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A NORTH-SOUTH TRANSECT OF THE GOOCHLAND TERRANE AND ASSOCIATED A-TYPE GRANITES, VIRGINIA-NORTH CAROLINA

Stewart S. Farrar
Eastern Kentucky University, Richmond, KY

Brent E. Owens
College of William and Mary, Williamsburg, VA

INTRODUCTION

The Goochland terrane is the southeastern- most and most interior massif of Grenville-age basement rocks of the southern Appalachians. It was named by Farrar (1982), and Glover et al. (1982), and was defined by Farrar (1984) as the areal extent of granulite-facies and retrogressed granulite-facies rocks of the eastern Virginia Piedmont, with possible extension southward into the northern North Carolina Piedmont (Fig. 1). The granulite facies metamorphic event is recognized by the occurrence of orthopyroxene-bearing assemblages in intermediate to mafic orthogneisses and sillimanite+ Kfeldspar in rocks of pelitic composition (Farrar, 1984). The definition of terrane boundaries is difficult in that granulite assemblages were overprinted by at least one later greenschist to amphibolite facies metamorphic event, with accompanying rehydration and ductile deformation of much of this granulite terrane, and with formation of numerous mylonite zones. These mylonite zones, of at least two generations, both bound the Goochland terrane and slice it into numerous fragments.

This belt of high grade gneisses and schists has long been known, and appears, among other places, on the 1932 Geologic Map of the United States. With the application of plate tectonic models to the southern Appalachians in the 1970's, it became apparent that much of the Piedmont comprised accreted terranes that developed elsewhere and were amalgamated in the Paleozoic to form the Appalachian belt (e.g. Hatcher, 1972; 1989). Any models that included Virginia showed at least one suture west of what is here called the Goochland terrane. What to do about this high-grade terrane? A number of possibilities have been proposed: (1) Many models assigned it to a higher-grade portion of one of the accreted arc-volcanic

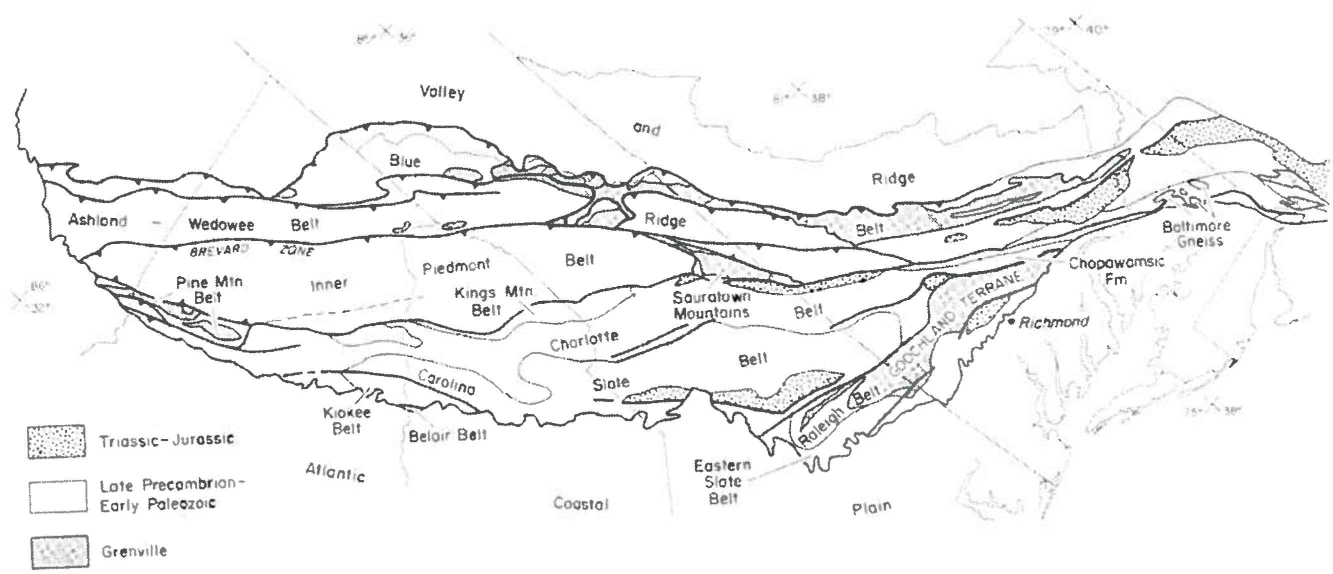


Figure 1. Distribution of Grenville terranes in the southern Appalachians

terranes of probable late Precambrian age. (2) Others (see Rankin, 1975; 1976) recognized that this terrane differed significantly from surrounding terranes and suggested it may have originated as part of another continent - perhaps Africa. (3) It could be a Grenville fragment of North America that was rifted away, had arc volcanics deposited on it, and was reemplaced onto North America. (4) It could be a thinned edge of North American Grenville, with, or without, nonconformable cover, exposed as a window through accreted terranes:

The nonconformity hypotheses certainly had a familiar ring. All previously described Grenville terranes of the southern Appalachians (Fig. 1), including those of the Blue Ridge, Pine Mountain belt, Sauratown Mountains, Baltimore Gneiss domes, West Chester prong, and Honey Brook upland, comprise deep crustal Grenville basement rocks, exposed by erosion and nonconformably overlain by upper Precambrian to lower Paleozoic units of sedimentary and/or volcanic origin. These overlying sequences all have stratigraphic ties, or probable ties, to North America, which help to confirm the North American (Laurentian) origins of these terranes. The more internal (southeastern) of these terranes are then exposed through allochthonous cover. When mapping of the Goochland terrane defined domes of gneiss (State Farm) surrounded by amphibolite and metapelitic rocks, it was natural to assume that this would be another case of Grenville gneiss domes nonconformably overlain by a volcanic/sedimentary sequence. When the first radiometric age control became available, giving a Grenville age for the State Farm (Glover et al., 1978; 1982), this was combined with the rarity of pelitic rocks elsewhere in the Grenville of the southern Appalachians to further support the nonconformity hypothesis. Farrar (1984) argued against the nonconformity hypothesis for the Goochland Terrane, saying the entire terrane was metamorphosed to granulite facies, and that this granulite metamorphism was, in all probability a Grenville event.

Glover, in a series of articles based largely on geophysical data, culminating in Glover et al. (1997), has discussed the tectonic role of the northern (James River traverse) portion of the Goochland terrane as one of several basement thrust sheets clipped off the eastern (present orientation) thinned, rifted, margin of Laurentia during amalgamation of the terranes which comprise the southern Appalachians. Other such slices include the Blue Ridge thrust sheets themselves, and additional Grenville slices buried under the Coastal Plain sediments of Virginia and Maryland to the east. Rather complex thrust, strike-slip, and late normal faulting combined to expose the Goochland Terrane in a huge window through overlying accreted terranes. These faults now comprise the boundaries of the Goochland Terrane. This Glover et al. (1997) model interprets the existence of Laurentian crust in the subsurface approximately to the present continental margin.

Following the model of Glover et al. (1997), the Goochland terrane was part of Laurentia through Grenvillian mountain building and late Precambrian rifting events, only becoming allochthonous during Paleozoic accretionary thrusting which emplaced it farther onto the continent. According to this model the Goochland Terrane rocks were subjected to most of the same tectonic events as the Blue Ridge Grenville. These would include Grenvillian intrusive, metamorphic and deformational events and late Precambrian rifting with its deformational and intrusive events. Paleozoic records could be expected to differ in that these slices ended up in different positions within the Appalachian Orogen.

GOOCHLAND TERRANE

This field guide will start with the northern, more extensively described James River traverse (Fig. 2.), and then progress southward into the proposed continuation of this terrane, the Meherrin River traverse, which some authors (see Sacks, 1999) prefer to discuss as the Raleigh terrane. The terrane is bounded on the west by the Spottsylvania lineament, the Lakeside mylonite zone, then an indefinite boundary the authors haven't examined, then the Nutbush Creek mylonite zone, and at the southern end the D2 decollement of Farrar (1985b) and the Rolesville granite. On the east it is bounded by the Hylas mylonite zone, then a complex interfingering of mylonites (Fig. 2) that eventually becomes the Hollister mylonite zone, then to the D2 decollement that is cut by the Castalia and Rolesville granites on the south. A convenient subdivision between the two portions of the terrane would be the Lake Gordon to Hylas mylonite zone, which others speculate, separates Goochland terrane from speculative extensions to the south.

