THE ORIGIN AND TECTONIC SIGNIFICANCE OF THE MAFIC-ULTRAMAFIC ASSOCIATION IN THE CENTRAL VIRGINIA BLUE RIDGE POST-GRENVILLE COVER SEQUENCE

by

Wendi R. Thompson

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APPROVED:

L. Glover, III, Co-Chairman

R.D. Law, Co-Chairman

B. Bekken

K.A. Eriksson

A.E. Gates

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Blacksburg, Virginia

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Dr. Lynn Glover, III, and Dr. Richard D. Law, Co-Chairmen

Department of Geological Sciences

(ABSTRACT)

The question of whether the mafic and ultramafic rocks of the central Virginia Blue Ridge are part of a Late Proterozoic to Ordovician ophiolite-bearing sequence or part of an intrusive-extrusive sequence related to the Late Proterozoic Iapetan rifting has major implications for Appalachian tectonic models. Current models consider most of the Blue Ridge cover sequence to be ophiolitic mélange that was obducted onto Laurentia, thus implying a suture or terrane boundary is associated with the rocks.

Detailed field mapping and petrography of three typical mafic-ultramafic complexes in the central Virginia Blue Ridge (the Catfish, Flat Creek, and Schuyler complexes) indicate that these bodies do not show characteristics that resemble ophiolites. The three complexes are broadly conformable with stratigraphic layering, and the Lynchburg Group host strata form a continuous and conformable stratigraphic sequence unbroken by faults and without evidence of mélange. Contacts between the mafic-ultramafic bodies and the host rocks are sharp and show no strong evidence for faulting or other disturbances. Internal contact relations and the presence of autoliths indicate that these bodies were derived from multiple injection of a fractionating basaltic magma.

The characteristics of the Catfish, Flat Creek, and Schuyler complexes confirm that the mafic-ultramafic association is an intrusive sequence rocks intimately related to the Late Proterozoic Iapetan rifting. The rocks are not part of a Late Proterozoic to Ordovician ophiolite sequence or mélange. Therefore, there are no sutures or terrane boundaries in the central Virginia Blue Ridge.

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INTRODUCTION

The origin and tectonic significance of the mafic-ultramafic association in the Blue Ridge post-Grenville cover sequence has been a subject of dispute for over 60 years. The majority of current tectonic models consider most of the cover sequence to be ophiolitic mélange that was obducted onto Laurentia (Rankin, 1994; Rankin and others, 1989; Horton and others, 1989; Keppie and others, 1989; Hatcher, 1989; Hatcher, 1987; Stanley and Ratcliffe, 1985; Conley, 1985; Hatcher and others, 1984; Abbott and Raymond, 1984). This implies that a terrane boundary or suture of Late Proterozoic to Ordovician age is associated with the rocks (figure 1). Several lines of evidence have been used to support these models: 1) the linear distribution of the mafic and ultramafic rocks along the Blue Ridge, which was first recognized by Hess (1939; 1955); 2) tectonomagmatic discriminant diagrams of Blue Ridge basalts, which are considered an important argument for the presence of ophiolites since some of the rocks plot in the MORB and/or OIB and IAB fields (Wang and Glover, in press); and 3) where most studies have been carried out, the rocks are intensely deformed and metamorphosed, which has led to their interpretation as tectonic mélange.

Wang and Glover (1992), however, demonstrated that ambiguous or incorrect results are obtained when using the tectonomagmatic discriminant diagrams if the basalts were actually intruded into continental crust (e.g., figure 2). The basalts tend to either plot in more than one field on a single diagram or in different fields on different diagrams. Therefore, when used alone, the diagrams may give an incorrect tectonic classification. Also, recent studies of the Virginia post-Grenville cover rocks, particularly the Lynchburg Group, by Wehr (1985), Wehr and Glover (1985), Kline (1991), and Wang and Glover (in press), show that they represent a typical rift sedimentary suite. No evidence of mélange structures were found in the Lynchburg Group.

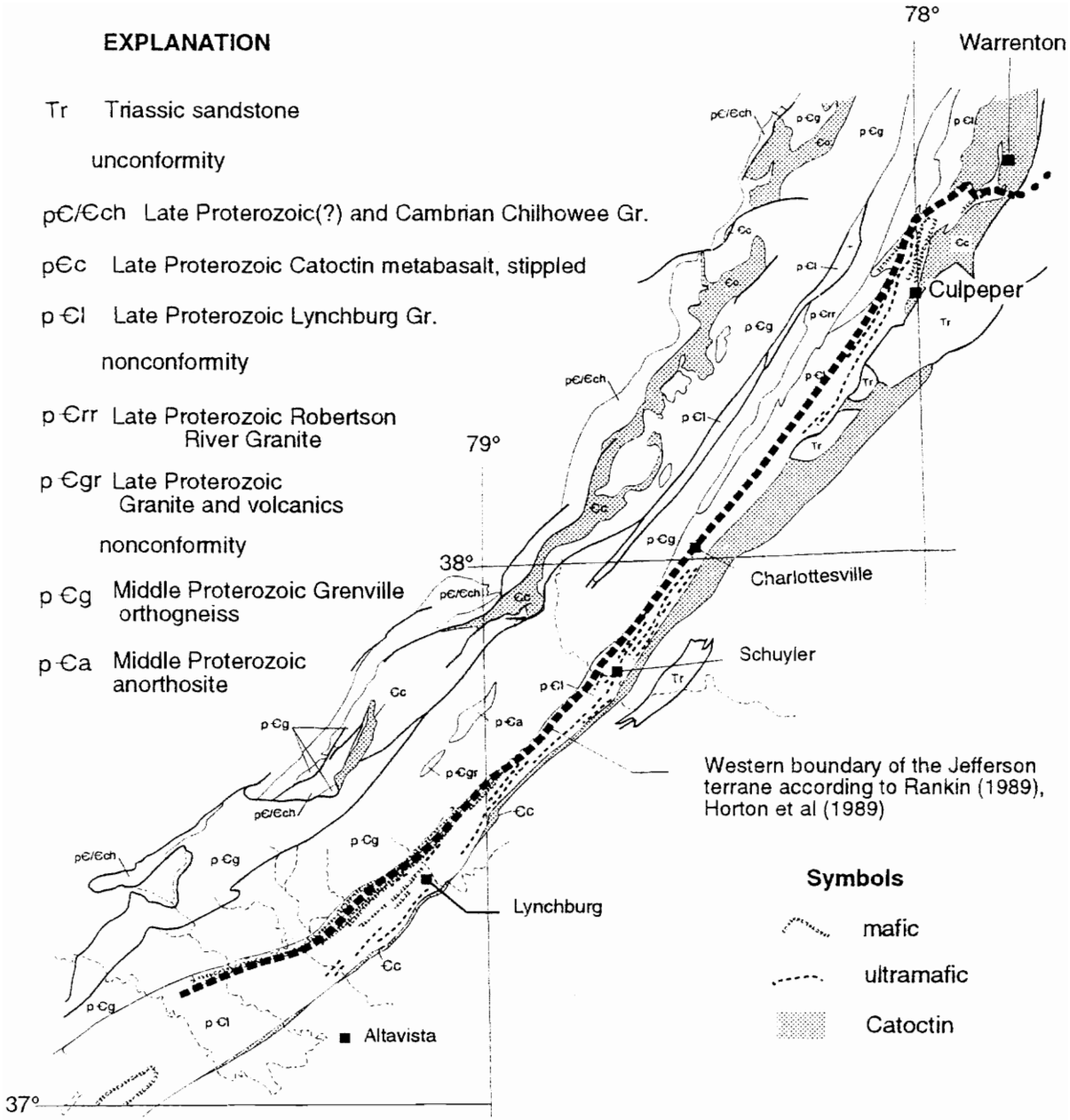

Figure 1. Virginia Blue Ridge showing terrane boundary of Rankin (1990) and Horton and others (1989). From Glover and others (1995).

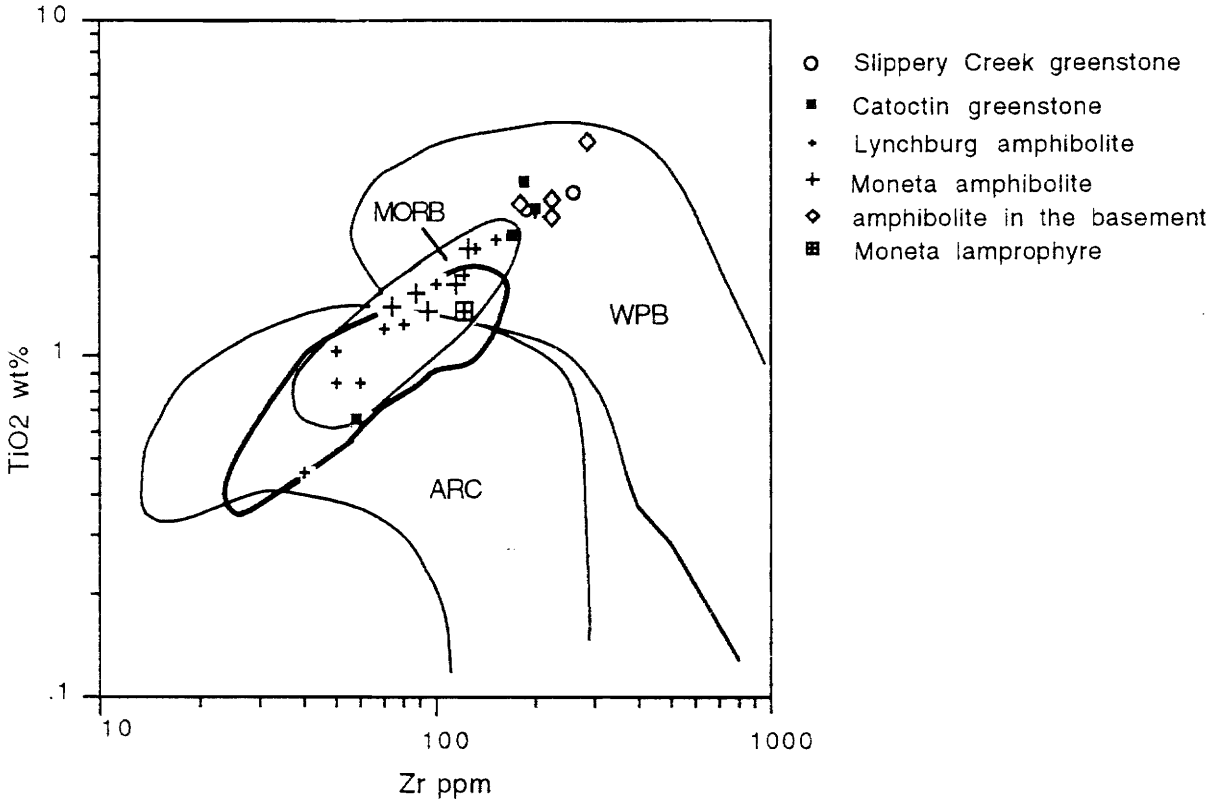

Figure 2. Example of tectonic discriminant diagram used for Blue Ridge basalts. From Wang and Glover (in press). Field with dark border is that of eastern North American Jurassic basalts (Wang and Glover, 1992).

For these reasons, the question of whether the mafic and ultramafic rocks are part of a Late Proterozoic to Ordovician ophiolite-bearing sequence or part of an intrusive-extrusive sequence related to the Late Proterozoic Iapetan rifting has major implications for Appalachian tectonic models. That is why detailed field evidence is essential to resolve the geologic framework question of the presence of absence of ophiolites and a suture. Until now, the field relations have been largely overlooked or not examined in detail. This is partly because of the intense deformation and metamorphism of the rocks where most studies have been carried out. Also, in the past, field geologists have not thought it necessary to rigorously record observational details of contact relations. Thus, the older literature may have simply recorded or implied that a particular mafic contact was conformable with little justification, because there was no concern that this might someday be challenged. In the central Virginia Blue Ridge, most of the mafic and ultramafic rocks were mapped and interpreted as intrusive bodies. In the vicinity of Lynchburg, Virginia, the mafic-ultramafic association was mapped and discussed by Brown (1958). Brown included hornblende-plagioclase amphibolites (mafic rocks) and the closely associated ultrabasic rocks comprised of amphibole-chlorite schist (metapyroxenite), serpentinite, soapstone, and peridotite in his suite of "sill-and-dike-like" rocks. Brown also suggested that the ultramafic rocks might be extrusive because this would explain the localization parallel to bedding and the association of these rocks with the Catoctin lavas. The famous serpentine-soapstone deposits at and near Schuyler, Virginia, were discussed early on by Watson (1907), Burfoot (1930), and Hess (1933). Hess (1933) was the first to examine in detail the mineralogy and lithology of the Schuyler body and concluded that it was a differentiated sill. He found the following sequence of rocks in the body (from bottom to top): 1) ultramafic rock with talc-chlorite-actinolite-calcite assemblages, 2) gabbroic rock

with hornblende-actinolite assemblages, and 3) silicic rock with quartz-albite-microcline-chlorite-hornblende assemblages. More recently, Greenberg and Milici (1965) discussed the petrography of the soapstone deposits and concluded that they were part of a metamorphosed sill. Fairley and Protska (1958) prepared a map of the Schuyler deposits, from the Rockfish River north, towards Old Dominion, Virginia. Their mapping shows the deposits as sills as well. The most recent map of the Schuyler body was included in Wehr's (1983) work on the Lynchburg Group in the Rockfish River area. He mapped the Schuyler complex as a sill, but a detailed examination of the body was beyond the scope of his study. Explanations for how the mafic and ultramafic rocks originated include fractional crystallization of basaltic magmas to diapiric intrusion, as suggested by Hess (1933, 1939, 1955), Bloomer and Werner (1955), Brown (1958), and Epenshade (1954).

These earlier studies emphasize how important conducting detailed studies of contact relations really are. Although they appear to have interpreted the dominantly intrusive nature of these bodies correctly, the evidence was sufficiently ambiguous to permit reinterpretation under the new paradigm of plate tectonics. With the advent of plate tectonic theory, many workers began rethinking the earlier ideas of the mafic-ultramafic association as a series of intrusive rocks. The sill-like nature of these bodies recorded by earlier workers was discounted on the basis of their extremely long linear distribution in the Blue Ridge, geochemistry, and the intensity of the metamorphism and deformation (giving the appearance of mélange) in the areas where most studies were undertaken, and thus the idea that they represent ophiolites was born. From this followed the popular suture or terrane boundary model. The choice between the two views, rifted margin sequence or collisional ophiolitic mélange, is a major problem of Appalachian modeling. Therefore, it is the purpose of this study to examine in detail the internal and external contact relations and petrography of three typical mafic-ultramafic complexes in central Virginia in order to

determine their nature and origin. Fortunately, in the central Virginia Blue Ridge, field relations are structurally and metamorphically relatively simple and well exposed.

THE CATFISH MAFIC COMPLEX OF THE MAFIC-ULTRAMAFIC SUITE

Introduction

The Catfish mafic complex is located on the east bank of the James River, just north of business route US 29 in Lynchburg, Virginia (figure 3). It is one of a large number of mafic and mafic-ultramafic bodies that occur in the Lynchburg Group. The Catfish is a small (< 2 km long), linear, mafic complex which occurs near the top of the locally overturned Late Proterozoic Lynchburg rocks that are part of the Blue Ridge post-Grenville cover sequence. The Catfish mafic complex and the Lynchburg Group rocks are located on the southeast limb of the Blue Ridge anticlinorium. The rocks consistently strike northeast-southwest.

Host Rocks

Regionally, the Lynchburg II Group rocks, host for the Catfish mafic complex, are comprised of three lithologies (Wang, 1991): feldspathic meta-arenites, mica schists, and metaconglomerates. Wang (1991) interpreted these lithologies to be mudstones and feldspathic arenites that were deposited as turbidites.

The Lynchburg II host rocks at the Catfish locality are herein divided into three parts (pCl_{2I}, pCl_{2II}, pCl_{2III}) primarily on the basis of lithology (figure 4, Table 1). The 50 meter section described here is part of a larger, continuous outcrop along both sides of the James River.

