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Abstract

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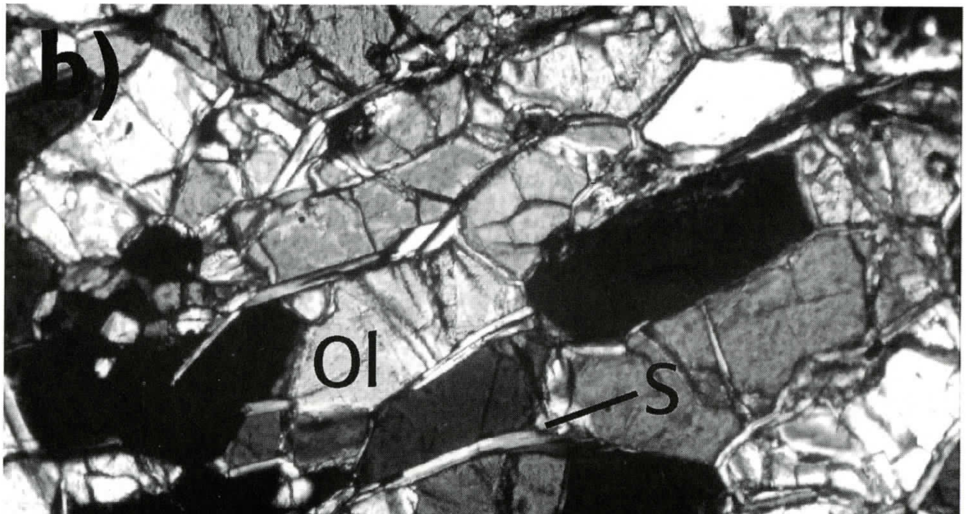
SOUTHEASTERN GEOLOGY

Selected Ultramafic and Related Rocks of the Southern Appalachian Orogen: Petrology and Tectonic Significance



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4) Make certain that all photographs are sharp, clear, and of good contrast.
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SOUTHEASTERN GEOLOGY

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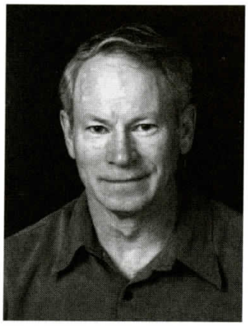
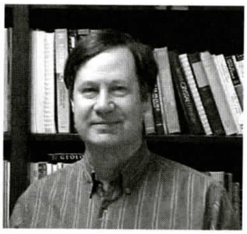


Since Summer Field Camp in the Coast Ranges of California in 1966, Loren A. Raymond, has had an interest in petrotectonics. A native of California, he earned both B.S. (1967) and M.S. (1969) degrees in Geology from San Jose State College, and a Ph.D. (1973) from the University of California, Davis, where he addressed unresolved problems of sedimentological, metamorphic, and tectonic history in the Franciscan Complex of the California Coast Ranges. Aside from brief teaching assignments at Napa College in California and Southern Oregon State College in Ashland, Oregon, Loren has spent his career, from 1972 until the present, engaged in teaching, research, and administration at Appalachian State University in Boone, North Carolina. At Appalachian, Loren's main research interests in the Southern Appalachian Orogen have been focussed on the tectonic history, ultramafic rocks, block-in-matrix rock units, and metamorphism in the Blue Ridge Belt. His research, in part, has been supported by a grant from the National Science Foundation. In addition to his petrotectonics research, Loren has consulted in Latin America on earthquake hazards, landsliding, and construction sites and does similar consulting, plus fracture trace analysis for well siting and other geological consulting in the Southern Appalachian Mountains, as a licensed geologist in the State of North Carolina. Loren has published more than 80 books, articles, abstracts, and field guides. Included among his publications are the edited volume, Geological Society of America Special Paper 198 - Melanges: Their Nature, Origin and Significance, the textbook Petrology: The Study of Igneous, Sedimentary, and Metamorphic Rocks, and papers on faulting in California and block-in-matrix rock bodies, ultramafic rocks, and metamorphism in the North Carolina Blue Ridge Belt.



Richard D. Warner earned his B.S. degree (1966) from MIT and his Ph.D. degree (1971) from Stanford University. He has long had an interest in the petrology of mafic and ultramafic rocks, stemming from his investigation of liquidus and subsolidus phase relations involving olivines and pyroxenes in the system CaO-MgO-SiO_2-H_2O for his dissertation. Following his Ph.D., Rich was awarded a 2-year NRC Resident Research Associateship at NASA's Goddard Space Flight Center, where he worked in the Planetology Branch and was introduced to the lunar science program. He then went to the University of New Mexico as a research associate, and there he continued his research on moon rocks, with particular emphasis on lunar mare basalts. Since 1980, Rich has been at Clemson University in South Carolina. Here his research has primarily been concerned with the mineralogy and petrology of ultramafic bodies in both the Blue Ridge and Piedmont belts, and with the geochemistry and petrology of Mesozoic diabase dikes. A third area of interest has been the integration of opaque oxide petrology with rock magnetism (magnetic petrology). Rich is a licensed geologist in the state of South Carolina, and currently serves on the South Carolina Board of Registration for Geologists. He has published more than 40 scientific papers and over 50 abstracts on subjects ranging from experimental petrology and lunar sample analysis to the magnetic petrology of lower crustal rocks from various tectonic settings and the mineralogy-petrology-geochemistry of southern Appalachian mafic and ultramafic rocks.

PREFACE

This issue of *Southeastern Geology* is devoted to five papers that were originally presented at a symposium held during the Southeastern Section Meeting of the Geological Society of America in Athens, Georgia, on March 25, 1999. The symposium was entitled "Ultramafic Rocks and Eclogites in the Southern Appalachian Orogen: Petrology and Tectonic Significance". Nine papers were presented, of which five dealt with ultramafic rocks, and these are the five papers that are collected here.

Bodies of ultramafic rock are scattered along the length of the Appalachian orogen, from Newfoundland to Alabama. The bodies are distributed in two parallel chains, with those occurring in the Blue Ridge belt belonging to a western chain, and the more widely dispersed and generally smaller bodies found in the Piedmont belt being part of an eastern chain. The first four papers in this volume are concerned with ultramafic rocks in the Blue Ridge belt of western North Carolina. They are arranged geographically from north to south. The first paper, by Raymond, Love and McCarter, discusses the Hoots ultramafic body, located northwest of Boone. The Hoots ultramafic body is fairly typical of the Blue Ridge ultramafic bodies, in having experienced multiple (at least three) stages of metamorphism. In the second paper Swanson examines a number of ultramafic bodies in the Spruce Pine area, and relates the various metamorphic mineral assemblages to the availability of fluids during metamorphism. The next two papers address different aspects of the Buck Creek ultramafic body, one of the largest in the Blue Ridge belt. Warner considers the metamorphic history, primarily of the metadunite, and notes the effect of variable amounts of hydration on the metamorphic mineralogy. Berger, Cochrane, Simons, Savov, Ryan and Peterson focus on the REE geochemistry of the related mafic rocks (amphibolites, metatroctolites, etc.) and the insights they provide into the origin of the mafic/ultramafic complex. The last paper in this volume, by Owens and Uschner, deals with metamorphosed ultramafic bodies that occur in the central Piedmont belt of Virginia, part of the eastern ultramafic belt. A variety of rock types is present, some of which (e.g., chlorite schists) are clearly the products of metasomatic alteration, but others, such as chlorite-amphibole schists, may represent metamorphosed amphibole-bearing peridotites.

What have we learned from these studies? To begin with, the ultramafic rocks in the southern Appalachians are clearly metamorphic rocks, and, hence, metamorphic rock names such as metadunite, metaharzburgite, etc. are preferable. It is also evident that the metaultramafic rocks preserve a history of multiple episodes of metamorphism. They have experienced variable amounts of hydration, and hydrated assemblages, especially, are sensitive recorders of fluid interactions during metamorphism. Many questions still remain to be resolved, however. For example, what are the ages of the metamorphic events that affected the ultramafic bodies? Was there an Acadian peak of higher temperature metamorphism after a post-Taconic cooling? How were the ultramafic bodies emplaced, and what tectonic significance can be attached to their distribution? Do they represent subcontinental mantle or plutonic parts of an ophiolite or some other type of ultramafic rock? A combination of careful field mapping, detailed petrography, major and trace element geochemistry, and age determinations are needed to obtain answers to these questions.

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PETROLOGY OF THE HOOTS ULTRAMAFIC BODY, BLUE RIDGE BELT, NORTHWESTERN NORTH CAROLINA

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ABSTRACT

The Hoots Ultramafic Body, one of numerous ultramafic bodies in the Blue Ridge Belt of the Southern Appalachian Orogen, is located near the base of the Gossan Lead Block. The 9400 m^2 body is surrounded by hornblende schist and gneiss that, like the enclosed ultramafic body, have experienced multiple episodes of metamorphism. At least three successively lower grade events have modified the mineralogy and texture of the weakly foliated metadunite, metaharzburgite, and metaorthopyroxenite of the Hoots body. Primary textures and structures are absent or have been intensely modified. Amphibolite or granulite facies olivine + chromite + orthopyoxene assemblages are replaced by tremolite/actinolite + talc-bearing amphibolite facies and serpentine- and magnesite-bearing greenschist facies assemblages. The major element chemistry of the Hoots rocks is typical of ultramafic rocks of ophiolitic and alpine types, and high Mg numbers in olivine and orthopyroxene, with low Mg numbers and high Cr numbers in spinels typify alpine ultramafic rocks. REE are compatible with locally enriched, residual cumulate material, perhaps both depleted and enriched parts of an ophiolite cumulate. The deformed metaorthopyroxenite layers may be residual fractionated layers, but are more likely dikes of pyroxenite in a MORB/ophiolite cumulate. The MORB chemistry of associated hornblende schists and gneisses is consistent with an ophiolite interpretation. The association of small dismembered masses of ophiolitic (?) mantle rocks, eclogitic MORB, and pelitic schist at the base of the Gossan Lead Block argues for subduction and exhumation of dismembered ocean floor rocks at a convergent margin.

INTRODUCTION

Alpine ultramafic rock bodies form a crudely linear array in the Blue Ridge Belt along the western core of the southern Appalachian Orogen (Pratt and Lewis, 1905; Hunter, 1941; Hess, 1955; Larrabee, 1966, Misra and Keller, 1978). Hess (1955) suggested that the ultramafic or serpentine belts conceptually link island arcs and mountain systems and that the belts, including those in the southern Appalachian Orogen, mark the axes of mountain systems. In modern plate tectonic interpretations, these belts of ultramafic rock mark suture zones, where plates have collided, commonly generating an orogen (e.g., Dietz, 1963; Moores, 1970; 1981; Dewey and Bird, 1970; Brewer and Woodward, 1988; Adams and others, 1995).

The nature, history, and significance of the southern Appalachian ultramafic bodies have long represented subjects of interest. A number of questions have been raised with regard to these rocks, especially those of the Blue Ridge Belt, and some of the problems persist. The questions include the following:

(1) Are Blue Ridge ultramafic rocks igneous or metamorphic rocks?

(2) What types of mafic-ultramafic complexes are represented by Blue Ridge ultramafic bodies?

(3) How were Blue Ridge ultramafic rocks emplaced?

(4) What was the role of serpentinization in the history of these rocks?

(5) What is the petrologic history of these rocks, including their P-T-t histories?

(6) What is the age of the ultramafic rock bodies?

(7) Why do these rock bodies appear to occur in two major thrust blocks — the Gossan Lead and Fries blocks, each of which seems to have a different history?

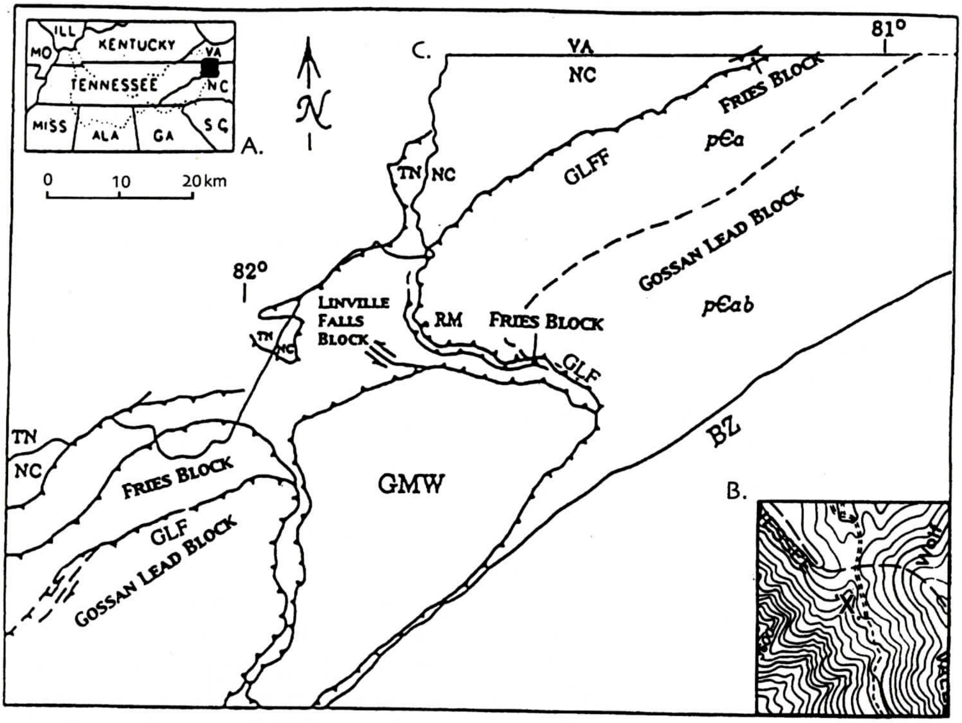


Figure 1. Location of the Hoots ultramafic body. A. Location of study region relative to surrounding states. B. Topography in the area of the Hoots ultramafic body (from SW 1/4 of the Zionville, N.C. 7 1/2′ quadrangle). C. Generalized geologic map of northwestern North Carolina showing thrust faults and blocks (based on Brown, and others, 1985; modified from Raymond and Abbott, 1997). BZ = Brevard Fault Zone; GLF = Gossan Lead Fault; GLB = Gossan Lead Block; GLFF = Gossan Lead and Fries Faults; GMW - Grandfather Mountain Window; FB = Fries Block; FF = Fries Fault; LFB = Linville Falls Block; PCa = Ashe Metamorphic Suite; pCab = Alligator Back Metamorphic Suite; RM = Rich Mountain (Hoots and McNeil) ultramafic bodies.

(8) What do the ultramafic rocks tell us about the tectonic history of the Blue Ridge Belt?

We have developed reasonably good answers to questions (1), (4), and (5); but the answers to the remaining questions are either controversial or unknown.

Solutions to the larger questions about the ultramafic bodies and rocks depend on clarification of the petrology of individual ultramafic bodies. Here we discuss the petrology and structure of a small, but distinctive ultramafic body — the Hoots Ultramafic Body — in the Gossan Lead Block, the fault block above the Gossan Lead Fault (Swanson, 1980; Raymond and Abbott, 1997). We also discuss issues relevant to the history of this and other Blue Ridge ultramafic bodies that are illuminated by study of the Hoots body.

The Hoots Ultramafic Body occurs northwest of the town of Boone, North Carolina at the base of the Gossan Lead Block, between Buckeye and Grassy Knobs and southwest of Wolf Ridge (Fig. 1). The body crops out just west of the Tennessee Valley Divide at elevations between 3910 to 4020 feet (~ 1200m) above mean sea level, in the Zionville, NC 7.5′ quadrangle (Fig. 2). The Hoots body is accessible via a private road that extends west from Junaluska Road, but access is restricted and permission to cross properties between Junaluska Road and the Hoots property is required.

The Hoots body is unusual in containing discontinuous layers of metaorthopyroxenite within the dominant metadunite and metaharzburgite (Swanson, 1980; Raymond and Abbott, 1997; Raymond and others, 1998; Ray-

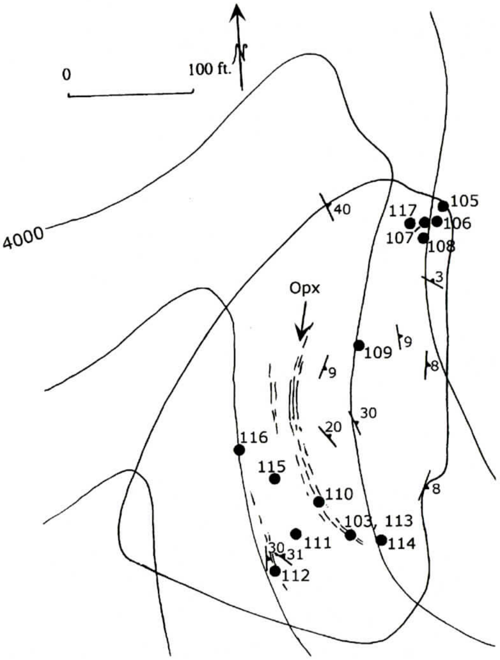


Figure 2. Map of the Hoots ultramafic body showing generalized zone of pyroxenite veins, attitudes of internal foliations, and sample localities. The locality is in the Zionville, N.C. 7.5' quadrangle, 0.4 km west of Wolf Ridge.

mond and others, 1999). This body is one of several ultramafic bodies noted in the area by Pratt and Lewis (1905) and Larrabee (1966). It and the nearby McNeil body, together referred to as the Rich Mountain Ultramafic Bodies, were the subjects of reports by Hearn and others (1977), Callahan and others (1978), and Swanson (1980).

METHODS OF ANALYSIS

The Hoots Ultramafic body was studied in the field using normal interpretive mapping methods and compass and pace traverses, until access was terminated by a right-of-access dispute. In the laboratory, handspecimen-slab examination of structures and thin section petrography were performed. Point counts of 300 to 800 points per section were conducted on one section each from nine representative rocks from the body. Because the data were collected as a single large set, error estimates are not considered to be accurate (Neilson and Brockman 1977), but representative error estimates based on a Bernoulli process in which the sample is assumed to be representative of the rock and the grains are considered to be independent of one another were calculated for samples RM 101 and RM 116 and are presented with point count data in Table 1. Inasmuch as the rocks are foliated and banded with extensive textural and structural variations from place to place, these point count data should only be considered to be approximations that give a sense of the mineralogical variation within the Hoots body.

Whole rock chemical analyses were provided by Acme Analytical Laboratories of Vancouver, B.C. Samples were analyzed by ICP/MS techniques using $LiBO_2$ fusion. REE were compared to Standard SO-15. Electron beam microprobe analysis using the JEOL electron beam microprobe of the University of Georgia were conducted on minerals from representative samples.

TECTONIC SETTING AND REGIONAL GEOLOGY

The Blue Ridge Belt of western North Carolina consists of northwest verging thrust faults that separate thrust blocks bearing diverse rocks (Fig. 1). The Gossan Lead (thrust) Fault bounds the Gossan Lead Block (of the Eastern Blue Ridge Belt) on the west and the Brevard Fault Zone bounds the Gossan Lead Block on the east (Stose and Stose, 1957; Hatcher, 1978; Raymond, 1998). The Gossan Lead Block contains both the Ashe and Alligator Back metamorphic suites. Constituents of the Ashe Metamorphic Suite are pelitic schist and gneiss, biotite-quartz-feldspar semischist, amphibole schist and gneiss, ultramafic rocks (the focus of this paper), and minor to rare amounts of dolomitic marble and polymict metaconglomerate (Rankin and others, 1973; Abbott and Raymond, 1984). Amphibole schist and gneiss dominate the Ashe Metamorphic Suite immediately north of Boone. Pelitic rocks and semischists increase in abundance both to the southwest and the northeast (Abbott and Raymond, 1984). Rocks of the Ashe Metamorphic

Table 1. Modes of Hoots Ultramafic Rocks

	RM 101	RM 103	RM 104	RM 106	RM 107	RM 108	RM 109	RM 115	RM 116
Ol	16.9+/- 1.3*	28.6	0.0	82.6	91.6	89.7	49.0	80.7	45.6+/- 2.2
Opx	60.4+/- 1.7	28.0	93.6	5.2	6.3	6.7	18.4	1.7	34.0+/-2.1
Opq	0.9+/- 0.3	0.7	0.6	2.0	0.3	0.3	2.0	6.3	2.4+/- 0.6
Amp	12.5+/- 1.1	5.3	2.3	1.4	0.0	2.6	1.8	0.3	2.2+/- 0.6
Chl	6.6+/- 0.9	34.0	3.0	4.6	0.0	0.3	17.4	10.0	14.0+/- 1.5
Tlc	0.0	0.0	0.0	0.4	0.0	0.0	4.0	0.3	0.0
Ser	1.7+/- 0.4	0.7	0.3	1.8	2.0	0.3	0.4	0.7	0.0
Mag	1.0+/- 0.3	2.7	0.0	2.0	2.0	0.0	7.0	0.0	1.8+/-0.5
TOTAL†	100	100	99.8	100	100.2	99.9	100	100	100
n=	800	300	300	500	300	300	500	300	500

Ql = olivine; Opx = orthopyroxene; Opq = opaque minerals; Amp = amphiboles, Including tremolite, actinolite, and anthophyllite; Chl = chlorite; Tlc = talc Ser = serpentines; Mag = magnesite
* - values in percent; † - totals may not equal 100% due to rounding errors

Suite show evidence of metamorphic and deformational events of Paleozoic age developed during the major Appalachian orogenic events — the Middle Ordovician Taconic Orogeny, the Devonian Acadian Orogeny, and the Late Carboniferous-Permian Alleghenian Orogeny (Long and others, 1959; Butler, 1972; Goldberg and Dallmeyer, 1997). The age of protoliths of the Ashe Metamorphic Suite is assumed to be Neoproterozoic. The Alligator Back Metamorphic Suite is largely devoid of ultramafic rocks and will not be discussed further.