James River Traverse

Where first defined along the James River traverse (Fig. 3), the Goochland Terrane comprises, in structural succession, the State Farm Gneiss, Sabot

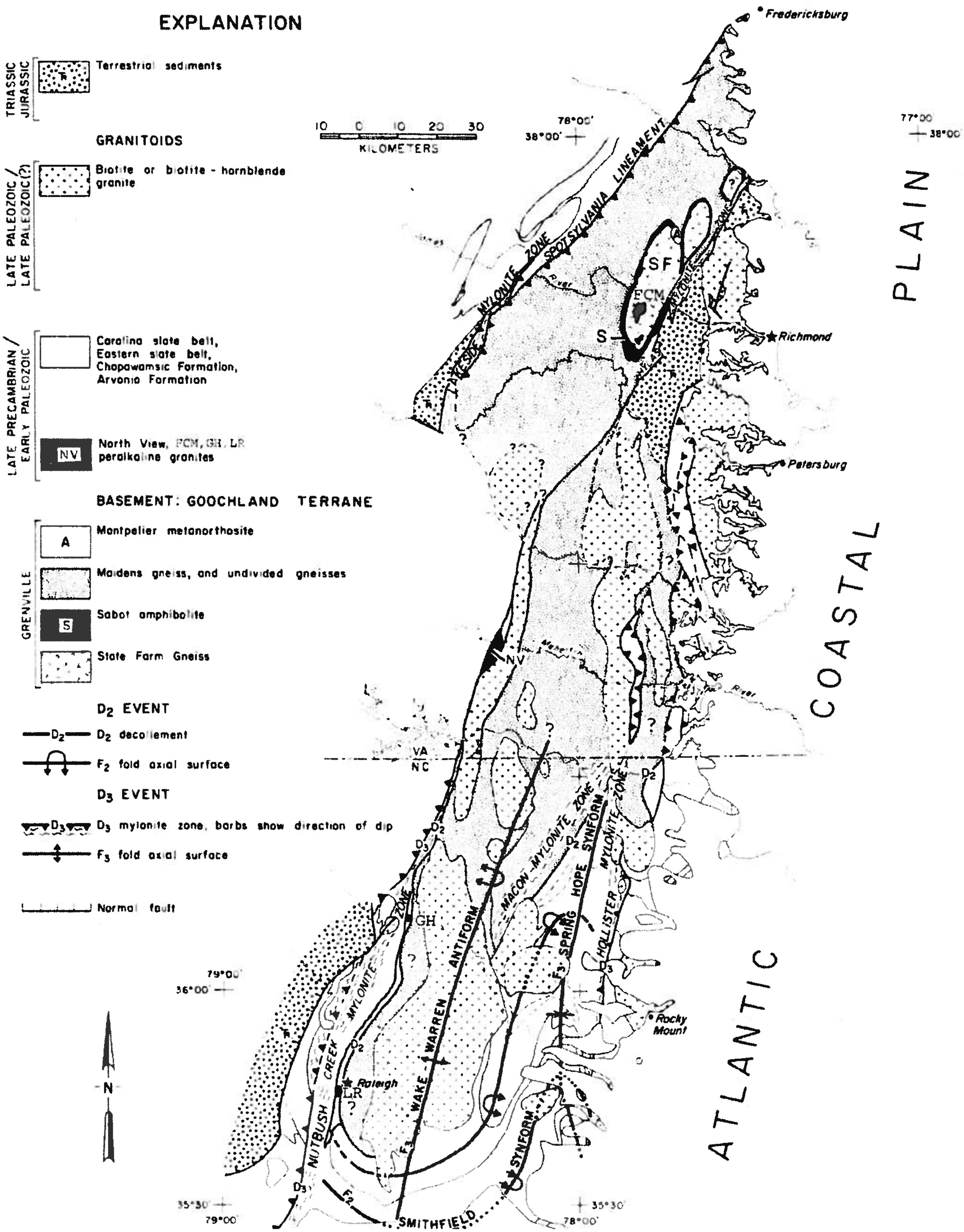
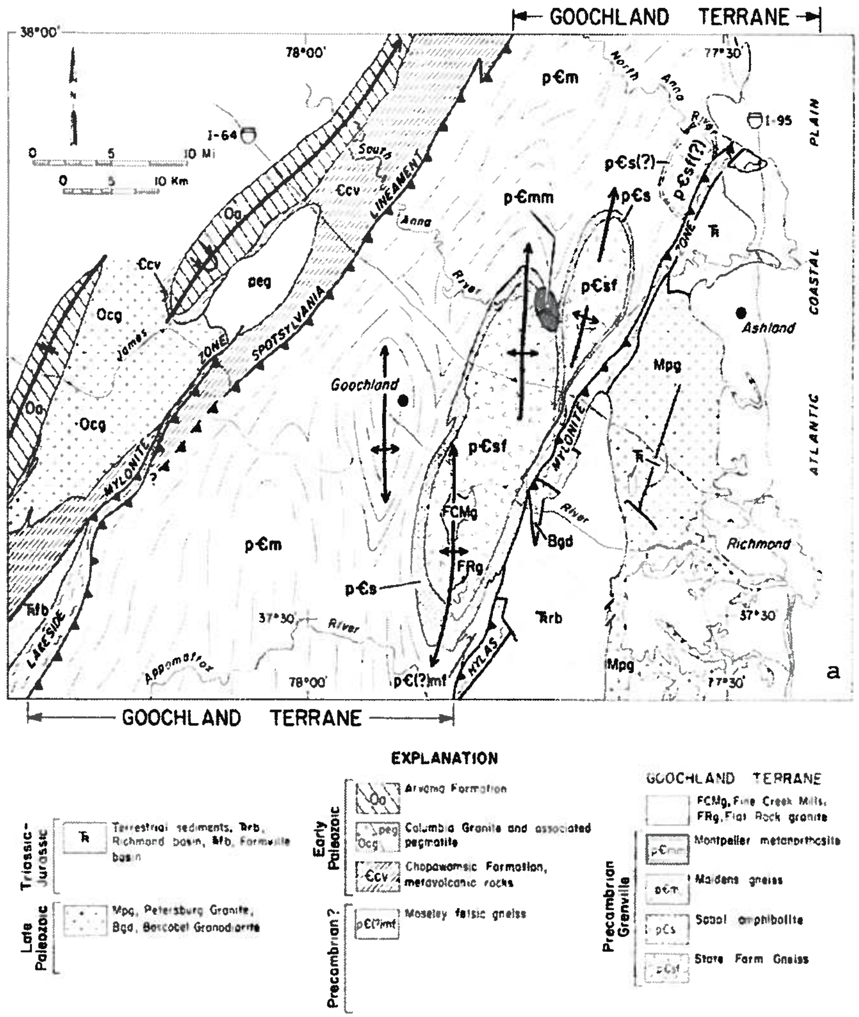


Figure 2. Geologic map of the Goochland terrane, modified from Farrar (1984; 1985b).



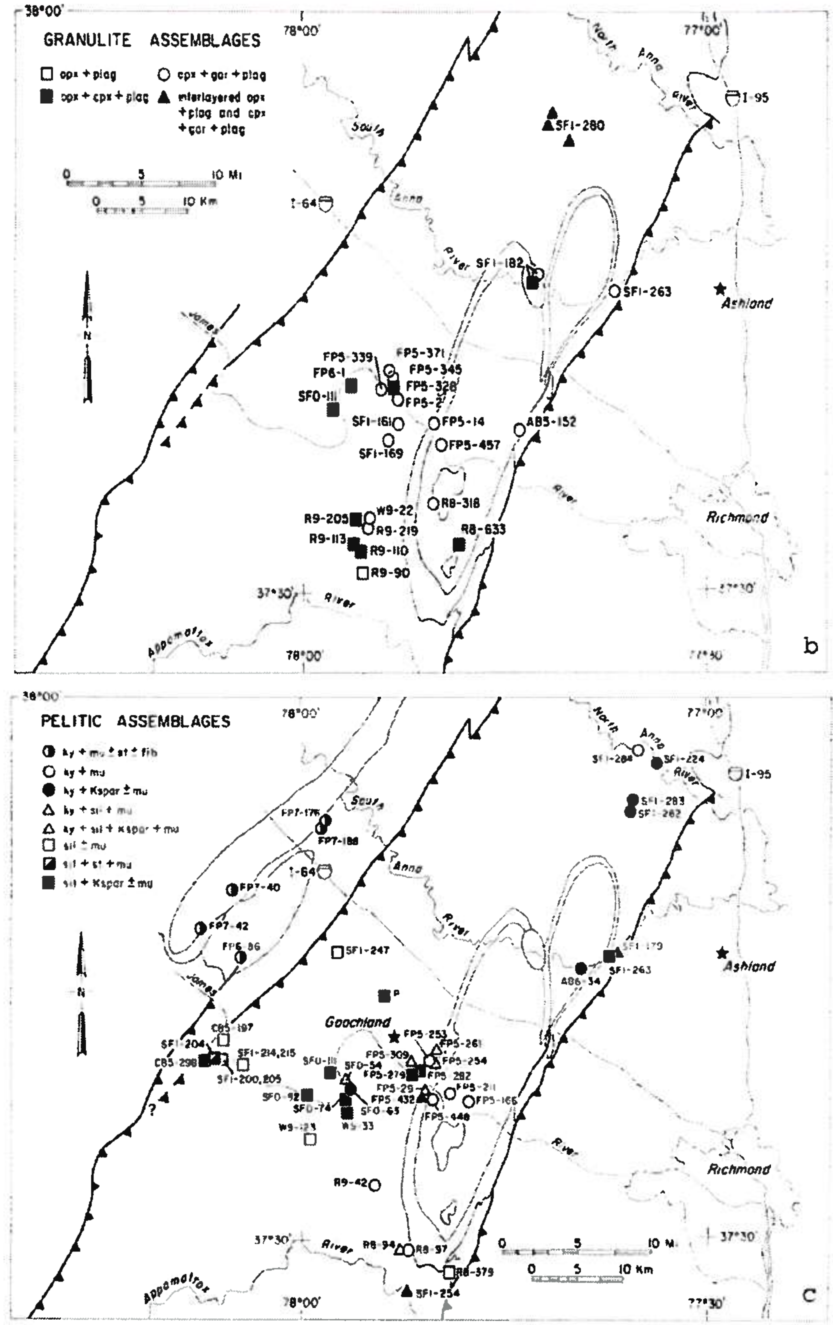


Figure 3. (a) Geologic map of the James River traverse; (b) distribution of granulite assemblages; and (c) distribution of pelitic assemblages used to define the areal extent of the Goochland terrane in the area of the James River traverse. Modified from Farrar (1984).

