TECTOGENESIS OF THE HYLAS ZONE
AND
EASTERN PIEDMONT
NEAR RICHMOND, VIRGINIA

by

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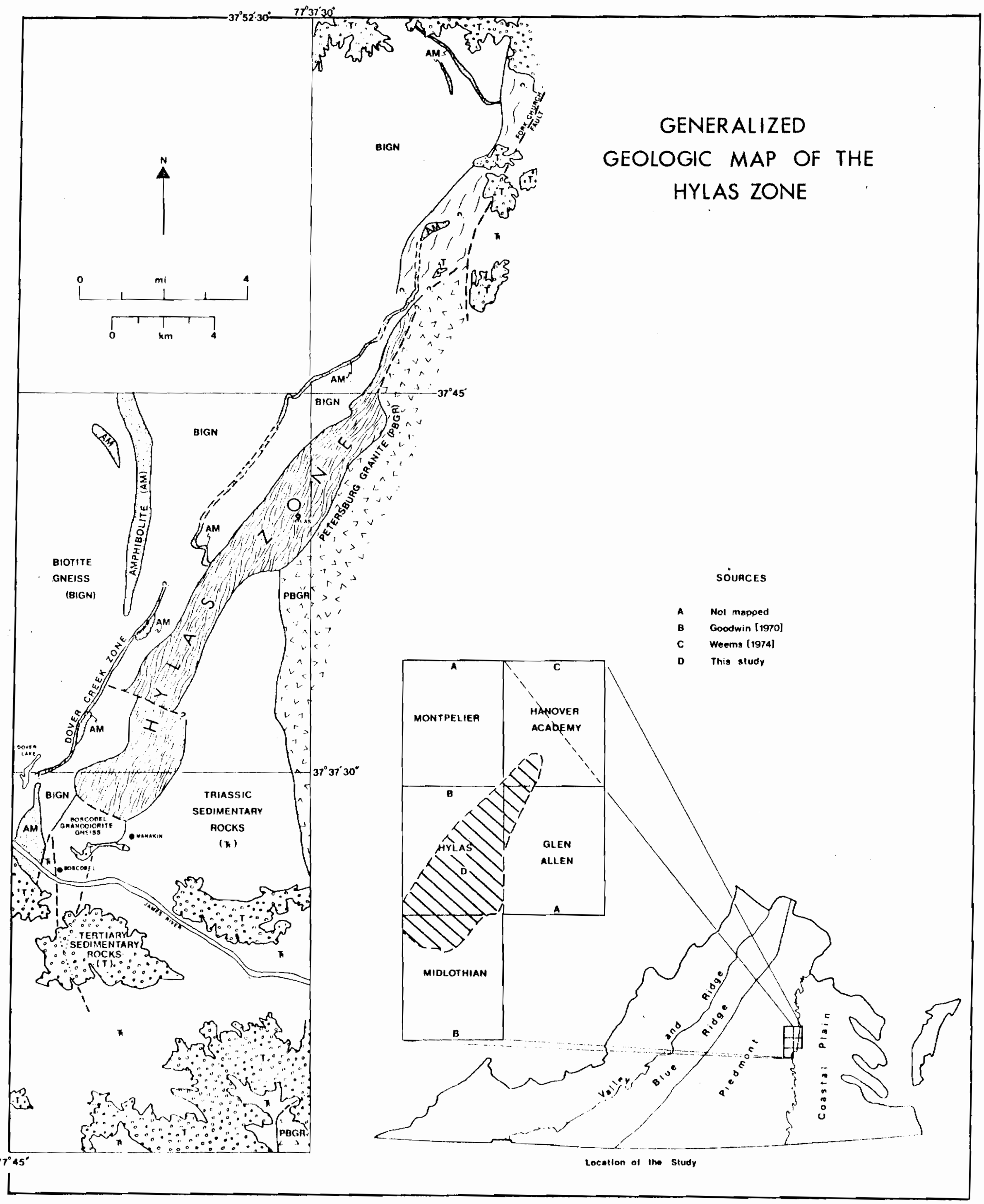
INTRODUCTION

Since Johann David Schöpf (1787; Spieker, 1972, p. 76-77) described the Petersburg Granite in the James River channel through Richmond as ". . .a hardened dough whose constituents, when it was still soft and fluid, were not properly kneaded together." many geological investigations have been conducted in the Piedmont of Virginia. Yet few detailed studies have been published concerning that section of the eastern Virginia Piedmont along the James River between Richmond and Columbia. The present study forms the eastern part of a geological strip map traverse along the James River between these two localities (Poland, 1976; Bourland, 1976) conducted under the direction of Dr. Lynn Glover, III.

The primary goal of this investigation was to determine the nature and tectonic history of a zone of cataclasis referred to as the Hylas zone (Weems, 1974). In the course of field investigations, sections of the Midlothian, Hylas, Glen Allen, Hanover Academy and Montpelier 7 1/2 minute quadrangles were covered (Fig. 1). Previous work by Brown (1937), Goodwin (1970) and Weems (1974) aided in the description of the general geology.

Because of apparent low metamorphic grade and fine grain size, previous workers in the Hylas zone area described the mylonites and ultramylonites as aporhyolite (Brown, 1937) or metavolcanic rocks (Goodwin, 1970). Bobyarchick and others (1976) presented evidence to show that these rocks were, indeed, cataclastically retrograded equivalents of gneiss and amphibolite. In the following text, the geology and tectogenesis of the Hylas zone and surrounding area are described.

Figure 1. - Location of study area on generalized geologic map compiled from Goodwin (1970), Weems (1974) and this study. Quaternary sedimentary rocks have been removed from the illustration.


GENERALIZED GEOLOGIC MAP OF THE HYLAS ZONE
37°52'30"
77°37'30"
37°45'
37°37'30"
77°45'
N
0 mi 4
0 km 4
BIGN
AM
BIOTITE GNEISS (BIGN)
AMPHIBOLITE (AM)
HYLAS ZONE
PETERSBURG GRANITE (PBGR)
PBGR
DOVER CREEK ZONE
DOVER LAKE
BOSCOBEL GRANODIORITE GNEISS
MANAKIN
BOSCOBEL
TRIASSIC SEDIMENTARY ROCKS (₮)
TERTIARY SEDIMENTARY ROCKS (T)
JAMES RIVER
FORK CHURCH FAULT
SOURCES
A Not mapped
B Goodwin [1970]
C Weems [1974]
D This study
MONTPELIER
HANOVER ACADEMY
HYLAS
GLEN ALLEN
MIDLOTHIAN
Valley and Ridge
Blue Ridge
Piedmont
Coastal Plain
Location of the Study

METHODS AND TERMINOLOGY

Approximately 60 days of field mapping at a scale of 1:24,000 were spent collecting structural data and rock specimens. Grain size, as applied to field and hand specimen descriptions of rock samples, was based on standard sedimentary grain size scales such as are found in Compton (1962, p. 213) or Pettijohn, Potter and Siever (1973, p. 71).

Thin sections were stained for potassium feldspar and plagioclase according to the method of Norman (1974). Anorthite content of plagioclase was determined by flat stage measurements using the method of Michel-Lévy so that values given are only approximate. Modal analyses averaged about 500 counts per slide and were measured on a 1 mm x 1 mm grid. Mineral assemblages listed in the text are given in order of increasing abundance.

Cataclastic descriptions and nomenclature are generally after Higgins (1971). The series protomylonite-mylonite-ultramylonite (Higgins, 1971, p. 7) was followed because all cataclastic lithologies were obviously mylonitized and still retain cataclastic textures.

Descriptions of x-ray, geochronology and geophysics studies are presented in appropriate appendices following the main text.

STRATIGRAPHY OF METAMORPHIC ROCKS

The metamorphic terrane west of the Hylas zone is dominated by a layered sequence of metasedimentary and metavolcanic rocks in the State Farm Gneiss, Sabot Amphibolite and eastern gneiss complex. The Boscobel granodiorite gneiss appears to have been a pre- or syn-metamorphic igneous intrusion which now lies concordant to the regional primary metamorphic foliation. The layered rocks have apparently been thrust over from the southeast by Petersburg(?) Granite along the Hylas zone. Later high angle faulting along the Hylas zone and sedimentation in the tectonic lowlands produced during Triassic time formed the Richmond Basin.

State Farm Gneiss (Sfgn). - A two feldspar-quartz biotite gneiss comprises about 40 percent of the metamorphic sequence in the area. The gneiss is herein divided into two map units separated by the Sabot Amphibolite (Fig. 2). The unit above the Sabot Amphibolite, the eastern gneiss complex, is structurally complex and is obscured by cataclasis in the Hylas zone as well as by intense weathering and vegetative cover. Biotite gneiss structurally below the Sabot Amphibolite is referred to as State Farm Gneiss (*See* restrictive definition *in* Poland, 1976). This restricts Brown's (1937) upper boundary of the formation to those gneisses structurally beneath the Sabot Amphibolite. Brown considered biotite gneiss in the present study area to be a part of his State Farm Gneiss, which he thought originated as an igneous mass injected into older "Wissahickon" biotite schist. This interpretation, however, is not supported by the present study.

The State Farm Gneiss is a layered gneiss complex of heterogeneous bulk composition ranging from diopside-quartz-biotite-plagioclase gneiss to garnet-quartz-biotite-plagioclase-K feldspar gneiss (*See* Appendix 1). Hornblende content is as much as 15 percent in intercalated amphibolitic layers. Layering varies from a few cm to several m in thickness.

Texturally, the State Farm Gneiss is medium to coarse grained with a well-developed foliation and conspicuous layering. Coarser gneissic phases are characteristically garnetiferous with rounded, locally rotated garnets as much as 1.5 cm in diameter. Granitic gneiss locally occurs near the contact with Sabot Amphibolite, as on the Chesapeake and Ohio railroad 0.3 km (0.2 mi) east of Sabot.

By increase in biotite content (30 percent or more) at some localities the gneiss grades into a schist. On Tuckahoe Creek, northeast of Centerville, the biotite gneiss consists of alternating 3 to 6 cm thick layers of biotite schist and felsic gneiss with sharp contacts. This distinctive lithology has not been observed elsewhere in the map area but Kingston and Weems (1976) have mapped a similar unit north of the Hylas quadrangle.

The State Farm Gneiss west of the Sabot Amphibolite comprises the structurally lowermost unit in the area and perhaps the oldest unit assuming the entire sequence is not overturned. Hornblende gneiss west of Dover Creek is older than or at least coeval with the overlying biotite gneiss. These gneisses form the core of a large regional F_2 antiform the axis of which lies to the west of the study area (Poland, 1976).

Goodwin (1970, p. 6) subdivided gneisses in the Hylas and Midlothian quadrangles into granite gneiss and biotite gneiss, although he realized these lithologies are commonly interlayered. He gave no interpretation for the origin of the felsic gneisses. Weems (1974) concluded that the biotite gneiss is largely of sedimentary origin based on estimated chemical composition calculated from modal analyses and estimates of chemical compositions of minerals in the gneiss. Field and petrographic evidence suggest the State Farm Gneiss originated as a interlayered sedimentary-volcanic unit (*See* Conclusions).

Hornblende-microcline gneiss (hmgn). - Garnetiferous hornblende-plagioclase-microcline gneiss (AB5-280, Appendix 1) crops out on the western ridge parallel to Dover Creek in the southwestern quadrant of the Hylas quadrangle. The extent of this unit beyond the western boundary of the mapped area is not known.

The hornblende-microcline gneiss is conspicuous in the field because it is massive and highly resistant. Minor biotite or granite gneiss is interlayered with this unit and biotite schist and minor amphibolite (AB5-282, Appendix 1) structurally overlie it immediately to the east. The hornblende-microcline gneiss is shown (Fig. 2) as a distinct unit within the State Farm Gneiss.

Sabot Amphibolite (Sam). - The Sabot Amphibolite, as defined by

Poland (1976), separates State Farm Gneiss on the west from structurally higher gneisses in the eastern gneiss complex on the east. Rocks probably correlative with the Sabot Amphibolite occur in the Hylas zone. Estimated thickness of the amphibolite ranges between 140 m (460 ft) and 207 m (680 ft). The Sabot Amphibolite is lithologically distinct from the enclosing biotite and granite gneisses and grades structurally downward into the State Farm Gneiss by interlayering, as observed on the Chesapeake and Ohio railroad 0.5 km (0.3 mi) east of Sabot. Hornblende content varies from 35 percent (AB5-161a, AB5-383, Appendix 1) to as much as 65 percent (AB5-272, Appendix 1) so that the formation actually consists of amphibolite (greater than 40 percent amphibole) and amphibole gneiss (less than 40% amphibole and little or no biotite). Amphibole gneiss generally grades into amphibolite. The upper contact of the Sabot Amphibolite is concealed in part by faulting and cataclasis in the Hylas zone, although cataclastic equivalents may continue into the zone (Fig. 2).

Garnet-quartz-plagioclase-hornblende gneiss (amphibolite) is the most persistent mineral assemblage. Euhedral green hornblende, locally altered to magnetite and chlorite, and subhedral plagioclase (approx. An_{30}) with local polysynthetic twinning and sericitization, constitute about 75 percent of the rock. Anhedral quartz as rounded, interstitial blebs or polygonized veins makes up as much as 15 percent of the rock. Euhedral sphene is relatively abundant with magnetite and pyrite constituting the opaque fraction. Epidote group minerals are insignificant as primary metamorphic minerals but crystallized later in discordant fractures to form veinlets transecting the foliation and cutting directly across mineral grains. In protomylonitized or noncataclastic amphibolite on the periphery of the Hylas zone, hornblende was chloritized, plagioclase was tectonically deformed and quartz was polygonized.

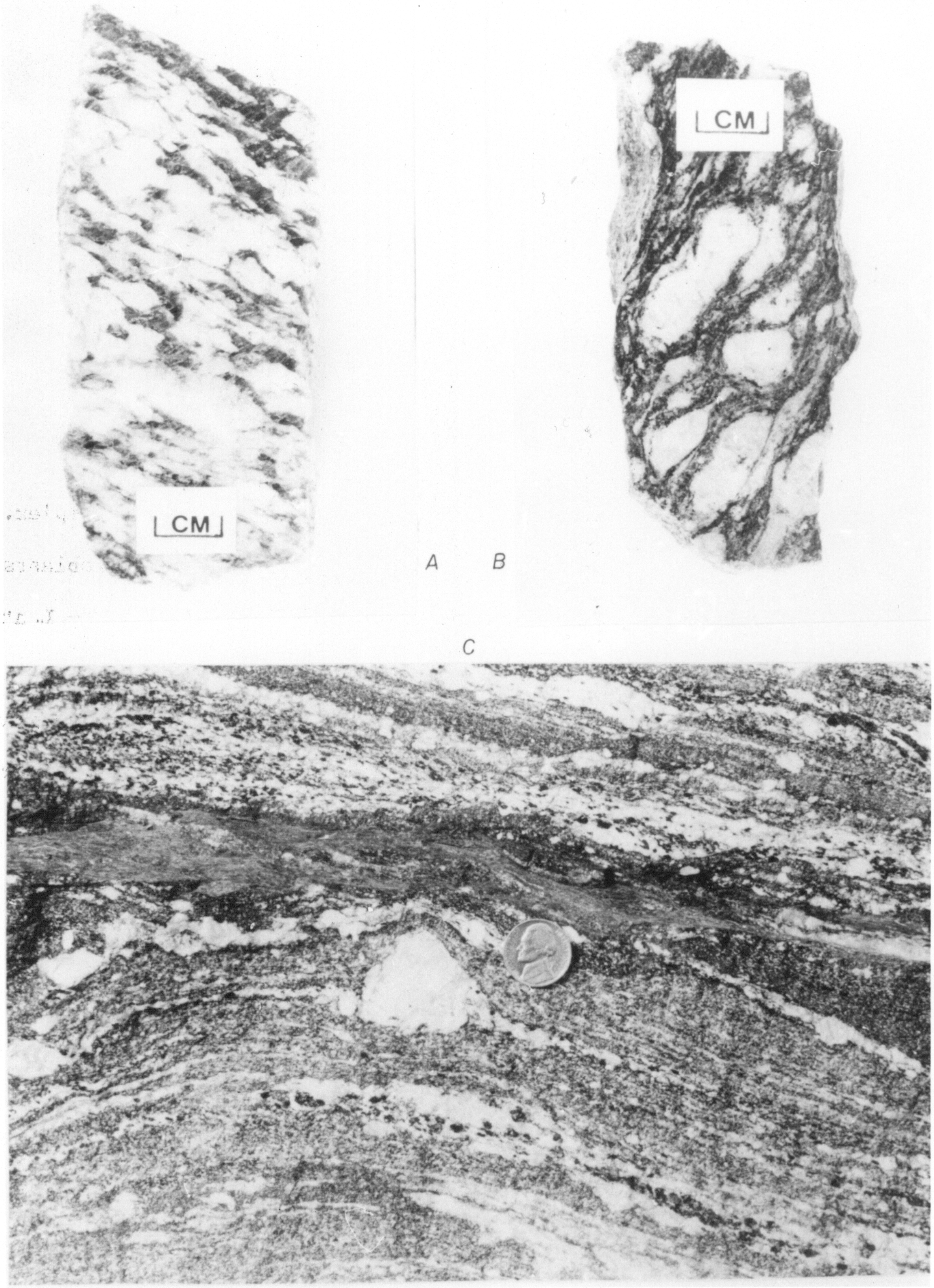
The outcrop pattern of the Sabot Amphibolite is shown in Figure 2 as lenslike and discontinuous. The preferred interpretation is that the unit underwent dismemberment by folding so that present exposures are formational remnants or portions of plunging folds. A second interpretation is that the protolith was lenticular and discontinuous.

Since the Sabot Amphibolite is known to be interlayered with State Farm Gneiss and with overlying gneisses, it is likely that the amphibolite is of the same age as its stratigraphic neighbors.

Eastern gneiss complex (Egnc). - Intercalated quartzose biotite-plagioclase gneiss (AB5-228, AB5-237, AB5-243, AB5-246, AB5-252, Appendix 1) and schist of similar mineralogy (AB5-240, Appendix 1) constitute the eastern gneiss complex, which structurally overlies Sabot Amphibolite. Conspicuously abundant, boudinaged coarse generation 1 microcline pegmatites (*See* section on pegmatites) and concordant coarse grained quartz-microcline augen gneiss also characterize the eastern gneiss complex (Plate 1). It appears correlative by structural position and bulk composition, in part, to the Maidens Gneiss (Poland, 1976) and to Weems' (1974, p. 9) upper biotite gneiss unit. The Hylas zone truncates the eastern continuation of the unit.

The eastern gneiss complex is best exposed in the northwestern

PLATE 1. - Examples of augen gneiss in the eastern gneiss complex. *A* - Felsic augen gneiss with large white microcline porphyroblasts (augen) in a matrix of quartz and plagioclase (AB5-347). *B* - Lenticular plagioclase and microcline porphyroblasts in a matrix of partially chloritized biotite and quartz (AB6-23). *C* - Coarse grained Sabot Amphibolite near the western border of the Hylas zone; blocks on the entrance road to the Richmond quarry north of Interstate 64. Dark layer above coin is a chloritized shear zone.


CM
CM
A
B
C

Glen Allen quadrangle and the southwestern Hanover Academy quadrangle where the formation was not obscured by weathering or cataclasis in the Hylas zone. The lithology varies from a fine to medium grained, well layered garnet-biotite-microcline-plagioclase-quartz gneiss (microcline in elongate augen as much as 5 cm long) to medium to coarse grained, dark gray, porphyroblastic garnet-biotite-hornblende-quartz-plagioclase gneiss with poorly developed compositional layering. Microcline-quartz-biotite-plagioclase schist occurs in subordinate quantities.

Plagioclase, which averages 38 percent of the rock, varies in anorthite content from about An_{12} to An_{34} (flat stage measurements). Generally euhedral biotite is commonly brilliant orange-red in color and pleochroism, becoming green-brown and green with increasing alteration closer to the Hylas zone. Biotite constitutes approximately 17 percent of the unit. K feldspar, which seems limited to augen and pegmatitic layers, is mostly microcline distinguished by cross-hatched twinning. Accessory minerals vary depending on the intensity of retrogressive alteration but, in the least altered samples, are comprised of magnetite, pyrite, zircon, sphene, epidote, scapolite, apatite and kyanite.

Retrogressive alteration of lithologies in the eastern gneiss complex was accomplished by cataclasis during the Hylas zone deformation. Petrographically, the result of this alteration was chloritization of iron-magnesium minerals and epidotization of plagioclase and scapolite.

Rocks on the periphery of the Hylas zone were intensely altered and typically contain subconcordant chloritized shears (AB5-246, AB5-252, Appendix 1). Cataclasis, other than slight polygonization of quartz, is not evident in these rocks and the main structural style of deformation was fracturing (AB5-252, Appendix 1). Epidote + chlorite + magnetite crystallized in fracture spaces. Retrogression was mainly pseudomorphic with biotite nearly totally replaced by chlorite + magnetite ± sphene.

Potassium metasomatism is indicated by the conspicuous presence of microcline augen gneiss and local anomalous potassium enrichment (AB5-383, Appendix 1) in rocks, which outside the eastern gneiss complex, are not so affected.

Weems (1974, p. 11) found that his upper and lower biotite gneiss units, separated by Sabot Amphibolite of this study, were petrographically identical. Appendix 1 shows that the petrographic variations between State Farm Gneiss and rocks in the eastern gneiss complex are a consistently higher quartz content in the State Farm Gneiss and lower overall microcline content in the eastern gneiss complex. Consequences of these discrepancies are discussed later in the text but overall composition and structure of the two units indicate they may have shared a common or similar origin.

Boscobel granodiorite gneiss (Bgdgn). - The Boscobel granodiorite gneiss, as defined herein, is a medium grained microcline-biotite-quartz-plagioclase orthogneiss with interlayered generation 1 granitic pegmatites. Outcrops are mainly restricted to the Boscobel Granite Corp. quarry (Fig. 2). The unit is covered or truncated by a fault north of Highway 6. The 1928 Geologic Map of Virginia (Stose, 1928) shows rocks in this area as a wedge of Wissahickon gneiss. Steidtmann (1945, p. 61-62) briefly discussed the lithologies in the Boscobel quarry and also associated them with Wissahickon gneiss. Brown (1937, p. 16) called the coarse pegmatites Petersburg Granite which "thoroughly invaded" aporhyolite. Following that interpretation, the 1963 Geologic Map of Virginia (Calver, 1963) showed an interfingering relationship between granite and metavolcanic rocks. Goodwin (1970, Plate 2) mapped the same kind of relationship. The present interpretation (Fig. 2) is that the northward extensions of Petersburg Granite shown by previous authors are outcrops of the abundant generation 1 pegmatites associated with the Boscobel granodiorite gneiss.

Steidtmann (1945, p. 62) described three kinds of rocks in the Boscobel Granite Corp. quarry: (1) ". . . a fine grained, pale green rock composed of quartz, albite-oligoclase and . . . biotite", (2) medium to coarse grained pegmatitic granite composed of quartz, microcline and plagioclase, and (3) a "hybrid" rock consisting of mixtures of the first two lithologies. He also noted (Steidtmann, 1945, p. 62) secondary calcite, chlorite, pyrite, crystalline quartz and a "tarry substance". Samples of Steidtmann's first lithology taken for this study (AB4-1, Appendix 1) constitute the type lithology for the Boscobel granodiorite gneiss.

It is a gray to green, depending on the amount of alteration, medium grained rock with a weak to moderate gneissic layering. Microtextures are approximately equigranular with subhedral to euhedral plagioclase and microcline porphyroblasts as much as 0.5 mm in length. Plagioclase is locally zoned and microcline has cross-hatched twinning. Biotite and chloritized biotite with magnetite and sphene make up approximately 20 percent of the rock. The biotite generally occurs as well distributed folia interstitial to anhedral quartz and feldspar and, less frequently, in mafic aggregates with epidote, opaques and retrogressive chlorite. Magnetite grains locally have calcite rims. Steidtmann (1945, p. 62) called this lithology a dacite, apparently to correspond to Brown's (1937, p. 15-16) aporhyolite. The modes for this rock plot in the granodiorite field in the I.U.G.S. classification (1973). A metamorphic foliation is defined by the alignment of biotite and elongate quartz grains as well as the gneissic layering.

Pink and white coarse grained pegmatites as much as 1.2 m (4 ft) thick are concordantly intercalated with the granodiorite gneiss. The contacts are locally scalloped in cross section because of small scale folding. Plagioclase, quartz and microcline are the main constituents (*See* section on pegmatites). On the western face of the Boscobel Granite Corp. quarry, small, euhedral garnets as much as 1 cm in diameter formed in and a few cm to the side of the contact zone with biotite gneiss in the eastern gneiss complex.

Fracturing, hydrothermal alteration and open space mineralization in the Boscobel granodiorite gneiss accompanied Triassic faulting. Intense sericitization of plagioclase, retrogression of biotite to chlorite (AB4-1c, Appendix 1) and the formation of calcite and minor laumontite on fracture and joint surfaces occurred in the alteration zones. Euhedral quartz crystals as much as 3 mm in length crystallized as drusy coatings in cavities in the rock. Many of the fracture surfaces are coated with a fine, black pyrolusite film. Highly contorted chlorite veins in the Boscobel quarry are common to rocks peripheral to the Hylas zone and probably originated as shears during the Hylas deformation.

The massive appearance, composition, occurrence of zoned plagioclase grains and abundance of generation 1 pegmatites of the Boscobel gneiss suggest that this unit formed as a granitic or granodioritic intrusion.

INTRUSIVE ROCKS

Petersburg(?) Granite (Pbgr). - The Petersburg Granite was shown on the 1928 Geologic Map of Virginia (Stose, 1928) as a large batholithic body of Precambrian age. Bloomer (1939, p. 141) surmised from xenoliths in the granite and structural relations to Triassic sediments that the Petersburg is Paleozoic. Wright and others (1975) published a consolidation age of the granite from zircons of 330 ± 8 m.y. Contacts of the Petersburg Granite with country rocks in the study area are largely obscured by the Hylas zone, Triassic faulting and sedimentary cover. Bloomer (1939, p. 142) reported oligoclase-biotite-hornblende gneiss in apophyses in Chesterfield County. Biotite gneiss xenoliths and basaltic xenoliths are exposed in the James River in Richmond.

Watson (1906) described three types of Petersburg Granite: (1) light gray, medium to coarse grained granite with phenocrysts from 1 to 5 mm long, (2) a finer grained dark blue granite of approximately the same composition, and (3) a porphyritic granite with idiomorphic potassium feldspar phenocrysts as much as 5 cm (2 in) long. He believed the blue granite to be intrusive into the gray granite.

The Petersburg Granite in this area is predominantly a coarse grained two-feldspar muscovite-biotite granite with a poorly to moderately developed metamorphic(?) foliation. Granite porphyry phases are gradational into relatively equigranular or microphaneritic granite. Potassium feldspar is poikilitic to nonpoikilitic, euhedral to subhedral microcline with cross-hatched twinning. Plagioclase is subhedral and ubiquitously sericitized. Zoned plagioclase is identified as having preferentially sericitized cores. Amoeboid myrmekite which makes up approximately 1 to 6 percent of the rock, surrounds or embays large microcline phenocrysts. The myrmekite is locally micrographic (AB6-16, Appendix 1) where anhedral quartz blebs are arranged in a plumose structure. Quartz phenocrysts were variably polygonized according to the degree of metamorphic foliation present (AB6-7, AB6-9, AB6-11, AB6-16, AB6-28, Appendix 1). Biotite content is never greater than 10 percent. Brown biotite is dominant in less altered samples (AB6-11, Appendix 1) but was increasingly replaced by green biotite and retrogressive chlorite upon approaching the Hylas zone (AB5-261, AB5-262, Appendix 1) and elsewhere is intrafolial with chlorite (AB5-358, Appendix 1). Sphene, magnetite and hematite formed along cleavage in the highly chloritized biotite. Most epidote present is anhedral and formed retrogressively along fractures or on borders of plagioclase. However, some epidote, especially those grains which are zoned (AB5-356, Appendix 1), is probably primary.

Where affected by fracturing and brecciation (AB5-356, Appendix 1), sericitization and retrogression are particularly intense. Laumontite formed in fracture voids around fragments of microcline and plagioclase.

Foliations are delineated by alignment of muscovite and biotite and by dimensional orientation of polygonized quartz plates or lenses.