Metamorphic grade in the Ashe Metamorphic Suite increases progressively from southern Virginia toward the southwest, reaching the kyanite grade of the amphibolite facies near the Grandfather Mountain Window (Rankin and others, 1973; Abbott and Raymond, 1984; McSween and others, 1987). Local retrograde relicts of eclogite facies metamorphism exist there, in amphibole gneisses near the Gossan Lead Fault (Abbott and Raymond, 1997). West of the Grandfather Mountain Window, eclogite occurs at the base of the Gossan Lead block (Willard and Adams, 1994; Adams and others, 1995). Farther south, in the central North Carolina Blue Ridge Belt, the rocks are sillimanite grade (Butler, 1973). Acadian and Alleghanian retrograde metamorphic assemblages overprint eclogite facies and Taconic amphibolite facies metamorphic assemblages (Abbott and Raymond, 1984; Adams and others, 1995; Goldberg and Dallmeyer, 1997). Imbricate thrust faulting was associated with and followed retrograde metamorphism during the Alleghanian Orogeny (Abbott and Raymond, 1984).

West of the Gossan Lead Block, the Fries Fault underlies the Fries Block (Stose and Stose, 1957; Raymond, 1998). North of the Grandfather Mountain Window, this block is composed largely of mylonites and associated gneisses and granoblastites, but northward and southwestward from the Window, it consists of a diverse array of rocks including various schists and gneisses, migmatites, mylonites, ultramafic schists and granoblastites, and pyroxene granoblastites (Stose and Stose, 1957; Bryant and Reed, 1970; Merschat, 1977; Brown and others, 1985; Raymond and others, 1989).

The Gossan Lead and Fries blocks, and other blocks of the Blue Ridge Belt, overlie a deep-seated décollemont (Cook and others, 1979). The Blue Ridge Belt is dissected by splay faults, including the Gossan Lead and Fries faults, that extend upward from the decollement and bound the thrust blocks.

Blue Ridge ultramafic rock bodies, with minor exceptions that crop out along fault zones, occur in the two Eastern Blue Ridge thrust blocks — the Gossan Lead and Fries blocks (Larrabee, 1966; Brown and others, 1985; Raymond, 1987; Brewer and Woodward, 1988; Raymond, 1995, ch. 31; Raymond and Abbott, 1997). Some bodies, like the Webster-Addie and Lake Chatuge bodies, occur at the base of thrust blocks, whereas many others occur relatively near the bases of these blocks (see Hopson and others, 1989 for a review). Still other bodies occur within thrust blocks that contain pelitic schists, hornblende schists and gneisses, and other rocks. The Gossan Lead Block, containing most of the ultramafic bodies in northern North Carolina and southern Virginia, contains rocks of the Ashe Metamorphic Suite, considered to represent metamorphosed oceanic crust and overlying sediment formed in an ocean basin that was east of Laurentia (Rankin, 1970; Hatcher, 1978; Abbott and Raymond, 1984; Misra and Conte, 1991; but see Wehr and Glover, 1985).

Structural studies reveal that Blue Ridge ultramafic rocks form bodies that are typically 0.2-2 km long, although much smaller and much larger bodies exist (e.g., Hunter, 1941; Miller, 1951; McElhaney and McSween, 1983; Swanson, 1981, in this volume; Raymond and others, 1998). Some bodies are folded sheets, whereas others are ellipsoidal in shape. The bodies are generally conformable with the overall trends of foliation and some rock units in the surrounding country rocks, but there also appear to be some generally discordant relationships. In detail, where contacts are exposed, a "blackwall" schist (Sanford, 1978; Swanson, 1981) or other hydrous schist commonly forms an envelope with conformable foliation around the bodies. The most common rock types in the ultramafic bodies are dunite, harzburgite, and various chlorite and talc schists, but other rock types, including serpentinite exist locally.

Three to five metamorphic assemblages, most of which represent successively lower grade hydrous recrystallization events, occur in the ultramafic rocks. In some bodies, the rocks are predominantly chlorite, talc, or other schists that appear to have replaced olivine-bearing rocks (Swanson and Raymond, 1976; Raymond, 1995, p.667ff). These metamorphic events likely occurred during the Taconic, Acadian, and Alleghenian orogenies, the same events that affected the enclosing country rocks (Abbott and Raymond, 1984). The relatively close spatial association of eclogites and retrograded eclogites with some ultramafic rock bodies, considered in conjunction with the earliest mineral phase assemblages of the ultramafic rocks, suggests very deep crustal or mantle metamorphism in the early history of these masses (Adams and others, 1995; Raymond and Abbott, 1997).

The chemistries of the ultramafic rocks and associated mafic schists and gneisses in the Blue Ridge Belt suggest that the ultramafic rocks represent a variety of rock bodies ranging from ophiolitic oceanic crust to volcanic arc and ocean island substrates (McSween and Hatcher, 1985; Misra and Conte, 1991; Tenthorey and others, 1996). While the contacts of the bodies provide no definitive evidence of faulting (inasmuch as most contacts are recrystallized by post-emplacement metamorphism), there is no evidence of igneous emplacement. There are no dikes, sills, or apophyses attached to the bodies, no remnants of contact metamorphism or chilled margins, and no internal zoning or other structures that would suggest that the bodies are discrete intrusions. Locally, some layering exists that may have resulted from fractionation, but many of the bodies are too small to have experienced such fractionation within a magma chamber of their present size. The Hoots Ultramafic Body is just such a body. The body is small and appears to lie within a more extensive mass of hornblende schist and gneiss of the Ashe Metamorphic Suite. Nearby, that rock has been shown to be retrograded eclogite (Abbott and Raymond, 1997), and regionally, the rocks represent MORB protoliths (Misra and Conte, 1991). The Hoots body lies structurally above and just east of the Gossan Lead Fault, but occurs at the structural base of the Ashe Metamorphic Suite.

THE STRUCTURE OF THE HOOTS ULTRAMAFIC BODY

The Hoots Ultramafic Body is approximately 96m X 98m (Fig. 2). None of the contacts are exposed, but nearby outcrops consist of hornblende schist and gneiss. These country rocks have foliations that trend N0°–N30°W and dip 10°–40° northeast.

The dominant rock of the Hoots Ultramafic Body is metadunite, but local layers of metaharzburgite and metaorthopyroxenite make this body distinctive (Figure 3, Table 1). The layers

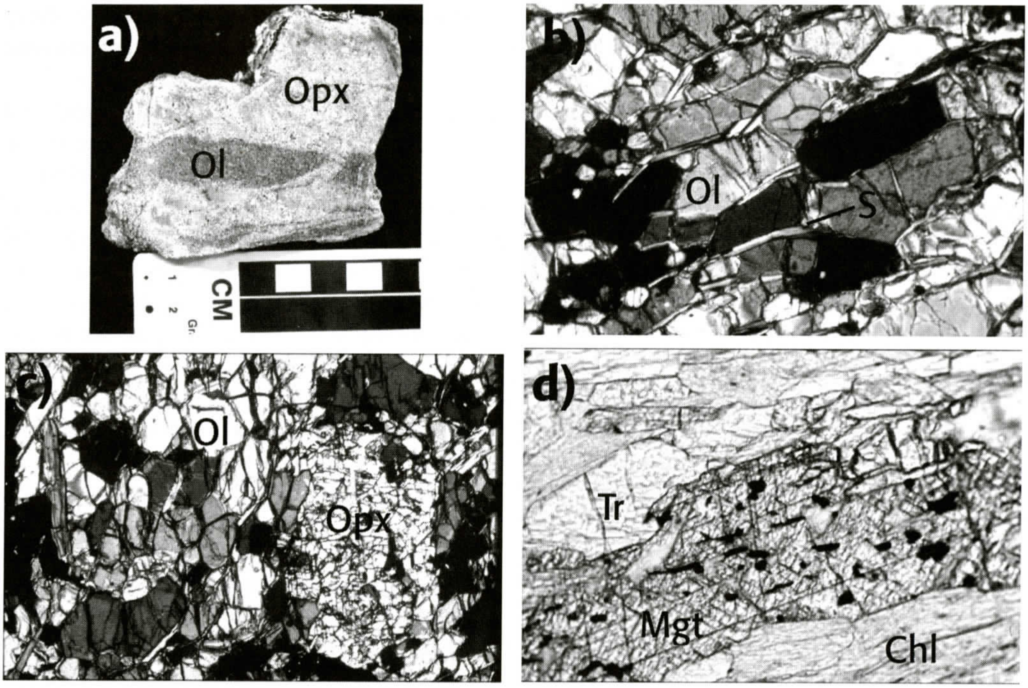


Figure 3. Photograph and photomicrographs of Hoots rocks. a) (upper left) Photograph of rock slab showing metaorthopyroxenite (Opx) and discontinuous metadunite layers (Ol) (Sample RM103). b) (upper right) Photomicrograph of equigranular tabular texture in metadunite layer with some mesh-textured serpentine (S). Ol = olivine. (Sample RM 107). Width of field is 4mm. c) (lower left) Photomicrograph of porphyroblastic texture in metaharzburgite (Sample RM 107) Ol = olivine; Opx = orthopyroxene. Width of field is 8mm. d) (lower right) Photomicrograph of magnesite vein (Mgt) cutting tremolite/actinolite(Tr) - chlorite (Chl) in altered harzburgite (Sample RM 103a). Width of field is 2 mm.

of metaharzburgite are diffuse and layers of metaorthopyroxenite are discontinuous. The metaorthopyroxenite occurs as a series of 5mm to 0.5m thick layers near the center of the body.

The rocks have a weak fabric that trends generally northwest, crudely parallel to the fabric of the country rock. Around the margins of the body there is some variation in strike of the fabric, with trends generally paralleling the contact. Local shear planes, some containing hydrous magnesium silicate minerals and magnesite, cross-cut metaorthopyroxenite layers at low angles and locally parallel these layers. These deformational features and metamorphic recrystallization have generally destroyed all primary textures and structures, with the possible exception of the pyroxenite layers.

PETROGRAPHY

The Hoots rocks are dominantly metadunites with equigranular mosaic, equigranular tabular, and porphyroblastic textures (Fig. 3b). The metaharzburgites have similar textures. Metaorthopyroxenites are characterized by allotrioblastic-granular textures. All of these textures are metamorphic and reflect post-crystallization metamorphic events.

Four metamorphic assemblages, representing at least three neocrystallization events, occur in the Hoots body. The oldest phase assemblage consists of olivine + chromite ± orthopyroxene (Fig. 3c).

A second assemblage consists of olivine + chromite ± orthopyroxene + chlorite + tremolite/actinolite ± anthophyllite ± talc.

The third and fourth assemblages are low temperature assemblages consisting of mesh-textured lizardite + magnetite and veins of magnesite ± chlorite (Fig. 3d; Table 1).

Table 2. Chemistries of Hoots Ultramafic Rock

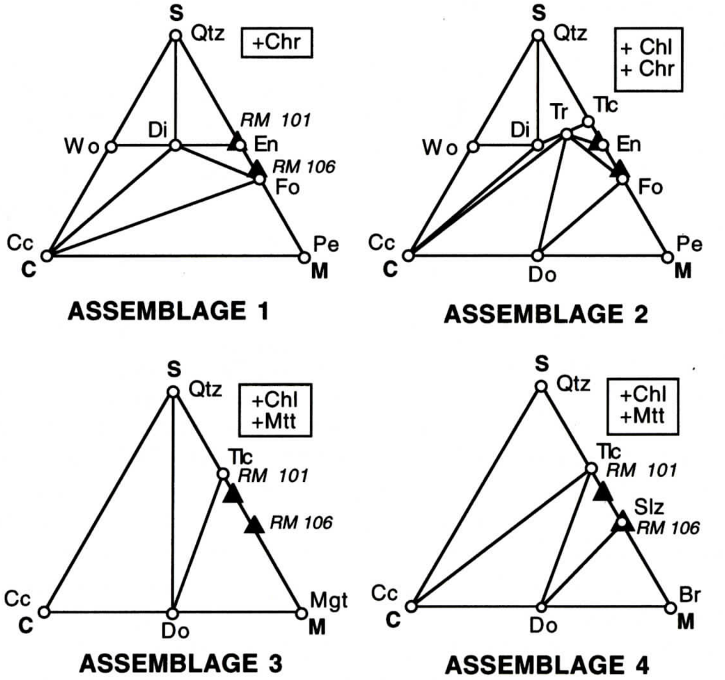
	RM 101	RM 106	RM 109	RM 116
SiO_2	56.39*	41.48	44.83	41.46
TiO_2	0.03	0.02	0.02	0.02
Al_2O_3	0.46	0.42	0.57	0.98
FeO†	7.39	8.35	9.73	8.56
MnO	0.17	0.11	0.15	0.10
MgO	33.48	48.57	42.95	46.90
CaO	1.40	0.08	0.16	0.13
Na_2O	0.07	<0.01	0.03	0.07
K_2O	<0.04	<0.04	<0.04	<0.04
P_2O5	0.06	0.02	0.09	0.05
LOI	0.2	0.3	0.7	1.0
TOTAL	99.96	99.83	99.86	99.83
Mg# =	89	91	89	91

* - values in wt. percent; † = total iron as FeO

In Figure 4, these four assemblages are depicted on CMS phase diagrams (Bowen, 1940; Raymond, 1995, p. 517ff.). Assemblage 1 represents granulite or uppermost amphibolite facies conditions, Assemblage 2 — amphibolite facies conditions, and assemblages 3 and 4 — lower amphibolite/upper greenschist facies conditions and greenschist facies conditions, respectively (Evans, 1977; Raymond, 1995, p. 563). The presence of magnesite reflects the occurrence of a CO_2-bearing fluid early in the last stage of metamorphism, a fluid that became H_2O-rich later in the same metamorphic event.

ROCK AND MINERAL CHEMISTRY

The chemistry of selected Hoots ultramafic rocks is provided in Table 2. The major element chemistries are typical of those of ophiolitic and abyssal ultramafic rocks of corresponding types (e.g., Varfalvy and others, 1997; Gruau and oth-



ASSEMBLAGE 1

ASSEMBLAGE 2

ASSEMBLAGE 3

ASSEMBLAGE 4

Figure 4. CMS phase diagrams of the four phase assemblages of the Hoots ultramafic body. Assemblages 3 and 4 are depicted as subsets of the same low grade assemblage. Black triangles are representative compositions of Hoots rocks. Br = brucite; Cc = calcite; Chl = chlorite; Chr = chromite; Di = diopside; Do = dolomite; En = Enstatite; Fo = forsterite (olivine); Mgt = magnesite; Mtt = magnetite; Pe= periclase; Qtz = quartz; Slz = serpentine (lizardite); Tlc = talc; Tr = tremolite; Wo = wollastonite. Rm numbers are sample numbers. C = CaO; M = MgO; and S = SiO^2.

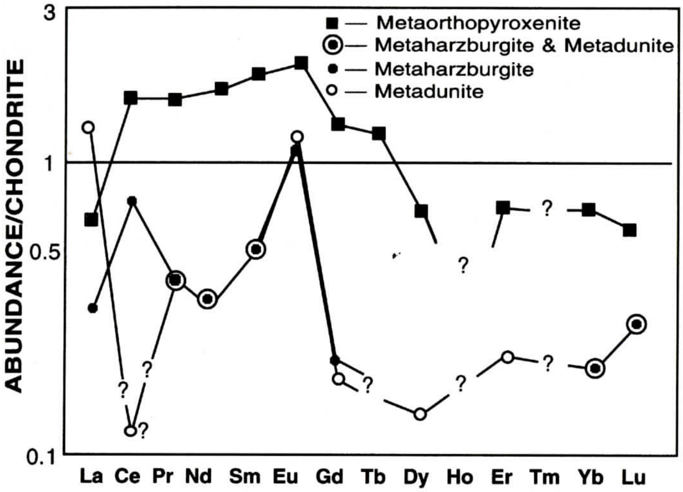


Figure 5. REE diagram showing REE patterns for metadunite, metaharzburgite, and metaorthopyroxenite from the Hoots Ultramafic body.

ers, 1998; Parkinson and Pearce, 1998). As expected, the orthopyroxene dominated sample (sample RM101) is more siliceous than the dunite and olivine-dominated metaharzburgite. MgO values are typical of harzburgites and orthopyroxenites, as are the rather low alumina values. Mg numbers fall between 85 and 93. Lime is also low, as expected, except in the metaharzburgite that contains some Ca-amphibole.

A REE diagram (Fig. 5) reveals that many element abundances in metaharzburgite and metadunite are below detection limits and most are depleted relative to the chondrite reference. The curves appear to show slightly greater LREE than HREE, a weak U-shape, and a positive Eu anomaly. Similar curves are typical of depleted mantle rocks in ophiolitic and ocean crustal settings (Gruau and others, 1998; Liou and Zhang, 1998; Parkinson and Pearce, 1998). For example, the unusual slightly positive europium anomaly is distinctive and a similar curve was considered by Liou and Zhang (1998) to represent residual cumulate material that perhaps had been metasomatized. The REE curve for the metaorthopyroxenite with metaharzburgite bands is unusual in having slight enrichment in LREEs, like curves presented by Piccardo and others (1988) for relatively undepleted mantle material.

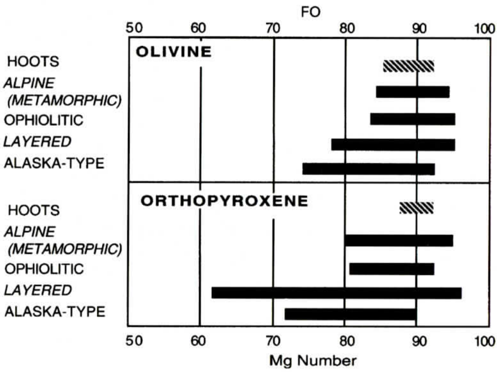


Figure 6. Plot of Mg number and Fo content of orthopyroxenes and olivines, respectively, from dunites, harzburgites, and orthopyroxenites of Alaska-type, lopolithic layered, ophiolitic, (alpine) metamorphic, and the Hoots ultramafic bodies. Data from numerous sources.

Mineral chemistries reveal the high magnesium contents of these alpine ultramafic rocks (Table 3). The orthopyroxenes have Mg numbers in the range of 87 to 93 (Fig. 6). Olivines show a similar range, with Fo values of 85 to 92 (Fig. 6). Chromium spinels fall at the upper end of the Mg number - Cr number diagram of Dick and Bullen (1984), a position characteristic of chrome spinels from alpine type bodies (Fig. 7). A few spinels are zoned in Ti with a Ti-richer core (i.e., the cores have a small ulvospinel

Table 3. Representative Chemistries of Hoots Minerals

OLIVINES						
	RM 103A-3/	**RM 112-6**	**RM 112-7**	**RM 112-8**	**RM 113-1**	**RM 117-4**
SiO_2	39.88*	40.70	40.70	40.55	40.87	40.42
TiO_2	nd	nd	nd	nd	nd	nd
Al_2O3	0.00	0.00	0.00	0.00	0.00	0.00
FeO†	10.43	9.55	9.59	9.72	7.93	8.24
MnO	0.17	0.14	0.15	0.10	0.14	0.16
MgO	49.09	49.60	50.01	49.61	50.49	50.32
CaO	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.14	0.18	0.26	0.14	0.37	0.39
TOTAL	99.72	100.17	100.72	100.17	99.80	99.53
Cations/4 oxygens						
Si	0.9851	0.9952	0.9907	0.9924	0.9964	0.9906
Al	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ca	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Mg	1.8078	1.8078	1.8149	1.8103	1.8352	1.8387
Fe	0.2155	0.1953	0.1953	0.1990	0.1617	0.1689
Mn	0.0036	0.0028	0.0031	0.0030	0.0030	0.0034
Ni	0.0028	0.0036	0.0051	0.0028	0.0072	0.0077
TOTAL	3.0148	3.0047	3.0091	3.0075	3.0034	3.0092
Mg#/Fo =	89	90	90	90	92	92
ORTHOPYROXENES						
	RM 103A-1	**RM 110-1**	**RM 112-5**	**RM 113-1**	**RM 117-1**	**RM 117-5**
SiO_2	57.81*	57.85	58.11	58.04	57.88	58.03
TiO_2	0.05	0.00	0.06	0.01	0.03	0.00
Al^2O_3	0.19	0.30	0.10	0.00	0.11	0.06
FeO†	7.08	7.94	6.46	5.52	5.54	5.75
MnO	0.22	0.23	0.19	0.14	0.21	0.14
MgO	34.73	34.18	35.27	35.75	36.01	35.80
CaO	0.09	0.11	0.08	0.08	0.10	0.08
Cr_2O_3	0.08	0.15	0.03	0.07	0.00	0.06
TOTAL	100.25	100.78	100.29	99.64	99.88	99.92
Mg#	90	88	91	92	92	92
Cations/6 oxygens						
Si	1.9923	1.9911	1.9952	1.9977	1.9891	1.9939
Ti	0.0012	0.0000	0.0014	0.0003	0.0007	0.0000
Al	0.0077	0.0120	0.0042	0.0000	0.0043	0.0025
Ca	0.0034	0.0042	0.0028	0.0029	0.0036	0.0030
Mg	1.7843	1.7537	1.8052	1.8346	1.8450	1.8337
Fe	0.2040	0.2286	0.1855	0.1587	0.1591	0.1650
Mn	0.0063	0.0068	0.0056	0.0041	0.0062	0.0042
Cr	0.0022	0.0042	0.0008	0.0002	0.0000	0.0015
TOTAL	4.0014	4.0006	4.0036	4.0013	4.0079	4.0039
En =	90	88	91	92	92	92
SPINELS						
	RM 103A-1	RM 103-3	RM 112-5R	RM 112-5C	RM 112-51	RM 117-2
SiO_2	0.02*	0.00	0.00	0.00	0.00	0.02
TiO_2	0.19	0.21	1.11	1.95	1.17	0.06
Al_2O_3	5.15	7.41	6.91	4.08	3.93	5.43
FeO†	32.77	28.48	30.02	32.22	30.47	29.70
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	4.73	5.27	5.94	5.78	5.47	5.21

CaO	0.00	0.01	0.02	0.00	0.02	0.01
Cr_2O_3	52.40	52.80	53.43	52.94	56.89	55.42
NIO	0.05	0.00	0.05	0.11	0.00	0.03
TOTAL	95.30	94.19	97.49	97.07	97.96	95.89
Mg# =	20	25	26	24	24	24
Cr# =	87	83	84	90	91	87
Catiions/4 oxygens						
Si	0.0008	0.0000	1.0000	0.0000	0.0000	0.0008
Ti	0.0054	0.0059	0.0301	0.0540	0.0321	0.0018
Al	0.2288	0.3244	0.2928	0.1771	0.1685	0.2368
Ca	0.0000	0.0006	0.0009	0.0000	0.0009	0.0005
Mg	0.2657	0.2917	0.3181	0.3174	0.2971	0.2874
Fe	1.0334	0.8842	0.9023	0.9928	0.9278	0.9191
Mn	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cr	1.5623	1.5499	1.5183	1.5419	1.6379	1.6211
Ni	0.0016	0.0000	0.0016	0.0031	0.0000	0.0009
TOTAL	3.0980	3.0567	3.0641	3.0863	3.0644	3.0683
* - values in percent; † = total iron as FeO; nd = not determined						

component). TiO_2 varies from 0.2 to 1.95 weight percent. Rims have lower Mg numbers and higher Cr numbers.