Unit pCl_{2I} is the stratigraphically lowest unit in the sequence. It encloses the Catfish mafic complex. That part exposed above the mafic complex is 13 meters thick and

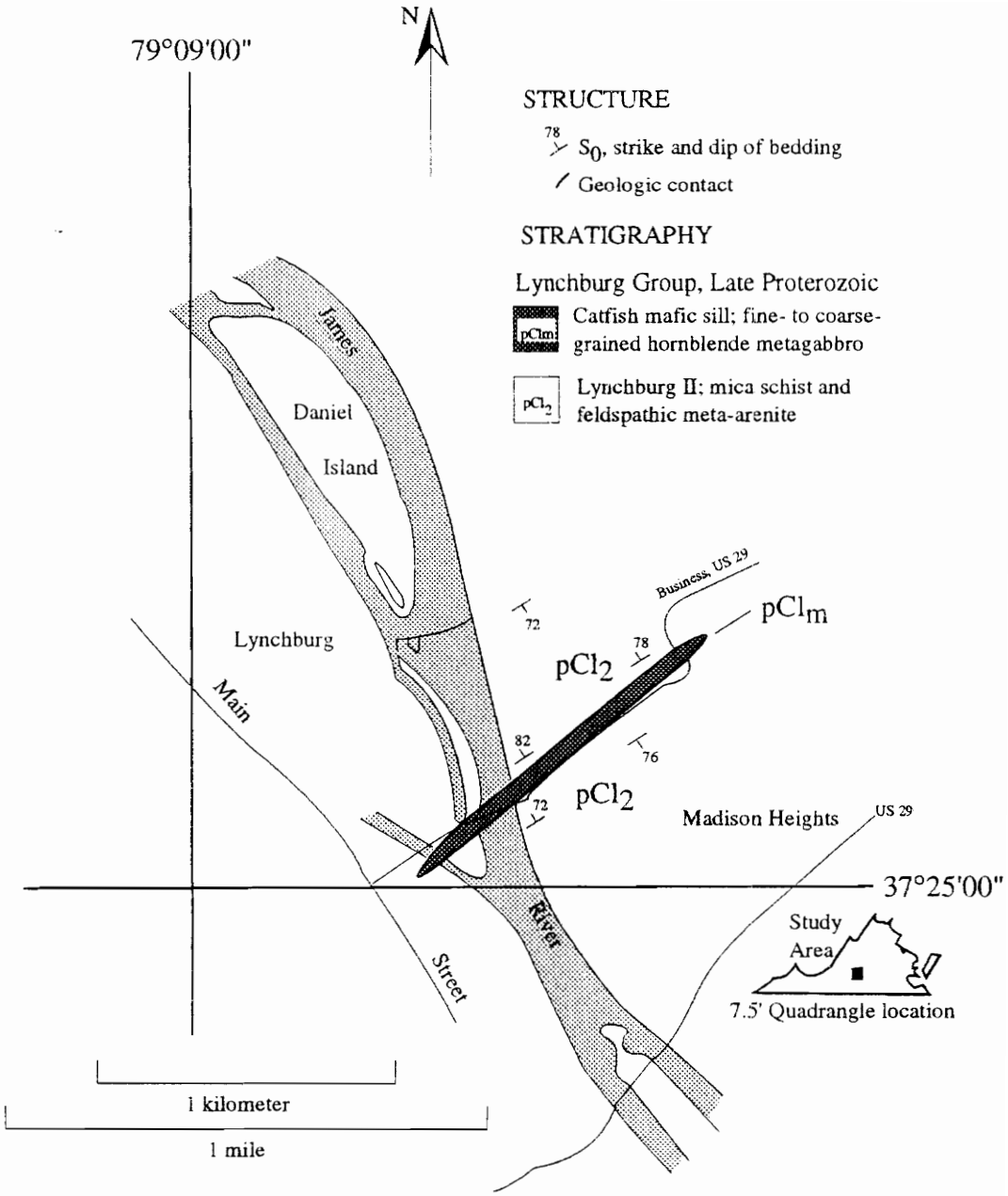

Figure 3. Map of the Catfish mafic complex along the east bank of the James River, Lynchburg, Virginia.

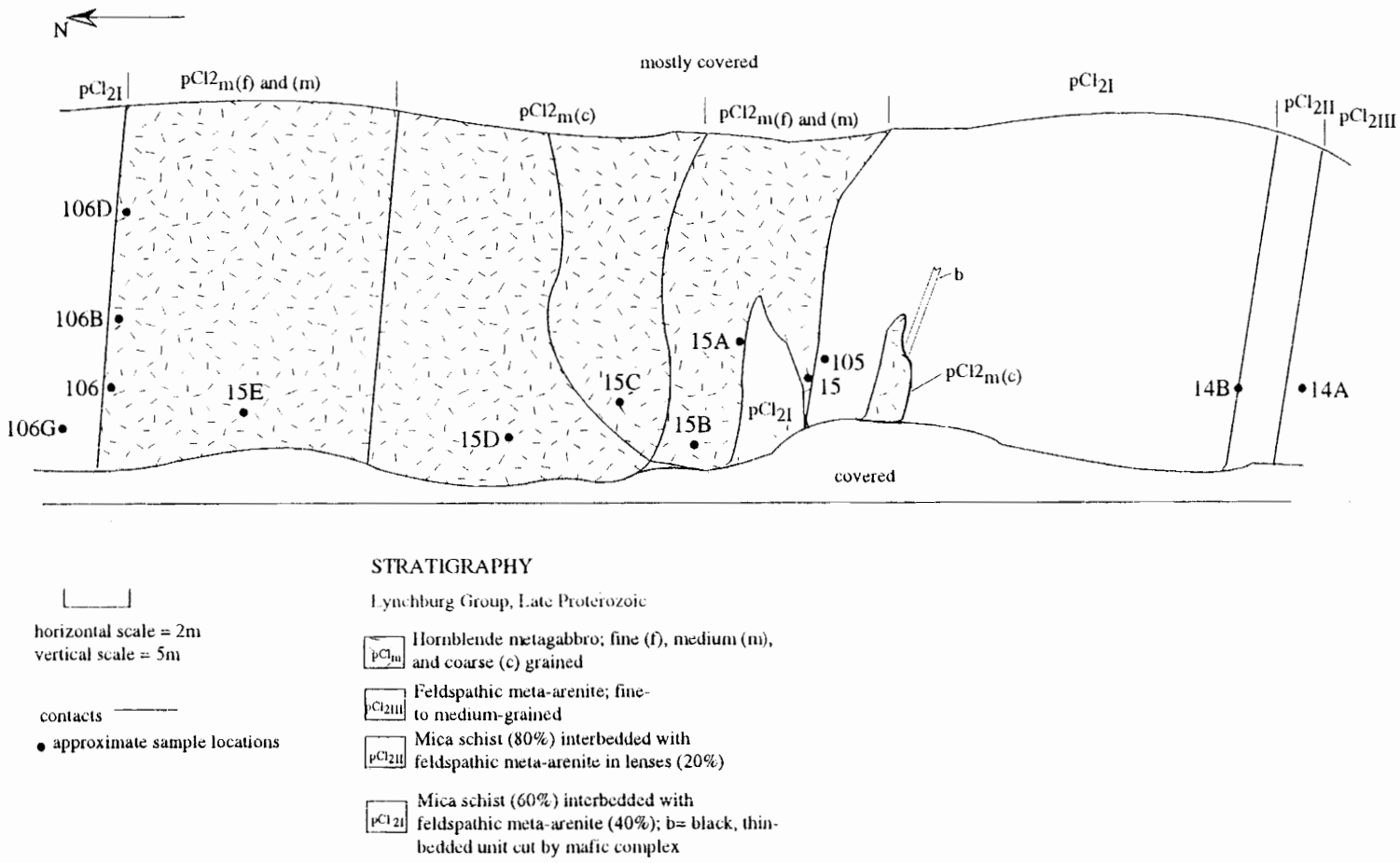

Figure 4. Cross-section of the Catfish mafic sill complex just north of US Business Rte 29, along the James River, Lynchburg, Virginia.

Table 1. Stratigraphy and petrography of the Catfish mafic complex and host rocks.

Stratigraphy	Rock Types and Sample #'s	Petrography	Mineralogy
pCl_{2m}	Hornblende metagabbro (15, 15A, 15B, 15C, 15D, 15E, 106, 106B, 106D)	salt-and-pepper appearance in hand sample; fine- to coarse-grained; pervasive foliation sub-parallel to that developed in host rocks; hornblende is commonly poikiloblastic and in rare cases kink bands are developed; plagioclase forms granoblastic mosaics	plagioclase (22-69%) + hornblende (28-63%) + opaques (1-8%) + biotite (≤3%) + sphene (≤3%) ± calcite (trace-13%) ± garnet (trace) ± chlorite (trace) ± zoisite (trace)± quartz (trace)
pCl_{2III}	Feldspathic meta-arenite (14A)	gray, thin bedded, fine- to medium-grained; foliation subparallel to bedding	quartz (48%) + muscovite (29%) + plagioclase (14%) + biotite (11%) + opaques (1%)
pCl_{2II}	Mica schist (80%) interbedded with feldspathic meta-arenite lenses (20%) (14B)	gray, thin- to medium-bedded, fine- to medium-grained; foliation subparallel to bedding; crenulation cleavage	quartz (69%) + plagioclase (19%) + biotite (13%) + opaques (5%) ± garnet (trace)
pCl_{2I}	Mica schist (60%) interbedded with feldspathic meta-arenite (40%) (105, 106G)	gray, medium bedded, medium- to coarse-grained; foliation subparallel to bedding; crenulation cleavage; in contact with mafic complex	quartz (58-84%) + plagioclase (18%) + biotite (14-17%) + opaques (2-3%) ± muscovite (8%)

the part below about 10 meters thick. Unit pCl_{2I} is medium bedded, consisting of approximately 60 percent fine-grained mica schist interbedded with 40 percent medium- to coarse-grained feldspathic meta-arenites. Quartz, plagioclase, and biotite are the major minerals present; magnetite and muscovite are minor minerals.

Unit pCl_{2II} is 1.5 meters thick, conformable, and comprised of approximately 80 percent mica schist interbedded with 20 percent feldspathic meta-arenite in lenses. These rocks are thin- to medium-bedded, and fine- to medium-grained. The major mineral constituents are quartz, plagioclase, and biotite, with minor magnetite and garnet.

Unit pCl_{2III} is very thin (< 1 meter) and typically consists of thin- bedded, fine- to medium-grained feldspathic meta-arenite. It is the stratigraphically highest unit in the sequence and is conformable with unit pCl_{2II}. Quartz, muscovite, plagioclase, and biotite are the major minerals present, with minor amounts of magnetite.

In all three units, primary sedimentary features are preserved. These include parallel laminations and bedding. Grain-size grading can be discerned rarely. Additionally, soft-sediment deformation (figure 5) is evident in a 1 meter long core that was obtained from the present location of the John Lynch bridge, which is located at the Catfish site, just south of the exposure of pCl_{2III}. The core, which is part of unit pCl_{2III}, is characterized by alternating zones of sand (meta-arenite) and clay (schist). The schist layers and fragments are characterized by parallel laminations which are commonly folded. The meta-arenite wedges into and interfingers with the schist layers (figure 5). These features are characteristic of sediment slumps in a deep water setting (Stow, 1986), and are present in beds a meter in thickness or less, which are bounded by a thin- to medium-bedded metasedimentary sequence.

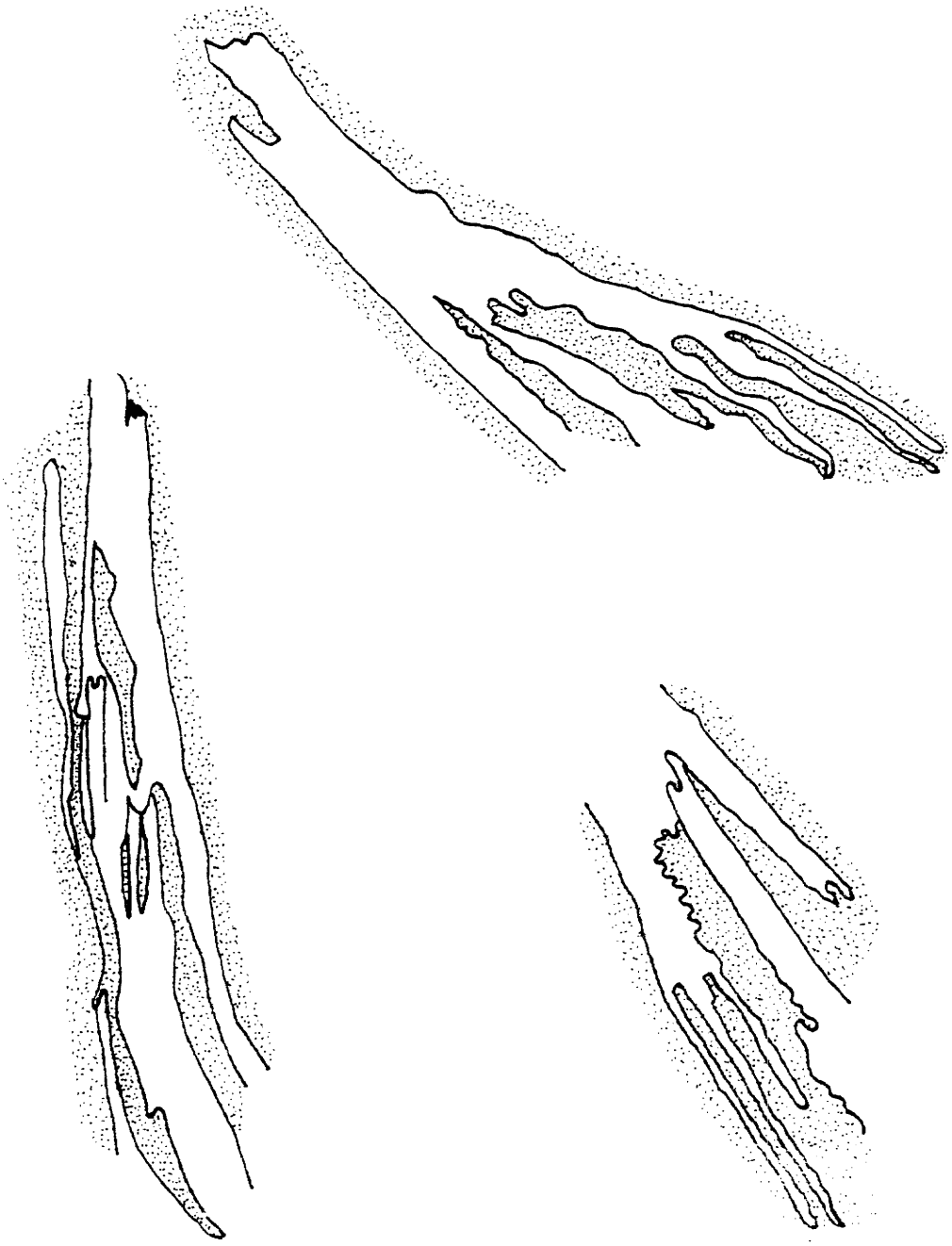

Figure 5. Examples of soft-sediment deformation resulting from slumping. These features are present in a 1 meter long core taken from the present site of the John Lynch bridge at the Catfish locality. The stippled-pattern represents the sand zone (meta-arenite) and the non-patterned areas represent the clay zone (schist). Figure is to scale of 1:1.

Mafic Complex

The Catfish mafic complex is 22 meters thick and is enclosed within unit pCl_{2I} (figure 4). Detailed field mapping indicates that the contact between the Catfish complex and the Lynchburg II metasedimentary rocks is generally concordant, but locally discordant and is sharp and unfoliated.

Petrography

The mafic rocks of the Catfish complex are hornblende metagabbros (Table 1). The rocks have a salt- and -pepper appearance in hand sample and consist largely of hornblende and plagioclase. Accessory minerals include magnetite, sphene, biotite, calcite, garnet, and chlorite. A quartz vein, which is several centimeters thick and about 1 meter long, is present near the base of the Catfish complex. Twenty-one thin sections from samples taken across the Catfish complex and adjacent host rocks (figure 4) were examined and at least 500 points per sample were counted for modal percentages.

Hornblende makes up as much as 63 percent of the metagabbro. It is subhedral, and typically inequigranular, ranging in size from < 1 mm to 3 mm. It is common for grains to be either elongate subparallel to their c-axes or to occur as stubby prisms displaying the typical amphibole cleavage. It is commonly poikiloblastic and with a well-developed mosaic-texture.

Plagioclase is also an abundant mineral, making up as much as 69 percent of the rocks. Plagioclase crystals are generally rounded, small (< 1 mm), equant, and commonly form well-developed granoblastic mosaics, interlocking at 120 ° triple junctions. Composition varies from An_{34} to An_{58} (andesine) as determined using the Michel-Levy method. It is commonly zoned and twinned.

Many of the accessory minerals are present as alteration products. Biotite and calcite overgrows hornblende whereas chlorite largely replaces it. Calcite fills in small veins. Commonly, magnetite is rimmed by sphene. While magnetite is generally an accessory mineral, it may constitute as much as 8 percent by volume of the rock. Garnet is subhedral to euhedral, typically fractured and embayed. It is overgrown by calcite, chlorite, and zoisite and contains inclusions of plagioclase and quartz.

Structure

General Statement

Based on field and petrographic evidence, at least two deformational events, D_1 and D_2, have affected the Catfish mafic complex and the Lynchburg host rocks (Table 2).

While the dip-directions in the Lynchburg area are generally toward the southeast (> 68°), the Catfish locality is one of a few areas where the sequence is overturned, dipping steeply toward the northwest. The sequence was determined to be overturned using graded beds and basal scouring surfaces which consistently young toward the southeast (Wang, 1991).

No faults, either on the local or regional scale, have been recognized at the Catfish locality. Additionally, no features indicative of intense shearing have been found on either the outcrop or thin section scales.

D_1 Deformation

D_1 is the strongest deformation recorded in the study area. D_1 deformation is defined by a pervasive foliation (S_1) of biotite and muscovite that is very nearly parallel to bedding. The foliation appears to be penetrative in hand sample, especially in the mica schists of units pCl_{2I} and pCl_{2II}.

Table 2. Summary of the structure and metamorphism of the Catfish mafic complex and host rocks.

Age*	Structure	Metamorphism
Late Paleozoic (Alleghanian ?)	D_2: localized crenulation cleavage (S_2) and rare rotated garnet porphyroblasts in the mica schists of the host rocks; kink bands occurring locally in hornblende grains in the hornblende metagabbros.	M_2: retrograde metamorphism to greenschist facies; chlorite and calcite replaces hornblende and garnet in the hornblende metagabbros.
Early Paleozoic (Cambrian or Taconic ?)	D_1: pervasive foliation (S_1) defined by oriented micas in the metasedimentary host rocks and by oriented amphiboles in the hornblende metagabbros; S_1 is nearly parallel to bedding (S_0).	M_1: prograde metamorphism to amphibolite facies.

* Ages of deformation and metamorphism are from Glover and others (1995).

The S_1 foliation in the hornblende metagabbros is defined by weakly oriented hornblende and is parallel to S_1 in the host rocks. Overall, however, an igneous texture is retained by the Catfish mafic complex.

D_2 Deformation

The second deformation event is defined by a spaced crenulation cleavage (S_2) and is found only in the mica schists of units pCl_{2I} and pCl_{2II}. It strikes 024 and dips at 29° SE, which is parallel to the D_1 structures. In the hornblende metagabbros, the second deformational event is preserved as locally developed kink bands, which are restricted to hornblende grains.

Metamorphism

General Statement

Two regional metamorphic events are recognized in the Catfish mafic complex and the enclosing Lynchburg II rocks (Table 2). Petrographic observations of samples from the study area as well as microprobe analyses of both mafic and sedimentary protoliths by Wang (1991), suggest a prograde metamorphism to amphibolite facies followed by a retrograde event to greenschist facies. There is no evidence that suggests contact metamorphism occurred at the contact between the Catfish complex and the host rocks.