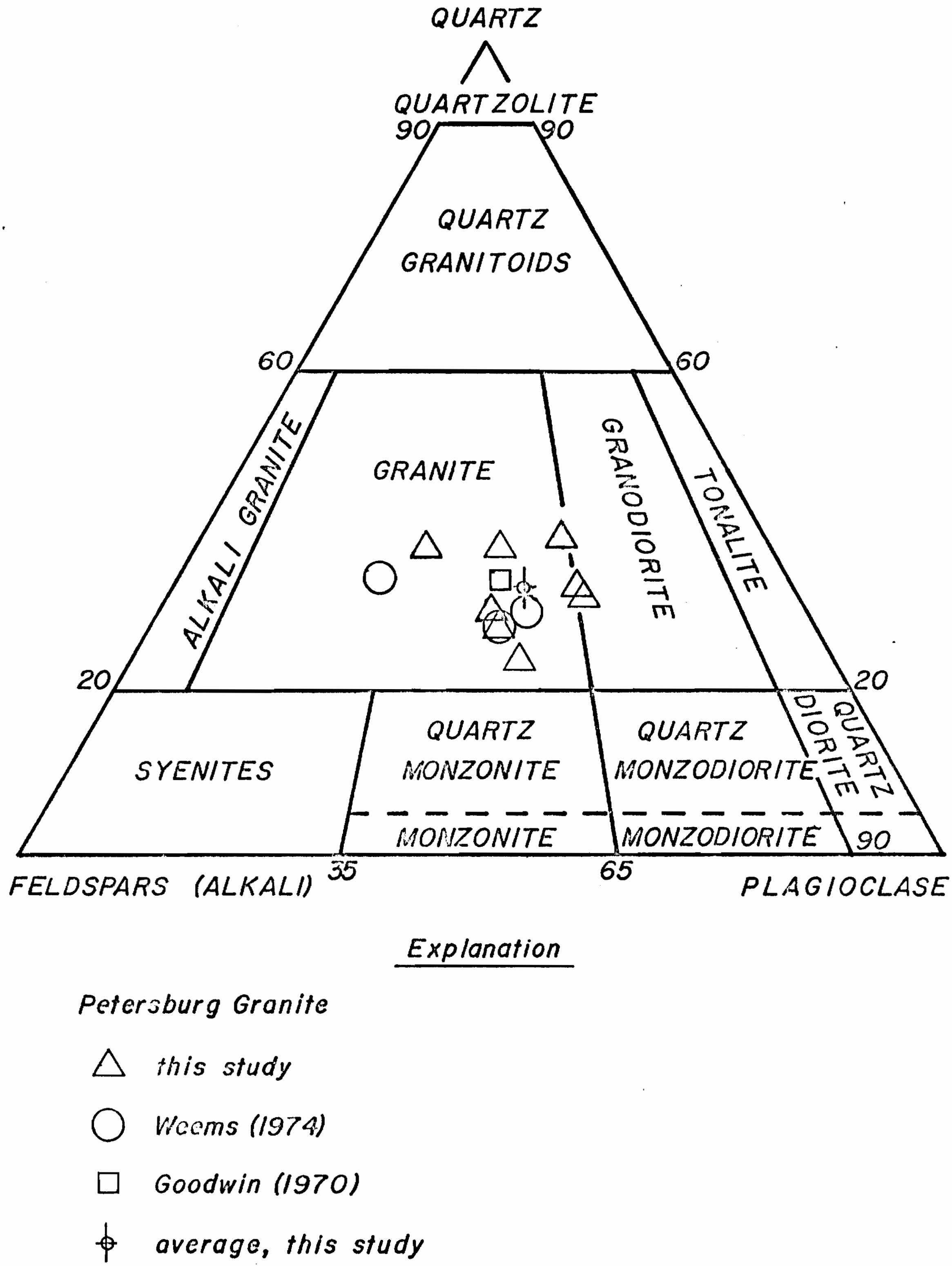
Weems (1974, p. 14) suggested that the Petersburg is a subsolvus granite by its lack of perthitic microcline. He also suggested (Weems, 1974, p. 14), however, that metamorphism could have obliterated any original perthitic textures.

Using the I.U.G.S. classification (1973), all the Petersburg

Granite in the study area is granite or granodiorite. Most samples fall in the granite field near the granodiorite boundary (Fig. 3). Goodwin's modes for quartz monzonite porphyry (1970, p. 12; cf. AB5-358, Appendix 1) is granite porphyry by this classification. Weems' (1974, Appendix I, Table 4) samples R-5284, R-5285 and R-5286 are all within the granite field (Fig. 3). Wright and others (1975) indicated all their samples were quartz monzonites, although no modal analyses were given.

The questioned correlation of Petersburg Granite to granite and/or metagranite in the study area stems from the lack of direct correspondence to dated outcrops some 16 to 24 km (10 to 15 mi) to the east in Richmond. However, modal analyses, textures and lithologic and grain size variations as well as structural relations suggest that a tentative correlation to Petersburg Granite is feasible.

Figure 3. - Plot of quartz-alkali feldspar-plagioclase ratios for Petersburg Granite on the I.U.G.S. (1973) classification for igneous rocks. Data from Goodwin (1970) and Weems (1974) are included for comparison.


QUARTZ
QUARTZOLITE
90
90
QUARTZ GRANITOIDS
60
60
ALKALI GRANITE
GRANITE
GRANODIORITE
TONALITE
20
20
SYENITES
QUARTZ MONZONITE
QUARTZ MONZODIORITE
QUARTZ DIORITE
MONZONITE
MONZODIORITE
90
FELDSPARS (ALKALI)
35
65
PLAGIOCLASE
Explanation
Petersburg Granite
this study
Weems (1974)
Goodwin (1970)
average, this study

Diabase Dikes. - Several olivine tholeiitic diabase dikes (Wilkinson, 1967, p. 181) have been mapped in the study area and appear to have discordantly intruded amphibolite, cataclastic rocks in the Hylas zone and Triassic sedimentary rocks (Fig. 2). Border zones in about half these dikes were obscured by weathering but the distribution of colluvium and measurements of exposed dikes indicate thicknesses generally less than 5 m. They trend about a northerly strike and dip steeply from 70 degrees to vertical. Dike intrusion appears to have been preferential, but not totally restricted, to rocks with well developed joint sets.

Dikes in the study area vary texturally from ophitic to subophitic with olivine and augite crystals as much as 2 mm in diameter. Plagioclase (An_{52}), 0.1 mm to 3 mm long, occurs in lath-like crystals either enclosed by pyroxene in ophitic textures or enclosing pyroxene in local diabasic textures. Colorless to brown locally crystallitic intersertal glass, now devitrified, formed roughly spherical masses.

Pyroxene, primarily brown to purple-brown, faintly pleochroic augite and minor colorless pigeonite (low 2V), were locally altered to chlorite and talc(?). Olivine exhibits a variety of alteration products mainly consisting of light green antigorite veins and rims, euhedral dark brown to black spinel (picotite), magnetite (probably secondary), hematite and chlorite. Plagioclase is relatively unaltered except for incipient hematization in microfractures caused by ground water saturation.

No absolute ages for diabase dikes in the study area are available but, because they are known to intrude Late Triassic sedimentary rocks and have not been observed to cut Cretaceous rocks (Roberts, 1928, p. 62), a likely time for intrusion was about 195 m.y. to 136 m.y. ago.

Pegmatites (p). - Concordant, slightly discordant and highly discordant coarse felsic pegmatites are found throughout the mapped area. At least three generations of pegmatites have been observed. Criteria for distinguishing generation 1 pegmatites from generation 2 or 3 pegmatites are mainly the geometric relationships to country rocks and cross-cutting relationships among generations. Microcline, quartz and albitic plagioclase are the dominant mineral constituents of all generations. Muscovite is usually present and is locally abundant as crinkled books. Garnet, biotite, hornblende and secondary stilpnomelane are found in minor amounts.

Generation 1 pegmatites are the oldest. Generally, they are from 0.3 m to 3 m (1 to 10 ft) thick and strongly transposed into the regional primary foliation. Generation 2 and 3 pegmatites usually are found as stringers 1 to 3 cm thick. The relationships of these two sets of pegmatites to country rocks are more clearly observed in the metamorphic rocks west of the study area (*See* Poland, 1976). However, generation 2 pegmatites appear to be partially or totally deformed in F_2 folds (*See* Structural Geology I section) and cut across generation 1 pegmatites. Generation 3 pegmatites were relatively undeformed and cut across the foliation and prior pegmatite generations discordantly.

With the possible exception of some felsic pegmatites in the Boscobel granodiorite gneiss, all generations in the study area probably formed during metamorphism

TRIASSIC SEDIMENTARY ROCKS (Tr)

Triassic sedimentary rocks in the area lie within a northern closure of the Richmond Basin (Calver, 1963). Roberts (1928) first reported on the lithologies and economic resources of Triassic rocks in Virginia. Goodwin (1970) gave a general account of the rock units in the Hylas and Midlothian quadrangles and Weems (1974) presented a discussion of the stratigraphy and structure in the Taylorsville Basin which lies northeast of the study area. Exposures are sparse and generally confined to the borders of the basin. Stratigraphic correlation is not attempted here because the data is insufficient.

Lithologies present in the study area are: (1) coarse fanglomerate, arkose conglomerate and quartz pebble conglomerate, (2) coal, and (3) interlayered muscovitic subarkose and hematitic, zeolite-bearing mudstone.

Conglomerate (Trf). - Very coarse, boulder fanglomerate occurs on the western border of the basin and locally on the eastern border. Granitic, arkosic conglomerate was deposited nonconformably upon Petersburg Granite. Quartz pebble conglomerate is interlayered with subarkose.

The fanglomerate units are well exposed south of the Rockville and Royal Quarries in Little Tuckahoe Creek, southeast of Kain Road in a tributary to Little Tuckahoe Creek, and on State Road 623 1.8 km (1.1 mi) south of Highway 250. Subrounded boulders are as large as 0.6 m (2 ft) in diameter. Granite, granite gneiss, pegmatite gneiss and minor biotite gneiss make up the bulk of the clasts, although Goodwin (1970, p. 18) noted that angular metavolcanic clasts (cataclastic clasts of this paper) are dominant on the western border of the basin. The matrix in the fanglomerate is a brown to green weathering, medium to fine grained micaceous arkose or subarkose with generally poor layering.

Quartz pebble conglomerate, such as crops out in streams south of the Rockville Quarry and southwest of Kain Road near the eastern edge of the Hylas quadrangle, contain well rounded clasts and are interlayered with cross-bedded, weakly graded subarkose. Quartz pebbles are as much as 7 cm in diameter and gneissic boulders are common.

Arkosic conglomerate (AB5-263, AB5-264, Appendix 1) that was deposited nonconformably on the Petersburg Granite grades into Triassic subarkose and mudstone on the east side of the basin. A similar sequence was developed from felsic mylonites along the west side of the basin.

The arkose conglomerate units are of course compositionally similar to underlying granite. They are thick bedded, coarse grained and weather to a buff or brown sand. The arkose crumbles easily, has rounded or subrounded quartz and feldspar grains and rare greenstone grains (epidote-chlorite aggregates). The distinction between arkose and granite is obvious in thin section. Epidotized and sericitized plagioclase and yellow-green pleochroic chlorite are common in grains and clasts in the arkose. Rounded lithic fragments of quartz-feldspar gneiss, chlorite schist and muscovite schist occur with quartz and feldspar grains cemented by silica and minor hematite. Authigenic idiomorphic heulandite comprises 2 to 5 percent of the rock. The arkose conglomerates appear to grade basinward into medium and fine grained arkose and subarkose.

Fanglomerates are the result of coalescing alluvial fans from tectonic land on the west, northwest and locally east basin borders. Interlayering with alluvial sands suggest that tectonism was pulsating throughout deposition. Quartz pebble conglomerate probably formed as stream deposits.

Coal. - Coal and interlayered black mudstone are mostly restricted to the eastern and western margins of the Triassic basin in the Midlothian quadrangle. The Triassic coals in the Richmond Basin are reported to have been the first mined in America (Nicolls, 1904; Roberts, 1928, p. 94-95). Prospects and abandoned mines are found east of the Boscobel Quarry and along Gayton Road. Goodwin (1970, p. 13) reported fossil plant stems and leaves from debris along Gayton Road, south of Church Road in the Hylas quadrangle. Coal generally occurs as seams only a few inches thick although locally it may be as much as 1 m (3 ft) thick.

Subarkose and Mudstone. - The predominant lithologies in the Richmond Basin in the study area are highly weathered, interlayered micaceous subarkose and muscovite-chlorite-quartz-hematite mudstone (AB5-360, Appendix 1). The subarkose is black and carbonaceous when fresh, weathers to an orange-brown sand and locally contains rounded quartz pebbles. Sedimentary structures such as grading, cross-bedding and channel fills are locally present.

Interlayered with the subarkose is red quartz mudstone with a hematite (now limonite and clay) matrix making up 40 to 60 percent of the rock. Euhedral heulandite in the mudstone appears to be authigenic.

Extensive petrographic investigation of sedimentary rocks in the Richmond Basin would probably reveal wide-spread occurrence of zeolite minerals.

Depositional environments in the Richmond Basin were initially high energy alluvial (fanglomerate) followed by quiescence in lacustrine (subarkoses, mudstones) and paludal (coal, black carbonaceous sediments) environments. The occurrence of fossil fish and similar lithologies in the Taylorsville Basin (Weems, 1974, p. 21) further supports this interpretation.

TERTIARY GRAVELS (Tal)

Loosely consolidated alluvial quartz pebble gravels in a reddish sand or clay matrix form a thin, intermittent veneer over older rocks in the study area. Most outcrops occur in the Midlothian quadrangle. Red mudstone or siltstone is locally interbedded with gravel.

Quartz pebbles as much as 5 cm (2 in) long are well rounded. Weems (1974, p. 30) reported clasts of feldspathic quartzite, vein quartz and siliceous tuff in a boulder bed at the base of the Aquia Formation. Goodwin (1970, p. 19-23) found two distinct units of Tertiary gravels which occur at different elevations and vary in weathering characteristics. He reasoned that the higher gravel, which occurs on flat upland surfaces, was the older unit. Outcrops in the study area are too sparse to distinguish separate units.

A Tertiary age for these rocks is suggested by their overlying relationship, unconformable in part (Weems, 1974), to Cretaceous sedimentary rocks just out of the study area (Weems, 1974) and elsewhere in the Coastal Plain (Calver, 1963).

STRUCTURAL GEOLOGY I - PRE-HYLAS ZONE DEFORMATIONS

Deformation of rocks in the study area is polyphase and varies from the Paleozoic regional amphibolite facies metamorphism to late Paleozoic(?) mylonitization, and Mesozoic to Tertiary(?) brecciation and high angle faulting. The tectonite history is herein presented in chronological order by deformational regimes, D_n, and by the corresponding structural elements, such as S_n, L_n and joints. Foliation is defined (Turner and Weiss, 1963, p. 97) by any mesoscopically recognizable S-surface of metamorphic origin, and thus includes some compositional layering, dimensional and locally crystallographic orientation of mineral grains, schistosity and fluxion structure in cataclastic rocks. For practical reasons, sedimentary bedding (S_o) is herein included as one of the families of S-surfaces present in the study area. Lineations are defined in one of two ways: (1) the intersection of two S-surfaces (L_{1x2}, L_{cxs}), and, (2) by alignment of long axes of mineral grains or elongation of crystals (L_b, L_h, L_{Ef}).

On the regional scale, geometric analysis of the metamorphic rocks in the area is hampered by poor exposure and the absence of thin, continuous marker units to define fold patterns. The Sabot Amphibolite, although relatively thin, is discontinuous in outcrop probably because of dismemberment by folding. Therefore, the structural interpretation is based mainly on study of mesoscopic folds, shears, lineations and foliations and tectonite fabrics in thin section.

D_1. - The earliest and most intense deformation initiated as a

ductile response to regional stress during amphibolite facies metamorphism.

D_1 tectonic elements - S_1, F_1

S_1 is the primary planar discontinuity resulting from the metamorphism of sedimentary and igneous protoliths to rocks of the metamorphic terrane. The average attitude for this foliation is N28E42SE (Fig. 4A). S_1 is distinguished by dimensional and crystallographic orientation of biotite and muscovite. In amphibolite, hornblende porphyroblasts are aligned so that their long axes define a set of planes parallel to the regional foliation, S_1. Although small scale sedimentary structures were certainly obliterated in the protoliths, large scale bulk compositional transitions (S_o) are parallel to the trend of S_1.

Isoclinal, commonly recumbent folds with S_1 axial planar are designated F_1 folds. These folds are best observed where generation 1 or 2 pegmatites have been deformed to produce F_1 isoclines.

D_2. - D_2 is a second regional deformation that deformed S_1.

D_2 tectonic elements - S_2, L_{1x2}, L_b, L_h, F_2

S_2 can rarely be measured directly in the field. Instead, the lineation produced by the intersection of S_1 and S_2, L_{1x2}, is more readily observed. Figure 4D shows that the lineations L_b (biotite alignment) and L_h (hornblende alignment) were approximately colinear with L_{1x2}. The occurrence of a mescoscopically or microscopically visible S_2 foliation in this area is usually restricted to the crests of F_2 folds. S_2 is expressed as a weak cleavage and partial realignment of of biotite folia across S_1.

F_2 folds tend to be tight and to face NW. Observed F_2 folds range in amplitude from 5 cm to 3 m (10 ft). Where there is a competency difference in folded compositional layers, such as along Stone Horse Creek in the southwestern Hanover Academy quadrangle, less competent layers fractured. Here, garnetiferous granite gneiss fractured and late, massive vein quartz filled the fractures.

Boudinage and Augen Structure. - Boudinage and augen structure in generation 1 pegmatites and granite gneiss west of the Hylas zone in the Hanover Academy and Glen Allen quadrangles were created during the D_1-D_2 period. The sequential transition from concordant pegmatite to boudinaged layers and finally to augen gneiss can be observed in the field. Pinch and swell structures were the first to develop, especially in biotite schist or gneiss where the relatively incompetent material flowed into low pressure areas between thickened pegmatite lenses (refer to Ramberg, 1955, p. 515-516). With further accentuation of thickened lenses and rupture of the original pegmatite layer through deformation, the structures are more properly designated boudins (Cloos, 1947). Although most of the boudins are polycrystalline plagioclase-quartz-microcline, large euhedral microcline porphyroblasts locally occupy core zones. In rocks where a relatively fine grained groundmass of either quartz-feldspar or biotite-quartz-feldspar formed, the boudins are smaller and have a lenticular shape. These are referred to as augen gneisses, although some of the augen are polycrystalline.

D_2 was responsible for much of the present structural configuration and outcrop patterns in the metamorphic terrain outside influence of the Hylas zone. Rheological implications suggest that D_1 was an intense, ductile deformation at low amphibolite facies temperatures and pressures but that D_2 was less ductile, less incompetent and resulted in more open folding (than F_1 recumbent isoclines).

HYLAS ZONE TECTONICS

D_3. - D_3 is a period of low angle, northwestward directed late Paleozoic(?) thrusting under approximate greenschist facies conditions resulting in the formation of protomylonites, mylonites and ultramylonites within the shear zone and retrogression and local shearing and buckling of rocks peripheral to the cataclasis.

D_3 tectonic elements - S_c, S_s, L_{cxs}, L_{Ef}, F_s, *intrafolial folds*

Cataclasis during D_3 appears in two roughly parallel, linear zones herein referred to as the Dover Creek zone and the Hylas zone (Fig. 2).

Dover Creek Zone. - The Dover Creek zone is a narrow, linear mylonitized zone which extends over at least 7.2 km (4.5 mi) N30E in the Hylas and Midlothian quadrangles. It is a D_3 tectonite with the undulatory cataclastic foliation, S_c, approximately parallel to S_1 (Fig. 4A and 4B). Shear within the Dover Creek zone was apparently imbricate and undulose because cataclastic outcrops are frequently off strike or repeated across strike. Obvious dislocation along the shear zone is not conspicuous, although in at least two localities (AB5-161b, AB5-175a, Appendix 1) mylonitized rocks form the western boundary of bodies of Sabot Amphibolite. If the intensity of cataclasis diminishes toward the northeast, the style of deformation could pass into folding with mylonites in the Dover Creek zone approximately axial planar. However, map symmetry of lithologic units in this study and that of Goodwin (1970, Plate 1) do not suggest any fold of proportions necessary for such a relationship.

Petrographically, rocks in the Dover Creek zone are characterized by retrogression, recrystallization and dislocation of mineral grains (Plates 2 and 3). Mafic minerals, mainly biotite and hornblende, were comminuted and recrystallized to a pleochroic, black cryptocrystalline cataclastic matrix of fine biotite folia, hornblende microporphyroclasts, epidote, minor chlorite and well distributed magnetite and pyrite. Idioblastic sphene is conspicuously abundant both as porphyroclasts and as porphyroblasts in relict hornblende porphyroclasts. It was locally replaced by epidote. Plagioclase and microcline occur as tectonically rounded and subrounded porphyroclasts as much as 4 cm long. Quartz, ubiquitously polygonized, locally forms jackets around feldspar porphyroclasts and extends into low pressure regions to either side of the porphyroclast. Polygonized quartz lenses were also deformed into micro-intrafolial folds. The fine matrix and quartz lenses flow around feldspar porphyroclasts, many of which rotated during cataclasis so that their long axes are now normal to the cataclastic foliation.

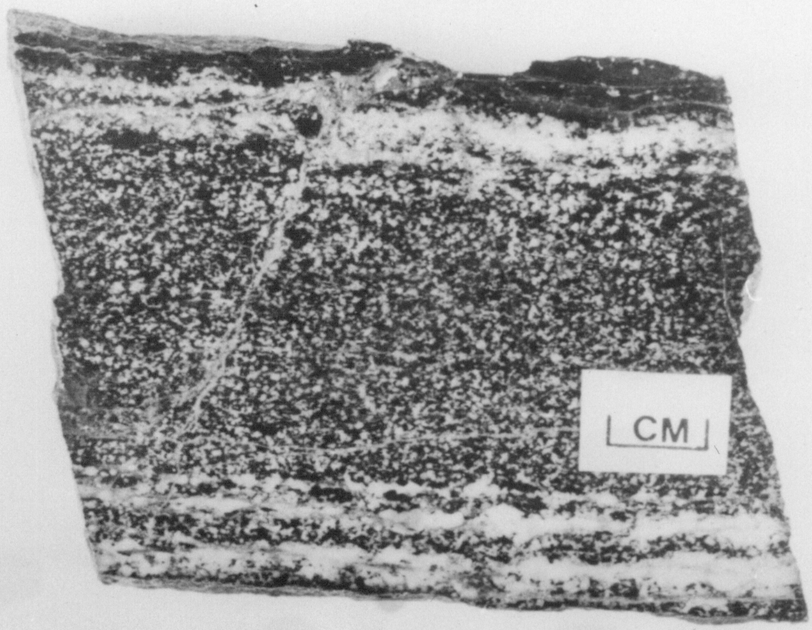
Garnets were shattered and dislocated as angular fragments as much as 1 cm long. Biotite and chlorite are common alteration products on angular garnet porphyroclasts. Locally, new muscovite porphyroblasts as much as 1 mm long formed during cataclasis parallel to the fluxion structure (AB5-102, Appendix 1). Although also found as poikiloblasts in feldspar porphyroclasts, the porphyroblastic muscovite is generally confined to the fine grained matrix. Because of this fine, black matrix and large feldspar porphyroclasts, mylonites in the Dover Creek zone are easily recognized in the field.

Deformation of the Dover Creek zone mylonites is characterized by

PLATE 2. - Sequential mylonitization of Sabot Amphibolite in the Dover Creek zone. *A* and *B* - non-cataclastic amphibolite (AB5-161a). Discordant fracture in left half of *A* contains epidote. Plane light, 10x. *C* and *D* - Protomylonite-mylonite of more felsic layer in the amphibolite. Plagioclase porphyroclasts are elongate parallel to S_c. Hornblende porphyroclasts remain as cores in lenses of brown chlorite, magnetite and minor epidote. Polygonized quartz formed undulatory layers flowing around porphyroclasts. (AB5-175a), plane light, 25x. *E* and *F* - Ultramylonite containing plagioclase porphyroclasts and quartz-microcline megaporphyroclasts (from adjacent pegmatite at sample location). Plagioclase porphyroclasts are well-rounded and surrounded by a black cryptocrystalline matrix of magnetite, chlorite, epidote and quartz. (AB5-161b), plane light, 10x.