DISCUSSION AND CONCLUSIONS

The data presented here allow us to comment on a number of issues related to the nature and significance of Blue Ridge ultramafic rocks. The Hoots ultramafic rocks are definitely metamorphic, as revealed by textures and mineral chemistry. The position of the chrome spinels in the Mg#-Cr# diagram clearly places these rocks among alpine (metamorphic) ultramafic rocks. Both deformation and recrystallization have erased most evidence of protolith characteristics. Yet, the chemistry of the Hoots rocks, notably the REE chemistry and mineral chemistry data, suggests that the Hoots rocks are altered cumulate rocks, perhaps both depleted and enriched parts of an ophiolite cumulate.

The pyroxenite layers are of particular interest, but their origin remains problematical. The layers could represent fractionally crystallized layers, dikes, or partial melt restites. They have been deformed and some grains have "tails" and grain margin recrystallization. The discontinuous nature of the "layers" of metaorthpyroxenite and interlayered metadunite is compatible with a fractional crystallization cumulate origin, rather than an intrusive origin — provided that these layers still retain their original character. Some clearly do not, and other layers form a meshwork of intersecting and bifurcating metaorthopyroxenite that appears more like a set of veins. The REE chemistry of the rocks permits the interpretation that the dunites and harzburgites were depleted cumulate rocks that were locally intruded by dikes of pyroxenite. The Ti and Zr values of the ultramafic rocks are also consistent with a MORB/ophiolite origin (e.g., see Rerdmick and others, 2000). In addition, the MORB chemistry of surrounding hornblende schists and gneisses (Misra and Conte, 1991) is consistent with an ophiolite interpretation for the associated ultramafic rocks. The data do not, however, allow unequivocal determination of the nature of the pyroxenite protoliths, especially because of the extensive deformation and recrystallization that has affected the rocks.

Serpentinization has not affected the Hoots body significantly. The third phase of metamorphism did produce some serpentine as a mesh-textured replacement of olivine and as local veins. Clearly, this serpentine developed relatively late.

The three stages of metmorphism of the Hoots rocks, revealed by incompletely overprinted assemblages of metamorphic minerals, are consistent with the scenario of declining P,T conditions over time presented by Abbott and

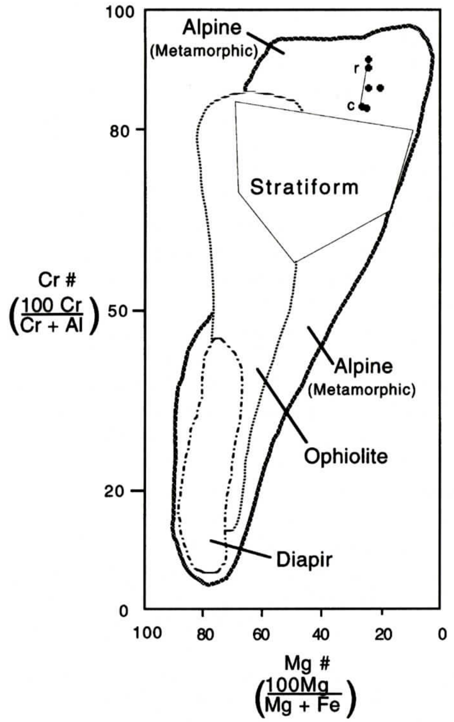


Figure 7. Mg number - Cr number diagram showing fields for chrome spinels from ultramafic diapirs, ophiolites, stratiform bodies, and alpine-type masses. Small dots represent Hoots chrome spinel analyses (c = core, r = rim) (modified from Dick and Bullen, 1984; Leblanc, 1987).

Raymond (1984). Combining assemblages (3) and (4), each of the three assemblages represents a metamorphic event of progressively lower grade that may correspond to a major orogenic event. Beginning with eclogite facies metamorphism, followed by amphibolite or granulite facies metamorphism during the Taconic Orogeny, the rocks with amphibole- (tremolite/actinolite and anthophyllite-) bearing assemblages responded to amphibolite facies conditions, perhaps during the Acadian event. Serpentine and other veins likely represent an Alleghenian greenschist facies event. The original age of the ultramafic rock bodies remains unknown, but is likely Neoproterozoic.

How were the ultramafic rocks emplaced in the eastern Blue Ridge Belt? By itself, the Hoots Ultramafic Body does not help to clarify this subject. The lack of exposure of the contact prevents conclusions about local relationships. Nevertheless, the association of small dismembered masses of ophiolitic (?) mantle rocks, eclogitic MORB, and pelitic schist at the base of the Gossan Lead Block both north and west of the Grandfather Mountain Window (Adams and others, 1995; Abbott and Raymond, 1997), argues for subduction and exhumation of dismembered ocean floor rocks in a melange at a convergent margin.

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ULTRAMAFIC ROCKS OF THE SPRUCE PINE AREA, WESTERN NORTH CAROLINA: A SENSITIVE GUIDE TO FLUID MIGRATION AND METAMORPHISM

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ABSTRACT

Small pods and lenses of variably hydrated ultramafic rocks are a widespread minor component of the Ashe Metamorphic Suite within the Gossan Lead Thrust Block of western North Carolina. The Ashe Metamorphic Suite includes mica schist and gneiss and amphibolite locally intruded by granitoid rocks of the Spruce Pine Plutonic Series. Olivine in the ultramafic rocks systematically becomes more Fe-rich with increasing hydration of the rocks and is in chemical equilibrium with various metamorphic phases (e.g., chlorite, anthophyllite, etc.), indicating that it is a product of metamorphic recrystallization. Thus, the ultramafic rocks are metamorphic rocks.

The system $MgO-SiO_2-H_2O$ with a small amount of Fe can be used to model mineral assemblages in the Spruce Pine metaultramafic rocks. Other components are controlled by the occurrence of a particular phase. Tremolite takes up Ca and chlorite ties up Al over a wide range of pressure and temperature conditions, and hence these phases are possible additions to metamorphic assemblages in the Spruce Pine ultramafic rocks.

Mineral assemblages in the metaultramafic rocks reflect recrystallization at the same conditions (amphibolite facies) as the pelitic schists from the western part of the Gossan Lead Thrust Block. Variable degrees of hydration give rise to a variety of mineral assemblages. Forsterite±enstatite without any talc or anthophyllite is the "driest" assemblage. The assemblages anthophyllite+enstatite+forsterite and talc+anthophyllite+forsterite are more hydrated, and the assemblage talc+forsterite without anthophyllite or enstatite is the most hydrated. Serpentine-bearing assemblages are not in equilibrium with the other silicate phases and reflect retrograde metamorphism. The apparent lack of abundant fluid during decompressional cooling resulted in multiple mineral assemblages being preserved in individual ultramafic bodies. Thus these rocks are very sensitive recorders of fluid flow and metamorphism. Several bodies near the center of the thrust block show more extensive hydration, perhaps related to proximity of Spruce Pine granitoid stocks. Less hydrated ultramafic rocks are found near the Gossan Lead Fault, in the same area as eclogitic mafic rocks. This suggests that the dry high grade mafic rocks survived complete hydration and preserved their high grade assemblages due to a lack of abundant fluids in this part of the fault block.

INTRODUCTION

The reactivity of Mg-rich bulk compositions has long been known to experimental geochemists and the Mg-rich systems were some of the first to receive experimental attention by hydrothermal methods (e.g. Bowen and Tuttle, 1949). Rapid nucleation and growth kinetics promote the growth of minerals in mafic and ultramafic igneous systems. The addition of small amounts of water to these rocks at subsolidus temperatures results in the formation of a variety of "alteration" or metamorphic phases. A well-defined set of mineral equilibria define the metamorphism of ultramafic protoliths over a wide range of pressures and temperatures (Winkler, 1976; Evans, 1977). Furthermore, the low Si content of ultramafic rocks makes them very

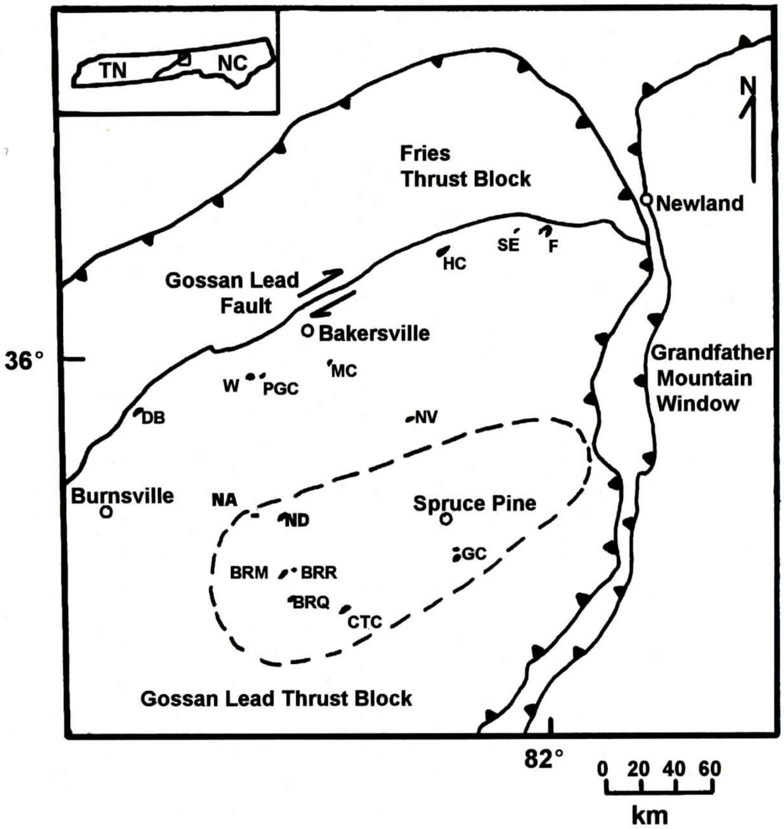

Figure 1. Metaultramafic rocks of the Gossan Lead Thrust Block. Lines with teeth on one side are the thrust faults (after Stewart and others, 1997). Bodies include Day Book (DB), Woody (W) Pleasant Grove Church (PGC), Mine Creek (MC), Henson Creek (HC), Senia (SE), Frank (F), Newdale Anthophyllite (NA), Newdale Dunite (ND), Blue Rock Mine (BRM), Blue Rock Road (BRR), Blue Rock Quarry (BRQ), Crabtree Creek (CTC), Normanville (NV), and Grassy Creek (GC). The dashed line represents the approximate outcrop area of the larger stocks in the Spruce Pine suite (taken from Brobst, 1962).

reactive with respect to other common rock types. Metasomatic reaction zones, forming the so called "blackwall" (Jahns, 1967), often mark the contact zones between ultramafic rocks and more Si-rich bulk compositions. Ultramafic rocks are so reactive that some of the low grade reactions producing serpentine (serpentinization) are thought to occur at surface conditions (Barnes and O'Neil, 1969). The reactivity and diversity of mineral assemblages over a wide range of conditions makes ultramafic protoliths sensitive recorders of metamorphism.

Ultramafic rocks are a widespread minor component of the rocks of the Blue Ridge Province of the southern Appalachian Mountains. Hess (1955) recognized the belt of ultramafic rocks in the Blue Ridge Province and another, less well defined belt, in the Piedmont region. Larrabee (1966) provided a more detailed compilation of these rocks and Misra and Keller (1978) summarized the abundant literature. When composed mainly of olivine and/or pyroxene, these ultramafic rocks have been given igneous names such as dunite or harzburgite, despite the fact that virtually all of these rocks contain metamorphic minerals such as chlorite or tremolite and the olivine and pyroxene are metamorphic. When the proportion of obvious metamorphic minerals is higher, metamorphic names, such as chlorite-tremolite-talc schist or soapstone have been used to describe them. In this paper the prefix "meta" will be added to igneous rock names to indicate the metamorphic character of these rocks.

ULTRAMAFIC ROCKS OF THE GOSSAN LEAD THRUST BLOCK

The Gossan Lead Thrust Block (formerly the Spruce Pine Thrust Sheet of Butler, 1972; Stewart and others, 1997; Adams and Trupe, 1997; Raymond, 1998) is the structurally highest fault block in the central part of western North Carolina. Recent studies have recognized that the Gossan Lead Fault, the boundary between the Gossan Lead Thrust Block and the Fries Thrust Block, is really an amphibolite facies dextral strike-slip shear zone. Butler (1972) identified several episodes of deformation and associated metamorphic recrystallization in the rocks of the Gossan Lead Thrust Block starting in the Ordovician and ending in the Pennsylvanian Periods. Abbott and Raymond (1984) recast the metamorphic history described by Butler (1972) to a continuous declining counter-clockwise P-T path. Adams and Trupe (1997) extended the range of the declining P-T path. Studies of the structures (Stewart and others, 1997; Adams and Trupe, 1997) generally confirmed the model proposed by Butler (1972). Goldberg and Dallmeyer (1997) used Nd-Sm and Ar-Ar techniques to date the metamorphism in the Gossan Lead Thrust Block. They found clusters of ages corresponding to the higher grade events proposed by Butler (1972), but the latest, lowest grade Alleghanian event was not found in the geochronology. This indicates that this low grade metamorphic event took place below the lowest closure temperature (about 350 ° C for muscovite) of the minerals used in the Ar-Ar geochronology (Goldberg and Dallmeyer, 1997).

The rocks of the Gossan Lead Thrust Block are mainly mica schists and gneisses, along with amphibolite of the Ashe and Alligator Back Metamorphic Suites. Mineral assemblages in the pelitic rocks include the Barrovian index minerals garnet, kyanite, staurolite, and sillimanite. Mafic rocks contain clinopyroxene, hornblende, epidote and garnet. Peak regional metamorphic conditions in most of the Gossan Lead Thrust Block correspond to the upper amphibolite facies (Butler, 1972; Abbott and Raymond, 1984; Willard and Adams, 1994). However, Willard and Adams (1994) and Adams and others (1995) described eclogite, locally overprinted by amphibolite facies mineral assemblages along the Gossan Lead Fault near Bakersville, NC (Figure 1). Ultramafic rocks, largely confined to the Ashe Metamorphic Suite, occur as small lens-shaped bodies that generally parallel the foliation of the enclosing metamorphic country rocks. Light-colored, coarse-grained granitoid rocks of the Spruce Pine Plutonic Series intrude both the ultramafic and enclosing country rocks. The granitoid rocks form small isolated tabular stocks that in many cases intrude along the regional foliation of the country rocks. Some of the granitic rocks are sheared (Stewart and others, 1997) others are folded and contain mineral foliations (L. A. Raymond, pers. comm., 2000). Hundreds of small dikes and sills of pegmatitic granitoid bodies are scattered throughout the region.

The ultramafic rocks are mainly metadunites, with minor amounts of metaharzburgite and metaorthopyroxenite. More hydrated metaultramafic rocks include amphibole chlorite-talc-schists and chlorite-talc schists (soapstone). Contact zones between the metaultramafic rocks and the country rocks are marked by a metasomatic reaction zone produced during regional metamorphism. Immediately adjacent to the metaultramafic rock is a zone of anthophyllite and/or talc. Further removed from the metaultramafic rock contact is a zone of talc that may contain minor anthophyllite, chlorite or vermiculite. A zone of chlorite marks the boundary between the contact zone and amphibolite, whereas vermiculite (weathered phlogopite) marks this zone when the country rock is mica schist or gneiss.

Mining operations (Murdock and Hunter, 1946; Conrad and others, 1963) have revealed that the ultramafic rocks are pods and lenses without any root zone. Most workers (summarized by Misra and Keller, 1978) cite the early tectonic emplacement of the ultramafic rocks into the country rocks and the subsequent deformation of the ultramafic rocks along with the country rocks. The lack of any evidence of magmatic intrusion together with the pod-like form of the ultramafic bodies suggests these are alpine-type ultramafic rocks (e.g. Raymond, 1995, p. 667 ff).

The purpose of this paper is to use the ultramafic rocks of the Gossan Lead Thrust Block (Figure 1) as compositionally sensitive monitors of metamorphic conditions. Initially, the mineral assemblages in the ultramafic rocks are correlated to the P/T conditions recorded by the mafic and pelitic country rocks. Having established the metamorphic character of the ultramafic rocks, the relation of metamorphism as recorded by the metaultramafic rocks to the local preservation of high grade eclogite along the Gossan Lead Fault is then examined.

ULTRAMAFIC ROCKS NEAR THE GOSSAN LEAD FAULT

Seven of the ultramafic bodies examined in this paper occur near the Gossan Lead Fault (Figure 1). These bodies are composed mainly of metadunite with small amounts of metaharzburgite and metaorthopyroxenite. Swanson (1995) pointed out the occurrence of these olivine-(and pyroxene-) rich rocks in the areas of higher metamorphic grade. Mafic rocks near the Gossan Lead Fault are locally eclogitic (Willard and Adams, 1994; Adams and others, 1995; Adams and Trupe, 1997). However, the eclogitic and ultramafic rocks show evidence of recrystallization at lower metamorphic grades, metamorphism that presumably occurred during decompression cooling from peak metamorphic conditions (Raymond and Abbott, 1997).

Day Book

The Day Book body (Figure 1, Table 1) appeared to consist of two bodies in the mid 1970's, however, subsequent mining activity reveals that the two bodies are probably connected (Raymond and Abbott, 1997). In this paper the term Day Book refers to both bodies.

The excellent exposures provided by an active mining operation have attracted several workers to Day Book rocks. Kulp and Brobst (1954) and Swanson (1981) studied the reaction of metadunite with intruding granitic magma at Day Book. Interaction of the ultramafic rocks with the silicic magma produced a metasomatic reaction zone consisting of almost monomineralic bands of vermiculite, talc, and anthophyllite. Swanson (1981) reported on the mineralogy and petrology of the Day Book ultramafic rocks as have other studies (Dribus and others, 1976; Neuhauser, 1982; Raymond, 1995; Raymond and Abbott, 1997).

Metadunite is the common rock type at Day Book (Table 2). Lesser amounts of metaharzburgite and rare metachromitite occur as layers and pods. Layers of metachromitite represent relict igneous layering. The metadunites contain slightly more MgO than SiO_2, one to two weight percent Al_2O_3, about one percent H_2O, and no reported CaO (Hunter,1941; Kulp and Brobst 1954). The low Fe contents are reflected in Mg numbers of 91.4 to 92.8.

Olivine compositions from the metadunites (Table 2) are similar to those reported in previous studies (Carpenter and Phyfer, 1975, Swanson, 1981; Lipin, 1984). Interstitial olivine in metachromitite layers is more Mg-rich (samples DB154B and 154D, Table 2) than the olivine from the metadunites. Swanson (1981) reported that the accessory chromites are higher in Cr than the segregated chromite, but Lipin (1984) reported that the accessory chromites are lower in Cr. Both authors found the segregated chromites contained more Al than the accessory chromite. McCormick (1975) reported on the crystal chemistry of high-Cr chlorite ("kammererite"= chromian clinochlore) from Day Book. Swanson (1981) also indicated that the composition of chlorite from a pod of chromitite is that of chromian clinochlore.

Swanson (1981) noted multiple periods of recrystallization in the Day Book rocks. Porphyroclasts of olivine and orthopyroxene are enclosed in fine-grained olivine with an equigranular polygonal texture. Both accessory and segregrated chromite are rimmed by chlorite. Tremolite often has coronas of magnesio-

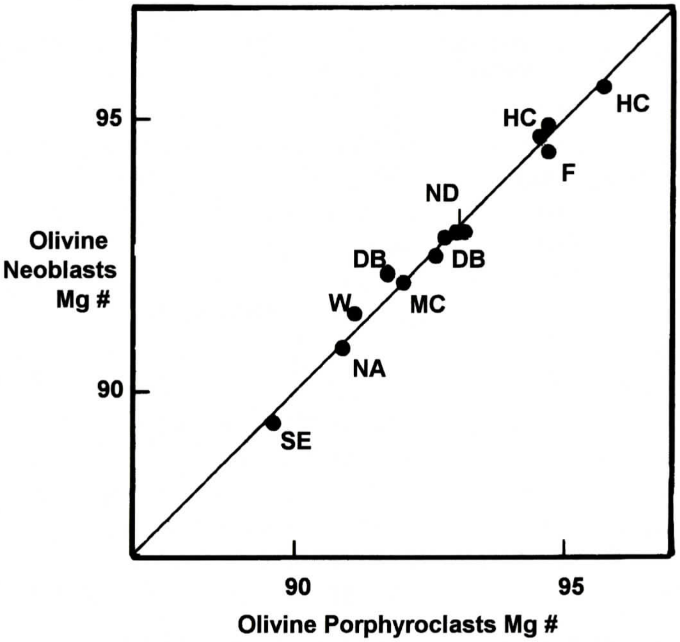

Figure 2. Compositions (Mg number = Mg/Mg+Fe x 100) of coexisting olivine porphyroclasts and neoblasts from different bodies. Compositions determined by electron microprobe analyses at the University of Georgia. Details available from the author. Body abbreviations as in Figure 1 caption.

cummingtonite. Veins of talc, chlorite, tremolite, and magnesite cut the metadunites and appear to be related to in the intrusion of granitoid rocks (Swanson, 1981). Serpentine minerals form both veins and a meshwork surrounding olivine grains in some of the metaultramafic rocks. The serpentine meshwork is composed mainly of antigorite (Swanson and others, 1985). The antigorite-bearing assemblage is cut by talc+/-amphibole+/-magnesite assemblages in some samples (Swanson and others, 1985). Veins of chrysotile+/-lizardite+/-magnetite cut all of the earlier mineral assemblages (including the serpentine meshwork) and often coat fracture surfaces in the metaultramafic rock (Swanson and others, 1985). Dribus and others (1976), however, reported anthophyllite cutting serpentine veins in olivine. Tien (1977) reported on a variety of carbonate minerals with serpentine minerals on fracture surfaces.