Amphibolite, and Maidens Gneiss (Glover and Tucker, 1979). The State Farm is a meta-intrusive complex of dominantly granodiortic to granitic composition, with small gabbroic bodies and minor included lenses of pelitic gneiss. Where least deformed it has relict coarse intrusive textures. The Sabot is dominantly a sheet-like body of hornblende-plagioclase amphibolite with varying amounts of augite and garnet. Similar, less extensive sheets of amphibolite occur in the structurally overlying Maidens. The Maidens Gneiss is an extensive and variable map unit that should eventually be further subdivided. It comprises pelitic gneiss, biotite-quartz-plagioclase gneiss, biotite-hornblende-quartz-plagioclase gneiss, orthopyroxene-bearing intermediate-to-mafic gneisses, hornblende-plagioclase amphibolite, biotite granitic gneiss, clinopyroxene-plagioclase calcsilicate rock, minor marble, and minor quartzite.

State Farm Gneiss

The state Farm Gneiss (Brown, 1937; Poland, 1976; Reilly, 1980) (Figs. 2; 3) is medium- to coarse-grained, massive to moderately layered, and variably foliated. Much of it is a biotite-garnet-hornblende-quartz-Kfeldspar-plagioclase gneiss. Modal analyses by Reilly (1980) give ganodiorite to tonalite compositions and small gabbroic bodies have been found. It would appear that the map unit comprises several intrusive bodies with a range of compositions, with narrow screens of pelitic gneiss and schist caught between the plutons. Where least deformed, the gneiss is massive and coarse-grained with some granulite facies assemblages preserved. Elsewhere, the granulite pyroxene is pseudomorphically replaced by hornblende+quartz+/-garnet+/-biotite.

The Grenvillian whole-rock Rb/Sr age of 1031+/-94 Ma (Glover et al., 1982) has recently been confirmed by U-Pb zircon geochronology. Three samples from the main State Farm Gneiss dome, which span a range from 57 to 75 wt. % SiO_2, yield upper intercept ages of ~1039 Ma, ~1046 Ma, and ~1022 Ma, respectively (Owens and Tucker, 1999, and unpublished results). These ages are interpreted as the time of crystallization of the igneous protoliths, which were broadly granitic in composition.

Sabot Amphibolite

The Sabot amphibolite (Poland, 1976; Reilly, 1980) structurally overlies the State Farm Gneiss complex. The Sabot is dominantly a medium- to coarse-grained hornblende-plagioclase amphibolite which in places has plentiful coarse-grained augite, partially replaced by hornblende. It has minor interlayers of quartz-biotite-plagioclase gneiss, quartz-feldspar leucogneiss, and thin pelitic gneiss layers. The main Sabot is in the form of a sheet 0.7-1.0 km thick, exposed around the periphery of the State Farm antiform and the subsidiary State Farm domes to the northeast (Figs. 2; 3). Thinner, less continuous amphibolite units in the structurally overlying Maidens Gneiss may be related in origin to the Sabot.

Maidens Gneiss

The heterogeneous Maidens Gneiss (Poland, 1976) structurally overlies the Sabot amphibolite. Lithologic variability, combined with structural complexity and lack of exposure combine to make subdivision difficult. However, eventually it will be subdivided into at least three units. (1) Immediately overlying the Sabot is a dominantly pelitic unit with subordinate amphibolite, dirty quartzite, and minor marble with associated calcsilicate layers. Minor peraluminous granite dikes are sillimanite-bearing. This unit surrounds each of the Sabot-ringed domes. Here this unit is called the Hewlett metapelite. (2) To the west of (above?) the pelitic unit lies a thick sequence dominated by biotite-hornblende-plagioclase gneiss and containing the most continuous preserved granulite assemblages of orthopyroxene-clinopyroxene granulite gneiss and clinopyroxene-garnet granulite gneisses. The type location Maidens cave exposure is dominantly biotite–hornblende–quartz-plagioclase gneiss. The best granulite exposures are referred to as the Old Bandana granulite. Although these gneisses dominate this part of the Maidens, there are pelitic interlayers. Some of these exposed along the James River have granulites and pelitic gneisses interlayered on a scale of 10's of centimeters. Coarse augen granitic gneisses and small marble pods surrounded by calcsilicate layers also occur in this unit. (3) The westernmost unit is dominated by a variety of biotite granitic gneisses, some relatively fine-grained, some with coarse augen. Interlayered with the granitic gneisses are subordinate layers of biotite-hornblende gneiss and pelitic gneiss.

There is no age control on the Maidens along the James River, but Horton et al.(1995) report an igneous zircon age of 1035+/5 Ma on a hornblende-biotite granitoid gneiss in the Maidens 20 km southwest of the State Farm dome, near Amelia Court House.

Montpelier Anorthosite

The Montpelier anorthosite is a small massif of alkalic anorthosite, dominated in its igneous assemblage by antiperthite in very large, blocky crystals up to at least 40 cm in length (referred to by collectors as moonstone) with accompanying concentrations of coarse quartz with smokey rims. In much of the body ilmenite, and its metamorphic byproducts rutile and titanite, are the only mafic minerals. Elsewhere, there are mafic clots of very large augite, hypersthene, ilmenite, biotite, and apatite, with their accompanying metamorphic biotite, hornblende, garnet, rutile, and titanite.

Most of the Montpelier anorthosite body was strongly deformed and recrystallized under granulite facies conditions and again, later, under amphibolite facies conditions. There was major grain-size reduction with the creation of a strongly layered anorthositic gneiss from the originally massive body. This layering was isoclinally folded and refolded into complex fold interference patterns. With recrystallization, the feldspar formed separate oligoclase and microcline grains, the quartz was flattened into lenses, and the mafic minerals recrystallized to smaller biotite, hornblende, garnet, rutile and titanite.

Aleinikoff et al. (1996) describe this anorthosite and the dating of one very large zircon and smaller zircons collected from crushing of this anorthosite, giving a crystallization age of 1045 +/- 10 Ma for the anorthosite. Age of Grenville metamorphism, and age of late Paleozoic cooling are discussed below.

Despite its small size, the Montpelier anorthosite is significant in that it appears to have one of the most evolved compositions of any anorthosite on earth (or any other planet!). Specifically, whole-rock analyses show that Montpelier feldspars are unusually alkalic (~$An_{26}Or_{21}$), and it is the most potassic anorthosite yet recognized (Fig. 4a). Figure 4a also shows that Montpelier is more evolved than the Roseland, Virginia anorthosite (located in the Blue Ridge), but that both are enriched in alkalis relative to other anorthosites in the Grenville Province of Quebec. In addition, Figure 4b shows that Montpelier is probably the most Ba-rich of all anorthosites, consistent with its high K. The Roseland body also contains high Ba, but levels of Sr in Roseland and Montpelier are more like those at St. Urbain rather than the unusually Sr-rich Labrieville massif. Collectively, the atypical compositional similarities shared by Montpelier and Roseland suggest some common source characteristics or petrogenetic process. in their origin. Furthermore, Montpelier and Roseland are essentially the same age (~1045 Ma). Thus, these anorthosites seem to provide a link, albeit poorly understood, between the Goochland terrane and Laurentia (as represented by the Blue Ridge Grenville).

