

TECTOGENESIS AND METAMORPHISM OF THE PIEDMONT
FROM COLUMBIA TO WESTVIEW, VIRGINIA ALONG
THE JAMES RIVER

by

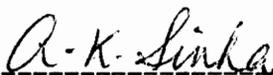
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in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
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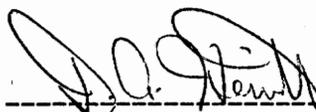
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To my mother: Mrs. Betty Bourland

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INTRODUCTION

General

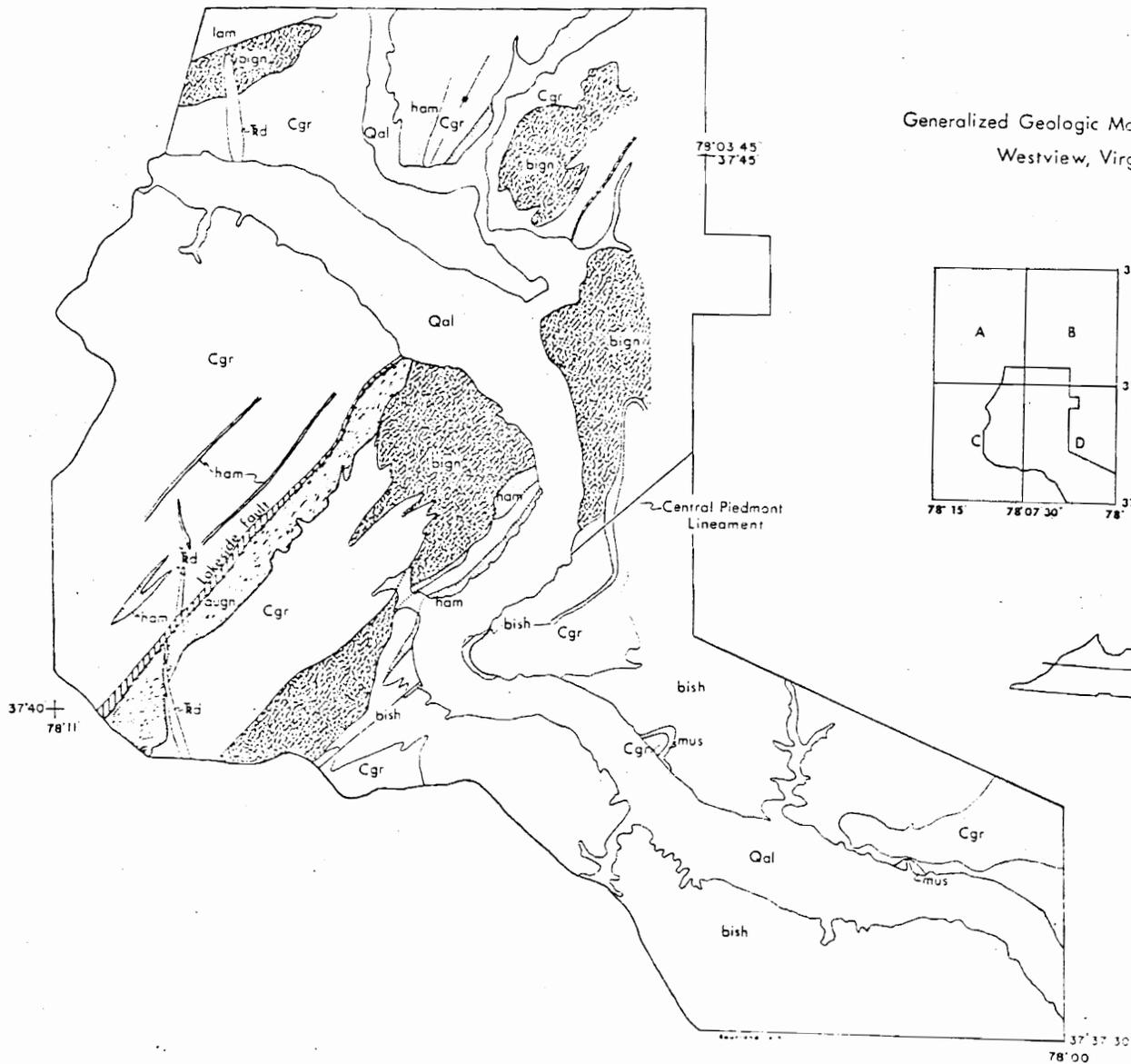
The Piedmont of east central Virginia is a geologically little known region between the better known Maryland and North Carolina Piedmont. The geology along the James River of central Virginia was studied in order to: 1) investigate the central Piedmont lineament as a possible root zone or suture zone, 2) determine the sequence of tectonic events, 3) determine the metamorphic facies and P-T conditions, 4) investigate the possibility of recent, possibly surface breaking faulting, along the central Virginia seismic zone, and 5) determine protolithologies and geologic history of the area. Encompassed by this traverse is the area from Columbia to Westview, Virginia along the James River and the area south of the River to Lakeside Village, Virginia, from latitude $37^{\circ} 37' 30''$ to $37^{\circ} 46'$ and longitude 78° to $78^{\circ} 10'$ (Plate 1 and Fig. 1). Mapping covers part of four 7 1/2 minute quadrangle maps, Columbia, Caledonia, Cartersville, and Lakeside Village.

Previous Work

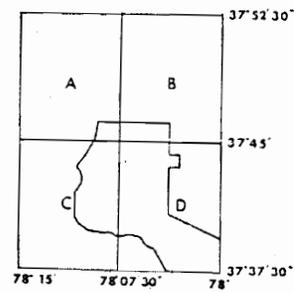
The geologic map of Virginia (1963) shows three units in this area, the Columbia metagranite, granite and hornblende gneiss, and schist. These units are based on mapping conducted by Taber, 1913, Jonas (1932), and Stose and Stose (1948).

Later publications by Smith, Milici, and Greenberg (1964) on Fluvana County, and Brown (1963, 1969), Brown and Griswald (1970), Brown and Rosa (1974), and Brown (1976) on the Dillwyn quadrangle,

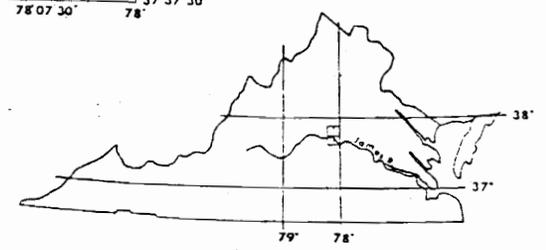
Figure 1. Generalized location and geologic map of the area along the James River from Columbia to Westview, Virginia.



Generalized Geologic Map From Columbia To Westview, Virginia



- 7 1/2 Quadrangles
- A Columbia
 - B Caledonia
 - C Lakeside Village
 - D Cartersville



indicated a complex set of lithologies just west of this area and several structural events previously unrecognized in the Virginia Piedmont.

Smith and others (1964) listed chemical analysis of the Columbia metagranite (reported from Taber, 1913) along with Rb/Sr data on K-feldspar and whole rock analyses. Fullagar (1971) provided additional Rb/Sr whole rock and mineral analyses from which he derived a consolidation age of the granite as well as a time of metamorphism. Of additional importance to the age relations in the region, are fossils found in the Ordovician Arvonian slate by Darton in 1892, by Watson and Powell in 1911, and by Tillman in 1970.

DESCRIPTION OF GEOLOGIC UNITS

Layered Lithologies

Biotite Gneiss (bign)

Biotite Gneisses interleaved with hornblende-biotite gneiss and pods of amphibolite and calc-silicate rocks are the oldest units in the area and comprise 1/5 of the surface outcrop. Biotite gneiss along with biotite-hornblende gneiss and amphibolite are found throughout the traverse along the banks of the James River and north and south of the river in the eastern half of the area (Plate 1). Calc-silicates occur in isolated layers in the biotite gneiss also accompanying amphibolite pods or layers. Biotite augen gneiss occurs in several areas where Columbia granite has intruded the gneissic terrain.

Biotite gneiss is equigranular to subequigranular and banded in light and dark layers. Layering is caused by the segregation of biotite and quartz-feldspar layers. Layers are usually 2-5 cm wide and are commonly cut by the injection of pegmatites. Foliation nearly always parallels layering. Biotite-hornblende gneiss is also banded and is similar to biotite gneiss in appearance, except that hornblende porphyroclasts are individually discernable in the dark bands, and are only rudely aligned to the foliation. Biotite-hornblende gneiss commonly occurs between the biotite gneiss and amphibolite as a compositional gradation between the two.

Major mineral abundances for both biotite gneiss and biotite-hornblende gneiss are listed in Appendix A, part I. Plagioclase (An₂₀₋₂₅) in the biotite gneiss has albite and carlsbad twinning and is

rarely zoned. Plagioclase and quartz are sutured and have a granoblastic texture. Microcline occurs as fractured small grains in the matrix or as large porphyroclasts surrounded by myrmekitic quartz and plagioclase. Biotite is both green and red-brown, either in clumps or small grains grown between plagioclase and quartz grains. Larger grains of biotite are foliated whereas smaller grains are randomly oriented. Muscovite and biotite are similar in size and occur individually or intergrown. Epidote occurs as euhedral, skeletal, or rounded grains in or near biotite and also as inclusions in quartz, plagioclase, hornblende, and garnet. Clinozoisite is the common epidote group mineral present; however, in thin section near hornblende, epidote is also present. A red-brown allanite is common as cores of the epidote grains. Garnets are not abundant in the biotite gneiss and are only slightly more common in biotite hornblende gneiss.

Biotite gneiss in the northwestern section of the traverse and in other scattered areas, is interlayered in a progression from granite to an amphibolite gneiss. In these sequences, scapolite occurs in the biotite and biotite-hornblende gneisses.

Augen Gneiss (augn)

Augen gneiss is a subordinate lithology (only 1/10 the outcrop area) of the biotite gneiss, occurring between biotite gneiss and metagranite and formed either as a result of granulation of the granite or from feldspathization of the biotite gneiss near granite intrusives. A similar augen gneiss reported by Brown (1969) is associated with the Hatcher complex and formed from granulation of the Hatcher monzonite/

diorite. Augen gneiss from the Dillwyn area and augen gneiss from the central and western portions of this traverse are therefore similar in occurrence and probably similar in origin. Perhaps augen gneisses and schists east of Cartersville and Pembroke (Plate I), in the central and eastern areas, are the same unit, but there are no exposures that would tie the east and west augen gneisses together, and the two units differ slightly in composition. All this seems to say there are two separate augen units of possibly different age. In addition, there is an augen gneiss that parallels and is cut by the Lakeside fault zone. This is the same augen gneiss retrograded and recrystallized because of its proximity to the fault zone.

Augen gneiss and retrograde augen gneiss have augen 2-20 mm in long dimension, common euhedral plagioclase (An_{25-30}) and rare microcline, embedded in a fine grained dark matrix. In thin section augen appear to have granulated borders and show strain effects, such as bent twin laminae.

Matrix material is a well foliated mass of biotite and muscovite, fractured grains of plagioclase and microcline, sutured grains of quartz in long curved lenses, and flattened tear shaped garnets (Appendix I, part A, sample CB5-269). Plagioclase averaged An_{25-30} and varies greatly, twins are commonly sheared and bent, and plagioclase is myrmekitic with quartz around microcline augen. Fractured microcline grains and microcline perthitic augen generally 4-8 mm in diameter show well developed grid twinning. Quartz has been recrystallized into flattened lenses or flattened and polygonized individual grains with wavy

extinction. Biotite is red-brown like that in biotite gneiss, and varies from 2-10 mm in length. Muscovite is intergrown with biotite, but may occur as single augen. Poikiloblastic muscovite is common with inclusions of quartz. Garnets are also poikiloblastic or euhedral unzoned individual grains. Some garnets are tear shaped and cut across the plane of foliation, appearing rolled or recrystallized in a field of flattening perpendicular to that of the foliation (Fig. 2). Although no epidote is found in the augen gneiss, an epidote rich layer occurs with it and is described in the section on calc-silicates and the migmatitic zone.

In addition to the systematic occurrence of augen gneiss between Columbia granite and biotite gneiss, a thick unit of augen gneiss is exposed paralleling the post-metamorphic Lakeside fault zone near Lakeside Village in the southwest area, striking northeast to the James River. In this belt of shearing and retrograde metamorphism, gneisses have a cataclastic and polymetamorphic texture which becomes more conspicuous as the fault zone is approached. Augen gneiss in this belt has been retrograded, and at the fault has been further sheared.

The augen gneiss has a mylonitic texture according to Higgins' (1971) classification. Quartz is highly flattened and polygonized or completely granulated. Most prophyroclasts (over 80%) are unzoned plagioclase (An_{25}), microcline and microperthitic clasts also are found, and uncommonly muscovite and biotite clasts occur. The matrix in order of abundance is quartz, plagioclase, biotite with secondary chlorite, muscovite, microcline, and epidote. These minerals have the same associations as those in augen gneiss found in other areas of the traverse

Figure 2. Tear shaped garnet normal to the foliation (sample CB5-269, mag x 250) quartz-plagioclase-K-feldspar-biotite gneiss.



except for the retrograde metamorphism.

Biotite is wholly replaced by chlorite as the fault zone is approached. On the outer portions of this zone, biotite is unaltered and augen are very elongate, but as the fault zone is approached, augen become smaller, more numerous, and more rounded, and chlorite pseudomorphed biotite. Near the fault augen are sericitized and chlorite is the dominant mica. Epidote is also retrogressive because it is only found in the matrix with chlorite and unlike epidotes in the biotite gneiss, it has no core of allanite.

In the Lakeside fault zone, the augen gneiss is cut by small fractures that cut individual augen and cut across the foliation. In these fractures are microbreccia fragments of quartz and heulandite. This second retrograde metamorphism indicates reactivation of the fault that produced a microbreccia in fractures, shearing of prior cataclastic fabric, and the retrograde mineral assemblage quartz-heulandite.

Hornblende Amphibolite (ham)

Amphibolite composed dominately of hornblende occurs interleaved with biotite-hornblende gneiss, biotite gneiss, and Columbia granite. At 40 percent hornblende in thin section, biotite is almost nonexistent; hornblende becomes the dominate mineral and therefore, rocks of this composition are designated hornblende amphibolite. From the east to west portions of the traverse, amphibolites occur in many forms, but there are two primary types: 1) A layered amphibolite (ham) is interleaved with biotite gneiss and granite, and occurs as xenoliths in the granite, and as blocks and pods in the migmatitic zone. (Plate 1).

2) Massive amphibolite (ham) occurs in the northern and western portions of the traverse usually near Triassic dikes. Types 1 and 2 are mapped as "ham" in Plate 1.

The main hornblende amphibolite (ham) is a layered sequence of feldspar-quartz layers with epidote or garnet next to black or dark green bands of amphibolite-plagioclase-epidote. Felsic layers are mosaics of quartz, plagioclase, and hornblende with abundant epidote, clinozoisite, garnet, and sphene. Plagioclase is generally An₂₅₋₃₀ but varies greatly. Hornblende occurs as small stubby flakes locally associated with retrograde chlorite or biotite. Hornblende is associated with epidote and clinozoisite and has cores or inclusions of both these minerals. Epidote forms skeletal grains and clinozoisite tends to be euhedral. Garnets, if present, are small euhedral, red-brown garnets.

Amphibolite (and felsic gneiss) layers range from a few centimeters to nearly a meter thick. Massive amphibolites are likely thick amphibolite layers in poor exposures. Hornblende grains (<1 mm to 6 mm) are poikilitic with inclusions of quartz, plagioclase, epidote and clinozoisite. Plagioclase An₃₀₋₅₅ occurs as (1 - 0.5 mm) grains between hornblende crystals. Epidote and sphene also occur as (1 - 0.5 mm) grains. Zircon, apatite and magnetite are common in these layers.

Laminated Amphibolite (lam)

Thinly laminated amphibolites are restricted to an area 2 miles east of Columbia on State Road 667. This rock has almost equal amounts of plagioclase and hornblende (Appendix A, Part III, Sample 134) and 22% calcite, its appearance and mineralogy make it a unique lithology from

the other amphibolite units. Megascopically and microscopically, this unit has the appearance of a metasedimentary rock. Foliation as in most amphibolites is poorly defined, but bedding may be discernible from the light and dark laminations. In addition, in thin section, it can be seen that pyrite and magnetite occur in disseminated layers parallel to the plane of layering. In several places in the outcrops pods (2 cm wide on the average) of garnets with amphiboles radiating from them can be seen.

The three main minerals are, hornblende, plagioclase and calcite. Hornblende is typically green-blue and occurs in grains 1 mm to 2 mm in length. Plagioclase (An_{35}) occurs as small grains in an interlocking pattern between layers of amphibolite. Layers of magnetite and pyrite occur with the plagioclase layers. Calcite is anhedral, and occurs between hornblende and plagioclase grains in both layers. Epidote occurs enclosed in longer hornblende grains.

This thinly laminated rock which occurs near Columbia, may be correlative with the amphibolites in the Columbia syncline (Smith and others, 1964).

Calc-silicate Rock (cas)

Calc-silicate rocks occur throughout the traverse (Plate 1) either as thin layered sequences or as pods and thin granofels layers. The best exposure of layered calc-silicate interleaved with granite orthogneiss occurs in a stream paralleling Route 605 south of Willis River (south-east portion of Plate 1). A continuous sequence of epidote and epidote-pyroxene pods occurs along the cliffs on the south bank of the James

along strike from the migmatite zone south of Elk Hill (central Plate 1). Pods or granofelsic layers of this nature occur near amphibolite in biotite gneiss and biotite schist along both banks of the James River.