WOODY AREA

Two bodies of ultramafic rock occur in the Woody area (Figure 1) and the Woody body (Table 1), the larger of the two, was studied by several earlier workers (Conrad and others, 1963; Kingsbury and Heimlich, 1978; Raymond, 1995, p. 670; Raymond and Abbott, 1997). The Pleasant Grove Church body (Figure 1, Table 1), the smaller of the two bodies, is exposed in a small outcrop along a county road.

Metadunite and minor metaharzburgite both occur at Woody (Table 1). Metadunite is the common rock at Pleasant Grove Chruch. Kingsbury and Heimlich (1978) reported major element (Si, Al, Mg, Fe) compositions for several Woody samples. The rocks contain subequal amounts of SiO_2 and MgO with Mg numbers of 94.4 to 94.7 for the metadunites and 93.9 to 95.2 for the metaharzburgites.

Olivine from the metadunites in both bodies is slightly higher in Mg than the olivine in the metaharzburgite from the Woody body (Table 2). The Woody and Pleasant Grove Church

Table 1. Location and Rock Types

Body name	Abbreviation Figure 1	North latitude	West longitude	Country rocks[1]	Metaultramafic rocks[2]
Day Book	DB	35°58'01"	82°17'02"	a, mg, gr	d, hz, ch
Woody	W	35°58'29"	82°12'57"	ms, mg gr	d, hz, cs
Pleasant Grove Church	PGC	35°58'41"	82°12'32"	ms, mg	d
Mine Creek	MC	35°59'35"	82°09'35"	a, mg	d, hz, opx, cs
Henson Creek	HC	36°02'55"	82°03'24"	a, ms, mg	d, hz, opx
Senia	SE	36°03'49"	82°00'52"	a	d, hz, opx
Frank	F	36°04'04"	82°00'22"	a, ms	d, hz, opx, trs
Newdale Dunite	ND	35°54'42"	82°11'17"	a	d, hz
Newdale Anthophyllite	NA	35°55'00"	82°11'50"	ms, mg	d, as
Grassy Creek	GC	35°54'04"	82°03'48"	a, ms, mg, gr	d
Normanville	NV	35°57'28"	82°06'33"	a, gr	d, chs, cs
Blue Rock Mine	BRM	35°53'31"	82°11'50"	a, ms, mg, gr	acs, chs
Blue Rock Road	BRR	35°53'19"	82°10'58"	ms, mg gr	ts
Blue Rock Quarry	BRQ	35°52'48"	82°11'02"	a, ms, gr	ts
Crabtree Creek	CTC	35°51'34"	82°08'33"	a, ms, mg	chs

[1] a = amphibolite, mg = mica gneiss, ms = mica schist, gr = granitoid rocks

[2] d = metadunite, hz = metaharzburgite, ch = metachromitite, opx = metaorthopyroxenite, cs = magnesiocummingtomite-chlorite schist, trs = tremolite-talc schist, as = anthophyllite schist, chs = chlorite-magnesiocummingtonite schist, acs = anthophyllite chlorite schist, ts = chlorite-talc schist

rocks are characterized by the occurrence of hydrous phases (Table 2), often with corona textures. Magnesiocummingtonite forms distinct prismatic crystals in several of the samples. In many cases anthophyllite forms an overgrowth on magnesiocummingtonite and, in some cases, is intergrown as lamellae with the clinoamphibole. Rare grains of tremolite occur in a few samples. Chromite shows a lattice texture (Lipin, 1984) with chlorite replacing some exsolved phase in the spinel and also forming a corona around the oxide. Kingsbury and Heimlich (1978) noted that anthophyllite in Woody rocks cuts olivine and areas of talc + serpentine. The significance of this is not clear, since the acicular character of anthophyllite makes it appear to "cut" olivine and talc, even when in equilibrium with these phases (B. W. Evans, pers. comm., 2000). Late-stage development of serpentine as a meshwork on olivine is common. Kingsbury and Heimlich (1978) stated that both antigorite and chrysotile serpentine are found in rocks from Woody.

Mine Creek

The Mine Creek body (Figure 1, Table 1) is exposed in a road cut and along a ridge adjacent to a subdivision. Metadunite dominates at Mine Creek, and lesser amounts of metaharzburgite, metaorthopyroxenite, and anthophyllite-talc schist occur as well.

Forsteritic olivine and enstatite are the most common minerals in Mine Creek rocks (Table 2). Deformed medium- to coarse-grained olivine porphyroclasts are surrounded by compositionally equivalent fine-grained olivine neoblasts (Figure 2). Trace amounts of chromite, some of it with the lattice texture (Lipin,1984), occur in most of the samples. Chlorite and talc are abundant in some samples and tremolite, often with a narrow corona of magnesiocummingtonite, is a common accessory phase (Table 2). Individual crystals of magnesiocummingtonite are abundant in the metaorthopyroxenite. Serpentine is abundant in the Mine Creek rocks and forms a meshwork around the olivine grains. Veins of serpentine also cut the olivine fabric.

Table 2. Modal Analyses[1] (volume percent) of Selected Samples

body[2]	sample #	Mg # ol[3]	olivine	en[4]	chrom[4]	ch[4]	trem[4]	cumm[4]	antho[4]	talc	serp[4]	ag[4]
DB	DB59A	92.6	96.6	0.0	0.6	0.6	0.0	0.0	0.0	2.2	<0.3	0.0
DB	DB66A	94.1	85.1	<0.3	<0.3	4.2	0.8	1.6	0.0	4.2	3.9	0.0
DB	DB134B	93.1	91.7	0.0	1.8	1.2	<0.3	0.0	0.0	0.0	5.3	0.0
DB	DB153	92.0	82.7	3.0	2.0	1.7	<0.3	4.7	0.0	4.6	1.3	0.0
DB	DB154B	96.8	41.0	0.0	40.0	12.0	0.0	0.0	0.0	0.0	6.7	1.0
DB	DB154D	95.0	0.0	0.0	69.3	29.3	0.0	0.0	0.0	0.0	0.0	1.3
W	W3	91.7	32.7	0.0	5.0	4.3	0.0	0.0	0.0	0.0	58.0	0.0
W	SP57QQ	91.3	54.0	26.3	1.0	5.0	<0.3	0.0	0.0	0.0	13.7	0.0
PGC	PGC5d	91.5	51.3	<0.3	<0.3	1.0	2.0	0.0	0.0	0.0	45.7	0.0
PGC	PGC5p	—	1.5	90.9	<0.3	<0.3	0.0	0.0	0.0	<0.3	6.1	0.0
MC	MC5B	91.5	40.7	1.0	0.3	16.0	0.3	<0.3	0.0	33.0	8.7	<0.3
MC	MC8	92.7	58.3	1.7	1.3	0.0	1.7	0.0	0.0	0.0	37.0	0.0
HC	HC2A	94.8	98.0	0.0	<0.3	0.7	0.7	0.0	0.0	0.0	0.0	0.7
HC	HC10B	93.7	6.0	48.7	<0.3	3.7	<0.3	<0.3	0.0	41.3	0.3	0.0
HC	HC11	91.8	41.3	20.7	0.7	6.3	20.3	7.7	0.0	0.0	3.0	0.0
SE	SE8	89.5	55.3	37.0	0.3	4.0	0.0	0.0	0.0	<0.3	3.0	0.0
SE	SE19d	91.7	71.2	8.0	2.9	4.7	0.4	0.0	0.0	0.0	12.8	0.0
SE	SE19p	—	19.2	57.8	<0.3	22.3	0.0	0.0	0.0	0.0	0.8	0.0
F	F2A	92.1	84.0	9.0	<0.3	3.0	0.7	0.0	0.0	0.0	3.3	0.0
F	F4B	90.9	22.3	0.3	0.3	<0.3	58.3	<0.3	0.0	11.0	0.7	7.0
F	F15	94.6	88.7	0.0	<0.3	2.0	1.0	0.0	0.0	0.7	7.3	0.0
F	F84-8	92.0	57.0	17.0	0.3	<0.3	35.3	<0.3	0.0	1.0	0.3	.0
ND	ND2	93.0	88.7	0.0	0.7	<0.3	0.0	0.0	0.0	2.0	8.3	<0.3
ND	ND6	92.5	65.7	3.0	1.7	2.0	0.0	0.0	0.0	17.7	10.0	0.0
ND	ND22	92.5	66.7	2.7	<0.3	<0.3	<0.3	0.0	0.0	2.7	27.7	0.3
GC	SP1	89.4	48.3	0.0	1.3	2.7	2.7	6.0	0.0	10.3	28.6	0.0
NA	NA4	90.8	46.3	0.0	0.3	7.0	0.0	0.0	45.3	1.0	0.0	0.0
NA	NA8	90.7	45.3	0.3	2.0	6.0	0.0	0.0	10.7	43.7	1.0	0.0
NA	NA10	90.3	82.0	0.0	0.7	10.0	0.0	0.0	2.3	3.3	1.3	0.3
BRM	97BR7A	87.6	1.3	0.0	3.0	0.3	0.0	9.7	0.0	65.7	0.0	20.0
BRR	SP37E	---	0.0	0.0	1.0	43.0	0.0	9.7	0.0	46.3	0.0	0.0
BRQ	BRQ3	—	0.0	0.0	4.7	30.7	0.0	3.3	0.0	61.3	0.0	0.0
CTC	SP16B1	—	0.0	0.0	1.7	11.7	12.3	54.0	0.0	20.3	0.0	0.0
NV	NV1	90.5	30.0	0.3	<0.3	21.3	0.7	13.0	0.0	0.0	0.0	0.0

1based on counts of 300 points in a thin section

2abbreviations for body names in Table 1

3Mg# = (Mg/Mg+Fe) x 100 in olivine based on electron microprobe analyses

4en = enstatite, chrom = chromite, ch = chlorite, trem = tremolite, cumm = magnesiocummingtonite, antho = anthophyllite, serp = serpentine, mag = magnesite

Henson Creek

The Henson Creek body (Figure 1, Table 1) was studied by Sharpe (1979). Pre-mining drilling revealed a bottom to the olivine-rich rock and apparently much of the rock was removed during mining. Current outcrops are limited to the outer parts of the body. Metadunite and metaharzburgite are the major rock types in Henson Creek, but olivine metaorthopyroxenite is also common (Table 2). Veins of metaorthopyroxenite cut the metadunites.

Chemically the Henson Creek rocks are essentially composed of Si, Mg, Fe, and O and have Mg numbers of 91.4 to 92.6 (Carpenter and Chen, 1978; Sharpe, 1979). Calcium contents vary from less than 0.1 weight percent CaO to over 1.5 weight percent. Water contents of one to two weight percent reflect the partially hydrated character of the rocks.

Henson Creek olivine is the most Mg-rich in the Spruce Pine area (Table 2). Accessory chromite grains are rare. Only in the talc-amphibole-magnesite veins or the veins of serpentine that cross cut the olivine fabric are hydrous phases abundant. Magnesiocummingtonite forms individual crystals and coronas on tremolite grains.

Frank Area

Two bodies of ultramafic rock occur in the Frank area (Figure 1, Table 1). The Frank body is the larger of the two and is one of the largest ultramafic bodies in the Spruce Pine area (Hunter, 1941). Frank rocks are discussed by Hunter (1941), Conrad and others (1963), Bluhm (1976), Carpenter and Chen 1978) and Raymond and Abbott (1997). The rocks from Senia, the smaller of the two bodies, were described by Hunter (1941).

Metadunite, metaharzburgite, and metaorthopyroxenites are the common rock types in both bodies, but metadunite is less common in the Senia body. Bluhm (1976) and Carpenter and Chen (1978) describe clinopyroxene from the Frank body, but I found only enstatite. Bluhm (1976); summarized by Raymond and Abbott (1997), mapped layers of peridotite (lherzolite containing about 15% clinopyroxene with a trace of orthopyroxene) and also noted that almost all of the "peridotite" is composed of orthopyroxenite. Apparently the "peridotite" identified by Bluhm (1976) is metadunite with tremolite and orthopyroxene. Metaorthopyroxenite forms small dikes (veins?) that cross cut metadunite fabrics in both bodies. Bluhm (1976) mentioned that some of the orthopyroxene-rich layers show boudinage in the Frank body.

Major element compositions for several metadunites and one metaorthopyroxenite from Frank and one metadunite from Senia are very similar with subequal amounts of MgO and SiO_2 (Carpenter and Chen,1978). Magnesium numbers for Frank metadunites range from 90.0 to 91.4, whereas a metadunite from Senia has a Mg number of 87.4. The Frank metaorthopyroxenite is higher in SiO_2 and lower in MgO and Fe than the metadunites (Carpenter and Chen, 1978) with a Mg number of 90.0. All of the rocks contain at least one weight percent H_2O and some samples contain over 10 weight percent H_2O.

Clearly both Frank and Senia contain olivine and/or orthopyroxene. Olivine from the metadunites and metaharzburgite from both bodies has about the same composition (Table 2), but the most Mg-rich olivine is in the metadunite. Orthopyroxene is commonly coarse-grained and contains inclusions of chlorite and tremolite oriented along the pyroxene cleavage. Chromite is not common and typically exhibits lattice texture (Lipin,1984) and a corona of chlorite. Tremolite is the common amphibole and a few samples have coronas of magnesiocummingtonite. Coarse-grained magnesite, often associated with talc and tremolite in veins, occurs in some of the olivine-rich Frank rocks. Serpentine commonly forms a meshwork on olivine in the olivine-rich rocks in both bodies and it also forms veins that cross cut the olivine fabric and meshwork.

Ultramafic Rocks Away from the Gossan Lead Fault

Eight ultramafic bodies examined in this study occur in the central part of the Gossan Lead Thrust Block far removed from the Burnsville Fault (Figure 1). These bodies are either olivine- or pyroxene-rich or olivine-poor. Some of the bodies do not contain any olivine or pyroxene. Relict olivine provides clues that these rocks did contain olivine at one time and that the present assemblage of hydrous minerals results from thorough hydration of the rocks.

Blue Rock Road Area

Three bodies of ultramafic rocks were examined in the Blue Rock Road area (Figure1, Table 1). The Blue Rock Mine body (Table 1) is pod-like with a maximum width of about 12 meters and a length of about 30 meters. Drilling during mining operations revealed the bottom of the ultramafic rock below the current mine floor (Conrad and others, 1963) and emphasizes the pod-like character of the Blue Rock Mine body. The Blue Rock Road body (Table 1) is exposed in a ditch along Blue Rock Road near Blue Rock Church and was briefly described by Raymond and Abbott (1997). The third body, Blue Rock Quarry (Table 1), was a quarry site for soapstone used by Native Americans (Mathis, 1982) and more recently by European Americans (Turner and others, 1998).

The most common rock type in these bodies is a chlorite-talc schist (Table 2) containing variable amounts of chlorite and anthophyllite (Turner and others, 1998). Smaller amounts of tremolite, magnesite and chromian magnetite occur in some samples. Schist composed entirely of chlorite occurs at Blue Rock Quarry and Blue Rock Mine and apparently represents part of the metasomatic reaction zone developed along the contact (Conrad and others, 1963). Rocks from Blue Rock Quarry have a restricted range of bulk compositions (SiO_2 = 52 to 55 wt.%) with low Ca and Al contents (Turner and Swanson, 1998). Magnesium numbers range from 87.5 to 89.0 (A. Turner, 1999, pers. comm., unpublished data).

A few relict olivine grains in the Blue Rock Mine and Blue Rock Road rocks have the lowest Mg numbers (87.0 to 88.3) of any of the Spruce Pine olivines (Table 2). Chromian magnetite (with coronas of chlorite) represents recrystallized chromite. Tremolite occurs in some of the rocks and it is usually overgrown by magnesiocummingtonite. Magnesite, enclosing magnesiocummingtonite and talc, is a late crystallizing phase in a few samples.

Newdale Area

The Newdale Dunite (Hunter, 1941; Vrona, 1979; Raymond and Abbott, 1997) and the Newdale Anthophyllite (Conrad and others, 1963) in the area of the Newdale community (Figure 1) were examined in this study. Much of the rock in both bodies was removed by the mining operations and only the outer parts of the bodies are still exposed. The Newdale Anthophyllite rock was composed mainly of enstatite partially replaced by anthophyllite and talc (Conrad and others, 1963), but sampling in 1977 revealed only anthophyllite-talc schists and olivine-talc-anthophyllite metadunite.(Table 2). Metadunite and metaharzburgite are the major rock types in the Newdale Dunite body. Partially serpentinized metadunite from the Newdale Dunite body is composed almost entirely of Si, Mg, O and Fe with a Mg number of 92.1 (Carpenter and Chen, 1978).

Olivine from Newdale Dunite is some of the most Mg-rich olivine from the Spruce Pine area, but olivine is less Mg-rich in the Newdale Anthophyllite body (Table 2). Talc is a major phase from both bodies. Anthophyllite is a major phase in the Newdale Anthophyllite rocks, but is rare in the Newdale Dunite body (Table 2). Minor amounts of tremolite appears in the Newdale Dunite rocks, but tremolite was not found in the Newdale Anthophyllite rocks. Chlorite is a minor phase in the Newdale Dunite rocks, but it is more common in the Newdale Anthophyllite rocks (Table 2). Olivine-rich rocks have a serpentine meshwork and veins of serpentine cut the meshwork.

Crabtree Creek

The Crabtree Creek body (Figure 1, Table 1) outcrops along a steep slope adjacent to Crabtree Creek. Variations of chlorite-, tremolite-,

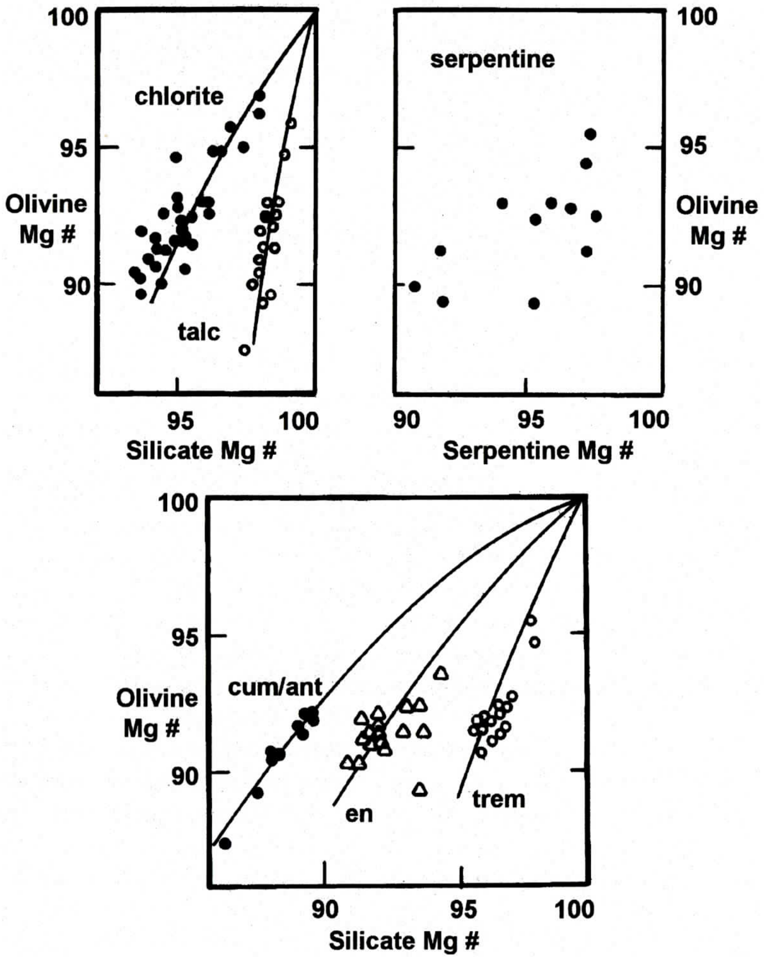

Figure 3. Compositions (Mg number = Mg/Mg+Fe x 100) of olivine and coexisting silicate minerals in the metadunites of the Spruce Pine area. Compositions determined by electron microprobe analyses at the University of Georgia. Details available from the author.

anthophyllite– and talc schist are the only rock types in the Crabtree Creek body, and olivine and pyroxenes are absent. Trace amounts of magnetite contain no evidence of former chromite. The rocks consist of subequal amounts of tremolite and magnesiocumingtonite enclosed in a chlorite-talc matrix. Acicular magnesiocummingtonite forms an overgrowth on some prismatic grains of tremolite. Serpentine is absent.

