| K-74 | Sodic part | 1.34 | 1.75 | 96.91 |
| | Potassium part | 97.30 | .12 | 2.57 |
| | Open beam | 69.77 | 1.95 | 28.28 |

# CONCLUSIONS

Volcanic textures and structures indicate that the pyroclastic rocks of unit II accumulated in both marine and non-marine environments. During part of this time volcanic activity waned and a unit of alternating layers of iron oxide and chert (?) accumulated in quiet, restricted, subaqueous conditions. The age of the intrusive Flat River Complex implies that the pyroclastic rocks of unit II began accumulating prior to 650 ± 30 m.y. ago, and continued until about 620 ± 20 m.y. (Glover and Sinha, 1973). All of these rocks are of low greenschist metamorphic grade.

The direct link between the volcanic rocks of unit II and the Flat River Complex established by Wright (1974), the closeness of the age of the Complex (650 ± 30 m.y.) and the age of the top of unit II (620 ± 20 m.y.), and petrographic data and comparisons with experimental results in the Ab-An-Or system all confirm that the Flat River Complex was emplaced at a depth of less than 1 km. and locally was surface breaking. The Flat River can be viewed as a fossil volcanic magma chamber that erupted to furnish pyroclastic debris for part of unit II.

Geochronology by Sinha (Glover and Sinha, 1973) and that presented in this report demonstrate that volcanicity dominated this part of the Carolina "slate" belt for at least 130 m.y.

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# APPENDIX I

## MODAL ANALYSES FROM ROCKS OF THE FLAT RIVER COMPLEX

| *Sample # | Plagioclase | Qtz | K-spar | Chl | Bio | Epi | Op | Sp |
|---|---|---|---|---|---|---|---|---|
| K-1 | 62 | 16 | 7 | 7 | - | 5 | 2 | 1 |
| K-3 | 44 | 21 | 23 | 4 | 2 | 5 | 1 | - |
| K-7 | 56 | 23 | 14 | 3 | 3 | - | - | 1 |
| K-10 | 51 | 22 | 15 | 2 | - | 8 | 1 | - |
| K-14 | 38 | 27 | 27 | 3 | 1 | 2 | 2 | - |
| K-32 | 46 | 31 | 20 | 2 | - | - | 1 | - |
| K-36 | 45 | 29 | 20 | 4 | - | 1 | 1 | - |
| K-39 | 43 | 31 | 18 | 3 | 3 | - | 2 | - |
| K-40 | 44 | 29 | 24 | 3 | - | - | - | - |
| K-48 | 48 | 27 | 22 | 2 | - | - | 1 | - |
| K-50 | 46 | 24 | 19 | 5 | 1 | 3 | 1 | 1 |
| K-51 | 31 | 26 | 30 | 3 | - | 8 | 2 | - |
| K-55 | 53 | 24 | 18 | 2 | 1 | - | 1 | - |
| K-58 | 44 | 28 | 20 | 5 | - | 3 | - | - |
| K-68 | 46 | 19 | 19 | - | 15 | - | 1 | - |
| K-70 | 51 | 24 | 12 | 11 | - | 1 | 1 | - |
| K-71 | 55 | 22 | 10 | 5 | 1 | 3 | 3 | 1 |
| K-72 | 44 | 23 | 26 | 6 | - | - | 1 | - |
| K-87 | 52 | 21 | 20 | 2 | 2 | 2 | 1 | - |
| K-96 | 51 | 23 | 22 | - | 4 | - | - | - |
| K-98 | 38 | 22 | 28 | 5 | 6 | - | 1 | - |
| K-116 | 46 | 21 | 27 | 4 | - | - | 2 | - |