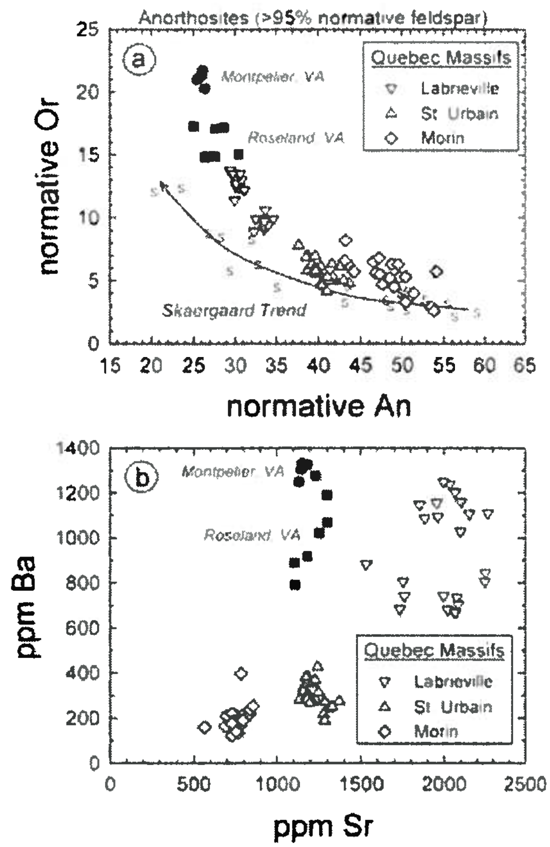


Figure 4. (a) A plot of whole-rock normative An vs. Or for anorthositic rocks of the Montpelier (filled circles) and Roseland (filled squares) anorthosites compared with data for the Labrieville, St. Urbain, and Morin massifs of Quebec [sources of data: Owens and Dymek (1999); Owens and Dymek (2001); and Owens and/or Dymek, unpublished results]. Also shown for reference are whole-rock compositions and a generalized trend arrow for the Skaergaard Intrusion, Greenland (data from McBirney, 1989). The two most evolved samples in the Skaergaard are from the sandwich horizon. (b) A plot of ppm Sr vs. ppm Ba in the same samples as in (a).

Late Proterozoic Granites

Several late Proterozoic granites have been found to intrude the State Farm Gneiss: the Fine Creek Mills, Flat Rock (Fig. 2, 3), and several smaller granitic plutons. The Fine Creek Mills and Flat Rock granites (Reilly, 1980) are medium- to coarse-grained, Kfeldspar rich, biotite or hornblende granites with accessory allanite, garnet, and fluorite. All of these granites are metaluminous, but they display the distinctive chemical signatures of A-type granites, including high Fe/Mg and Ga/Al, and high concentrations of Nb, Y, Zn, etc (see Discussion below). They are clearly intrusive into the State Farm Gneiss, and have a strong lineation to foliation imprinted on them in later tectonic events. New U-Pb zircon results for the Fine Creek Mills pluton indicate an age of ~629 Ma (Owens and Tucker, 2000). Similar results for the Flat Rock pluton and several other unnamed small bodies within the main State Farm Gneiss dome suggest widespread granitic magmatism in this area during the late Proterozoic (Owens and Tucker, unpublished results).

Meherrin River Traverse (Southern Goochland Terrane)

Farrar (1985a, 1985b) suggested that the interior of the Raleigh metamorphic belt comprises a southern continuation of the Goochland terrane. The rocks of this part of the Goochland terrane are characterized by an early, high grade event, evidence for which is lacking in the surrounding Carolina terrane and Spring Hope terrane (Eastern slate belt and outer Raleigh belt) rocks. Other workers (see Sacks, 1999, and references therein) prefer to refer to this as the Raleigh terrane. Farrar (1985a) subdivided this region into the Macon formation and the Raleigh gneiss. A third unit, Farrar's (1985a) Littleton gneiss lies along the eastern edge of the terrane and will not be visited or discussed further here. This terminology will be used in this guide, in that there appear to be no significant boundaries separating these rocks in southern Virginia from those described in North Carolina by Farrar (1985a).

Raleigh Gneiss

The Raleigh gneiss (Farrar, 1985a), described by Parker (1979) as Injected Gneisses and Schists, comprises layered biotite gneiss, biotite-hornblende gneiss, hornblende-clinopyroxene-quartz-plagioclase gneiss, amphibolite, minor pelitic gneiss and schist, and quartzite. Coarse-grained, gneissic, biotite granite dikes commonly parallel or cut gneissic layering at a low angle. In the Raleigh area, the unit is clearly dominated by the biotite gneiss and biotite hornblende gneiss with subsidiary hornblende-plagioclase amphibolite. In southern Virginia, the biotite gneiss and biotite-hornblende gneiss are more commonly accompanied by hornblende-clinopyroxene-quartz-plagioclase gneiss.

The contact between the Raleigh gneiss and adjacent Macon Formation is quite sharp but commonly interfingers as a result of large-scale isoclinal folds with axial planes approximately parallel to the NNE trend of the contact.

Macon Formation

The Macon formation (Farrar, 1985a) in North Carolina comprises pelitic schist and muscovite-biotite granitic gneisses. The schist consistently has textural and mineralogical evidence of an early sillimanite or sillimanite-Kfeldspar high-grade assemblage, but has been very much rehydrated to assemblages that range from greenschist to lower amphibolite facies. The granitic gneisses probably represent granitic intrusions into a pelitic pile, but the entire package has been very strongly deformed. The granitic rocks texturally range from protomylonites to ultramylonites and interlayered pelitic rocks are, in many cases, phyllonites. These textures are found in part because there are at least two generations of mylonites in this area: (1) the mylonites, later recrystallized, that are associated with the D2 decollement (Fig. 2); and (2) mylonite of the very wide Macon mylonite zone, and smaller zones which also cut the Macon formation.

Deformation is somewhat less intense in some of the Virginia portion of the Macon formation, and some of the early mineral assemblages are better preserved here.

Late Proterozoic(?) Granites

Along the western border of the Goochland terrane with the Carolina terrane, there are at least three peralkaline granite plutons, from north to south, the North View, Green Hill, and Lake Raleigh.

The North View pluton, in southern Virginia, lies along the border between the Goochland terrane, to the east, and the Carolina terrane to the west (Fig. 2). It is separated from the Goochland terrane proper by the late Paleozoic Buggs Island granite. The North View is roughly lenticular in plan view and is texturally and, to some extent, mineralogically zoned. Mylonite zones bound it on all sides, and thus its intrusive relationships are not clear. The North View has been overprinted by a greenschist or amphibolite facies metamorphic event that resulted in substantial recrystallization of the granite with the formation of a foliation of variable strength. Exposures of medium-grained North View granite cut by mylonite zones indicate that most of the western and eastern edges of the pluton have been cut off. The northern and northeastern boundaries of granite are porphyritic with a fine-grained or granophyric groundmass. Although also cut by mylonites, these exposures must be very close to the pluton's intrusive contact. The least deformed texture of the pluton interior is a medium-grained, light gray, hypersolvus, peralkaline granite, texturally characterized by blocky mesoperthitic feldspar with a slightly finer-grained groundmass of quartz, aegirine (Fig. 5a), riebeckite (Fig. 5b), and magnetite (Bentley, 1992). Accessory minerals include fluorite, Y-bearing garnet, and a Y-carbonate. The hypersolvus nature of this granite, combined with its fine-grained to granophyric border facies indicate that it was a very shallow intrusion. Horton et al. (1999) determined a U/Pb zircon age of 571 ± 5 Ma for the North View granite.

Two peralkaline granite masses have been found in what has been described (Farrar, 1985a) as the Falls leucogneiss, which borders most of the North Carolina portion of the Raleigh gneiss on the west. Over most of its length, the Falls has been described as a leucocratic biotite or magnetite granite with a strong foliation or lineation. Two bodies within the Falls are mineralogically peralkaline granites (Fig. 5). The Green Hill granite is fine-grained, and strongly foliated or lineated. Quite thorough recrystallization has resulted in most of the perthite recrystallizing to separate microcline and albite, but relict mesoperthite is preserved. Mafic minerals include aegirine-augite (Fig.5a), riebeckite (Fig. 5b), magnetite, and Y-bearing garnet. The Lake Raleigh granite has very similar feldspars, and mafic minerals include aegirine (Fig. 5a) and magnetite. The development of the strong foliation and lineation of these bodies has destroyed evidence of their igneous textures.