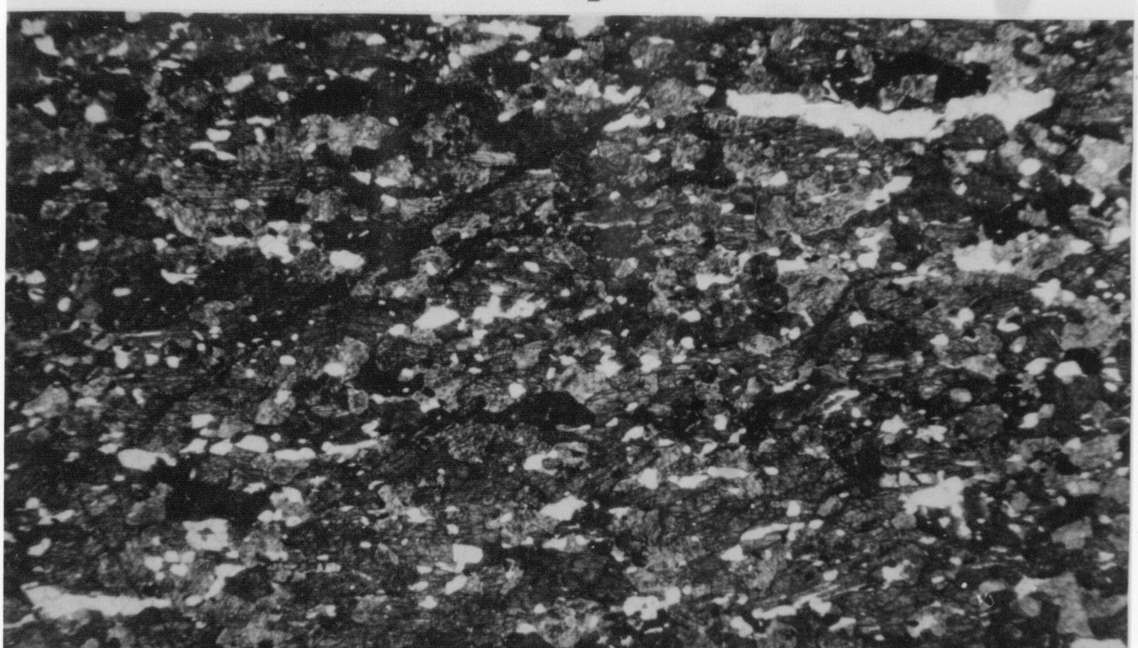
Scale: 10x - 1.3 cm x 1.1 cm

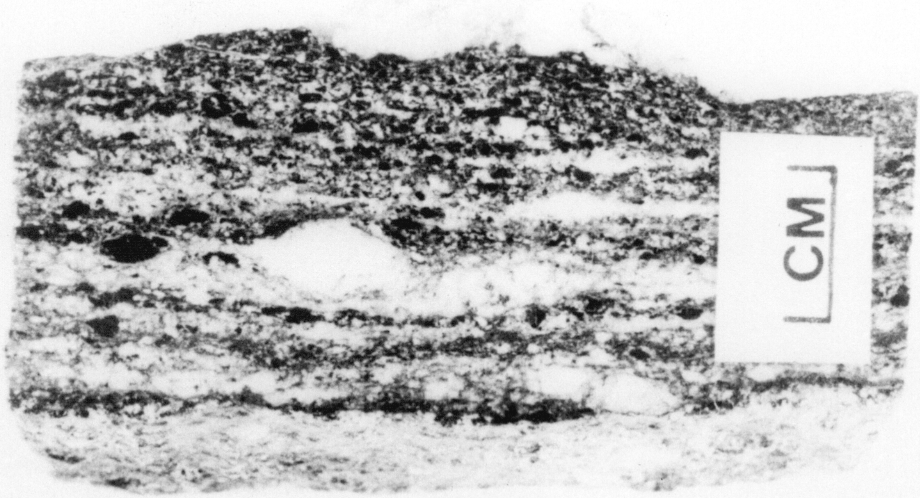
25x - 0.5 cm x 0.4 cm



A

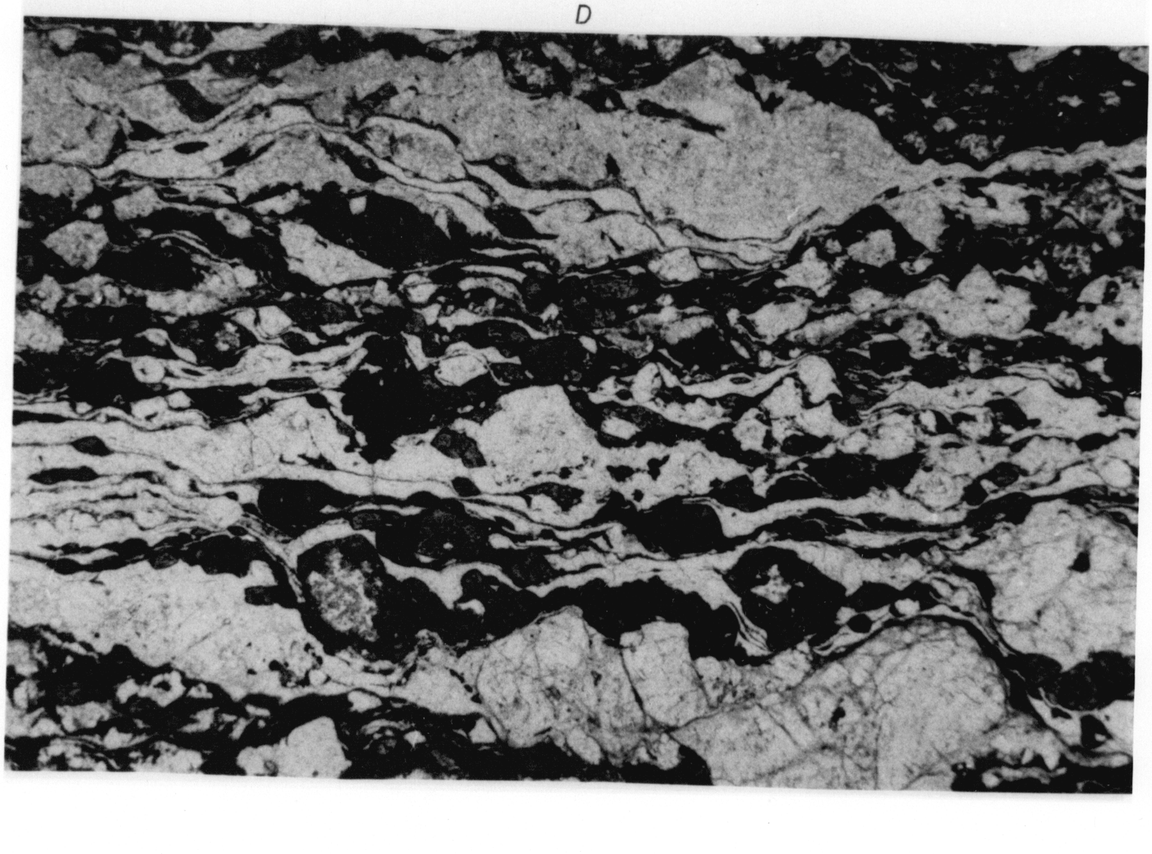
B





C

D



E

F

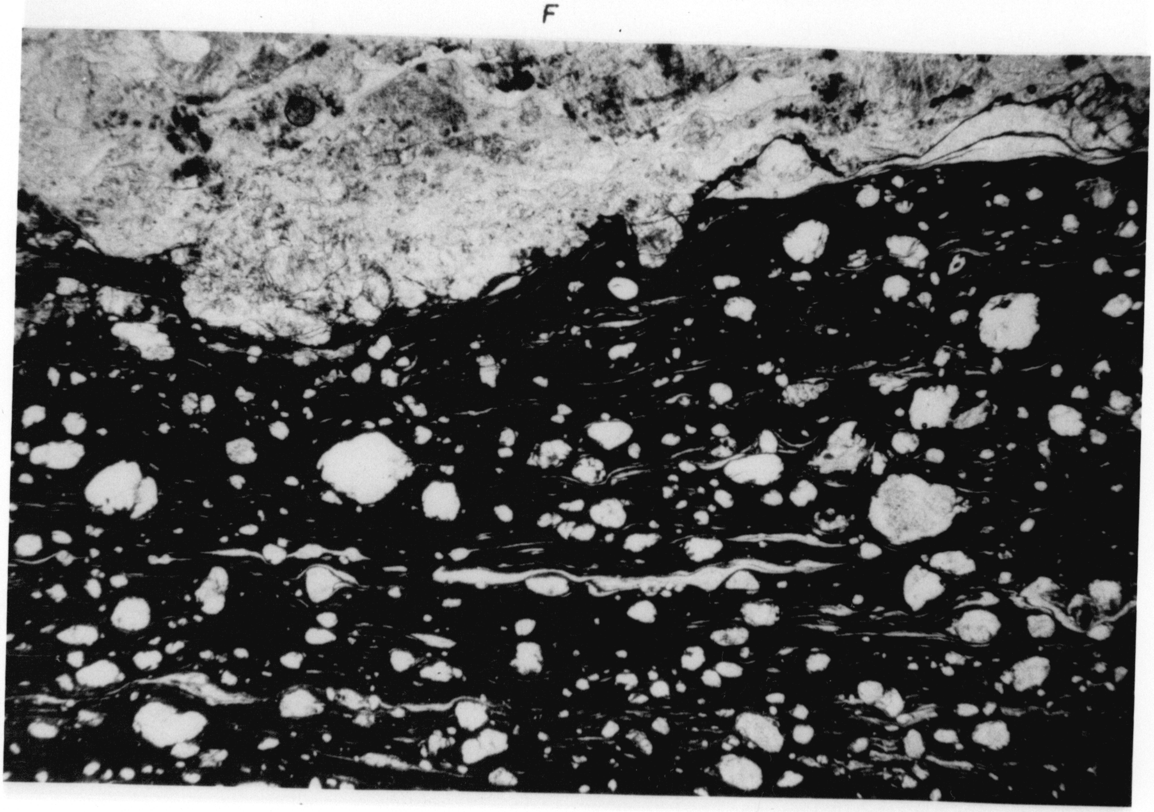
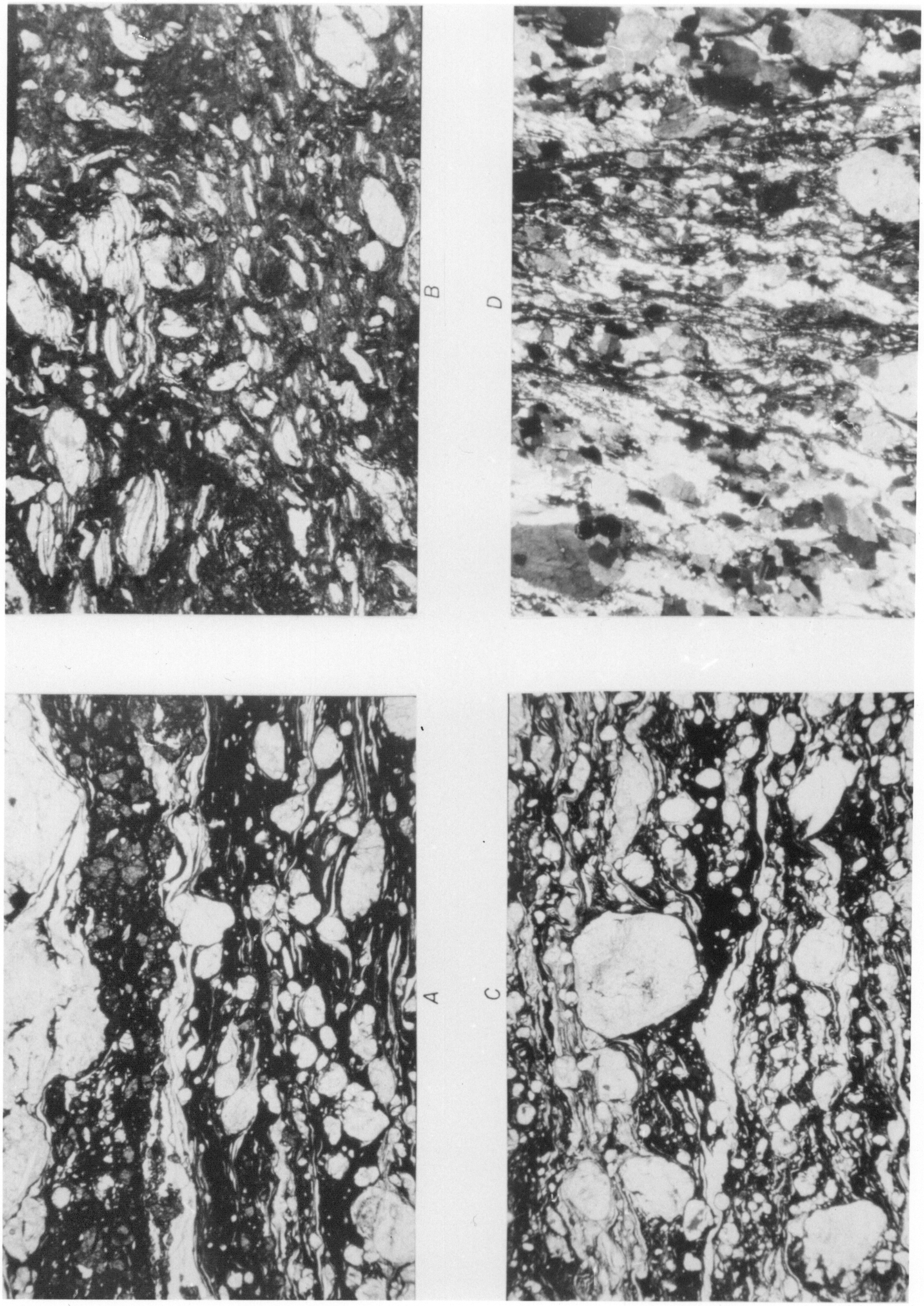


PLATE 3. - *A* - Photomicrograph of a mylonite in the Dover Creek zone (AB5-75) showing garnet porphyroclasts (in dark layer at top of photograph) and undulatory folding of quartz ribbons. Plane light, 10x. *B* - Photomicrograph of a Dover Creek zone ultramylonite (AB5-102) with deformed (F_s?) new muscovite porphyroblasts in black matrix. Plane light, 25x. *C* - Photomicrograph of protomylonite of biotite gneiss (AB5-237) in small shear zone between the Dover Creek zone and Hylas zone in the Hanover Academy quadrangle. Crossed nicols, 10x. *D* - Photomicrograph of mylonite in the Dover Creek zone (AB5-342) showing rounded feldspar porphyroclasts and intrafolial folding of quartz ribbons. Original lithology was probably a hornblende-biotite gneiss. Plane light, 10x.

Scale: 10x - 1.3 cm x 1.1 cm

25x - 0.5 cm x 0.4 cm


B
D
A
C

numerous, highly contorted intrafolial folds in the fluxion structure. Muscovite porphyroblasts reflect this deformation by occurring as wrinkled, folded folia and flattened "z" or "s" shaped grains. This period of deformation must have taken place near the end of Dover Creek zone mylonitization since it affected recrystallized minerals in the fluxion structure (quartz, biotite and magnetite) and new minerals (muscovite, sphene and epidote). The only evidence for post-tectonic crystallization is minor acicular stilpnomelane cutting across the cataclastic foliation and secondary hematite in fractures.

The determination of protoliths of the Dover Creek zone mylonites by petrology is obscured by homogenization of minerals by retrograde reactions and cataclasis. Field relations and local abundance of relict hornblende suggest some of the protoliths may have been amphibolite or amphibole gneiss. Other mylonites were apparently derived from biotite gneiss or hornblende-biotite gneiss.

Hylas Zone. - The Hylas zone (Weems, 1974, p. 14) consists of mylonitized granite gneiss, biotite gneiss and amphibolite in a roughly linear northeast trending belt. It is exposed on sections of at least six 7 1/2 minute quadrangles for a known distance of approximately 40 km (25 mi). The Hylas zone is covered to the northeast, near Verdon, by Tertiary sediments and to the southwest, across the James River, by Triassic sedimentary rocks in the Richmond Basin. The surface width of the zone in the study area, variable because of truncation by later faulting and covered intervals, ranges from a maximum in the Hylas quadrangle of 2.4 km (1.5 mi) to about 0.5 km (0.3 mi) in the Hanover

Academy quadrangle. Assuming an average dip of 40 degrees for the cataclastic foliation (Fig. 4B), this gives a zone thickness in the area of maximum exposure of 1.6 km (1 mi).

Until Weems' (1974, p. 14-16) report, rocks in the Hylas zone were thought to be aporhyolite or metavolcanic rocks (Stose, 1928; Brown, 1937; Calver, 1963; Goodwin, 1970). Because of the anomalously lower metamorphic grade, the finer grained cataclastic rocks were correlated with metavolcanic rocks in the Carolina slate belt in southern Virginia and North Carolina (Brown, 1937, p. 16). Goodwin (1970, p. 11-12) interpreted the metavolcanic rocks to lie unconformably on older amphibolite and biotite gneiss to the west in a synclinal trough. He did note (Goodwin, 1970, p. 11) that ". . . much of the rock appears to have a cataclastic texture."

Compositions within the Hylas zone are dominantly felsic (AB5-31, AB5-139, AB5-172, AB5-291, AB5-312, AB5-326, AB5-331, AB5-365, AB5-381, Appendix 1) and were, for the most part, granite gneiss or biotite gneiss.

Generally, Higgins' (1971, p. 3) classification for cataclastic rocks has been followed here. Some ultramylonites contain a large amount of recrystallized or neomineralized material but are not named blastomylonite because they retain a distinctly ultramylonitic texture.

S_c is the cataclastic foliation (average attitude N54E40SE, Fig. 4B) formed during the D_3 event by one or a combination of the following processes:

(1) The polygonization and elongation of quartz porphyroblasts in response to stress and possibly aided by the introduction of water (Jones, 1975) during cataclasis.

(2) The retrogressive alteration of hornblende, biotite, garnet and epidote to the generalized assemblage chlorite-epidote-sphene-magnetite-quartz. Because recrystallization was syntectonic, the new minerals were oriented preferentially in the foliation. Where relict biotite or hornblende does occur, the mafic alteration dust occupies pressure shadows and lamellar trails around the porphyroclasts. Garnet, a relatively minor mineral in the Hylas zone rocks, tended to fracture and be dislocated parallel to S_c in angular chlorite-rimmed porphyroclasts. Porphyroclastic(?) epidote grains are almost ubiquitously zoned from a brown pleochroic allanitic core. In non-cataclastic rocks peripheral to the Hylas zone alteration was pseudomorphic.

(3) Tectonic rounding and elongation of feldspar porphyroblasts. Pink microcline porphyroclasts as much as 6 cm (2.4 in) long are the most common coarse feldspar relicts. Albitic plagioclase was locally polygonized in the cataclastic matrix. In some of the more felsic lithologies, polygonized quartz sheaths surround feldspar porphyroclasts. Eye-shaped porphyroclasts in mylonites and ultramylonites appear to have been rotated during cataclasis locally but generally lie with their long axes in the plane of S_c (*See* Plate 4).

(4) Cataclastically derived compositional layering primarily developed in ultramylonites (Plate 5). These may have been mistaken for welded tuffs by earlier workers. The laminated character of many of these rocks cannot be directly attributed to original layering. With increasing deformation, mineral grains were smeared out parallel to the developing S_c and porphyroblastic crystals such as microcline or plagioclase were potential sources for resulting felsic layers. The

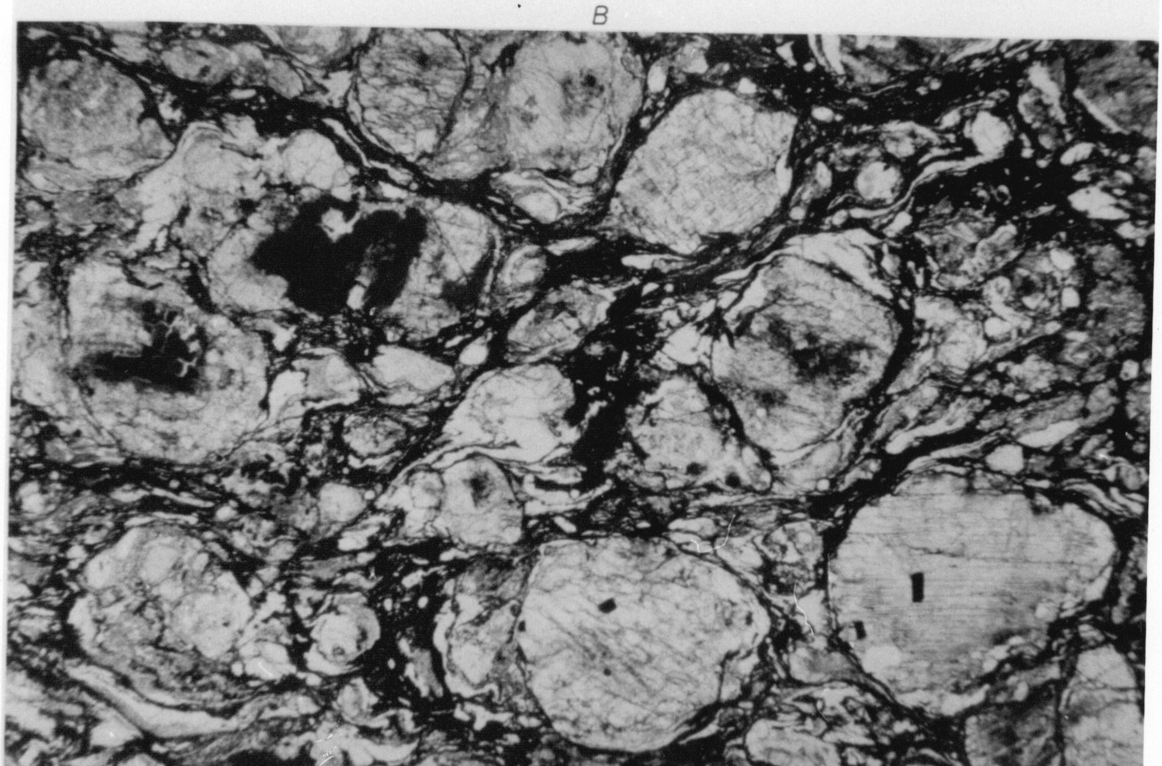
characteristic association of polygonized quartz and feldspar porphyroclasts could be explained in one of three ways: (a) relict mineralogy, (b) liberation of quartz by feldspar alteration, or (c) the migration of quartz to low pressure regions between resistant feldspar porphyroclasts analogous to some boudinage mechanisms (Gay and Jaeger, 1975). The compositional layering appears to be primarily of cataclastic origin and, thus, constitutes the cataclastic foliation, S_c.

PLATE 4. - Coarse grained protomylonite (AB5-137) of biotite gneiss (?) in the Hylas zone. Small amplitude crinkling of layers in *A* produced crenulation lineations in S_c. *B* shows rounded porphyroclasts of plagioclase and microcline in a matrix of quartz, chlorite and opaque minerals. Plane light, 10x.

Scale: 10x - 1.3 cm x 1.1 cm

A

B



S_s is a shear cleavage (Ramsay, 1967, p. 389) associated with folding of the cataclastic rocks near the termination of D_3 (Plates 5, 6 and 7A). It is axial planar to F_s. Because the cleavage is widely spaced and because of poor exposure, the actual planar discontinuity is rarely observed in mapping. However, the crenulation formed by the intersection of S_c and S_s, L_{cxs}, is locally displayed on exposures of mylonite and ultramylonite. Figure 4D and field observations indicate that the long axes of feldspar porphyroclasts, L_{Ef}, were approximately colinear with L_{cxs} and must have been aligned during cataclasis in the stress field which was later to control the more brittle shearing and folding (F_s) in the cataclastic rocks. S_s has been observed on the microscopic scale (Plate 6), the mesoscopic scale (Plates 5 and 7A) and the subregional scale in a fold in mylonites and ultramylonites in the Vulcan Materials Company quarry (also known as Royal quarry).

Figures 4A and 4B indicate that the dominant trends of S_1 and S_c were approximately parallel. Since no relict S_1 foliations have been observed in the cataclastic rocks, it is likely that the strongly developed S_1 foliation guided the orientation of S_c and/or the stress fields were approximately equally oriented.

S_c was highly disturbed (Fig. 4B) and unlike S_1 has two diametrically opposed maxima. This distribution is the result of folding about an axis defined by L_{cxs} or, in other words, F_s folds. F_s folds transpose S_c and are asymmetric folds with limbs overturned to the southeast or northwest. Such a relationship is not evident in the gneissic terrain because F_1 and F_2 are, respectively, isoclinal or near-isoclinal with their axial planes concordant to S_1 (or S_2).

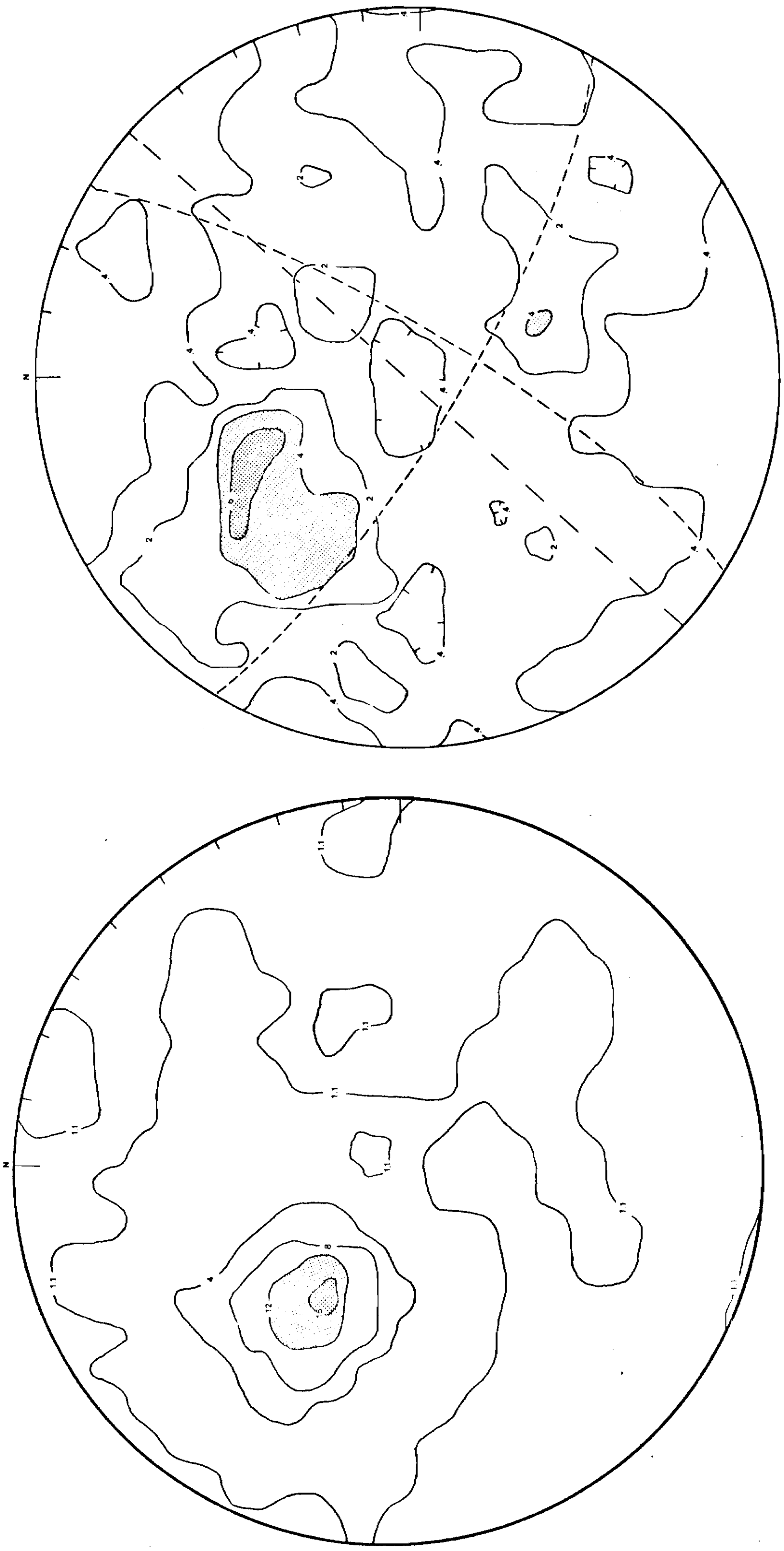
Figure 4. - Lower hemisphere projections of structural data. Light stipple and dark stipple pattern represent, respectively, the next to highest and highest percent contoured areas.

A. 226 poles to S_1 in gneisses. Contours at 1.1%, 4%, 8%, 12% and 16%. Average attitude is N28E42SE.

B. 137 poles to S_c in the Hylas zone with superimposed joint planes (short dashed lines) from *C* and average trend of F_s (long dashed line) from *D*. Contours at 0.4%, 2%, 4% and 6%. S_c has been rotated by F_s in D_3 and probably by fracturing and faulting in D_4.

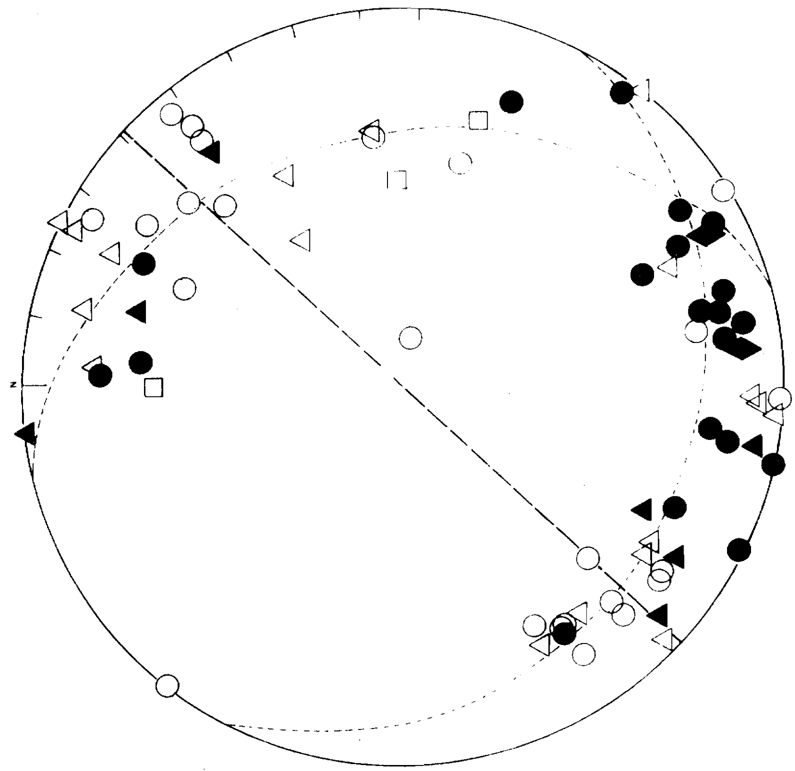
C. 164 poles to joint surfaces in the study area and planes (short dashed lines) represented by maxima. Note that the maxima represent 2 average attitudes of: N32E78SE and N59W78SW. Contours at 0.3%, 2%, 4% and 6%.

D. 74 lineations. Open circles - L_{Ef} in Hylas zone; closed circles - L_{Ef}, L_h, L_b in gneisses; open triangles - L_{cxs} in Hylas zone; closed triangles - L_{1x2}; closed diamonds - L_{1x0}; open squares - slickenside striations. Average trend of F_s (from L_{cxs}) is shown as a long dashed line. Short dashed lines represent great circle girdles defined by distribution of lineations.



B

A



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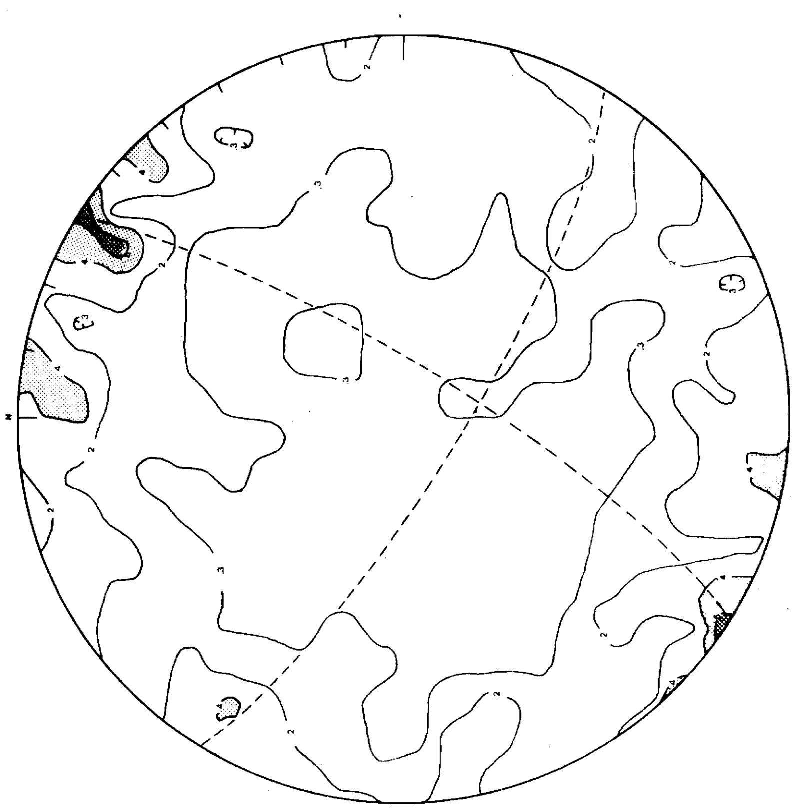


C

PLATE 5. - Hylas zone ultramylonites. *A* - Mafic ultramylonite (LG5-1) of Sabot Amphibolite. S_s shear transposed S_c and caused a gentle crenulation in the rock. *B* - Felsic ultramylonite (AB5-380) showing lenticular feldspar layer, feldspar porphyroclasts and zeolite + calcite filled fractures.

A

B

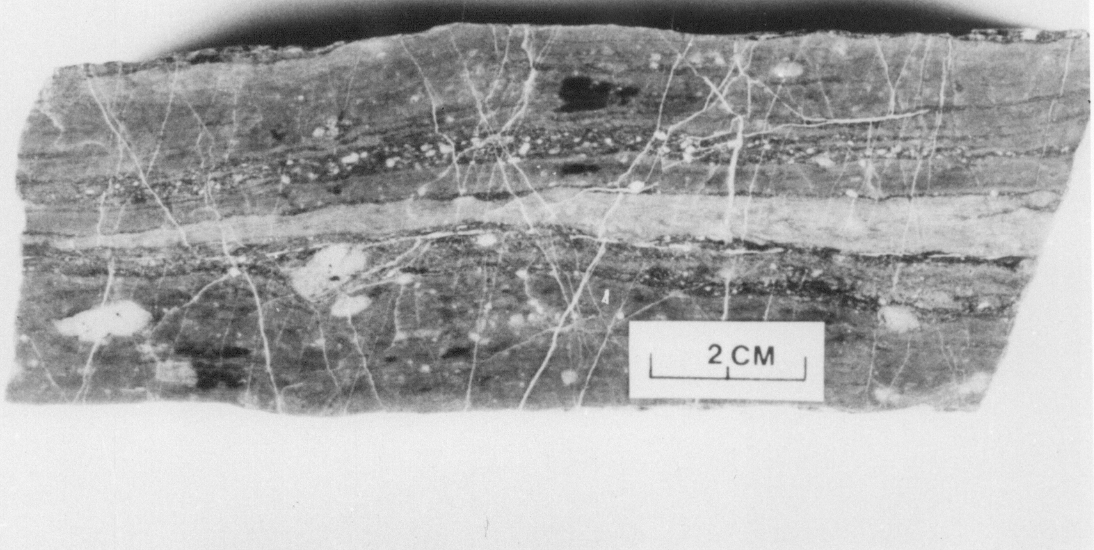
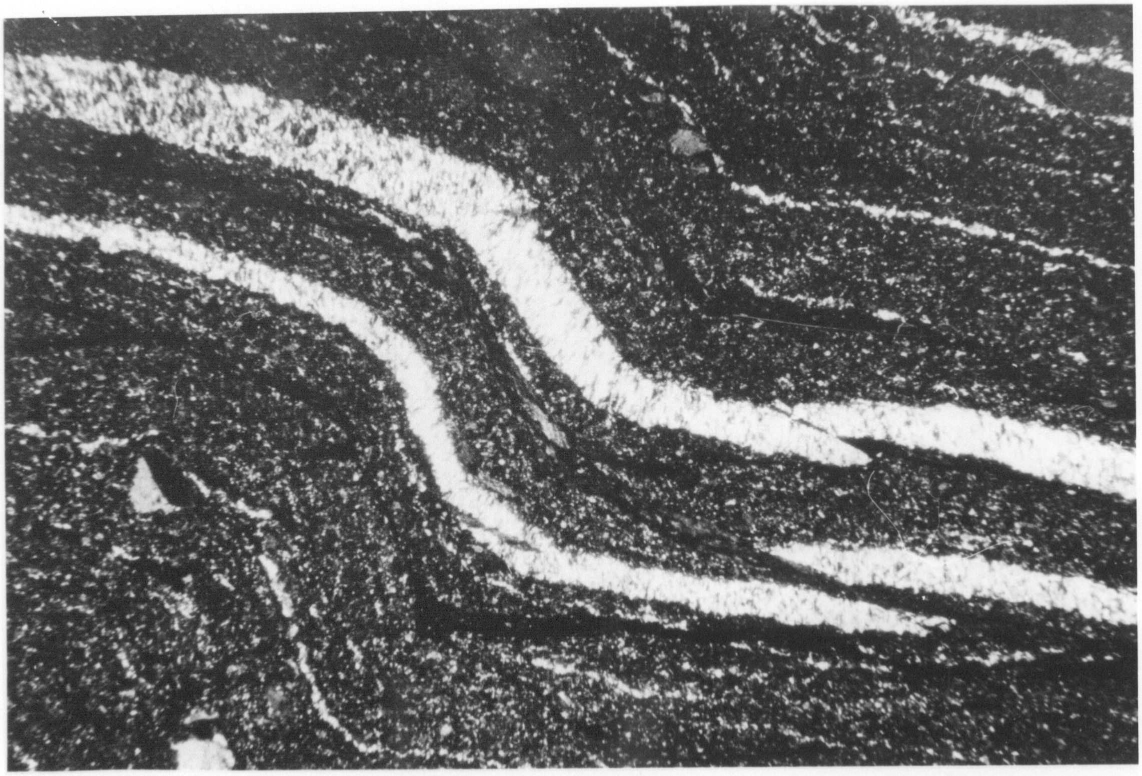


PLATE 6. - Examples of S_s and F_s. *A* - Mafic ultramylonite (LG5-1) where S_s (lower right to upper left) offset and folded polygonized quartz laminations in S_c. Crossed nicols, 10x. *B* - Muscovitic felsic ultra-mylonite (AB5-172) showing S_c (approx. horizontal) overprinted by S_s (lower left diagonally to upper right). Plane light, 10x.