The layered rock is banded with a conspicuous inner layer of quartz + calcite and an outer brown layer of biotite (Fig. 3). Foliation parallels this layering. Most commonly, these layered rocks are found along with hornblende amphibolite layers. Calc-silicates are compositionally zoned with varying amounts of quartz, plagioclase (averaged An_{35-55}), hornblende-actinolite, diopside, epidote, scapolite, biotite, chlorite, and garnets. Zoning is probably the effect of metasomatic diffusion during metamorphism (Vidale, 1969; Orville, 1969). Layering and the internal as well as lateral continuity suggest an original sedimentary protolith.

Quartz and calcite usually form the internal layer or the central portions of pods. Quartz and plagioclase in an interlocking mosaic, occur in every zone. Plagioclase varies in composition from andesine to labradorite but does not seem zone dependent for composition. Diopside, along with layers of 80% clinozoisite are also internal layers, while layers rich in amphibole combined with diopside, chlorite, and biotite tend to be in external layers. Clinozoisite may occur in any layer commonly as 4-5 mm long skeletal grains. Biotite is nearly always a red-brown variety like that in the biotite gneisses. Sphene also occurs in every zone associated with biotite and/or epidote. Magnetite and apatite as well as zircons are present throughout.

South, along strike from Elk Hill pods of completely epidotized

Figure 3. Layered calc-silicate rock (CB6-46). The layers are approximately 1-2 cm thick in this specimen. The inner layer is quartz-calcite-plagioclase-sphene-epidote, and the darker outer layer is biotite-quartz-scapolite-plagioclase-epidote-actinolite. (mag x 2.25)



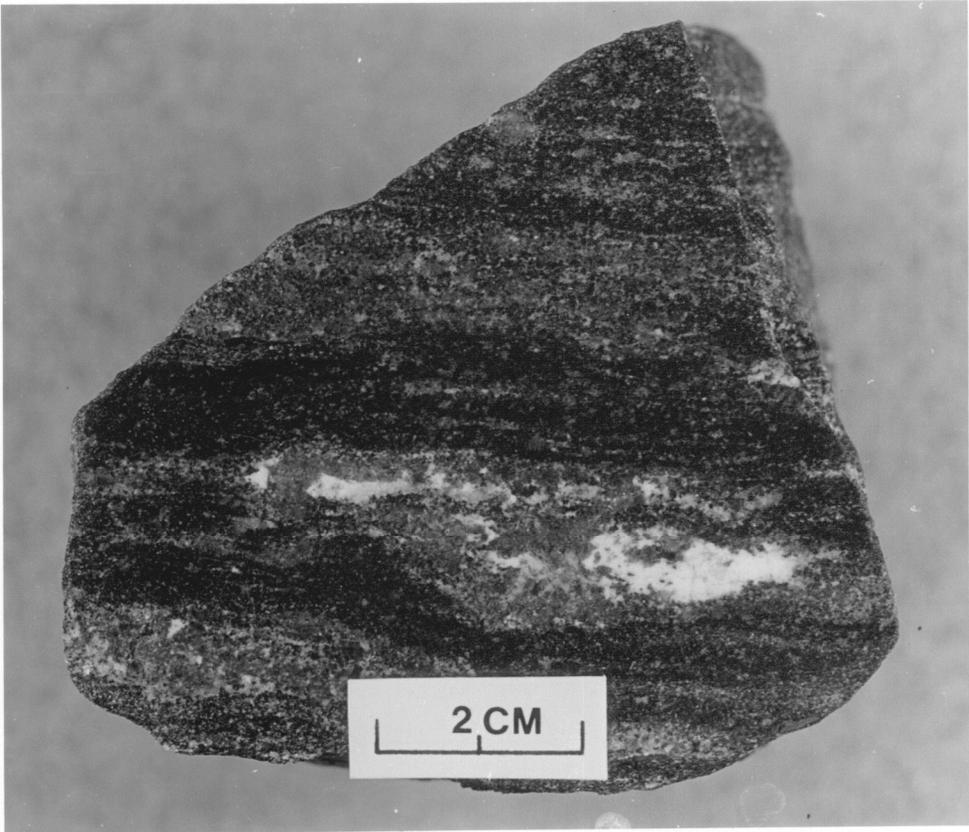
amphibole (Fig. 4) are found along with biotite schist and gneiss and amphibolite layers. These pods (1 m across the long dimension) are augen shaped and look as if they were pipes through the surrounding rocks. Epidotization could therefore, be either the result of local alteration or a metamorphic segregation that reflects an original compositional difference.

Biotite Schist (bish)

Biotite schist is interlayered with granitic rocks throughout the southeastern half of the traverse. Biotite gneiss (20% biotite) passes into biotite schist (35-45% biotite) going towards Cartersville in the central portions of the traverse (Plate 1). There appears to be a gradational contact between biotite gneiss and biotite schist. In this same area, biotite schist, muscovite schist, muscovite-sillimanite schist, and biotite-garnet schist are interlayered, and intruded by metagranitic rocks. Where schists were intruded, a biotite-augen schist that has large unrounded clasts was formed. Biotite schist in this traverse is distinguished from biotite gneiss by containing more than 30% biotite and displaying less of the layered texture of the gneisses farther north.

Strongly foliated biotite and muscovite folia are interleaved with granoblastic folia composed of quartz, plagioclase (An_{25-55}), biotite and garnet (Appendix A, Part III). Prophyroclasts of plagioclase (An_{25}) are common in biotite augen schists and occur scattered throughout the biotite schists. General description of the biotite augen schist is the same as that for the biotite augen gneiss only with an increase in the

Figure 4. Layered epidotized amphibolite rock (CB5-180). Lighter layers are epidote and plagioclase, the darker layers are hornblende and diopside. (mag x 1.4)



amount of biotite and muscovite in the ground mass. Garnets are anhedral tear shaped to ameboid, poikilitic with inclusions of biotite and quartz. Elongated garnets are oriented normal and parallel to the foliation in the biotite. Sillimanite needles (fibrolite) are found around garnets in biotite schists near the bend of the James River.

Muscovite Schist (mus)

Muscovite schist occurs with biotite schist and in isolated localities on both sides of the James River in the eastern half of the traverse. Muscovite schist from the area around the big bend in the James River 1-1½ miles west of Cartersville, Virginia has sillimanite in the muscovite folia; there is little K-feldspar present, so the sillimanite suggests a mineral assemblage near the first sillimanite isograd.

Muscovite may compose 90% of the rock, but more commonly is 50% and is intergrown and crosscutting with biotite folia (Appendix A, Part III).

Folia of biotite (red-brown) are interleaved with granoblastic folia of quartz and plagioclase (An₂₀). In muscovite schists from the far eastern portion of the traverse, small pods of quartz or thin (1-2 cm) layers of quartz occur in masses of muscovite. Garnets are rounded and have granulated borders. Chlorite replaced biotite locally in the mica folia. Along small fractures in the muscovite schist, pyrite and magnetite occur with quartz. Zircons and apatite are accessory minerals.

Chlorite Schist (csh)

Occurrences of chlorite schist (greenstone) are limited to small areas barely large enough to be map units. One area is approximately 0.5

miles southeast of Elk Hill, Virginia (central portions, Plate 1) where chlorite schist is interleaved with biotite augen gneiss and biotite-hornblende gneiss and not far removed from a zone of biotite schist. The second occurrence is along the south banks of the James River near the big bend (central portion, Plate 1). This thin (40-80 ft. thick) layer of schist has a sharp contact with Columbia granite and grades into an amphibolite interlayered with biotite-augen schist and biotite gneiss. In this vicinity, chlorite schist is probably a retrograded amphibolite gneiss.

Mineralogically, chlorite schists from both localities are the same. This soft green rock is primarily chlorite after amphibole (Appendix A, Part IV). The amphibole is usually zoned with a core of pleochroic hornblende and a nonpleochroic outer rim of tremolite (Appendix B, Part III, probe analysis and Fig. 10). Talc occurs in small rounded masses in bundles of chlorite, and some small grains of diopside are associated with talc. Clinozoisite is common in both localities, and in the second may be associated with a general trend towards epidotization in other amphibolites. Magnetite is the major opaque mineral associated with some pyrite. Chlorite schists have one foliation paralleling regional foliation incised by individual chlorite folia, and a second incipient crenulation cleavage seen in outcrop.

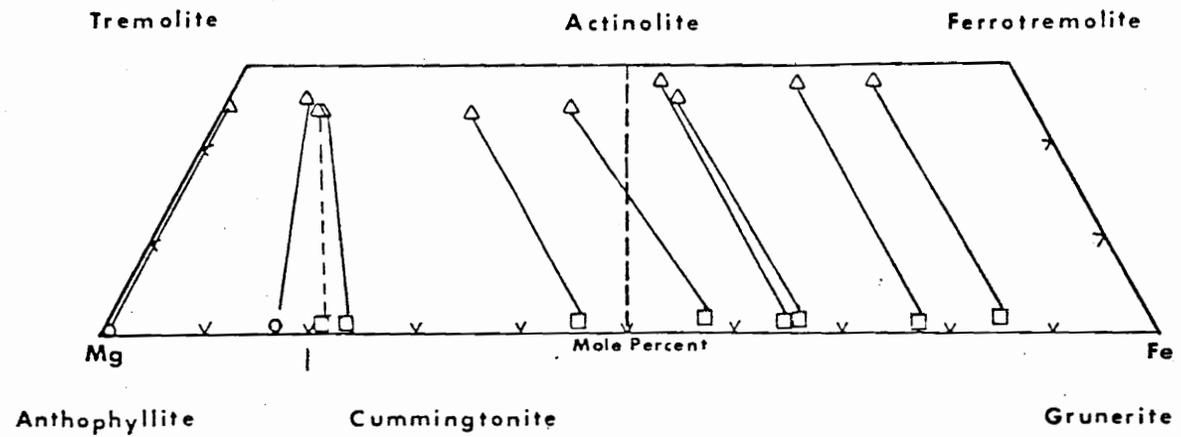
Ultramafic Rocks (ulm)

Meta-ultramafic rocks occur as chlorite-amphibolite-talc pods throughout the far northwestern portions of the Columbia metagranite in this traverse and along both flanks of the Hardware Anticline in the

Dillwyn Quadrangle (Brown, 1969). These bodies shown on Plate 1 are 50-100 feet in diameter and occur as long (0.25 miles at maximum) ridges in the forks of streams or as interlayered segments along with amphibolite xenoliths in the granite.

Ultramafic pods are grayish-green schistose rocks composed of chlorite and talc with minor amounts of tremolite, and red spots composed of cummingtonite and anthophyllite (?) (Appendix B, Part II, probe analysis of ultramafic, and Fig. 5). Chlorite and talc are primarily metamorphic derivatives of the amphiboles; however, some talc may be pre-metamorphic. Magnetite and chromite are common in some locales as small disseminated grains. Even in thin section, it is difficult to discern one penetrative foliation, but there is a layering between chlorite folia.

Figure 5. Amphibole quadrilateral after Cameron (1975) for coexisting amphiboles that contain less than 2.5 wt. percent Al_2O_3 and 1.8 wt percent MnO. Dashed line indicated the position of the actinolite-tremolite and cummingtonite (or possibly anthophyllite) join found in the ultramatics of this traverse. Symbols: circles, anthophyllite; squares, cummingtonite-grunerite; triangles, tremolite-actinolite.

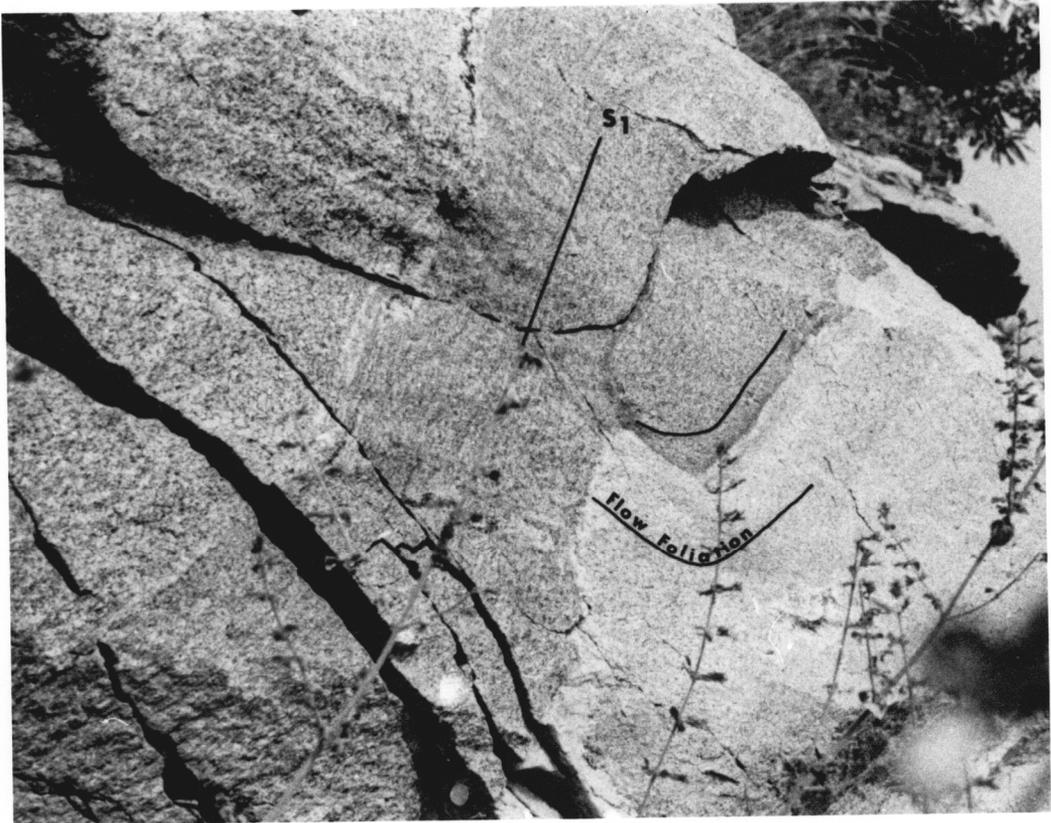


*Intrusive Rocks*Columbia Metagranite (Cgr)

Layered lithologies (i.e. biotite gneiss, hornblende-biotite gneiss, hornblende amphibolite, biotite schist, and the calc-silicate pods) are invaded by extensive locally concordant and discordant plutonic rocks ranging in composition from tonalite to granite (Fig. 6). Contacts between granitic rocks and the enclosing rock are concordant in detail and the granite therefore appears to be an interlayered lithology. However, in certain outcrops, large xenoliths of biotite gneiss, amphibolite, and calc-silicates are found, and on the west flanks of the Columbia syncline the Columbia metagranite clearly intrudes the Chopawamsic volcanics (Higgins 1973, Smith and others 1964). Where the granite has intruded the gneissic terrain in the central portion of the area, a migmatitic zone developed, and near this zone the enclosing rocks are cut by myriad dikes, pods, and clots of pegmatite. A similar description is suited to schists in the eastern half of the traverse that are interleaved with granite.

The granitic unit in this region was first named the Columbia granite by Jonas (1932), although Taber (1913) mapped and reported chemical analyses for a granodiorite at Columbia, Virginia. Smith and others, (1964) identified the Columbia granite as a "granodiorite unit." Brown (1969) recognized the Columbia as a metagranite and proposed the name Hatcher complex for intrusive plutonic rocks of this area. Brown suggested the renaming of the unit based on possible confusion with the sedimentary Pleistocene Columbia Group. Because it seems unlikely that

Figure 6. The Columbia Metagranite from the Cowherd Quarry showing an apparent flow foliation and S_1 foliation. This location is just within the city limits of Columbia, Virginia.



Columbia granite and Columbia Group sediments will be confused, and because there is no discrepancy with the American Commission on Stratigraphic Nomenclature (1961) the modified name Columbia Metagranite will be used herein.

Tonalite from the Cowherd Quarry as well as granite and granodiorite from the northern and southern portions of the traverse are fine to medium grained, light gray with a well developed foliation. Foliation is defined by 0.5 mm long biotite flakes, or larger masses of biotite and small green epidote grains in the biotite folia. In the Cowherd Quarry there are isolated knots and layers of biotite formed from the dikes and the segregation of minerals from xenoliths of biotite gneiss and amphibolite. There is also an apparent flow foliation between autoliths of granite (Fig 6). In areas away from the Cowherd Quarry, xenoliths and autoliths are rare and no flow foliation is evident, however, there is a well developed second foliation that is rather consistent throughout the area (refer to structure section and Plate 1).

The Columbia Metagranite is typically an inequigranular mosaic of quartz, plagioclase, and microcline (Appendix A, Part V). The texture is predominately granoblastic with random 0.1-1 mm small flakes of biotite and muscovite with random grains of epidote. Plagioclase is the primary feldspar in granite from the Cowherd Quarry, but from other localities has approximately the same abundance as microcline (Appendix A, Part V). Plagioclase varies in An content from An_{15-30} . Plagioclase may be faintly zoned and shows well developed albite and Carlsbad twins. Microcline formed small irregular grains intergrown between plagioclase and quartz grains, and in some localities, formed porphyroblasts very

similar to those in the augen gneiss.

Biotite forms small stubby green-brown flakes randomly oriented in the granoblastic framework. Biotite and muscovite are intergrown or occur as fringes on biotite groups, this gives muscovite the appearance of having formed after biotite (Appendix A, sample 14). Larger muscovite grains (1-4 mm) have a mottled texture and are commonly oriented normal to the foliation of the biotite. Epidote is found along with biotite and muscovite and within biotite clumps. Allanite forms the cores of large skeletal epidote grains. Around muscovite and epidote are ameboid calcite grains. Calcite is also found around anhedral garnets. Pyrite and magnetite may be seen in some localities. Zircons and apatites are found in minor amounts.

Both biotite gneiss and amphibolite are found as xenoliths in local outcrops of granite. Amphibolite, especially in the southwest section of the area, regionally crops out as long pods in the granite, but neither the xenoliths nor pods of layered rocks show a discordant foliation to that of the granite. Chilled contact zones are common around amphibolite xenoliths and some calc-silicate layers.