Normanville

The Normanville "body" (Figure 1, Table 1) consists of a few outcrops surrounded by mica schist (Brobst, 1962). Most of the ultramafic rocks do not contain any olivine or pyroxene and consist largely of hydrous phases. One sample contains olivine and rare enstatite in a matrix of amphibole and chlorite (Table 2). Chlorite-magnesiocummingtonite schist is the most common rock type.

Chlorite, tremolite, and magnesiocummingtonite are the dominant minerals in the Normanville rocks. Trace amounts of Fe oxide (former chromite?) are surrounded by coronas of chlorite. Talc is a rare component in two of the samples. Coarse-grained magnesite is minor. Serpentine is absent.

Grassy Creek

Two bodies of ultramafic rock, collectively called the Grassy Creek body, include (Figure1, Table 1) a northern body called the Spruce Pine North body by Raymond and Abbott (1997). This body and the one to the south are called the Grassy Creek body in this paper to avoid confusion with other "Spruce Pine" features. The southern Grassy Creek body forms a small hill in a storage yard of a utility company and the northern body is exposed in a road cut and a yard. The rocks are serpentinized metadunites.

Both bodies have been extensively hydrated with olivine and chromite being partially replaced by hydrous phases. Olivine is less Mg-rich than in most of the other bodies (Table 2). Tremolite is a common minor phase and typically has a corona of magnesiocummingtonite. Variable amounts of talc and chlorite occur in the rocks (Table 2). Serpentine in moderate to major amounts forms a meshwork around the olivine. Veins of serpentine cut the meshwork and all of the other silicate phases in the metadunites.

MODELING ULTRAMAFIC MINERAL ASSEMBLAGES

Chemical analyses of Spruce Pine metaultramafic rocks show the rocks are rich in Mg with minor amounts of Al and Ca (Hunter, 1941; Kulp and Brobst, 1954; Kingsbury and Heimlich, 1978; Carpenter and Chen, 1978; Sharpe, 1979; Turner and Swanson, 1998). The Mg and Fe contents are reflected by the high Mg numbers of the silicate minerals (Swanson, 1999). To a first approximation mineral assemblages in the metaultramafic rocks can be represented by the system $MgO-SiO_2-H_2O$ with a modest amount of Fe. Evans and Guggenheim (1988) used thermodynamic data to adjust the Fe-free phase equilibria in the $MgO-SiO_2-H_2O$ system for Fe contents typically found in metaultramafic rocks. The addition of even modest amounts of Fe to the $MgO-SiO_2-H_2O$ system greatly expands the stability field for anthophyllite (Evans and Guggenheim, 1988; Raymond and Abbott, 1997).

Evans (1977) discussed the role of Ca and Al in metaultramafic mineral assemblages. He concluded that these components are often represented by a particular mineral phase (diopside or tremolite for Ca; spinel or chlorite for Al) that is stable over a wide range of P-T conditions. In the Spruce Pine metaultramafic rocks, chlorite is found in rocks from every body (Table 2). Additionally, chlorite is found in virtually every rock with abundant olivine and/or enstatite, further supporting the metamorphic heritage of these rocks. Chlorite forms coronas on chromite grains and is found with talc, tremolite, and magnesite in veins that cut the olivine fabric. Yet in some rocks, chlorite does show equilibrium textures with olivine (chlorite sheets with (001) faces against granoblasitc olivine with triple grain boundaries of 90°, 90°, 180°). Tremolite is also a common accessory phase, but is not as widespread as chlorite. Tremolite shows both equilibrium and nonequilibrium textures with olivine, similar to chlorite. Some rocks containing olivine + chlorite +/- enstatite do not contain tremolite. Considering the "buffering" of Al by chlorite and Ca by tremolite, the $MgO-SiO_2-H_2O$ system with a small amount of Fe is a good model for Spruce Pine metaultramafic mineral assemblages.

Textural evidence for multiple periods of crystallization and recrystallization and equilibrium is widespread in the Spruce Pine metaultramafic rocks (e.g.Swanson, 1981; Raymond, 1995; Raymond and Abbott, 1997). Phases such as chlorite are in textural equilibrium with both early and late assemblages. Swanson (1981) used the lack of reaction relationships in three phase assemblages at triple grain contacts as evidence for equilibrium between these phases. Such occurrences do not, however, guarantee equilibrium. The lack of reaction relationships could merely reflect sluggish reaction kinetics between the phases.

Another way to consider equilibrium between phases is to look for consistent patterns of compositional variation of components common to both phases. Olivine was selected as the basis for comparison to the other silicate minerals, because it is the most common phase (Table 2). In many bodies olivine occurs as large

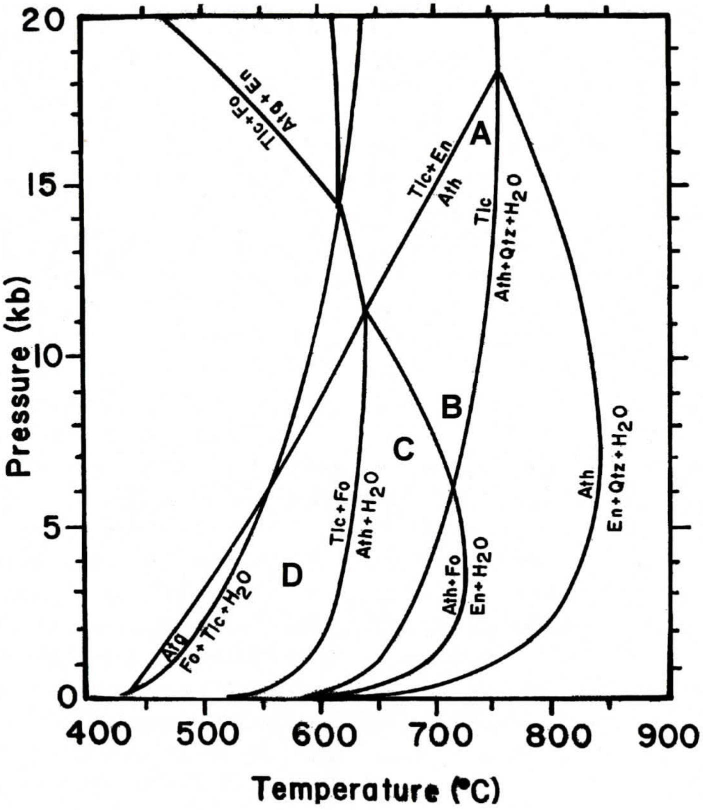

Figure 4. Diagram showing the equilibria in the system MgO-SiO$_2$-H$_2$O with an appropriate amount of Fe added (from Evans and Guggenheim, 1988). Letters refer to compatibilities shown on Figure 5 and include P/T conditions corresponding to those recorded by eclogites (A), amphibolites (B), and pelitic schists (C, D) from the western part of the Spruce Pine thrust sheet (Willard and Adams,1994; Adams and others, 1995; and Adams and Trupe,1997).

kinked porphyroclastic grains, surrounded, and locally replaced by fine-grained neoblasts of olivine that typically have 120° triple point grain boundaries. Compositional zoning is absent. Furthermore, compositions of the porphyroclasts and fine-grained olivine are the same within individual thin sections (Figure 2) reflecting the relatively rapid kinetics of Fe/Mg exchange in olivine.

Partitioning of Fe/Mg between olivine and coexisting silicate minerals is illustrated in Figure 3. Talc, tremolite, and magnesiocummingtonite/anthophyllite show good compositional variation with olivine, suggesting that these phases are in equilibrium with olivine. Chlorite and enstatite compositions generally vary systematically with olivine, but there is significant scatter in the data suggesting disequilibrium (Figure 3). At least some of the scatter is related to apparent textural disequilibrium. Enstatite forms relict porphyroclasts in some samples and is in veins of metaorthopyroxenite that cut the olivine fabric in others. A similar argument can be made for the chlorite coronas on chromite or the chlorite in tremolite + chlorite + talc + magnesite veins. Serpentine compositions show no relation to olivine compositions (Figure 3). This is not surprising given that the serpentine is replacing the olivine and is composed of several different minerals (Swanson and others, 1985). Based on these compositional relations talc, tremolite, magnesiocummingtonite/anthophyllite and at least some chlorite and enstatite are in compositional equilibrium with coexisting olivine, whereas some chlorite, orthopyroxene, and serpentine are not.

Table 3. Mineral Assemblages

Body	En+Fo[1]	A+En+Fo	A+Tlc+Fo	A+Fo	Tlc+Fo	A+Tlc
---------------Olivine-rich bodies near Burnsville Fault----------------						
Day Book	X		X	X	X	
Woody	X					
Pleasant Grove Church	X					
Mine Creek	X					
Henson Creek	X	X		X	X	
Senia	X					
Frank	X		X	X	X	X
-------------Olivine-rich bodies away from Burnsville Fault------------						
Newdale Dunite			X		X	
Grassy Creek			X			X
-------------Olivine-poor bodies away from Burnsville Fault------------						
Blue Rock Mine			X			X
Blue Rock Quarry						X
Blue Rock Road						X
Newdale Anthophyllite			X			X
Normanville				X		X
Crabtree Creek						X

[1] En = enstatite, Fo = olivine, A = anthophyllite/cummingtonite, Tlc = talc

Reaction curves in the system $MgO-SiO_2-H_2O$ plus appropriate quantities of Fe (Figure 4) produce the compatibilities in Figure 5. The metamorphic conditions reported by Adams and coworkers (Willard and Adams, 1994; Adams and others, 1995; Adams and Trupe, 1997) for pelitic and mafic rocks from the western part of the terrane (A-D, Figures 4 and 5) are also shown on Figure 4. To the east, in the vicinity of Spruce Pine, there is a much higher density of granitic intrusions (Figure 1) and some workers (Raymond and Abbott, 1980; anonymous reviewer, 2000) suggest structural doming of the country rocks and lower metamorphic grade compared to rocks in the western part of the terrane. The sequence A-D (Figure 4) represents a progressive cooling of the rocks following a peak in regional metamorphism (Adams and Trupe, 1997). Forsterite + enstatite assemblages, typical of ultramafic igneous rocks are represented on the $MgO-SiO_2$ side of the triangle and this is the appropriate range of bulk compositions for the Spruce Pine ultramafic rocks. Hydration of this bulk composition during metamorphism results in the mineral assemblages shown in Figure 5.

Mineral Assemblages in the Spruce Pine Metaultramafic Rocks

Mineral assemblages in Spruce Pine metaultramafic rocks represented on Figure 5 are reported in Table 3 for the various bodies. Not included in this list of mineral assemblages are the serpentine-bearing assemblages, because serpentine is not in equilibrium with the other silicate phases. Also not included are the talc + enstatite assemblages. The reaction curve talc + enstatite = anthophyllite is very poorly known experimentally (B. W. Evans, pers. comm., 2000) and, thus, the significance of talc + enstatite assemblages is not clear. The bodies are listed in order by general structural position and olivine content (Table 3). Generally, the bodies with abundant olivine have olivine Mg numbers above 90. Only trace amounts of relict olivine are found in the Normanville and Blue Rock Mine bodies and olivine has not been found in the Blue Rock Road, Crabtree Creek, and Blue Rock Quarry bodies. The bodies that contain

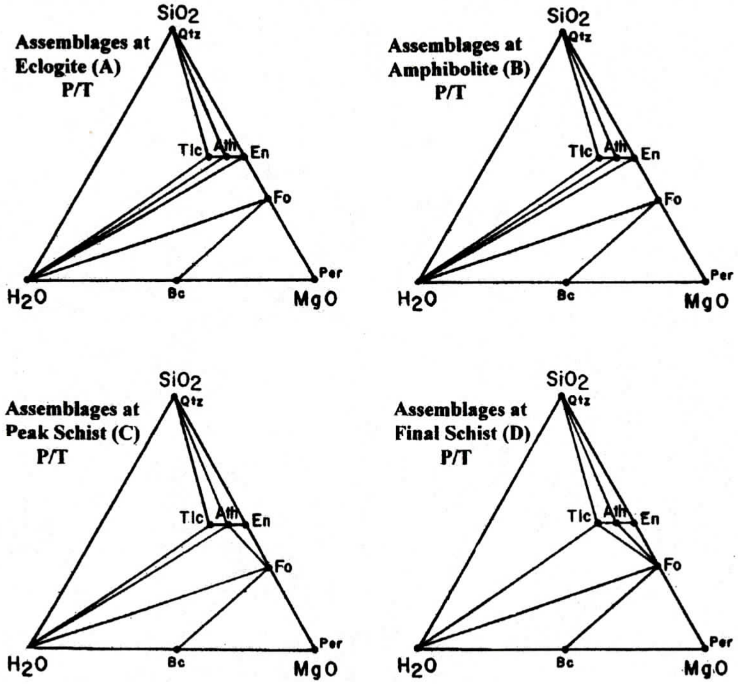

Figure 5. Mineral compatibilities in the system MgO-SiO_2-H_2O. Metamorphic conditions (A, eclogite; B, amphibolite; C, peak schist; and D, final schist) refer to P/T conditions represented in Figure 4. Compatible assemblages include chlorite ± clinopyroxene (A) and chlorite ± tremolite (B, C, D)

abundant olivine (the olivine-rich category of Swanson (1995, 1997) show a variety of mineral assemblages that reflect the P-T conditions (C and D, Figures 4 and 5) defined by the pelitic schists in the western part of the Spruce Pine thrust sheet. Bodies with little or no olivine were more hydrated than bodies with abundant olivine. In the olivine-rich bodies the extent of hydration was generally small and only locally produced rocks composed of just one or two reaction products. In the olivine-poor (or absent) bodies the extent of hydration was much greater and resulted in completely hydrated metaultramafic rocks consisting of talc + anthophyllite (+chlorite+/-tremolite). These hydrated metaultramafic rocks did not record lower grade, serpentine-bearing, mineral assemblages. Apparently the partially hydrated olivine-rich rocks contain enough olivine (and/or pyroxene) to promote fractures and fluid pathways as the rocks cool to lower grades to allow fluid circulation and formation of serpentine. The completely hydrated metaultramafic rocks with their matrix of talc + chlorite +/- amphibole do not promote fracturing and thus do not record the lowest grade (serpentine) assemblages.

Consideration of the assemblage talc + anthophyllite (without olivine or pyroxene; Figure 5) shows that this assemblage cannot be produced from typical ultramafic bulk compositions along the MgO-SiO_2 side line without the addition of H_2O and Si (or the loss of Mg). This implies that these completely hydrated metaultramafic rocks either had more Si-rich bulk compositions, that Si was added to the bulk composition, or that Mg was lost; perhaps at the time of hydration. Turner and Swanson (1998) found that the range of SiO_2 content for the Blue Rock Quarry body (one of the completely hydrated bodies) was 52-55 wt.% and this is higher than the 39-42 range reported for metadunites from the Spruce Pine area (Hunter, 1941; Kulp and Brobst, 1954; Carpenter and Chen, 1978; Kingsbury and Heimlich, 1978;

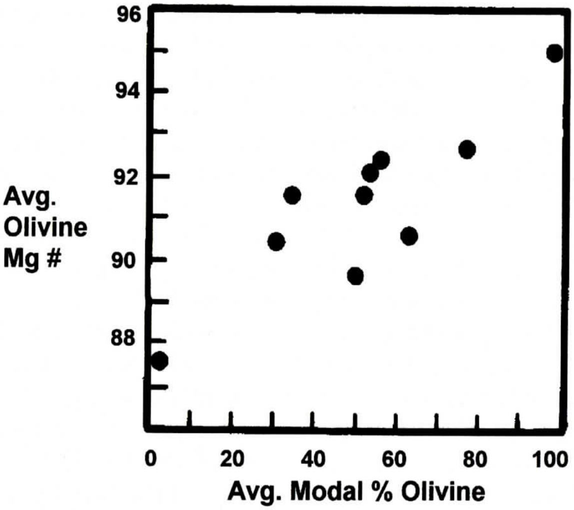

Figure 6. Average composition (Mg number = Mg/Mg+Fe x 100) of olivine in relation to the average modal percentage of olivine (based on point counts using 300 points) in metadunites from the Spruce Pine area.

Sharpe, 1979). Evidence of metasomatic exchange between the metaultramafic bodies and the country rocks is common. Zones of chlorite, anthophyllite, talc, and phlogopite (now vermiculite) are common along the contacts between the metaultramafic bodies and the country rocks. However, the extent of these reaction zones is similar in both the olivine-rich and olivine-poor bodies, suggesting no significant difference in component exchange (and hence change in bulk composition) between the olivine-rich and olivine-poor bodies and the country rocks.

DISCUSSION

Ultramafic rocks of the Spruce Pine area are metamorphic rocks. Olivine shows systematic variation in composition with changes in mineral assemblages and olivine abundance (Figure 6). Most of the Spruce Pine ultramafic rocks are composed of olivine plus various hydration products. Chromite and pyroxene only account for a few modal percent of the metadunites (Table 2), thus the modal olivine percentage can be used to estimate the percentage of hydration products (tremolite, talc, serpentine, etc.). As discussed previously, the compositions of the various hydrated silicate minerals show varying degrees of correlation with olivine chemistry and the sum of these variations accounts for the scatter in Figure 6. However, the general pattern of more Mg-rich olivine in rocks low in hydrated phases is clear. This, together with the similarity of olivine porphyroclast and neoblast compositions (Figure 2), reinforces the metamorphic character of the olivine.

Mineral assemblages in the ultramafic rocks generally reproduce the same range of P/T conditions defined by Adams and Trupe (1997) for the country rocks. Figure 4 shows the metamorphic conditions defined by Adams and Trupe for eclogitic rocks (A, Figure 4) and Figure 5 shows the mineral compatibilities at these conditions. These conditions are transitional between high pressure granulite and eclogite facies and the rocks are relatively dry. At these grades, ultramafic bulk compositions plot along the $MgO-SiO_2$ join between enstatite and forsterite (Evans, 1977). In addition to forsterite and enstatite, metaultramafic rocks that contain Al and Ca should contain chlorite as the aluminous phase (B. W. Evans, pers. comm., 2000) and clinopyroxene as the Ca-bearing phase (Evans, 1977). However, the Spruce Pine metaultramafic rocks do not contain clinopyroxene, thus, eclogitic/transitional granulitic conditions are not recorded by the Spruce Pine ultramafic rocks.

At conditions represented by the amphibolites of the Spruce Pine area (B in Figure 4), the phase compatibilities in the system MgO-SiO$_2$-H$_2$O (B, Figure 5) are equivalent to those represented by the eclogites (Figure 5A). The aluminous phase is chlorite, however, and the Ca-bearing phase is tremolite (Evans, 1977). Spruce Pine ultramafic rocks from several bodies (Table 2) contain the assemblage forsterite + enstatite + chlorite +/- tremolite and appear to record the same amphibolite facies P/T conditions as the amphibolites (B, Figure 5). However, this same assemblage is found in dry rocks at lower grades (C and D, Figure 5).

Peak conditions for the pelitic schists of the Spruce Pine thrust sheet (C in Figure 4) are represented by mineral assemblages shown in Figure 5C. Spruce Pine ultramafic rocks from the Henson Creek body (HC, Table 3) contain the assemblage anthophyllite + forsterite + enstatite (along with chlorite+/-tremolite) and thus record the same P/T conditions as the peak conditions recorded by the schists.

The final P/T conditions recorded by the Spruce Pine schists (D in Figure 4) are represented by mineral assemblages shown in Figure 5D. Spruce Pine ultramafic rocks from several bodies (Table 3) record the assemblage talc + anthophyllite + forsterite and thus record the same P/T conditions as the final conditions recorded by the schists.

The Spruce Pine ultramafic rocks also contain serpentine-bearing mineral assemblages reflecting greenschist facies conditions not recorded by the conventional geothermobarometry shown on Figure 4 (A, B, C, D). However, such greenschist facies assemblages (sericite after plagioclase, chlorite after biotite) are recognized in the Spruce Pine country rocks (e.g. Butler, 1972) and probably correspond to the serpentinization events (Abbott and Raymond, 1984).

Ultramafic bodies that are rich in olivine contain a greater diversity of mineral assemblages, reflecting varying degrees of hydration, than more hydrated bodies (Table 3). Bodies, such as Day Book, Henson Creek, and Frank record the relatively dry assemblage olivine +/- enstatite (+ chlorite +/- tremolite) and the more hydrated assemblage talc + anthophyllite + forsterite (+chlorite +/- tremolite) as shown in Table 3. This range of assemblages records a range of hydration. The preservation of abundant olivine and/or enstatite in these rocks provided a brittle medium that, when fractured, provided a pathway for fluids to enhance recrystallization. However, given the abundance of olivine and/or enstatite in these rocks, the total amount of fluids entering the rock must have been small.

The olivine-poor ultramafic bodies contain only one or two assemblages, and these reflect complete or nearly complete hydration of olivine and enstatite. The assemblage talc + anthophyllite (+ chlorite +/- tremolite) forms the schists and soapstones that are the only rock type in some bodies (Table 3). None of the samples from the Blue Rock Road, Blue Rock Quarry, or Crabtree Creek bodies contain any olivine, but they do contain large amounts of talc and chlorite along with anthophyllite and tremolite. The Normanville and Blue Rock Mine bodies contain only trace amounts of relict olivine (and no pyroxene) in a matrix of chlorite + talc +/- anthophyllite +/- tremolite. These olivine-poor rocks have been completely hydrated as the amphibole and phyllosilicate-forming reactions have gone to completion. Once these rocks were hydrated, further cooling did not result in the formation of serpentine. Thus the talc chlorite amphibole schists in the Spruce Pine area differ from olivine-rich metaultramafic rocks in their degree of hydration.