Scale: 10x - 1.3 cm x 1.1 cm

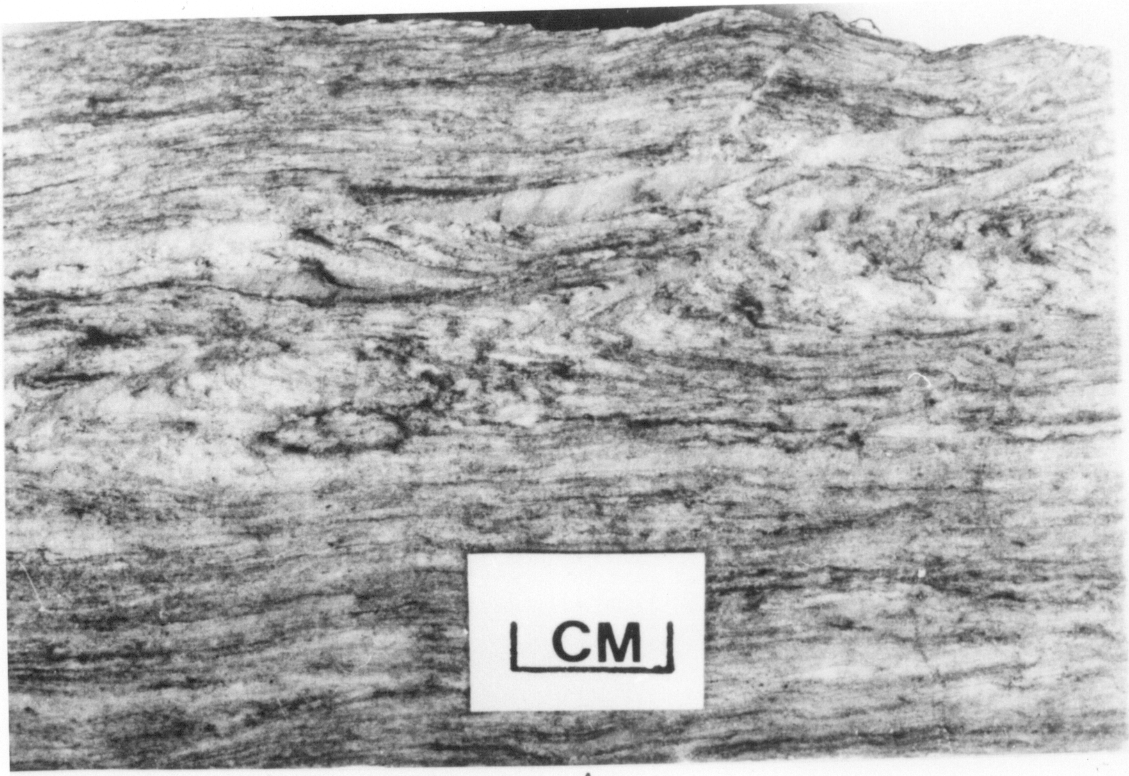


A

B

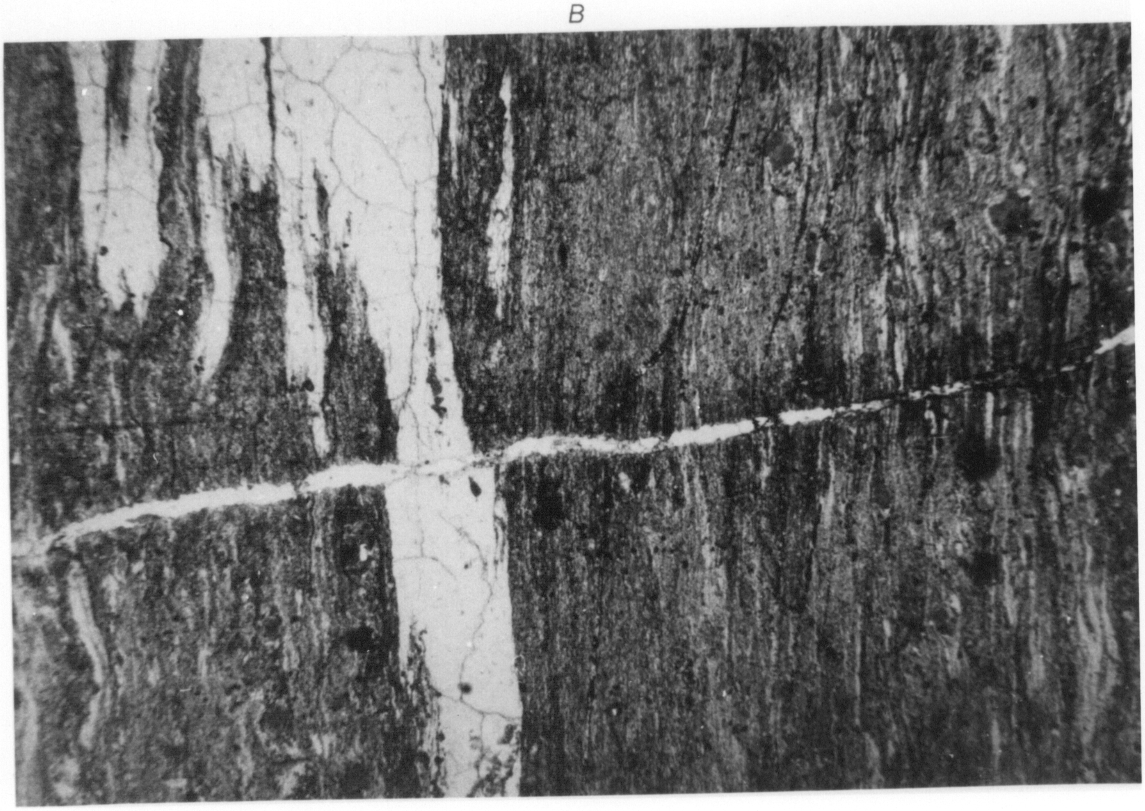
PLATE 7. - *A* - Displacement of S_c by S_s and resulting crenulations in S_c (at top of slab). These crenulations formed L_{cxs}. *B* - Felsic ultramylonite (AB5-291) showing a late discordant quartz-filled fracture cutting jagged quartz laminations and fluxion structure. Plane light, 10x.

Scale: 10x - 1.3 cm x 1.1 cm



A

B



All lineations have been rotated about one of two girdles defined on Figure 4D. This deformation may be related to regional buckling at the end of D_3 or, more likely, high angle faulting and jointing in D_4. Much of the scatter in S_c is related to the same mechanism as well as expected undulations in variably mylonitized zones. S_1 does not show a distribution like S_c because of the greater distance to the zone of faulting and fracturing and greater resistance to jointing. The diminution of grain size and weakening of grain to grain bonds in mylonites and ultramylonites during cataclasis created a medium less anisotropic and more brittle than the gneisses for new stress to act upon.

Weems (1974, Plate 1) showed the Hylas zone/Petersburg Granite contact in the southwestern Hanover Academy quadrangle to be, in part, unfaulted. The Fork Church Fault (Weems, 1974, Plate 1) separates the Hylas zone or Petersburg Granite from sediments in the Triassic Taylorsville Basin. However, brecciated granite (AB5-356, Appendix 1) in Beech Creek off State Road 657 suggests this fault continues southwestward to terminate in the southwestern Hanover Academy or northwestern Glen Allen quadrangle. Either the Fork Church Fault splays south and southwestward at the South Anna River or Weems' (1974, Plate 1) southern extension is a stratigraphic contact as on the eastern and parts of the western border of the Richmond Basin to the south. Thus, the Hylas zone rocks have been truncated against downfaulted Petersburg Granite along the Fork Church Fault in the Hanover Academy quadrangle. In the Glen Allen and Hylas quadrangles this contact is either covered or concealed by Triassic sediments.

The only evidence which might indicate an original igneous contact between the gneisses and Petersburg Granite occurs in the first horseshoe bend in the South Anna River north of Highway 33 and in the Richmond Stone quarry. In the first locality, hornblende-biotite gneiss was intensely deformed and intruded by numerous felsic pegmatite and pink granitic dike swarms. Quartz pods and mafic segregations are common. Here, and in a few outcrops north and south along the river very coarse, strongly foliated felsic augen gneisses occur. To the southeast a few meters in a small stream, the granitic gneisses were transposed into felsic ultramylonites. In the Richmond Stone quarry, conspicuously coarse grained amphibolite and amphibole gneiss were highly folded into variably oriented isoclinal folds uncharacteristic of F_1, F_2 or F_s. In addition, coarse boudinaged felsic pegmatites are conspicuously abundant in the eastern gneiss complex close to Hylas zone rocks. All of these areas were overprinted by small shears and retrogression associated with Hylas zone tectonics.

If these rocks are apophyses or areas in close proximity to the Petersburg contact, then the Hylas zone could represent a major disjunction between a western autochthon composed of biotite gneiss, granite gneiss and amphibolite and an allochthonous eastern plate composed mainly of Petersburg Granite. The southeastward dipping S_c appears to steepen near the boundary of the upper plate.

Some of the coarse grained felsic ultramylonites and mylonites are compositionally equivalent to granite mapped as Petersburg Granite. Considering the nature of the Hylas zone, the assumption that granite was caught up within the shear zone itself is entirely tenable. Retrogression of non-cataclastic lithologies extends both into Petersburg Granite and the gneisses to the west, giving further credence to an allochthonous origin for the granite in this area.

This interpretation does not, of necessity, mean that the Hylas zone tectonics occurred after 330 m.y. ago. The 330 ± 8 m.y. age for Petersburg Granite (Wright and others, 1975) is 24 km (15 mi) or more to the east. The discovery of a metamorphic foliation in granite in the study area contrasts with the character of granite in Richmond and Petersburg. However, the style of deformation and associated retrograde metamorphism do suggest that the Hylas zone formed in late Paleozoic time.

STRUCTURAL GEOLOGY II - POST-HYLAS ZONE TECTONICS

Following the D_3 period of deformation, regional tectonic activity did not occur again until Late Permian or Early Triassic time. This activity, D_4, differs from previous regimes in that it was partly extensional (Hadley and Devine, 1973, p. 3) whereas D_1, D_2 and D_3 were primarily compressional and associated with regional prograde metamorphism or localized retrograde metamorphism. Two periods of fracturing and faulting in D_4 have been recognized and were separated in time by less than 100 m.y. or about the length of time from Early Triassic to about Middle Cretaceous (United States Geological Survey Geologic Names Committee, 1972).

Tectonism younger than D_4 other than Cenozoic uplift has not been determined in the study area. However, displacement of Coastal Plain sediments on reverse faults along strike of the Hylas zone and Richmond Basin in Maryland (Jacobeen, 1972) and similar features elsewhere in the Coastal Plain (Howell and Zupan, 1974; Heron, 1959; Glaser, 1971; Hadley and Devine, 1974, p. 3-4), controlled in part by late Mesozoic and early Cenozoic crustal arching, may have had precursors in tectonically unstable areas initiated in D_3 and D_4.

D_4. - A period consisting primarily of crustal fracturing and the production of a set of parallel fault troughs generally restricted to the Appalachian axial belt (Rodgers, 1967, p. 420). Terrestrial clastic sediments, considered Upper Triassic Newark Series, were deposited in the

structural basins and later warped (Rodgers, 1967, p. 420; Goodwin, 1970, Plates 1 and 2; Weems, 1974, Plate 1), and transected by northwest-trending faults (Rodgers, 1967, p. 420; Roberts, 1928, p. 72-74). Intercalated tholeiitic basalts are absent in the Richmond Basin (Roberts, 1928) in contrast to the abundance of extrusives in the Newark Basin in New Jersey. Extrusive flows are minor and occur at the top of the section in the Newark-Gettysburg Basin in Pennsylvania (Faill, 1973, p. 727). D_4 is probably equivalent, in part, to what has traditionally been called the Palisades disturbance (Rodgers, 1967, p. 420).

D_4 tectonic elements - northeast-trending joints and faults (A faults), northwest-trending joints and faults (B faults), slickensides and broad anticlinal or synclinal warping of basinal sediments.

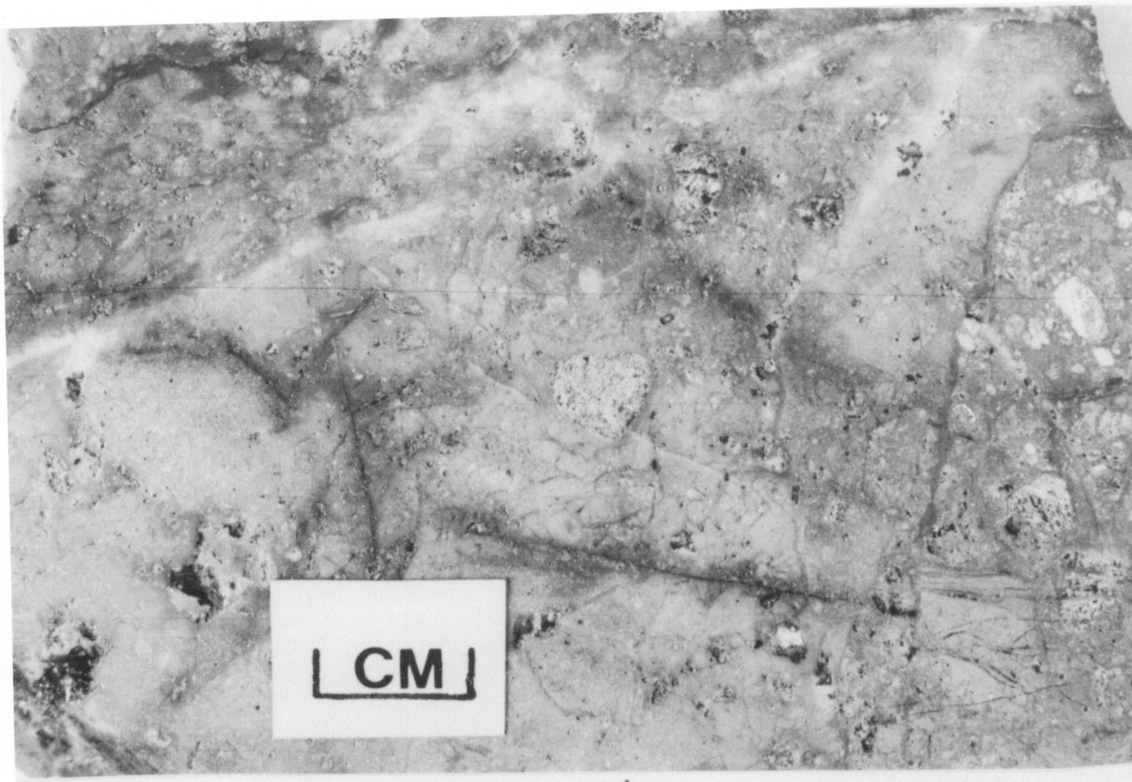
D_4 in the study area was initiated as synchronous crustal downwarp, fracturing, high angle faulting and sedimentation in tectonic lowlands, which have been called graben (Rodgers, 1967, p. 420). The basins produced in Virginia actually resemble half-graben structures and have been thought to be bounded on the west by a more less continuous western border fault (Roberts, 1928, p. 75). This structure or group of structures, rarely observed in the field, was discerned by relatively straight contacts and opposing dips between Triassic sediments and basement rocks on the west (or east where present), the abundance of coarse fanglomerates on western basinal margins and slickensides on basement and basin rocks.

Controversy exists as to whether the northeast-trending border faults are as extensive as previously thought, whether they were precursors to basin formation or whether they formed as a result of other tectonism prior to faulting, or were ever present at all. Few detailed investigations of the border faults in the Richmond Basin have been conducted, although Weems (1974, p. 47) located and described the Fork Church Fault which separates sediments in the Taylorsville Basin from Petersburg Granite or Hylas zone rocks. Studies in the Newark-Gettysburg Basin area (Ratcliffe, 1971, Faill, 1973), the northeastern Appalachians (Woodward, 1975), the Connecticut Valley (MacFayden, 1975), the Triassic rocks in Maryland (Nutter, 1975) and the Wadesboro Basin in North Carolina and South Carolina (Randazzo and others, 1970) suggest that the Triassic boundary fault system(s) (the "local basin" (Russell, 1892; Barrell, 1915; Sanders, 1963) and "broad terrain" concepts (Klein, 1969) will not be discussed here) are locally complex (Randazzo and others, 1970), were preceded by simple downwarp and sedimentation (Faill, 1973) or may even have had origins in Precambrian time (Ratcliffe, 1971, p. 125). This wide variation of interpretations supports a probable mixed origin for many of the Triassic basins in the Appalachians.

The western boundary of Triassic sediments in the Richmond Basin has been shown by Goodwin (1970, Plates 1 and 2) and others (Calver, 1963; Roberts, 1928; Stose, 1928) to be a fault contact. Observed faults in the Boscobel quarry (the Boscobel Fault; Roberts, 1928; p. 84) and in the Hanover Academy quadrangle (the Fork Church Fault; Weems, 1974, Plate 1) as well as topographic lineaments, such as east of State Road 623 in the Midlothian quadrangle, support this interpretation. However, where the Triassic/Hylas zone boundary crosses State Road 623 in the Midlothian quadrangle, the transition from weathered, felsic mylonite to weathered, orange-red mylonite to overlying red Triassic sub-arkose can be observed. The interlayering of coarse to very coarse fanglomerate and relatively finer grained clastics on the west side of the basin indicates pulsating rather than continuous syndepositional tectonism. This and the previous observation convey the interpretation, as shown on Figure 2, that the surface expression of the western and northern margins of the Richmond Basin in the study area are locally faulted and, elsewhere, a nonconformity. The eastern boundary of the Richmond Basin in the study area, floored primarily by Petersburg Granite, is also nonconformable with coarse arkose lying directly on granite. The northeast-trending faults will henceforth be referred to as A faults.

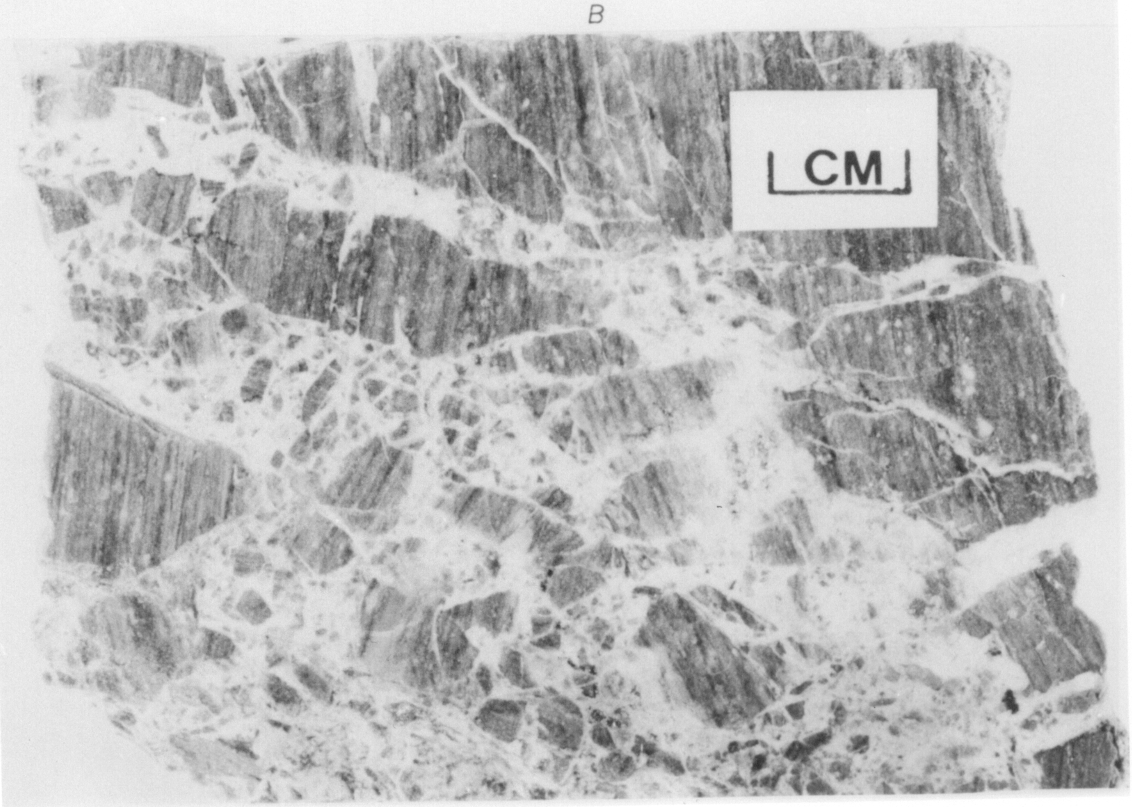
B faults are northwest-trending high angle faults which transect A faults and appear to offset Triassic sediments (Fig. 2). These structures, which have been observed in most of the major basins (Randazzo and others, 1970, p. 1002-1003; Meyertons, 1963, p. 38; Ratcliffe, 1971, p. 126; Sanders, 1963; Rodgers, 1967, p. 420) are antithetic to A faults and, in turn, to the Appalachian "trend" in the central and southeastern Appalachians. Foliations in the Hylas zone and gneisses peripheral to the Hylas zone were rotated to the northwest in and marginal to B fault zones. Brecciated (AB5-365, Appendix 1) and microbrecciated (AB5-326, Appendix 1) ultramylonite and mylonite were produced where these faults cut across the Hylas zone (Plate 8). Quartz, calcite and laumontite crystallized in open spaces created by brecciation of cataclastic rocks (AB5-365, Appendix 1). On the other hand, quartz, heulandite and hematite, now mostly limonite, appear to be the dominant minerals in neomineralized zones associated with B faults and, locally, within apparent A fault zones (such as the northeast-trending fault on the Chesapeake and Ohio railroad west of Boscobel). Sample HCC, from a B fault mineral zone,

PLATE 8. - Polycataclastic rocks. *A* - Microbrecciated felsic ultramylonite (AB5-326). Round white patches are highly weathered clasts of feldspathic ultramylonite. Cavities contain a crystalline quartz druse. *B* - Brecciated felsic ultramylonite (AB5-365) from the Rockville Stone Company quarry. Fractures are filled with laumontite, calcite and quartz. Note little offset in angular clasts in this particular specimen.



A

B



exhibits the following stages of development in thin section: (1) crystallization of vein quartz and heulandite in the initial open spaces, (2) formation of mesoscopically visible slickensides on quartz veins and microshears delineated by polygonized quartz and zones of fine grained heulandite, (3) growth of doubly-terminated quartz crystals as much as 0.8 mm long into remaining cavities; interrupted in later stages of mineralization by two periods of hematization, represented by orange-red zones in the quartz terminations. Some of the larger quartz crystals partitioned the cavities into smaller spaces. (4) formation of a fine quartz druse on cavity walls after cessation of the second hematite period in (3), and (5) sealing of open spaces by locally botryoidal hematite. Brecciated felsic ultramylonite (AB5-326, Appendix 1) from the same fault zone lacks this complete sequence because open spaces created by brecciation were sealed by heulandite + quartz. Similar microshears in heulandite are present, however.

Figure 4C shows that there are two concentrations of poles to joint planes in the study area. When the planes to maxima are superimposed over this diagram, the two dominant joint attitudes are N32E78SE and N59W78SW. When the average orientation planes are superimposed over the pi-diagram for S_c (Fig. 4B), part of the scatter in S_c can be related to joint trends which, in turn, are parallel to D_4 A faults and B faults in the area.

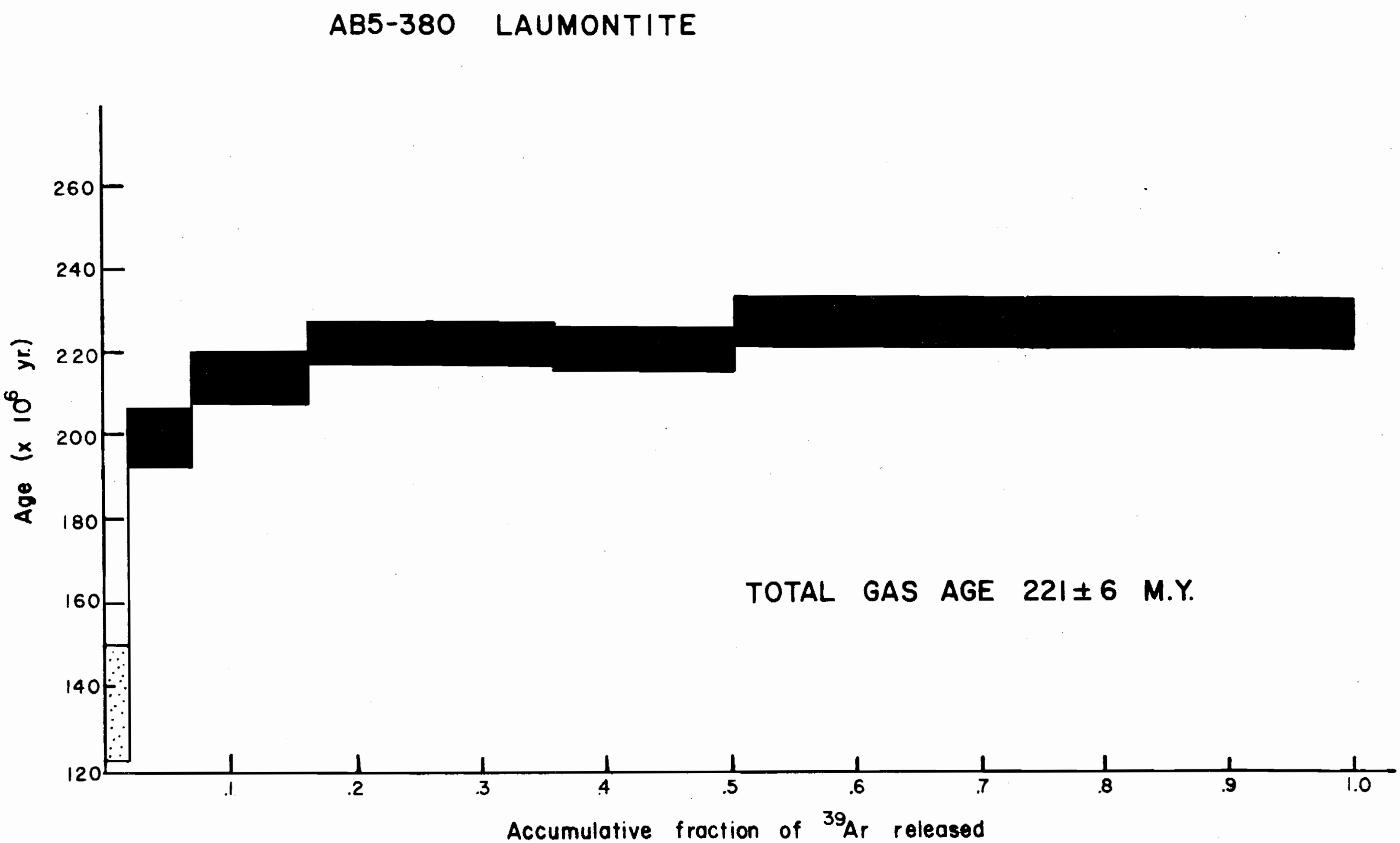
Resolution of conjugate stress orientations inferred from the joint analyses was not possible because of the observed variation in orientation and relatively small amount of area covered. However, by examination of the geometric aspects of D_3 and D_4 and the superposition of structural (tectonic) elements, an interpretation of the tectonogenesis of D_4 can be presented.