M_1 Metamorphism

The rocks at the Catfish locality were interpreted by Wang (1991) to be metamorphosed to epidote-amphibolite facies. However, the abundance of hornblende, along with the composition of plagioclase (An_{34} to An_{58}) and the absence of epidote in the

Catfish mafic body indicates that it has been metamorphosed at amphibolite grade. The stable metamorphic mineral assemblage of the Catfish mafic body is plagioclase + hornblende + magnetite + sphene + biotite ± garnet. In the Lynchburg II Group host rocks, the stable metamorphic mineral assemblage is quartz + plagioclase + biotite + muscovite ± garnet. M_1 is synchronous with D_1 as evidenced by the M_1 micas that define the S_1 surfaces (Wang, 1991).

M_2 Metamorphism

The retrograde metamorphism to greenschist facies was much less pervasive than the M_1 event. This event occurred during the second deformational event (D_2). Evidence for this metamorphism is seen only in the hornblende metagabbros and is marked by rare replacement of hornblende by chlorite and more commonly, by overgrowths of calcite on hornblende. Also, when present, garnet porphyroblasts are overgrown by chlorite and calcite.

Contact Relations

The lower contact between the Catfish mafic complex and the Lynchburg II host rocks is not as well-exposed as the upper contact. However, it is very similar to the upper contact in that it is sharp, unfoliated, and generally concordant with bedding (figure 4). No strong evidence for a contact aureole, faulting, shearing, or other disturbance has been recognized in either outcrop or thin section at either the lower or upper contact.

Contacts within the mafic complex are boundaries separating changes in grain size (figure 4). The central 10 meters of the Catfish complex is coarse-grained, whereas the margins are fine- to medium-grained. Internal contacts vary from sharp to abruptly gradational over 15 cm. Contacts within the Catfish complex are parallel to the mafic rock-

country rock contact and are generally concordant with bedding in the host rocks. Also, mafic autoliths as much as 2 cm in width and 10 cm in length occur near the base of the coarse-grained interior.

The upper contact between the complex and the host strata is sharp and generally concordant, but locally discordant (figure 4). The most felsic part of the mafic complex is in contact with the Lynchburg rocks. Locally, the coarse-grained member of the Catfish complex cuts across the stratigraphy and truncates a thin-bedded metasedimentary unit within pCl_{2I}.

The contact between the metasedimentary host rocks and the mafic complex is also exposed in a boulder of unweathered rock that is located on the river bank just below the road which was dislodged during construction of the road (figure 6). It is located on the river bank just below the road. The contact is sharp and concordant. Additionally, the thin bedding and laminations present in the country rock are undisturbed (figure 6).

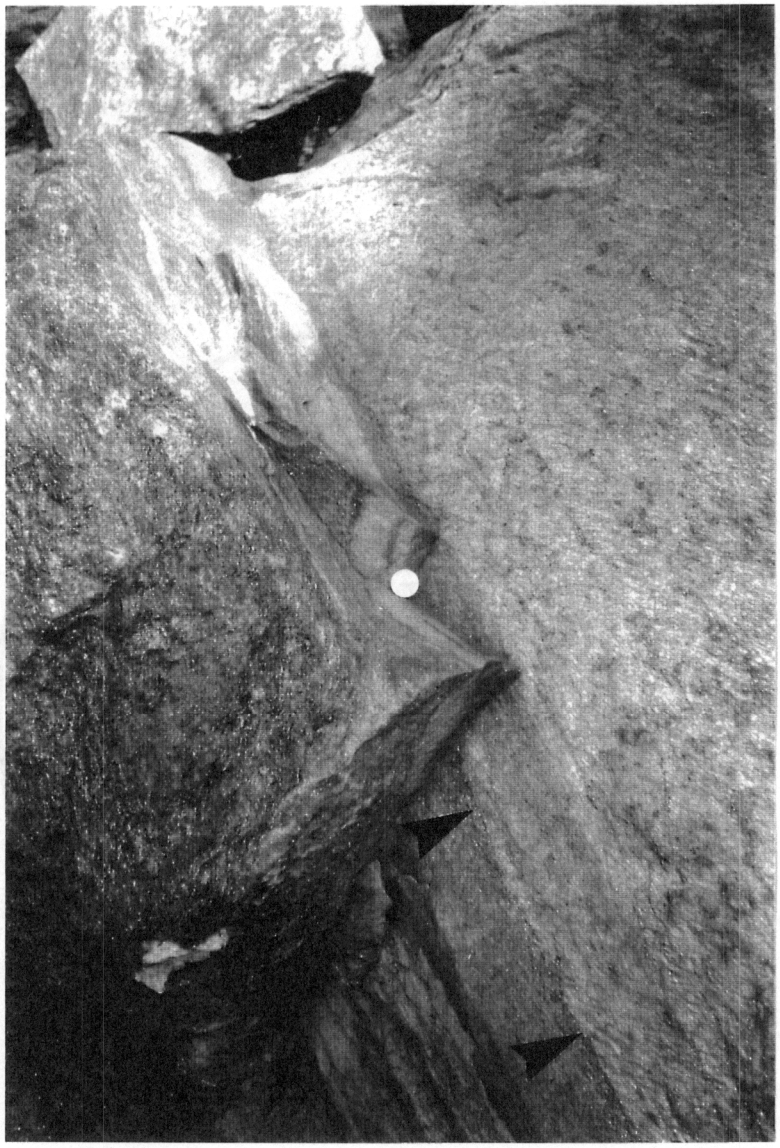

Figure 6. Contact between the metasedimentary host rocks and the Catfish mafic complex in a boulder located on river bank just below road level at the Catfish locality. The metagabbro is to the left and the host rocks are to the right. Nickel is for scale.

Discussion and Conclusions

The detailed field mapping and petrography of the Catfish mafic complex and the Lynchburg II host rocks indicates that the Catfish complex is a sill and not a small ophiolite fragment. The stratigraphy of the host rocks and Catfish mafic complex indicate that the Catfish is broadly conformable with stratigraphic layering. Host Lynchburg strata appear to form a continuous and conformable stratigraphic sequence unbroken by faults and without evidence of mélange as proposed by most workers (Rankin, 1994; Rankin and others, 1989; Horton and others, 1989; Keppie and others, 1989; Hatcher, 1989; and many others). Additionally, the continuity of bedding and parallel laminations commonly observed in the Lynchburg would not be present in a mélange or near thrust-related ophiolites.

The layering and petrography of the Catfish complex itself also suggest that it originated as a mafic intrusive body. The sharp contacts separating grain-size changes within the Catfish as well as the presence of mafic autoliths in the sill indicate that there were multiple injection events into the same intrusive complex. Had there been just a single intrusive event, the contacts within the interior of the Catfish sill would have been gradational and no autoliths would be expected. Coarse-grained gabbro intrusion of the metasediments also shows grain-size variation developed elsewhere before injection into the fine-grained gabbro. Also, the overall igneous texture retained by the hornblende metagabbro indicates that while the igneous amphibole and plagioclase changed composition during regional metamorphism (M_1), the same mineral species and textural relations were retained. The presence of some fluid allowed diffusion to take place along grain boundaries, but since the hornblende metagabbro was initially relatively dry, the

metamorphism was incomplete, such that, in effect, the hornblende and plagioclase pseudomorphed themselves, preserving the igneous textures. Additionally, even though there is little evidence for the presence of a contact metamorphic aureole at the Lynchburg-Catfish contact, it is reasonable to suggest that such a feature would have been overprinted by the regional metamorphism (M_1) and deformation (D_1).

The Catfish sill was emplaced into the Lynchburg rocks prior to any of the regional structural and metamorphic events. Both observations in the field and in thin section indicate that the hornblende metagabbro has been subjected to the same two episodes of deformation and metamorphism that affected host Lynchburg strata.

Therefore, the contact relations and petrography of the Catfish mafic complex and the Lynchburg host rocks do not support an ophiolite stratigraphy. Instead, the Catfish complex originated as a gabbroic sill that resulted from multiple injection of a relatively dry mafic magma into the Lynchburg host rocks during continental rifting.

THE FLAT CREEK MAFIC-ULTRAMAFIC COMPLEX

Introduction

The Flat Creek mafic-ultramafic complex crops out in several places along routes US 29 and US 460 on the west edge of Lynchburg, Virginia (figure 7). It is typical of many of the mafic-ultramafic bodies that are present in the Late Proterozoic Lynchburg Group cover sequence rocks. The Flat Creek complex is a linear body which is present near the top of the Lynchburg III Group. This mafic-ultramafic complex and the Lynchburg Group rocks are located on the southeast limb of the Blue Ridge anticlinorium and strike northeast-southwest.

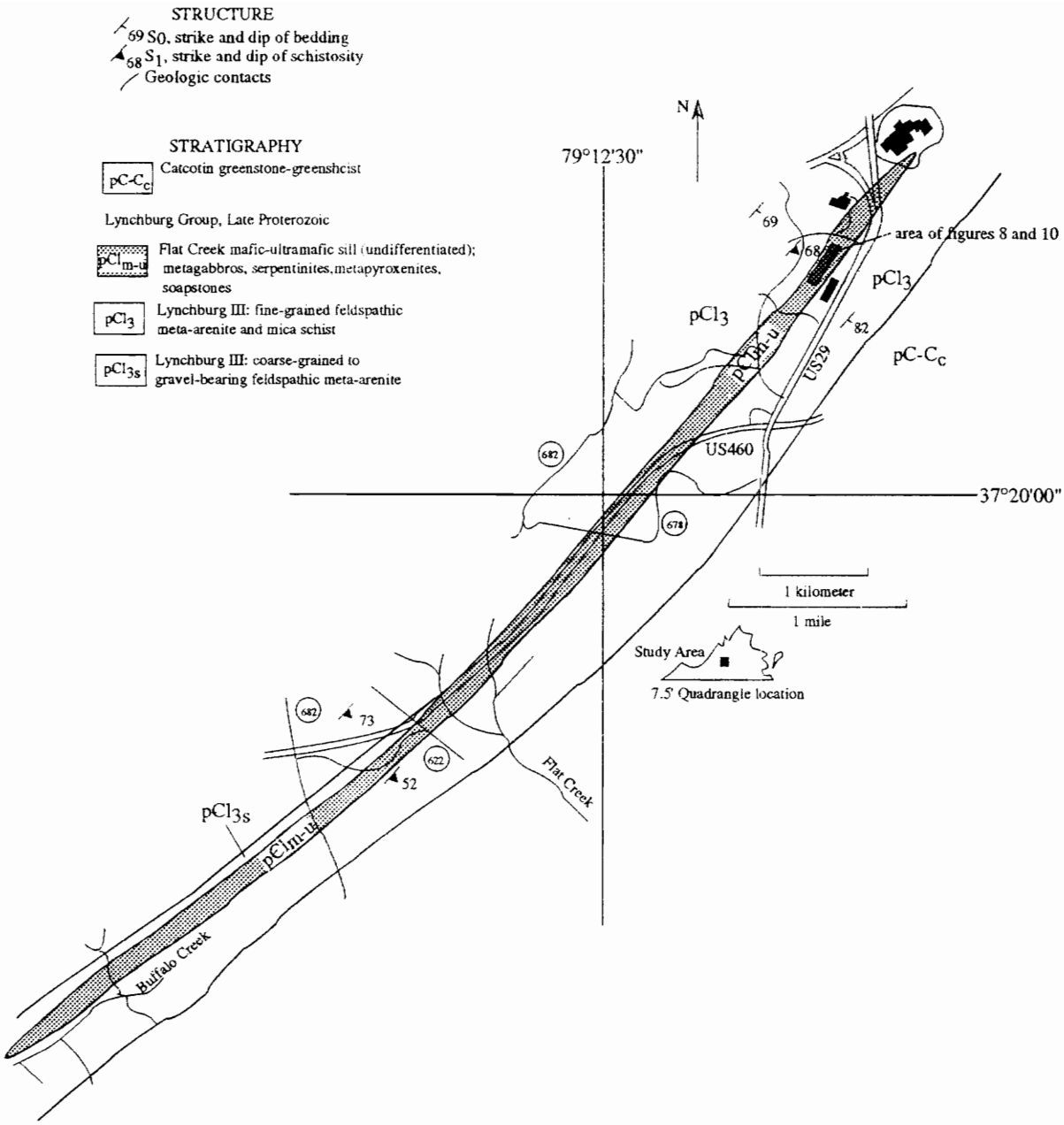

Figure 7. Geologic and location map of the Flat Creek mafic-ultramafic complex, Lynchburg, Virginia.

Host Rocks

The Lynchburg III Group, host for the Flat Creek mafic-ultramafic complex, is comprised of the following lithologies (Wang, 1991): fine-grained meta-arenites and mica schists and coarse-grained to conglomeratic feldspathic meta-arenites (Table 3). Wang (1991) interpreted the protoliths of these rocks to be fine-grained to conglomeratic feldspathic arenites, siltstones, and mudstones deposited as turbidites.

The Lynchburg III rocks conformably overlie the Lynchburg II Group and are in turn conformably overlain by the Catoctin Formation in the study area. These metasediments are typically thin- to thick-bedded. Graded beds and parallel laminations are some of the primary sedimentary features frequently observed. Quartz, plagioclase, muscovite, and biotite are the major metamorphic minerals present. Magnetite, K-feldspar, garnet, epidote, and sphene are locally present in lesser amounts. A more detailed description of the host rocks is beyond the scope of this paper and is presented elsewhere (Wang, 1991).

Mafic-Ultramafic Complex

The Flat Creek mafic-ultramafic complex is as much as 225 meters thick and is approximately 10 kilometers long. The contact between the Lynchburg III metasedimentary host rocks and the Flat Creek body is exposed in several locations along US route 460. Detailed field mapping indicates that the contact is mostly concordant and sharp.

Table 3. Petrography of the Flat Creek mafic-ultramafic complex and host rocks.

Rock Type and Sample #'s	Petrographic Features	Mineralogy	Probable Protoliths
serpentinite (W1, W3a, W3b, W10, W11, W23)	dark green, fine-grained, commonly schistose; pseudomorphs of olivine and pyroxene; relict igneous textures.	serpentine (43-83%)+ tremolite (11-31%)+ chlorite (trace-14%)+ magnetite (1-12%) ± talc(trace-19%)± clinopyroxene (trace-3%) ± orthopyroxene (0-2%)± magnesite (trace-1%)± olivine (trace)	peridotite
metapyroxenite (W2, W7, W8, W12, W14, W15, W18, W19, W20, W21, W22)	green, fine- to medium-grained, massive to schistose; metamorphic overgrowth textures; magnetite pseudomorphs after olivine.	chlorite (32-83%)+ tremolite (8-56%) + clinopyroxene (5-28%)+ magnetite (trace-9%)± orthopyroxene (0-3%)	pyroxenite
soapstone (W9)	greenish, commonly schistose; pseudomorphs after olivine; relict igneous textures.	talc (36%)+ magnetite (24%)+ chlorite (17%)+ serpentine (14%)+ tremolite (9%)	peridotite and/or pyroxenite
phlogopite schist (W24)	dark grayish brown, fine- to medium-grained; metamorphic overgrowth textures.	phlogopite (50%)+ clinopyroxene (39%)+ tremolite (6%) + chlorite (6%)+ magnetite (trace)	clinopyroxenite
metagabbro (W5, 61)	green, medium- to coarse-grained; schistose; metamorphic overgrowth textures.	actinolite/hornblende (52-65%) + clinozoisite (22-33%) + plagioclase (11-12%) + sphene (1-3%)± cummingtonite (trace) ± clinopyroxene (trace)	gabbro

Table 3. Petrography of the Flat Creek mafic-ultramafic complex and host rocks (continued).

Rock Type and Sample #'s	Petrographic Features	Mineralogy	Probable Protoliths
*Lynchburg III host rocks (meta-arenites and mica schists)	* fine-grained meta-arenite and mica schist; thin- to medium-bedded, graded bedding anf bedding-parallel laminations common; coarse-grained to gravel-bearing meta-arenite; light gray to gray, thin- to thick-bedded; some beds are graded.	* quartz (35-65%) + plagioclase (10-35%) + muscovite (5-50%) + biotite (3-15%) ± K-feldspar (0-15%) ± garnet (0-5%) ± epidote (0-7%) ± sphene (0-2%)	*feldspathic arenites, siltstones, and mudstones
"metasomatic" rocks (24, 25, 26)	fine-grained; schistose; variable composition 4-15 cm from Flat Creek-host rock contact.	clinozoisite (44-52%) + amphibole (10-23%) + quartz (18-30%) + plagioclase (4-5%) + sphene (4-5%) + biotite (1-4%) + epidote (trace-5%)	----------

* Petrographic data for host rocks is from Wang (1991).

Petrography

Five major rock types comprise the Flat Creek mafic-ultramafic complex. They are: serpentinite, metapyroxenite, soapstone, phlogopite schist, and metagabbro (Table 3). Twenty-one thin sections from the study area (figure 8) were examined and at least 500 points per sample were counted for modal compositions.

Serpentinite

The serpentinite is characteristically dark green in color, fine- to coarse-grained and commonly schistose. The typical assemblage of minerals includes serpentine, tremolite, chlorite, magnetite, talc, and magnesite. Relict primary igneous minerals include clinopyroxene, orthopyroxene, and rare olivine. Based upon composition, the protolith of the serpentinite is believed to have been peridotite.

Serpentine is the most abundant mineral, and constitutes as much as 83 percent of the rocks. It is present in a variety of forms, such as fibrous, randomly oriented flakes, asbestos veins, and as pseudomorphs. Most pseudomorphs are presumably after olivine as evidenced by the shape of the grains. Magnetite commonly occurs at the margins of the serpentine pseudomorphs, preserving original igneous texture (figure 9). Serpentine may be partially replaced by talc as well.