Outside of this traverse on the western flanks of the Columbia syncline, the Columbia granite intrudes volcanics, probably Chopawamsic volcanics or a contemporaneous unit (Higgins, 1973; Smith and others, 1964; Brown, 1976). Because the grade of metamorphism is lower (greenschist) (Smith and others, 1964) than that along this traverse, it is easier to observe the effects of the intrusion of granite into volcanics. These volcanics appear to be shallow surface extrusives that have been

discordantly cut by the Columbia Metagranite possibly their source or a shallow level pluton of contemporaneous origin (Higgins, 1972). Both the volcanics and granite in this area are sodic.

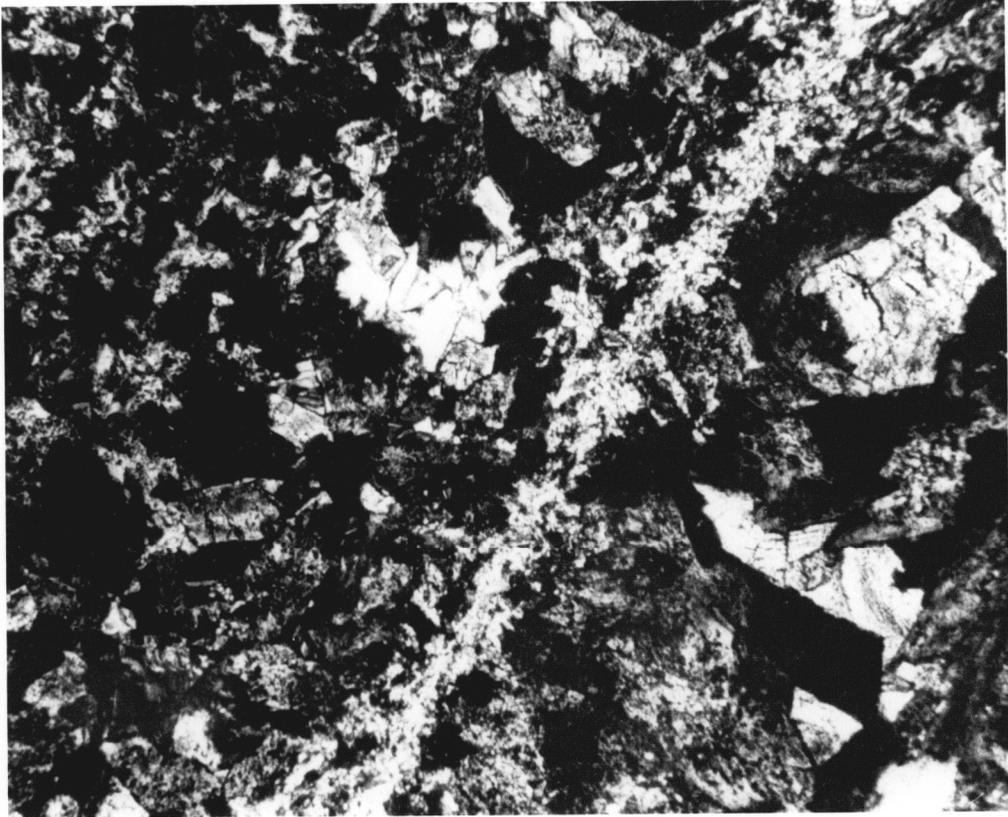
Retrogressed Columbia Metagranite From the Lakeside Fault Zone

Retrogressed granite found along the Lakeside fault zone has a more equigranular texture and appears coarser grained than granite from other areas. Plagioclase and microcline occur as finely ground grains with strained quartz (Appendix A, Part V). Muscovite only occurs in isolated patches. Chlorite has apparently replaced biotite throughout the granite close to the fault. Epidote and chlorite occur near fractures, and fractures are filled with hematite veins that show slickensides.

Fractures cut across the foliation of the granite and may even shear individual plagioclase grains. In these fractures, is a microbreccia of sheared quartz grains and small amounts of prehnite and zeolite (heulandite (?)). In one locality, quartz radiates into the fractures with prehnite filling the inner spaces (Fig. 7), and in this same sample, small grains of adularia can be found.

There are two retrograde mineral assemblages in granite which indicate reactivation of the Lakeside fault. The first is a greenschist retrogression of biotite to chlorite yielding some magnetite, and displaying the chlorite-epidote mineral assemblage in some fractures. The second assemblage consists of prehnite and strained quartz filling fractures that cut across earlier mineral assemblages. Lowering of temperature during movement along the fault is indicated by the presence of zeolite and prehnite filling small hairline fractures along the fault.

Figure 7. Photomicrograph of prehnite and quartz filling in a fracture (CB6-52) in the Columbia Metagranite. The light layer cutting across the photograph diagonally is prehnite. (mag x 630).



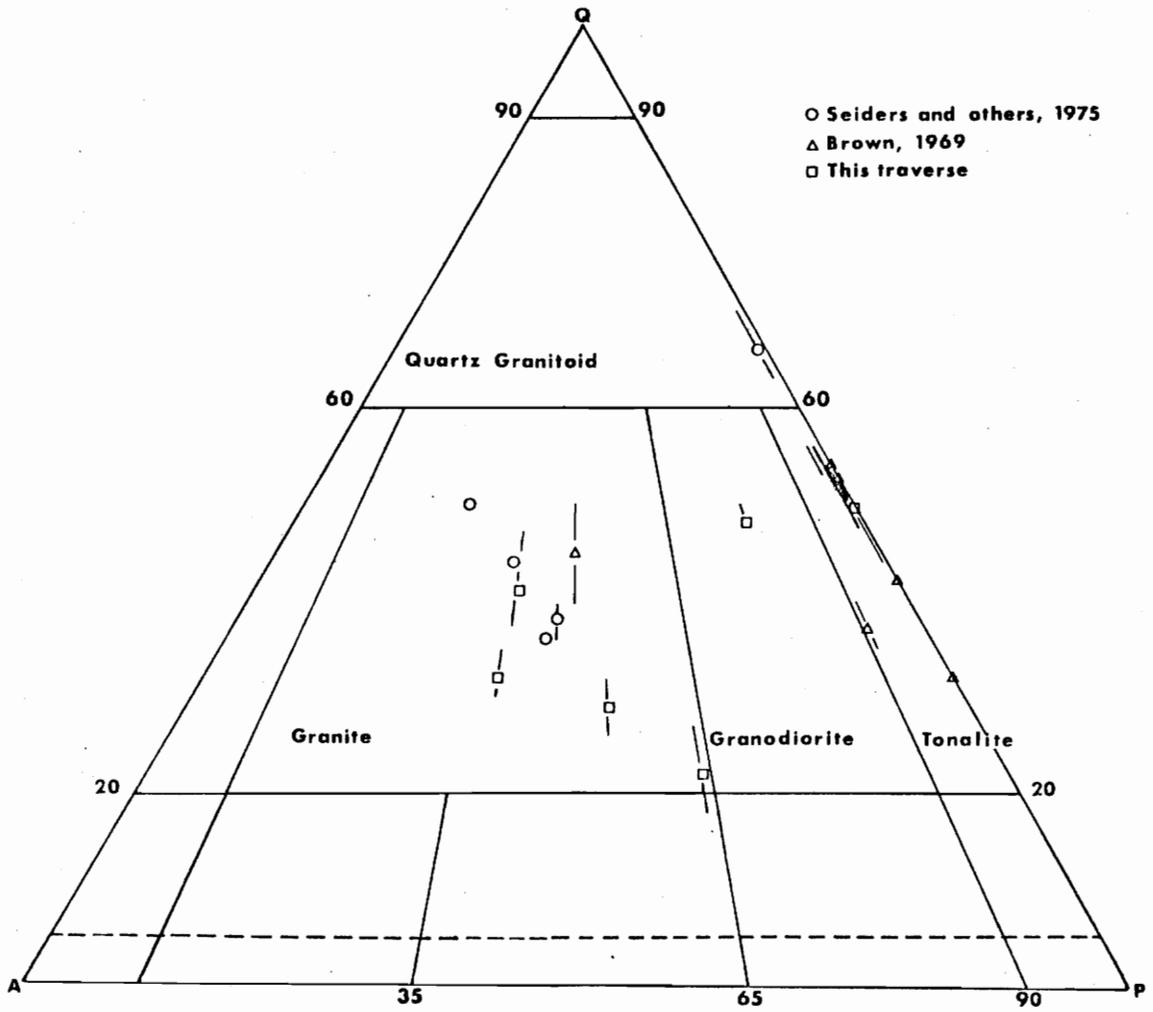
Modal and Microprobe Analyses

Microprobe analyses for the Cowherd Quarry sample of Columbia Metagranite along with its modal analyses and modes for a selection of granites across the traverse are given in Appendix A, Part V. Modal analyses for Columbia Metagranite from the Dillwyn Quadrangle (Brown, 1969) and this traverse along with modes for the Occoquan adamellite (Seiders and others, 1975) are plotted on a QAP graph (Fig. 8) like that upon which the IUGS systematic classification for igneous rocks is based (Geotimes, 1973, p. 26). Intrusive rocks from these areas are similar in age (Seiders and others, 1975) and composition. Rocks from both areas appear to have a bimodal distribution in composition being either tonalites or granites. Using Brown's (1969) modes and the modes of granites from this area, there is an apparent shift from tonalites in the Dillwyn Quadrangle, to granite compositions along this traverse. There is no field evidence to suggest that there are two magma series or even different plutons involved.

Age of the Columbia Metagranite

There are several reported ages for the formation of the Columbia Metagranite (Smith and others, 1964). Fullagar (1971) using Rb-Sr whole rock data, combined with whole-rock Rb-Sr ratios from Smith and others (1964), derived a whole rock age of crystallization for the Columbia Metagranite of 590 ± 80 m.y. Using mica and K-felspar plus the whole-rock data, an isochron (Fullagar, 1971, p. 2850) yields an age of 342 ± 70 m.y. for the metamorphism. Sinha (personal communication, 1976) has a 547 ± 10 m.y. date on a zircon sample from the Columbia that he

Figure 8. Quartz (Q) - K-feldspar (A) - plagioclase (P) diagram comparing modal analyses of the Columbia Metagranite from this traverse and the Dillwyn Quadrangle (Brown, 1969) and the Occoquan adamellite (Seiders and others, 1975). Modal percentages are listed in Appendix A, Part V. Lines through the symbols indicate the percent biotite in the samples, percentage being read directly from the graph between the two ends of the line.



believes is the age of crystallization.

Fossiliferous Arvonian Slate unconformably overlies the Columbia Metagranite and also gives a younger age limit on the Columbia Metagranite. Evidence for an unconformity (Brown, 1969) is based primarily on two observations: 1) the garnet zone at the terminus of the Arvonian syncline parallels the regional structure more closely than the contact zone and 2) there is a conglomeratic quartz-mica schist at the base of the Arvonian Formation (Taber, 1913; Brown, 1969; and Rodgers, 1970, p. 193). Late middle to middle late Ordovician fossils found in several areas in the Arvonian Slate (Darton, 1892; Watson and Powell, 1911; Stose and Stose, 1948; Tillman, 1970) indicate that the granite is older than late Ordovician. Because the foliation throughout this traverse can be traced into the Arvonian syncline (Glover, personal communication) the regional metamorphism must be younger than late Ordovician. Therefore, the original age of crystallization 547 ± 10 m.y. and age of thermal peak 342 ± 70 m.y. agree with fossil ages.

There are 2 foliations in the Columbia Metagranite both close to the major foliation in this area, similar to the two foliations of the Occoquan Adamellite (Seiders and others, 1975). However, locally, the S_1 foliation in the Columbia is a flow foliation which is parallel to the regional stress foliation, suggesting some recrystallization of the granite at the time S_1 was being locked in. This may indicate remobilization during the 342 ± 70 m.y. thermal peak.

Pegmatites (peg) and Migmatites (mig)

Pegmatites from this traverse are of two types; foliated and

nonfoliated. Both are compositionally granitic with some exception where pegmatites are found in or next to amphibolites. Foliated pegmatites (pre-S₁) are commonly found folded along with amphibolites and in some areas the foliated species is found with a foliation parallel to biotite gneiss. Nonfoliated pegmatites (post-S₂) are the most numerous. Large nonfoliated pegmatite bodies nearly 0.2 km wide and 0.5-2 km long are found north of Byrd Creek in the northwest portions of the traverse in the same area Brown (1937) referred to as the "pegmatite belt." Other nonfoliated pegmatites are numerous, small (less than 1 foot) veins cutting across amphibolites and biotite gneiss, showing as many as three crosscutting generations of pegmatites. During weathering, these pegmatites form ridges where they are massive. Foliated pegmatites (pre-S₁) are found in the northwest parts of the traverse, while the nonfoliated pegmatites (post-S₂ or S₃) are found in every lithology throughout the traverse.

Both species of pegmatite are similar in chemical composition (Appendix A, Part V) being rich in microcline and having small amounts of plagioclase and muscovite. Microcline is coarse grained in the nonfoliated pegmatites, 0.5-10 cm wide, surrounded by a finer grained matrix of plagioclase and quartz. Muscovite is in small flakes interstitial to the large microcline crystals.

Pre-S₁ pegmatites are finer grained and equigranular. Microcline, the dominate mineral, sometimes forms large clumps but more commonly small individual grains surrounded by myrmekitic quartz-plagioclase. Allanite commonly has rims of epidote. Muscovite is in the form of long

(averaging 3 mm) skeletal flakes very well foliated. These rocks have a layered appearance with the muscovite segregating feldspar-quartz layers. Near amphibolites, pegmatites become more abundant in plagioclase. In biotite gneiss pre-S₁, pegmatites are parallel to the layering of the gneiss and have very little mica. Garnet as large as 3 mm can be found in pegmatites in the biotite gneiss.

Pegmatites increase in abundance toward a migmatitic zone approximately 1 mile south of Elk Hill, Va. From field evidence, it appears that this region has been injected by late stage material from the Columbia Metagranite. Large disoriented blocks 5-10 feet across of biotite gneiss and amphibolite are cut and separated by myriad aplitic pegmatites. Some of the amphibolite blocks show contact rims rich in epidote and biotite, while the biotite gneiss blocks have concentrations of biotite on their outer rims. Even the small blocks of granite that are found in this zone are cut by pegmatites. Either there is no consistent foliation in the pegmatites, or the various blocks have been rotated. Drag folds on a scale of 2-5" can be seen along the sides of some of the larger blocks. Smaller ptygmatic pegmatites (post-S₂ or S₃) cut through the larger veins and across the blocks. Areas adjoining the migmatitic zone are augen gneisses and schists with augen increasing toward the migmatite. Approximately 1.5 miles southeast of Pemberton in the southeast section of the traverse, pegmatites are abundant and the calc-silicates in this area are boudinaged. The predominate lithology is an augen schist. Here also pegmatites are in cross-cutting ptygmatic folds as well as folded along with the foliation. Throughout this area, it appears that the granite has injected the original

lithology, and pegmatites accompanied and post dated injection of the granite.

Triassic Diabase Dikes

Diabase dikes occur in the western half of the traverse (Plate 1). Diabase dikes, often cited as Triassic dikes, are common throughout the Piedmont all along the east coast of the U.S. (Weigand and Ragland, 1970). Specifically, from this region, both Brown (1969) and Smith and others (1964) report diabase dikes from their areas. Diabase dikes are considered Triassic or possibly younger because they commonly intrude Triassic sediments; however, none have been observed intruding Cretaceous rocks. Weigand and Ragland (1970) report radiometric ages of 200-230 m.y. for dikes scattered throughout the Piedmont.

Triassic dikes from this area intrude the Columbia Metagranite and the hornblende amphibolite. Dikes range from 3 meters thick to 300 meters thick and vary from a few meters long to nearly 1,700 meters. Generally, the dikes strike $N5^{\circ}-10^{\circ}W$ but several are N-S, while only a few smaller dikes strike northeast (Plate I).

Diabase rocks are dark green or black and generally fine grained. They have rectangular joint patterns and weather to spheroidal boulders. Dikes are subophitic to ophitic with laths of labradorite composing 40-60 percent of rock. Pyroxene is pigeonite with limited augite and rare orthopyroxene. Olivine is subophitic to microporphoritic, between plagioclase laths. In the dike from along the Willis River biotite and chlorite, are interstitially present probably as alteration products. Magnetite and ilmenite occur in small amounts.

METAMORPHISM

Regional Metamorphism M₁

Structurally and metamorphically, the section of the Piedmont studied in this traverse appears to have experienced a single prograde metamorphic event. Based on Rb-Sr ages of the Columbia Metagranite from the Cowherd Quarry (Fullagar, 1971 and Sinha, 1976 personal communication) and ages from other lithologies from other Piedmont localities (Higgins, 1973; Hopson, 1964; Pavlides, 1976) this metamorphism occurred at approximately 350 m.y. A single pervasive regional foliation, corresponding to this metamorphism, can be found in both the metagranite and country rocks of this traverse.

The prograde metamorphic assemblages of the area belong to the middle to upper amphibolite facies of a kyanite-sillimanite facies series (Fig. 9). Only sillimanite has been recognized in this region of the traverse, but kyanite has been described 1 mile north of the Cowherd Quarry (Smith and others, 1964) and a few miles to the SW in the Arvonian syncline.