S_c steepens in dip to the southeast (Fig. 2) where the Hylas zone apparently plunges beneath an allochthonous Petersburg Granite plate. F_s folds (for example, in the Vulcan Materials Company quarry) have upright to slightly overturned axial planes and were produced during the brittle late stages of deformation in the Hylas zone. The orientation of these two elements and the relative susceptibility of Hylas zone rocks to fracturing (see discussion in Hylas zone Tectonics section) would then provide a segment of crustal instability preferentially oriented for high angle faulting and fracturing under a primarily horizontal extensional stress in early D_4 time.

Ar^{40}/Ar^{39} release spectra for laumontite from fracture planes in the Hylas zone (AB5-380, Appendix 1; Appendix 3) suggest a mineralization age of 221 $\pm$ 6 m.y. (Fig. 5) or at about the Permo-Triassic boundary. Roberts (1928, p. 137-139) described the paleontological evidence, up to 1928, which suggested the flora in sediments in the Richmond area were Lower Jurassic (Rogers, 1842; Lyell, 1947; Bunbury, 1847), Rhaetic (Lower Jurassic; Fontaine, 1883) or Keuper (Late Triassic, Stür, 1888; Zeiler, 1888; Shaler and Woodworth, 1899; Ward, 1900; Berry, 1912). Weems (1974, p. 17) reported Late Triassic fossils from the Taylorsville Basin.

If the geochronology is accurate, D_4 tectonism began about 20 m.y. before the Triassic event (Palisades disturbance of New England) is generally accepted to have occurred. The discrepancy between paleontological and geochronological ages might be explained by assuming

Figure 5. - Plot of accumulated incremental ^{39}Ar release fractions against calculated ages. Temperature increments of (°C) 225, 340, 450, 525, 600 and fusion were held for one hour each. See Appendix 3 for the analytical data.


AB5-380 LAUMONTITE
Age (x 10^6 yr.)
260
240
220
200
180
160
140
120
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Accumulative fraction of 39Ar released
TOTAL GAS AGE 221 ± 6 M.Y.

crustal fracturing began at depth before erosion and deposition occurred in Late Triassic time. The depositional environments of the oldest sediments, i.e., fanglomerate and coarse arkose, are not notably fossiliferous and the possibility exists that fossil bearing strata were not deposited in the Richmond Basin until Late Triassic time. Still the Falling Creek Formation, the oldest Triassic unit in the Taylorsville Basin, contains vertebrate remains and palynomorphs suggestive of a Late Triassic (Late Karnian or Early Norian) age (Weems, 1974, p. 17).

The maximum age of B faults and associated northwest-trending joint sets, following the above discussion, should be post-190 m.y. ago because these features appear to be superimposed on Late Triassic sediments, A faults and the northeast trending joint sets. Undoubtedly, synclinal and anticlinal warping of Triassic sediments can be correlated to uneven subsidence or crustal readjustment beneath the basin at this time. Diabase dikes which cut cataclastic rocks, Triassic sedimentary rocks and Piedmont crystalline rocks without offset have not been observed to intrude Cretaceous sediments in Virginia (Roberts, 1928, p. 62) or elsewhere (King, 1961). No Jurassic strata exist in the study area so a more exact minimum age for B faults and joints cannot be fixed.

The northwest orientation of B faults of unproven slip direction, strike-slip faults (Meyertons, 1963; Sanders, 1962) and joint sets in the study area and elsewhere and the roughly east-west trending central Virginia seismic zone (Bollinger, 1973a) transect the general Appalachian "trend" and are more indicative of structural trends (axes) in the Coastal Plain (Gernant, Gibson and Whitmore, 1971, p. 6; Hadley and Devine, 1974). On a larger scale, these features appear comparable to east-west fracture zones (Kentucky River fault zone, Rough Creek fault zone, Cottage Grove fault zone) along the 38th Parallel in the central stable region of the eastern United States (Hadley and Devine, 1974, Sheet 1). Some of the faults in these zones are covered by Upper Cretaceous sediments showing no offset at the north edge of the Mississippi Embayment (Hadley and Devine, 1974, p. 3).

In effect, it appears that the stress fields which controlled or were modified by Appalachian structures were reoriented or entirely overprinted by a new system in Mesozoic time.

Cretaceous and Cenozoic Tectonism. - Cretaceous and younger tectonism or epiorogenic uplift in the study area is evidenced by a thin veneer of Tertiary gravels lying unconformably on Cretaceous, Triassic and Paleozoic rocks. However, studies in the Atlantic Coastal Plain reveal both warping and fault displacement of sedimentary and basement rocks (Jacobeen, 1972; Glaser, 1971). Some sedimentation and faulting appear to have been controlled by older structures.

The Cape Fear Arch in North Carolina and South Carolina was active during Early Cretaceous and Eocene time (Hadley and Devine, 1974, p. 3) as probably were the Salisbury embayment and its complementary arch in Maryland and Delaware (Hadley and Devine, 1974, p. 3), where Eocene faulting has been suggested (Cederstrom, 1945). Cretaceous to Miocene high angle faulting was reported in Prince Georges County, Maryland, by Jacobeen (1972). Howell and Zupan (1974) described post-Cretaceous high angle reverse and/or oblique faulting of Late Cretaceous sedimentary rocks in South Carolina and related these features to formation of the

Cape Fear Arch. Spangler and Peterson (1950) recorded unusually large sediment thicknesses west of the Potomac River Bridge in Virginia and Maryland. The Aquia (Paleocene) depositional basin (Shifflett, 1948) lies nearly on strike of this area to the southeast, as do the Taylorsville Basin and Hylas zone still farther south. Weems (1974, p. 55) postulated that renewed Tertiary subsidence along a northeastward extension of the Hylas zone-Taylorsville Basin complex may have been responsible for the Aquia Basin and unusual sediment thickness. He also suggested that the structure and abnormal thickness of the St. Marys Formation in the Ashland quadrangle could have resulted from similar Miocene tectonism (Weems, 1974, p. 55).

Erosion of the Appalachians appears to have been continuous or semi-continuous since Triassic time (Rodgers, 1967, p. 421) and probably since at least Middle Ordovician time for much of the Piedmont (Lynn Glover, III, personal communication). Mathews (1975, p. 818) calculated from the sedimentary prism on the floor of the western Atlantic Ocean that Cenozoic denudation accounted for 400 km^3/km (of coast line) of erosion along the coast from Georgia to Newfoundland. In the south, beyond influence of subsequent glacial erosion, the Cenozoic denudation rate has been calculated at 1.6 km^3/km^2 in 60 m.y. (Mathews, 1975, p. 820). Numerous unconformities are present in the Cretaceous and Tertiary column (Rodgers, 1967, p. 422) so that uplift or subsidence may have been intermittent. Assuming the present crest of the Appalachian Mountains as the western border of the source area, 2 km of sediment has been removed since the start of Cenozoic time (Mathews, 1975, p. 818). Rodgers (1967, p. 422) concluded that the bulk of erosion of the Appalachians occurred in or before Cretaceous time.

METAMORPHISM

Prograde Metamorphism (M_1). - From petrographic studies, no discontinuity exists in the regional prograde metamorphism. In terms of mineral assemblages, non-retrograded sections of the State Farm Gneiss, Sabot Amphibolite and eastern gneiss complex were subjected to amphibolite facies metamorphism in the kyanite-sillimanite facies series (*See* Miyashiro, 1973). The presence of kyanite (AB6-34, AB6-35, AB5-228, Appendix 1) suggests these rocks formed in the lower temperature part of the amphibolite facies.

The amphibole in amphibolites and gneisses is green to green-brown euhedral hornblende. Abundant metamorphic epidote in one amphibolite sample (AB6-54, Appendix 1) appears anomalous, although it is generally poikiloblastic with quartz and has locally reacted with hornblende. Euhedral diopside in one sample of biotite schist (AB5-152, Appendix 1) perhaps indicates this lithology was originally a basite or calcareous pelitic sediment. Biotite, which rarely occurs in the amphibolites, is brown to orange-red and euhedral in plates or, occasionally, fibrous folia. Flat stage measurements of plagioclase fall in the albite-oligoclase to andesine range. Red-brown subhedral, locally poikiloblastic, garnet is present throughout the area except for the Sabot Amphibolite, which rarely contains garnet.

K feldspar is absent or minor in the eastern gneiss complex and Sabot Amphibolite, where it was introduced or concentrated metasomatically, but occurs in moderate amounts (i.e., greater than 5-10 percent) in granitic phases of the State Farm Gneiss. Microcline, locally exhibiting cross-hatched twinning, is the dominant potassic feldspar. Potassium metasomatism in the eastern gneiss complex (*See* eastern gneiss complex section) was probably concurrent with peak in M_1 and was primarily developed as microcline pegmatites and microcline augen gneiss.

Typical assemblages from the metamorphic rocks are:

1) garnet-biotite-microcline-quartz-plagioclase gneiss,
2) garnet-epidote-magnetite-sphene-quartz-plagioclase-hornblende-biotite schist,
3) epidote-garnet-sphene-microcline-diopside-quartz-plagioclase-biotite schist,
4) muscovite-magnetite-kyanite-garnet-quartz-plagioclase-biotite schist,
5) sphene-quartz-plagioclase-hornblende-amphibolite.

Retrograde Metamorphism (m_2). - One period of localized metamorphism after M_1 has been recognized in the study area. m_2 is the syntectonic retrograde alteration that took place as a result of cataclasis in the Hylas zone. This event produced mineral assemblages typical of the greenschist facies. It should be noted that m_2 resulted in apparent metastable mineral assemblages because retrogression was commonly incomplete within the zone, relict biotite porphyroblasts being an example (AB5-137, Appendix 1).

m_2 retrogression was probably facilitated by localization of water in shear zones. Sample AB5-237 (Appendix 1), from a minor shear zone outside the Hylas zone, had the original assemblage garnet + allanite + scapolite + hornblende + biotite + quartz + plagioclase and produced the retrograde assemblage calcite + magnetite + epidote + chlorite + quartz + (plagioclase). Most of the alteration was pseudomorphic, such as epidote after scapolite and brown chlorite after hornblende. Primary mineral alteration in the Dover Creek zone was accompanied by comminution and recrystallization of mafic minerals and quartz. Hornblende, which locally formed porphyroclastic relicts, was altered to produce biotite + magnetite + sphene. Biotite recrystallized to minute pleochroic mats of brown chlorite(?) folia to form, along with minor epidote, the dense cataclastic matrix in most of the Dover Creek zone rocks. Chloritization of garnet porphyroclasts was observed.

m_2 metamorphism in the Hylas zone was difficult to discern because: (1) the dominant protoliths were granitic and do not develop diagnostic assemblages at the greenschist grade, and (2) the area was heavily overprinted by hydrothermal alteration during Triassic time. The primary retrograde minerals in felsic rocks within the zone are chlorite, muscovite (normally sericitic), epidote, quartz, magnetite and, perhaps, albitic plagioclase. The mafic body north of Interstate 64, from petrographic and x-ray data, consists of epidote + chlorite (clinochlore) + quartz + albite (LG5-1, Appendix 1). Field mapping suggests this body was originally Sabot Amphibolite.

The best evidence for greenschist retrogression in the Hylas zone comes from rocks on the periphery of the zone where alteration was pseudomorphic and not associated with pervasive cataclasis and where the mineralogies contain more mafic minerals (AB5-144a, AB5-145, AB5-191, AB5-373, AB5-195, AB5-246, AB5-252, Appendix 1). Here, hornblende, locally preserved as cores in epidote-chlorite aggregates, and biotite relicts, laminated with chlorite in areas of incomplete alteration, indicate the greenschist facies metamorphism. Feldspars, both plagioclase and microcline, are commonly turbid and sericitized or epidotized. Euhedral sphene inclusions in chlorite appear where hornblende or biotite was destroyed. Discordant epidote veinlets and subconcordant chloritized shears probably formed as a result of cataclasis in the Hylas zone.

Assemblages produced during m_2 and their probable protoliths (in parentheses) are:

1) pyrite-quartz-chlorite-plagioclase-epidote ultramylonite (amphibolite),
2) magnetite-epidote-quartz-chlorite-plagioclase gneiss (biotite gneiss),
3) muscovite-chlorite-epidote-quartz-plagioclase gneiss (biotite gneiss),
4) muscovite-chlorite-microcline-plagioclase-quartz ultramylonite (granite gneiss),
5) epidote-chlorite-muscovite-microcline-plagioclase-quartz mylonite (biotite granite gneiss).

Zeolite Paragenesis (m_3). - Zeolite occurrences in the Virginia and North Carolina Piedmont are widespread (Privett, 1974; Law Engineering and Testing Company, 1976) but were thought to be limited to fracture fillings and hydrothermal alterations in igneous contact zones. Three zeolite environments were discovered in this study: (1) laumontite in multiple fractures, including joint planes, in cataclastic rocks in the Hylas zone, (2) heulandite in Triassic arkose and mudstone in the Richmond Basin, and (3) heulandite in mineralized zones produced as fractures by B faults but probably sealed at depth during Triassic sedimentation. Paragenetic sequences, have not been recognized in the study area, as they have elsewhere (Law Engineering and Testing Company, 1976) but appear to define two chronologically separate periods of formation.

Laumontite in the cataclastic rocks was determined optically and by x-ray diffractometer methods (Appendix 4). The association laumontite + calcite + quartz is characteristically found as a fine pink and white druse on joint surfaces, while idiomorphic crystals as much as 1 cm long ± calcite formed on open cavity linings. Single crystal determinations of larger crystals were unsuccessful because of multiple fibrous twinning. Fresh zeolite samples are restricted to quarries, as outside these localities limonite has infiltrated and replaced minerals in fracture systems.

Ar^{40}/Ar^{39} gas release spectra were obtained for laumontite samples (AB5-380, Appendix 1) from the Hylas zone. AB5-380 (fine druse) produced a well defined plateau age of 221 ± 6 m.y. It is believed that AB5-380, by virtue of its reliable age determination and mode of occurrence, represents the initial crustal fracturing and hydrothermal mineralization of D_4. In the medium-pressure zeolite facies metamorphism section of the Taringatura area, New Zealand (Coombs, 1954; Coombs and others, 1959), laumontite appears at a present stratigraphic depth of 5.2 km (17000 ft) (Coombs and others, 1959) and a temperature of about 180°C (Miyashiro, 1973, p. 151). However, Liou (1971, Fig. 5 and Fig. 10) showed the upper stability limits of laumontite at 3 kb P_{H_2O} and about 275°C. Coombs and others (1959, Table 1) reported naturally occurring laumontite at 195-220°C and depths of 150-275 m and greater (Coombs and others, 1959, p. 72) in the Wairakei geothermal area, New Zealand. Because no source for an anomalously high geothermal gradient is known at the time of formation of AB5-380, a depth based on normal conditions must be assumed. The temperature of formation of laumontite at 3 kbar P_{H_2O} would be about 275°C (Liou, 1971). A minimum pressure value has not been established.

Heulandite appears to be confined to Triassic sedimentary rocks (AB5-263, AB5-264, AB5-360, Appendix 1) and mineralization in fracture zones created by faulting (AB5-326, Appendix 1). The presence of this zeolite in the sedimentary rocks is attributed to burial metamorphism (m_b). The heulandite is idiomorphic, frequently displaying characteristic cross-sections, and is relatively unaltered. Some crystals appear to have replaced plagioclase.

The pressure-temperature range of heulandite is not well known because of the difficulties in establishing equilibrium conditions in the laboratory (Coombs and others, 1959, p. 87-88). Coombs and others (1959, p. 88, also Fig. 2) deduced from the experimentally determined analcime + quartz → albite boundary and the coincidence of the heulandite → laumontite + quartz transition with this boundary at 5.2 km (17000 ft) in the Taringatura area that the upper temperature stability of heulandite in such a situation is about 200°C.

Roberts (1928, p. 165) considered estimates of 6.1 km (20,000 ft) for the Triassic section in Virginia "absurd" but this is very likely close to the maximum original thickness of sediments in the Richmond Basin. A minimum value cannot be presented with available evidence.

Bloomer (1939, p. 144) reported stilbite (not identified during this study) from horizontal joints within Petersburg Granite 9.7 km (6 mi) west of Richmond. This joint set was not observed in the study area but it can probably be related to sheeting during unroofing of the pluton. Bloomer (1939, p. 144) thought the horizontal joints antedated vertical joint sets, as the latter contained no stilbite, but structural relations in the present study suggest just the opposite was true. It is possible that stilbite mineralization either postdated heulandite formation or occurred at a shallower, cooler level during the same period.

CONCLUSIONS

Major conclusions are shown diagrammatically in Figure 6 and referenced in the explanation following that illustration. Regional information included in this figure was taken from studies conducted in the central and eastern Piedmont of Virginia and northern North Carolina generally east of an axis defined by Kings Mountain, North Carolina, Danville, Virginia, and Arvonia, Virginia and bound on the east by Coastal Plain sedimentary rocks.

A comprehensive regional synthesis integrating the geology of the Piedmont near the Hylas zone into the entire central and southern Piedmont is beyond the scope of this study. Higgins (1972), Glover and Sinha (1973), Brown (1970, 1976), and others (*See* explanation to Fig. 6) describe various syntheses of the formation of Piedmont lithologies.

Protolithologies. - Gross geometry and mesoscopic compositional variation within the layered sequence of lithologies comprising the State Farm Gneiss, Sabot Amphibolite and the eastern gneiss complex suggest that these units were primarily stratified sedimentary and volcanic rocks. Although minor sedimentary and igneous structures are lacking and it is doubtful that any mineral grains other than zircons are pre-metamorphic relicts, certain speculations as to provenance and environment of deposition for these sequences are herein introduced.

Modal analyses of the State Farm Gneiss (Appendix 1; Poland, 1976) show that plagioclase is dominant over potassium feldspar. Biotite (plus retrogressive chlorite), though highly variable from layer to layer, generally constitutes more than 10 percent of the modal assemblage.

Quartz is also variable in relative abundance but averages around 17 percent (Appendix 1), which differs from an average of 29 percent quartz reported in State Farm Gneiss west of the study area by Poland (1976). Intercalated mafic biotite or hornblende-biotite schists, locally containing pyroxene (AB5-152, Appendix 1), rarely exceed more than a few tens of centimeters in thickness.

Based on modal felsic mineral content of these metamorphosed rocks, the State Farm Gneiss approximates an unmetamorphosed quartz-intermediate feldspathic graywacke (Pettijohn, Potter and Siever, 1973, p. 202) which Crook (1970) recognized as being of a mixed sedimentary and volcanic provenance characteristic of tectonically active continental margins. Equivalent volcanic rock types for the more felsic phases of the State Farm Gneiss would be dacite to quartz andesite (I.U.G.S., 1973). Potassium deficient (low microcline) layers in the State Farm Gneiss usually exhibit an increase in biotite, hornblende, calcic plagioclase and locally, diopside. The intimate but distinct interlayering of mafic schist and gneiss with metagraywacke(?) suggests that they may have originally been intercalated calcareous, aluminous sediments or mafic volcanic flows or pyroclastic debris. The typical association of graywacke and volcaniclastic deposits is in turbidite sequences of Alpine-type orogenic events (Pettijohn, Potter and Siever, 1973, p. 206 and p. 270).

The Sabot Amphibolite is rather homogeneous in mineralogy but variable in relative mineral percentages (Appendix 1). From field observations, it would appear that most of this variation resulted from segregation of felsic and mafic minerals during metamorphism. Small felsic dikes are numerous in the amphibolite.

Primary igneous textures and structures, such as amygdules, are absent from the Sabot Amphibolite but its gradational and interlayered lower contact with the State Farm Gneiss suggests that it originated as an interstratified body. The locally massive appearance and homogeneous internal composition make a mafic, probably basaltic, volcanic flow a likely protolith for the Sabot Amphibolite.

The eastern gneiss complex presents a problem in interpretation because the effects of metasomatism must be considered. Modal analyses (Appendix 1) show that the eastern gneiss complex is depleted in microcline content to an extent greater, on the average, than potassium deficient layers in the State Farm Gneiss. Localization of feldspar in pegmatite layers or coarse augen gneiss can be of magmatic or metamorphic origin (Vernon, 1976, p. 221).

The preferred interpretation of this study is that intrusion of a granitic magma, relations of which are now largely obscured by the Hylas zone, released K^+ and perhaps H_2O into the country rock, probably during metamorphism, to form the abundant pegmatites in the eastern gneiss complex. Bulk composition and gross structure suggest a stratified, primarily sedimentary origin dominated by graywacke interlayered with minor aluminous pelites (for example, AB5-228, AB5-246, Appendix 1). Weems (1974) reached the same conclusion. Poland (1976) described zircon suites from the State Farm Gneiss and Maidens Gneiss (a possible correlative to the eastern gneiss complex) and concluded that the two units were derived from different provinces (provenances?).

Protolithologies within the Hylas zone are not easily defined because of pervasive cataclasis and associated retrograde metamorphism. Modal analyses of felsic cataclastic rocks, where possible, indicate compositions ranging from granite to granodiorite and do not appear to approximate any rock types in the study area other than the Boscobel granodiorite gneiss. It is possible that shearing in the Hylas zone, at least in the part mapped for this study, was primarily taken up within a pre-existing concordant plutonic body (Boscobel granodiorite gneiss?) forming the upper surface of an overthrust plate. Considering that the upper thrust plate was coarse grained, weakly foliated Petersburg(?) Granite, a tenable assumption is that most of the deformation was produced in the underlying medium to fine grained, foliated gneiss. Microcline bearing phases of the cataclastic rocks might be relict pegmatites such as are found interlayered with Boscobel granodiorite gneiss in the Boscobel Granite Corp. quarry (Fig. 2).

Metamorphism. - All rocks in the study area older than sedimentary rocks in the Richmond Basin have been through one prograde metamorphism to lower amphibolite facies (M_1). Localized retrogression to greenschist (m_2) and zeolite (m_3) facies occurred after the prograde event along thrust zones and in fracture zones.

M_1 is thought to have reached its thermal peak at 342 ± 70 m.y. ago when Rb-Sr reequilibration occurred in the Columbia Granite (Hatcher Complex; Fullagar, 1971). A maximum age for the last regional metamorphism of about 450 m.y. ago is set by Middle to Late Ordovician fossils in the Arvonia slate. The garnet isograd in that region cuts diagonally across the Arvonia syncline (Brown, 1969). Petersburg(?)

Granite appears to have at least one metamorphic foliation indicating that the metamorphism probably lasted until about 330 ± 8 m.y. ago (if that age applies to this granite).

m_2 retrogression caused by cataclasis in the Hylas zone must have occurred after the last regional metamorphism and before m_3 and D_3 began about 221 ± 6 m.y. ago. Thus, shearing and synchronous cataclastic retrograde metamorphism which formed the Hylas zone probably took place sometime in the range of 320 m.y. to 221 m.y. ago.

m_3 and the following burial metamorphism in Triassic time are retrograde in the sense that mineralogies of the zeolite facies were superimposed on older assemblages of greenschist facies. Initial fracturing at depth began at 221 ± 6 m.y. ago, the probable crystallization age of void-filling minerals. Formation of heulandite was caused by the accumulation of sediments in the Richmond Basin until the temperature, as a function of depth of burial, was sufficient to permit crystallization of that zeolite. It is possible that Coastal Plain cover may have contributed to the total bulk of sediments at the time of heulandite formation, but this cannot be ascertained in the study area.

Structure. - The sequence of structural events, or tectonogenesis, of the Hylas zone area has been documented in detailed chronological order in the preceding text. As a review, this sequence is tabulated below.

S_1, S_2, F_1 and F_2 (D_1 and D_2) were produced during and slightly past the thermal peak of metamorphism. D_1, the initial regional deformation, resulted in a pervasive foliation (S_1) axial planar to isoclinal folds which are usually recumbent in the plane of S_1. D_2 followed D_1, although it also occurred within the amphibolite facies, and is defined by a non-penetrative alignment of biotite (S_2) approximately axial planar to asymmetric, open F_2 folds which have locally been observed to refold F_1 folds (Poland, 1976). Bourland (1976) has postulated a northwest-trending set of very open folds (F_3) which have an associated S_3 foliation. The time F_3 formed is uncertain. Its style suggests that this fold period post-dated F_1 and F_2.

The Dover Creek zone and Hylas zone formed in Late Paleozoic time by northwestward-directed shearing and probably thrusting which resulted in the formation of cataclastic foliations and associated folds (S_c, S_s, F_s, intrafolial folds). Petersburg Granite was apparently thrust over felsic gneiss and amphibolite. Small chloritized shears, epidote veinlets and undulatory warping of rocks west of the cataclastic zone were contemporaneous.

Fracturing and northeast oriented high angle normal(?) faulting began around 221 m.y. ago and was intermittently active throughout deposition of fanglomerate and arkose in the Richmond Basin during Late Triassic time. Northwest oriented fractures (joints) and faults are indicated to be post-Late Triassic and pre-Cretaceous because they apparently affected Triassic sediments but, from available evidence, did not offset diabase dikes which, in turn, have not been observed to cut Cretaceous sedimentary rocks.

Recent data (Jacobeen, 1972; Hadley and Devine, 1974; Mixon and Newell, 1976; York and Oliver, 1976) in the central and southern Piedmont indicate that reactivation of pre-existing structural discontinuities has initiated Cretaceous to Cenozoic faulting in the Coastal Plain. Many of these late features were high angle reverse faults (Mixon and Newell, 1976). High angle reverse faulting of Eocene to Miocene age in the Brandywine area in Prince Georges and Charles Counties, Maryland, (Jacobeen, 1972) can be projected southeastward through a northeast recess in the Potomac River and thence into the northeast-trending faults of the Taylorsville-Richmond Basins where these structures are emergent from beneath the Coastal Plain (Hadley and Devine, 1976, Sheet 1).

If the structural history of this zone is similar to the sequence of events in the Hylas area, a Late Paleozoic thrust zone of large regional dimensions has been defined and its control over later episodes of faulting has been active at least through Tertiary time.

Regional Implications. - From evidence collected for this and adjacent studies (Poland, 1976; Bourland, 1976), four general statements of regional importance follow:

(1) Only one regional prograde metamorphic event took place and this occurred at about 350 m.y. ago. This may represent part of the Acadian orogeny (Rodgers, 1970, p. 217) in the eastern central Appalachian Piedmont.

(2) It appears that large scale folded structures were formed during D_2 (these would be F_2 folds) after the metamorphic peak but under continued amphibolite facies conditions; no large scale F_1 folds have been mapped. However, D_1 was the optimum period for nappe-like structures to have formed in terms of the apparent rheolo-

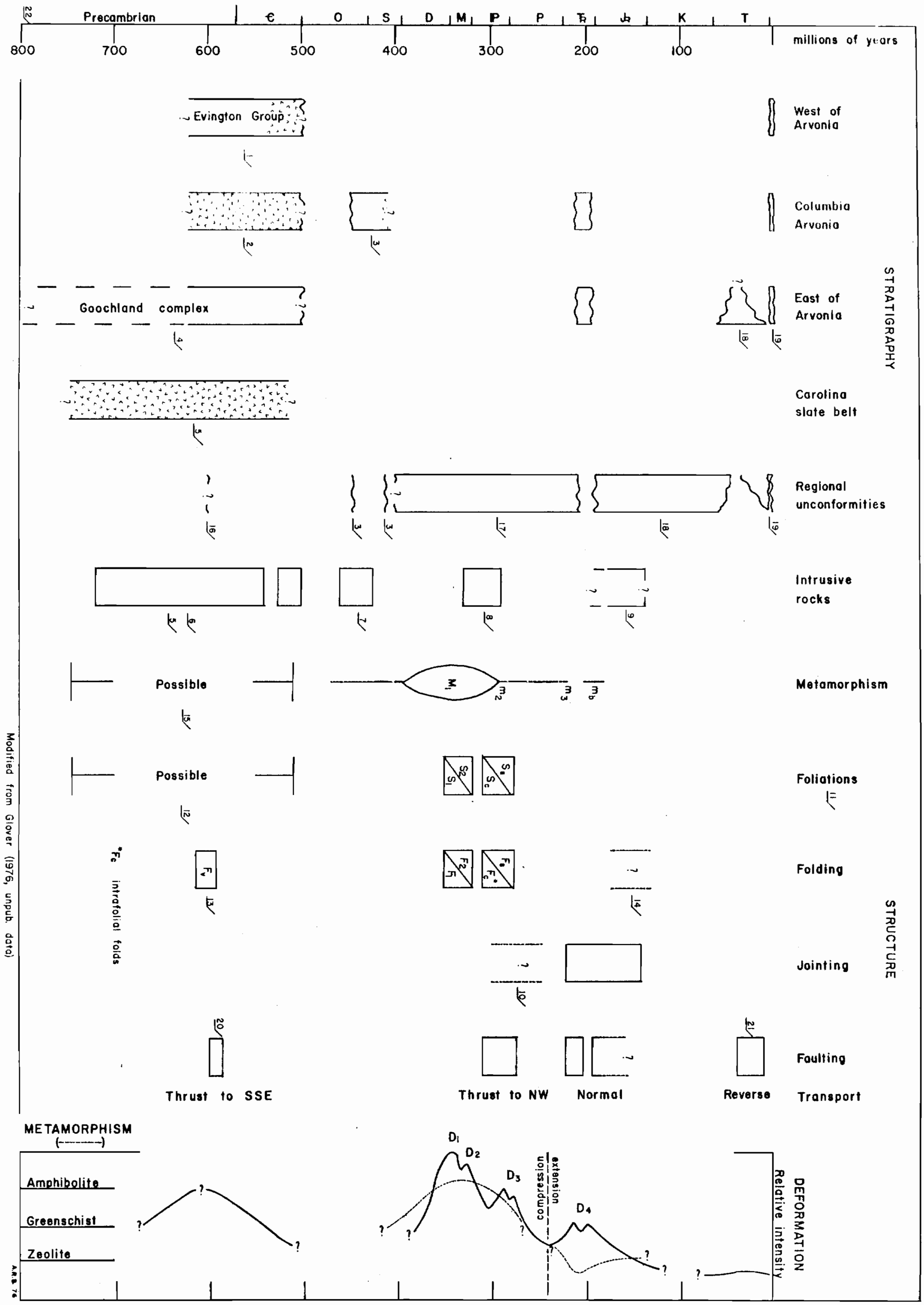
gy and systemic stress at that time. It is equally possible that such structures continued to form throughout D_1-D_2 time and that D_2 represents terminal attenuation of the rocks as recrystallization continued.