Tremolite comprises as much as 31 percent of the serpentinite. Grains are typically subhedral to anhedral and are usually less than 1 mm in length. It is commonly partially altered to chlorite, magnetite, serpentine, and talc.

In the serpentinite, magnetite preserves relict igneous textures and provides a clue to the original composition and texture of these rocks. Iron in the Mg site of the olivine or

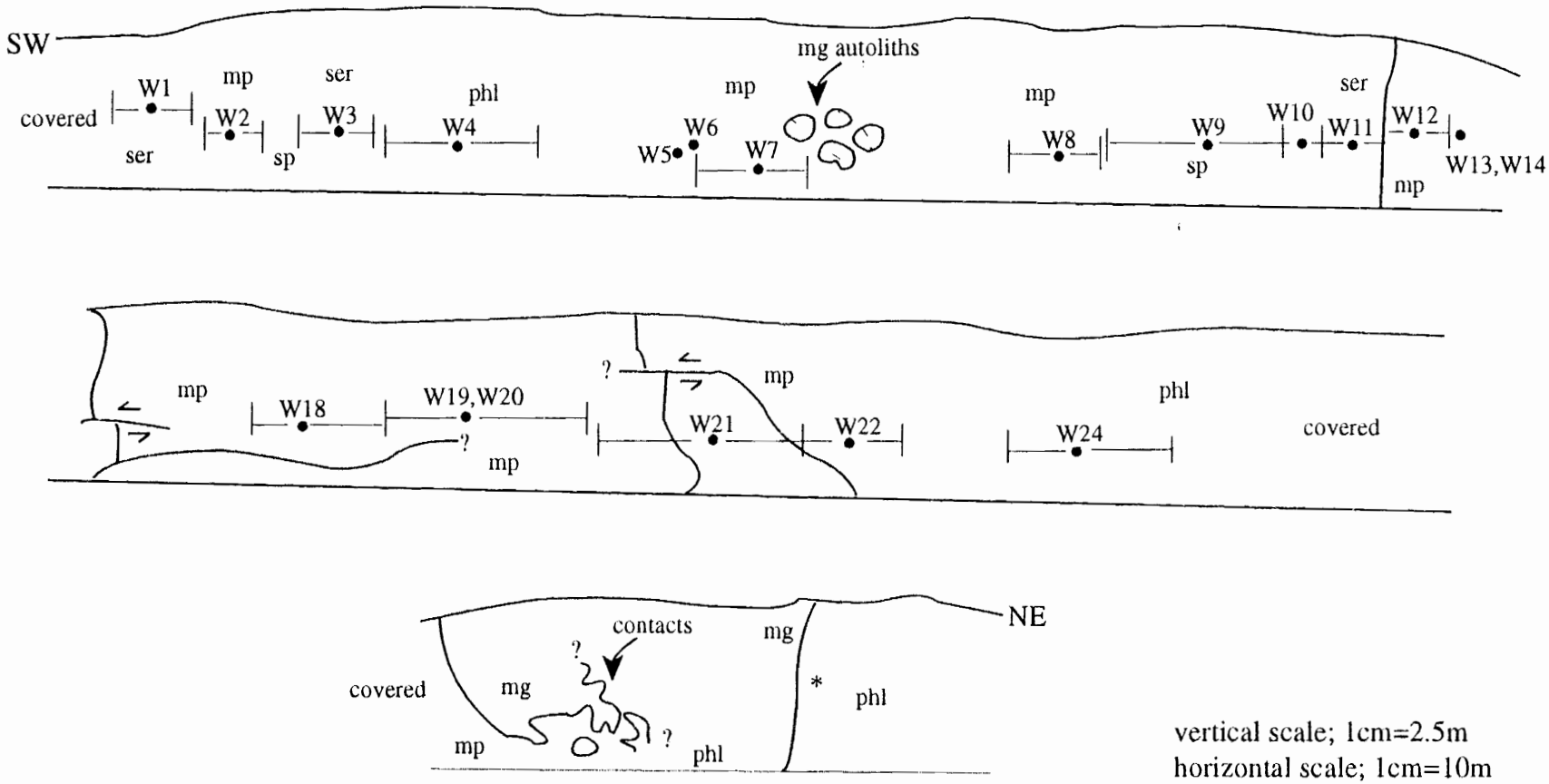

Figure 8. Outcrop map at Walmart shopping center, Lynchburg, Virginia, immediately west of site of figure 10. View is approximately parallel to strike (NE-SW). ser= serpentinite; mp= metapyroxenite; phl= phlogopite schist; sp= soapstone;mg= metagabbro. Numbers (e.g., W1) correspond to samples taken across the outcrop. Contacts, displacements on faults, and metagabbro autoliths enlarged to show detail. * Outcrop approximately opposite the NW corner of the Walmart building. Vertical height approximately 7.5 meters; horizontal distance approximately 520 meters.

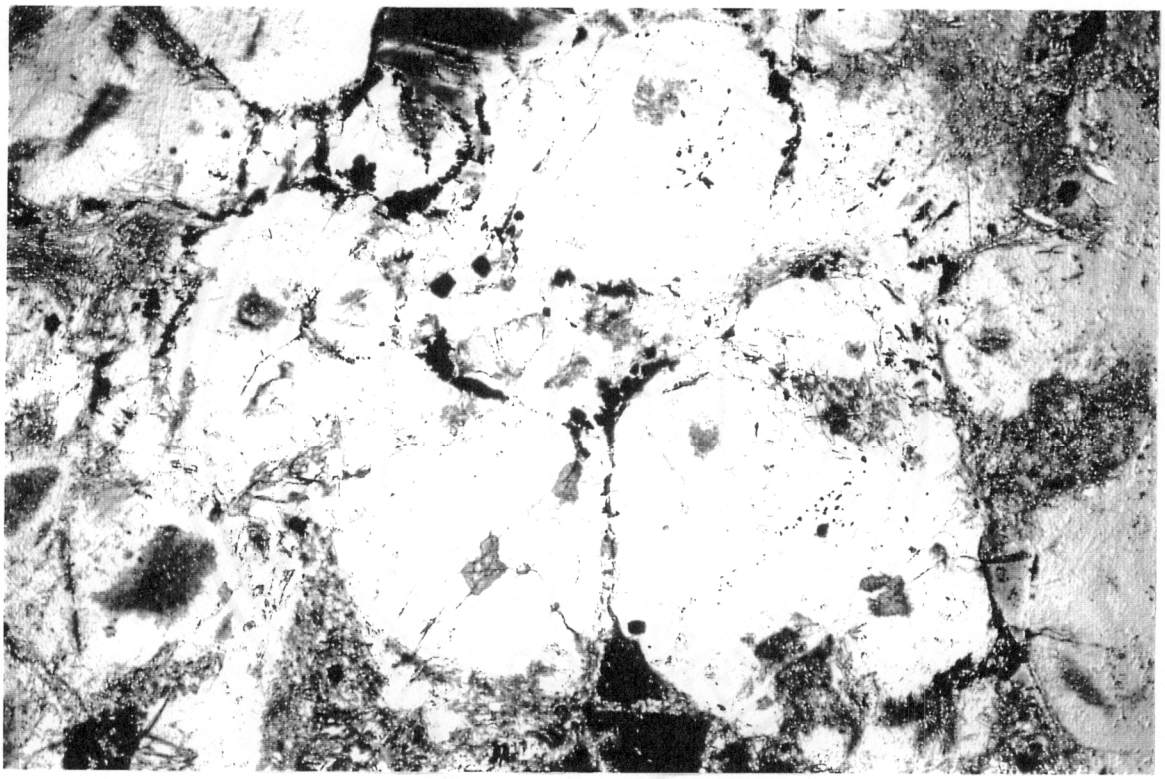

Figure 9. Serpentine pseudomorphs after olivine, rimmed by magnetite. Horizontal field of view is about 6 mm across; plane polarized light.

pyroxene forms magnetite during serpentinization because all of the iron cannot be accommodated in the serpentine (Hyndman, 1985).

Minor amounts of clinopyroxene and orthopyroxene occur as large relict grains as much as 3 mm in size. These pyroxenes are partially altered to serpentine, tremolite, and magnetite.

Metapyroxenite

The metapyroxenite (chlorite-tremolite schists) is green in color, fine- to medium-grained, and massive to schistose. The typical mineral assemblage in these rocks is chlorite, tremolite, and magnetite. Clinopyroxene and orthopyroxene are present as relict primary igneous minerals.

Chlorite is the most abundant mineral present, comprising as much as 83 percent of the metapyroxenite. Individual grains vary between 0.25 mm and 1.5 mm in length. Commonly, chlorite is twinned and exhibits dark gray interference colors, but anomalous blues and olive drab colors occur throughout the rocks. Chlorite partially replaced the pyroxene and tremolite.

Tremolite makes up around 56 percent of the rocks. Grains are typically subhedral to anhedral and locally occur as bladed laths. Grain size is highly variable, ranging from approximately 1 mm up to 2.5 mm. Some tremolite shows undulose extinction and rare crenulations that are restricted to the grain interior. Also, intergrowths among the amphibole is quite common.

As much as 28 percent of the metapyroxenite is comprised of primary igneous clinopyroxene. The grains are subhedral to anhedral and range in size from about 1 mm to 3 mm. Exsolution lamellae are common. The clinopyroxene is locally partially replaced by tremolite, magnetite, and chlorite.

In the metapyroxenite, magnetite is locally present as dustings in tremolite and pyroxene. However, the most striking feature is that it also outlines the shape of former grains that are located near the center of tremolite grains. These pseudomorphs are probably after olivine based upon shape and the abundance of relatively unaltered clinopyroxene.

Soapstone

The soapstone (talc-serpentine schists) is greenish in color and commonly schistose. The typical mineral assemblage includes talc, serpentine, magnetite, chlorite, and tremolite. Magnesite, pyrite, and pyrrhotite are present in trace amounts. The protolith of the soapstone is thought to have been peridotite and/or pyroxenite, based upon composition.

Talc is the most abundant mineral present, comprising about 36 percent of the rock. It occurs as an alteration product of serpentine.

Serpentine, which makes up about 14 percent of the soapstone, occurs primarily as asbestos veins, randomly scattered throughout the rock. The veins are typically < 1 mm thick and several millimeters long. Pseudomorphs after olivine are present as well. Serpentine alteration to talc may be partial or complete.

Magnetite comprises as much as 24 percent of the soapstones. It commonly occurs as small (< 1 mm) randomly scattered grains, or as large grains (as much as 6.5 mm) that are probably pseudomorphs after pyroxene. The magnetite grains typically enclose the serpentine-talc pseudomorphs of olivine, which resembles cumulate texture.

Chlorite is another major mineral, and comprises about 17 percent of the rocks. It exhibits anomalous blue and olive drab interference colors and may be dusted with magnetite. The anomalous interference colors indicate that the chlorite is magnesium-rich.

Grain size is highly variable, ranging from < 1 mm up to around 6 mm. It is an alteration product, probably after pyroxene and olivine.

Tremolite occurs in relatively small amounts in the soapstone (about 9 percent), as compared to the other rocks present in the Flat Creek mafic-ultramafic complex. The grains are typically very small, subhedral to anhedral, and are randomly scattered through the soapstone. Some grains exhibit zoning, particularly on grain edges.

Phlogopite schist

The phlogopite schist is typically dark grayish brown in color and fine- to medium-grained. The mineral assemblage consists of phlogopite, tremolite, chlorite, and trace amounts of magnetite. Clinopyroxene is present as a relict primary igneous mineral.

The phlogopite comprises about 50 percent of these schists. It commonly wraps around the pyroxenes and tremolite, defining the foliated nature of the rock. Additionally, it commonly overgrows tremolite and pyroxene.

As much as 39 percent of the rock is composed of clinopyroxene. The grains are typically subhedral to anhedral and may be as much as 1 mm in size. Typical pyroxene cleavage and exsolution lamellae are commonly present. Some overgrowths of either phlogopite or tremolite are present. The tremolite overgrowths usually are present at grain edges and, in most cases, do not completely overgrow the clinopyroxene.

Tremolite and chlorite are present in small amounts, usually about 6 percent. Tremolite is present as overgrowths on the edges of the clinopyroxene, as noted above. Additionally, it is locally overgrown by phlogopite. The chlorite is intergrown with the phlogopite, and in a few cases, has replaced it.

Metagabbro

The metagabbro is green in color, medium- to coarse-grained, and schistose. The typical mineral assemblage includes actinolite, plagioclase, and clinozoisite with minor sphene and cummingtonite. Clinopyroxene and hornblende are primary relict igneous minerals.

Actinolite and hornblende are the two most abundant minerals and together comprise as much as 65 percent of the rocks. Grains are typically subhedral to anhedral and about 1 mm in size. The amphiboles are frequently twinned, especially near grain edges. Additionally, actinolite commonly overgrows hornblende.

Clinozoisite is also an abundant mineral, comprising about 33 percent of the rocks. It occurs as very small (< 0.5 mm) bladed laths forming an aggregate of grains between the much larger amphiboles.

Plagioclase makes up as much as 12 percent of the metagabbro. Grains are generally small (< 0.5 mm) and commonly show twinning and/or zoning.

Sphene, cummingtonite, and clinopyroxene are present in minor amounts (typically < 1 percent). Sphene is commonly present as small masses randomly scattered throughout the metagabbro. Cummingtonite is most commonly present in the center of the other amphiboles and is distinguished by multiple twinning. The clinopyroxene is subhedral to anhedral, exhibits typical pyroxene cleavage, is commonly fractured, and approximately 1 mm in size. Exsolution lamellae occur locally. Along grain boundaries, clinopyroxene is commonly partially replaced by amphiboles.

Structure

General Statement

Two deformation events, D_1 and D_2, have been recognized based on field studies and thin section examination (Table 4). It should be noted that D_1 and D_2 refer to the same structural events affecting the Catfish mafic complex and the Lynchburg II host rocks.

The dip-directions of the rocks are consistently towards the southeast, following the regional trend. The dip-angles of the rocks are generally steep, ranging from 56° to 90°, but shallower dips exist (i.e., 42° to 49°).

Only small scale faults have been observed in the vicinity of the Flat Creek mafic-ultramafic complex; no regional scale faults have been recognized. Field mapping shows that even though small outcrop scale folds are common, no regional scale folds have been recognized in the Lynchburg Group rocks (this study; Wang, 1991). The stratigraphy is not repeated. Additionally, there is no evidence for shearing greater than a half meter found on either the thin section or outcrop scale.

D_1 Deformation

The Flat Creek complex and metasedimentary host rocks were most strongly affected by the D_1 deformation. A pervasive foliation (S_1) is the primary indication of this event. In the Lynchburg III metasediments, S_1 is defined by oriented micas and flattened quartz-feldspar aggregates (Wang, 1991). S_1 is oriented nearly parallel to bedding.

The S_1 foliation is defined by oriented chlorite, phlogopite, and serpentine in the ultramafic rocks. It is defined by oriented amphiboles and flattened feldspar in the metagabbro. The foliation in the Flat Creek mafic and ultramafic rocks is parallel to that in the Lynchburg III host rocks, striking northeast-southwest and dipping southeast.

Table 4. Summary of the structure and metamorphism of the Flat Creek mafic-ultramafic complex and host rocks.

Age*	Structure	Metamorphism
Late Paleozoic (Alleghanian?)	D_2: localized crenulation cleavage and kink bands; microfolds situated in plane of the S_1 foliation.	M_2: little evidence preserved in either the host rocks or the mafic and ultramafic rocks.
Early Paleozoic (Cambrian or Taconic?)	D_1: pervasive foliation (S_1) defined by oriented micas and flattened quartz-feldspar aggregates in metasedimentary host rocks; S_1 defined by oriented micas and serpentine in ultramafic rocks and by oriented amphiboles and flattened feldspar in the metagabbros; S_1 oriented nearly parallel to bedding (S_0).	M_1: prograde metamorphism ranging from greenschist to epidote-amphibolite facies.

* Ages of deformation and metamorphism are from Glover and others (1995).

D_2 Deformation

The second deformation event is of low intensity and is only locally developed. D_2 structures are oriented subparallel to D_1 structures. This event is characterized by kink bands in the serpentinite and metapyroxenite of the Flat Creek complex. Additionally, small microfolds (F_2), have been observed in the mafic and ultramafic rocks in the field.

Evidence of the second deformation event in the Lynchburg III Group rocks is characterized by crenulation of the more micaceous rocks (Wang, 1991).

Metamorphism

General Statement

Two regional metamorphic events have affected the Flat Creek mafic-ultramafic complex and the metasedimentary host rocks of the Lynchburg III Group (Table 4). Petrographic observations of samples from the study area as well as microprobe analyses of both mafic and sedimentary protoliths by Wang (1991), suggest a prograde metamorphism to greenschist facies. A retrograde metamorphism of very low intensity occurred subsequent to the first event. These two metamorphic events are the same regional events affecting the Catfish mafic complex and Lynchburg II host strata. However, the Catfish rocks are at a higher grade than the Flat Creek and Lynchburg III rocks because the metamorphic grade increases down-section (Wang, 1991).

M_1 Metamorphism

The Flat Creek mafic and ultramafic rocks contain assemblages representative of greenschist facies. The stable greenschist facies assemblage in the metagabbro is actinolite + clinozoisite + plagioclase + sphene, and in the ultramafic rocks is serpentine + chlorite +

tremolite + talc + magnetite. Evidence for metasomatism is present at the top margin of the Flat Creek body, where there is a notable change in mineral composition. In metagabbro thin sections 15 cm to 4 cm from the contact with the host strata, amphibole and plagioclase present in the metagabbro were replaced by clinozoisite and quartz. The percentage of amphibole falls to about 10 percent and plagioclase to 4 percent. Clinozoisite accounts for as much as 52 percent of the rock and as much as 30 percent quartz is present. These effects are not seen in the Lynchburg host rocks.

In the Lynchburg III metasedimentary rocks, the stable greenschist metamorphic mineral assemblage is quartz + muscovite + biotite + plagioclase + epidote ± magnetite (Wang, 1991). The micas that define the S_1 surfaces indicate that M_1 is synchronous with D_1 (Wang, 1991).