The more hydrated ultramafic bodies (Newdale Anthophyllite, Normanville, Blue Rock Road, and Blue Rock Mine, Figure 1) occur in the central part of the thrust sheet, while the less hydrated bodies (Day Book, Woody, Pleasant Grove Church, Mine Creek, Henson Creek, Senia, and Frank) generally occur near the Gossan Lead Fault (Figure 1). Two olivine-rich bodies (Grassy Creek, Newdale Dunite) occur away from the fault (Figure 1), but these bodies do not contain the relatively dry assemblage forsterite + enstatite (+ chlorite +/- tremolite) that characterizes the other olivine-rich bodies (Table 3). Fluid flow is expected in the vicinity of the Gossan Lead Fault, but this does not appear to be the case, based on the occurrence of the less hydrated ultramafic bodies in this area (Figure 1). The type of country rocks immediately surrounding the ultramafic bodies seems to be related to the degree of hydration of the ultramafic rocks. Several of the less hydrated bodies (F, HC, SE; Table 1) are enclosed entirely in amphibolite. Other less hydrated bodies (W, DB, PGC, MC; Table 1) are enclosed in a mixed sequence of amphibolites with mica schists and gneisses. A good example of the control of host country rocks on the hydration of the metaultramafic rocks is shown by the Newdale Dunite and Newdale Anthophyllite bodies (Figure 1 and Tables 1 and 2). The Newdale Anthophyllite body is hosted by mica schist. The Newdale Dunite body is surrounded by interlayered amphibolite and mica schist and gneiss. It appears that migration of fluids to the ultramafic bodies was more prevalent in the mica-rich country rocks.

The degree of hydration of the ultramafic bodies also correlates with proximity to granitic bodies of the Spruce Pine Plutonic Suite. Figure 1 shows the area of outcrop of the larger Spruce Pine granitic stocks. Many of the hydrated ultramafic bodies (BRR, BRM, BRQ, NA, NV, CTC, GC; Figure 1) are located in this same area. Swanson (1981) found that intrusion of a Spruce Pine style pegmatite into the Day Book body produced veins with tremolite + chlorite + talc + forsterite assemblages that locally contained magnesite. The more complete hydration of metaultramafic rocks near the locus of plutonic activity may be a larger scale manifestation of the same process.

CONCLUSIONS

Ultramafic rocks in the Spruce Pine area are metamorphic rocks. Mineral assemblages in the metaultramafic rocks (Table 3) near the Gossan Lead Fault include forsterite ± enstatite (± tremolite ± chlorite) and represent a relatively dry assemblage (Figure 5). The assemblages anthophyllite + enstatite + forsterite (Figure 5) and talc + anthophyllite + forsterite (Figure 5) represent the progressive hydration of the ultramafic protolith. All of these assemblages are consistent with the same P/T range recorded by the pelitic schists in the western part of the Spruce Pine thrust sheet (C and D, Figure 4).

Olivine compositions also show the metamorphic character of the ultramafic rocks. Olivine from more hydrated ultramafic bodies (BRM, SP, NV, NA, Table 2) is slightly more Fe-rich than in less hydrated bodies. These bodies also do not record the olivine+/-enstatite (no talc or anthophyllite) assemblage (Table 3). The olivine compositions (expressed as Mg number = (Mg/Mg + Fe) x 100) change as the Mg numbers of the hydrous phases change (Figure 3), and these hydrous phases have higher Mg numbers than coexisting olivine. Thus, as the proportion of hydrous phases increases, more Mg enters the hydrous phases, leaving olivine slightly more Fe-rich (Figure 6). This correlation between olivine composition and associated metamorphic mineral assemblages shows that the olivine is of metamorphic origin and that the ultramafic rocks really are metamorphic rocks.

All of the ultramafic bodies near the fault (Figure 1) are olivine-rich, yet they contain a wide range of mineral assemblages involving hydrous phases (Table 3). Despite the wide range in hydrous mineral assemblages found in these bodies, the rocks are mainly composed of anhydrous phases (olivine and pyroxene) and the rocks are relatively dry. The various hydrous mineral assemblages found in these rocks represent the incomplete hydration of the rocks due to lack of fluid to promote complete recrystallization. Availability of fluids to the bodies was controlled, in part, by the nature of the country rocks surrounding these bodies and by the ability of fluids to move through these rocks. There is ample evidence of recrystallization in these rocks (talc is often seen to replace anthophyllite; anthophyllite replaces magnesiocummingtonite; and tremolite, magnesite, talc, and serpentine replace olivine, etc.), but the extent of these hydration/carbonation reactions is seldom complete.

In contrast, ultramafic rocks from the central part of the thrust sheet contain a higher proportion of hydrous phases. Coincidently, this central area is the locus of granitoid pluton emplacement (Raymond and Abbott, 1980). Even bodies considered olivine-rich (ND and GC, Figure 4) in this area lack the "dry" assemblage forsterite + enstatite (+/- tremolite and chlorite, but without talc or anthophyllite (Figure 5). Several of the bodies do not contain any olivine and two contain only trace amounts of relict olivine (Tables 1 and 2). The assemblage talc + anthophyllite (+/- tremolite and chlorite, C and D, Figure 5) is common in these hydrated ultramafic bodies (Table 3), and this reflects the more hydrated character of these rocks. Intrusion of granitic magma into the Day Book body was accompanied by fluids that produced talc + anthophyllite (+/- olivine +/- magnesite) mineral assemblages (Swanson, 1981), and similarly, the more hydrated character of the metaultramafic rocks in the central part of the fault block may be related to the intrusion of larger volumes of granitic magma in this area.

The driest mafic and ultramafic rocks in the Spruce Pine area are found near the base of the Gossan Lead Thrust Block. The occurrence of eclogitic mafic rocks (Willard and Adams, 1994; Adams and others, 1995, Adams and Trupe, 1997) is restricted to an area near Bakersville (Figure 1) along the fault. Also along this fault are the olivine-rich metaultramafic rocks (DB, W, MC, HC, F, and PGC; Figure 1) that contain the highest grade assemblages. Away from the fault the mafic and metaultramafic rocks are more hydrated and, in the case of the mafic rocks, contain lower grade mineral assemblages.

To the north of the Grandfather Mountain window, north of Boone, North Carolina mafic and ultramafic rocks near the base of the Gossan Lead Thrust Block are drier than equivalent lithotypes away from the fault (Abbott and Raymond, 1997; Swanson, 2000, Raymond and others, in this volume). Retrograded eclogite is found near the base of the fault and amphibolite is found away from the fault. In the same area metaultramafic rocks contain the "dry" assemblage enstatite + forsterite (Swanson, 1980; Raymond and Abbott, 1997, Raymond and others, 1999; Raymond and others, in this volume), and more hydrated metaultramafic rocks occur away from the fault (Raymond and Abbott, 1997). The area north of Boone does not have the concentration of granitic intrusions found in the Spruce Pine area and the origin of fluids responsible for complete hydration of these ultramafic rocks is unclear.

The occurrence of less hydrated, higher grade metamorphic rocks near a major fault, with more hydrated, lower grade rocks away from the fault seems contrary to our notions about fluid flow along shear zones and faults (e.g. Burkhardt and others, 1992; McCaig and others, 1995). However, this is exactly the situation with mafic rocks in the Spruce Pine thrust sheet. The origin of the fluids responsible for hydration within the fault block may be from granitic intrusions or from some other source higher in the fault block, a source that has been removed by erosion. The source of the fluids remains unclear. What is clear is that the occurrence of high grade mafic rocks along the Gossan Lead Fault is a function of preservation during cooling related to a general scarcity of such fluids.

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MINERALOGY AND PETROLOGY OF METAULTRAMAFIC ROCKS AT BUCK CREEK, NORTH CAROLINA

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ABSTRACT

The ultramafic body at Buck Creek in Clay County, North Carolina is one of the largest in the southern Appalachians. It consists largely of metadunite but locally contains lenses of metatroctolite. The body is surrounded by amphibolites belonging to the Chunky Gal Mountain mafic complex. All rock types have experienced polyphase metamorphism.

The characteristic prograde assemblage in the metadunite is olivine + chromite ± chlorite. Typically, olivine has recrystallized to a medium-grained granoblastic texture with occasional larger porphyroclasts. Chromite is almost always surrounded by chlorite and commonly exhibits lattice texture with lamellar chlorite intergrowths. Calcic amphibole (tremolite or edenite partly retrograded to tremolite) is present in many samples, but pyroxenes are extremely rare. Late-stage veins of antigorite + talc and/or dolomite ± chlorite ± magnetite penetrate some areas of the metadunite.

Olivine compositions show a greater range than previously reported. Overall variation is from $Fo_{83.5}$ to $Fo_{91.4}$. Individual samples, however, usually vary by less than 1 mol% Fo. The least magnesian olivines occur adjacent to late-stage veins or in samples with prominent antigorite growth along olivine cleavage planes. Chromite is mostly Mg-Al-poor; intermediate to Mg-Al-rich compositions occur in samples where chromite is isolated from chlorite. Chlorite contains appreciable Cr, especially laths associated with lattice chromites.

Application of the olivine-spinel geothermometer yields a minimum estimate for peak metamorphic temperatures of 700±25°C. Maximum temperature estimates (~800°C) are constrained by the coexistence of chlorite + edenite combined with the general absence of calcic pyroxene. An occurrence in one sample of orthopyroxene together with talc, olivine, and minor anthophyllite suggests peak metamorphic pressures of 11-12 kb. Subsequent retrograde metamorphism (T ~540°C) in the presence of CO_2-bearing fluids has affected the metadunite. This event was marked by growth of tremolite (from edenite) and antigorite and the formation of veins containing antigorite, talc, and carbonate minerals.

INTRODUCTION

The Buck Creek metadunite is reportedly the largest ultramafic body in the Blue Ridge Province of the southern Appalachian Mountains (Hunter, 1941). It is located in Clay County in western North Carolina, near Highway 64 about 10 km west of Winding Stair Gap and nearly 20 km east of Hayesville. Buck Creek lies in the Hayesville thrust sheet (Hatcher, 1976) and is enveloped by amphibolites belonging to the Chunky Gal Mountain mafic-ultramafic complex (McElhaney and McSween, 1983). Country rocks in this thrust sheet have been metamorphosed under granulite facies conditions (Absher and McSween, 1985; Eckert and others, 1989) and preserve the highest grade Paleozoic mineral assemblages in the southern Appalachians.

A notable feature at Buck Creek is the presence of a variety of rock types in addition to the predominant metadunite (Hadley, 1949; Kuntz, 1964). The polylithologic nature of the body is important for unraveling its metamorphic history. Metatroctolites associated with the metadunite, for example, have a documented history of polyphase metamorphism (Tenthorey and others, 1996; Thomas and others, 1999); the metadunite must have had a similar history. The goal of this study is to characterize the metamorphic mineralogy of the metadunite with the aim of reconstructing the post-emplacement sequence of deformation and recrystallization experienced by the ultramafic rocks. The results of this study complement the studies on associated mafic rocks reported previously (e.g., Tenthorey and others, 1996) and by Berger and others (in this volume).

PREVIOUS WORK

The earliest geologic maps of the Buck Creek area were published approximately a century ago (Lewis, 1896; Pratt and Lewis, 1905). At that time much of the interest centered on the occurrence of corundum in the Buck Creek rocks. The olivine deposits at Buck Creek were described decades later by Hunter (1941). He conservatively estimated that about 300,000,000 tons of olivine occur at Buck Creek. During World War II interest was renewed in the corundum deposits, resulting in a detailed investigation of the Buck Creek area by the U.S. Bureau of Mines, together with the U.S. Geological Survey. In the course of the field work more than 9,000 feet of surface trenches were dug and a number of old prospect cuts were reopened. The resulting maps of the Buck Creek ultramafic body were published by Hadley (1949). In addition to 'dunite'[1], a number of other mappable rock units were identified, the most significant being 'troctolite'[1]. Metatroctolite, a resistant ridge former, was found to occur in lenses up to nearly 500 meters long. Associated with the metatroctolite lenses are corundum-bearing amphibolites (termed edenite-amphibolite by Hadley, 1949), pale green to bright emerald green in color. A series of minor faults offsets the metatroctolites and amphibolites. A zone of chlorite-rich rocks was mapped marginal to the northern part of the main metadunite body. Actinolite-chlorite veins were found to penetrate many areas of the metadunite; the larger veins commonly contain hornblende and plagioclase or zoisite, together with minor amounts of corundum.

The first detailed petrographic study of the Buck Creek metadunite was conducted by Kuntz (1964), whose mapping confirmed the general field relations described by Hadley (1949). Kuntz estimated olivine compositions by measuring their optic axial angles with a universal stage. He reported a mean composition of Fo_{94}, with a variance in individual thin sections from Fo_{92} to Fo_{96}, and he noted an increase in olivine Fo content toward the center of the body. Sailor and Kuntz (1973) undertook a petrofabric investigation, in which they found that the dominant fabric was discordant to the regional foliation. Further petrologic and geochemical data, including Rb-Sr isotopic ratios, were reported by Kuntz and Hedge (1981). These authors concluded that the Buck Creek rocks form a comagmatic suite and constitute an ophiolite complex. McElhaney and McSween (1983) found olivine compositions to be less magnesian (Fo_{88-89}) than reported by Kuntz (1964), based on microprobe analyses, primarily from near the periphery of the ultramafic body.

Subsequent investigations in the Buck Creek area have dealt primarily with the metatroctolites and related corundum-bearing amphibolites (Ranson and others, 1991; Farrier and Ranson, 1994; Tenthorey and others, 1996). The most comprehensive account is that by Tenthorey and others (1996), who described complex symplectic coronas in the metatroctolites. The coronas formed from metamorphic reactions between primary olivine and plagioclase. These authors noted the occurrence of sapphirine-bearing assemblages, from which they inferred peak metamorphic conditions of 9-10 kb and 850°C. A remapping of the Buck Creek mafic-ultramafic complex has recently

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[1] To emphasize the metamorphic nature of these rocks, the terms metadunite and metatroctolite will subsequently be used instead of the igneous rock names.

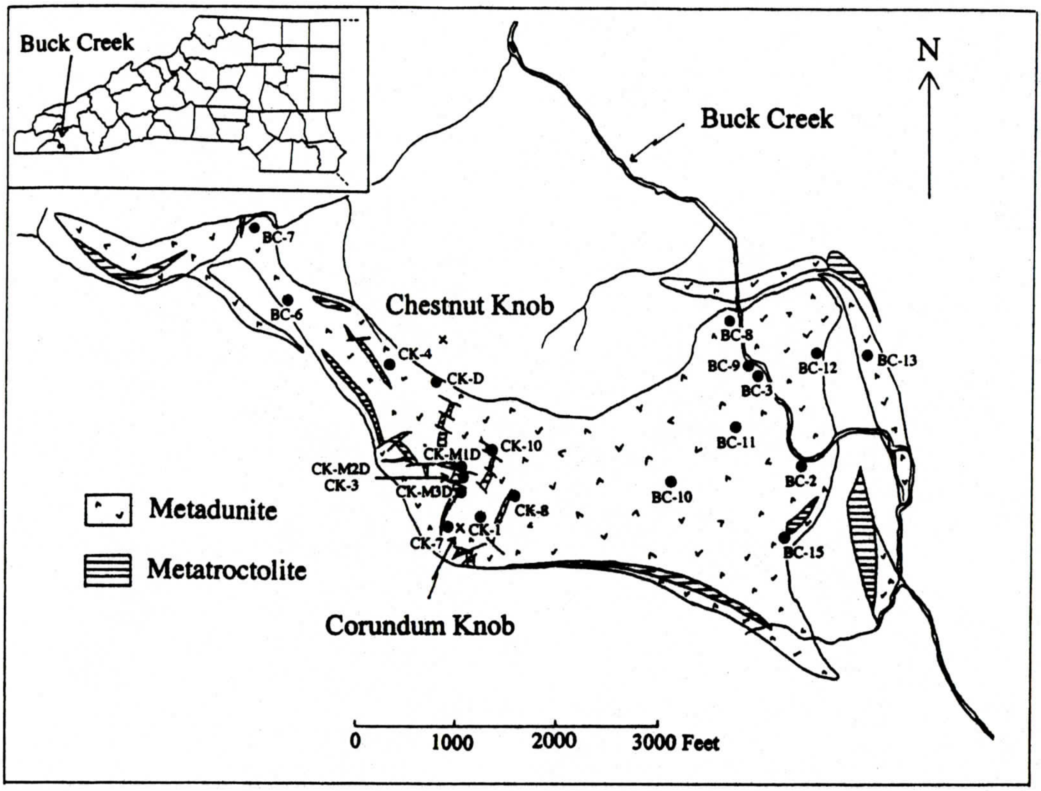


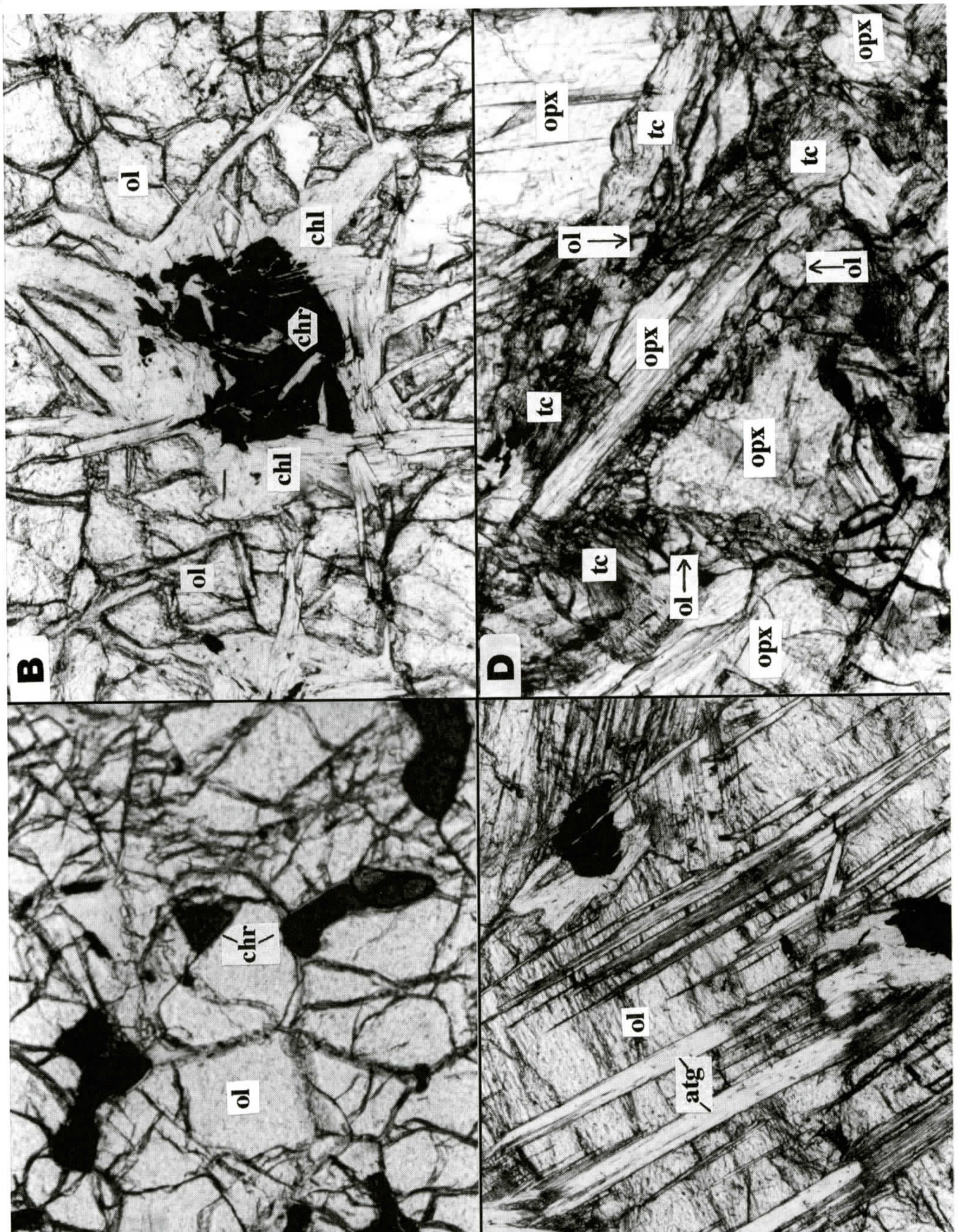
Figure 1. Map of Buck Creek ultramafic body showing major lenses of metatroctolite (after Hadley, 1949). Locations of metadunite samples studied in this investigation are indicated by small filled circles and identified by number. Insert (top left) shows location of the Buck Creek ultramafic body in western North Carolina.

been carried out by the University of South Florida group (Emilio and others, 1998; Ryan and Peterson, 1999; McCoy and others, 1999; Morman and others, 1999; Thomas and others, 1999). Their focus has been almost exclusively on the mafic rock units, and Berger and others (this volume) report new geochemical data for metatroctolites and amphibolites.

In contrast to the interest recently bestowed on the metatroctolites and amphibolites at Buck Creek, relatively little attention has been paid to the metadunites. Raymond (1995, p. 673) reviewed the petrology and structure of the Buck Creek metadunite and summarized its metamorphic mineral associations. Gibson (1997) and Hann and Warner (1998), as a preliminary phase of this investigation, described the mineralogy of the metadunite and provided new mineral and bulk compositional data.

FIELD SAMPLING AND ANALYTICAL METHODS

A simplified version of Hadley's (1949) map is shown in Figure 1. The main metadunite body is elongated (about 2.5 km), generally in an east-west direction. The filled circles indicate locations where metadunite samples were collected. CK-numbers refer to samples obtained at or near the metatroctolite lenses extending along the ridge between Corundum Knob and Chestnut Knob. Many of the rocks are relatively fresh due to the extensive trenching in this area. Several samples of metatroctolite were also collected, including massive metatroctolite and thin slivers of metatroctolite in places where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metatroctolite and metadunite are finely interlayered. Metadunite samples collected elsewhere in the Buck Creek body have BC-numbers.