(3) The time of formation of the Hylas zone appears integral into a Late Pennsylvanian or Permian compressional event in the southeastern Appalachians (Hatcher, 1972; Rankin and others, 1973, p. 31-33 and Figure 3). Although a long polytectonic history is evident in the Brevard Zone (Roper and Justus, 1973; Odom and Fullagar, 1973), abundant evidence suggests Late Paleozoic faulting within at least part of the same zone (Stonebraker and Harper, 1973; Reed and Bryant, 1964; Reed, Bryant and Myers, 1970; Bryant and Reed, 1970; Hatcher, 1970, 1971, 1972; Higgins, 1966, 1968; Wampler, Neathery and Bentley, 1971). Greenschist assemblages near the central Piedmont lineament probably were formed in Late Paleozoic time, although it is not known whether this area defines a fault (Bourland, 1976). Whether these events are related is as yet uncertain.

(4) Possible causes of recent seismicity in the southeastern United States have been reviewed by Bollinger (1973b) and York and Oliver (1976). It was thought that the dominant northwest-trending joints and faults in the study area might be related to the central Virginia seismic zone (Bollinger, 1973b, p. 397) which is also oblique to the general regional structural trends. However, microearthquake monitoring conducted during this study (Appendix 5) showed that the average occurrence rate for a single seismograph station within the Hylas zone (Fig. 2) was the same as was found for the entire central Virginia seismic zone (one

microearthquake every 8 days; Bollinger, 1975). It could not be ascertained that the recorded events actually occurred within the Hylas zone. Multiple station recording might better define the location of approximate epicenters and relate recent seismicity to documented structures.

Figure 6. - Summary diagram of geologic history in the central and eastern Piedmont of Virginia and North Carolina east of an axis defined by Kings Mountain, North Carolina, Danville, Virginia, and Arvonia, Virginia, and bound on the east by Coastal Plain sedimentary rocks. Explanations and references to data shown on this diagram are given in Table 1.



Precambrian
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700
600
500
400
300
200
100
millions of years
Evington Group
West of Arvonia
Columbia Arvonia
Goochland complex
East of Arvonia
STRATIGRAPHY
Carolina slate belt
Regional unconformities
Intrusive rocks
Metamorphism
Possible
Foliations
Folding
F_c intrafolial folds
Jointing
STRUCTURE
Faulting
Thrust to SSE
Thrust to NW
Normal
Reverse
Transport
Modified from Glover (1976, unpub. data)
METAMORPHISM
Amphibolite
Greenschist
Zeolite
D_1
D_2
D_3
D_4
compression
extension
DEFORMATION
Relative intensity

TABLE 1

EXPLANATION TO FIGURE 6

(1) Evington Group rocks west of Arvonia, Virginia, occur in the James River synclinorium near Lynchburg, Virginia, (Rankin and others, 1973, p. 35) and have been tentatively correlated with the Alligator Back Formation (Rankin and others, 1973, p. 35) along the Blue Ridge escarpment in southern Virginia and northern North Carolina. The Alligator Back Formation consists of laminated metagraywacke intercalated with pelitic rocks (phyllite at low metamorphic grade) and amphibolites interpreted as metamorphosed mafic volcanic rocks (Rankin and others, 1973). Earlier studies of the Evington Group were by Brown (1951, 1953, 1958) and Espenshade (1954, p. 14-20).

Smith, Milici and Greenberg (1964), Ern (1968) and Brown (1969) described Evington Group and Evington Group(?) (Brown, 1969, p. 6) metasedimentary and metavolcanic rocks in areas just west of the Arvonia syncline. Smith, Milici and Greenberg (1964, p. 7) indicated that a paragonite unit in lower(?) Evington Group overlies the Catoctin Formation in Albemarle County. Stratigraphy within the Evington Group was proposed by Brown (1941, 1953, 1958) and Espenshade (1954) as: the Candler Formation (phyllite, metagraywacke, mica schist and minor quartzite), the Archer Creek Formation (siliceous graphitic schists and blue-gray marble) and the Mount Athos Formation (Furcron, 1935, p. 22-33; quartzite, muscovite schist and white marble). Metamorphosed mafic and intermediate volcanic rocks in younger(?) sections of the Evington Group in the Lynchburg quadrangle were named Slippery Creek greenstone

(Brown, 1951, 1953, p. 93) but later studies outside the James River synclinorium (Smith, Milici and Greenberg, 1964; Ern, 1968; Brown, 1969) did not continue this useage. In fact, the stratigraphic sequence and protolithologies in the Evington Group are only well known from exposures in the James River synclinorium where many sedimentary and igneous structures were preserved (Brown 1958, 1970). Brown (1976) suggested that the chaotically-deformed metagraywacke, greenstone volcanics and ultramafic plutonic rocks of the Evington Group(?) near Shores, Virginia, could represent a tectonic mélange scraped off the sea floor during subduction.

Age relations of the Evington Group in the area immediately west of Arvonia are uncertain. If the high grade schists and gneisses flanking the Whispering Creek Anticline (Brown, 1969, 1970, p. 345) can be correlated with Evington Group(?) rocks, they must be older than 595 ± 80 m.y., the age of the intrusive Hatcher Complex (Fullagar, 1971). Brown (1970, p. 344) indicated that the Candler Formation, supposedly comprising the lower Evington Group, conformably overlies Catoctin greenstone in the James River synclinorium. If this interpretation is accurate, the Evington Group could be as old as about 820 m.y., the approximate age of the Catoctin Formation (Rankin and others, 1969), which formed during the "Blue Ridge plutonic-volcanic event" (Sinha, 1976). On the other hand, Brown has suggested (1969, p. 47-48; 1970, p. 345) that some of the rocks he mapped as Evington Group(?) or Candler Formation in the Dillwyn quadrangle could be equivalent to the Lynchburg. Because of this confusion in correlation, the maximum age of the Evington Group is shown on Figure 6 as about 595 m.y. A younger age limit of about 450 m.y. for Evington Group(?) rocks is extrapolated from stratigraphic relations in and around the Arvonia syncline.

(2) Metamorphosed volcanic and minor metasedimentary rocks unconformably underlie the Arvonia Formation in the Arvonia, Long Island and Columbia synclines (Smith, Milici and Greenberg, 1964; Ern, 1968; Brown, 1969). The Hatcher Complex intruded rocks near the Arvonia syncline believed to be metadacites and greenstones (Smith, Milici and Greenberg, 1964; Brown, 1970). Brown (1969) included these metavolcanics in the Evington Group(?) although Ern (1968) and Smith, Milici and Greenberg (1964) made no such correlation. It is uncertain whether interlayered schist and gneiss southeast of the Arvonia syncline represent this metavolcanic sequence (Brown (1969, p. 11) suggests these rocks are primarily of sedimentary origin) or older rocks, but apparently bimodal layered sequences flanking the Columbia syncline (Smith, Milici and Greenberg, 1964; Bourland, 1976) may be higher grade equivalents of the metavolcanics. A minimum age for this unit is determined by the overlying Arvonia Formation (approx. 450 m.y.) and intrusion of the Hatcher Complex (approx. 595 m.y.).

Regional correlations for the metamorphosed volcanic and sedimentary rocks have been Chopawamsic-James Run volcanics in Maryland (Higgins and others, 1971; Higgins, 1972, 1973; Higgins and others, 1973; Glover, 1974; Seiders and others, 1975; Pavlides, 1976; Glover, 1976) and, speculatively, with youngest rocks in the Carolina slate belt (Higgins, 1972; Glover, 1974, 1976).

(3) Slate, conglomeratic schist, quartzite and garnet-amphibole-quartz rock (Brown, 1969) in the Arvonia Formation (Watson and Powell, 1911,

p. 36-43) in the Arvonia syncline have been widely studied, mainly because they have only been affected by greenschist metamorphism and contain abundant recognizable fossil data (Darton, 1892; Watson and Powell, 1911; Stose and Stose, 1948; Applegate, 1955; Tillman, 1970). The Bremo member of the Arvonia Formation occurs either at the top (Smith, Milici and Greenberg, 1964, p. 14; Brown, 1970, p. 345) or medial or lower (Brown, 1969, p. 31) part of the section. Smith, Milici and Greenberg (1964, p. 14) described Arvonia or Arvonia equivalent rocks in the narrow Long Island syncline west of Arvonia and the Columbia syncline east of Arvonia. Brown (1969) and Brown and Griswold (1970) presented structural interpretations of the Arvonia slate district and nearby areas.

Conglomeratic, pyroclastic quartz-mica schists of the Buffards Formation overlie rocks in the Arvonia Formation with angular unconformity (Brown, 1969, p. 33) and apparently represent the youngest Paleozoic sedimentary rocks in the area (Brown, 1969, p. 48), perhaps Lower Silurian (Brown, 1970, p. 347).

The age of slate in the middle part of the Arvonia Formation has been well defined by fossil data as Middle to middle Late Ordovician (Trenton or Barnveldian to Maysvillian) (*See* Tillman, 1970). Conglomeratic quartz-mica schist at the base of the Arvonia lying on Hatcher Complex rocks north of the James River led early workers (Taber, 1913, p. 41-42; Stose and Stose, 1948, p. 396-397) to believe an unconformity existed there. Brown (1969, p. 32, 1970, p. 345) and Rodgers (1970, p. 193) concurred with this interpretation. Brown and Sunderman (1954), Brown (1962) and Smith, Milici and Greenberg (1964,

p. 14) suggested that granite or granodiorite (the Hatcher Complex) was intrusive into the Arvonia Formation but the presence of a regional garnet isograd cutting across the Arvonia syncline (Brown, 1969, Plate 1) and a probable consolidation age of 595 m.y. for the Hatcher Complex (Fullagar, 1971), along with fossil evidence, preclude such an interpretation.

Correlations based on stratigraphy, geochronology, geophysics and dubious fossil data relate the Arvonia Formation or slate in the Arvonia Formation to Quantico Slate in northern Virginia (Watson and Powell, 1911; Higgins, 1972, p. 1009; Pavlides, 1976). However, conflicting evidence has been presented (Seiders and others, 1975) to this interpretation and controversy exists in the literature (Seiders, 1976, discussion; Higgins, 1976, reply).

(4) Metamorphosed sedimentary, volcanic and plutonic rocks east of the Columbia syncline and west of the Richmond Basin are informally named the Goochland complex because of uncertainties in correlation. References to rocks in this complex are: Stose (1928), Brown (1937), Calver (1963), Goodwin (1970), Weems (1974), Bobyarchick and others (1976), Kingston and Weems (1976), Poland (1976) and Bourland (1976) and several references to Petersburg Granite listed in the text.

Biotite gneiss and schist, amphibolite and amphibole gneiss and (amphibole-biotite) gneiss intruded before or during metamorphism by granitic to tonalitic magmas (Hatcher Complex or Columbia Granite, Fine Creek Mills Granite (Poland, 1976), Boscobel granodiorite gneiss and possibly Petersburg Granite) dominate the geology. A somewhat disrupted sequence of biotite schist, muscovite schist and chlorite schist containing lensoidal calc-silicate and ultramafic pods occurs just west of and along the central Piedmont lineament (Bourland, 1976) in the Cartersville-Elk Hill area. The metamorphic grade reaches sillimanite zone east of the central Piedmont lineament (Bourland, 1976) and near Thorncliff (Poland, 1976) but overall mineralogies indicate kyanite zone metamorphism.

None of the Goochland complex rocks appear to be high grade equivalents of the Arvonia Formation so they must be older than the approximately 450 m.y. old unconformity beneath the Arvonia Formation. The schist sequence, described above, may be related to metavolcanics flanking the Columbia syncline. Intrusion of the Columbia Granite at 595 m.y. ago (Fullagar, 1971) places a minimum age limit on possibly older rocks in the area. A maximum age cannot be determined at the present time.

(5) Explanations of the stratigraphy, structure and geochronology of the western Carolina slate belt were given in Tobisch and Glover (1969), Tobisch and Glover (1971), Glover and Sinha (1973), Wright (1974), McConnell (1974), Briggs (1974) and McConnell, Glover and Sinha (1976), and references therein. Correlation with possibly coeval volcanic rocks along the James River and elsewhere is speculative and inconclusive (Pavlides, 1976). Carolina slate belt rocks are included in Figure 6 for comparison.

(6) The Columbia Granite or Hatcher Complex in the Cowherd quarry just east of Columbia, Virginia, has been dated using Rb-Sr whole rock data as being 595 ± 80 m.y. old by Fullagar (1971). Smith, Milici and Greenberg (1964, Appendix II) reported the following ages from the same location: 301 ± 15 m.y. (K-Ar on biotite), 400 ± 125 m.y. (Rb-Sr on

whole rock and K feldspar) and 400 ± 50 m.y. (lead alpha on zircon). The zircon age was reported to be the age of intrusion but it now seems doubtful that this value has any geological significance.

(7) This period of igneous activity is included as reference to Higgins' (1973, p. 186, Figure 7) 425 m.y. old "late" plutons (Wetherill and others, 1966; Higgins, 1972, Table 1).

(8) Granitic plutons primarily represented by Petersburg Granite (330 ± 8 m.y.; Wright, Sinha and Glover, 1975) and, possibly, the Berea pluton (approx. 350 m.y.; Pavlides, 1976).

(9) Diabase dikes of inferred Jurassic (Late Triassic(?) age.

(10) Older joints observed at the Catawba Nuclear Plant site in South Carolina (Law Engineering and Testing Co., 1976). Triassic and later(?) joints are discussed in the text.

(11) Foliations refer to tectonic-metamorphic S-surfaces.

(12) Glover (unpublished data).

(13) Glover and Sinha (1973).

(14) Syn- and post(?)-depositional warping and gentle folding of sedimentary rocks in the Richmond and Taylorsville Basins were implied in Goodwin (1970, Plates 1 and 2) and Weems (1974, Plate 1).

(15) Glover (unpublished data).

(16) Glover and Sinha (1973).

(17) A hiatus in the sedimentary record equivalent to about 180 m.y. extends from above the Buffards Formation to Late Triassic sedimentary rocks in the Richmond Basin.

(18) Because Coastal Plain sedimentation has been omitted, another hiatus is represented between Newark Series (Triassic) rocks and west-

ward prograding Tertiary gravels which intermittently and unconformably lie on Triassic and Paleozoic rocks.

(19) Alluvial sand and gravel rest unconformably above all older lithologies in channel deposits of small and moderate sized streams as well as in overbank (mainly floodplain and local terrace deposits) areas of large streams, creeks and rivers (Allen, 1965).

(20) Glover and Sinha (1973), Wright (1974).

(21) Faulting of post-Triassic sedimentary rocks along a northern extension of the Hylas zone and elsewhere is discussed in the text.

(22) Time scale taken from United States Geological Survey Geological Names Committee (1972).

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APPENDIX 1

MODAL ANALYSES
AND
PETROGRAPHIC DESCRIPTIONS

Modal analyses of selected rock samples and descriptions of thin sections are presented in Appendix 1. Note that all petrographic descriptions are not accompanied by a modal analysis. Each set of modes is followed by appropriate descriptions. Analyses of rocks from the Hylas zone were limited to those in which all mineral grains could be identified. Ultimately, only medium and coarse grained rocks were counted.

Numbers appearing in parentheses or as superscripts refer to notations listed in Table 1-1.

TABLE 1-1

NOTATIONS IN MODAL ANALYSES

(1) Numbers in parentheses indicate approximate anorthite content from flat stage measurements. Unmodified percentages indicate that no approximation was possible.

(2) Refers to white mica in Hylas zone rocks.

(3) Generally refers to epidote and clinozoisite.

(4) Estimated percentages.

(5) Other than in the matrix.

APPENDIX 1
MODAL ANALYSES

	State Farm Gneiss (Sfgn)								
	AB4-2	AB5-70	AB5-156	AB5-152	AB6-34	AB6-35	AB5-348	AB5-280	AB5-338
Plagioclase(1)	37.8(15)	41.5(10)	37.6(15)	30.6(31)	30.5	39.4(19)	36.1	28.2(28)	26.2
Microcline	19.7	1.0	16.0	4.0	0.3	1.6	35.0	44.0	1.3
Quartz	23.2	34.5	22.7	9.2	14.7	24.7	16.2	8.2	10.5
Biotite	13.8	10.0	13.4	43.4	33.0	31.3	7.6	0.2	29.3
Muscovite(2)	-	-	-	-	0.3	0.8	-	-	-
Chlorite	3.0	m	-	m	m	-	2.4	-	-
Stilpnomelane	-	-	-	-	-	-	-	-	-
Garnet	0.3	2.1	1.9	0.8	11.4	1.0	-	1.5	0.2
Hornblende	-	6.4	7.1	-	-	m	-	16.7	26.8
Diopside	-	-	-	6.7	-	-	-	-	-
Epidote(3)	0.3	4.1	-	1.7	0.6	0.2	1.5	0.2	0.9
Allanite	-	m	-	-	-	-	-	m	-
Scapolite	-	-	-	-	-	-	-	-	-
Calcite	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	6.5	0.2	-	-	-
Sphene	1.1	-	1.5	3.3	0.3	-	0.9	0.3	3.2
Apatite	-	-	-	m	-	0.2	-	-	-
Zircon	m	-	m	m	m	m	m	0.2	m
Tourmaline	-	-	-	-	-	-	-	0.2	-
Magnetite	0.5	0.3	-	-	2.5	0.6	2.2	0.5	1.5
Pyrite	-	-	-	0.4	-	-	m	-	-
Hematite	-	-	-	-	m	-	m	m	-
Leucoxene	-	-	-	-	-	-	-	-	-
Laumontite	-	-	-	-	-	-	-	-	-
Heulandite	-	-	-	-	-	-	-	-	-
Clay	-	-	-	-	-	-	-	-	-
Matrix	-	-	-	-	-	-	-	-	-
# Points	370	388	638	519	367	502	559	648	466

APPENDIX 1

PETROGRAPHIC DESCRIPTIONS

AB4-2 State Farm Gneiss 0.3 km (0.2 mi) southeast along the Chesapeake and Ohio railroad from Sabot station. Midlothian: 4166000 mN 257800 mE.

Coarse grained locally garnetiferous, conspicuously layered biotite-granite gneiss.

Myrmekitic intergrowths of quartz in plagioclase are common near microcline-plagioclase interfaces. Quartz also forms poikiloblasts in albitic plagioclase and elongate inclusions along cleavage in shredded biotite folia. Chlorite formed locally after biotite.

AB5-70 State Farm Gneiss 0.8 km (0.5 mi) in the second east trending stream from Dover Creek north of Highway 6. Midlothian: 4167000 mN 258400 mE.

Medium grained, poorly layered biotite-granite gneiss.

Plagioclase exhibits pericline and albite twinning and contains poikiloblasts of quartz, shredded biotite and epidote. Myrmekite developed around some microcline porphyroblasts. Garnet and hornblende(?) appear to have been retrograded to brown and green chlorite. Biotite formed both tabular porphyroblasts and finer shredded or splayed folia in the matrix. It locally has greenish-brown pleochroism. Alteration suggests that minor retrogression took place after the primary crystallization.

AB5-156 State Farm Gneiss in small east trending stream valley 0.2 km (0.1 mi) northeast of the north end of Dover Lake. Hylas: 4168300 mN 258400 mE.

Coarse grained garnetiferous biotite-granite gneiss with conspicuous compositional layering on a scale of 0.1 cm. Brown-red garnets are as much as 0.5 cm in diameter.

The porphyroblastic texture consists of brown pleochroic biotite with sphene inclusions, generally untwinned plagioclase (An_{15}), euhedral poikiloblastic hornblende locally altered to brown chlorite, and rounded to skeletal poikiloblastic (quartz, feldspar and biotite) garnet locally altered to biotite. Except for the substitution of hornblende for chlorite, the composition here is equivalent to AB4-2.

AB5-152 State Farm Gneiss in stream bed off the southwest side of the Glen Allen housing development. Hylas: 4169000 mN 259000 mE.

Medium to coarse grained, dark green to black, moderately layered biotite schist.

Euhedral porphyroblasts consist of orange brown pleochroic biotite, polysynthetically twinned plagioclase (An_{30-35}) and pale green, strongly birefringent, poikiloblastic (plagioclase and quartz) diopside. Rounded prismatic clots of brown and green chlorite usually associated with biotite may have been orthopyroxenes. Euhedral sphene is conspicuously abundant. S_1 is well defined by the orientation of biotite porphyroblasts.

AB6-34 State Farm Gneiss outcrops on the south bank of the South Anna

River under the bridge on State Road 673 at Casco. Hylas: 4180800 mN 266150 mE.

Gray to dark gray, medium grained, well layered kyanite-garnet-biotite schist with compositional layering on a scale of 0.2 cm.

Garnet, kyanite, biotite and feldspar porphyroblasts formed in a relatively fine grained matrix of biotite, feldspar and anhedral quartz. Rounded, poikiloblastic garnets were locally altered to chlorite and magnetite. The quartz, plagioclase and biotite poikiloblasts are oriented approximately parallel to S_1. Biotite in the matrix, however, terminates at garnet boundaries. Kyanite porphyroblasts have high relief, low to moderate birefringence and occur as flat, euhedral plates and bladed crystals parallel to the foliation. Microcline seems restricted to lenticular felsic layers.

AB6-35 State Farm Gneiss outcrops on the south side of the South Anna River at the bridge on State Road 673 at Casco. Hylas: 4180900 mN 266200 mE.

Medium grained, moderately layered, strongly foliated kyanite bearing biotite schist.

Biotite and muscovite folia are euhedral and primarily define S_1. Rounded garnets are non-poikiloblastic. Kyanite occurs as large grains of high relief and locally shows undulose extinction. There is a strong crystallographic parallelism of biotite and kyanite illustrated by their synchronous extinction positions.

AB5-348 State Farm Gneiss 0.3 km (0.2 mi) south of Gilmans Bridge on the east side of the South Anna River. Hanover Academy: 4184700 mN 272150 mE.

Porphyroblastic augen gneiss with pink microcline augen as much as 4 cm (1.6 in) long in a gray to dark green groundmass of biotite, feldspar and quartz.

The (biotite) granite gneiss, containing large porphyroblasts of microcline (augen) and lenticular aggregates of microcline, appears to have been highly altered. Plagioclase was abundantly sericitized and locally chloritized and epidotized. Green biotite was locally altered to chlorite. Quartz was characteristically polygonized around microcline porphyroblasts. The undulatory S_1 foliation, defined by feldspar and biotite orientation, was transected by small veins filled with epidote and chlorite. Most of the alteration here is attributed to Hylas zone tectonics.

AB5-280 State Farm Gneiss 0.8 km (0.49 mi) in first northwest trending stream north of Dover Lake. Hylas: 4168950 mN 257950 mE.

Coarse grained gneiss with hornblende porphyroblasts as much as 1 cm long. Compositional layering is poor and foliation is weakly defined because of the massive nature of the rock.

Microcline and plagioclase are both present with rare microcline perthite and myrmekite. Poikiloblastic hornblende and garnet are the dominant mafic minerals. Poikiloblasts in subhedral hornblende are quartz, allanite, minor epidote, magnetite and plagioclase which locally shows polysynthetic twinning. These inclusions tend to parallel the amphibole cleavage. Anhedral, reddish garnets usually have sphene poikiloblasts in concentric zones. The core and outer zone are relatively non-poikiloblastic. Plagioclase where completely enclosed by hornblende contains parallel rods or laths of magnetite. Plagioclase has narrow albitic boundary zones where it is in contact with microcline. The following grain boundary types were observed: (1) local sharp serrate on microcline-plagioclase contacts, (2) rounded serrate or scalloped on hornblende-plagioclase contacts and (3) mosaic interlocking grains in primarily felsic areas.

AB5-338 State Farm Gneiss 0.6 km (0.3 mi) in second east trending stream from Dover Creek 0.8 km (0.5 mi) south of State Road 644. Hylas: 4170100 mN 259500 mE.

Medium to coarse grained, moderately layered hornblende-biotite schist associated with large, angular blocks of pink and white vein quartz as much as 0.3 m (1 ft) in diameter.

The dominant mineralogy is composed of euhedral red-brown pleochroic biotite, plagioclase (An_{24}), hornblende and conspicuously abundant sphene. Hornblende and biotite occur in approximately equal amounts. Bluish birefringent subhedral epidote locally appears as inclusions in biotite and hornblende. A strong S_1 foliation is defined by biotite and hornblende.

APPENDIX 1 (continued)
MODAL ANALYSES

	--Sfgn-				Sabot Amphibolite (Sam)				
	AB5-282	AB5-11	AB5-58	AB5-161a	AB5-195	AB5-231b	AB5-272	AB5-383	AB5-396
Plagioclase(1)	26.2	40.0	32.2	27.2	48.5	27.8(25)	29.8(30)	1.8	30.6(25)
Microcline	-	-	-	1.4	5.7	-	-	49.1	-
Quartz	11.0	8.8	13.0	6.9	8.2	2.7	m	4.3	1.1
Biotite	0.4	-	-	-	-	-	1.8	-	-
Muscovite(2)	-	-	-	-	0.2	-	-	-	-
Chlorite	m	2.2	m	m	14.5	-	-	-	-
Stilpnomelane	-	-	-	-	-	-	-	-	-
Garnet	5.5	-	-	-	-	-	m	0.2	0.2
Hornblende	54.4	46.6	48.8	56.2	12.8	62.6	64.8	38.5	64.5
Diopside	-	-	-	-	-	-	-	-	-
Epidote(3)	m	-	m	7.3	5.1	6.8	-	3.7	-
Allanite	-	-	-	-	-	-	-	-	-
Scapolite	-	-	-	-	-	-	-	-	-
Calcite	-	-	-	-	0.3	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-
Sphene	1.0	0.2	3.2	1.0	3.3	m	3.6	1.6	2.8
Apatite	-	m	m	m	m	m	-	0.8	-
Zircon	m	-	m	-	-	-	-	-	-
Tourmaline	-	-	-	-	-	-	-	-	-
Magnetite	1.4	2.0	2.4	-	1.2	m	-	-	0.6
Pyrite	-	-	-	-	m	-	-	-	m
Hematite	-	0.2	0.4	-	m	-	-	-	0.2
Leucoxene	-	-	-	-	-	-	-	-	-
Laumontite	-	-	-	-	-	-	-	-	-
Heulandite	-	-	-	-	-	-	-	-	-
Clay	-	-	-	-	-	-	-	-	-
Matrix	-	-	-	-	-	-	-	-	-
# Points	489	500	537	507	509	437	500	491	532

PETROGRAPHIC DESCRIPTIONS

AB5-282 State Farm Gneiss in dry stream bed between first and second northeast trending tributaries northeast of Dover Lake. Hylas: 4169050 mN 258000 mE.

Coarse grained, equigranular garnet-quartz-hornblende-plagioclase amphibolite with indistinct compositional layering. Garnets are as much as 2 mm in diameter.

Biotite flakes are ubiquitously distributed as poikiloblasts in garnet, hornblende and plagioclase. Some magnetite appears to be euhedral after sphene.

AB5-11 Sabot Amphibolite 1.3 km (0.83 mi) southeast along the Chesapeake and Ohio railroad from Sabot and 120 m (400 ft) north in small stream below artificial dam. Hylas: 4165200 mN 258100 mE.

Coarse, dark green to black amphibolite. Quartzo-feldspathic layers contain hornblende porphyroblasts as much as 2 cm long. The primary foliation is defined by a dimensional orientation of plagioclase and hornblende.

Plagioclase and hornblende have been altered somewhat. Feldspars were locally sericitized and amphiboles were altered to produce magnetite and minor calcite.

AB5-58 Sabot Amphibolite in first east trending stream off Dover

Creek north of Highway 6. Midlothian: 4166400 mN 258000 mE.

Medium to coarse grained, well foliated amphibolite with a weak lineation formed by hornblende porphyroblasts. Plagioclase was highly sericitized and iron oxides formed on hornblende.

Poikiloblastic hornblende contains porphyroblasts of plagioclase, quartz and minor epidote.

AB5-161a Sabot Amphibolite 0.8 km (0.5 mi) in east trending stream northeast of Dover Lake. Hylas: 4168300 mN 259100 mE.

Coarse to medium grained amphibolite with hornblende porphyroblasts as much as 0.5 cm long. Compositional layering is conspicuous. Epidote veinlets cut across the foliation.

Hornblende is poikiloblastic with plagioclase and quartz inclusions while quartz and epidote poikiloblasts are found in characteristically sericitized plagioclase. Epidote and chlorite veinlets cut across foliation and mineral grains with little or no offset in the truncated features.

AB5-195 Sabot Amphibolite just south of the branch in Anderson Creek north of the Richmond Stone Quarry. Hylas: 4175100 mN 264400 mE.

Medium to coarse grained, highly altered amphibolite which was folded into a northeastward plunging, northwestward asymmetric open antiform. Foliation is undulatory. Small slightly discordant shears contain epidote and chlorite.

Epidotization, chloritization and sericitization dominate the present mineralogy. Hornblende was locally altered to epidote + chlorite. Plagioclase was locally intensely sericitized so that the porphyroblasts were totally replaced by muscovite. Chlorite commonly formed on plagioclase boundaries. Epidote porphyroblasts are homoaxial to pleochroic allanite cores. Euhedral pyrite is conspicuously abundant. Blocky calcite now fills irregular to straight intergranular voids. The retrogressive alteration was syntectonic because the greenschist mineralogy forms the present primary foliation. There is no evidence for transposition of an earlier foliation nor is there textural evidence suggesting post-tectonic crystallization.