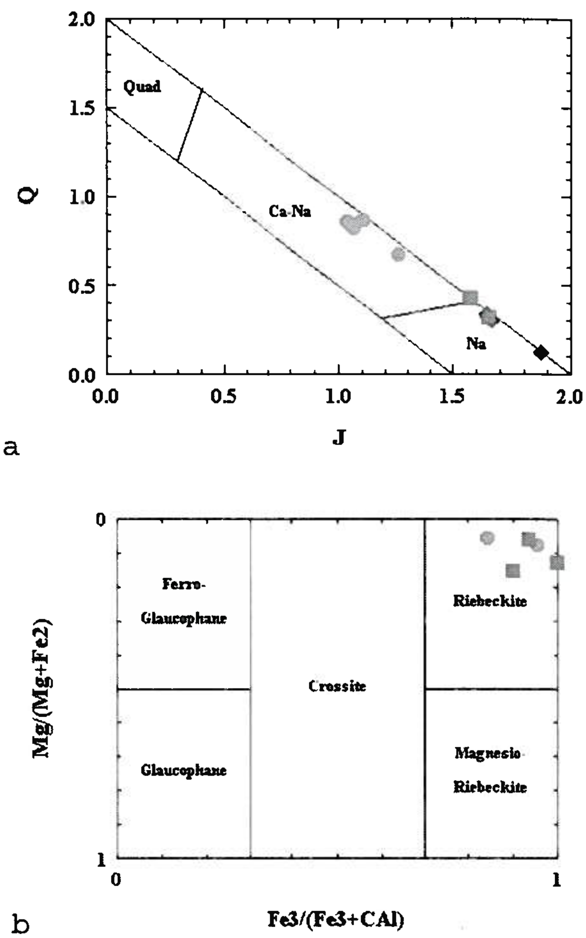


Figure 5. (a) Q-J plot for sodic pyroxenes. Na are aegirine and Ca-Na are aegirine-augite. Squares are North View; circles are Green Hill; diamonds are Lake Raleigh. (b) Classification of sodic amphiboles. Squares are North View; circles are Green Hill.

METAMORPHISM

Metamorphic Event I

The James River traverse rocks were metamorphosed to granulite facies (Fig. 3b), as described by Farrar (1984). There are granulite assemblages preserved within the State Farm Gneiss, Sabot Amphibolite, Maidens Gneiss, and Montpelier Anorthosite that document this event. Distribution of orthopyroxene and clinopyroxene+garnet assemblages are shown in Figure 3 and pyroxene compositions are shown in Figure 6. As described above, the most plentiful granulite assemblages are found in the central unit of the Maidens Gneiss, which is described here as the Old Bandana granulite. In pelitic compositions this granulite event is represented by coexisting Kfeldspar and sillimanite (Fig. 3c). The only inconclusive area in the northern Goochland Terrane is the northeastern-most pelitic unit (the Hewlett metapelite of the Maidens), where no preserved sillimanite has been found.

The Meherrin River traverse rocks were metamorphosed to high metamorphic grade (probably granulite facies). In the Union Mill area of the Raleigh gneiss (Stops 9, 10), assemblages of hornblende-augite-quartz-plagioclase probably represent this metamorphic event. In the Macon metapelite surviving assemblages of garnet-sillimanite-Kfeldspar represent this

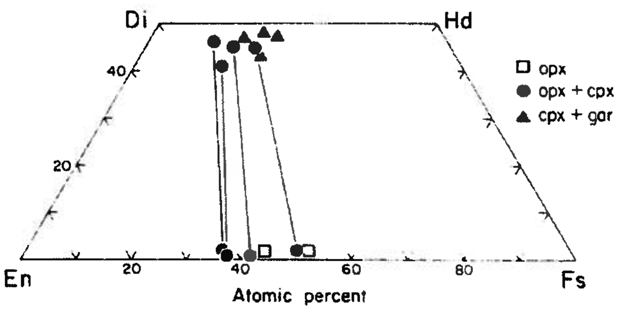


Figure 6: James River traverse pyroxenes; tie lines connect coexisting pyroxenes. Modified from Farrar (1984).

event. Although the sillimanite and Kfeldspar are not commonly preserved in contact, they are preserved in the same rock, separated by retrograde minerals. Examples of the relict pyroxene gneisses and sillimanite-bearing pelitic rocks are shown in Farrar (1985a; 1985b) and Stoddard et al.. (1987).

Metamorphic Event II

The James River traverse rocks have been overprinted by a second, amphibolite facies metamorphic event. Orthopyroxene and clinopyroxene have, in large part, been replaced by hornblende and biotite (Farrar, 1984). Pelitic gneisses with sillimanite+Kfeldspar have commonly been recrystallized to muscovite+kyanite+/-staurolite. In many individual samples the sillimanite and Kfeldspar have been completely removed, but, as seen in Figure 3, sillimanite survives in some samples across the entire traverse except the northeastern corner, near Hewlett (see Stop 1), where kyanite+Kfeldspar$\pm$muscovite is found. Probably the kyanite has replaced sillimanite in this assemblage, but no relict sillimanite survives. If the kyanite+Kfeldspar were a stable assemblage, it would represent much higher temperature and pressure than is found in the rest of the region for the second metamorphic event.

The Meherrin River traverse shows a greenschist to lowermost amphibolite facies second event. Pyroxene-bearing assemblages show major replacement by epidote+chlorite+actinolite at greenschist facies and hornblende at amphibolite facies. Pelitic gneiss shows major replacement by muscovite+chlorite+/- chloritoid at greenschist facies and staurolite at lower amphibolite facies. These replacements are essentially the same as found in the North Carolina part of the terrane (Farrar, 1985a; 1985b).

DISCUSSION-CONCLUSIONS

The Goochland Terrane was defined (Farrar, 1984) by the presence of the granulite, and assumed granulite, assemblages of metamorphic event I described above. This terrane is separated from adjacent terranes by a combination of Mesozoic normal faults, Alleghanian mylonite zones (Hylas zone, Lakeside zone, Nutbush Creek zone, Hollister zone) and recrystallized pre-Alleghanian mylonite zones (Spottsylvania lineament, D2 decollement) (Fig. 2). At its southern terminus in North Carolina the Alleghanian Rolesville and Castalia granites cut the D2 decollement. In Virginia the Burkville granite may also cut the boundary.

Evidence of Grenvillian Intrusions into and Metamorphism of the Goochland Terrane

The Goochland terrane was interpreted to be Grenville in age based on the Grenvillian whole-rock Rb/Sr age of 1031+/- 94 Ma (Glover et al., 1982) for the State Farm Gneiss, the similarity of the Montpelier Anorthosite to the Grenville Roseland Anorthosite of the Virginia Blue Ridge, and the fact that these rocks, and none of the surrounding terranes had been metamorphosed to granulite facies. The Grenville age of the State Farm Gneiss has recently been confirmed by U-Pb zircon geochronology. Specifically, three samples from the main State Farm gneiss dome, which span a range from 57 to 75 wt. % SiO_2, yield upper intercept ages of ~1039 Ma, ~1046 Ma, and ~1022 Ma, respectively (Owens and Tucker, 1999, and unpublished results). These ages are interpreted as the time of crystallization of the igneous protoliths, which were broadly granitic in composition. In addition, these ages indicate that the State Farm protoliths were approximately coeval with the ~1045 Ma crystallization age of the Montpelier anorthosite, as dated by Aleinikoff et al. (1996). The Grenvillian age of this terrane is further supported by the report of an igneous zircon age of 1035$\pm$5 Ma (Horton et al., 1995) on a hornblende-biotite granitoid gneiss in the Maidens Gneiss southwest of the State Farm dome.

Also, Aleinikoff et al. (1996) determined a metamorphic zircon age of 1011$\pm$2 Ma for the Montpelier Anorthosite. We interpret this metamorphic age to also apply to the rest of the contiguous Goochland terrane, in that a younger granulite event would have resulted in a younger metamorphic age.

The atypical compositional similarities shared by

Montpelier and Roseland anorthosites (described above) suggest some common source characteristics or petrogenetic process in their origin. These chemical characteristics, plus the fact that the Montpelier and Roseland are essentially the same age (~1045 Ma), combine to suggest that these anorthosites provide a link, albeit poorly understood, between the Goochland terrane and not just Laurentia in general, but specifically that part exposed in the Virginia Blue Ridge.

Late Proterozoic A-type Granites and Rifting

An interesting feature of the State Farm Gneiss zircon results (Owens and Tucker, 1999) is that all samples define discordia with lower intercepts of ~600 Ma, reflecting Pb loss or new metamorphic zircon growth in the late Proterozoic. This late Proterozoic "event" in the Goochland terrane can now be correlated with emplacement of several granitic plutons, including the Fine Creek Mills and Flat Rock granites. New U-Pb zircon results for the Fine Creek Mills pluton indicate an age of ~629 Ma (Owens and Tucker, 2000). Similar results for the Flat Rock pluton and several other unnamed small bodies within the main State Farm gneiss dome suggest widespread granitic magmatism in this area during the late Proterozoic (Owens and Tucker, unpublished results). However, the zircon systematics for all samples are complex in that most fractions plot near the lower end of discordia, and show variable amounts of Grenvillian (~1 Ga) inheritance. These results probably indicate that the late Proterozoic granites were derived from Grenvillian crust, either the State Farm gneiss or an equivalent Grenville-age source.

Some insights into the tectonic setting of this late Proterozoic magmatism can be gained from the chemical characteristics of the granites. All are metaluminous, but they display the distinctive chemical signatures of A-type granites, including high Fe/Mg and Ga/Al, and high concentrations of Nb, Y, Zn, etc. (Fig. 7). Thus, these granites share somecompositional features with the late Proterozoic Robertson River igneous suite in the Blue Ridge, interpreted to represent a failed episode of Laurentian rifting at ~735-702 Ma (Tollo and Aleinikoff, 1996).