Polished thin sections were prepared from the metadunite (and metatroctolite) samples and examined with a Jenapol U polarizing transmitted and incident light microscope. Modal abundances were obtained using a Swift Model F automatic point counter. A total of 500-750 points were counted per section. Compositions of minerals were analyzed with a JEOL JXA-8600 scanning electron microprobe at the University of Georgia. Analyses were made using a 15 nanoamp beam current at an accelerating voltage of 15 KV, and corrected for differential matrix effects using the procedure of Bence and Albee (1968). Chromite analyses were recalculated on the basis of stoichiometry to determine Fe_2O_3 and FeO from total Fe. Backscattered electron images of selected areas were obtained by making use of the SEM capabilities of the microprobe.

Bulk oxide compositions for selected metadunite samples were determined by plasma emission spectrometry at the University of South Florida (see Tenthorey and others, 1996, for a discussion of analytical methods). Also analyzed were abundances of important trace elements such as Cr and Ni. Trace and rare earth element (REE) abundances in additional metadunite and metatroctolite samples were determined via instrumental neutron activation at the Oregon State University Radiation Center.

GENERAL DESCRIPTION OF METADUNITES

The characteristic assemblage of the metadunites is olivine + chromite ± chlorite (Figure 2A,B). Olivine modal abundances in 21 thin sections that were point counted range from 42% to 90% (Table 1). This is close to the range (49-92%) reported by Kuntz (1964). The olivine is variably (up to 28%) replaced by serpentine (chrysotile and/or lizardite) and Fe-oxide along irregular fractures. Chromite generally is present in amounts from 1-3%, with 5% chromite being the highest observed abundance. Chlorite was found in all but one sample (CK-M3D). Typically, chlorite makes up about 5% of the rock, but several samples contain 20% or more chlorite.

In addition to the above minerals, small amounts of calcic amphibole occur in many samples; BC-13A (20%) and BC-2A (5%) contain the most amphibole. About one third of the samples contain antigorite as a retrograde phase (Figure 2C). Antigorite is particularly abundant in BC-8 and BC-10 (Table 1). Carbonate minerals occur in about half the samples. Dolomite appears to be most common, but magnesite and calcite have each been identified (by EDS spectra) in several thin sections. Most samples contain trace amounts of sulfide, chiefly pentlandite. Except in veins cutting metadunite, talc is rarely present.

An important feature of the Buck Creek metaultramafic rocks is the almost complete absence of pyroxenes. Trace amounts of diopside are present in BC-9, but otherwise calcic pyroxene is altogether lacking. Calcic pyroxene does occur in symplectic intergrowths in associated metatroctolites, however. Kuntz (1964) similarly noted a dearth of pyroxene. He reported trace amounts of diopsidic augite in just four of 40 metadunite thin sections examined. Orthopyroxene, along with anthophyllite, occurs in only one sample, CK-1B (not listed in Table 1 because metadunite makes up only a minor portion of the thin section). Orthopyroxene is common, however, in symplectites in metatroctolite.

A number of samples are cut by veins con-

Figure 2. Photomicrographs (plane polarized light) illustrating mineralogy and textures in Buck Creek metadunites. Long dimension of field of view is approximately 1 mm in all samples. A. Equigranular olivine (ol) and deep brown chromite (chr) in CK-M3D. This sample lacks chlorite. B. Chlorite-bearing dunite, CK-4. Chromite (opaque) is enclosed by an aggregate of chlorite (chl) laths, which separates the chromite from surrounding olivine. C. Crystallographically oriented serpentine (antigorite, atg) laths in olivine, BC-3. D. Orthopyroxene (opx) crystals rimmed by talc (tc) and olivine, CK-1B.

Table 1. Modal abundances in Buck Creek Metadunites

Sample	Olivine	Chromite	Chlorite	Amphibole	Antigorite	Carbonate
CK-M3D	79 (18)	3				
CK-3C	86 (10)	3	0.8			
CK-M2D	76 (14)	1.3	7			
CK-8B	74 (2)	2.0	20			2.7
CK-M1D	69 (4)	5	21			0.8
CK-D	82 (13)	0.8	3.5	0.1		0.5
BC-12A	74 (20)	0.8	4	1.4		
BC-9*	79 (14)	2.1	4	0.5		0.9
CK-7	76 (17)	1.4	5	0.4		
BC-7	78 (14)	1.5	5	1.1		
BC-2A	86 (6)	2.1	1.5	5		
BC-6	63 (28)	2.5	5	0.9		0.7
BC-15A	53 (24)	0.3	16	6		0.9
CK-10	70 (6)	0.7	20	0.3		1.3
BC-13A	42 (12)	2.5	22	20		0.7
BC-2B	88 (2)	1.5	4		4	0.5
BC-10#	76 (2)	0.9	3.5		16	
BC-8	51 (<1)	1.5	6		30	11
BC-3#	90 (<1)	1.1	1.4	Tr	7	
BC-11	88 (2)	1.0	5	0.3	4	
CK-4	82 (3)	1.6	6	2.1	5	

*Contains trace amount of diopside #Contains minor talc (< 1%)
Numbers in () indicate abundance of late-stage replacement products (chrysotile, etc.) in olivine

sisting of hydrous minerals, commonly in association with a carbonate mineral. All of the veins examined in thin section contain serpentine (antigorite), and most contain talc and/or dolomite in addition. If present, talc is usually the most abundant vein mineral (up to 80% of vein may be talc). Chlorite, tremolite, and magnetite also occur as vein minerals, but in lesser amounts.

Bulk chemical analyses of five metadunite samples (Table 2) reveal slight, but important, compositional differences. The Corundum

Table 2. Bulk chemical analyses of Buck Creek metadunites.

	CK-M1D	CK-M3D	BC-7	BC-9	BC-11
SiO_2 (%)	39.2	38.7	42.1	39.6	39.7
TiO_2	0.13	0.12	0.13	0.12	0.13
Al_2O_3	1.69	1.23	0.74	0.41	0.45
FeO	12.9	11.6	9.4	12.4	13.3
MgO	44.6	46.4	46.3	45.2	44.5
MnO	0.18	0.18	0.16	0.18	0.21
CaO	1.13	1.03	1.21	1.60	1.47
Na_2O	0.05	0.08	0.19	0.11	0.13
K_2O	0.01	0.01	0.01	0.01	0.01
Total	99.89	99.35	100.24	99.63	99.90
Mg#	86.1	87.7	89.7	86.6	85.6
Ni (ppm)	1650	2100	2700	3650	1300
Cr	4450	4700	5400	3000	3550

Mg# = 100 x Mg/(Mg+Fe)

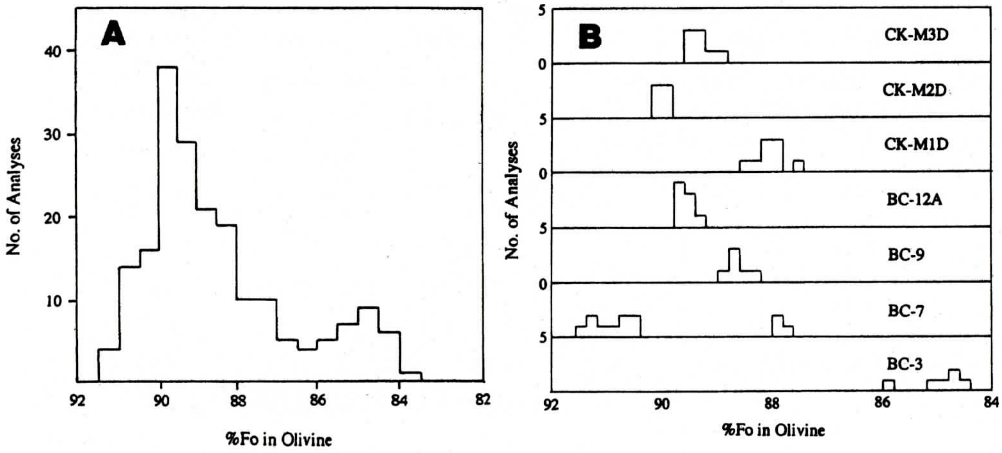

Figure 3. Histograms of olivine compositions in Buck Creek metadunites. A. Data for all samples. B. Data for selected individual samples.

Knob samples, which are proximate to metatroctolite, have distinctly higher Al_2O_3 abundances. Iron oxide varies by about 4 weight percent and MgO by nearly 2 weight percent, producing perceptible differences in Mg# from sample to sample. CaO is highest in BC-9, which is the only sample containing calcic pyroxene. Ni and Cr both show significant variation among the rocks analyzed.

MINERALOGY

Olivine

Olivine is by far the most abundant mineral in the Buck Creek metaultramafic rocks (Table 1). Most metadunites exhibit an equigranular texture (Figure 2A), with equant to subequant crystals of olivine between 0.5 and 2 mm in diameter. Larger crystals occur in many samples, and locally porphyroclasts range up to 8 mm in diameter. Olivine crystals commonly show slight to moderate undulatory extinction. In some samples strain recovery has produced areas of finer-grained olivine with 120° triple junctions. Cleavage is poorly developed or lacking in a majority of samples, but in some samples (010) cleavage is well-developed, and less distinct (100) cleavage also occurs.

Replacement of olivine by chrysotile and/or lizardite plus associated minerals, along fracture surfaces and grain boundaries, has occurred to a greater or lesser extent in all samples (Table 1). Distinct from this paragenesis is the prominent occurrence in some samples of antigorite laths oriented along olivine cleavage planes (Figure 2C).

Olivine compositions range from $Fo_{83.5}$ to $Fo_{91.4}$, with a peak concentration at $Fo_{89\pm1}$ (Figure 3A). This range (nearly 8 mol% Fo) is greater than previously reported. Kuntz (1964), for example, found a variation of less than 4 mol% Fo. The maximum at about Fo_{89} is less magnesian than determined optically by Kuntz (1964), but closely matches previously published results based on microprobe analyses (McElhaney and McSween, 1983; Lipin, 1984; Tenthorey and others, 1996). No evidence was found for an increase in Fo content toward the center of the dunite, as was reported by Kuntz (1964). In fact, the most magnesian olivines occur in BC-7 and BC-2, samples from opposite margins of the body (Figure 1). No correlation between olivine composition and position in the body was observed in this study.

Figure 3B shows that the variation in olivine composition within individual samples is generally 1 mol% or less. Differences from sample to sample correlate with bulk rock chemistry. For example, BC-7 has a Mg# (= 100 x Mg/(Mg+Fe)) higher than CK-M3D, which in turn has a higher Mg# than CK-M1D (Table 2). Cor-

Table 3 Representative microprobe analyses of minerals in Buck Creek metadunites.

	CK-M3D		CK-7		BC-7		BC-3		BC-2A		CK-1B		
	ol	chr	chr	chl	ol	ol	ol	atg	eden	tr	anth	opx	ol
SiO_2 (%)	41.0	0.02	0.04	32.4	40.9	40.3	40.3	42.3	46.6	58.4	60.0	58.4	40.0
TiO_2		0.04	0.78	0.11					0.65	0.03			
Al_2O_3		46.7	1.37	15.9				1.45	10.4	0.27	0.18	0.22	
Cr_2O_3		20.1	49.8	2.92				0.63					
Fe_2O_3		2.44	15.0										
FeO	10.4	16.3	28.3	3.6	9.0	11.8	13.7	4.7	3.5	2.06	8.7	7.9	15.3
MgO	49.2	15.3	2.43	31.7	49.9	47.7	46.7	37.5	19.8	23.5	28.2	34.4	45.6
MnO	0.10	<0.05	<0.05	<0.05	0.14	0.28	0.18	<0.05	<0.05	0.06	0.40	0.22	0.25
NiO	0.25	0.08	0.08		0.23	0.12	0.24	0.06					0.19
CaO									11.8	11.9	0.25	0.09	
Na_2O									3.2	1.07	0.02	<0.02	
K_2O									0.26	0.06			
Total	100.95	100.98	97.80	86.63	100.17	100.20	101.12	86.64	96.21	97.35	97.75	101.23	101.34
Oxy-gens	4	4	4	14	4	4	4	7	23	23	23	6	4
Si	0.998	0.001	0.002	3.092	0.997	0.996	0.995	2.002	6.658	7.992	8.102	1.998	0.994
Ti		0.001	0.022	0.008					0.070	0.003			
Al		1.510	0.060	1.784				0.081	1.748	0.043	0.028	0.009	
Cr		0.437	1.472	0.220				0.024					
Fe^{3+}		0.050	0.422										
Fe^{2+}	0.212	0.373	0.885	0.287	0.183	0.243	0.282	0.185	0.420	0.236	0.984	0.225	0.317
Mg	1.785	0.625	0.135	4.507	1.814	1.756	1.719	2.651	4.218	4.804	5.683	1.757	1.687
Mn	0.002				0.003	0.006	0.004			0.007	0.046	0.007	0.005
Ni	0.005	0.002	0.003		0.005	0.002	0.005	0.002					0.004
Ca									1.813	1.749	0.036	0.003	
Na									0.893	0.285	0.005		
K									0.048	0.010			
Sum	3.002	2.999	3.001	9.898	3.002	3.003	3.005	4.945	15.868	15.129	14.884	4.001	3.007
Mg#	89.4			94.0	90.8	87.8	85.9	93.5	90.0	95.3	85.2	88.6	84.2

Abbreviations: ol, olivine; chr, chromite; chl, chlorite; atg, antigorite; eden, edenite; tr, tremolite; anth, anthophyllite; opx, orthopyroxene
Analyses: CK-M3D - olivine and coexisting chromite (inclusion in olivine); CK-7 - "lattice" chromite and coexisting exsolved chlorite; BC-7 - first olivine is typical of dunite portion of sample, second olivine is adjacent to talc-rich vein; BC-3 - olivine and coexisting serpentine (oriented along (010) cleavage); BC-2A - edenite and coexisting tremolite (mantles edenite core); CK-1B - anthophyllite and associated orthopyroxene and olivine (orthopyroxene is being retrograded to olivine + talc, see Figure 2D).

responding olivine compositions are, BC-7 - $Fo_{90.5-91.4}$; CK-M3D - $Fo_{88.9-89.5}$; and CK-M1D - $Fo_{87.5-88.4}$ (Figure 3B). In general, olivine in chlorite-rich samples is less magnesian. For example, olivine in CK-M1D, which contains three times as much chlorite (Table 1), is 2 mol% lower in Fo than olivine in CK-M2D. The most Mg-poor olivines occur in samples with abundant antigorite formation along (010) planes (e.g., BC-3). Also, in samples where metadunite is cut by serpentine-bearing veins, olivine grains adjacent to the veins have lower Fo than olivines elsewhere in the rock. An example is sample BC-7, wherein olivines near a talc-tremolite-dolomite-serpentine vein contain 3 mol% less Fo than other olivines (Table 3; Figure 3B).

Chromite

Chromite occurs as an important accessory mineral in all metadunite samples. It exhibits a wide variety of textures, including all chromite textures described by Lipin (1984). Most commonly, chromite crystals are surrounded by an aggregate of chlorite laths that separates the chromite from olivine (Figure 2B). Many chromite crystals contain chlorite intergrowths

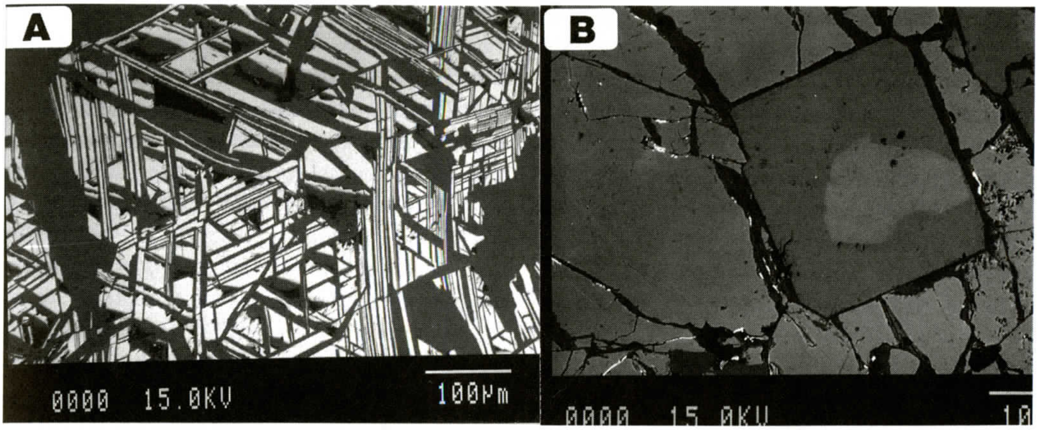

Figure 4. Backscattered electron images of Buck Creek samples. A. Lattice texture in chromite formed by chlorite (dark) oriented along {111} planes of host chromite (white); sample CK-4. B. Euhedral calcic amphibole bordered by olivine (BC-2A). Lighter-colored central portion of crystal is edenite; darker area mantling edenite is tremolite (see analyses in Table 3).

oriented along {111} planes (Figure 4A). Following the terminology of Lipin (1984), such chromites are designated as "lattice chromites". Irregular, poikiloblastic chromite and "clean" chromite are less common. Small chromite inclusions in olivine (type B chromite of Lipin, 1984) or discrete chromites bounded only by olivine are present in some samples, but are volumetrically insignificant except in the least chlorite-rich samples (CK-M3D and CK-3C). In these two rocks chromite occurs exclusively as deep brown crystals in direct contact with olivine (Figure 2A).

Chromite exhibits much more extensive compositional variation than is shown by associated silicate minerals. Type B chromites are Al-rich, whereas lattice and poikiloblastic chromites typically have very low Al contents (Figure 5A). Clean chromites are Al-rich if they are associated with olivine (no chlorite), but they are Al-poor if chlorite is present. Although the majority of chromites are compositionally homogeneous, zoned crystals occur in some samples. Zoned chromites may have any of the textures noted above. Tie lines in Figure 5A connect core and rim compositions of individual zoned crystals; the trend is for Mg and Al to decrease and Fe^{3+} and Cr to increase from core to rim.

Chromite analyses for selected individual samples are plotted in Figure 5B. The data show that individual samples significantly differ in their chromite chemistry. CK-M3D, for example, is populated exclusively by Al-rich chromite, whereas chromites in CK-M2D, CK-M1D, BC-7, and BC-3 are all Al-poor. The former sample contains deep brown, clean chromite, whereas the latter mostly contain lattice chromites. Samples BC-9 and BC-12A both contain zoned chromite crystals, which undoubtedly accounts for their wider compostional range.

Chlorite

Chlorite occurs as discrete lath-shaped crystals dispersed between olivine grains, as aggregates of crystals surrounding chromite (Figure 2B), and as lamellar intergrowths in lattice chromites (Figure 4A). Typically, chlorites in the Buck Creek dunites contain between 15 and 20 weight percent Al_2O_3. They also contain appreciable Cr_2O_3. Chlorite intergrowths in lattice chromite have the highest amounts of Cr_2O_3 (up to 3 weight percent - Table 3). Chlorites have higher Mg#s than coexisting olivine.

Calcic Amphibole

About half of the metadunite samples con-

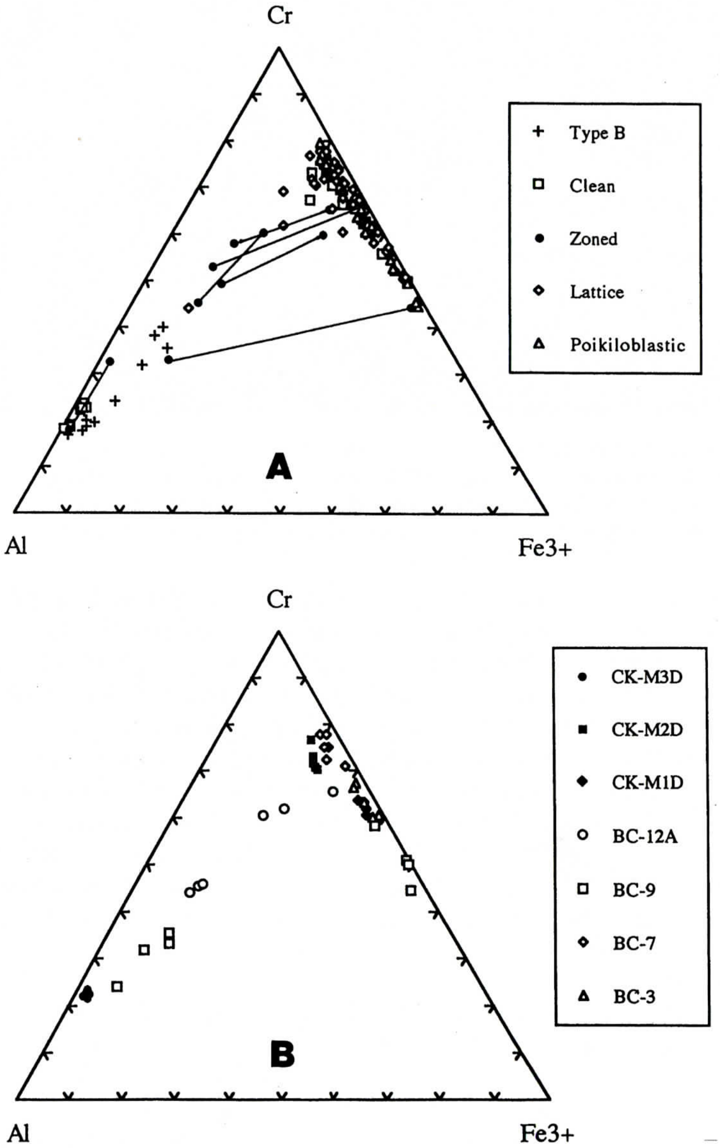

Figure 5. Compositions of Buck Creek chromites plotted on ternary Al-Cr-Fe^{3+} diagram. A. Data for all samples, discriminated according to chromite textural groups. Core-rim compositions of zoned crystals are connected by solid lines. B. Data for selected individual samples.

tain calcic amphibole (Table 1). Two different types of calcic amphibole occur at Buck Creek - edenite and tremolite. Frequently, both types are present in the same rock and show a textural association that consists of a core of edenite rimmed by tremolite (Figure 4B). Compositionally, the two amphiboles are characterized by distinctly different SiO_2 and Al_2O_3 contents, with SiO_2 higher in tremolite and Al_2O_3 higher in edenite (Table 3). Na_2O, FeO, and TiO_2 are all significantly higher in edenite, whereas tremolite is more Mg-rich.