AB5-231b Sabot Amphibolite 95 m (320 ft) southeast along Stone Horse Creek from the South Anna River southwest of Ground Squirrel Bridge on Highway 33. Hanover Academy: 4182100 mN 269050 mE.

Coarse grained epidote-hornblende-plagioclase amphibolite. Foliation is undulatory and the lithology is variable from amphibolite to amphibole gneiss. Quartz and quartzo-feldspathic intercalations are common as are discordant felsic pegmatites. Garnetiferous zones are present locally.

Hornblende, plagioclase and epidote porphyroblasts occupy a slightly finer groundmass of mosaic interlocking plagioclase and quartz. Plagioclase grain boundaries are irregular and where enclosed by hornblende the crystals are zoned to a sericitized core. Amoeboid plagioclase locally embays epidote. Hornblende and, to a lesser extent, epidote are poikiloblastic with included anhedra of plagioclase, quartz or hornblende (in epidote). Epidote was not observed to form poikiloblasts.

Epidote (epidote, minor clinozoisite) occurs in discreet, gradational layers possibly reflecting original compositional variations.

AB5-272 Sabot Amphibolite 0.5 km (0.3 mi) east on the Chesapeake and Ohio railroad from Sabot. Midlothian: 4166000 mN 257700 mE.

Medium to coarse grained, black to dark green amphibolite. A massive appearance is present because of the ubiquitous distribution of minerals, equant grain size and general lack of compositional layering on a small scale.

Euhedral hornblende contains rare poikiloblasts of plagioclase. Sericitization of feldspar developed locally. Euhedral sphene is relatively abundant and oriented parallel to the foliation defined by dimensional orientation of hornblende and plagioclase. Locally garnets are present. Lenticular, felsic pegmatites are parallel to the foliation.

AB5-383 Sabot Amphibolite 1.6 km (1 mi) south on 622 from Rockville and in Anderson Creek on east side of road. Hylas: 4176100 mN 263900 mE.

Coarse grained, well layered amphibole gneiss. Feldspars are white altering to pink and hornblende is locally green in color. Numerous discordant epidote filled fractures cut across the foliation. Exposed surfaces have limonite coatings.

Feldspar grains show undulatory extinction, are subhedral and have sutured grain boundaries. Epidote veinlets truncate or cut across all earlier structures and minerals and appear to be the latest feature present.

AB5-396 Sabot Amphibolite 0.6 km (0.4 mi) southwest of Centerville in stream. Hylas: 4172100 mN 262000 mE.

Coarse grained, massive but well foliated amphibolite. The rock is green from weathering and exposed surfaces have limonite coatings. There are locally feldspar rich layers as much as 0.5 cm thick. The rock is highly jointed.

APPENDIX 1 (continued)
MODAL ANALYSES

	--Sam-	--------------Eastern gneiss complex (Egnc)--------------						Bgdgn	-Pbgr--
	AB6-54	AB5-228	AB5-237	AB5-246	AB5-252	AB5-240	AB5-243	AB4-1	AB5-261
Plagioclase(1)	33.0(20)	22.2	41.4(25)	50.0	32.9	37.0	40.7(28)	44.2	38.2
Microcline	-	20.3	-	0.2	1.3	8.1	-	6.5	30.5
Quartz	2.9	31.2	32.9	14.9	26.4	24.9	26.9	27.7	21.6
Biotite	-	16.9	16.8	2.6	m	27.1	4.6	19.1	1.0
Muscovite(2)	-	1.0	-	m	m	1.1	0.1	0.4	0.7
Chlorite	-	-	4.2	17.3	18.4	1.3	2.1	1.1	5.8
Stilpnomelane	-	-	-	-	-	-	-	m	-
Garnet	-	7.8	0.1	12.1	-	0.4	2.4	-	-
Hornblende	52.2	-	0.6	-	-	-	13.4	-	-
Diopside	-	-	-	-	-	-	-	-	-
Epidote(3)	9.1	m	2.8	0.4	19.5	0.2	0.9	0.7	0.7
Allanite	-	-	-	-	-	-	-	-	-
Scapolite	-	-	0.8	-	-	-	-	-	-
Calcite	-	-	-	m	m	-	2.1	0.2	-
Kyanite	-	0.3	-	-	-	-	-	-	-
Sphene	2.7	0.3	-	1.2	-	-	m	m	m
Apatite	-	-	-	-	-	-	m	m	m
Zircon	-	m	-	m	m	m	m	m	-
Tourmaline	-	-	-	-	-	-	-	-	-
Magnetite	-	m	0.3	1.2	1.5	m	6.6	m	-
Pyrite	-	-	-	-	-	m	-	m	-
Hematite	0.2	m	-	m	-	m	-	-	1.4
Leucoxene	-	-	-	-	-	-	-	m	-
Laumontite	-	-	-	-	-	-	-	-	-
Heulandite	-	-	-	-	-	-	-	-	-
Clay	-	-	-	-	-	-	-	-	-
Matrix	-	-	-	-	-	-	-	-	-
# Points	525	587	712	496	538	543	754	1119	416

APPENDIX 1 (continued)

PETROGRAPHIC DESCRIPTIONS

AB6-54 Sabot Amphibolite outcrops in southeast-trending stream on the southeastward bend in the South Anna River. Hylas: 4180900 mN 267800 mE.

Coarse grained, dark green to black, well layered amphibolite with felsic intercalations as much as 3 cm (1.2 in) thick.

Porphyroblastic euhedral epidote, hornblende and plagioclase comprise the dominant mineralogy. Plagioclase (An_{15-25}) locally shows both albite and pericline twinning. Hornblende is somewhat poikiloblastic and is mutually embayed with epidote. The epidote has characteristic cross-sections and poikiloblasts of vermicular quartz and is locally rimmed by narrow zones of hornblende(?).

AB5-228 Eastern gneiss complex 122 m (400 ft) southwest on the south side of the South Anna River from Ground Squirrel Bridge on Highway 33. Hanover Academy: 4182050 mN 269800 mE.

Fine to medium grained, well layered, gray garnetiferous biotite gneiss. Weathering of garnets produces a reddish-orange spotted appearance in the rock.

Poikiloblastic garnets are round and contain inclusions of quartz and biotite. Brilliant orange-red biotite folia are generally straight and parallel but were locally diverted by garnet porphyroblasts. The biotite also appears to coarsen around garnet. Plagioclase was commonly sericitized. Rare skeletal muscovite plates may have replaced kyanite.

AB5-237 Eastern gneiss complex 0.6 km (0.4 mi) northeast on the south side of the South Anna River from Ground Squirrel Bridge on Highway 33. Hanover Academy: 4182700 mN 270100 mE.

Coarse grained, moderately layered, black to gray porphyroblastic biotite gneiss with angular white plagioclase porphyroblasts as much as 3 cm long.

A mylonitic texture developed in this rock. Hornblende, as much as 2 mm long, and plagioclase are euhedral but have been deformed and locally retrogressively altered. Porphyroclastic plagioclase, commonly surrounded by polygonized quartz sheaths, were rounded and bent into "s" shapes, as shown by deformed twin lamellae. Hornblende broke down to form green-brown biotite, which formed incipient chlorite. Quartz was upiquitously polygonized. Subhedral scapolite is turbid, ragged and was locally pseudomorphed by epidote.

The metamorphic foliation (S_1) and the apparent mylonitic foliation are parallel. The cataclasis can be attributed to the location of the sample inside a shear zone related to the formation of the Hylas zone.

AB5-240 Eastern gneiss complex 1.3 km (0.8 mi) northeast on the east side of the South Anna River north of Ground Squirrel Bridge on Highway 33. Hanover Academy: 4183250 mN 270600 mE.

Medium grained, gray porphyroblastic biotite gneiss schist with white plagioclase porphyroblasts as much as 1.5 cm long.

Biotite folia occur as layered masses or fine flakes between feldspar porphyroblasts. Compositional layering is gradational from biotite rich layers to microcline-plagioclase-quartz layers. Chlorite alteration of biotite is minor. Some of the larger plagioclase porphyroblasts are antiperthitic and commonly surrounded by microcline.

AB5-243 Eastern gneiss complex 2.1 km (1.3 mi) northeast on the east side of the South Anna River from Ground Squirrel Bridge on Highway 33. Hanover Academy: 4183000 mN 271100 mE.

Medium to coarse grained garnetiferous biotite-hornblende gneiss with poorly developed compositional layering.

Retrogressive alteration of grains, particularly mafic minerals, was extensive. The following alterations or associations were observed in thin section: (1) garnet to magnetite + chlorite + sphene and locally bordered by muscovite, (2) biotite to chlorite + sphene, (3) plagioclase to sericite, (4) hornblende to biotite or brown chlorite commonly associated with calcite. Skeletal muscovite porphyroblasts locally intergrown with plagioclase or minute acicular to bladed muscovite in biotite may be replacements of kyanite or sillimanite. The tendency of iron-magnesium minerals to clot together and the bulk composition of this rock suggest that it may have originally been mafic.

The original metamorphic assemblage aluminosilicate(?) + plagioclase + quartz + hornblende + biotite + garnet produced a retrogressive assemblage of chlorite + epidote + magnetite + calcite + muscovite (sericite).

AB5-246 Eastern gneiss complex 2.0 km (1.2 mi) northeast on the east side of the South Anna River in the first horseshoe bend north of Ground Squirrel Bridge on Highway 33. Hanover Academy: 4183200 mN 271250 mE.

Medium grained, poorly foliated, dark green and white speckled chlorite-plagioclase gneiss (originally biotite gneiss). Some polished surfaces appear to be limonite slickensides.

Retrogression was similar to AB5-243 and produced the alterations: (1) biotite to chlorite, (2) garnet to chlorite + magnetite and, (3) plagioclase to sericite. Minor small shears are also chloritized. Garnet porphyroblasts are poikiloblastic and elongate parallel to the foliation (S_1). Poikiloblasts in the garnets are also aligned to the foliation. Chlorite and biotite form stubby splay-like aggregates and are locally bent.

AB5-252 Eastern gneiss complex 0.4 km (0.2 mi) northeast of State Road 670 in east-west trending tributary to Stone Horse Creek. Glen Allen: 4180300 mN 269300 mE.

Fine grained, brecciated chlorite-epidote gneiss with white plagioclase augen as much as 1.5 cm in diameter. Numerous epidote veinlets cut across the poorly developed foliation.

Quartz occurs in strained, elongate anhedral grains and locally cuts across feldspar porphyroblasts in veins. Polygonized veins also cut across larger quartz grains. Biotite, now primarily altered to chlorite + magnetite, formed interstitially between quartz grains or quartz and plagioclase grains. Large, locally zoned, epidote was probably part of the original metamorphic assemblage whereas epidote + chlorite + magnetite fine grained aggregates formed in late fractures.

Some of these irregular fractures show offset of 1.5 mm to 2.0 mm.

AB4-1 Boscobel granodiorite gneiss in northeast wall of the Boscobel Granite Corp. quarry. Midlothian: 4164100 mN 259800 mE.

Medium grained, gray to green, moderately foliated biotite granodiorite gneiss.

Plagioclase is subhedral with polysynthetic twinning and local zoning. K feldspar is mostly microcline showing cross-hatched twinning. Subhedral to euhedral, stubby biotite folia are locally chloritized. Myrmekite developed around larger microcline porphyroblasts.

AB4-1c Boscobel granodiorite gneiss north wall of the Boscobel Granite Corp. quarry. Midlothian: 4164100 mN 259800 mE.

Medium to coarse grained, green and pink, chlorite granite gneiss. Highly altered equivalent of AB4-1.

Plagioclase was replaced by calcite and sericite. Chlorite with included magnetite and sphene(?) apparently replaced biotite. Quartz occurs as polygonized lenses or layers. Euhedral to subhedral laumontite crystallized locally in fractures. (no modal analysis)

AB5-261 Petersburg Granite 0.2 km (0.1 mi) west of the intersection of Gayton Road and Church Road in stream. Hylas: 4168550 mN 267300 mE.

Coarse grained, moderately weathered granite with euhedral to subhedral pink microcline phenocrysts as much as 1.8 cm long.

The cores of zoned plagioclase crystals were sericitized. Myrmekite intergrowths of vermicular quartz in anhedral plagioclase constitute about 5 percent of the rock. Green biotite was locally altered to chlorite and is always accompanied by euhedral sphene along cleavage planes. Alignment of biotite, anhedral quartz and some feldspar phenocrysts define a weak metamorphic(?) foliation.

APPENDIX 1 (continued)
MODAL ANALYSES

	Petersburg Granite (Pbgr)							pegmatites (p)	
	AB5-262[4]	AB5-355	AB5-358	AB6-7	AB6-9	AB6-11	AB6-28	AB5-29	AB5-78
Plagioclase(1)	26(12)	34.7(10)	33.2(11)	36.1	40.9	39.0	22.8	24.3	32.0
Microcline	22	31.3	31.7	20.0	18.9	22.4	34.1	22.2	47.2
Quartz	30	25.4	27.5	36.1	28.3	29.2	34.4	29.4	20.0
Biotite	m	2.5	2.1	5.4	10.2	7.5	4.8	-	m
Muscovite(2)	2	3.2	0.4	1.8	0.2	1.8	m	10.5	m
Chlorite	10	1.8	4.3	m	0.6	m	1.9	7.5	1.0
Stilpnomelane	-	-	-	-	-	-	-	-	-
Garnet	-	-	-	-	-	-	-	m	-
Hornblende	-	-	-	-	-	-	-	-	-
Diopside	-	-	-	-	-	-	-	-	-
Epidote(3)	2	0.7	m	0.7	0.8	-	1.3	m	-
Allanite	-	-	-	-	-	-	-	-	-
Scapolite	-	-	-	-	-	-	-	-	-
Calcite	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-
Sphene	m	0.2	m	m	-	m	m	-	-
Apatite	-	-	-	-	-	-	m	-	-
Zircon	-	-	m	m	-	m	-	-	-
Tourmaline	-	-	-	-	-	-	-	-	-
Magnetite	m	-	0.5	m	-	-	0.8	m	-
Pyrite	-	-	m	-	-	-	-	m	-
Hematite	1	m	0.4	-	m	0.2	-	3.9	m
Leucoxene	-	-	-	-	-	-	-	-	-
Laumontite	-	-	-	-	-	-	-	-	-
Heulandite	-	-	-	-	-	-	-	2.1	-
Clay	-	0.2	-	-	-	-	-	m	-
Matrix	-	-	-	-	-	-	-	-	-
# Points	-	556	564	449	491	559	378	333	316

PETROGRAPHIC DESCRIPTIONS

AB5-262 Petersburg Granite 0.3 km (0.2 mi) southwest on Gayton Road from the intersection with Church Road, due west in stream. Hylas: 4168300 mN 267200 mE.

Orange brown to reddish pink weathering microphaneritic granite.

Zoned plagioclase was sericitized and locally epidotized. Some crystals with polysynthetic twinning were bent. Chlorite, retrograded from green biotite, is the major mica. Weak foliation is defined by chlorite and some quartz and feldspar phenocrysts.

Myrmekite is approximately 4 percent of the rock.

AB5-355 Petersburg Granite 0.3 km (0.2 mi) southeast of Gilman on State Road 657 in Beech Creek on southwest side of road. Hanover Academy: 4184000 mN 272650 mE.

Coarse to medium grained microphaneritic granite with pink microcline phenocrysts as much as 1 cm long.

Brown biotite (altered to minor chlorite), muscovite and epidote form a moderately developed foliation which locally cuts across feldspars. Myrmekite constitutes approximately 2 percent of the rock.

AB5-356 Petersburg Granite 0.3 km (0.2 mi) southeast of Gilman on State Road 657 in Beech Creek 61 m (200 ft) southwest of road. Hanover Academy: 4183900 mN 272650 mE.

Fractured, microbrecciated microphaneritic granite. Subhedral microcline and plagioclase were broken and invaded by quartz. Muscovite and chlorite, possibly after biotite, form isolated, bent folia or braided wisps of shredded folia. Epidote often occurs in association with chlorite and as zoned phenocrysts(?) in the groundmass. Myrmekite composes about 1 percent of the rock.

Fracture zones in the section contain euhedral to subhedral platy laumontite and fragments of microcline and plagioclase. Some of the fractures show minor offset (less than 0.5 mm). (no modal analysis)

AB5-358 Petersburg Granite 0.5 km (0.3 mi) west on Highway 250 from Gayton Road in stream on north side of road. Hylas: 4171100 mN 267200 mE.

Very coarse biotite granite porphyry with pink microcline phenocrysts as much as 3 cm long.

Microcline and plagioclase phenocrysts were sericitized. Most chlorite is retrogressive after biotite. The foliation is concealed by a strong linear fabric formed by microcline phenocrysts. Myrmekite is approximately 1 percent of the rock.

AB6-7 Petersburg Granite 120 m (400 ft) east in Chickahominy River from State Road 624. Glen Allen: 4175100 mN 271750 mE.

Massive, highly jointed pink granite and granite porphyry. The porphyritic phases are strongly lineated and gradational into microphaneritic or equigranular granite.

Microcline, albitic plagioclase and quartz phenocrysts are surrounded by a groundmass of polygonized quartz, green-brown biotite and musco-

Microcline locally has wavy string perthite intergrowths. Sericitized cores in plagioclase indicate original zoning. Epidote porphyroblasts formed along fractures in plagioclase.

Locally micrographic amoeboid quartz-plagioclase myrmekite bordering and embaying microcline is common. Quartz intergrowths in untwinned plagioclase are plumose and, more characteristically, vermicular.

Biotite (minor retrogressive chlorite), muscovite, polygonized quartz and a weak orientation of phenocrysts define the foliation.

AB6-9 Petersburg Granite 1.2 km (0.7 mi) in west-southwest trending branch of Chickahominy River west of State Road 624. Glen Allen: 4175200 mN 270600 mE.

Medium to coarse grained biotite granodiorite with a well developed foliation. An interlayered equigranular granitic pegmatite about 7.6 cm (3 in) thick has the same foliation.

Plagioclase has sericitized cores. Myrmekite making up about 6 percent of the rock, was observed to embay microcline. Some of the plagioclase in the myrmekite has polysynthetic twinning and the quartz intergrowths locally formed across plagioclase-plagioclase grain boundaries. The foliation is well defined by biotite and polygonized quartz.

AB6-11 Petersburg Granite 1.3 km (0.8 mi) in west-southwest trending branch of Chickahominy River west of State Road 624. Glen Allen: 4175300 mN 270500 mE.

Medium to coarse grained biotite granite with microcline phenocrysts as much as 1.4 cm (0.5 in) long.

Microcline is locally pe-thitic and plagioclase is sericitized. Light brown to black pleochroic biotite occurs in gneissic layers with muscovite. Myrmekite constitutes approximately 3 percent of the rock.

Two weakly to moderately defined foliations are present. The oldest is delineated by parallelism of euhedral biotite and minor muscovite folia in the groundmass. The second foliation is best developed, transposes the earlier foliation and is defined by parallelism of biotite and muscovite layers and individual folia elsewhere in the groundmass. There is also a tendency for recrystallized(?) quartz blebs and porphyroblasts to align dimensionally to the mica foliation. The two foliations are almost mutually perpendicular. Their origin remains uncertain.

AB6-16 Petersburg Granite 0.5 km (0.3 mi) north in Black Haw Branch from State Road 624. Glen Allen: 4176150 mN 271700 mE.

Moderately weathered granite porphyry with pink microcline phenocrysts as much as 7 mm long. Alignment of microcline forms L_{Ef}.

Zoned plagioclase has sericitized cores. Larger microcline phenocrysts are poikiloblastic. Most of the inclusions are sericitized plagioclase and chloritized biotite or retrogressive chlorite. Crystalloblastic chlorite, some of which may be retrogressive after biotite, and the dimensional orientation of polygonized, "flattened" quartz outline the metamorphic foliation. Poikiloblasts in microcline are concordant or subconcordant to similarly aligned minerals in the groundmass.

Myrmekite, making up about 3 percent of the rock, is locally micrographic with vermicular quartz blebs forming plumose structures in plagioclase. (no modal analysis)

AB6-28 Petersburg Granite 0.5 km (0.3 mi) south in stream from Church Road. Hylas: 4167650 mN 268100 mE.

Well foliated porphyritic granite with pink microcline phenocrysts as much as 6 mm long.

Microcline phenocrysts are poikiloblastic and plagioclase is sericitized. Chlorite formed from the alteration of plagioclase and biotite and also appears porphyroblastic in minor amounts. Quartz is typically polygonized and has invaded fractures in broken and bent plagioclase phenocrysts. Amoeboid myrmekite (approx. 2 percent) locally embayed microcline borders. Inclusions in microcline define the foliations. The oldest(?) consists of sericitized plagioclase and chloritized biotite subparallel to some phenocrysts in the groundmass. The second foliation consists of small plagioclase porphyroblasts(?), chlorite, chloritized biotite and muscovite parallel to polygonized quartz and mica folia in the groundmass.

Some of the retrogression, fracturing of plagioclase and polygonization of quartz may be attributed to cataclastic activity in the nearby Hylas zone.

AB5-29 East side of dirt road beside sewage lagoons west of Manakin Farms on Highway 6. Midlothian: 4165700 mN 259400 mE.

Medium to coarse grained, buff to orange weathering metapegmatite. The primary foliation is locally deformed by high angle fractures.

Microcline is turbid and sericitized. Euhedral heulandite is intimately related to feldspar or found in discreet veins. Stilpnomelane and muscovite bend around feldspars and are transected by hematite filled fractures. All features are overprinted by weathering alterations.

AB5-78 0.5 km (0.3 mi) on stream east of Dover Lake. Hylas: 4168000 mN 258650 mE.

Coarse grained granoblastic felsic pegmatite about 3 m (10 ft) thick.

String or thread microcline perthite is the dominant feldspar and the remarkable parallel orientation of perthitic intergrowths defines a foliation. Sericitization of feldspars developed locally. Myrmekitic and micrographic quartz intergrowths are common in feldspar.

APPENDIX 1 (continued)
MODAL ANALYSES

	pegmatites (p)					Dover Creek zone (DCz)			
	AB5-89	AB5-155	AB5-161c	AB5-316	AB5-364	AB5-73[4]	AB5-75	AB5-99	AB5-102
Plagioclase(1)	46.6	40.0(6)	8.0	24.8	32.6	30	22.3	17.8	21.1
Microcline	4.0	34.9	65.1	48.5	33.2	-	13.0	16.4	m
Quartz	32.2	22.2	26.8	25.0	30.0	15	28.1	29.4	8.2
Biotite	-	0.3	-	-	m	8(5)	2.3(5)	9.6(5)	0.2(5)
Muscovite(2)	4.7	m	m	1.7	0.6	-	-	-	12.8
Chlorite	3.0	-	-	-	0.2	m(5)	m(5)	1.4(5)	1.2(5)
Stilpnomelane	-	m	-	-	-	m	m	-	m
Garnet	m	0.3	-	-	2.2	1	5.8	3.6	m
Hornblende	-	2.2	-	-	-	5	0.3	-	-
Diopside	-	-	-	-	-	-	-	-	-
Epidote(3)	9.4	0.3	-	-	-	3(5)	m(5)	0.6(5)	m(5)
Allanite	-	-	-	-	-	-	-	-	-
Scapolite	-	-	-	-	-	-	-	-	-
Calcite	-	-	-	-	-	-	-	-	-
Kyanite	-	-	-	-	-	-	-	-	-
Sphene	-	-	-	-	-	4	2.1	3.2	m
Apatite	-	-	-	-	-	-	-	-	-
Zircon	m	-	-	-	-	m	m	m	m
Tourmaline	-	-	-	-	-	-	-	-	-
Magnetite	-	-	-	-	-	m(5)	m(5)	m(5)	1.7(5)
Pyrite	-	-	-	-	-	-	-	-	m
Hematite	-	m	-	-	0.2	m	-	m	m
Leucoxene	-	-	-	-	-	-	-	-	-
Laumontite	-	-	-	-	1.0	-	-	-	-
Heulandite	-	-	-	-	-	-	-	-	-
Clay	-	-	-	-	-	-	-	-	-
Matrix	-	-	-	-	-	28	26.8	18.0	54.7
# Points	298	370	410	516	503	-	609	439	413

PETROGRAPHIC DESCRIPTIONS

AB5-89 0.5 km (0.3 mi) west in northwest trending branch on stream parallel to sewage lagoons west of Manakin Farms. Midlothian: 4166100 mN 259000 mE.

Massive appearing poorly foliated metapegmatite.

The dominant feldspar is sericitized and epidotized albite. Epidote also occurs as crystalline aggregates in an unoriented fracture network cutting across mineral grains.

AB5-155 78 m (260 ft) in small stream valley 0.2 km (0.1 mi) northeast of Dover Lake. Hylas: 4168200 mN 258400 mE.

Medium to coarse grained, foliation (S_1) pegmatite gneiss.

The following alteration features were observed in thin section: (1) hornblende to green biotite + stilpnomelane and possibly biotite to stilpnomelane, (2) plagioclase to sercite, (3) skeletal plagioclase surrounded and embayed by microcline. The microcline is only locally weakly perthitic. (4) Quartz recrystallized to a polygonized matrix where individual plates have somewhat diffuse boundaries. Some stilpnomelane appears to have recrystallized post-tectonically, as the folia have no preferred orientation.

AB5-161c 0.8 km (0.5 mi) east in first east trending stream north of Dover Lake. Hylas: 4168500 mN 259150 mE.

Very coarse grained "milky" mylonitic pegmatite.

Microcline was intensely fractured and locally sericitized. A fine, near cryptocrystalline matrix was formed from comminuted quartz and feldspar.

AB5-316 0.3 km (0.2 mi) northwest of the end of State Road 676 in Broad Branch. Hylas: 416880 mN 261200 mE.

Coarse to very coarse, pink and white microcline pegmatite.

Large microcline porphyroblasts contain inclusions of muscovite, quartz, twinned plagioclase and are locally perthitic. Plagioclase was highly sericitized and polysynthetic twins were locally bent. Sericitized plagioclase often forms boundaries of large microcline megaporphyroclasts. Quartz recrystallized into polygonized veins which appear to flow around feldspars. Microcline was locally broken up into angular cleavage fragments with interfragmental spaces occupied by quartz and muscovite.

AB5-364 0.5 km (0.3 mi) northeast along State Road 623 from crossing over Broad Branch. Hylas: 4168300 mN 263500 mE.

Coarse grained, white to buff weathering pegmatite. Nearly vertical quartz veins as much as 1 cm thick cut the foliation (S_1).

Microcline forms large anhedral crystals with inclusions of plagioclase, quartz and muscovite. Albite porphyroblasts are sericitized and locally show albite and Carlsbad twinning. Quartz is interstitial and occurs as thin stringers, locally associated with muscovite, cutting feldspar porphyroblasts. Irregular cross-cutting fractures were first filled by quartz and then by laumontite. Both walls of the fractures have optically continuous quartz coatings with laumontite in the central voids. Hematite appears to have replaced fracture fillings locally.

AB5-73 64 m (211 ft) east of Dover Lake in small stream valley. Midlothian: 4167200 mN 257900 mE.

Black to dark green, orange-red weathering mylonite with white and pink feldspar porphyroclasts as much as 3 cm long. Compositional layering is poorly developed and the porphyroclasts do not appear strongly aligned.

Plagioclase porphyroclasts are rounded or eye shaped and frequently are swathed in a polygonized quartz jacket extending to either side of the porphyroclast in pressure shadows. Euhedral sphene was locally altered to epidote. A fluxion structure is defined by the orientation and deformation of polygonized quartz lenses and by layering in the cryptocrystalline magnetite-chlorite matrix. Minor post-tectonic stilpnomelane apparently grew across the fluxion structure.

AB5-75 127 m (422 ft) east of Dover Lake in small stream valley. Midlothian: 4167400 mN 257950 mE.

Black, poorly layered mylonite with pink feldspar porphyroclasts as much as 4 cm long. Fractured, dislocated garnets are as much as 2 cm in diameter.

The fine matrix is composed mainly of polygonized quartz and associated pleochroic, comminuted chlorite(?) and opaque minerals. Intrafolial folds in the fluxion structure are especially well developed in the deformation of polygonized quartz lenses.

AB5-99 1 km (0.6 mi) east in stream running through Glen Allen housing development from Dover Creek. Hylas: 4169250 mN 259400 mE.

Coarse grained, weathered mylonite with gneissic layering and augen shaped pink feldspar porphyroclasts as much as 2 cm long.

Garnets are not highly fractured but are poikiloblastic and contain inclusions of most every other mineral in the section. Clinozoisite and epidote are distinct with clinozoisite occurring as large (0.5 mm) porphyroclasts showing anomalous blue pleochroism.

AB5-102 1.3 km (0.8 mi) east in stream running through Glen Allen housing development from Dover Lake. Hylas: 4169250 mN 259600 mE.

Cryptically layered, fine grained black to dark green ultramylonite with feldspar porphyroclasts locally reaching 1.5 cm in length. Small muscovite folia are distributed throughout the matrix.

Plagioclase porphyroclasts were tectonically rounded and rotated during cataclasis. The ultramylonitic matrix is composed of biotite, opaque minerals and chlorite(?). Muscovite porphyroblasts (1.5 mm) are syn-tectonic and were bent into "s" or "z" shapes. Retrogressive chlorite occurs: (1) as minute folia along the boundary between plagioclase porphyroclasts and the matrix, (2) as rims or intrafoliae on or in biotite grains, (3) as alteration of shattered and dislocated garnets, and (4) in small veins cutting across the cataclastic foliation.

Folding apparently took place near the end of cataclasis as both fluxion structure and syn-cataclastic porphyroblasts were deformed.