The North View, Green Hill, and Lake Raleigh peralkaline granites, which border the southern Goochland terrane on the west, share petrographic similarities to the peralkaline members of the Robertson River suite as well. The only age control for this group is the U/Pb zircon age of 571±5 Ma for the North View

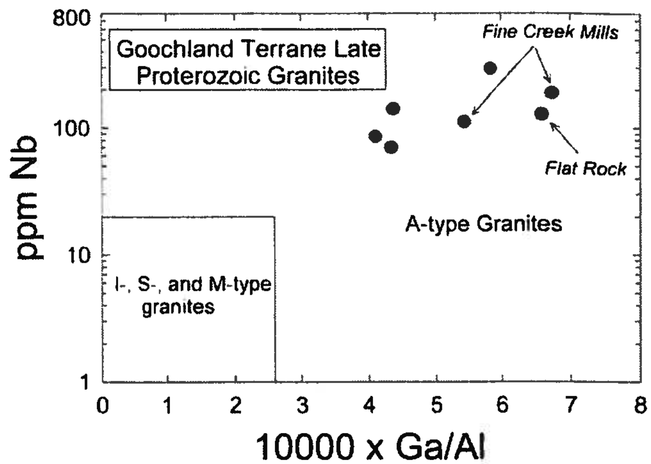


Figure 7. A plot of 10000 x Ga/Al vs. ppm Nb for Late Proterozoic granites in the Goochland Terrane. Unlabelled points represent analyses from small unnamed bodies. Diagram modified from Whalen et al. (1987).

granite (Horton et al., 1999).

A plausible interpretation for all of these A-type to peralkaline granites of the Goochland Terrane is that they also reflect late Proterozoic rifting. Although their ages are ~100 Ma younger than the Robertson River and Crossnore suite of granites of the Blue Ridge, interestingly, the ~600±30 Ma ages for the Goochland A-type granites are just slightly older than reported ages (~570 Ma) for the Catoctin metabasalts and metarhyolites in the Blue Ridge, which are thought to represent successful Iapetan rifting of Laurentia (Badger and Sinha, 1988; Aleinikoff et al., 1995). As for the alignment of the North View, Green Hill and Lake Raleigh plutons along the edge of the exposed Goochland terrane, it is quite reasonable to expect that they would intrude along extensional fractures in the thinned edge of the Laurentian craton, and that this fracture could be reactivated by later faulting.

Alleghanian Age of Metamorphic Event II

How many metamorphic events occurred during the Paleozoic in this terrane is not known. It is known that there were a number of Alleghanian granitic intrusions into the southern part of this terrane, and along its eastern boundary, and that these were emplaced at moderate depth. It has been shown that late Alleghanian cooling marked the end of metamorphism in the Raleigh belt of the North Carolina portion of the terrane (Russell et al., 1985) and that cooling was of a similar age (late Alleghanian) in the James River traverse (Gates and Glover, 1989; Aleinikoff et al., 1996).

Conclusion

Petrographic, geochemical and geochronologic evidence gathered in the last few years support the tectonic model of the Goochland Terrane as part of the tectonically thinned, rifted margin of Laurentia, intruded by A-type granites at about the time of successful rifting (~ 600 Ma). It probably remained part of Laurentia and was clipped off the margin and thrust up onto the continent with accreted terranes during Paleozoic compressional mountain building. Evidence available at this time suggests, but does not prove, that the southern Goochland terrane had the same tectonic history.

FIELD TRIP STOPS

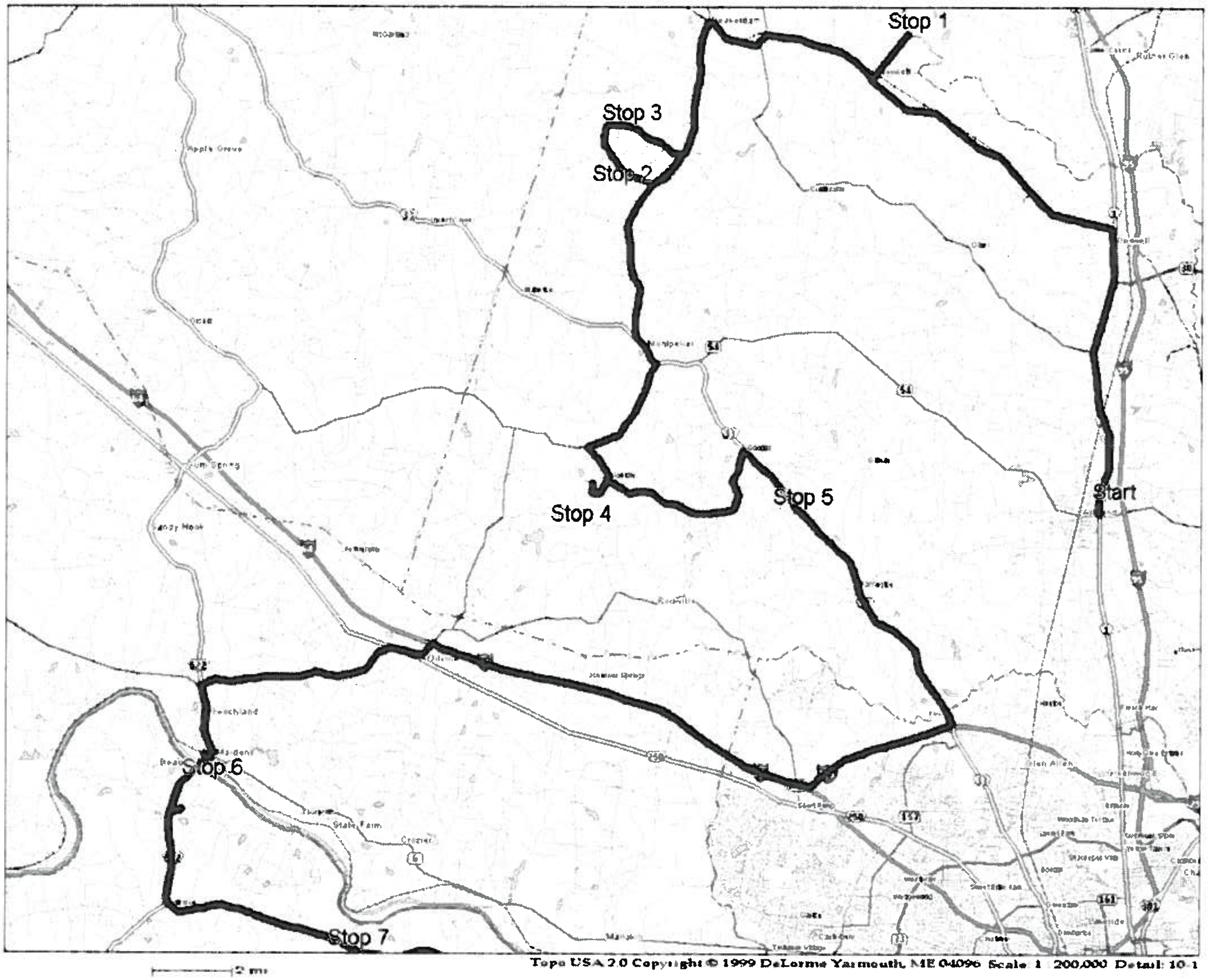


Figure 8. Field trip stops for Day 1.

DAY 1: TUESDAY APRIL 3

Stop 1. Hewlett metapelite of the Maidens Formation. Extensive exposures in the North Anna River at Butlers Bridge on CR 601 in the Hewlett quadrangle

Ledges in and adjacent to the river expose gently dipping, strongly layered, coarse-grained, pelitic gneiss. The assemblage biotite-plagioclase-garnet-kyanite-quartz-Kfeldspar is clearly identifiable in outcrop and thin section. Careful examination of thin sections has shown minor late-forming muscovite, which can also be seen concentrated along fractures in outcrop.

In this northeastern part of the Goochland terrane the pelitic gneiss consistently shows coexisting kyanite-Kfeldspar with no direct evidence of the preexisting sillimanite that is found in the pelitic gneisses to the west and south in the terrane. One of the challenges in working with these rocks is to eventually determine whether kyanite and Kfeldspar were a stable association in these rocks, and if so, whether this was in the Grenville event or the later Paleozoic metamorphism (Compare to Stop 5).

Stop 2. Old Bandana granulite. The outcrop is in a small meadow and streambed north of CR 733 at Tanyard Creek in the Beaverdam quadrangle. Get homeowner's permission to go on property.

The granulite gneiss is tan-weathering, fine-grained, thin-layered, with isoclinally refolded small-scale folds with axial planar foliation dipping steeply. The dominant gray, tan-weathering, gneiss shows biotite, quartz, and plagioclase, with minor garnet and a few grains of hypersthene large enough to be visible in outcrop. Subordinate green-gray layers comprise hornblende, garnet, augite, quartz, and plagioclase. Minor coarse-grained biotite granite dikes cut the gneiss at a low angle to foliation.