Poly-deformed biotite and muscovite schists containing sillimanite occur with boudins of calc-silicate (containing tremolite and diopside) along the margins of a migmatitic zone in the southeastern section (~ 1 mile east of Pemberton, Va.). Boudins of calc-silicate pods next to the migmatitic zone and interlayered with schists, show the metamorphic reaction:

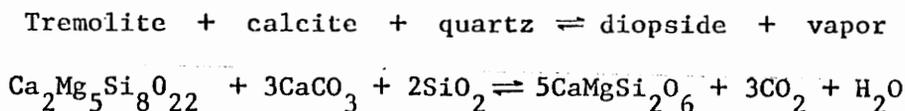
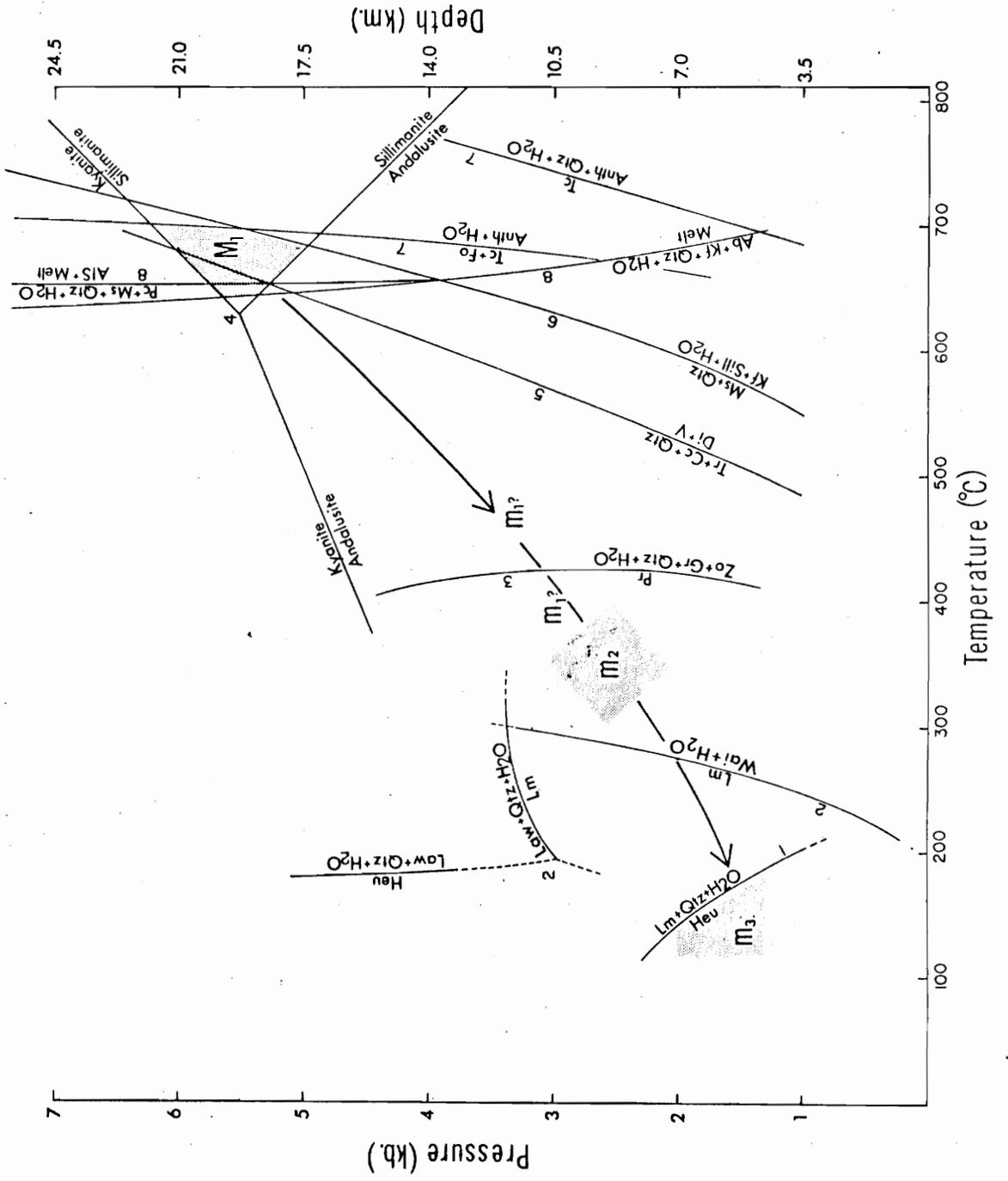


Figure 9. Diagrammatic representation of metamorphism in this traverse. M_1 is the regional metamorphism, and m_1 , m_2 , and m_3 are the retrograde assemblages found along the Lakeside fault and the Central Piedmont Lineament. 1) laumontite + quartz + $H_2O \rightleftharpoons$ heulandite, Thompson, 1971. 2) heulandite \rightleftharpoons lawsonite + quartz + H_2O Liou, 1971(a and b) 3) prehnite \rightleftharpoons ziosite + garnet + quartz + H_2O Liou 1971 (a and b) 4) alumino-silicate triple point Richardson and others, 1969. 5) tremolite + calcite + quartz \rightleftharpoons diopside + vapor, Slaughter and others, 1975. 6) muscovite + quartz \rightleftharpoons K-feldspar + sillimanite + H_2O , Chatterjee and Johannes, 1974. 7) talc + forsterite \rightleftharpoons anthophyllite + quartz + H_2O and talc \rightleftharpoons anthophyllite + quartz + H_2O , Evans and Trommsdorff, 1970. 8) albite + K-feldspar + quartz + $H_2O \rightleftharpoons$ melt and plagioclase + muscovite + quartz + $H_2O \rightleftharpoons$ melt, Merrill and others, 1970.



Diopside and tremolite occur in the cores of calc-silicate pods and in the outer layers of the pods they occur with clinozoisite, scapolite, plagioclase, and quartz. Temperature and composition of CO_2 for this reaction at 5 kb was determined by Slaughter, Kerrick, and Wall (1975). Temperature reaches a plateau at around $630^\circ \pm 10^\circ\text{C}$ between X_{CO_2} 30-80%. If Slaughter and others (1975) work is extrapolated to 6 kb, the temperature plateau is around $680^\circ \pm 15^\circ\text{C}$. Overlapping stability of the diopside-tremolite reaction and sillimanite stability field limits the pressure to $5-6\frac{1}{2}$ kb (Fig. 9). This is in close agreement with the granite minimum melting conditions and therefore an estimate of 5.5 ± 1 kb at $650 \pm 30^\circ\text{C}$ appears to be a reasonable one for this area. Variations in fluid compositions are inferred for the area based on the necessity of a CO_2 -rich fluid in the calc-silicates along with the need for a relatively H_2O -rich fluid in the clinozoisite pods and in the migmatites.

Rocks adjoining layered calc-silicates in the south central part of the traverse (CB6-46 on Plate 1) contain the metamorphic assemblage quartz, plagioclase (An_{20}), biotite, garnet, hornblende, and cummingtonite rimmed by hornblende. Garnets are rolled and have internally folded layers of magnetite. The hornblende, cummingtonite, garnet assemblage is like that found in metabasite terrains (Miyashiro, 1973) of moderate pressure, amphibolite facies.

In the western portions of the traverse south of Columbia metamorphosed ultramafic pods occur that contain the assemblage chlorite-talc-anthophyllite(?)-tremolite-cummingtonite. Microprobe analyses (Appendix B, Part II) plus x-ray diffraction and optical determinations indicate the presence of two amphiboles, cummingtonite and tremolite and possibly anthophyllite as a third phase. Large patches of amphibole show exsolution of either anthophyllite or cummingtonite after tremolite.

Anthophyllite-cummingtonite-talc coexist at 6 kb from 650^o-780^o $P_{H_2O} = P_{total}$ (Evans and Tromsdorff, 1970). However, variations of P_{H_2O} less than P_{total} can result in the formation of anthophyllite at lower temperatures (Greenwood, 1963). Schists from Cima di Gagnone, Ticino, Switzerland (Rice, Evans, and Tromsdorff, 1974) contain ultramafics with a tremolite-cummingtonite-anthophyllite assemblage in a talc-chlorite schist, very similar to ultramafics in this traverse. In addition, the schists are surrounded by pelitic rocks containing kyanite-staurolite-garnet-muscovite-quartz, metabasic containing almandine-hornblende-andesine, and marbles with diopside-forsterite. Grade of metamorphism in the Cima di Gagnone area and this region is middle to upper amphibolite facies.

Mafic composition rocks, biotite gneiss and biotite-hornblende gneiss contain a biotite, hornblende, garnet, epidote, and quartz assemblage in apparent equilibrium with plagioclase of An_{20-25} . Biotite-hornblende gneiss contains calcic scapolite ($n = 1.56 - 1.57$) similar to that in other middle to upper amphibolite facies terrains. (Shaw, 1960; Knorring and Kennedy, 1958).

M₁ which represents the major prograde metamorphism of the region reached temperatures of $650 \pm 30^{\circ}\text{C}$ and pressures of $5.5 \pm$ kb at about 340 m.y. ago.

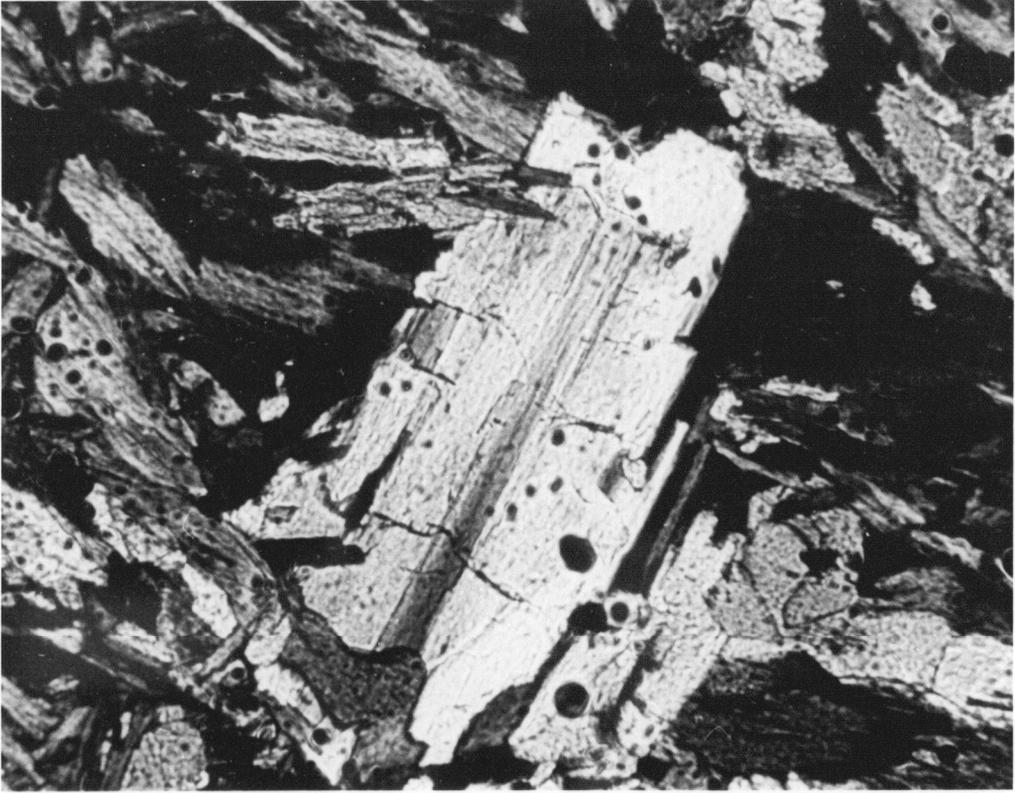
Retrograde Assemblage m₁

Low grade mineral assemblages occur as a result of retrogression along the Lakeside fault and Central Piedmont Lineament. Retrogression was promoted by shearing which periodically opened these rock systems to the effects of water and lower regional temperature and pressure.

Lithologies on both sides of the Lakeside fault show greenschist metamorphism. In the augen gneisses south of the fault, chlorite is associated with clinozoisite and zoisite paralleling and replacing the original foliation and infilling fractures close to the fault zone. A similar retrograde assemblage occurs in the granite along the fault zone where chlorite has replaced biotite and muscovite, and filled fractures along with small grains of epidote, clinozoisite, and quartz.

Local occurrences of greenstone in areas of no observed cataclastic deformation may represent retrogression of amphibolite. The two major occurrences are along strike from each other near the Central Piedmont Lineament in the central areas of the traverse. Neither outcrop shows a clearly exposed contact. Tremolite and epidote, common in both locales, are found in bundles in the chlorite folia. Hornblende has been retrograded to tremolite and chlorite (Fig. 10). It is possible that

Figure 10. Photomicrograph and tremolite rimming a hornblende in sample CB5-150. Tremolite is the white outer layer on the hornblende. (mag x 500)



the greenstones were formed in a zone of shearing. There is also a retrogression of biotite to chlorite in biotite schists containing sillimanite along the lineament. However, there is no field evidence that shows any displacement of units, nor is there evidence of a cataclastic fabric in any rocks in the area.

Minimum temperature and pressure for the chlorite, clinozoisite, and quartz assemblage is $345^{\circ} \pm 20^{\circ}\text{C}$ at 2.5 kb $P_{\text{H}_2\text{O}}$ (assuming $P_{\text{H}_2\text{O}} = P_{\text{total}}$; Nitsch, 1971). The chlorite-epidote assemblage can exist to temperatures of 550°C and higher pressures (Liou and others, 1974), but the temperature and pressure given above represent only the minimal metamorphic conditions for the presence of these minerals.

Retrograde Assemblages m_2 and m_3

Very low grade metamorphic mineral assemblages are isolated along the Lakeside fault in fractures cutting the original foliation and the low grade greenschist retrograde mineral assemblages (m_1). About a mile from the fault zone, fractures in granitic rocks are filled with a prehnite-quartz mineral assemblage (m_2), whereas closer to the fault fractures are filled with strained quartz and heulandite (m_3).

The prehnite-quartz-chlorite-adularia mineral assemblage (m_2) can be found in a range of temperature and pressure. Prehnite commonly occurs at temperatures between 300° and 400°C and pressures of less than

3 kb with fluids of low CO₂ and high H₂O content (Coombs, Horodyski, and Naylor, 1970; Stearns, 1968; Liou, 1971b). Adularia is more common in the lower temperature-pressure zones associated with laumontite and heulandite, and therefore would seem to justify lower temperatures and pressure. However, no laumontite or lawsonite has been found. It is, therefore assumed from this assemblage and the lack of zeolites, that $P_{\text{total}} = 2 \text{ kb}$ at around 350°.

Heulandite-quartz-chlorite-adularia (m₃) represent the lowest temperature-pressure metamorphic facies in rocks of this area. The most common limiting reaction for heulandite is: heulandite \rightleftharpoons laumontite + quartz, at 120°C 2 kb = P_{H₂O} (Thompson, 1971 and Zen and Thompson, 1974). However, no laumontite has been found in this area, so temperatures and pressures are probably lower. The heulandite-quartz field is shown in figure 9 and the slope of the heulandite curve is negative, so much lower pressures could still produce heulandite.

It seems from the above that there are three distinct low grade metamorphic assemblages present. One, (m₁) is on the border of green-schist facies temperatures and pressures. The other mineral associations m₂ and m₃ are at distinctly lower temperatures and pressures and probably represent other openings (open fractures) through additional episodic movements along the fault, during unroofing. In most cases, the lower grade assemblages (m₂, m₃) can actually be seen cutting the earlier assemblage (m₁) with none of the other metamorphic mineral zones that should form between them assuming continuous deformation and production of open spaces.

DEFORMATIONAL CHARACTER

Structural Features Formed During Regional Metamorphism

The S surfaces in this traverse indicate different deformational events correlative or nearly correlative with the thermal peak of regional metamorphism. Table 1 explains the use of symbols for structural elements in this traverse and their relation to deformation and metamorphism.

In the following descriptions, s-planes are considered to be pervasive planar features of metamorphic origin such as schistosity and layering caused by metamorphic differentiation (definition modified from Turner and Weiss, 1963). Lineations along this traverse are primarily formed by the intersection of two s-surfaces and are therefore designated by a symbol L_{1x0} , where subscripts indicate the s-planes involved. S_0 is not a pervasive s-surface, but is the designation for original bedding or compositional layering.

S_1 , F_1 , D_1

The first deformational event (D_1) is defined by a pervasive foliation, S_1 , parallel to compositional layering except at F_1 fold noses. S_1 megascopically and microscopically is defined by the planar orientation of platy and prismatic minerals. Generally, strike of S_1 is $N30^\circ - 60^\circ E$ and the dip SE. Appendix C, 1-4 is S_1 plotted on pi diagrams from four geographic domains. In the northwest, poles to S_1 indicate that S_1 has been folded about an F_2 axis striking NE (Appendix C, 1). South of this domain (Appendix C. 2) scatter of S_1 is caused by

Table 1. Relationship of deformational, structural, and metamorphic elements and their age in a traverse from Columbia to Westview, Virginia along the James River.