*Sample Locations in Appendix 3

# APPENDIX 2

## MODAL ANALYSES OF GRANOPHYRIC GROUNDMASS

| *Sample # | Qtz | Ab | Or |
|---|---|---|---|
| In % | | | |
| K-55 | 39 | 27 | 34 |
| K-3 | 40.5 | 19 | 40.5 |
| K-7 | 40 | 12 | 48 |
| K-39 | 41 | 24 | 35 |
| K-98 | 38.5 | 11 | 50.5 |
| K-36 | 40 | 29 | 30 |
| In wt. % | | | |
| K-55 | 41.1 | 24.3 | 34.5 |
| K-3 | 41.1 | 19.4 | 39.4 |
| K-7 | 40.7 | 12.8 | 46.5 |
| K-39 | 41.6 | 24.1 | 34.2 |
| K-98 | 41.1 | 29.19 | 30 |
| K-36 | 38.8 | 12.6 | 48.6 |

*Sample Locations in Appendix 3

# APPENDIX 3

## SAMPLE LOCATIONS

| Sample # | Latitude | Longitude |
|---|---|---|
| K-1 | 36°11"50" | 78°53'06" |
| K-3 | 36°11'12" | 78°53'30" |
| K-7 | 36°10'06" | 78°52'00" |
| K-10 | 36"12'36" | 78°52'06" |
| K-14 | 36°13'54" | 78°51'00" |
| K-32 | 36°08'06" | 78"51'12" |
| K-36 | 36°07'42" | 78°52'24" |
| K-39 | 36°10'18" | 78"51'54" |
| K-40 | 36"07'42" | 78°51'00" |
| K-48 | 36°09'12" | 78°50'42" |
| K-50 | 36°10'24" | 78°52'18" |
| K-51 | 36°10'18" | 78°50'24" |
| K-55 | 36°13'48" | 78°50'06" |
| K-58 | 36°12'18" | 78°52'18" |
| K-68 | 36°10'30" | 78°51'36" |
| K-70 | 36°10'42" | 78°51'54" |
| K-71 | 36°10'54" | 78°52'24" |
| K-72 | 36°10'48" | 78°52'18" |
| K-87 | 36°11'00" | 78°51'24" |
| K-96 | 36°11'54" | 78°50'36" |
| K-98 | 36°12'06" | 78°50'54" |
| K-116 | 36°13'54" | 78°51'36" |

# GEOLOGY OF THE LATE PRECAMBRIAN FLAT RIVER COMPLEX AND ASSOCIATED VOLCANIC ROCKS NEAR DURHAM, NORTH CAROLINA

by

Keith I. McConnell

## (ABSTRACT)

Isotopic dating of zircons from the Flat River Complex in the Carolina "slate" belt north of Durham, N.C. shows this intrusive complex to be 650 ± 30 m.y. old. Modal analyses of granophyric groundmass compared to experimental data, the presence of vent breccias and related pyroclastic deposits, and consideration of age relations between the intrusive and extrusive rocks indicate that the Flat River was emplaced at very shallow levels (< 1 km) and acted as the source for most of the volcanic material surrounding the complex.

The age determined for the Flat River Complex indicates that deposition of the volcanic rocks began prior to 650 m.y. ago and extends the slate belt volcanicity interval to 130 m.y. (520 to 650 m.y. b.p.) Both subareal and marine depositional environments are represented in the stratigraphic sequence.

## EXPLANATION

Qa
Alluvial deposits

TR
Triassic sediments

Quaternary
Triassic

Metamorphism

Mpf | Mpd | Mpm

Moriah Pluton
Mpf, granodiorite and adamellite
Mpd, dacite
Mpm, quartz diorite and minor gabbro

h
h, hydrothermally altered rocks

Bsf | Bsm

Butner Stock
Bsf, granodiorite and adamellite
Bsm, quartz diorite

Flat River Complex

X
Intermediate to mafic lavas

Y
Thin bedded tuffs with interbedded hematite - magnitite - quartz

$A_1$
Intermediate volcanic rocks

Z
Felsic pyroclastic rocks

Late Precambrian

**Contact**
Long and medium dashed where approximately located, short dashed where inferred.

**Fault**
Dashed where approximately located.

**Planar Features**

30
Strike and dip of inclined bedding.

inclined vertical
Strike and dip of foliation and/or cleavage.

Strike and dip of post - metamorphic non - penetrative cleavage.