M_2 Metamorphism

The second metamorphism was a retrograde event of very low intensity. This event occurred with D_2 and is marked by the rare replacement of phlogopite by chlorite.

Contact Relations

The lower contact between the Flat Creek body and the Lynchburg rocks is generally not exposed, but it can be constrained to less than about 1 meter. However, mapping it provided useful information about the size of the mafic-ultramafic complex and its general concordancy with the host strata. The host rocks show well-preserved bedding, graded beds, and parallel laminations. There is no evidence of intense shearing in either the host rocks or Flat Creek rocks on either the thin section or outcrop scales.

Field relations indicate that the Flat Creek suite of rocks represents an irregularly layered body, with ultramafic rocks at the base and gabbroic rocks on top (figure 10). The

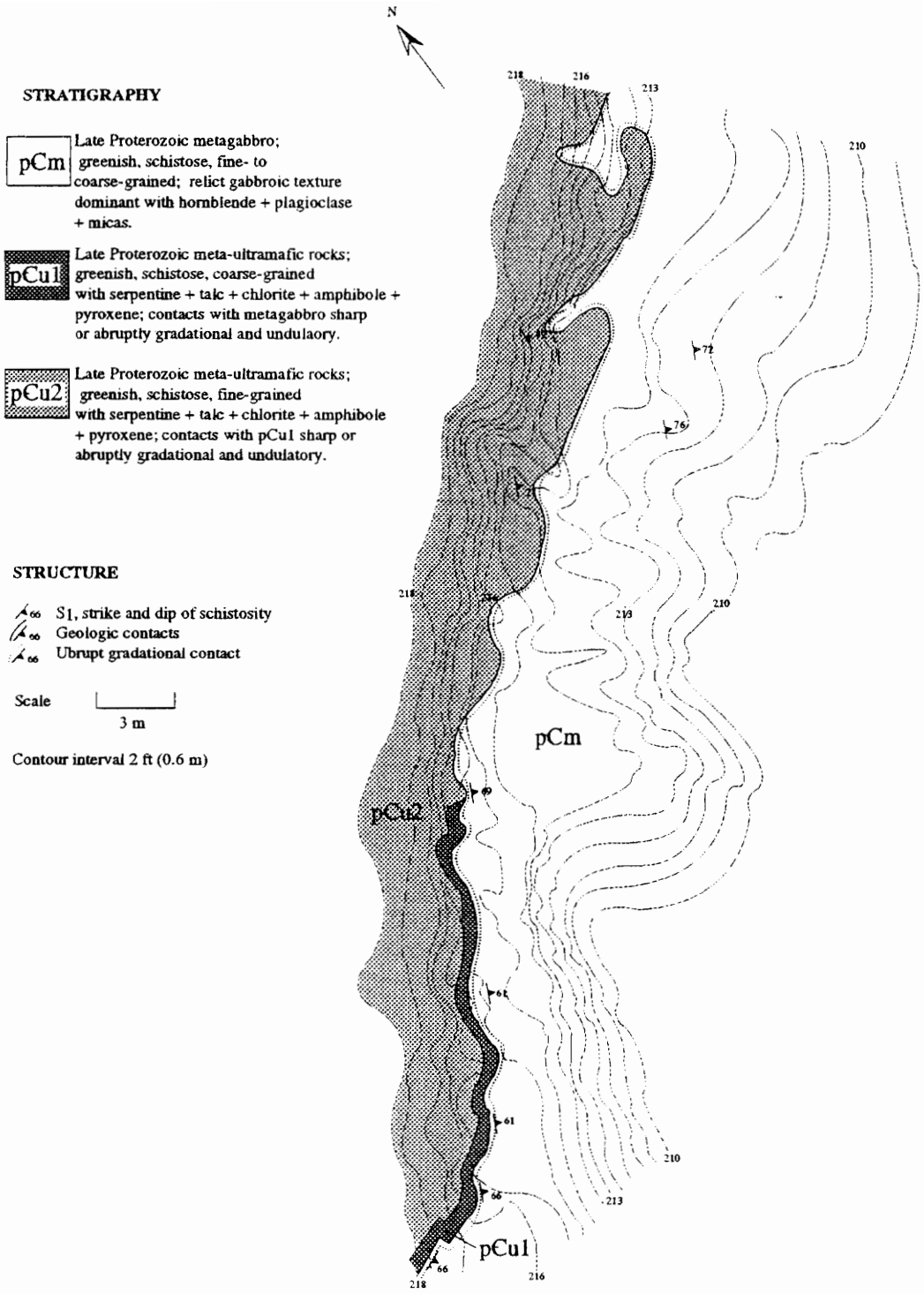

Figure 10. Outcrop map of Flat Creek mafic-ultramafic body at Walmart shopping center, Lynchburg, Virginia. Contacts and contours surveyed by plane table and alidade and coordinated with the Lynchburg 7.5' topographic sheet.

mafic and ultramafic layers are generally lenticular in shape. Only minor, small-scale shearing and faulting is present and is confined to within the complex (figure 8). Cross-cutting dikes in the Flat Creek complex indicate offset related to internal faulting to be on the order of half a meter or less (figure 8). Contacts within this body have been identified as irregular boundaries separating the metagabbro and the ultramafics (figures 8 and 10). In general, these contacts are sharp to abruptly gradational and highly undulatory (figure 11). However, the contact is locally gradational over about 1 meter. This is evidenced by the increase in the amount of feldspar present in the rocks. Additionally, rounded autoliths of metagabbro, which are typically several centimeters to half a meter in size, have been observed in the ultramafic rocks, and are commonly, but not always, bounded by dark rims (figure 12). Ultramafic autoliths, which are much more angular and of similar size, are also found within the metagabbro.

The upper contact between the Flat Creek rocks and the metasedimentary envelope rocks is generally concordant and sharp. Primary sedimentary features such as bedding, graded beds, and parallel laminations are preserved in the host strata and are undisturbed at the contact with the Flat Creek complex. There is no evidence for a contact aureole in the host rocks. Additionally, as much as 7 meter thick xenoliths of the Lynchburg III occur inside the Flat Creek complex. Where the xenolith contact is exposed, it is sharp, concordant, and without evidence of faulting or intense shearing.

Figure 11. Contact between the mafic and ultramafic rocks of the Flat Creek complex. The contact is sharp and irregular. The ultramafic rock is to the left and the mafic rock is to the right. Pen is for scale.

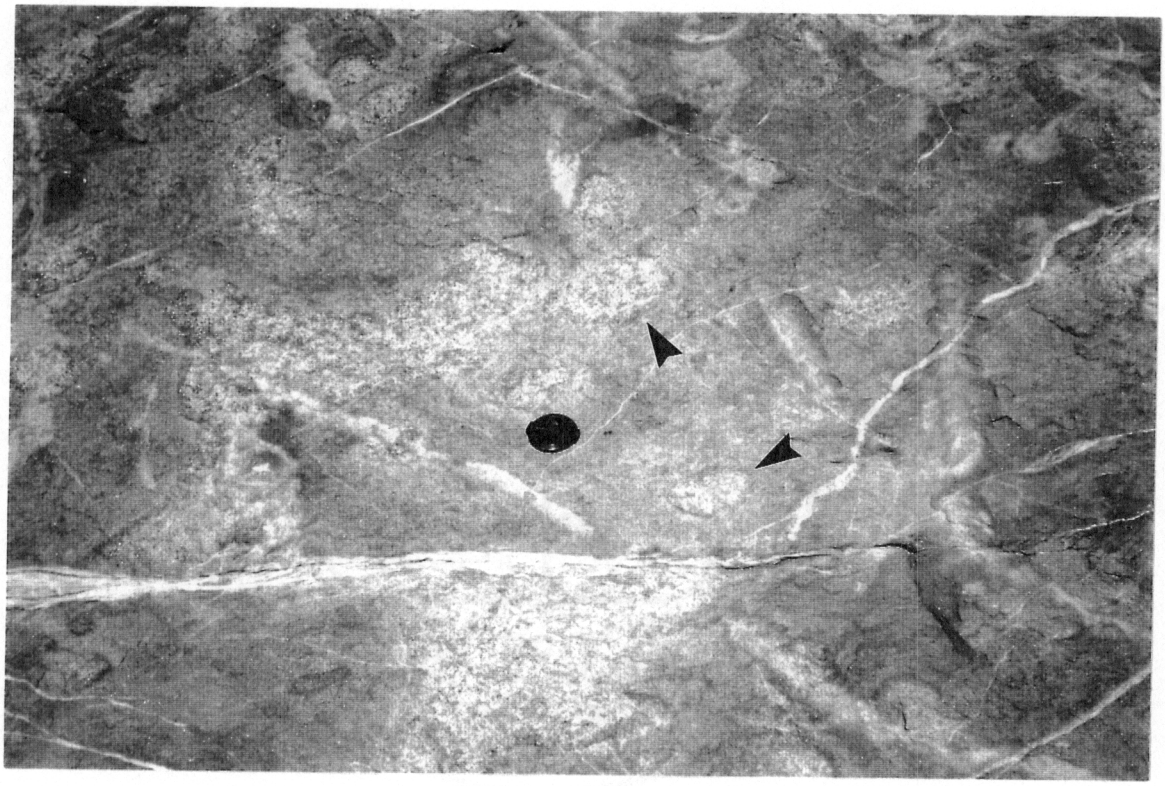

Figure 12. Metagabbro autoliths, several centimeters in size, within the ultramafic rocks of the Flat Creek complex. The dark rims bounding the autoliths are a commonly observed feature. Lens cap is for scale.

Discussion and Conclusions

The Flat Creek body is conformable with stratigraphic layering as indicated by the stratigraphy of the Lynchburg host rocks and the Flat Creek complex. The host rocks appear to form a continuous and conformable stratigraphic sequence which is not broken by faults. Additionally, there is no evidence of any mélange, as proposed by many workers (e.g., Rankin, 1994; Rankin and others, 1989; Horton and others, 1989; Keppie and others, 1989; Hatcher, 1989; Hatcher, 1987). The degree of preservation of bedding, graded beds, and parallel laminations commonly seen throughout the Lynchburg Group would not be present in a mélange or near thrust-related ophiolites. Also, field mapping revealed that the Flat Creek complex is layered and comprised of ultramafic rocks at the base and gabbroic rocks at the top. These relations suggest that the Flat Creek body is a sill and not part of an ophiolitic mélange.

The layering and petrography of the Flat Creek complex also suggests that it originated as an intrusive body, with ultramafic rocks at the base and metagabbro at the top. However, this body is not typical of a normally layered igneous body, which is commonly thought to be the result of crystal settling in which a single magma is involved. Instead, the sharp to abruptly gradational irregular contacts and the overall lenticular shape of the mafic and ultramafic layers indicate that multiple intrusion into the same sill complex must have taken place. This is also supported by the occurrence of metagabbro autoliths in the ultramafic rocks and vice versa. The angularity of the ultramafic autoliths as compared to the more rounded character of the metagabbro autoliths suggest reciprocal mixing of the magmas at different times and different locations due to the movement of the magma. The dark reaction rims surrounding the metagabbro autoliths suggest residuum melting during gabbro injection into a hotter magma. Additionally, the metasomatism present at the top

margin of the complex suggests that some water moved from the host rocks into the intrusion during M_1 (i.e., metasomatism), causing a breakdown of plagioclase and amphibole to form clinozoisite and quartz. Because the primary mineral assemblages were anhydrous implying an initially dry magma, there would not have been enough water present to cause significant metamorphism during intrusion. However, if a contact aureole had been initially present, it is likely that it would have been only weakly developed and was overprinted by the regional metamorphism (M_1).

While the nature of the magmatic origin of this meta-igneous intrusive complex is beyond the scope of this study, it is worthwhile to speculate. The rocks could have originated from an ultramafic (komatiitic) magma. However, this is probably unlikely because of the high temperatures required (1750 °C) (Cox, 1980). While an ultramafic origin is unlikely, it cannot be completely discounted, as rocks derived from such magmas do exist. Examples include the Zwartwater Suite of southeast Transvaal, South Africa (Verbeek and Hunter, 1993), komatiites from Cape Smith, Quebec, Canada (Bedard, 1987), and Gorgona Island, Columbia (Echevaria, 1980), and local occurrences of near-ultramafic picritic basalts in the Appalachians (Hess, 1933; Tracy et al, 1984). However, the most obvious explanation for the abundance of the mafics and ultramafics in the central Virginia Blue Ridge is that the primary magmas were high-Mg picrites which underwent low-pressure fractionation to produce the suite of rocks present, as suggested by Wang and Glover (in press), based upon chemical analyses of amphibolites and greenstones of igneous origin from the Lynchburg city area. A similar process has been suggested by Husch (1990) as an alternative origin for the Palisades sill. Therefore, the multiple intrusion of a fractionating picritic magma and derivative olivine- and pyroxene-rich crystal mush may explain the origin of the Flat Creek complex, which is part of the mafic-ultramafic association in the Appalachians (Misra and Keller, 1978; Wilson, 1989).

However, the local occurrence of gradational contacts between the metagabbro and ultramafic rocks over about a meter does suggest that crystal settling may have locally been one of the many dynamic processes involved during intrusion.

Regardless of magmatic origin, the Flat Creek sill was emplaced into the Lynchburg host strata before either of the two regional structural and metamorphic events. The mineral compositions of the rocks as well as the presence of both the S_1 and S_2 fabrics indicate that the mafic and ultramafic rocks of the Flat Creek intrusive underwent the same two episodes of deformation and metamorphism as the host rocks.

Therefore, the evidence presented herein indicates that the Flat Creek mafic-ultramafic complex and the Lynchburg Group host rocks do not support an ophiolite stratigraphy. Instead, the Flat Creek complex originated as an irregularly layered sill that resulted from multiple intrusion of a fractionating picritic magma into the Lynchburg host strata during continental rifting.

THE SCHUYLER MAFIC- ULTRAMAFIC COMPLEX

Introduction

The Schuyler mafic-ultramafic complex is located in the Rockfish River area at Schuyler, Virginia (figure 1). It is one of a number of bodies that comprise the Albemarle-Nelson soapstone deposits of Burfoot (1930). The Schuyler complex is a long body (< 10 km) which is located near the top of the Charlottesville Formation of the Late Proterozoic age Lynchburg Group (figure 13). It is along strike with and similar to the mafic-ultramafic association of the Lynchburg City area (figure 1).

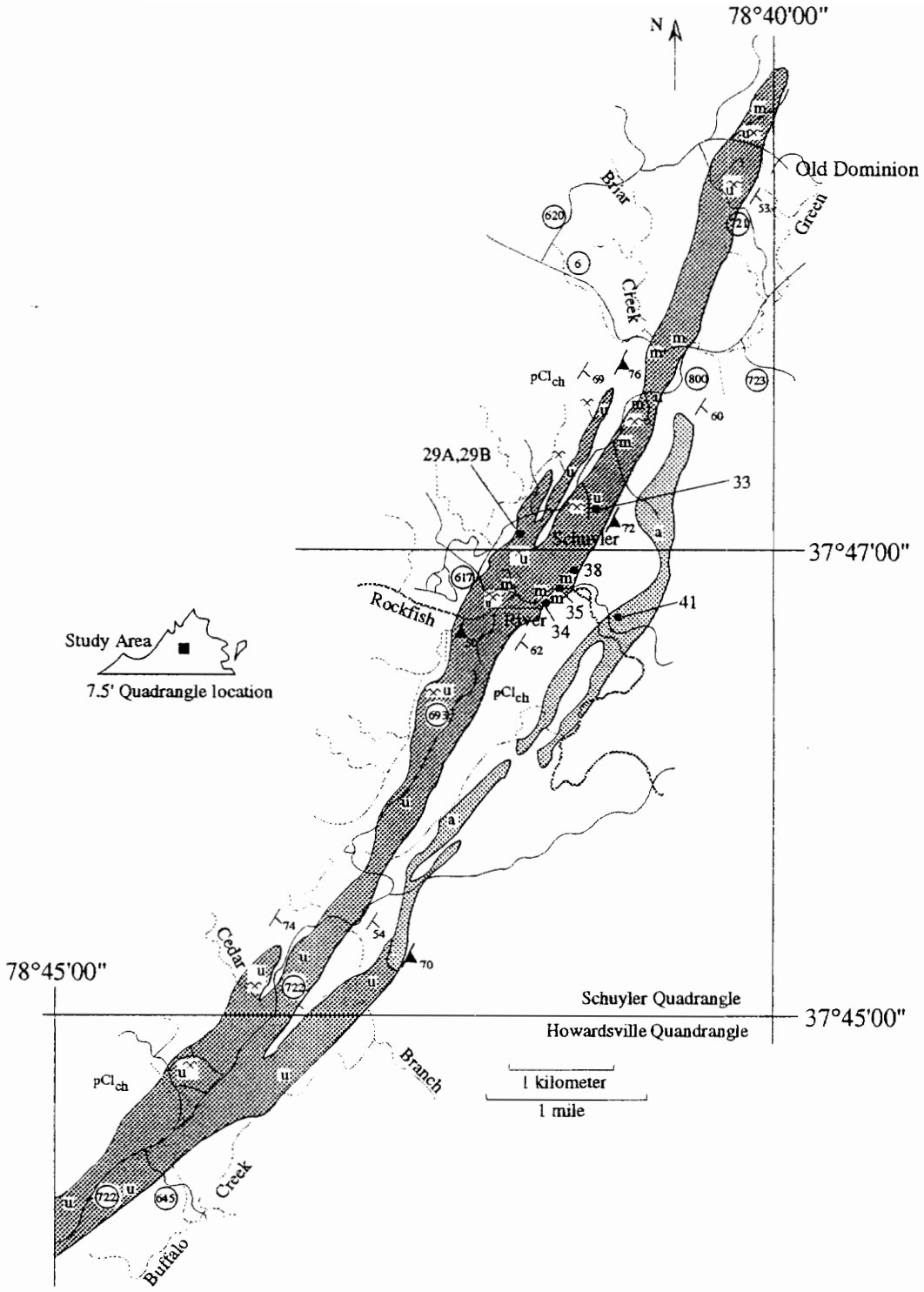

Figure 13. Map of the Schuyler mafic-ultramafic complex, Schuyler, Virginia.