Relationship of deformational, metamorphic, and structural elements
and their age in a traverse from Columbia to Westview, Virginia along
the James River

D _n Deformational Event	M _n Thermal Metamorphic Peak	S _n planar elements L _n linear elements F _n folds F _n fracture planes	Age (m.y.)	Comments	Localities
Unconformity in Columbia and Arvonias Synclines		S ₀ =compositional layering and bedding	S ₀ is pre Columbia metagranite 590±80m.y. (Fullagar, 1971)	Columbia granite intrudes older strata and is locally unconformably overlain by post-Columbian Arvonias metasediments, present only at western margin of map area.	
D ₁	M ₁	S ₁ , L _{0x1} , F ₁	342±70m.y. (Fullagar, 1971)	Pervasive S foliation across the eastern Piedmont and into the Arvonias and Columbia Synclines. Probably occurred near the crest on cooling slope of M ₁ curve.	1) 0.5 miles S.E. of Pemberton in banks of James River. 2) 0.8 miles S. of Elk Hill in banks of James River.
D ₂		S ₂ axial planar to F ₂ not observed as a separate S-surface L _{1x2} , F ₂	342±70m.y. (Fullagar, 1971)	Non-pervasive foliation across eastern Piedmont and parallel to axial planes of Arvonias and Columbia Synclines, which are F ₂ folds. P-T near that of S ₁ formation.	1) 0.8 miles N. of S.R.6 along banks of Byrd Cr., 0.4 miles E. of 603. 2) 1.0 miles W. of Cartersville in S. banks of James R. 3) 1.75 miles E. of Pemberton in banks of James River.
D ₃		S ₃ , F ₃	between 342±70m.y. (Fullagar, 1971) and 221±6 (Boby- archick, 1976)	Non-pervasive foliation across the eastern Piedmont. Formed on cooling slope of M ₁	1) 0.75 miles E. of S.R. 690, 0.5 miles N. of S.R. 686 along 690 in small stream 2) 0.25 miles E. of S.R. 605, 0.9 mile N. of 690 along 605
D ₄		S ₄ only locally developed F ₄ based on pi diagram with folded S ₃		Non-pervasive local foliation. P-T the same as S ₃ or lower, formed during waning metamor- phism.	1) 0.2 miles S. of S.R. 603 in W. banks of James R. 2) 0.1 mile N. of Island, Va. on S.R. 603, N. banks James River.
D ₅ Lakeside Fault Central Piedmont Lineament	m ₁ and m ₂ retrograde assemblages	f ₁	pre 221±6m.y. (Bobyarchick, 1976)	Fracture planes parallel to Lake- side fault greenschist to prehnite pumpellyite(?) facies metamorphism.	1) Big bend in James River, Plate I. 2) UTM grid coordi- nates 753000 mE, 4179200 mN.
Lakeside Fault	m ₃ retro- grade assem- blage	f ₂	about 221±6m.y. (Bobyarchick, 1976)	Fracture planes parallel Lakeside fault zeolite facies metamorphism.	1) 0.5 miles N.E. of S.R. 605 ± 0.5 miles N.W. of Willis River.

refolding of S_1 near the Lakeside fault zone. In the central domain (Appendix C, 3) S_1 trends $N30^{\circ}-55^{\circ}E$ and dips $15^{\circ}-20^{\circ}SE$. In the eastern domain S_1 , mainly schists, tends to be sub-horizontal (Appendix C, 4).

S_1 is axial planar to small isoclinal F_1 folds of early generation in amphibolites. F_1 folds are less prevalent than F_2 folds. F_1 folds are slip folds, and in the migmatitic zone, rheid slip folds (Whitten, 1966; Carey, 1954).

The highest grade metamorphic assemblages occur in the plane of S_1 and therefore S_1 and the thermal peak of metamorphism are coeval.

S_2 , F_2 , D_2

S_2 is non-pervasive. In gneissic and granitic rocks, it is more widely spaced than in biotite and muscovite schists where it may appear locally pervasive (crenulation cleavage) in handspecimen. In the gneissic terrain there is not a measurable S_2 foliation; however, there are F_2 folds and a lineation L_{1x2} seen on the limbs of F_2 folds. Poland (1976) to the east of this traverse also observed F_2 folds and this lineation and only locally found S_2 -planes.

F_2 folds occur in all domains of this traverse. This fold generation is open, locally recumbent, flexural slip (?) folds that refold S_1 . Locally parasitic folds occur along the limbs and ptygmatically folded pegmatites cut across folded surfaces. Shearing occurs parallel to S_2 in the noses of F_2 folds near the migmatitic zone. About 0.75 miles southeast of Pemberton, Virginia along the James River, F_1 folds are folded by F_2

and possibly F_3 . F_2 in this area are very tight flexural slip folds.

In outcrop, the style of F_2 folding varies in each domain as also indicated by pi diagrams (Appendix C, 1, 3, 4). Outcrops of F_2 folds from the northwest suggest F_2 is dominately open flexural slip with a subhorizontal axis, which is the pattern suggested from pi diagram Appendix C, 1. Outcrops and the pi diagram (Appendix A, 3) in the central domain, show F_2 to be tight isoclinal folds. Eastern schists show rare F_2 folds, and the pi diagram (Appendix C-4) indicates either open conical folds or no folding. Generally F_2 varies in geometry from open folds in the west, becoming compressed in the central area, and again opening in the east.

The second deformational peak (D_2), marked by the formation of S_2 and F_2 , is not accompanied by retrogressive metamorphism. Therefore, D_1 and D_2 were formed at approximately the same P-T conditions and during the same metamorphic event.

S_3 , F_3 , D_3

S_3 is a weak non-pervasive foliation occurring in granitic rocks at a shallow angle to S_1 . S_3 was identified by aligned muscovite and locally biotite, and elongated feldspar and quartz grains at an angle to the primary biotite foliation. S_3 strikes $N20^{\circ}-30^{\circ}W$ and varies in dip from $15^{\circ}-25^{\circ}NE$ (Appendix C, 5).

F_3 folds are only observed in 2 outcrops and tend to be small (wavelength of 1-2 feet) open folds with a subhorizontal axis.

In thin section, S_3 is defined by loosely aligned secondary muscovite which is cross cutting biotite. There are no signs of recrystallization

or retrogression along S_3 . Therefore, S_3 defines a third deformational event (D_3) on the waning side of the regional metamorphism (M_1).

Tobish and Glover (1971) also report a NW trending set of slip cleavage (S_3) in their Milton-Hager's Mountain generation, which also has a conjugate NE set of cleavages. This NE set has not been identified along the James River.

S_4 , F_4 , D_4

S_4 is a weak non-pervasive foliation seen in only four outcrops. Identification of S_4 in saprolite 0.25 miles east of State Road 603 along the west banks of the James River is based on alignment of platy and prismatic minerals similar to S_1 and S_3 .

Appendix C, 5 a plot of poles to S_3 , indicates S_3 was possibly folded about a NW trending axis, F_4 . According to the pi diagram (Appendix C, 5), F_4 like F_3 , appear to be open folds with inclined axial planes. F_4 is not observed in outcrop.

S_4 and F_4 are weakly expressed and are therefore difficult to place in time, however, F_4 must be post F_3 because of the folded nature of S_3 . S_4 and F_4 may define a fourth deformational event (D_4) or indicate a different phasis of D_3 .

Post Metamorphic Structures

Lakeside Fault Zone f_1 and f_2 , D_5

The Lakeside fault zone extends from Lakeside Virginia NE across the James River and dies out in the pegmatites 1 mile west of Fife, Virginia

(Plate I). It is a continuation of an unnamed Triassic fault (Brown, 1969) in the southeast portion of the Dillwyn Quadrangle. Movement along this fault in the Dillwyn area was Triassic and pre-emplacment of the Triassic dike which cuts the fault (Brown, 1969); however, investigation of metamorphic and structural evidence from this traverse indicate movement along this zone as early as ~340 m.y. and as late as post emplacement of Triassic (?) dikes.

The earliest mylonitic fabric in rocks near the fault zone occurs in augen biotite schists and gneisses 0.5 miles SE of the fault along the banks of the Willis River (Plate I). Augen gneisses and schists from this zone have recrystallized quartz grains with irregularly shaped augen of K-feldspar and plagioclase in a matrix that has well developed fluxion structure. The matrix is composed of biotite and muscovite. Appearance of this rock as well as its metamorphic grade, is similar to other augen gneisses in the traverse (section on biotite gneiss). S_1 in the augen gneiss parallels the regional S_1 . Presence of a mylonitic fabric defined by minerals corresponding to the regional grade of metamorphism and the parallelism of this fabric with a regional foliation, indicates that the fault zone was active ~340 m.y. ago during regional metamorphism.

In augen gneisses closer to the fault zone, the mylonitic fabric persists, but biotite is pseudomorphed by chlorite (CB6-13 and CB 6-12; Fig. 11a). The matrix is composed of chlorite and zoisite with augen of plagioclase and locally K-feldspar, both of which are altered to sericite (Fig. 11b). Across the fault, there is a similar chlorite zone in the

Figure 11. Photomicrographs (under plane polarized light) of
a) mylonite with stretched plagioclase augen and
chlorite pseudomorphing biotite (CB6-13) (mag x 200), and
b) sericitized and cataclastically deformed augen
gneiss approximately 200 ft. from the Lakeside fault
(CB6-12) (mag x 200).



a

b

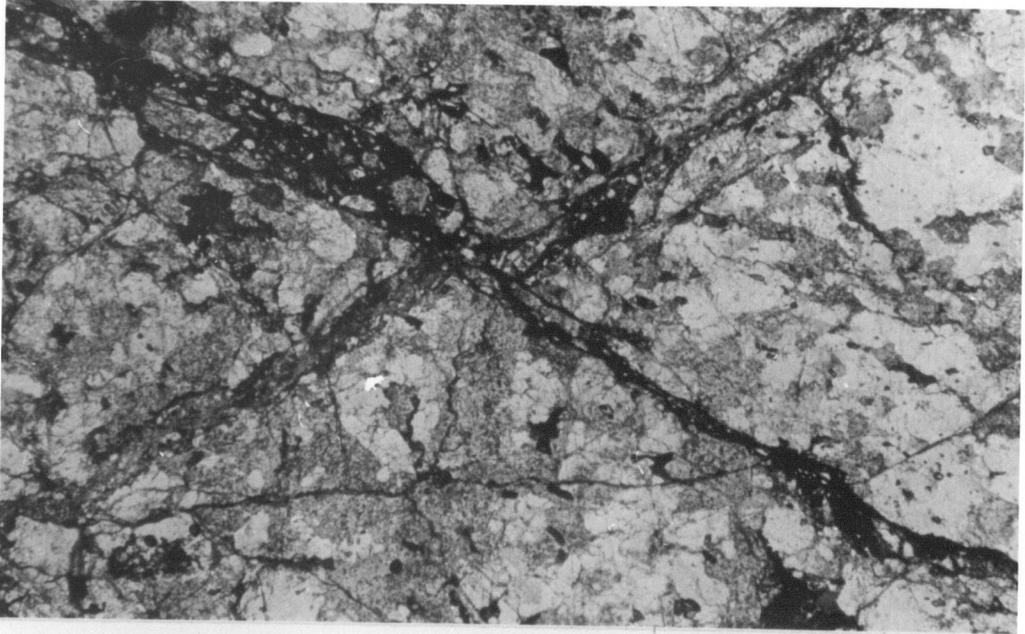


granites, but without the mylonitic fabric (CB6-37c). In both chlorite zones, there are fractures (f_1) that cross-cut the earlier foliation of the augen gneisses and the granite, which are filled with chlorite-quartz-zoisite (Fig. 12a). In granitic rocks, these same fractures may be filled by quartz-prehnite (Fig. 7). The cross-cutting fractures and low grade retrogressive mineral assemblages indicate movement along the Lakeside fault post M_1 (~ 340 m.y.) and pre- m_2 (221 ± 6 m.y. Table 1).

Rocks in and along side the fault zone (Plate 1) are brecciated breccias (Fig. 12b) with quartz fillings. In granite and biotite augen gneisses closest to the fault, there is a second fracture plane (f_2) filled with quartz-adularia-heulandite (m_3) and breccia fragments in the fault have an f_2 fracture filled with zeolite-quartz. Breccia fragments are also completely altered to quartz-sericite-hemitite with some relict chlorite. Quartz crystals have grown in the voids between fragments and are locally seen coated with hematite. The fault zone in the granite is a quartzite with conjugate fractures. Lower grade metamorphic assemblages in the far eastern section of the James River traverse (Bobyarchick, 1976) and the very low grade assemblage (m_3) found in f_2 are coeval. Bobyarchick has indications, through dating of laumontite (his m_3) in the Hylas zone, that the very low grade assemblage must be post 221 ± 6 m.y.

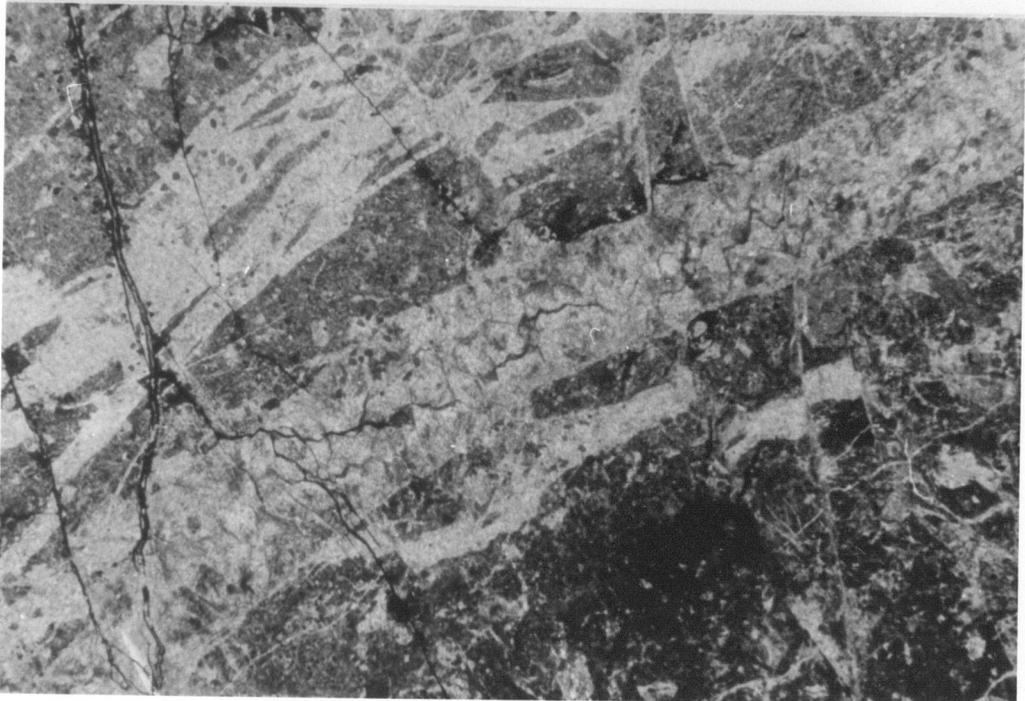
Because of the width (~ 1 mile) of the original mylonitic zone and the relatively shallow angle of dip ($\sim 30^\circ$ SE), the Lakeside fault may have originally been a thrust fault. A well developed mylonitic fabric is rare in high angle reverse or normal faults, such as occur bordering

Figure 12. Photomicrograph (under plane polarized light) of
a) sheared and sericitized augen gneiss showing displacement
of an f_1 fracture by an f_2 fracture (CB6-11) (mag x 200), and
b) breccia with internal zeolite and quartz fillings, and
radial quartz fillings between grains (CB6-6) (mag x 200).



a

b



Triassic basins, which further indicates thrusting at a time prior to the Triassic. Because the granite does not have a mylonitic fabric and the thrust dips SE, the southeast must have been thrust over the northwest.

The last movements of the fault occur in a narrow well defined zone filled with breccia fragments bisected by high angle fracture planes (f_1 and f_2 , which indicate a D_5). Narrowness of the zone, metamorphic grade, and its high angle of dip, indicate the Lakeside fault showed motions of high angle faulting either as a normal or reverse fault during a period of uplift and regional cooling possibly post 221 ± 6 m.y. (or post m_3).

Brown (1969) mapped a Triassic dike cutting the Lakeside fault. This traverse however, shows the fault cutting a diabase dike believed to be of Triassic age (Plate I). This discrepancy may indicate a different age of intrusion for the two dikes or more possibly, a younger phases of movement along the Lakeside fault.

Central Piedmont Lineament

From airborne magnetic surveys and geologic maps, Higgins (1972) and Glover (personal communication) have indicated the presence of a lineament in the Virginia Piedmont extending from near Danville to Fredericksburg, Virginia. The geologic map of Virginia (1963) indicates a discordance in regional trend from northeast to north across this zone. South of this traverse in central Virginia near Danville, the lineament is the root zone for the Smith River Allochthon (Glover, personal communication, Conley and Henika 1970, 1973 a, b). The allochthon is magnetically high while surrounding rocks are magnetically low. To the north of this

traverse, the magnetic lineament strikes into the Stafford Fault zone (Mixon, Southwick and Reed, 1972; Newell, Powell, and Mixon, 1976). Generally, northwest of the lineament there are short wavelength high amplitude magnetic anomalies and southeast are larger wavelength shorter amplitude magnetic anomalies.

In this traverse, northwest of the lineament (Plate 1) amphibolite bodies are common while southeast of the line the amphibolite bodies are rare. In addition to the difference in lithologies with magnetic susceptibility, the lineament also marks a compositional change, from gneisses containing amphibolite in the west to schists with quartzite and granite bodies in the east.

The Central Piedmont Lineament crosses the James River at the bend in the river. In the bend is an abundance of lithologies that have one prograde metamorphic assemblage and a later retrograde assemblage. Amphibolite is retrogressed to epidiosites and chlorite schists. Muscovite-biotite schists containing sillimanite are retrogressed to muscovite-biotite-chlorite schists. Plagioclase in the schists as well as in the biotite gneiss has been altered to epidote. It appears that every lithology in the area of the lineament and the bend in the river has experienced a retrograde metamorphism.

Structural styles also change across the lineament. S_1 dips steeply in the northwest and shallowly to the southeast (Plate I, Appendix C, 1-4). F_1 is tightly compressed along this zone, but is open to either side. S_3 is commonly seen in granitic rocks from the north and southwest domains and has not been observed in the southeast.

There is no evidence of cataclasis in either the migmatite along strike of the lineament to the north or in the bend in the river. Neither is there evidence for displacement other than juxtaposition of two chemically different lithologies. It is evident however that retrogression along the lineament follows a regional pattern of retrogression and must have occurred after approximately 340 m.y. in a zone that would allow local retrogression.

Joints

Stereographic projections of joints from across the traverse in all lithologies are shown in Appendix C, 6. There are 3 primary joint planes: $N65^{\circ}70^{\circ}E$, vertical; $N28^{\circ}30^{\circ}E$, nearly vertical; and $N20^{\circ}40^{\circ}W$ nearly vertical. The latter set parallels joints and fractures along the Lakeside fault zone.