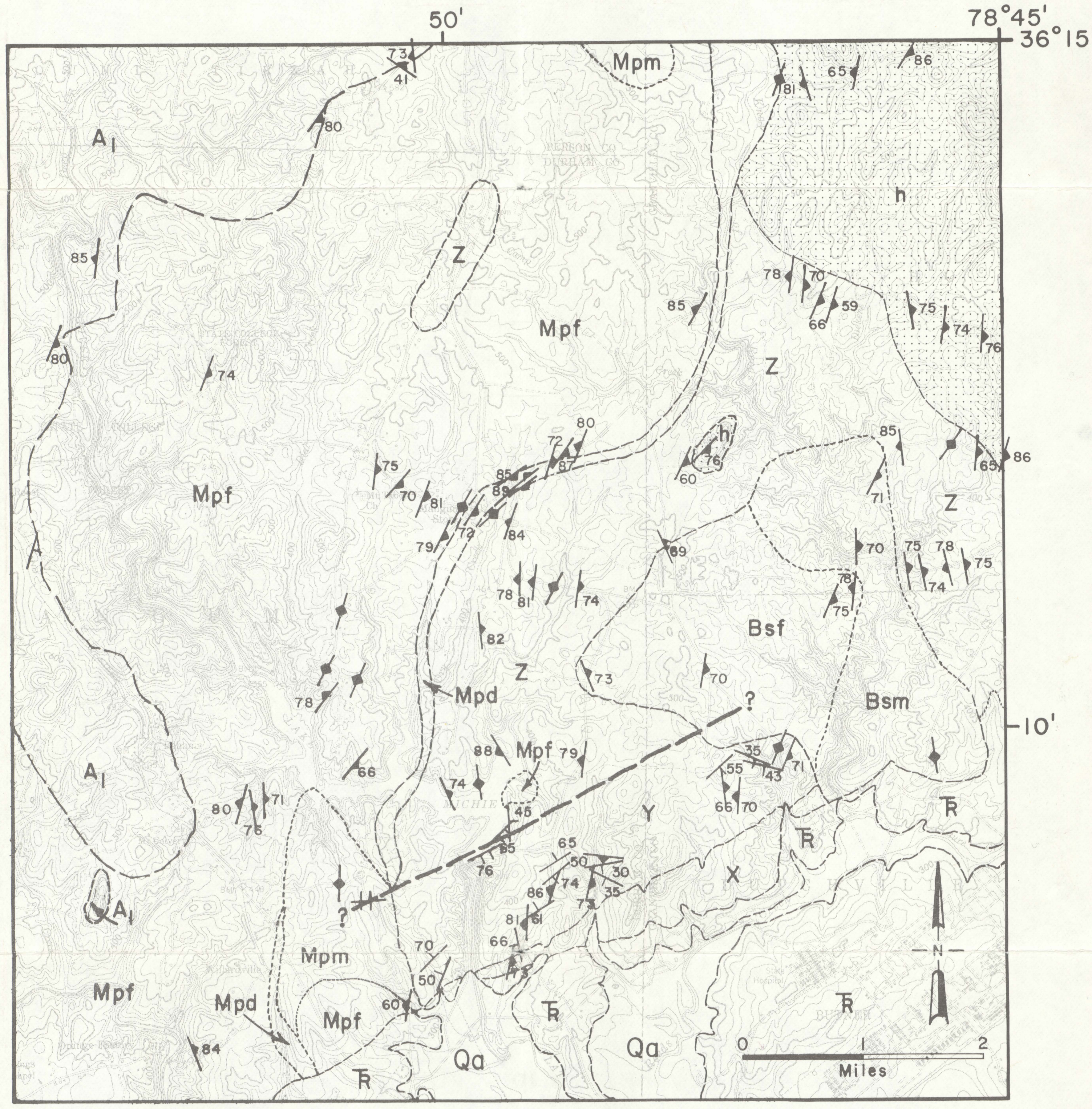

Fig. 5 Geologic Map of the NE Part of the Durham North, N.C. Quadrangle.