EXPLANATION

Stratigraphy

Schuyler mafic-ultramafic complex

pCl_{S-u} Ultramafic rock (u): soapstone and serpentinite; greenish to gray, fine-grained, schistose; locally contains screens of pCl_{ch}

pCl_{S-m} Mafic rock (m): metagabbro and granophyric metagabbro; green, medium-grained; massive to schistose; locally contains screens of pCl_{ch}

pCl_{S} Metadiorite: greenish tan, medium- to coarse-grained; massive to schistose

pCl_{a} * Amphibolite(a): hornblende metagabbro; dark greenish black to black, medium- to coarse-grained; in contact with Schuyler mafic-ultramafic complex

Late Proterozoic Lynchburg Group

pCl_{ch} * Charlottesville Formation: medium gray, coarsely laminated to thick bedded, fine- to coarse-grained feldspathic sandstone, siltstone, and mudstone; intercalated mafic and ultramafic rocks

Structure

45 S_0, strike and dip of bedding

58 S1,strike and dip of schistosity

Geologic contacts

• Sample locations

Figure 13. (continued) Map of the Schuyler mafic-ultramafic complex, Schuyler, Virginia. * From Wehr (1985).

Host Rocks

The Lynchburg Group in the Rockfish River area of central Virginia was divided into five formations by Wehr (1985), from oldest to youngest: Rockfish Conglomerate, Thorofare Mountain Formation, Ball Mountain Formation, the Charlottesville Formation, and the Swift Run Formation. According to Wang (1991), the Charlottesville Formation, which envelopes the Schuyler mafic-ultramafic complex, is approximately the stratigraphic equivalent of Lynchburg III in the Lynchburg City vicinity (figure 14).

The Charlottesville Formation is comprised of the following units (Wehr, 1985; the current study): schistose siltstone and mudstone with isolated beds of medium- to coarse-grained, metasandstone. The sandstone beds vary from a few millimeters to a meter in thickness. Primary sedimentary features such as graded beds, horizontal stratification, and flame structures are common. Major minerals are quartz, plagioclase, and biotite. Wehr (1985) suggested that these rocks were deposited by turbidity currents in deep water on the basis of abundant primary sedimentary structures and textures. For a more detailed description of the rocks of the Charlottesville Formation, the reader is referred to Wehr (1985).

Mafic-Ultramafic Complex

The Schuyler mafic-ultramafic complex is as much as 274 meters thick and at least 10 kilometers long (figure 13). The details of the contact relations are discussed later.

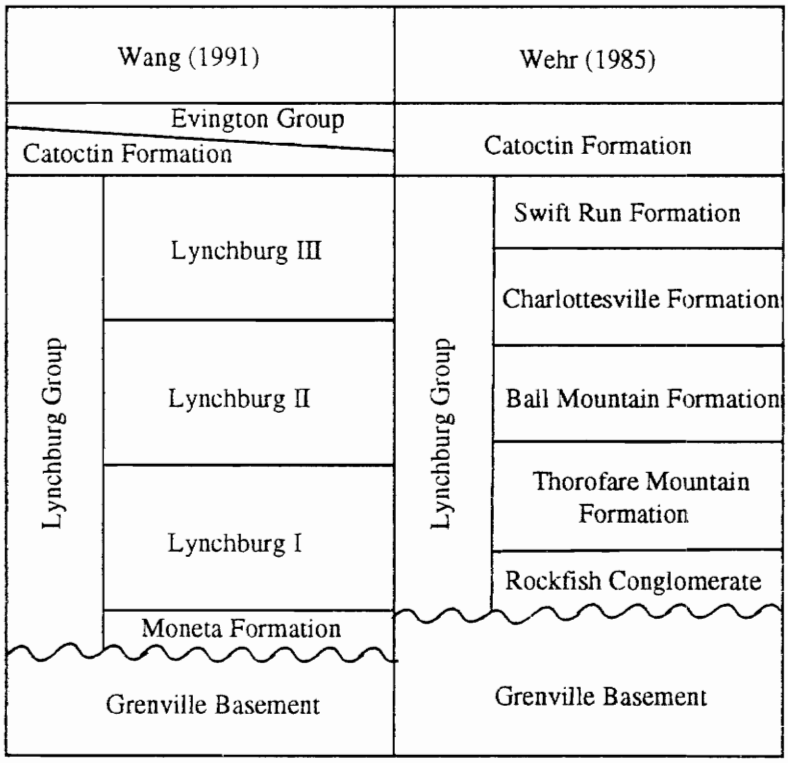

Figure 14. Stratigraphic correlation of the cover sequence rocks in the Lynchburg and Schuyler, Virginia areas (adapted from Wang, 1991).

Petrography

At least six rock types comprise the Schuyler mafic-ultramafic body. They are: soapstone, serpentinite, metagabbro, hornblende metagabbro, granophyric metagabbro, and metadiorite (Table 5). Due to poor outcrop exposure, only seven thin sections were examined (figure 13). At least 500 points per sample were counted for modal compositions.

Soapstone

The soapstone is light gray in color, generally fine-grained, and schistose. The typical assemblage of minerals includes talc, magnesite, chlorite, serpentine, and magnetite. The protolith of the soapstone is believed to have been peridotite, based upon composition.

Commonly, talc is the most abundant mineral, and makes up as much as 45 percent of the rocks. Talc may be several millimeters in length and defines the foliation. Additionally, it is present along the rims of magnesite veins, where it is oriented parallel to the foliation.

Magnesite, which may comprise as much as 47 percent of the soapstone, occurs in small veins usually less than 2 cm thick and few cm long, and as pseudomorphs ranging in size from less than 0.5 mm to 1 cm. The magnesite pseudomorphs are probably after pyroxene and/or olivine, based upon their shape. The largest pseudomorphs commonly contain inclusions of chlorite, talc, magnetite, and even small (< 0.5 mm) magnesite grains.

Chlorite makes up about 20 percent of the rocks. It exhibits olive drab interference colors, which suggest it is Mg-rich. Chlorite also defines the foliation, and with talc, occurs along the margins of magnesite grains in the preferred orientation.

Table 5. Petrography of the Schuyler mafic-ultramafic complex.

Rock Type and Sample #'s	Petrographic Features	Mineralogy	Probable Protoliths
soapstone (29A, 29B)	light gray, fine-grained, schistose, large pseudomorphs common; preferential orientation of talc and chlorite.	talc (24-45%) + magnesite (18-47%) + chlorite (17-20%) + serpentine (4-13%) + magnetite (5-6%)	peridotite
serpentinite (33)	dark greenish, fine-grained, schistose; pseudomorphs after olivine and relict igneous (cumulate) textures preserved.	serpentine (36%) + chlorite (21%) + talc (12%) + tremolite (12%) + magnetite (9%) + magnesite (3%)	peridotite
metagabbro (41)	green, medium-grained, massive to schistose; kink bands in chlorite and cummingtonite.	hornblende (55%) + clinozoisite (25%) + plagioclase (6%) + chlorite (4%) + muscovite (4%) + cummingtonite (3%) + sphene (2%)	gabbro
granophyric metagabbro (38)	greenish, medium-grained, massive to schistose; metamorphic overgrowth textures; granophyric texture.	actinolite/hornblende (40%) + plagioclase (20%) + clinozoisite (16%) + chlorite (9%) + sphene (7%) + biotite (3%) + quartz (3%) + magnetite (1%)	granophyric gabbro
felsic rock (34)	greenish tan, medium- to coarse-grained, massive to schistose.	epidote (33%) + clinozoisite (22%) + quartz (23%) + hornblende (14%) + sphene (8%) + feldspar (1%) + magnetite (1%) + chlorite (< 1%) + biotite (< 1%)	----------

Serpentine is commonly present in relatively small amounts, comprising less than 13 percent of the soapstones. It is not asbestiform and is randomly scattered throughout the rocks. It is always associated with talc and chlorite, which replace the serpentine. Serpentine is commonly dusted with magnetite.

Magnetite is minor amounts, generally less than 5 percent. It generally occurs as dustings in the more abundant minerals, or as small (< 0.5 mm) grains randomly scattered throughout the soapstone.

Serpentinite

Serpentinite is dark greenish gray in color, typically fine-grained, and schistose. The typical mineral assemblage includes serpentine, chlorite, talc, tremolite, magnetite, and magnesite. The protolith of the serpentinite is believed to have been peridotite, based upon composition.

Serpentine is the most abundant mineral, and constitutes as much as 36 percent of the rocks. It occurs mainly as 0.5 mm to about 1.5 mm pseudomorphs after olivine as evidenced by its shape (figure 15). The outlines of these former olivine grains are equigranular and subhedral to euhedral. Serpentine is commonly rimmed by talc, magnesite, magnetite, and tremolite. Locally, it is partially to fully altered to talc. Also, magnetite dustings are commonly observed in the serpentine.

Chlorite makes up about 21 percent of the serpentinite. Grain size is highly variable, ranging from < 0.25 mm to about 1.5 mm. It exhibits the anomalous blue and olive drab interference colors of magnesium-rich chlorite. It is commonly dusted with magnetite. Some of the larger chlorite grains poikilitically enclose serpentine pseudomorphs after olivine.

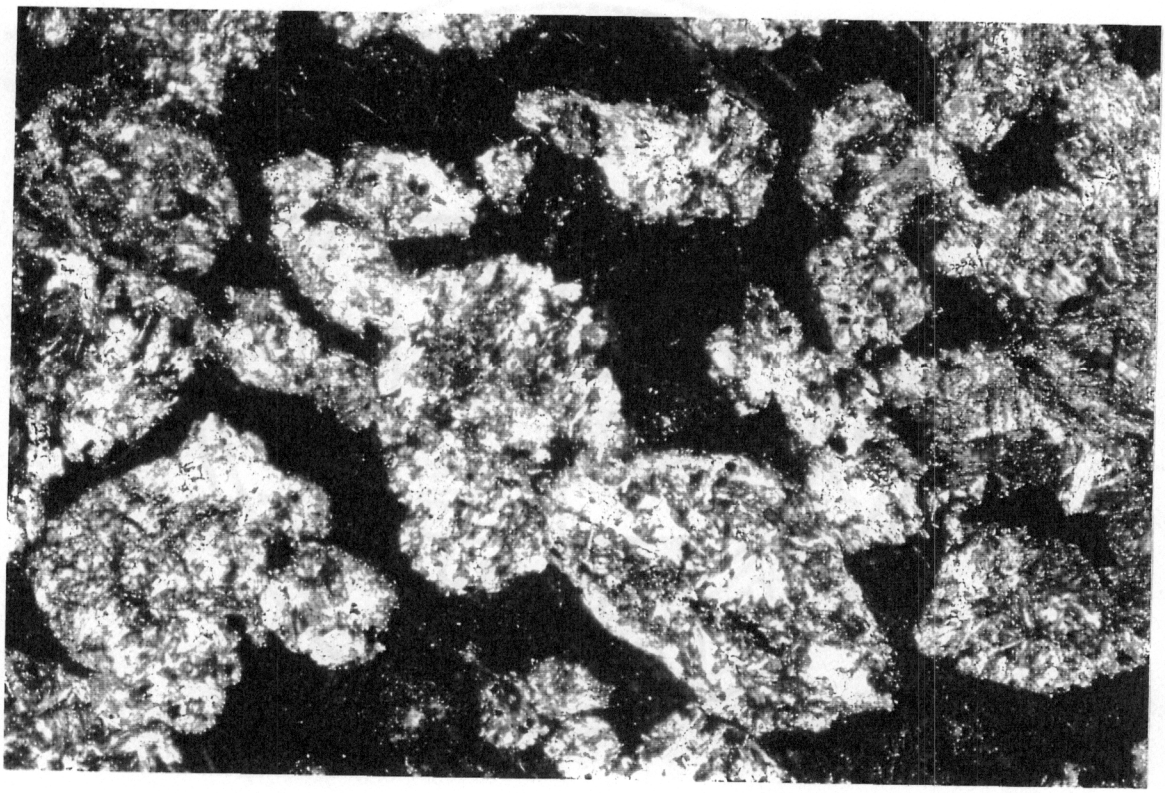

Figure 15. Serpentine pseudomorphs after olivine in serpentinite. Horizontal field of view is about 3.5 mm across; cross-polarized light.

Talc comprises about 18 percent of the rocks and is found along the edges of former olivine grains that are now entirely pseudomorphed by serpentine. It is an alteration product of serpentine, especially around the pseudomorph edges.

Tremolite makes up about 12 percent of the soapstones. The grains are typically very small and mostly anhedral. Tremolite is most commonly scattered randomly through the rocks and appears to be replaced by chlorite.

Magnetite and magnesite occur in lesser amounts than other minerals. Magnetite may comprise as much as 9 percent of the soapstones and commonly occurs as dustings on serpentine and chlorite grains or as small (< 0.5 mm) randomly scattered grains. It also outlines former olivine grains that have been completely replaced by serpentine. This is an important feature as it preserves relict cumulate igneous texture and it provides a clue as to the original composition of the rock. Magnetite was formed during serpentinization because all of the iron in the magnesium site of olivine and pyroxene cannot be accommodated in the serpentine (Hyndman, 1985). Magnesite only makes up about 3 percent of the rocks and occurs as an alteration product of serpentine. It commonly rims the serpentine.

Metagabbro

The metagabbro is green in color, medium-grained, and massive to schistose. The typical assemblage of minerals includes clinozoisite, plagioclase, chlorite, muscovite, cummingtonite, and sphene. Hornblende is a primary relict igneous mineral. This rock is compositionally very similar to the Flat Creek metagabbro.

Hornblende is the most common mineral present and accounts for as much as 55 percent of the rocks. Grains are subhedral to anhedral and as large as 1.5 mm in size.

Locally, it shows typical amphibole cleavage and is commonly twinned. Intergrowths of hornblende are common.

Clinozoisite comprises as much as 25 percent of the metagabbro. It is typically very small (< 0.25 mm), but grains as large as about 0.5 mm are present. Clinozoisite fills spaces between larger hornblende, forming an aggregate of grains.

Plagioclase makes up about 6 percent of the rocks. The grains are very small (< 0.25 mm) and locally twinned. They are interspersed between clinozoisite grains.

Chlorite comprises about 4 percent of the metagabbro. Grain size is very small, usually about 0.25 mm. Like the plagioclase, it is interspersed between clinozoisite grains.

Cummingtonite makes up about 3 percent of the rocks. It is distinguished by its characteristic narrow length-parallel twins. Cummingtonite locally rims hornblende.

Muscovite and sphene comprise about 5 percent of the rocks. The muscovite occurs as very small (< 0.25 mm) randomly oriented grains. The sphene occurs as small masses randomly scattered throughout the metagabbros.

Hornblende metagabbro

The hornblende metagabbro is very similar to the hornblende metagabbro of the Catfish mafic complex. It is greenish in color and consists largely of hornblende and plagioclase. Accessory minerals include clinozoisite, sphene, magnetite, and quartz.

Hornblende, which makes up as much as 60 percent of the rock, is subhedral to anhedral, inequigranular, and ranges in size from < 0.5 mm to 2 mm. It is commonly twinned and locally shows typical amphibole cleavage. Hornblende is commonly poikiloblastic. Intergrowths are not uncommon.

Plagioclase comprises as much as 25 percent of the hornblende metagabbro. Plagioclase crystals are typically lath shaped, twinned, and zoned. It is partially replaced by clinozoisite.

Clinozoisite, sphene, magnetite, and quartz account for about 15 percent of the rock. Clinozoisite occurs as very small grains (< 0.25 mm) and is distinguished by its high relief and anomalous blue to yellow interference colors. Sphene commonly occurs as rims on magnetite and replaces hornblende. Magnetite is always mantled by sphene. Quartz is closely associated with plagioclase.

Granophyric metagabbro

The granophyric metagabbro is greenish in color, medium-grained, and massive to schistose. It contains the following assemblage of minerals: hornblende, actinolite, plagioclase, clinozoisite, and chlorite, with lesser sphene, biotite, quartz, and magnetite. Hornblende is present as a primary relict igneous mineral.

Hornblende and actinolite comprise about 40 percent of the rocks. Grains are typically subhedral to anhedral and as much as 1 mm in size. These amphiboles locally show typical amphibole cleavage. Hornblende is commonly overgrown by actinolite.

Plagioclase makes up as much as 20 percent of the metagabbro. Commonly, grains may be as large as 2 mm, are lath shaped, subhedral to euhedral, and twinned. Composition was estimated at about An_{46} (andesine) by the Michel-Levy method. It is commonly sausseritized and altered to chlorite. However, the most striking feature observed in this metagabbro is the presence of igneous granophyric texture (figure 16). In gabbro, it occurs as a final interstitial product of eutectic or cotectic crystallization (Shelley, 1993).

Figure 16. Relict granophyric texture in granophyric metagabbro. Horizontal field of view is about 1.4 mm across; cross-polarized light.

Clinozoisite comprises about 16 percent of the granophyric metagabbro. It occurs as small (< 0.5 mm) bladed laths and aggregates. Locally, clinozoisite shows anomalous interference colors.

Chlorite makes up about 9 percent of the granophyric metagabbro. Grains are about 0.25 mm in size. It exhibits the anomalous blue interference colors of magnesium-rich chlorite. It commonly replaces both plagioclase and biotite.

Sphene, biotite, quartz, and magnetite collectively comprise about 15 percent of the granophyric metagabbro. Magnetite is surrounded by sphene. Locally, amphiboles are replaced by sphene and biotite. Chlorite locally replaced biotite. Quartz is intergrown with the plagioclase to produce granophyric texture, typical of shallow to intermediate depths of emplacement (Tuttle and Bowen, 1958; Briggs and others, 1978).