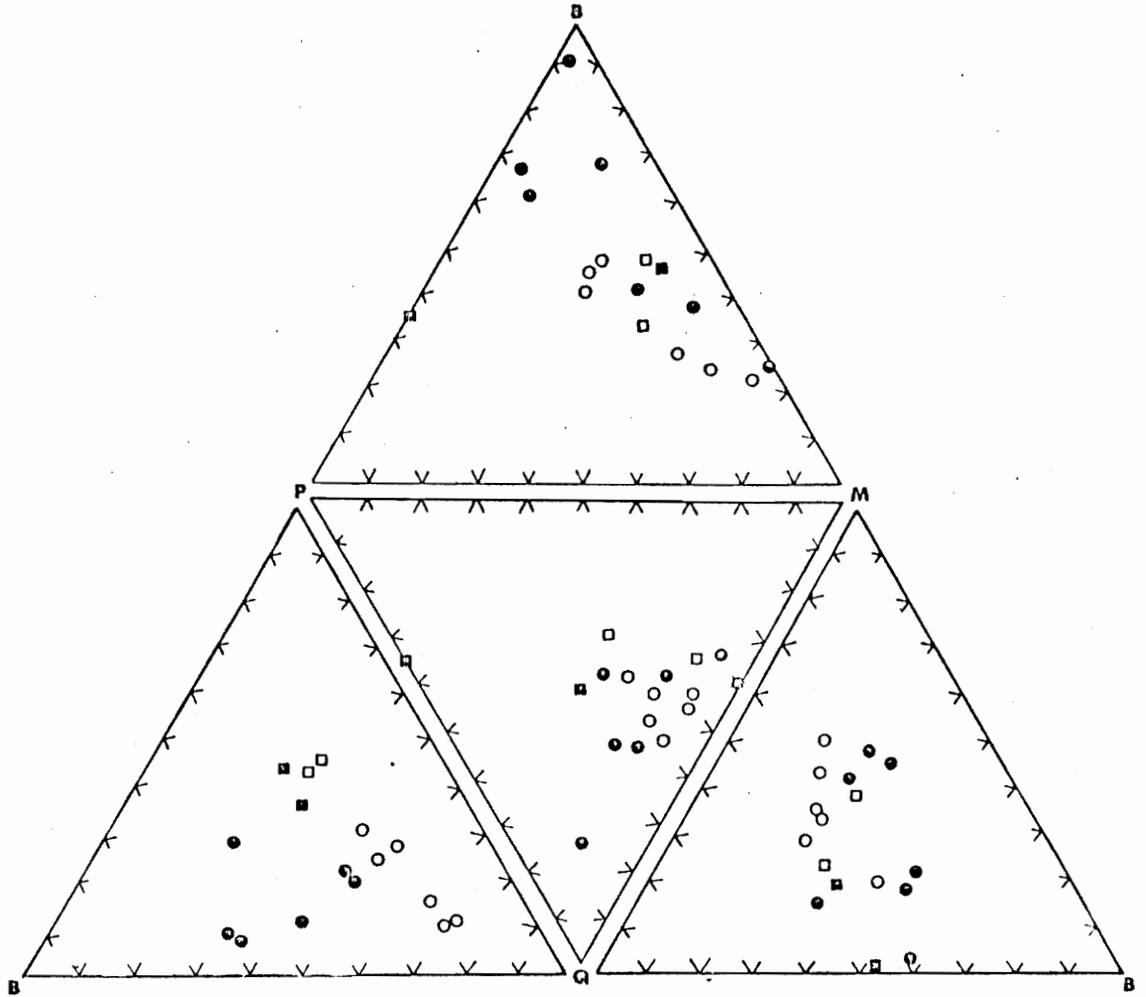
CORRELATION OF REGIONAL STRATIGRAPHY

Modal compositions of pelitic schists and metagraywackes from the Maryland Piedmont (Hopson, 1964) are plotted in figure 13 (see also Appendix A, Part I and III), along with modal analyses for biotite-muscovite schists and biotite gneiss from this traverse. Both areas were metamorphosed to amphibolite facies. Other modal analyses in the Central Piedmont differ greatly from modes along this traverse (Brown, 1969; Smith and others, 1964) and Hopson's (1964) and are not comparable in part, at least, because they are at a lower metamorphic grade. In the muscovite schists from this area, muscovite comprises on the average 39% of the rock, in Hopson's (1964) pelitic schist, the average is 28%. Those analyses given for pelitic schists show muscovite > biotite, and no biotite schists are listed. Many of the schists in this area have both biotite and muscovite and biotite > muscovite in biotite schists. Thus it appears from modal analyses, that the schists in this traverse are more alumina rich and modally different from Wissahickon pelitic schists.

Fig. 13 is similar to Fig. 73 of Bryant and Reed (1970) for both biotite and muscovite schists of the Inner Piedmont. The Inner Piedmont schists are interlayered in a biotite gneiss terrain with calc-silicates and amphibolites, much like schists are interlayered with gneisses of this traverse.

Mica schists from the Inner Piedmont and pelitic schists from Maryland are known to be metamorphosed shales (Hopson, 1964). Because there is a lack of any original sedimentary features in any of the rocks

Figure 13. Biotite (B) - muscovite (M) - plagioclase (P) - Quartz (Q) diagram for the modal analyses of pelitic schists and metagraywackes (Hopson, 1964) and biotite/muscovite schists and biotite gneiss from this traverse.



- | | |
|-----------------|----------------------------|
| ○ Hopson, 1964 | ○ Politic schist |
| □ This Traverse | ● Biotite/muscovite schist |
| ■ This Traverse | ■ Biotite gneiss |
| | □ Metagraywacke |

from this area is difficult to deduce a protolithology, but the modal similarities between this work and others (Hopson, 1964 and Bryant and Reed, 1970) seem to indicate an aluminous protolithology, possibly a shale.

Two modal analyses of biotite gneiss and two analyses of volcanic metagraywacke (Hopson, 1964) are given in figure 13. Hopson tabulated other analyses for metagraywackes from the Eastern Wissahickon, but these are not compositionally similar to gneisses from this traverse. Hopson, based on analyses of graywackes by Pettijohn (1963), concluded that biotite gneiss from the Maryland Piedmont represented metamorphosed graywackes; however, Bryant and Reed (1970) published similar modal analyses and some chemical analyses, which to them, indicate a volcanic protolithology. Mafic content of the biotite gneiss and the modal similarity to the Wissahickon metagraywacke, indicate that biotite gneiss from this area may be a metamorphosed volcanic graywacke.

Amphibolites and biotite amphibolites, except in areas of interlayered calc-silicates, are probably metamorphosed volcanic basaltic flows or tuffs (Bryant and Reed, 1970). Calc-silicates and amphibolite interlayered with them are probably derived from dirty limestones (Vidale, 1969). Ultramafic pods by their dislocated nature and ultramafic composition are igneous in origin, and may have been formed during a compressional tectonic event (Brown, 1976).

In summary, the Columbia Metagranite intruded a sedimentary pile of interlayered volcanics, graywackes with carbonate lenses, and shales 547 m.y. ago. A similar sedimentary sequence is suggested by the eastern Wissahickon but there is some confusion as to how old the Wissahickon may be (Seiders and others, 1975; Higgins 1972) and it is possible the Wissahickon may be younger or older than the metasediments in this area.

CONCLUSION

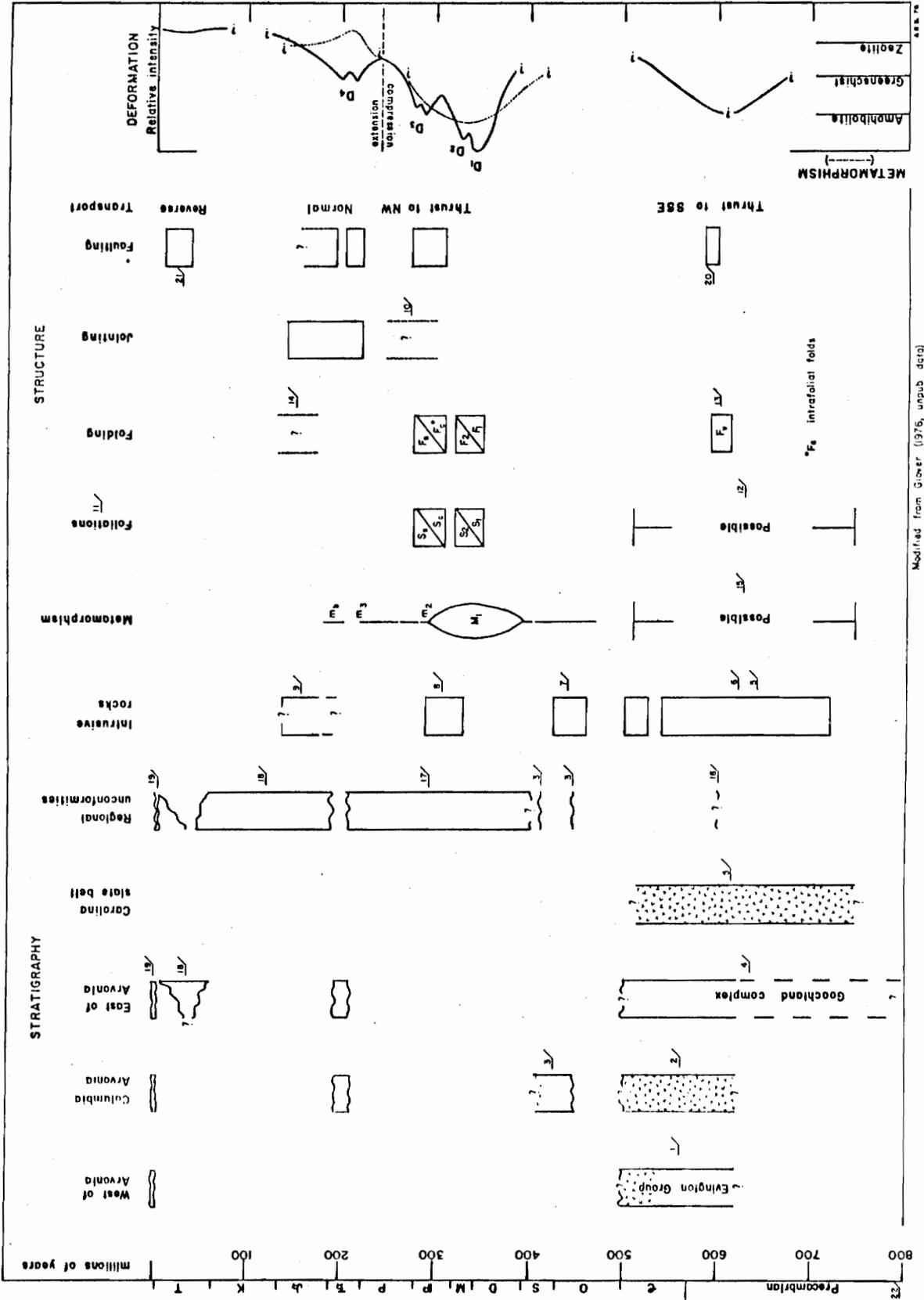
Bobyarchick (1976) has drawn a regional synthesis diagram which includes geologic, structural and metamorphic aspects of this traverse. (Fig 14).

Layered lithologies from this area represent a sequence of gray-wackes and shales that were intruded by Columbia metagranite 547 m.y. ago (Sinha, 1976, personal communication). The granite also intruded volcanics in the area west of the Columbia syncline. Unconformably overlying the layered rocks and granite are the Arvonian and Columbia syncline sequences of Middle-Late Ordovician age.

The entire area including the sequences in the Columbia and Arvonian synclines was metamorphosed ~ 350 m.y. ago (Fullagar, 1971). At the same time, metamorphism may have reached its peak in the Maryland Piedmont (Higgins, 1972). There are three or four deformational events during and after the peak of metamorphism. Also, around 350 m.y. the Lakeside fault was a thrust zone having southeast thrust over northwest. The grade of metamorphism reached sillimanite zone and possibly second sillimanite zone and melting occurred in a migmatitic zone during the peak of metamorphism.

Later movements (post 340 m.y. and slightly post 221 m.y.) along the Lakeside fault and Central Piedmont Lineament produced retrograde mineral assemblages which are indicative of lowered regional temperatures. Along the Lakeside fault there were cataclastic movements and the zone of cataclasis narrowed to a zone along which nearly vertical motion and brecciation took place.

Figure 14. Regional correlation of structural, deformational, and stratigraphic elements from the Carolina slate belt and Piedmont James River Traverses. References for the various elements are listed in Bobyarchick (1976).



Modified from Gover (1976, unpub. data)

Lastly, the region was injected by Triassic or Jurassic diabase dikes. There is an erosional unconformity between the layered lithologies and granite and colluvium and alluvium.

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APPENDIX A

MODAL ANALYSES

Appendix A, Part I

Modal analysis for biotite gneiss, biotite-augen gneiss, and biotite-hornblende gneiss. Total points counted for each sample are listed and description and location information follow.

Sample Nos.	Biotite gneiss		Biotite Augen gneiss			Biotite-Hornblende gneiss			
	5-43	5-51	6-13	5-65	5-174	5-218	5-59	5-67	5-140
Quartz	33	24.7	20.7	33.6	40.2	30.6	18.0	15.8	12.1
Plagioclase	33	42.7	25.8	17.8	30.3	19.8	37.2	25.1	18.8
Microcline			5.6	1.0		30.8			
Perthite			1.1			4.6			
Biotite	22.2	23.4	8.3	28.8	21.5	12.3	5.2	14.8	22.5
Muscovite	11.4		18.3	18.8	4.0	1.5			
Chlorite			18.1				tr	tr	tr
Epidote	tr	4.3	1.9		3.4		5.2	5.0	tr
Clinozoisite									10.1
Hornblende		4.4					34.4	36.8	32.0
Scapolite								3.0	3.7
Allanite		tr			tr			tr	
Sphene									.4
Zircon	tr				tr	tr			
Garnet		.3						tr	
Magnetite			.2						
Total Points Counted	600	400	618	500	600	600	600	620	580

Appendix A, Part I

CB5-43 0.33 miles southeast of the intersection of State Road 603 and 6, and approximately 0.16 miles south of State Road 6. N.W. Cartersville Quad.

Light gray and yellow-brown foliated biotite gneiss intruded by several 2-5 cm wide pegmatites. Sample is highly weathered so that biotite is white in hand specimen.

CB5-51 0.33 miles N of State Road 608. 1 mile south of the intersection of State Road 6 and 608. N.W. Cartersville Quad. near Elk Hill.

Gray to light gray layered rock with black phenocrysts hornblende. Lighter layers are quartz and plagioclase, while the darker layers are plagioclase, biotite, and hornblende. Small epidote grains can be seen throughout.

CB5-65 0.25 miles N of State Road 6, 1.25 miles west of Georges Tavern. N.W. Cartersville Quad.

Augen of plagioclase are partially weathered from a dark gray matrix of biotite, muscovite, quartz and plagioclase. Augen vary in size from .5-1 cm. There is a strong foliation which wraps around the augen. Garnets are present and can be 0.5 cm large.

Using a grid with 1 cm square squares the percentage of augen versus the percentage of matrix was calculated based on standard surface area. Percentage of augen is 35.0% and percent of matrix is 65.0%

CB5-174 0.5 miles W of State Road 6. 2 miles N of Pemberton, Va. on
State Road 6. along a stream. Central Cartersville Quad.

Biotite augen gneiss with large clasts of granite in what appears
to be a schistose contact zone between biotite gneiss and Columbia
Meta granite.

White plagioclase augen are set in a biotite rich matrix.

There is one strong foliation.

Augen are 52% while matrix is 48% figured as in CB5-65.

CB5-218 0.15 miles E of State Highway 45, 0.5 miles S of intersection
of State Road 618 and Highway 45. S. Central Cartersville
Quad.

This rock is a contact between the metagranite and biotite gneiss.
Biotite gneiss is dark gray with 5 mm thick white quartz-plagioclase
layers and plagioclase-microcline augen .8-1 cm in diameter. Augen
in the granitic rock are microcline usually 1 cm in diameter. In
outcrop these microcline augen are 3-6 cm in diameter and tend to
differentially weather from the rock. Small 1 mm wide garnets can be
seen in both lithologies.

Augen are 33% of the rock, the matrix 67%, calculated as in CB5-65.

CB6-13. 0.5 miles NE of bridge on State Road 605 and the Willis River
in a gap between two high ridges. E. central Lakeside Quad.

Dark green matrix of biotite and muscovite with chlorite. Augen are
predominately plagioclase with 2 augen of microcline. Foliation bends
around the augen and in hand specimen there is a strong fluxion
structure.

Percentage of augen was estimated at 30%.

CB5-59 0.15 miles N of State Road 6, and 0.5 miles W of intersection of State Roads 6 and 608. N.W. Cartersville Quad.

A coarsely crystalline white rock with hornblende cross-sections. Some sections of the rock are massive hornblende. Chlorite and biotite occur around the larger hornblende phenocrysts. There are small (<1 mm) green epidote grains. Garnet occurs in the lighter layers and is usually 5 mm in diameter. Upon weathering the rock becomes black. The rock is intruded by a 1" wide pegmatite predominately composed of quartz and microcline.

CB5-67 0.2 miles N of State Road 6, and 0.24 miles W of intersection of State Roads 608 and 6. N.W. Cartersville Quad.

Dark gray-green rock with hornblende and biotite flakes in a light gray matrix of plagioclase and scapolite, with scattered grains of quartz. Epidote in grains less than 1 mm is associated with biotite and hornblende. Garnets (1-2 mm in diameter) are well rounded. There seems to be only one foliation.