Stop 3. Old Bandana granulite. The small outcrops are along Roan Horse Creek north of CR 608 in the Beaverdam quadrangle.

Thin sections of this granulite (SF1-280; SF1-280-2) are described in Farrar (1984). SF1-280-2 is fine-grained bio-opx-qtz-plag gneiss with accessory apatite. SF1-280 is bio-hbd-cpx-gar-qtz-plag gneiss with accessory scapolite, titanite, opaque, and apatite. Both samples retain their granulite assemblages with little evidence of retrogression. The rock here and at Stop 1 is representative of the best preserved granulite assemblages in the Goochland terrane. Several samples of this have been almost completely anhydrous. In fresh exposures, the thin layered, hard, slabby gneiss rings like a bell on sampling.

Stop 4. Montpelier Anorthosite. Active quarry operated by U.S. Silica, at Gouldin in the Montpelier quadrangle. Visit only with prior permission. Hard hat required

The Montpelier anorthosite is a small massif of alkalic anorthosite, dominated in its igneous assemblage by an antiperthite in very large, blocky crystals that are up to at least 40 cm in length (referred to by collectors as moonstone) with accompanying concentrations of coarse quartz with smokey rims. In much of the body ilmenite, and its metamorphic byproducts rutile and titanite, are the only mafic minerals. Elsewhere, there are mafic clots of very large augite, hypersthene, ilmenite, biotite, and apatite, with their accompanying metamorphic biotite, hornblende, garnet, rutile, and titanite. There are also rare, apparently rounded enclaves of pyroxenite, where the pyroxenes show multiple generations of complex exsolution.

Most of the Montpelier anorthosite body was strongly deformed and recrystallized under granulite facies conditions, with further deformation later under amphibolite facies conditions. Recrystallization resulted in major grain-size reduction with the creation of a strongly layered anorthositic gneiss from the originally massive body. This layering was isoclinally folded and refolded into complex fold interference patterns that can be seen in some of the large quarry blocks. The transition from coarse to recrystallized was exposed over a distance of about a meter in a quarry wall, but can now apparently only be seen in loose blocks. With recrystallization, the feldspar forms separate oligoclase and microcline grains, there is flattening of the quartz into lenses and the mafic minerals are now mostly stringers of biotite, hornblende, garnet, rutile and titanite.

Large xenoliths of various weathered country rock gneisses and amphibolite are also exposed around the quarry. There is ongoing debate about whether these gneisses represent State Farm, Sabot, Maidens, or a combination of these units. Quarry walls also show two generations of basaltic dikes cutting the anorthosite. One generation is metamorphosed (apparently post-granulite) and now has an amphibolite assemblage. The second is post-metamorphic diabase, and may be related to other nearby Mesozoic dikes.

The recrystallized anorthosite, which is referred to locally as "aplite" is the preferred material for quarrying, and most of the active quarrying is of this unit. The large feldspars are difficult to crush, so the coarse unit is being avoided, and much of the coarse anorthosite is now buried under the conveyor belt system. Because this is an active quarry, the rock actually exposed varies from visit to visit.

Aleinikoff et al. (1996) describe this anorthosite and the dating of one very large zircon and smaller zircons collected from crushing of this anorthosite. Their interpretation of age of intrusion, age of Grenville metamorphism, and age of late Paleozoic cooling are discussed above.

Stop 5. Maidens metapelite. Outcrops on South Anna River at U.S. 33 bridge, Hanover Academy quadrangle. Metapelite outcrops on both sides of bridge.

This is typical of the metapelites of the Maidens that show evidence of two metamorphic events. Event 1 (granulite event) produced an assemblage of biotite-plagioclase-quartz-garnet-sillimanite-perthitic Kfeldspar. Event 2 converted some of the sillimanite+ Kfeldspar to muscovite + kyanite. All of these minerals are now present in this rock.

To the west, within 1 km along a fishing trail which follows the river, there are exposures of several other rock types of the Maidens, including: fine grained peraluminous granite layers which contain sillimanite; dirty quartzite with pelitic interlayers; garnet-diopside-plagioclase-scapolite calcsilicate; diopside-rich marble; and clinopyroxene-bearing amphibolite.

This metapelite, overlying the Sabot amphibolite, appears to be a major map unit and is continuous with the Hewlett metapelite of Stop 1. This unit, with granulite gneiss interlayers, also overlies the Sabot amphibolite along the James River to the west of the State Farm dome, and is interpreted to be the structurally lowest member of the Maidens Gneiss.

Stop 6. Maidens Formation granulite gneiss, biotite gneiss and biotite-hornblende gneiss. Maidens cave above railroad tracks east of Maidens, Goochland quadrangle.

This is the type locality of the Maidens Formation (Poland, 1976). This little rock overhang exposes thin layered, tan weathering, gar-biotite-hornblende-quartz-plagioclase gneiss, the dominate rock unit of the central part of the Maidens formation. This outcrop exposes a refolded isoclinal fold, illustrating the complex structures of this unit. Thin sections show that thin, green-gray layers have the same garnet-clinopyroxene-hornblende-quartz-plagioclase assemblage found in the Old Bandana granulite. It is interpreted that this is a retrograde amphibolite facies gneiss formed from an Old Bandana-type granulite gneiss.

Stop 7. Fine Creek Mills granite. At Fine Creek Mills in the Fine creek Mills quadrangle. Get permission at house before visiting exposure that is in yard on both sides of Fine Creek.

Coarse-grained, foliated, hornblende - quartz-plagioclase - Kfeldspar granite is well exposed in pavements along Fine Creek. This ~629 Ma A-type granite is one of several which intrude the Grenvillian State Farm Gneiss (see Discussion above).

END OF DAY 1; DRIVE TO SOUTH HILL, VA FOR OVERNIGHT STAY

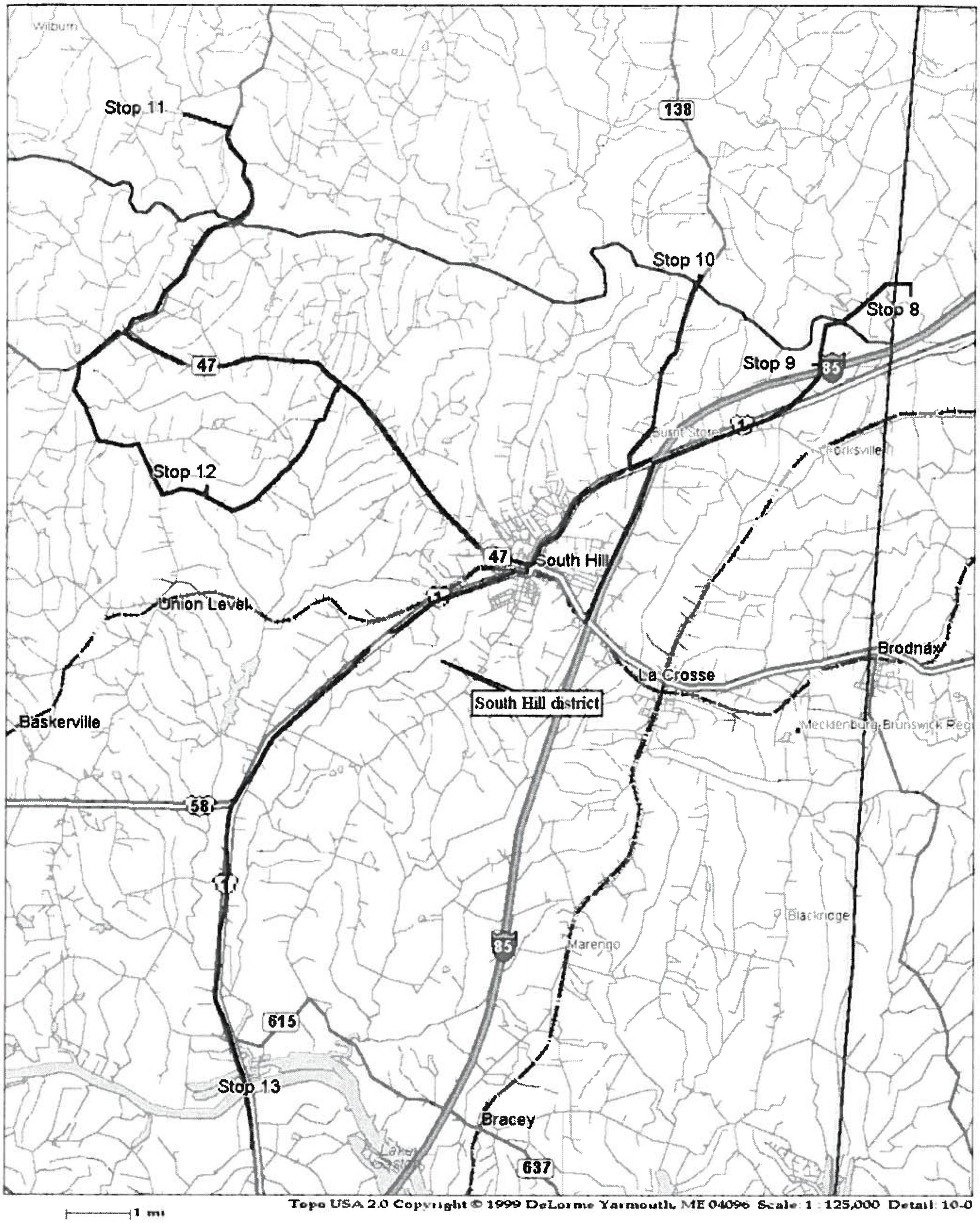


Figure 9. Field trip stops, Day 2 in the South Hill Virginia area., Goochland terrane.