Metadiorite

These rocks are greenish tan in color, typically medium- to coarse-grained, and massive to schistose. The typical mineral assemblage includes epidote, clinozoisite, quartz, hornblende, and sphene, with minor magnetite, chlorite, biotite, and feldspar.

Epidote is the most abundant mineral, comprising as much as 33 percent of the metadiorite. Grains are typically small (< 0.25 mm) and form aggregates that overgrow quartz and hornblende.

Clinozoisite is also abundant, making up as much as 22 percent of the rocks. Its character is very similar to the epidote; grains are typically small (< 0.25 mm), though larger grains have been observed, and aggregates with epidote are common.

Quartz makes up about 14 percent of the metadiorite. Grains may be as large as 3 mm in size. Serrated grain boundaries and undulose extinction are common.

Hornblende comprises about 14 percent of the rocks. Grains are typically subhedral to anhedral and between 0.5 mm and 3.0 mm in size. It is commonly twinned and shows typical amphibole cleavage. The hornblende is replaced by epidote, clinozoisite, sphene, and chlorite.

Sphene comprises about 8 percent of the rocks. It commonly encloses magnetite and overgrew hornblende.

Magnetite, chlorite, biotite, and feldspar account for less than 3 percent of the metadiorite. Magnetite is always mantled by sphene. Chlorite occurs as an alteration product. Biotite is generally partially chloritized. Feldspar is very rare.

Structure

General Statement

The two recognized deformation events, D_1 and D_2, are probably the same events that affected the mafic-ultramafic association and related host rocks in the vicinity of Lynchburg (Table 6). However, the deformation is not as intense in the Schuyler area. The rocks generally dip steeply to the southeast, from 52° to 90°. Way-up criteria such as graded beds indicate younging consistently toward the southeast (Wehr, 1983). Wehr (1983) recognized a small-scale thrust fault in the Schuyler area. However, work to the north by Kasselas (1993) has thrown into doubt the existence of a large fault in the Lynchburg Group. Also, there is no evidence on either the outcrop or thin section scale for dextral transpressional shearing related to deformation.

D_1 Deformation

This first structural event had the greatest impact on the Schuyler complex and the Charlottesville Formation host rocks. The S_1 pervasive foliation, which is the primary

Table 6. Summary of the structure and metamorphism of the Schuyler mafic-ultramafic complex and host rocks.

Age*	Structure	Metamorphism
Late Paleozoic (Alleghanian ?)	D_2: localized crenulation cleavage in metasedimentary host rocks; kink bands in mafic and ultramafic rocks.	M_2: greenschist facies; retrograde metamorphism evidenced by replacement of hornblende and biotite by chlorite.
Early Paleozoic (Cambrian or Taconic ?)	D_1: pervasive foliation (S_1) defined by oriented micas in metasedimentary host rocks and rocks of Schuyler complex; S_1 oriented nearly parallel to bedding (S_0).	M_1: greenschist facies metamorphism.

* Ages of deformation and metamorphism are from Glover and others (1995).

evidence for the D_1 deformation, is defined by oriented biotite in the host rocks (this study; Wehr, 1983). S_1 is oriented subparallel to bedding (S_0). In the mafic and ultramafic rocks, S_1 is defined by oriented chlorite, talc, and amphiboles. The foliation in the rocks of the Schuyler complex is parallel to that in the Charlottesville Formation, striking northeast-southwest and generally dipping southeast. Wehr (1983) reported that evidence for F_1 folding related to D_1 is very rare.

D_2 Deformation

The second deformation event, D_2, is only observed locally and is not pervasive. It is characterized by a crenulation cleavage and kink bands. The crenulation cleavage is mostly confined to the more pelitic rocks in the Charlottesville Formation (Wehr, 1983). Kink bands are rare and can be seen in thin section, where they are confined to the amphiboles and chlorite grains in the mafic and ultramafic rocks. Additionally, F_2 folds have been reported by Wehr (1983) on both the outcrop and thin section scales. The folds are tight to isoclinal, trend to the northeast, and plunge northward.

Metamorphism

General Statement

Petrographic observations of samples from the study area suggest the Schuyler complex and the host rocks of the Charlottesville Formation were subjected to greenschist facies metamorphism which was followed by a retrograde event of very low intensity (Table 6). This metamorphism is probably the same as that affecting the rocks in the Lynchburg area. However, the grade of metamorphism decreases along strike from Lynchburg towards Schuyler (Wang, 1991). Additionally, as with the Flat Creek complex,

there is evidence of metasomatism related to the regional metamorphism at the top of the Schuyler body.

M_1 Metamorphism

The Schuyler mafic and ultramafic rocks and the host rocks contain assemblages representative of greenschist facies. The stable greenschist facies assemblages in the ultramafic rocks is talc + serpentine + chlorite ± tremolite + magnetite + magnesite, and the mafic rocks is actinolite + plagioclase + clinozoisite + chlorite + sphene. The metadiorite near the top of the Schuyler complex has been metasomatized; amphiboles and plagioclase were altered to epidote, clinozoisite, and quartz. These rocks are quite similar to the rocks occurring at the top of the Flat Creek body.

In the metasedimentary host rocks of the Charlottesville Formation, the stable metamorphic mineral assemblage is quartz + plagioclase + micas, which is also greenschist facies. Greenschist facies minerals such as talc, chlorite, and micas define the S_1 surfaces which indicate that metamorphism and deformation are synchronous.

M_2 Metamorphism

Retrograde metamorphism of the Schuyler body and its host rocks was of minor intensity. Evidence for this event includes replacement of hornblende and biotite by chlorite. Chlorite replaced biotite along kink bands, which indicates that this second metamorphism occurred with D_2.

Contact Relations

The contact between the host rocks and the Schuyler complex is most commonly saprolitic (figure 17), but the rock types and structures are still discernible. Detailed

Figure 17. Saprolite contact between metasedimentary host rocks and ultramafic rock at the base of the Schuyler complex. The host rocks are to the left and the ultramafic rock is to the right. Pocket knife is on contact and is for scale.

observations indicates that the contacts are mostly concordant. One such contact is present at the base of the complex between the ultramafic rock and the host rocks (figure 17). Thin graded beds as much as 2 cm thick in the Charlottesville Formation host at the contact are preserved and undeformed. There is no observable deformation at the contact except for flattening in feldspar and amphibole, which is related to the regional D_1 deformation. Where observable, the foliation in the mafic-ultramafic complex is concordant with that developed in the host rocks. No faulted or sheared contacts have been found. Because the structural overprint was so slight, it was possible to preclude any possibility of shear except for a few cm. Other contacts reveal the same types of relationships. Additionally, screens and xenoliths of the Charlottesville metasedimentary rocks are found within the Schuyler complex.

Field relations indicate that the Schuyler mafic-ultramafic rocks form a layered body with ultramafic rock at the base and metagabbro and metadiorite at the top. Contacts between rocks within the body have not been observed in outcrop because of poor exposure and can only be generally inferred.

Discussion and Conclusions

Field mapping along with petrographic study of the Schuyler complex indicates that it is a sill, with ultramafic rocks at the base and gabbro and metadiorite at the top. The elongate Schuyler complex is generally conformable with stratigraphic layering in the Charlottesville Formation host rocks. Also, the host rocks form a continuous and conformable stratigraphic sequence that encloses the Schuyler complex. The host rocks are not broken by faults and show no evidence of mélange. This is contrary to what most workers have proposed (Rankin, 1994; Rankin and others, 1989; Horton and others, 1989; Keppie and others, 1989; Hatcher, 1989; and many others). Also, original bedding and

laminations, graded beds, and other delicate sedimentary features such as flame structures, are preserved near and at the contact of the Schuyler complex with the host rocks. These features would be unlikely near thrust boundaries of ophiolites or within a mélange.

The cumulate textured olivine in the ultramafic rocks and granophyric texture in the metagabbro indicate that the Schuyler complex was an igneous intrusion. It is likely that in the absence of evidence for thrusting, the intrusion was directly emplaced into the Charlottesville host rocks as a bedding-parallel sill prior to the metamorphism. As with the Flat Creek intrusive, the presence of metasomatism at the top margin of the body is probably the result of a transfer of water from the host rocks into the relatively dry intrusion. This transfer of water may have prevented intense contact metamorphism of host rocks from taking place (Hyndman, 1985). Any contact metamorphism associated with the intrusion could have been overprinted by regional metamorphism (M_1) and deformation (D_1).

The magmatic origin of the Schuyler sill was probably very similar to that of the Flat Creek intrusive in that it was derived from a picritic magma which underwent fractional crystallization to produce the suite of rocks present. However, the unique occurrence of the granophyric metagabbro near the top of the Schuyler sill, may represent more extensive differentiation of the magma and suggests that the intrusion was shallowly emplaced and cooled at a moderate rate (Tuttle and Bowen, 1958; Briggs and others, 1978).

As with the Catfish and Flat Creek complexes, the Schuyler complex was emplaced into the host strata prior to the regional structural and metamorphic events. The presence of both the S_1 and S_2 fabrics in the mafic and ultramafic rocks as well as their mineral compositions, indicates that they were subjected to the same two episodes of deformation and metamorphism as the host rocks of the Charlottesville Formation.

Therefore, the field relations and petrography of the Schuyler mafic-ultramafic complex and the Charlottesville Formation host rocks do no support an ophiolite stratigraphy. Rather, the Schuyler body originated as a sill which was emplaced into the host strata during continental rifting.

REGIONAL RELATIONS

The Catfish, Flat Creek, and Schuyler complexes are characteristic examples of mafic and ultramafic sills and dikes that occur in the Lynchburg Group metasedimentary cover sequence of the Blue Ridge. The Lynchburg Group sediments were deposited unconformably on the 1 GA Grenville basement between about 607 Ma (the age of the basal Lynchburg Moneta volcanics) and 571 Ma (the age of the overlying Catoctin greenschists-greenstones) (Glover and others, 1995). The sedimentary environments represented by the Lynchburg rocks are alluvial fan to slope apron to deep basinal submarine fan units and show a continuous record of rift basin evolution related to the opening of Iapetus Wehr, 1985; Wang, 1991).

The mafic and ultramafic sills and dikes were emplaced into the Lynchburg during the rifting event by dynamic processes. The Catfish sill was derived from multiple injections of a mafic magma in which the variation in grain-size and composition was related to the fractionation process. The Flat Creek mafic-ultramafic also sill originated from multiple injection of a fractionating picritic magma and derivative olivine- and pyroxene- rich crystal mush. These magma fractions underwent mixing during injection episodes because of the protracted nature of the magma movement (Glover and others, 1995; this study). Similarly, the Schuyler mafic-ultramafic sill was derived from multiple injection of a magma very similar to that of the Flat Creek body, but it experienced more

differentiation, resulting in the formation of granophyric gabbro near the top of this sill. Granophyric texture (Briggs and others, 1978), suggests that the Schuyler sill was shallowly emplaced and cooled at a moderate rate. Metasomatic alteration occurred in the margin of these bodies, but there are no contact aureoles discernible in the host rocks. This is probably because the magmas were dry, the intrusions were relatively narrow, and water moved from the host sediment into the basalt. Fractionation of picritic magma produced ultramafic rocks probably at temperatures near 1000 °C.

Following intrusion of the mafic and ultramafic bodies into the Lynchburg Group sediments, the Catoctin basalts were emplaced during the latest stages of rifting. The mafic and ultramafic bodies occur within about 500 meters of the Catoctin, which has led some workers, beginning with Reed and Morgan (1971), to propose that they are feeders of the Catoctin. However, geochemical analyses by Wang and Glover (in press) indicate that the mafic and ultramafic bodies are compositionally distinct from the Catoctin basalts. Additionally, Wang (1991) has shown that dikes compositionally relate to both of these magma suites are present in the Grenville basement rocks.

After emplacement of the Catoctin basalts, the rift to drift transition occurred about 570 Ma (Glover and others, 1995), and marked the first appearance of true oceanic crust. An important consequence of this interpretation is that all of the mafic and ultramafic rocks in the Lynchburg were emplaced during the rift stage.

Subsequently, a magmatic arc collided with Laurentia during the early Paleozoic (Taconic orogeny ?), leading to the metamorphism and deformation of the cover sequence and the mafic and ultramafic intrusive suite. This collision is marked by the central Piedmont suture, to the east of which lie magmatic arc rocks of Carolina terrane (Glover and others, 1995).

At least one other regional metamorphic and deformational event (Alleghanian orogeny ?) affected the mafic-ultramafic bearing cover sequence subsequent to the events described above, thus explaining the two fabrics present in the rocks.

CONCLUSIONS

Table 7. Summary of the evidence for and against placing a suture in the central Virginia Blue Ridge.

Evidence in favor of a suture	**Evidence against a suture**
Linear distribution of mafic and ultramafic rocks along the Blue Ridge argues for parallel imbricate thrusts	Mafic-ultramafic complexes are parallel to bedding and confined to the rifted margin sequence and no evidence for mélange or regional scale thrust faults in the Lynchburg Group of the central Virginia Blue Ridge
Some of the mafic rocks plot in the MORB and/or IAB or OIB fields on tectonomagmatic discriminant diagrams	Wang and Glover (1992; in press) demonstrated that tectonomagmatic discriminant diagrams give ambiguous or incorrect results for continental basalts
The rocks are commonly intensely deformed and metamorphosed where most studies have been conducted	In general, the rocks are not as nearly deformed and metamorphosed in Virginia
Contact metamorphism of country rocks typically absent	Lack of contact metamorphism attributed to the anhydrous nature of the magmas and the narrowness of the mafic-ultramafic complexes
	Recent detailed sedimentological studies of the Lynchburg Group by Wehr (1985), Wehr and Glover (1985), Kline (1991), and Wang (1991) show that the Lynchburg Group cover sequence rocks represent a typical rifted margin sequence. Also, the Lynchburg Group host strata form a continuous and conformable sequence
	Sharp, generally concordant contacts between country rocks and the mafic-ultramafic complexes

1. The detailed internal and external contact relations and petrography of the Catfish, Flat Creek, and Schuyler complexes confirm that the mafic-ultramafic association is a sill-like intrusive sequence of rocks derived from a fractionating picritic magma and derivative olivine- and pyroxene-rich crystal mush.

2. The mafic-ultramafic sills are confined to the Lynchburg rift sedimentary suite, and are therefore intimately related to the Late Proterozoic Iapetan rifting event. The findings from this study (Table 7) conflict with the idea that the mafic-ultramafic association is part of a Late Proterozoic to Ordovician (Taconic ?) ophiolite sequence or mélange. Therefore, there are no terrane boundaries or sutures in the central Virginia Blue Ridge.

3. The Late Proterozoic to Ordovician (Taconic ?) suture is located in the central Piedmont; the Lynchburg Group and associated mafic-ultramafic intrusives are west of this suture.

4. Because most workers correlate the central Virginia Blue Ridge mafic-ultramafic bearing cover sequence with similar strata in the southern Blue Ridge, these conclusions may apply there as well.

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Appendix

The Mafic-Ultramafic Sills of the Late Proterozoic Lynchburg Group in the Central Virginia Blue Ridge Cover Sequence

Field Trip Guide

By: Wendi R. Thompson

Orogenic Studies Lab
Department of Geological Sciences
Virginia Tech, Blacksburg, VA 24061

INTRODUCTION

The origin and tectonic significance of the mafic-ultramafic association in the Blue Ridge post-Grenville cover sequence rocks have been subjects of dispute for over 60 years. The majority of current tectonic models consider most of the mafic and ultramafic rocks in the Lynchburg Group/Ashe Formation to be ophiolitic mélange that was obducted onto Laurentia (e.g., Rankin, 1994; Rankin and others, 1989; Horton and others, 1989; Keppie and others, 1989; Hatcher, 1989). This implies that a suture or terrane boundary of Late Proterozoic to Ordovician age is associated with the rocks. However, others (Wehr and Glover, 1985; Glover, 1989; Wang and Glover, in press; Thompson, this volume) have proposed that the Lynchburg Group is a typical rifted margin sequence of Late Proterozoic age and that the mafic-ultramafic association is part of the rift tectonolithofacies. The choice between these two views, rift related intrusives or collisional ophiolitic mélange, is a major problem of Appalachian modeling. Therefore, it is the purpose of this field trip to show some of the evidence that supports the conclusion that the mafic and ultramafic rocks are rift related intrusives.

The study area is located on the southeastern limb of the Blue Ridge anticlinorium in central Virginia. The three mafic-ultramafic complexes studied were the Catfish and Flat Creek sills, which are located in Lynchburg, Virginia, and the Schuyler sill, which is located about 80 km to the north, along strike, in Schuyler, Virginia (figure 1). Stratigraphic relations across the Blue Ridge are shown in figure 2.