CB5-140 0.25 miles S of State Road 6 along Byrd Creek. N.W. Cartersville Quad.

A layered rock with 2 mm wide layers of quartz-plagioclase and biotite-hornblende-epidote. Garnets are 1-2 mm in diameter. There is one strong foliation.

A high birefringence scapolite occurs along with epidote and plagioclase. The index of refraction for the scapolite is 1.56-1.57.

Appendix A, Part II

Modal analyses of hornblende amphibolite and laminated amphibolite. Total points counted for each sample are listed and description and location information follow.

	Hornblende amphibolite					Laminated amphibolite
Sample nos.	5-72	5-73	5-130	5-290	5-123	5-134
Quartz	17.5	2.6			3.7	
Plagioclase	50.5	10.7	25.1	4.2	16.1	33.4
Microcline						
Biotite				3.1		
Muscovite	2.0	4.0				
Epidote	.3	} 14.6	15.6	} 8.0	10.9	1.6
Clinozoisite			tr			
Allanite						
Chlorite	4.5	3.3			tr	
Hornblende	26.9	64.8	57.5	84.7	47.4	35.7
Scapolite						
Sphene		tr	1.7	tr	5.4	
Zircon	tr		tr			
Garnet						
Talc		tr				
Calcite						22.3
Pyrite						2.5
Magnetite						2.5
Augite					16.3	
Total Points Counted	609	400	569	600	670	613

Appendix A, Part II

CB5-72 0.21 miles W. of State Road 608 along a small stream,
0.25 miles N. of State Road 6 on 608. N. central Cartersville Quad.

White layers with garnet interfingering with amphibole layers and amphibole phenocrysts in 1-2 cm wide layers. White layers are quartz and plagioclase with garnets, black layers are hornblende with epidote. Chlorite and epidote form rims around the hornblende. Hornblende phenocrysts vary from 0.5 cm - 6 cm in length. There is one foliation parallel to layering.

CB5-73 0.21 miles W. of State Road 608 along a stream 0.25 miles N. of State Road 6 on 608. N. central Cartersville Quad.

Dark green massive hornblende with 0.5 mm layers of plagioclase and epidote. Hornblende phenocrysts average 0.5 mm in length, and there is some secondary chlorite along outer edge of hornblende.

Thinly laminated gradational into thickly laminated dark gray amphibolite. Lamination varies from 0.25 mm - 2-3 cm thick. Thicker units show pods of garnet-amphibolite, where garnet is a core for radiating hornblende. The lighter gray lamellar layers are plagioclase with calcite. One strong foliation parallels compositional layering.

CB5-130 1.25 miles E of Columbia, Virginia on State Road 667.
Outcrops are along the road. SE Columbia Quad.

Massive black to dark green rock composed of hornblende and epidote with white flakes of plagioclase.

CB5-290 0.2 miles W of State Road along a stream. Universal transverse Mercator grid coordinates 4177200 m N and 754000 m E. W central Cartersville Quad.

Massive dark green rock composed of hornblende. Phenocrysts are as large as 1 cm in outcrop. (Outcrop is folded into a similar concentric fold).

CB5-123 Universal transverse Mercator grid coordinates 4177200 m N and 756000 m E. W Central Cartersville Quad.

Dark green rock with white plagioclase grains and small (<1 mm) green epidote grains. Hand specimen is fine grained. Chlorite is seen in outcrop but as only a trace in thin section. Sample is from an amphibolite layer in a biotite gneiss terrain.

CB5-134 2.7 miles northeast along State Road 667 from Columbia, Virginia. Outcrops are road banks along the highway.

Thinly laminated gradational into thickly laminated dark gray layered amphibolite. Lamination grades from 0.25 mm to 3.0 cm thick. Thicker layers have pods of garnet-amphibole, where hornblende radiates from a core of garnet. Lighter layers are calcite and plagioclase. The one foliation may reflect the original bedding.

Appendix A, Part III

Modal Analyses for biotite schist, muscovite schist, and modes by Hopson (1964) of pelitic schist (Wissahickon). Total points counted for each sample are listed and hand specimen description and location information follow.

Sample Nos.	Biotite schist				Muscovite gneiss and schist				Pelitic Schists ⁺	
	5-171-A	5-298	5-248	5-274	5-197-B	5-197'	5-208	5-265	M459-1	H27-4
Quartz	25.5	31.9	26.4	41.3	27.2	26	23.3	29.4	38.1	31.6
Plagioclase	24.7	9.8	8.5	18.9	20.4	14	9.0		18.6	19.1
Microcline	tr	7.4	3.8	0.7	24.0			7.4		2.2
Sillmanite		tr	3.0		tr	tr		0.3		
Biotite	32.7	43.8	35.0	21.4	5.6	15	21.3	15.6	13.6	9.2
Muscovite	17.5	1.1	16.6	14.4	22.5	30	42.4	45.4	22.4	24.9
Garnet		5.8	6.0			7	4.5	0.9	1.0	0.3
Chlorite				2.5		8			1.8	7.6
Staurolite									tr	
Hemotite	tr							tr		
Clinozoisite			0.6					0.7		
Epidote									0.2	0.8
Apatite				tr					0.2	tr
Zircon		tr		tr		tr		tr		tr
Talc										
Diopside										
Magnetite										
Tremolite										
Hornblende						tr			1.8	4.1
Total points counted	610	630	597	561	528		484	564		

' Average of two slides

+ Analyses of pelitic schist Maryland Eastern Wissahickon Formation (Hopson, 1964, p. 78-79) for comparison.

Appendix A, Part III

CB5-171A 1.1 miles west of the intersection of State Roads 625 and 45 in a small stream 0.25 miles E of the James River, W central Cartersville Quad.

Dark gray crenulated rock with round augen of plagioclase (<1 cm). The entire rock except for augen is fine grained. In hand specimen small white needles of sillimanite were seen in biotite folia. The outcrop is a narrow zone in sharp contact with the granite; however, augen are more numerous closer to the granite. West of this outcrop the schist grades into biotite gneiss.

CB5-298 0.2 mile E of State Road 602, 0.5 mile N of State Road 45, SW Cartersville Quad.

Layered black and white biotite garnet schist with lenses of quartz and plagioclase. In hand specimen there are small sillimanite grains between biotite folia. Garnets comprise 5-10% of the rock in hand specimen. There is a pegmatite approximately 1 foot wide that cuts across the outcrop.

CB5-248 0.35 miles S of State Road 618, 1.20 miles W of the intersection of State Roads 618 and 616, S central Cartersville Quad.

Folded biotite schist with boudinaged calc-silicate layers. The biotite schist has rounded augen (<1 mm - 2 cm long) of plagioclase and K-feldspar. Scattered sillimanite needles can be seen in the biotite folia which wrap around the augen. Garnets are anhedral and apparently cut across the foliation. This outcrop is part of a migmatitic zone.

CB5-274 0.5 miles W of Cartersville in the S banks of the James River, W central Cartersville Quad.

Layered black and white biotite schist. The white felsic segregations are also foliated and may be pre S_1 pegmatites. There is no sillimanite or garnet in outcrop or hand specimen. Augen are localized in outcrop and are rounded and angular.

CB5-197-B 1.0 miles NW of the intersection of State Roads 45 and 618 in the E banks of the James River, W central Cartersville Quad.

A white quartz-microcline-plagioclase gneiss rich in muscovite and granitic in appearance. Muscovite plates 5.0 mm across were seen in hand specimen and outcrop. Biotite only occurs in small <1 mm grains parallel to the muscovite. This unit is interlayered with biotite schists and biotite garnet schists.

CB5-197 1.0 miles NW of intersection of State Roads 45 and 618 in the E banks of the James River, W central Cartersville Quad.

Garnet rich, yellow-brown, layered schist with layers or lenses of muscovite-biotite and layers of quartzite 5-10 cm thick. There is a facies variation with the unit tending to a garnet quartzite. In hand specimen sillimanite can be seen in muscovite grains. Chlorite occurs in the biotite folia and around the larger garnets. There is one foliation parallel to compositional layering.

CB5-208 1.25 miles W of State Road 45 and intersection with 618 along the E banks of the James River. W central Cartersville Quad.

Poly-deformed muscovite-biotite schist with augen of plagioclase, and tear shaped garnets stretched parallel of the plane of foliation.

Locally there are quartz lenses. Augen are sheared and plastically deformed along with thin (1 mm) layers of quartz-plagioclase folded into subhorizontal isoclinal folds. Sillimanite occurs along with muscovite and in these thin layers.

CB5-265 .020 miles S of James River, 1.0 miles W of Cartersville in
S banks of the James River, W central Cartersville Quad.

Highly contorted brown saprock with 5 cm long augen of plagioclase in a folded matrix of muscovite-quartz-biotite-sillimanite. Garnets were observed in outcrop. Sillimanite needles as long as 1 mm have been observed in the muscovite folia.

Appendix A, Part IV

Modal analyses for chlorite schists, and metamorphosed ultramafic pods including modal analyses of metamorphosed ultramafic pods from the Dillwyn Quadrangle (Brown, 1969). Total points counted for each sample are listed and handspecimen description and location information follow.

	1+	2+	6-64	5-150	6-154
Hornblende		15			
Tremolite-				} 25	} 45
Actinolite	18	35	26		
Anthophyllite					
Cummingtonite			21		
Talc			8	7	2
Chlorite	20	26	33	56	50
Muscovite			12	tr	2
Magnetite-					
Illmanite	2		tr	tr	tr
Pyrite					tr
Sericite	60				
Epidote-					
Clinozoisite		20		12	
Diopside				tr	tr
Total points counted			320	520	568

+ Brown, 1969.

Appendix A, Part IV

CB6-64 UTM grid coordinates, 751000 m E, 4179200 m N, N central
Lakeside Quad.

Lustrious blue-green chlorite rich rock with red spots. Tremolite-actinolite needles are ubiquitous throughout. Some portions of the rock are talc rich while others are amphibole rich. There are two possibly three amphiboles: tremolite, cummingtonite, and anthophyllite.

In outcrop there is a poorly developed foliation. The major occurrence of this rock is not in contact with any other lithology.

CB5-150 0.75 miles W of State Road 45 and 0.6 miles SE of Elk Hill,
Va., Central Cartersville Quad.

Lustrious yellow-green chlorite rich rock with small grains of sulfides. Tremolite-actinolite needles can be seen in the chlorite ground mass. Foliation is rather uniform throughout. Surrounded by amphibolite and biotite gneiss in Columbia metagranite.

CB5-154 0.2 mile W of State Road 601, 0.6 miles S of the Willis
River, SW Cartersville Quad.

Lustrious yellow-green chlorite rich rock with magnetite and pyrite crystals (1 mm in diameter) embedded in the chlorite. Needles (1 mm - 2 mm) can be seen in the chlorite ground mass.

In outcrop the rock is in sharp continuous contact with amphibolite and disconformable contact with Columbia metagranite. There is a poorly developed foliation in hand specimen.

Appendix A, Part V

Modal analyses for Columbia Metagranite from this traverse and the Dillwyn Quadrangle, also including the Occoquan Adamellite are listed. Total points counted are listed and handspecimen description and location information follow.

Columbia Metagranite													
Sample Nos.	5-14	5-14	5-23	5-44	5-213	5-253	6-37c	1 ⁺	2 ⁺	4 ⁺	5 ⁺	7 ⁺	9 ⁺
Quartz	36	40	25	19	30	18	36	40	49	35	42	33	28
Plagioclase	29	40	42	44	26	36	49	45	43	21	57	51	60
Microcline	8		18	25	39	29	1			23		5	
Biotite	11	7	7	7	4	2		8	4	10		5	
Muscovite	11	5	8	4	1	14			4	6		3	10
Hornblende								4					
Epidote and Allanite	3	3		1		1	1	2		4		3	1
Calcite	2	2											
Sphene							0.5						
Pyrite	tr	tr		tr	tr								
Magnetite		tr			tr	tr	tr						
Garnet	tr	tr											
Apatite	tr			tr									
Chlorite					tr		12						
Total points counted	600	600	548	670	636	594	676						

+ Brown, 1969

Sample Nos.	Adamellite					Pegmatites	
	1 ^x	2 ^x	3 ^x	4 ^x	8 ^x	5-55	5-62
Quartz	44.5	28.9	39.3	41.5	32.2	34.1	35.1
Plagioclase	21.3	22.2	19.3	16.5	26.1	15.7	27.2
Microcline	2.9	25.4	30.0	24.0	31.9	38.9	28.5
Biotite	7.2	4.3	1.2	0.8		0.3	9.2
Muscovite	11.9	13.3	7.8	15.1		10.9	
Hornblende					9.5		
Epidote and Allanite	11.2	5.2	1.9	1.9	0.1		
Calcite							
Sphene	0.7						
Pyrite			0.4	0.2			
Magnetite						tr	
Garnet		0.1	0.1				
Apatite	0.3						tr
Chlorite		0.6					
Total Points Counted	2000	20.7	2000	2177	2010	584	467

^x Occoquan adamellite, Seiders and others, 1975, p. 488.

Appendix A, Part V

CB5-14 Cowherd Quarry, outskirts of Columbia, Virginia. SE
Columbia Quad.

Light gray granite with a well defined biotite foliation and a non-pervasive second foliation. (Locally a flow foliation is observed). In outcrop there are several autoliths and xenoliths as well as coarse grained pegmatites. In addition, there are muscovite quartz-calcite fracture fillings. There are narrow zones or fractures also filled with quartz-biotite-epidote.

The granite is quartz and plagioclase rich with only local K-feldspar. Garnets are small (<1.0 mm). Epidote grains occur with biotite. Muscovite is parallel and crosscutting the primary foliation. Generally, the rock is medium grained, but there are coarse grained functions.

CB5-23 0.5 miles SW of State Road 618, 1.1 miles S of Pemberton,
Virginia, in the N banks of the James River, Central
Cartersville Quad.

A light gray fine grained granite with 2 foliations both defined by biotite. Muscovite foliation was not observed in this rock. There are local fractures along which some mineralization (quartz-plagioclase) has occurred.

The granite is composed of plagioclase-quartz-microcline with approximately equal amounts of muscovite and biotite. Epidote occurs with biotite. Garnets were not observed.

In outcrop, the granite is in contact with an augen gneiss and

overlying that is a muscovite schist.

CB5-44 0.5 miles NE of Elk Hill in road bank on State Road 608,
NW Cartersville Quad.

Light gray granite with at least two fractions, one, slightly coarser grained, is an autolith, the other a fine grained granite. Samples of this granite have a granoblastic texture with small (1-2 mm) clasts of feldspar. There are also 1 mm thick felsic layers parallel to foliation. Foliation is defined by aligned biotite grains (4 mm).

This outcrop is in contact with a biotite-hornblende gneiss and the entire area is near a migmatitic zone.

CB5-213 UTM grid coordinates 4174200 m N, 755900 m E, W central
Cartersville Quad.

Weathered light gray to brown fine grained granite. Foliation is formed by biotite (<1 mm) with small epidote grains. The rock is a microcline-quartz-plagioclase granite with limited biotite. Garnets not observed.

This outcrop occurs in a biotite-garnet schist terrain.

CB5-253 1.1 miles W of Westview, Virginia, along banks of James
River, SE Cartersville Quad.

Highly weathered, fine to medium grained, plagioclase, microcline, quartz granite. The foliation is almost non-existent except for compositional layering and aligned biotite grains. Neither epidote nor garnet were observed in this locale.

In outcrop the granite is interlayered with a muscovite schist and amphibolite. The amphibolite unit may be a xenolith in the granite.

CB6-37C UTM grid coordinates 4177000 m N, and 753100 m E, W
central Lakeside Quad.

A brown and green granite. Foliation is defined by chlorite. Fractures are filled with hematite and have slickensides. Fractures are normal to the foliation.

The rock varies in grain size; near the fault it is fine grained, away from the fault it is coarser grained. Fractures are numerous near the fault and diminish away from it. There are in addition, several generations of pegmatites cutting the foliation and cut by fractures.

This is a plagioclase-quartz rock with chlorite and epidote as secondary minerals. The rock has an altered, possibly recrystallized appearance in hand specimen and thin section.

CB5-55 Below bridge on State Road 6 crossing Byrd Creek, 2 miles W
of Georges Tavern, NW Cartersville Quad.

Compositionally layered pegmatite with one foliation defined by muscovite. Generally, the rock is medium grained. The rock is a microcline-quartz-plagioclase granitic pegmatite. Neither epidote nor garnet was seen in hand specimen or thin section.

In outcrop, this rock is interlayered with a biotite-hornblende gneiss.

CB5-62 0.15 miles N of State Road 6, 1.75 miles W of Georges
Tavern, NW Cartersville Quad.

White medium grained unfoliated pegmatite that cuts through an amphibolite gneiss. Grains range from 1 mm to 3 cm in diameter. Compositionally, the rock is a quartz-microcline-plagioclase granite with

scattered biotite grains (up to 4 mm long). The pegmatite is approximately 2 feet wide.

APPENDIX B

MICROPROBE ANALYSES

Appendix B, Part I

Microprobe analysis for CB5-14, a metamorphosed granite

	Plagioclase		K-Feldspar	Garnet		Biotite	Muscovite
SiO ₂	62.23	62.86	64.28	37.23	37.70	34.71	46.03
TiO ₂				0.07	0.12	2.48	0.49
Al ₂ O ₃	23.68	23.57	18.09	21.02	20.94	17.46	31.30
FeO				30.03	28.27	23.06	5.39
MnO				2.13	4.13	0.45	0.07
MgO				1.14	1.12	6.34	1.18
CaO	5.34	5.38	0.00	7.79	7.85	na	na
Na ₂ O	8.74	8.75	0.74	na	na	0.10	0.29
K ₂ O	0.19	0.09	15.12	na	na	9.77	10.80
Total	100.18	100.66	98.23	99.41	100.12	94.37	95.45

na = not analyzed

Appendix B, Part I (cont.)