DAY 2: WEDNESDAY APRIL 4

Stop 8. Macon metapelitic gneiss-schist. Forksville quadrangle, VA. Park beside CR 621, 0 .5 km east of Aaron Creek. Walk south to steep bank of Meherrin river (Fig. 9).

Steep bank has outcrop and large slabs of complexly folded coarse-grained pelitic gneiss which retains large porphroblasts of garnet, Kfeldspar, and sillimanite, including sillimanite crystals 1-2 cm in length, most of which have been pseudomorphically replaced by muscovite, but commonly retain sillimanite cores. Quartz-muscovite-feldspar pods appear to be the result of retrogression of assemblages produced by partial melting at the high grade of the sillimanite-producing event. The chlorite-muscovite-quartz retrograde assemblage in this area suggests greenschist facies for the second event, although approximately two km to the north the occurrence of staurolite indicates borderline amphibolite facies for this late event. This major pelitic map unit extends southward into North Carolina where it was described by Farrar (1985b) as the Macon formation. It potentially correlates to the north with the pelitic Maidens Gneiss, which we saw yesterday.

None of the plentiful Raleigh belt pelitic schists surrounding the Goochland terrane to the west, south, or east have this metamorphic sequence of early high-grade sillimanite-Kfeldspar gneiss followed by greenschist to amphibolite facies retrogression.

Stop 9. Union Mill Gneiss, within the larger unit mapped as Raleigh gneiss. Forksville quadrangle, VA. Small stream valley west of CR 621 immediately north of Interstate 85.

Thin-layered, tan, slabby, biotite - quartz-plagioclase gneiss and biotite – hornblende – quartz - plagioclase gneiss, with thin layers of green-gray hornblende – clinopyroxene – quartz - plagioclase gneiss. Coarse-grained, foliated, muscovite-biotite granite layers are later dikes, which can be found to cut isoclinally folded gneiss layers.

Stop 10. Union Mill gneiss. Forksville quadrangle, VA, west of CR 138, 200 m north of Union Mill bridge over the Meherrin River.

The Union Mill gneiss, very similar to Stop 9, comprises interlayered biotite-quartz-plagioclase gneiss, biotite-hornblende-quartz-plagioclase gneiss, and hornblende – clinopyroxene – quartz - plagioclase gneiss. These medium to fine-grained, thin-layered, and isoclinally folded gneisses are cut at low to high angles by later, coarse-grained biotite granite dikes which are generally a few cm to tens of cm thick. These granitic dikes are, themselves, commonly foliated and folded.

The gneisses are cut by a post-metamorphic porphyritic dike that is also exposed along this little creek. Similar dikes are plentiful in this area.

Stop 11. North View peralkaline granite. Roadcut on CR 655 at Mason Creek in the North View quadrangle.

The North View pluton lies along the border between the Goochland terrane, to the east, and the Carolina terrane to the west (Fig. 2). It is separated from the Goochland terrane proper by the late Paleozoic Buggs Island granite. The North View is roughly lenticular in plan view and is texturally and, to some extent, mineralogically zoned. Mylonite zones bound it on all sides, and thus its intrusive relationships are not clear. The North View has been overprinted by a greenschist or amphibolite facies metamorphic event that resulted in substantial recrystallization of the granite with the formation of a foliation that is variably developed in this exposure, which is in the pluton interior. The least deformed rock here is a medium-grained, light gray, hypersolvus, peralkaline granite, texturally characterized by blocky mesoperthitic feldspar with a slightly finer-grained groundmass of quartz, aegirine, riebeckite, and magnetite. To the north, closer to the pluton border, the grain-size becomes finer, the feldspar more clearly porphyritic, and the groundmass in some areas is a granophyric intergrowth of feldspar and quartz.

Aleinikoff et al. (1999) determined a U/Pb zircon age of 571 ± 5 Ma for the North View granite, using samples from this location.

Stop 12. Buggs Island Granite. Quarry north of CR 655, South Hill quadrangle, VA.

Brief stop at gate of quarry in the Buggs Island granite to observe mineralogy and texture of this Alleghanian, foliated, two-feldspar, subsolvus, biotite granite to contrast it texturally and mineralogically with the North View granite.

Stop 13. Raleigh Gneiss. Under the south end of U.S. Route 1 bridge over the Roanoke River, Bracey quadrangle, Virginia.

Thin-layered, biotite gneiss, biotite-muscovite gneiss, and biotite-hornblende gneiss of the Raleigh gneiss of Farrar (1985a). The layered gneiss here is typical of a range of compositions that can be found within the Raleigh gneiss. Exposures to the east, along the shores of Lake Gaston, show varieties very similar to the Union Mill gneiss of Stops 9 and 10.

Stop 14. Macon formation pelitic schist. Business U.S. 158, 2 km east of Warrenton, Warrenton quadrangle, NC (Fig. 10).

Retrograde pelitic schist of the Macon formation of Farrar (1985a). Relict sillimanite is preserved in a foliation cut by the retrograde assemblage chlorite-muscovite-chloritoid. The condition of this exposure is poor, but small slabs of the schist with very visible chloritoid porphyroblasts are plentiful.

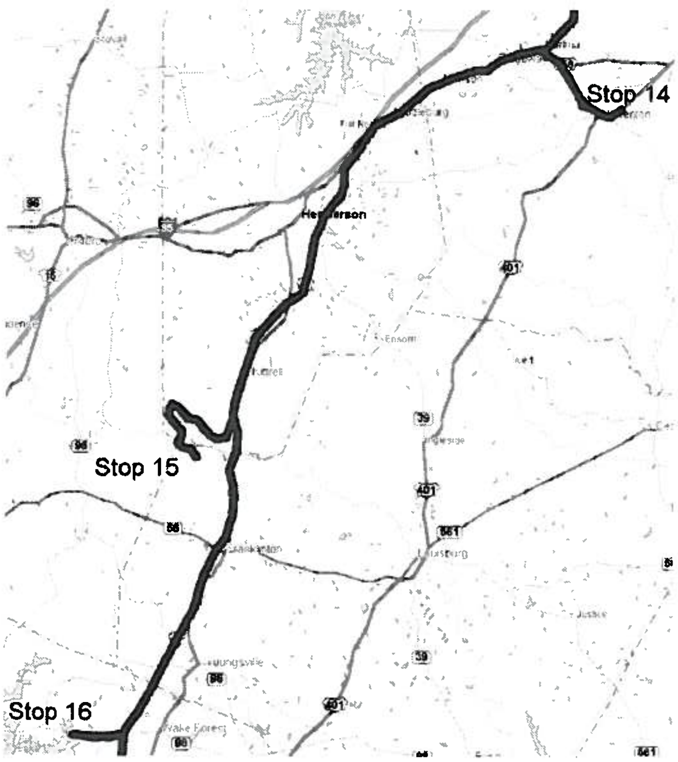


Figure 10. Field trip stops, Day 2 in the northern North Carolina Goochland terrane.

Stop 15. Green Hill peralkaline granite. Low roadcuts on both sides of Green Hill Road (CR 1203), 1 km south of the Tar River, Kittrell quadrangle, NC.

The Green Hill granite is a fine-grained, foliated and lineated magnetite+ riebeckite+ aegirine-augite+quartz+albite+microcline peralkaline granite with accessory Y-garnet and fluorite. The mafic minerals are generally too small to identify in outcrop, but the texture of the rock looks quite similar to the more strongly deformed parts of the North View. This exposure lies within the northern end of the Falls leucogneiss (Farrar, 1985a) and is very similar in mineralogy and texture to the Lake Raleigh granite near the southern end of the Falls leucogneiss - which we will not visit on this trip.

Stop 16 (Optional). If there is time, a brief stop will be made at a spectacular roadcut of Raleigh belt pelitic gneiss-schist on NC 98 west of Wake Forest.

This muscovite–biotite–staurolite–kyanite-quartz-plagioclase gneiss-schist, which lies outside the Goochland terrane, shows all indications of being a prograde mineral assemblage with no evidence, textural or mineralogical of an earlier sillimanite-bearing assemblage.

END OF FIELD TRIP: TRAVEL TO RALEIGH FOR WELCOMING PARTY OF THE 50th ANNUAL SE GSA MEETING.

ACKNOWLEDGMENTS

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