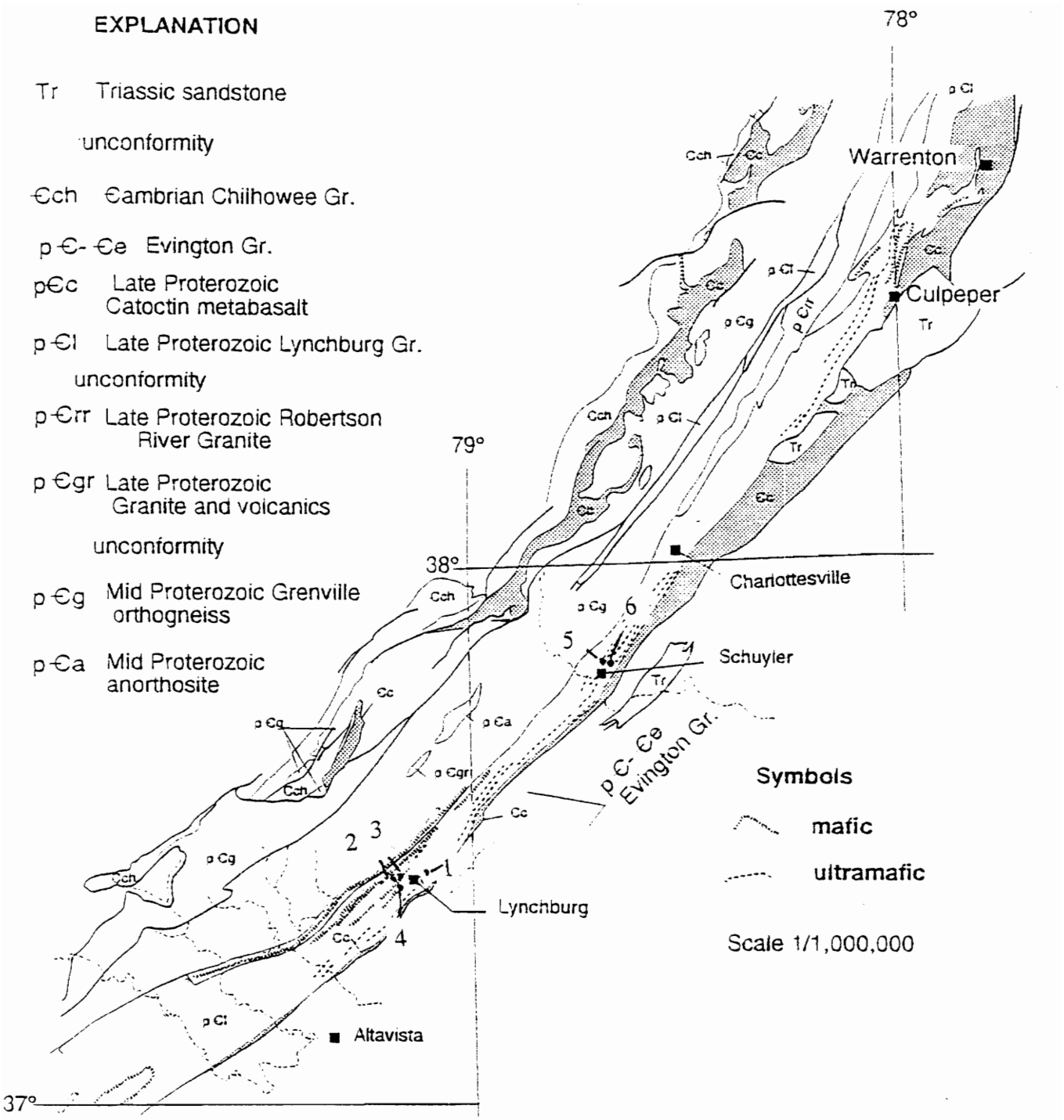

Figure 1. Virginia Blue Ridge, showing geology according to Glover and others (1995).

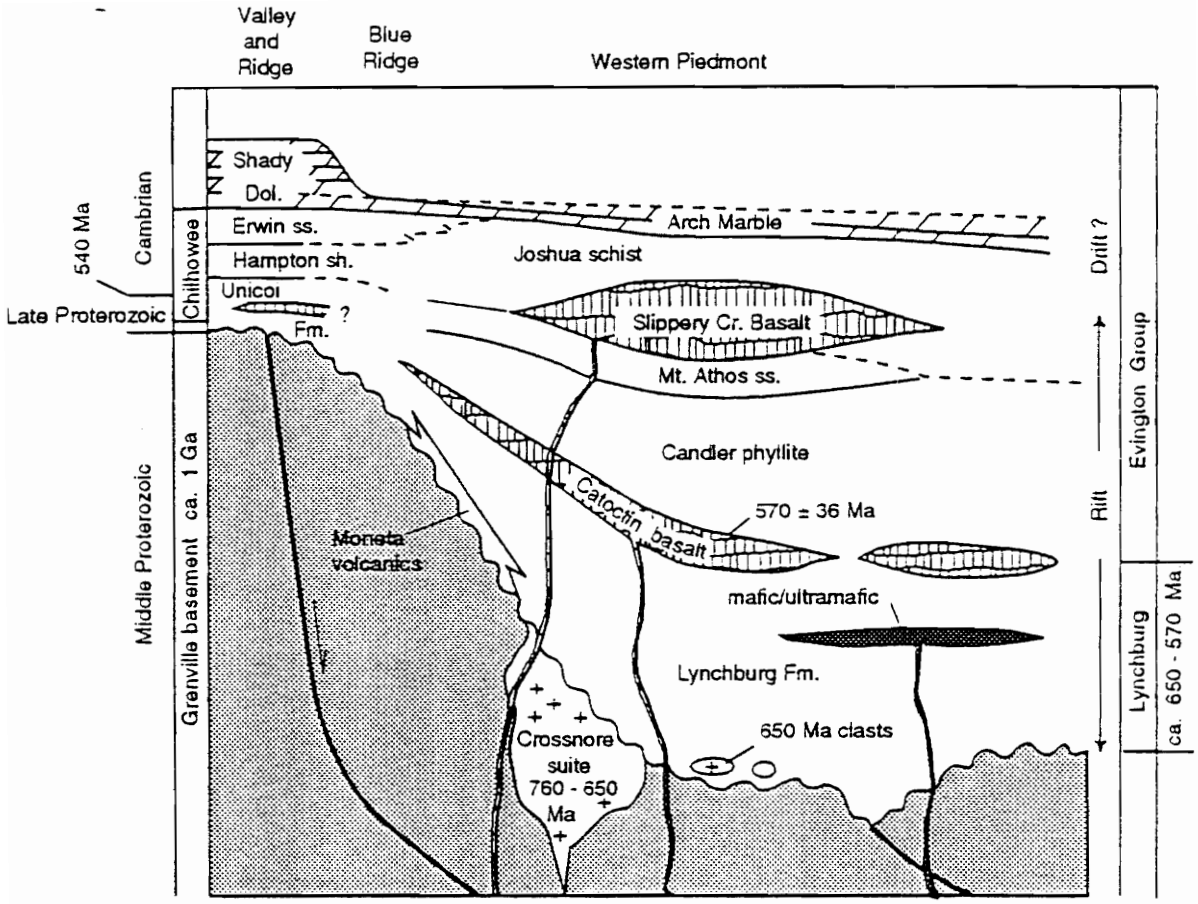

Figure 2. Stratigraphic relations across the Blue Ridge in central Virginia. From Glover and others (1995).

MAFIC-ULTRAMAFIC INTRUSIVES

The Catfish mafic sill is present near the top of the locally overturned Lynchburg II Group metasedimentary rocks (Stop 1). The Catfish sill is a small linear body, about 22 meters thick and 2 km long, and is comprised of fine- to coarse-grained hornblende metagabbro. The rocks have an overall igneous texture and contain mafic autoliths. Field observations indicate that the contacts with the country rocks are intrusive and there is no intense deformation along or near the contacts. Primary sedimentary features such as bedding and parallel laminations in the country rocks are undisturbed. Contacts within the sill are sharp to abruptly gradational, and along with the presence of the mafic autoliths, indicate that there were multiple injection events into this intrusive complex.

The Flat Creek mafic-ultramafic sill is present near the top of the Lynchburg III Group metasedimentary rocks (Stops 2 , 3, and 4). The Flat Creek sill is a long, irregularly layered body, as much as 225 meters thick and 10 km long, and is comprised of serpentinite, metapyroxenite, phlogopite schist, soapstone, and metagabbro. The ultramafic rocks are present at the base of the sill, and metagabbro is found at the top. Relict igneous textures are locally present in the rocks. Autoliths of metagabbro, which are commonly bounded by dark rims, and ranging from 10 cm to 0.5 meters in size are locally present in the meta-ultramafic rocks. Meta-ultramafic autoliths are also found locally in the metagabbro. Field observations indicate that the contacts with the country rocks are intrusive. There is no evidence for faulting or intense shearing at these contacts and primary sedimentary features in the host (i.e., bedding, graded beds, parallel laminations) are undisturbed. Country rock xenoliths are present within the Flat Creek sill. Where the xenolith contact is exposed, it is sharp, concordant, and shows no features indicative of intense shearing. Internal contacts are very complex in nature. In some places, the contacts

are sharp to abruptly gradational and highly irregular and undulatory. In other places, the contacts are gradational where the amount of feldspar present in the metagabbro decreases to less than 10% over a distance of about 0.5 meters. The internal contact relations and the presence of the autoliths indicate that multiple injection into the sill must have taken place. Geochemical analyses of the rocks by Wang and Glover (in press), show that the primary magmas were probably fractionating picrites and derivative olivine- and pyroxene-rich crystal mush.

The Schuyler mafic-ultramafic sill is present near the top of the Charlottesville Formation (approximately equivalent to the Lynchburg III Group) of the Lynchburg Group (Stops 5 and 6). It is as much as 274 meters thick and 10 km long and is comprised of soapstone, serpentinite, metagabbro, and metadiorite. Relict cumulate and granophyric textures are locally present. Contacts between the Schuyler sill and the country rocks are mostly saprolitic; however, discerning their nature is not problematic. The contact at Stop 5 is intrusive and thin, graded beds as much as 2 cm thick at the contact are undisturbed. There is no evidence for faulting or strong shearing at the contact. Other primary sedimentary features in the country rocks such as graded beds and flame structures are undisturbed as are screens of the country rocks which are present within the Schuyler sill. Internal contacts were not observed in the field due to poor outcrop exposure; however, field relations indicate that the ultramafic rocks are present at the base and metagabbro and metadiorite are present at the top. Based upon the sequence and nature of the rocks present, the magmatic origin of the Schuyler sill was probably very similar to that of the Flat Creek sill in that it was derived from a fractionating picritic magma. The granophyric texture may represent more extreme differentiation of the magma and suggests that the rocks of the Schuyler sill were shallowly emplaced and cooled at a moderate rate.

DISCUSSION AND CONCLUSIONS

The contact relations and petrography of the Catfish, Flat Creek, and Schuyler sills confirm that the mafic-ultramafic association is an intrusive sequence of rocks. The Lynchburg host strata form a continuous and conformable sequence which is unbroken by faults and there is no evidence of mélange. The degree of preservation of bedding and other sedimentary features would not be present in a mélange or near thrust related ophiolites. There is no intense deformation at or near the contacts and faults of a suture zone scale have not been found in the study area. Additionally, the Lynchburg Group host strata formed during the Late Proterozoic Iapetan rifting event. The sills are confined to the Lynchburg Group, and are therefore intimately related to the rifting event. Therefore, there are no sutures or terrane boundaries in the central Virginia Blue Ridge. Because most workers correlate the central Virginia Blue Ridge mafic-ultramafic bearing cover sequence with similar strata in the southern Blue Ridge, the conclusions may apply there as well.

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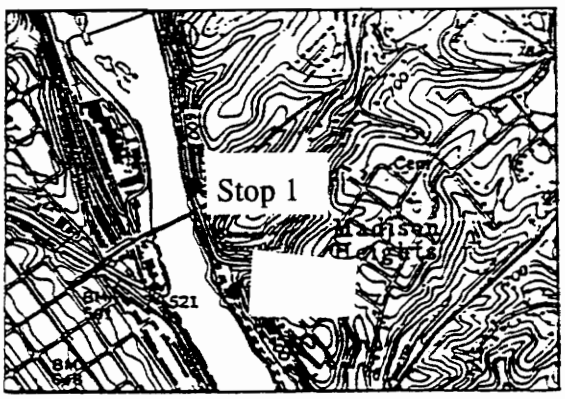
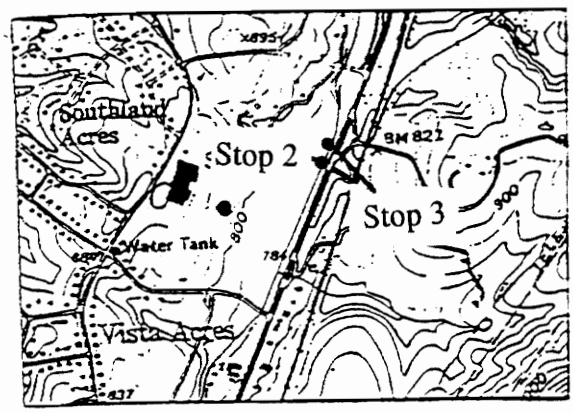
FIELD TRIP STOPS



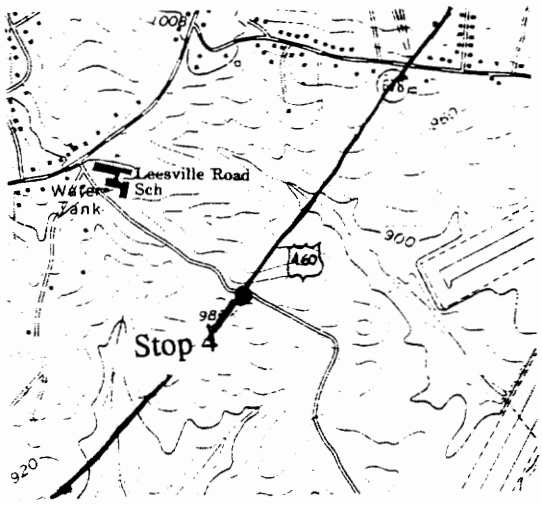
Stop 1 (WT4-14,15,105,106; WT5-101)- From US 460 to Lynchburg, exit onto Ward's Road and turn left. Go about 1.5 miles and turn right onto Fort Avenue and then left onto Memorial Avenue (turns into 5th St./ Bus. 29 north) after about another 2 miles. Turn right onto Rt. 685 (goes under the bridge) just after Bus. 29 crosses the James River. Stop under the bridge. The Catfish sill is located near the top of the locally overturned Lynchburg II Group. Note the intrusive contacts. The internal contacts indicate that there were multiple injections into the sill.



Stop 2 (WT4-12,49,96)-
Turn left off of Rt. 685 and head back over the bridge and continue on Bus. 29 south (5th St./Memorial Ave.). Go about 3 miles. Veer to the right back onto Fort Avenue. Continue for about 2 miles and then turn left onto Wards Road. Go for about 1.5 miles and stop at the Walmart shopping center on the right side of the road. The large outcrop of the Flat Creek sill provides excellent exposure. The sill is located near the top of the Lynchburg III Group. Sharp to abruptly gradational and highly undulatory contacts between the mafic and ultramafic rocks are present. Note the mafic autoliths with the dark rims in the ultramafic rock near the middle part of the outcrop. These features indicate that there were multiple injections into the sill.

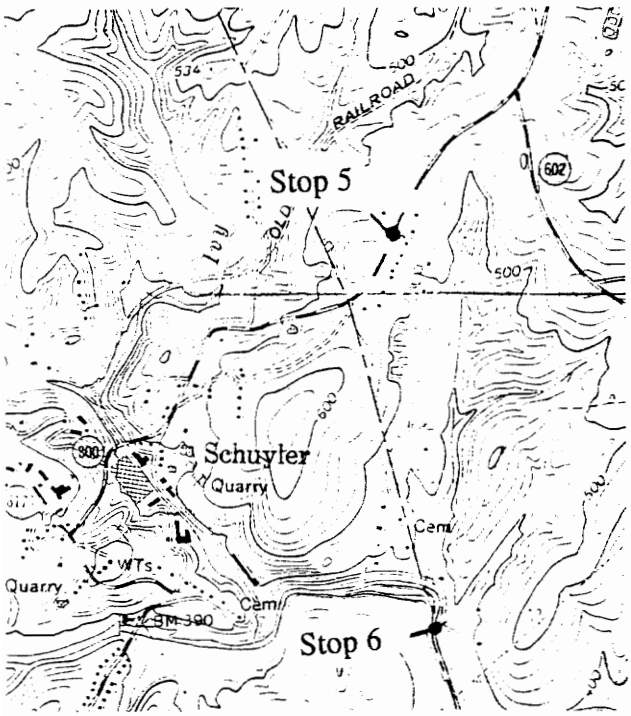
Stop 3 (WT4-12,49,96)-
Walk over to property east of the Walmart building. Gradational contacts over about 0.5 meters between the mafic and ultramafic rocks are present in saprolite outcrop,

outcrop, implying crystal settling may have locally occurred.



Stop 4 (WT5-23,24,25)-
Go south on Bus. 29 for about 0.5 miles. Turn right onto US 460 West towards the airport and go for about 1 mile. Stop on the side of the road just past the Airport Road exit. **NOTE: This is a very dangerous stop.** Walk across the road onto median strip. The roadcut outcrops are Lynchburg III and the Flat Creek mafic and ultramafic rocks. Note the sharp, concordant contacts between the Lynchburg III and the Flat Creek sill. The bedding is undisturbed and there is no evidence of faulting or intense shearing.

Stop 5 (WT5-30)-
Turn around and go back on US 460 East toward Lynchburg. Take the Ward's Road exit and turn left. Go for about 1 mile and exit onto US 29 (just past the River Ridge Mall entrance). Stay on US 29 for about 60 miles, heading towards Schuyler, Virginia. Turn right onto Rt. 6 and go for about 10 miles. Turn right onto State Road 800 and go for about 1.2 miles. Stop about 750 feet west of the Albemarle-Nelson county line (just outside of Schuyler, Virginia). Abandoned quarry is on the left side of the road. The contact between the Charlottesville Formation and the ultramafic rocks at the base of the Schuyler sill is exposed in saprolite outcrop in a ditch. The contact is sharp and concordant, and thin graded beds of the host are undeformed.



Stop 6 (WT5-31)-
Continue on State Road 800 into the town of Schuyler. Go for 0.7 miles and turn left onto Rt. 617. Go for about 1 mile, following the Rockfish River. The outcrop is above the river, where the Charlottesville Formation is very well exposed. Graded beds and flame structures are undisturbed and intact.

VITA

Wendi R. Thompson (VanDerHurst) was born in Lynchburg, Virginia on January 30, 1970. She grew up with her parents, three sisters, and a brother in and around Lynchburg, Virginia, and in Augusta, Georgia. She attended three high schools, and graduated from E.C. Glass in 1988. Wendi was the first person in her family to complete a college degree, graduating from Virginia Tech with a B.A. in Economics in 1992. She married Jeff VanDerHurst on March 29, 1996. Upon completion of her Master's Degree in Geology at Virginia Tech, she will be working as a geoscientist at Texaco Exploration and Production Inc., Offshore Division at New Orleans, Louisiana.

Wendi R. Thompson