Formula Basis	Plagioclase		K-Feldspar	Garnet		Biotite	Muscovite
Si	2.754	2.767	3.009	3.003	3.017	5.470	6.270
Ti				0.002	0.007	0.291	0.048
Al	1.234	1.223	0.998	1.999	1.974	3.241	5.010
Fe				2.025	1.890	3.038	0.611
Mn				0.144	0.279	0.060	0.008
Mg				0.135	0.131	1.484	0.236
Ca	0.253	0.253	0.000	0.672	0.671	na	na
Na	0.749	0.747	0.066	na	na	0.027	0.076
K	0.010	0.003	0.902	na	na	1.960	1.875

Appendix B, Part II

Microprobe analysis for CB6-64, a metamorphosed ultramafic pod

	Cummingtonite				Anthophyllite	
	1 ^o	2 ^o	3 ^o	4 [']	5 ⁺	6 ⁺
SiO ₂	57.32	56.82	57.97	57.37	56.01	57.02
TiO ₂	0.0	0.0	0.0	0.0	0.14	0.0
Al ₂ O ₃	0.93	1.13	1.12	1.06	2.96	1.40
H ₂ O	2.20	2.20	2.22	2.21	2.98	1.59
FeO	13.18	13.56	13.02	13.25	7.16	8.71
MnO	0.23	.27	0.25	0.25	na	.09
MgO	27.50	27.41	27.49	27.47	27.94	28.81
CaO	0.53	0.52	0.54	0.53	1.68	1.48
Na ₂ O	0.00	0.13	0.00	0.04	0.56	0.66
K ₂ O	0.00	0.00	0.00	0.00	0.19	0.0
Total	101.89	101.91	102.61	102.14	99.84	99.76

' Average of 1, 2, 3

+ Deer, Howie, and Zussman (1963) anthophyllite analysis 5 and 7

o Refer to Fig 5 for position of tie between cummingtonite, anthophyllite and tremolite for this traverse

Appendix B, Part II (cont.)

Formula Basis	24	24	24	24	24	24
Si	7.798	7.750	7.817	7.789	7.685	7.849
Al	0.149	0.182	0.178	0.170	0.315	0.226
Fe	1.500	1.547	1.468	1.505	0.819	1.003
Mn	0.027	0.031	0.029	0.029	0.0	0.011
Mg	5.576	5.573	5.525	5.558	5.714	5.911
Ca	0.077	0.076	0.078	0.077	0.247	0.218
OH	2.000	2.000	2.000	2.000	1.94	1.460

Appendix B, II (cont.)

	Talc		Tremolite
	1	2	3
SiO ₂	60.95	60.52	55.16
TiO ₂	0.08	0.07	0.09
Al ₂ O ₃	0.84	1.12	2.50
H ₂ O			
FeO	3.28	3.34	5.29
MnO	0.01	0.03	0.12
MgO	30.07	30.34	23.01
CaO	0.02	0.04	11.59
Na ₂ O	na	0.16	0.51
K ₂ O	na	0.08	0.00
Total	95.25	95.70	

Appendix B, II (cont.)

Formula Basis	11	22	23
Si	3.917	7.762	7.616
Al	0.062	0.169	0.405
Ti	0.003	0.003	0.008
Fe	0.175	0.357	0.607
Mn	0.00	0.00	0.012
Na	na	0.038	0.133
Ca	0.0	0.003	1.713
K	na	0.011	0.00

Appendix B, Part III

Microprobe analyses for CB6-154, a chlorite schist

	Hornblende		Tremolite	Chlorite
	1	2	3	4
SiO ₂	46.03	44.66	55.77	29.47
TiO ₂	0.61	0.67	0.01	0.08
Al ₂ O ₃	10.48	11.02	0.76	18.40
FeO	9.63	10.61	5.18	10.74
MnO	0.39	0.42	0.37	0.22
MgO	16.92	16.51	22.33	29.77
CaO	12.37	12.08	12.42	0.09
Na ₂ O	1.97	1.45	0.51	0.04
K ₂ O	0.14	0.10	0.00	0.00
Total	98.52	97.52	97.34	88.75

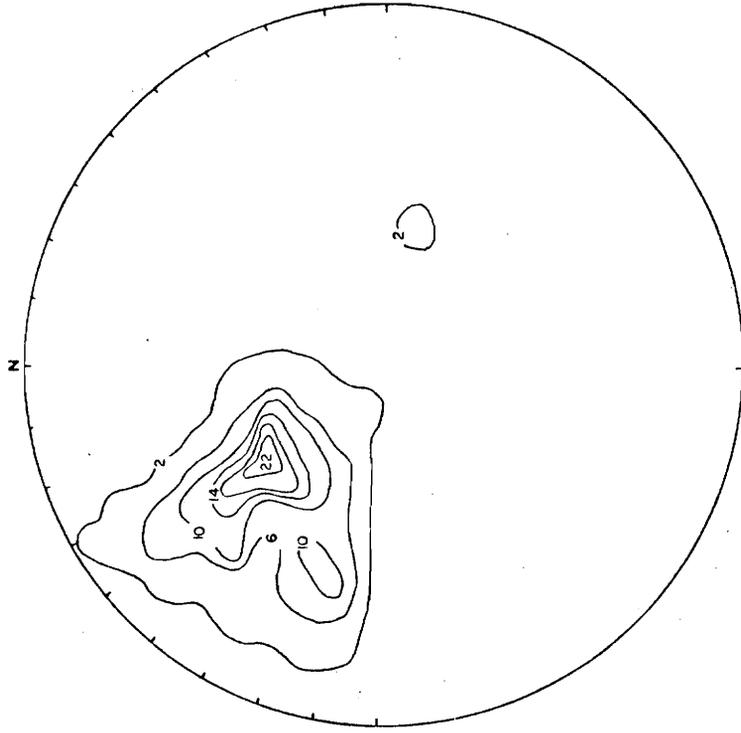
Appendix B, Part III (cont.)

Formula Basis	23	23	23	23
Si	6.600	6.498	7.792	5.680
Al	1.768	1.887	0.123	4.181
Fe	1.153	1.289	0.603	1.731
Mn	0.046	0.051	0.041	0.034
Mg	3.616	3.578	4.650	8.537
Ca	1.898	1.883	1.857	0.017
Ti	0.063	0.072	0.000	0.011
Na	0.547	0.405	0.135	0.011
K	0.025	0.017	0.000	0.000

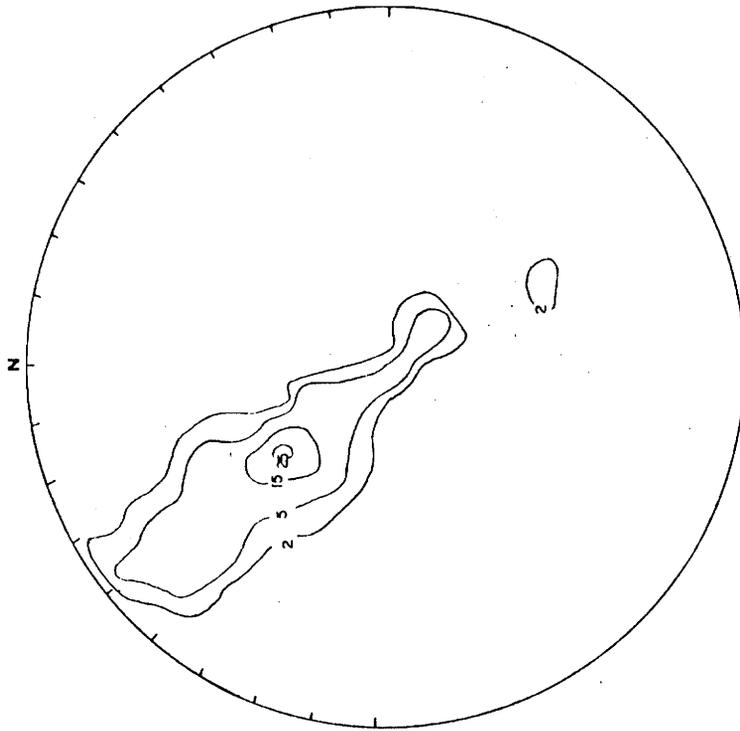
APPENDIX C

Structural pi Diagrams

- Appendix C-1. Poles to S_1 foliation for the northwestern domain (Plate 1).
76 poles.
- Appendix C-2. Poles to S_1 foliation for the southwestern domain (Plate 1).
126 poles.



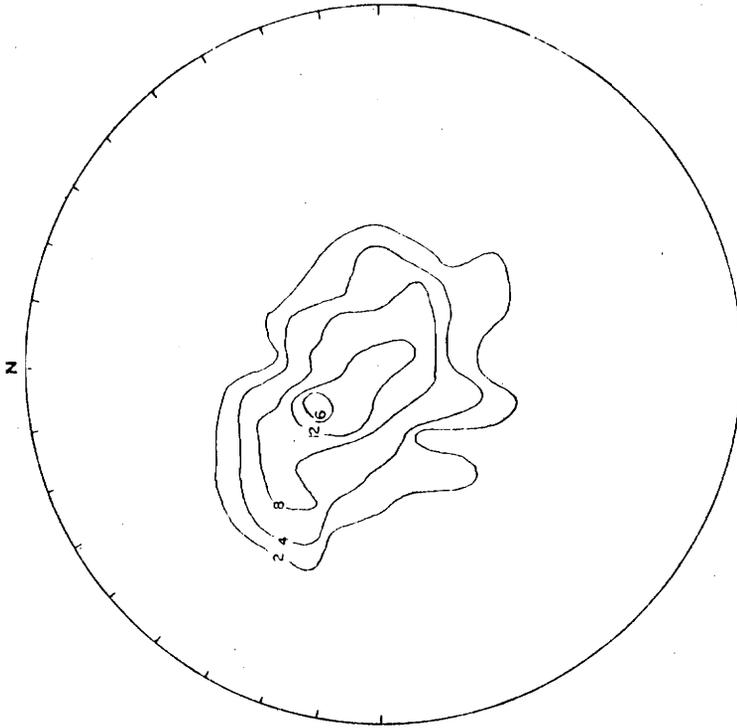
C-2



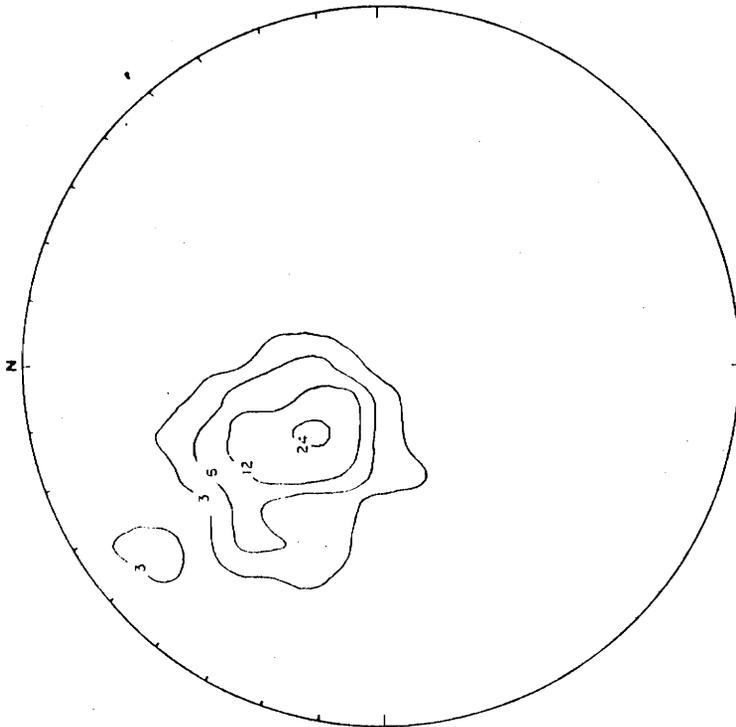
C-1

Appendix C-3. Poles to S_1 foliation for the central domain (Plate 1).
82 poles.

Appendix C-4. Poles to S_1 foliation for the southeastern domain (Plate
1). 97 poles.

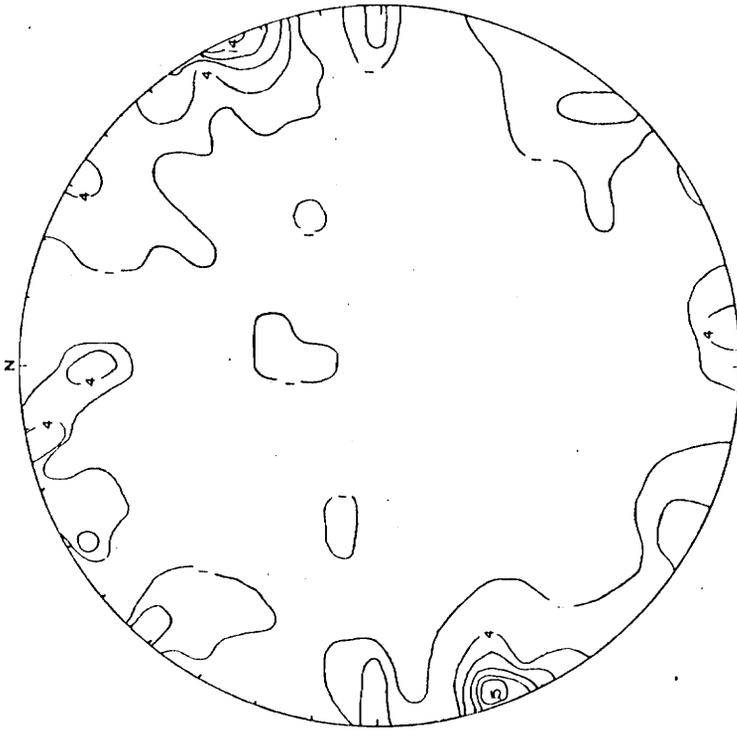


C-4

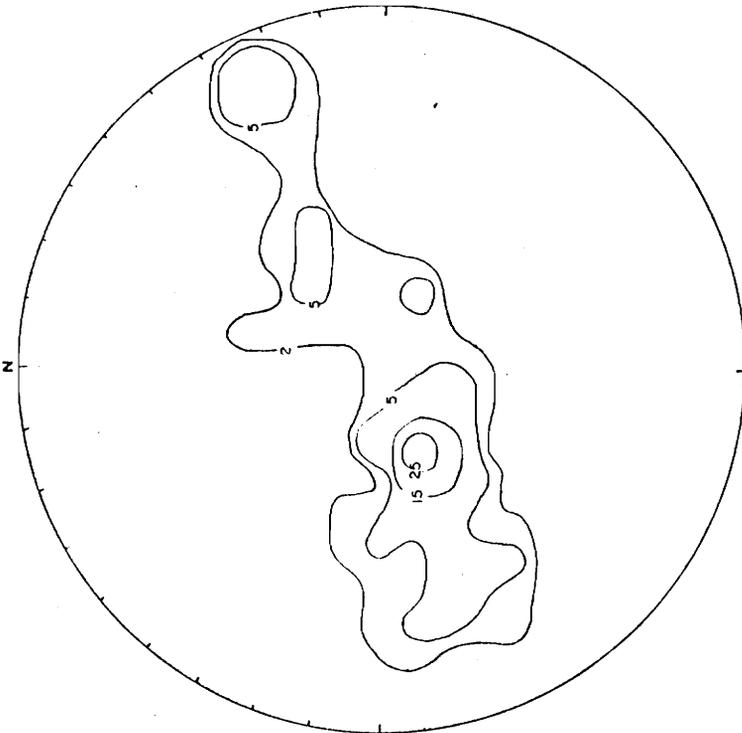


C-3

- Appendix C-5. Poles to S_3 foliation from the western domain (Plate 1).
46 poles.
- Appendix C-6. Poles to joints for the entire traverse (Plate 1).
147 poles.



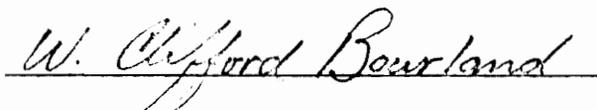
C-6



C-5

VITA

W. Clifford Bourland was born June 16, 1952 in Midland Texas. He graduated with honors from Monterey High School in Lubbock, Texas, in June 1970. In May 1974, he was accepted into Who's Who in American Colleges and Universities and later that month received his B.S. in Geosciences with honors in the Honors program from Texas Tech University, Lubbock, Texas. In August 1974, he enrolled in graduate school at Virginia Polytechnic Institute and State University, in the Department of Geological Sciences. Upon completion of the Master of Science degree in Geology, he will become a research associate with Dr. Lynn Glover III of Virginia Polytechnic Institute, and will be assigned to Columbia, South Carolina, to work on a project in geothermal heat source studies.

A handwritten signature in cursive script that reads "W. Clifford Bourland". The signature is written in dark ink and is positioned above a solid horizontal line.

W. Clifford Bourland

TECTOGENESIS AND METAMORPHISM OF THE PIEDMONT
FROM COLUMBIA TO WESTVIEW, VIRGINIA ALONG
THE JAMES RIVER

BY

W. Clifford Bourland

(ABSTRACT)

During Late Precambrian or Early Cambrian (~550 m.y.) a sequence of interlayered graywackes and shales was intruded by the Columbia granite. At approximately 340 m.y. the granite and sediments were metamorphosed to at least amphibolite facies. During the peak and waning stages of metamorphism, these lithologies experienced 3 or possibly 4 deformational events which occurred while faulting was initiated along the Lakeside fault zone. Retrogressive mineral assemblages in fractures along the Lakeside fault and Central Piedmont Lineament indicate that reactivations along these zones occurred during regional cooling and continued after 221 m.y. During Late Triassic or Early Jurassic, the region was intruded by diabase dikes. An erosional unconformity separates alluvium and colluvium from the layered and intrusive rocks.