APPENDIX 1 (continued)
MODAL ANALYSES

	DCz		Hylas zone rocks (Hz)						
	AB5-175a	AB5-342	AB5-85	AB5-137	AB5-144a	AB5-145	AB5-149	AB5-172	AB5-191
Plagioclase(1)	44.0	14.3	25.6(29)	25.7	38.9	34.7	29.6	17.9(10)	33.9
Microcline	-	19.2	1.4	16.5	-	8.9	10.4	21.3	3.6
Quartz	25.5	31.3	24.8	32.7	18.8	31.7	35.7	27.4	31.8
Biotite	2.6	0.8	-	3.9	-	-	4.2	-	-
Muscovite(2)	-	-	m	3.3	-	0.7	1.5	18.8	1.1
Chlorite	m	1.0	13.2	9.6	10.0	10.8	16.7	5.2	9.6
Stilpnomelane	-	-	-	-	-	-	-	-	-
Garnet	0.2	m	-	-	-	-	0.2	-	-
Hornblende	21.1	0.6	-	-	24.4	-	-	-	
Diopside	-	-	-	-	-	-	-	-	-
Epidote(3)	m	m	34.1	6.9	5.5	12.0	1.1	9.4	15.5
Allanite	0.4	m	-	-	-	-	-	-	-
Scapolite	-	-	-	-	-	-	-	-	-
Calcite	-	-	1.0	-	-	-	0.6	m	1.6
Kyanite	-	-	-	-	-	-	-	-	-
Sphene	-	1.4	m	m	2.5	1.2	m	-	2.9
Apatite	-	-	-	-	-	-	-	m	-
Zircon	-	m	-	-	-	-	m	-	m
Tourmaline	-	-	-	-	-	-	-	-	-
Magnetite	2.4	m	m	0.4	m	m	-	m	m
Pyrite	-	-	-	-	-	-	-	-	m
Hematite	m	-	-	-	-	-	m	m	-
Leucoxene	-	-	-	-	-	-	-	-	-
Laumontite	-	-	-	-	-	-	-	-	-
Heulandite	-	-	-	-	-	-	-	-	-
Clay	-	-	-	-	-	-	-	-	-
Matrix	3.7	31.1	-	1.0	-	-	-	-	-
# Points	455	482	501	490	512	426	527	563	560

APPENDIX 1 (continued)

PETROGRAPHIC DESCRIPTIONS

AB5-161b 0.8 km (0.5 mi) east in first east trending stream northeast of Dover Lake. Hylas: 4168300 mN 259200 mE.

Black to dark green, weakly layered mylonite with coarse pink plagioclase porphyroclasts (1 cm) and very coarse (6 cm) quartz-microcline megaxenoporphyroclasts in a fine grained matrix.

Rounded plagioclase and epidote porphyroclasts (some epidote is retrogressive) are in a brown pleochroic, cryptocrystalline matrix. Polygonized quartz locally rims plagioclase. Epidote porphyroclasts are usually zoned from allanite cores to rims of colorless, nonpleochroic epidote.

The pegmatite porphyroclast consists of coarse microcline with grid structure, highly sericitized plagioclase and polygonized, deformed quartz. The boundary between the megaporphyroclast and mylonite is sharp.

(No modal analysis)

AB5-175a 0.8 km (0.5 mi) east in Tuckahoe Creek from bridge on State Road 621, 0.6 km (0.4 mi) northwest of Centerville. Hylas: 4173500 mN 262000 mE.

Finely laminated (1 to 5 mm) mylonitic-protomylonitic biotite-hornblende-quartz-plagioclase gneiss with local lenticular and elongate felsic layers. A mylonitized amphibolite or amphibole gneiss.

Poikiloblastic hornblende porphyroclasts as much as 2.5 cm long were tectonically rounded, comminuted and retrograded to produce much of the local mylonitic-ultramylonitic matrix. The hornblende formed retrogressive biotite (which then formed minor chlorite) and/or allanite and magnetite. Some epidote has allanitic cores. Plagioclase is rounded, generally untwinned and locally polygonized. Minor garnet was fractured, dislocated and retrograded to chlorite and magnetite.

AB5-342 0.8 km (0.5 mi) east in second east trending tributary of Dover Creek from State Road 644. Hylas: 417050 mN 259700 mE.

Gneissic layered, black to dark green mylonite with pink and white plagioclase and microcline porphyroclasts as much as 2 cm long.

Coarse porphyroclasts occupy a very fine pleochroic, cryptocrystalline matrix. Hornblende is altered to allanite, hematite (secondarily) and idioblastic sphene. Fluxion structure and intrafolial folds are well developed.

AB5-31 1.7 km (1.1 mi) northeast on dirt road off Highway 6 west of Manakin Farms. Midlothian: 4166900 mN 260100 mE.

Very fine grained, gray and white laminated ultramylonite with rare pink microcline porphyroclasts as much as 6 cm (2.4 in) long.

The elongate porphyroclasts are aligned with their long axes parallel to S_c. Polygonized quartz, feldspar and neomineralized chlorite and muscovite form the cataclastic matrix. Epidote is present in minor amounts and the quartz commonly occurs as flattened lenses.

(No modal analysis)

AB5-60 0.6 km (0.4 mi) east in the first tributary to Dover Creek north of Sabot across Highway 6. Midlothian: 4166650 mN 258300 mE.

Coarse to fine grained, apparently non-foliated green mylonite-ultramylonite with rounded, elongate pink and white feldspar porphyroclasts as much as 1 cm (0.4 in) long.

The green pleochroic matrix is fine grained epidote, chlorite and polygonized quartz. Calcite crystallized locally in fractures.

(No modal analysis)

AB5-85 1.2 km (0.8 mi) north of Highway 6 in stream parallel to dirt road beside sewage lagoons west of Manakin Farms. Midlothian: 4166700 mN 259350 mE.

Black to dark green, coarse grained chloritized gneiss with subhedral pink and white feldspar porphyroblasts in felsic layers and cut by generally concordant epidote veinlets.

The epidote-chlorite-microcline-quartz-plagioclase gneiss (present mineralogy) was probably a biotite gneiss or a hornblende-biotite gneiss. Abundant chlorite with inclusions of sphene and magnetite and dimensionally oriented, strained quartz porphyroblasts as much as 2 mm long define the foliation. Irregular epidote veinlets 1 mm or less wide transect S_1 at generally high angles. Epidote also occurs as porphyroblasts and as euhedral poikiloblasts in plagioclase. Plagioclase grains were bent and broken near epidote veinlets. Small quartz veins appear to cut across the epidote veinlets.

AB5-137 300 m (1000 ft) west of Hickory Haven in Readers Branch.

Hylas: 4171700 mN 263400 mE.

Coarse grained, well laminated black and dark green augen gneiss (mylonite-protomylonite) with rounded pink microcline porphyroclasts as much as 6 cm (2.4 in) long. The foliation S_c is highly contorted.

The augen are in a very fine grained brown-green biotite-epidote-chlorite matrix. Quartz is ubiquitously polygonized and in the matrix with muscovite forms intrafolial folds around and between feldspar porphyroclasts. The original rock was probably biotite gneiss.

AB5-139 1.0 km (0.6 mi) west of Hickory Haven in Readers Branch.

Hylas: 4171850 mN 263100 mE.

Very fine grained, weakly laminated green ultramylonite of intermediate composition with rare feldspar porphyroclasts about 2 mm long. The rock is highly jointed.

Plagioclase was sericitized, chloritized and is associated with calcite. Polygonized quartz and fine folia of muscovite and chlorite form the fluxion structure which is deviated around feldspar augen. A second pseudo-foliation was formed by the displacement of minute muscovite flakes by small plagioclase porphyroclasts or lenses of polygonized quartz in the matrix.

(No modal analysis)

AB5-144a northwest side of the Richmond Crushed Stone Co. quarry.

Hylas: 4174600 mN 263800 mE.

Coarse grained, green to black retrogressively altered hornblende gneiss with subhedral to anhedral, fractured, turbid white plagioclase porphyroblasts as much as 5 cm (2 in) long.

The present mineralogy is chlorite + hornblende + plagioclase + quartz. Chlorite with numerous sphene inclusions formed from the breakdown of hornblende. Locally, zoned epidote (non-allanitic cores) and chlorite aggregates pseudomorphed hornblende porphyroblasts. Epidote with allanite cores is believed to be part of the original metamorphic assemblage.

AB5-145 third level on the west side of the Richmond Crushed Stone Co. quarry. Hylas: 4174600 mN 263800 mE.

Coarse to medium grained chlorite-microcline-plagioclase-quartz gneiss (present mineralogy) featuring coarse pink microcline porphyroblasts in a medium to fine grained black or dark green matrix. Numerous concordant and highly discordant epidote veinlets are present.

Feldspars were ubiquitously sericitized and sausseritized. Epidote porphyroblasts usually have allanite cores and are locally skeletal with fine epidote and chlorite on borders. Fine epidote also occurs in small shears (approx. 0.5 mm wide) parallel to S_1 which is defined by retrogressive chlorite and quartz. High angle fractures (70 to 80 degrees to foliation) contain chlorite and muscovite and transect the foliation. Original lithology was biotite gneiss or hornblende-biotite gneiss.

AB5-149 southeast side of the Rockville Stone Company quarry. Hylas: 4174900 mN 266300 mE.

Coarse to medium grained, dense, dark green mylonite-protomylonite with rounded feldspar porphyroclasts 2 to 3 cm long. Muscovite and chlorite layers are exposed on some foliation surfaces.

The mylonitic matrix is composed of polygonized quartz, plagioclase, porphyroblastic muscovite and finely comminuted-recrystallized biotite and finely distributed magnetite and sphene(?). The original lithology was probably a biotite gneiss.

AB5-172 120 m (380 ft) west of State Road 623 on the south ridge of Tuckahoe Creek. Hylas: 4172800 mN 264000 mE.

Fine grained felsic ultramylonite with abundant shredded and aggregated muscovite.

Rare microcline porphyroclasts are no larger than 1 mm. S_c is defined by polygonized quartz and plagioclase, muscovite and minor chlorite. A weak, widely spaced (approx. 2 mm) shear cleavage cuts across S_c at 70 to 80 degrees. This cleavage is defined by chlorite in the minute shear zones and general bending of muscovite folia.

AB5-191 Anderson Creek just northwest of the Richmond Crushed Stone Co. quarry. Hylas: 4174650 mN 264300 mE.

Fine to medium grained, weakly layered, retrograded gneiss.

The present dominant mineralogy is quartz + plagioclase + chlorite + epidote. Feldspar was highly sericitized, especially along cleavage. Epidote is faintly pleochroic brown and locally has chlorite rims and/or inclusions of opaques. Some of the epidote crystals are suggestive of amphibole forms and may have pseudomorphed hornblende. Quartz is strained and polygonized and twinned plagioclase was locally bent.

The metamorphic foliation is transected by low angle (approx. 35 degrees) chloritized shears. Fragments of mineral grains were caught in the shears locally. This rock was an amphibole gneiss or biotite-hornblende gneiss.

APPENDIX 1 (continued)
MODAL ANALYSES

	Hz				Triassic rocks		
	AB5-291	AB5-331	AB5-373	AB5-381	AB5-263	AB5-264	AB5-360[4]
Plagioclase(1)	33.1(30)	29.9(10)	45.0	43.1	17.5	8.5	-
Microcline	25.6	14.6	2.9	21.9	27.7	32.2	-
Quartz	29.5	25.0	0.2	22.9	39.6	44.4	10
Biotite	-	-	-	-	-	m	-
Muscovite(2)	0.4	2.8	1.2	1.9	2.8	2.6	2
Chlorite	6.0	20.5	14.2	4.4	3.0	2.0	8
Stilpnomelane	-	-	-	-	-	-	-
Garnet	-	-	-	-	-	-	-
Hornblende	-	-	33.6	-	-	-	-
Diopside	-	-	-	-	-	-	-
Epidote(3)	0.8	1.7	0.6	4.6	6.2	4.2	-
Allanite	-	-	-	-	-	-	-
Scapolite	-	-	-	-	-	-	-
Calcite	-	3.0	2.3	0.4	-	-	-
Kyanite	-	-	-	-	-	-	-
Sphene	-	-	m	-	-	-	-
Apatite	m	-	-	-	-	-	-
Zircon	-	-	-	-	-	-	-
Tourmaline	-	-	-	-	-	-	-
Magnetite	-	-	-	0.2	-	-	-
Pyrite	-	m	-	-	-	m	-
Hematite	4.6	m	-	-	-	-	-
Leucoxene	-	-	-	-	-	-	-
Laumontite	-	2.5	-	0.6	-	-	-
Heulandite	-	-	-	-	2.0	5.5	20
Clay	m	-	-	-	-	m	-
Matrix	-	-	-	-	-	-	60
# Points	501	528	485	480	498	574	-

PETROGRAPHIC DESCRIPTIONS

AB5-291 0.4 km (0.3 mi) southeast in Tuckahoe Creek from the intersection of State Road 623 and the Tuckahoe Creek southwest of Hylas. Hylas: 4175600 mN 266500 mE.

Fine grained, brown weathering felsic ultramylonite.

Plagioclase porphyroclasts as much as 0.3 cm in diameter were tectonically rounded, sericitized and fractured during cataclasis. The fractures were sutured by quartz. Muscovite wisps in the cataclastic matrix formed, apparently, from the decomposition of feldspar. High angle fractures with offset of about 0.5 mm now contain limonite and hematite.

AB5-312 0.6 km (0.3 mi) from the south end of State Road 676 on the southernmost tributary of Broad Branch. Hylas: 4168100 mN 261050 mE.

Medium grained, highly weathered, microbrecciated felsic protomylonite-mylonite.

Feldspars were sericitized and locally deformed. Quartz was polygonized and fragments of the polycrystalline grains were preserved as microbreccia clasts in fracture zones. Muscovite and biotite form fine folia and wisps parallel to the cataclastic foliation.

The rock is transected by numerous iron oxide-filled fractures of no apparent regular orientation. Some of the fractures have angular fragments of plagioclase, quartz, muscovite and minor biotite.

(No modal analysis)

AB5-326 270 m (900 ft) southeast in stream from crossing of State Road 676 east of Hermitage Country Club. Hylas: 4170100 mN 262000 mE.

Dense, siliceous, fine grained non-foliated microbrecciated felsic ultramylonite.

Heulandite is abundant in the matrix and in fractures. Coarser heulandite occurs as polycrystalline void fillings and irregular to straight fracture fillings. Some straight zeolite zones are bound on either side by finer grained heulandite(?).

(No modal analysis)

AB5-331 180 m (600 ft) east in Broad Branch from end of pavement on State Road 676. Hylas: 4169200 mN 262000 mE.

Green, medium to fine grained felsic ultramylonite with pink microcline porphyroclasts locally as much as 1 cm long.

Plagioclase was ubiquitously sericitized and locally has rims of coarse muscovite. The fine matrix is composed of polygonized quartz, feldspar and acicular to bladed muscovite all of which form a cataclastic foliation. The section is irregularly fractured and laumontite + calcite fill many of the fractures. Laumontite and calcite show no distinct relationship: (1) laumontite veins with no calcite, (2) calcite masses with no laumontite, (3) interpenetrant laumontite + calcite in fractures and (4) fractures lined with calcite and containing a central core of laumontite. The original lithology was probably a granite gneiss.

AB5-365 northern side of the Rockville Stone Company quarry. Hylas: 4174950 mN 266300 mE.

Fine grained, well laminated, green brecciated felsic ultra-mylonite (average matrix grain size 0.05 mm). Pink feldspar porphyroclasts are rounded and as much as 1 cm long. Brecciation created voids which were first filled by silica and then calcite and laumontite. Quartz layers parallel to S_c are cut by the later brecciation features.

Microcline and plagioclase porphyroclasts are highly altered and contain inclusions of muscovite and epidote. Rusty stains locate pyrite euhedra. The composition of the ultramylonitic matrix is chlorite + epidote + muscovite + microcline + quartz + plagioclase.

(No modal analysis)

AB5-373 east side of the Richmond Crushed Stone Co. quarry. Hylas: 4174250 mN 264000 mE.

Coarse grained, highly altered dark green to black amphibolite transected by pink and white calcite filled veins. Epidote occurs on some fracture surfaces.

Low angle shears in the amphibolite produced the following retrogressive alterations: (1) hornblende to calcite + chlorite + sphene and (2) plagioclase to muscovite. Crystalline calcite formed in voids between hornblende and plagioclase porphyroblasts. Euhedral pleochroic chlorite folia and sericite masses occur together with sphene and (later) calcite in the small shear zones which locally cut across mineral grains. Some plagioclase grains have microcline cores where surrounded by hornblende.

AB5-381 southeast side of the Vulcan Materials Company quarry. Hylas: 4174700 mN 266800 mE.

Massive, weakly layered, highly jointed, medium to fine grained gray felsic ultramylonite. Joint surfaces are coated by abundant laumontite and calcite.

Feldspar porphyroclasts were commonly highly sericitized. The ultramylonitic matrix is composed of felsic minerals (microcline, plagioclase and quartz), muscovite in thin, undulatory ribbons and epidote. The epidote grains locally have rims of magnetite and/or hematite. A fluxion structure is defined by the orientation of foliated neomineralized muscovite stringers and opaque particle trails around epidote.

Calcite and laumontite formed in fractures both parallel and discordant to the foliation (S_c). Sparry calcite generally occurs in fractures parallel to the foliation and seems to be restricted to one side of the fracture. The fractures were then sealed by laumontite. Highly discordant fractures usually contain only laumontite.

LG5-1 northwest side of the Rockville Stone Company quarry. Hylas: 4174900 mN 266300 mE.

Fine grained dark green, well laminated mafic ultramylonite. The cataclastic foliation (S_c) is locally cut by a shear cleavage (S_s). The dominant mineral assemblage is quartz, chlorite, epidote, pyrite and albite. Polygonized quartz laminations were offset by minute shears containing chlorite. Discordant late fractures contain laumontite and calcite. The original lithology was probably an amphibolite.

(No modal analysis)

AB5-263 0.3 km (0.2 mi) south of the intersection of Church Road and Gayton Road in stream west of Gayton Road. Hylas: 4168350 mN 267150 mE.

Light brown weathering, coarse grained arkose conglomerate. Clasts are mainly subangular feldspar and quartz plus minor epidote.

Plagioclase was sericitized and epidotized so intensely that muscovite-epidote aggregates locally replaced the crystal. Muscovite and yellow-green pleochroic chlorite are intergrown in mats or splay-like folia. Quartz occurs as anhedral grains and as polygonized-recrystallized pods. Rounded lithic fragments are quartz-feldspar gneiss, foliated chlorite schist and muscovite schist.

AB5-264 0.3 km (0.2 mi) south of the intersection of Church Road and Gayton Road in stream west of Gayton Road. Hylas: 4168350 mN 267150 mE.

Highly weathered, coarse grained arkose conglomerate with clasts composed mainly of feldspar plus quartz and muscovite. Weathers to a coarse brown sand.

A number of low relief, first order gray birefringent, angular grains (2V=35, sign = +) are heulandite. The zeolite is found throughout the rock and is not restricted to veins. Plagioclase was highly sericitized and epidotized while microcline remained relatively unaltered. Minor light brown pleochroic biotite altered to chlorite, locally along cleavage. Much of the quartz occurs in polygonized veins. Hematite is interstitial to feldspar locally and may be a cementing agent.

AB5-360 0.6 km (0.4 mi) south on Gayton Road past its intersection with Church Road. Hylas: 4168000 mN 267200 mE.

Very fine grained, orange brown weathering mudstone.

Silt sized quartz, muscovite, chlorite and heulandite are in an amorphous hematitic (now limonite and clay) matrix. Heulandite has angular faces and some grains are apparently euhedral.

APPENDIX 2

LOCATION OF TYPICAL EXPOSURES OF ROCK UNITS

Lithology	Quadrangle	Sample #	Location
		State Farm Gneiss	
biotite-granite gneiss	Midlothian	AB4-2	Along the C & O railroad east of Sabot.
biotite schist	Hylas	AB6-34	South bank of the South Anna River under bridge at Casco.
hornblende-microcline gneiss	Hylas	AB5-280	In stream northwest of Dover Lake.
		Sabot Amphibolite	
amphibolite	Midlothian	AB5-272	Along the C & O railroad east of Sabot.
altered amphibolite	Hylas	AB5-373	Richmond Quarry.
amphibolite	Hanover Academy	AB5-231b	Along Stone Horse Creek from South Anna River.
		Eastern gneiss complex	
garnetiferous biotite gneiss	Hanover Academy	AB5-228	South side of South Anna River southwest of Ground Squirrel Bridge.
quartz-feldspar augen gneiss	Hanover Academy	-	Under Gilmans Bridge.

Lithology	Quadrangle	Sample #	Location
		Boscobel granodiorite gneiss	
biotite-quartz-plagioclase gneiss	Midlothian	AB4-1	Boscobel Quarry.
		Petersburg Granite	
granite porphyry	Hylas	AB5-358	In branch to Little Tuckahoe Creek by Highway 250 west of Gayton Road.
granite and granite porphyry	Glen Allen	AB6-7	Along Chickahominy River east of State Road 624.
		Triassic sedimentary rocks	
arkose	Hylas	AB5-263, AB5-264	In stream parallel to Gayton Road near intersection with Church Road.
fanglomerate	Hylas	-	1.1 mi. along State Road 623 from Highway 250.
fanglomerate	Hylas	-	Southwest in stream from Kain Road.
		Hylas zone rocks	
retrograded amphibolite	Hylas	AB5-373	Richmond Quarry.
felsic protomylonite-mylonite	Hylas	-	In Broad Branch west of the end of State Road 676.

Lithology	Quadrangle	Sample #	Location
	Hylas zone rocks (continued)		
felsic ultramylonite	Hylas	-	Rockville and Royal Quarries.
felsic ultramylonite	Hylas	-	In stream near bridge northeast of St. Matthews Church.
felsic ultramylonite	Hylas	AB5-172	On ridge southwest of intersection of State Road 623 and 622.
felsic ultramylonite	Hylas	AB5-31	About 1 mi. northwest of Manakin Farms on dirt road.
mafic ultramylonite	Hylas	LG5-1	Rockville Quarry.
microbreccia	Hylas	AB5-326	On ridge across from golf course on State Road 676.
brecciated felsic ultramylonite	Hylas	AB5-365	Rockville Quarry.

APPENDIX 3

GEOCHRONOLOGY

Samples of fine grained laumontite from a joint surface in a felsic ultramylonite in the Hylas zone were analyzed by Dr. John F. Sutter of the Ohio State University to obtain $^{40}Ar/^{39}Ar$ age dates. Analytic data for the determination are shown in Table 3-1. Ages were calculated using the formula:

$$t = 1/\lambda \ \ln(1 + J(^{40}Ar_r/^{39}Ar_K)$$

where $1/\lambda = 1.885 \times 10^9$ yr. and J is a measure of the integrated fast neutron flux as found from the monitor mineral data. Analytical precision is expressed as a 2σ error based on extrapolation of data points.

The rock sample, AB5-380, is a fine grained, light gray to green-gray, massive ultramylonite composed primarily of quartz, plagioclase and microcline with microcline porphyroclasts (as much as 2 cm long); minor minerals are chlorite, muscovite, epidote, magnetite and hematite. A fluxion structure is defined by the alignment of comminuted and recrystallized quartz, plagioclase and mica and the orientation of quartz pressure shadows around microcline or plagioclase porphyroclasts. The rock generally lacks strong compositional layering. Microscopically idiomorphic laumontite occurs with calcite in fracture fillings oriented as much as 70 degrees to the cataclastic foliation (S_c). Colo of the zeolite varies from white to pink.

John Sutter (personal communication, 1976) suggested that the $^{37}Ar/^{39}Ar$ ratios, a sensitive measure of the relative K/Ca ratio, indicated a calcium content too low for AB5-380 to be laumontite. However, an x-ray diffraction pattern run on the same sample correlates very clearly with the calculated pattern shown in Borg and Smith (1969) and other precisely determined patterns by the author (see Appendix 4) for laumontite. Chemical analyses should clarify this problem.

The total gas age for laumontite sample AB5-380 is 221 ± 6 m.y. Figure 5 in the text shows age calculations expressed diagramatically.

TABLE 3-1

ANALYTICAL DATA FOR $^{40}Ar/^{39}Ar$ INCREMENTAL HEATING EXPERIMENT
(Each temperature was held for one hour)

$J = 0.004145 \pm 0.000040$

Temp. (°C)	$^{40}Ar/^{39}Ar$ (measured)	$^{37}Ar/^{39}Ar$ (corrected for ^{37}Ar decay)	$^{36}Ar/^{39}Ar$ (measured)	F	^{39}Ar (% of total)	$^{40}Ar_r$* (%)	$^{36}Ar_{Ca}$ (%)	Age ** (x 10 yr.)
225	299.62	5.05077	0.93592	18.09	2.12	6.02	0.15	136 ± 14
340	84.96	0.45936	0.19239	27.03	5.10	31.82	0.06	200 ± 7
450	68.79	1.19526	0.13244	29.00	9.69	42.13	0.24	214 ± 6
525	56.23	0.04545	0.08662	30.13	20.73	53.59	0.01	222 ± 5
600	50.82	0.06543	0.06902	30.02	15.15	59.09	0.03	221 ± 5
Fusion	67.93	0.07264	0.12228	31.09	47.20	45.77	0.02	228 ± 6
Total Gas	68.77	0.29992	0.12862	30.04	100.00	43.69	0.06	221 ± 6

* $^{40}Ar_r$ = radiogenic ^{40}Ar; $^{36}Ar_{Ca}$ = calcium derived ^{36}Ar, calculated using data from Dalrymple and Lanphere (1971)

**Data plotted on Figure 5 in the text

APPENDIX 4

LAUMONTITE UNIT CELL REFINEMENT

A Norelco x-ray diffractometer was used to obtain precise two theta values of laumontite powder from the Hylas zone. Refinement of the cell parameters was performed using a least squares refinement program (Appleman and Evans, 1973). Values obtained in this study are comparable to previously published data (Breck, 1974; Borg and Smith, 1969).

Samples for analysis (AB5-370) were taken from the Rockville Stone Quarry. The lithology here is a fractured and brecciated epidote-chlorite-quartz-microcline-plagioclase mylonite. Late mineralization in the fractures includes laumontite, calcite, quartz and limonite. The laumontite is pink and white, euhedral and occurs both as a fine druse and in cavity fillings as larger crystals as much as 1 cm long. Samples for the x-ray determination were taken from larger crystals relatively devoid of limonite microfracture fillings. Because of intense weathering in this region, the open pore space minerals are usually restricted to fresh exposures in quarries.

Samples were pulverized and mounted on a glass slide in an acetone slurry with BaF_2 included as an internal standard. The Norelco diffractometer was set for a scanning rate of 0.5 degrees two theta per minute. The record was made at 40 kV and 30 mA. Instrument settings were 200 counts per second at a time constant of 2. One oscillation from 8 degrees two theta to 60 degrees two theta and down was performed. The two theta values were averaged and recorded as observed data.

TABLE 4-1

LAUMONTITE CELL PARAMETERS

Standard errors are shown in parentheses.

	Breck, 1974	Borg and Smith, 1969	This study
a	14.74 A	14.75 A	14.736 (8) A
b	13.07 A	13.10 A	13.093 (6) A
c	7.55 A	7.57 A	7.548 (7) A
beta	$111^{\circ}9'$	112°	$111^{\circ}46'$ (4')

APPENDIX 5

MICROEARTHQUAKE MONITORING

A portable seismograph (Sprengnether MEG-800) was operated for a total of 770 low-noise hours (32 days) during the periods 23 June, 1975 to 30 July, 1975 and 26 November, 1975 to 14 December, 1975 in the Hylas zone (Fig. 2). The survey was complete down to a magnitude of about 0.5 at 20 km. Four microearthquakes recorded during the survey period were:

TABLE 5-1

MICROEARTHQUAKES

Date	Magnitude*	Distance (km) from the seismograph
24 June	-0.4	<20 km
1 July	+0.1	<20 km
24 July	+1.3	>25 km
11 December	-1.6	<10 km

*Bollinger (1976, in press)

Because only one seismograph was used, it could not be determined that these events actually took place within the Hylas zone. The average occurrence rate (one microearthquake every 8 days) was the same as found by Bollinger (1975) for the central Virginia seismic zone. One of the 26 sites involved in that study was near Manakin (Fig. 2).

VITA

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Andy R. Bobyarchick

TECTOGENESIS OF THE HYLAS ZONE AND EASTERN PIEDMONT NEAR RICHMOND, VIRGINIA

by

Andy R. Bobyarchick

(ABSTRACT)

Detailed structural and petrographic studies of the Hylas zone northwest of Richmond, Virginia, reveal that Late Paleozoic thrusting to the northwest produced a zone of protomylonite, mylonite and ultramylonite from felsic gneiss and amphibolite. The thrusting event, which initiated retrograde metamorphism to greenschist facies, carried an allochthonous plate of coarse-grained, locally porphyrytic Petersburg(?) Granite over a layered sequence of metamorphosed sedimentary and volcanic rocks now represented by biotite gneiss, biotite schist and amphibolite. Non-cataclastic rocks west of the Hylas zone have undergone at least two periods of deformation (D_1, D_2) prior to cataclasis. Prograde metamorphism (M_1) was concurrent with deformation and is inferred to have occurred about 342 ± 70 m.y. ago. The Hylas zone deformation (D_3) caused a pervasive cataclastic foliation (S_c) and a later widely spaced shear cleavage (S_s) to be formed in rocks in the fault zone. Deformation was accompanied by retrograde metamorphism (m_2) to greenschist facies mineral assemblages. Fracturing and high angle faulting (D_4) was superimposed on the Hylas zone about 221 ± 6 m.y. ago under zeolite facies temperatures and pressures; laumontite, calcite and quartz crystallized in open spaces at this time. Sedimentation in the basin created by D_4 faulting and downwarp occurred during Late Triassic time to form the Richmond Basin. Northwest-trending joints and faults appear to have formed post-221 m.y. ago and pre-Creta-

ceous time. Cenozoic reverse faulting along strike of the Hylas zone in the Coastal Plain of Maryland may indicate a continuation of this polytectonic zone to the north.