Serpentine

Serpentine occurs in a variety of textural associations. Chrysotile and/or lizardite are ubiquitous as late-stage, low grade phases developed along fracture planes and grain boundaries. Antigorite is an important vein mineral, commonly comprising between 10 and 30% of any given vein. Antigorite is present in some samples as lamellar intergrowths oriented along (010) and, more rarely, (100) cleavage planes in olivine (Figure 2C). The extent to which the latter texture is developed strongly correlates with proximity to serpentine-bearing veins. Antigorite always has a higher Mg# than coexisting olivine (Table 3). Antigorite also occurs as overgrowths on chlorite. In this association the serpentine typically forms a pseudomorph of chlorite.

Other Minerals

Talc is restricted in occurrence primarily to serpentine-bearing veins that cut the metadunite. Otherwise, only sample CK-1B (described separately) was found to contain abundant talc. Carbonate minerals also occur in serpentine-bearing veins, and they may be present as scattered crystals within the metadunite. Dolomite appears to be the principal vein carbonate. The carbonate mineral in metadunite may be dolomite (e.g., CK-M1D), magnesite (e.g., BC-8), or calcite (e.g., BC-15A). In one sample (CK-8B), both dolomite and magnesite are present. Magnetite occurs in association with serpentine along fractures in olivine and as a minor phase in some serpentine-bearing veins. Small crystals of pentlandite are widely disseminated throughout the metadunite. Composite crystals of pentlandite + pyrrhotite were also found in some samples.

CK-1B

The uniqueness of this sample merits a separate description. This heterogeneous rock consists of metadunite surrounded gradationally by a talc-rich zone in which are orthopyroxene-rich lenses. The talc-rich areas contain abundant irregular olivine crystals and scattered orthopyroxene crystals, along with minor chlorite and scattered acicular crystals of tremolite. The orthopyroxene-rich areas contain talc, some very fine-grained olivine, and, locally, anthophyllite. Chlorite and rare tremolite also occur. In one

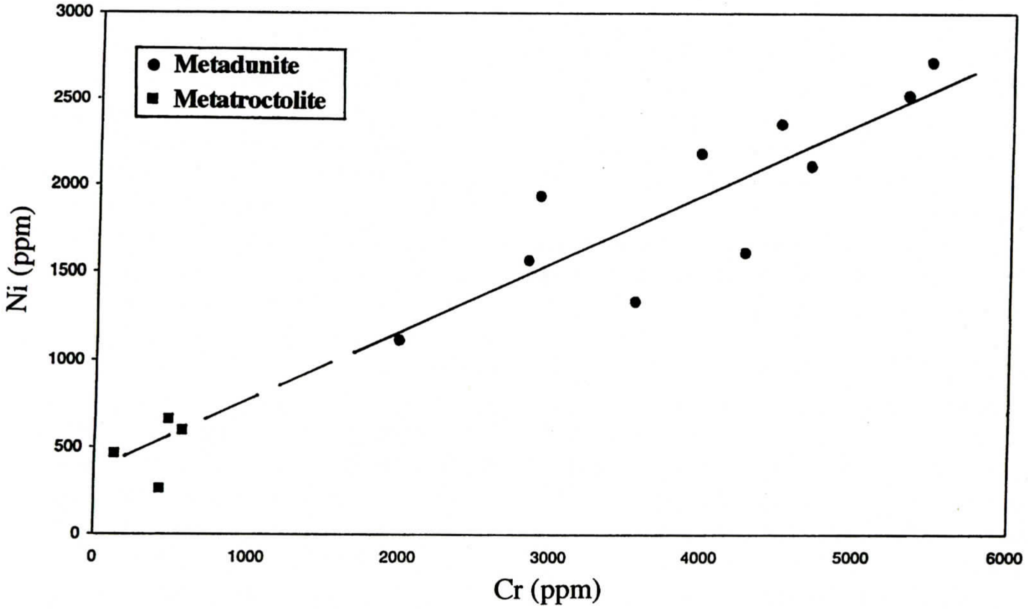

Figure 6. Plot of Cr vs. Ni in Buck Creek rocks. Except for sample BC-9 (which is unusually Ni-rich and plots outside the diagram), the data indicate a linear relationship. The straight line was obtained by linear regression of the metadunite analyses; note that the metatroctolites plot on the projection of the metadunite trend.

part of the sample orthopyroxene is coarse-grained and consists of subparallel elongate crystals up to about 1 cm in length. The orthopyroxene crystals commonly have irregular outlines and are invariably enclosed by talc plus minor olivine (Figure 2D). This texture indicates that the orthopyroxene is being replaced by talc + olivine. Representative analyses of orthopyroxene, olivine, and anthophyllite in CK-1B are given in Table 3.

PETROGENETIC DISCUSSION

Several lines of evidence indicate that the metadunite and associated metatroctolites at Buck Creek are genetically related, and in fact crystallized from the same magmatic source. First are the field relations: not only are the mappable metatroctolite lenses in large part or in whole enclosed within the main metadunite body (Figure 1), but also in several trenched exposures the two lithologies are seen to be finely interlayered or interfingered. In places the layers have thicknesses on the order of 1-2 centimeters. Second, geochemical parameters indicate that the rocks form a comagmatic suite (Kuntz and Hedge, 1981). Tenthorey and others (1996) plotted Al_2O_3 vs. MgO and CaO vs. MgO co-variation diagrams for metatroctolites and metadunites from Buck Creek, and showed that the rocks define a trend between olivine-rich (metadunite) and anorthite-rich (metatroctolite) end members. Similarly, a plot of Cr vs. Ni for Buck Creek rocks makes it evident that the metatroctolites fall on the same trend as the metadunites (Figure 6). Third, mineral compositions in the two rock types are virtually identical. Olivine in metatroctolites has a composition of Fo_{88-90} and contains ≥ 0.2 weight percent NiO, which closely matches olivine compositions in Buck Creek metadunites (Figure 3A). Chromite in metatroctolites is aluminous and has Cr/(Cr+Al) very similar to chromites in CK-M3D and CK-3C.

The above considerations suggest that the metadunite and metatroctolite were comagmatic and that they may have originated as a layered cumulate series. The protoliths had a simple mineralogy: olivine and accessory Al-rich chromite in metadunite and olivine-calcic plagioclase adcumulates with minor Al-rich chromite in metatroctolite (Tenthorey and others, 1996). Data from this study provide no definitive insight into the tectonic setting of the ultramafic-mafic protolith, but others have suggested that the rocks at Buck Creek are of ophiolitic origin (Kuntz and Hedge, 1981; McElhaney and McSween, 1983; Shaw and Wasserburg, 1984; McSween and Hatcher, 1985; Lacazette and Rast, 1989; Raymond and others, 1989; Tenthorey and others, 1996; Ryan and Peterson, 1999). The interlayering of metadunite and metatroctolite may reflect derivation from the transition zone between ultramafic and gabbroic parts of an ophiolite cumulate complex (Coleman, 1977).

Metamorphism of the Buck Creek rocks was accompanied by varying degrees of hydration. In the case of the metatroctolites, this resulted in a progression of rock types from nearly anhydrous rocks in which olivine and plagioclase reacted in part to produce complex coronas consisting of two-pyroxene/spinel symplectites, to partially hydrated rocks in which most or all of the olivine was reacted to yield symplectic coronal assemblages containing calcic amphibole ± sapphirine, to more thoroughly hydrated edenite-margarite schists (McCoy and others, 1999). The metadunites likewise are marked by metamorphic assemblages reflective of differing amounts of hydration. Samples CK-M3D and CK-3C contain the association olivine + aluminous chromite (association A-1 of Raymond and Abbott, 1997). This assemblage equates to that of the ultramafic protolith, and so the consequence of metamorphism has primarily been a recrystallization of the rock. Metadunites partly hydrated during metamorphism contain olivine + chromite + chlorite ± calcic amphibole (association A-2, Raymond and Abbott, 1997), while more extensively hydrated rocks are characterized by a greater abundance of chlorite (e.g., CK-M1D) or the additional presence of antigorite. Since chlorite and serpentine both have higher Mg#s than coexisting olivine, olivine in the latter rocks tends to be more Mg-poor than in the more anhydrous dunites (Swanson, in this volume, has noted

Table 4. Buck Creek geothermometry

Sample	Method		Result
Metadunite			
CK-M3D	Olivine-Spinel Geothermometer[1]		690°C
CK-3C	"	"	725°C
CK-10	"	"	675°C
Metatroctolite			
CK-0	Olivine-Spinel Geothermometer		705°C
"	Two-Pyroxene Geothermometer[2]		770°C
CK-T	"	"	810°C

[1] Roeder and others, 1979

[2] Wells, 1977

Other T estimates:

800-850°C	Buck Creek metatroctolites (Tenthorey and others, 1996)
715-750°C	Chunky Gal Mtn amphibolites (McElhaney and McSween, 1983)
750-775°C	Winding Stair Gap granulites (Absher and McSween, 1985)

similar relationships in metaultramafic rocks near Spruce Pine). The range in olivine compositions shown by the Buck Creek metadunites (about 8 mol% Fo) can in part be attributed to varying degrees of hydration during metamorphism (sample-to-sample differences in bulk rock MgO and FeO (Table 2) also contribute to the observed variation in olivine Fo).

Several aspects of the mineralogy of the Buck Creek metadunite can be utilized to constrain metamorphic P-T conditions. The coexistence of olivine and chromite may be used to determine temperatures of metamorphism using the olivine-spinel geothermometer (Roeder and others, 1979). Only type B chromite crystals or chromite bounded solely by olivine (i.e., with no associated hydrous minerals) were chosen for thermometry. The results (Table 4) indicate metamorphic temperatures of 700±25°C for the Buck Creek metadunite. Lipin (1984) reported comparable olivine-spinel temperatures for Buck Creek and other Blue Ridge metadunite bodies.

Tenthorey and others (1996) estimated peak metamorphic temperatures of 800-850°C for associated metatroctolites, based on application of the two-pyroxene geothermometer (Wells, 1977) to pyroxene pairs developed during formation of two-pyroxene/spinel coronas, and on the occurrence of sapphirine-bearing symplectites. Coexisting olivine and chromite in an olivine-rich metatroctolite (sample CK-0) yield a temperature (705°C) similar to those obtained for metadunite samples (Table 4). Coronal pyroxene pairs in the same rock and another sample give two-pyroxene temperatures of 770°-810C. It thus appears that the olivine-spinel geothermometry results in lower temperature estimates. Diffusion of Mg and Fe between olivine and chromite may occur down to ~700°C (Lipin, personal communication), and this could result in lower temperatures than recorded by the two-pyroxene assemblages. The olivine-spinel temperatures are therefore considered to represent a minimum value for metamorphism of the Buck Creek metadunite. A maximum value is constrained by the mineralogy of the metadunite. Chlorite plus calcic amphibole stably coexist in metaultramafic rocks to temperatures of at least 740°C, and possibly as high as 800°C (Bucher and Frey, 1994, p. 157). The occurrence of diopside in one metadunite sample (BC-9) supports a peak temperature toward the upper end of this range, as onset of diopside formation (replacing calcic amphibole) is near 800°C (Bucher and Frey, 1994). The characteristic presence of calcic amphibole (edenite) rather than calcic pyroxene suggests that temperatures did not exceed 800°C, however, and were probably slightly lower. Peak temperatures for metamorphism of the Buck Creek metadunite are thus estimated to be between 700°C and 800°C.

The metamorphic temperatures at Buck Creek obtained in this study are comparable to those determined for the mafic rocks that envel-

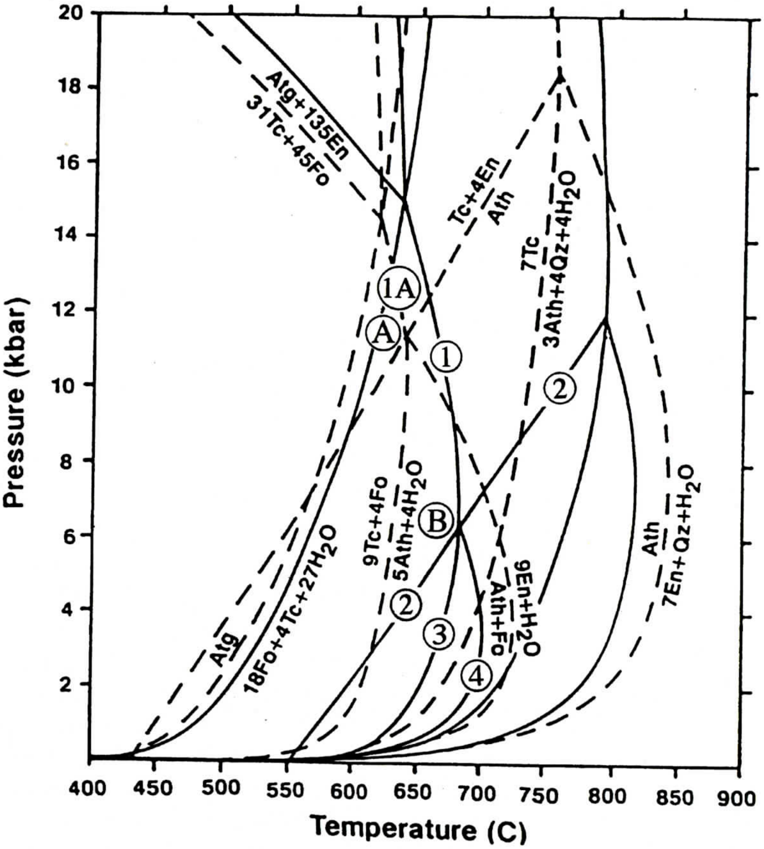

Figure 7. Petrogenetic grid for ultramafic rocks showing reaction curves for the Fe-free system MgO-SiO_2-H_2O (solid lines) and for Fe-bearing ultramafic rocks (dashed lines). Diagram is reproduced from Evans and Guggenheim (1988). Invariant points A and B correspond to the Fe-bearing and Fe-free systems, respectively. Curve labeled 1A is the reaction 5En + H_2O = Tc + Fo in Fe-bearing rocks (see text for discussion). Reactions numbered 1-4 are equivalent reactions in the Fe-free system: (1) 5En + H_2O = Tc + Fo (2) Ath = Tc + 4En (3) 5Ath + H_2O = 9Tc + 4Fo (4) 9En + H_2O = Ath + Fo

op the ultramafic body. McElhaney and McSween (1983) reported temperatures of 715-750°C for type I Chunky Gal Mountain amphibolites based on plagioclase-hornblende and clinopyroxene-hornblende exchange equilibria. Still higher temperatures (750-775°C) have been suggested for granulites at Winding Stair Gap, which is located approximately 8 km ENE of Buck Creek, and is considered to represent the thermal axis of Paleozoic metamorphism in the southern Appalachians (Absher and McSween, 1985).

Constraint on the pressure conditions during metamorphism of the Buck Creek metadunite is provided by the phase relations in sample CK-1B. Petrographic evidence (Figure 2D) suggests that orthopyroxene in this rock is being retrograded to talc + olivine. In the system MgO-SiO_2-H_2O the reaction that is occurring here can be written as

enstatite + water = talc + forsterite.

This reaction (1 in Figure 7) is only encountered at pressures above invariant point B (greater than 6 kb). At lower P enstatite breaks down to anthophyllite + forsterite (reaction 4), with anthophyllite subsequently being converted to talc + forsterite (reaction 3) at a lower temperature (Evans and Guggenheim, 1988; Raymond and Abbott, 1997). The addition of iron to the system in amounts appropriate for alpine ultramafic rocks changes the positions of the reaction curves - the pertinent curves are shown in Figure 7 as dashed lines. The corresponding invariant point in the Fe-bearing system is A, and the minimum pressure at which the reaction of orthopyroxene to form talc + olivine (reaction 1A) occurs is between 11 and 12 kb. At lower pressures orthopyroxene breakdown would produce anthophyllite + olivine (Figure 7). As noted earlier, minor anthophyllite is present in CK-1B, in association with orthopyroxene. This may indicate that pressure was close to that of the invariant point (A) involving talc, enstatite, forsterite, anthophyllite and water (i.e., P of 11-12 kb). Such a pressure estimate accords well with peak metamorphic pressures inferred from associated metatroctolites. Tenthorey and others (1996) argued that the occurrence of sapphirine-bearing assemblages in symplectite coronas required pressures to have reached at least 9-10 kb, while Emilio and others (1998) concluded that the mineralogy of related edenite-margarite schists additionally constrained pressures to between 10 and 11.5 kb.

Evidence for later retrograde metamorphism of the metadunites is widespread and includes the following: (1) tremolite overgrowths on edenite (Figure 4B); (2) formation of antigorite lamellae in olivine (Figure 2C); (3) pseudomorphous replacement of chlorite by antigorite; and (4) growth of mesh-textured lizardite along olivine fracture surfaces and grain boundaries. The development of (1-3) appears to be related to the presence of serpentine-bearing veins. The retrograde assemblage, olivine + antigorite + tremolite, is stable over a narrow temperature range, near 540°C (Bucher and Frey, 1994, p. 157). The mineralogy of the associated veins (antigorite ± talc ± tremolite ± chlorite ± carbonate) is compatible with this assemblage (Evans, 1977), indicating that the retrograde metamorphism accompanied vein formation. The fluid phase introduced during this stage must have had variable proportions of CO_2 (Trommsdorff and Evans, 1977) to account for the various occurrences of dolomite, magnesite, or calcite in different metadunite samples. The formation of (4) represents a later event at still lower temperatures (association A-5 of Raymond and Abbott, 1997).

Results from this study indicate that the metadunites at Buck Creek record a history of granulite facies metamorphism (700-800°C at P of 11-12 kb) followed by retrograde lower amphibolite or upper greenschist facies metamorphism at temperatures near 540°C. Tenthorey and others (1996) proposed that the metatroctolites at Buck Creek experienced two stages of prograde metamorphism, the first (~800°C at 5-7 kb) producing anhydrous two-pyroxene/spinel coronas and the second (~850°C at 9-10 kb) forming hydrous sapphirine-bearing assemblages. Subsequent retrograde effects are evident but poorly constrained. There is no thermobarometric evidence in the mineralogy of the metadunites for two-stage prograde metamorphism. However, as noted earlier, the metadunites are similar to the metatroctolites in that they show varying degrees of hydration. Perhaps the least hydrated metadunites (e.g., CK-M3D) are representative of the first (anhydrous) stage while the chlorite-bearing metadunites were formed during the second (hydrous) stage. Alternatively, both metadunites and metatroctolites may have undergone a single episode of prograde metamorphism, and the different assemblages simply reflect local variations in the amount of hydration that the rocks experienced (Swanson, in this volume). The latter interpretation also accords with the conclusion reached by Eckert and others (1989) for the nearby Wayah granulite-facies metamorphic core, that it was produced during a single prograde (Taconic) metamorphic event.

The retrograde lower amphibolite/upper greenschist facies metamorphism clearly involved hydration of the ultramafic rocks, as it produced antigorite-bearing assemblages and veins containing antigorite and talc. Other ultramafic bodies in the southern Blue Ridge record a similar history of hydration during retrograde metamorphism (Abbott and Raymond, 1984; Raymond and Abbott, 1997; Swanson, 1995; 2000; in this volume). Whether the retrograde event that affected the Buck Creek rocks correlates with a specific orogeny (e.g., Acadian) or resulted from monotonic cooling from the peak Taconic metamorphism (Raymond and Abbott, 1997) remains an open question.

CONCLUSIONS

1) The Buck Creek ultramafic body consists of metadunite and subordinate metatroctolite. The two rock types are comagmatic and may have originated as a layered cumulate series, possibly as part of an ophiolite sequence.

2) Metadunite and associated metatroctolite were recrystallized during metamorphism and are now metamorphic rocks. Metamorphic assemblages indicate varying degrees of hydration. Most metadunite was partially hydrated and is characterized by the metamorphic assemblage olivine + chromite + chlorite ± edenite.

3) Peak temperatures during metamorphism of the metadunite were 700-800°C, and peak pressures were 11-12 kb. Comparable metamorphic P-T conditions have been reported for the metatroctolites and surrounding Chunky Gal Mountain amphibolites.

4) Retrograde (~540°C) metamorphism of the metadunite, related to metasomatic formation of serpentine-talc-carbonate veins, produced assemblages containing antigorite and/or tremolite.

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INSIGHTS FROM RARE EARTH ELEMENTS INTO THE GENESIS OF THE BUCK CREEK COMPLEX, CLAY COUNTY, NC

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ABSTRACT

The Buck Creek complex is among the largest and most lithologically diverse of the mafic/ultramafic bodies found in the eastern Blue Ridge province of the southern Appalachians. Rare-earth element (REE) analyses on a representative suite of Buck Creek amphibolites and meta-troctolites supplements an ongoing undergraduate research program examining the origins and history of mafic/ultramafic units in southwestern North Carolina. While some of the REE (particularly Ce) show effects of the metamorphic alteration of the Buck Creek complex, overall its REE systematics reflect the compositions of igneous protoliths. "High Ti" and "Low Ti" amphibolites show REE patterns consistent with basaltic and cumulate gabbroic protoliths, indicating an ocean crustal origin for the Buck Creek Complex.

Buck Creek amphibolites show similarities in REE systematics to the Group 2 amphibolites of Misra and Conte (1991), as well as to a garnet pyroxenite from the nearby Lake Chatuge complex. Amphibolites from the Carroll Knob mafic complex and pyroxenites from the Moore's Knob and Webster-Addie bodies show overall lower rare earth element abundances, and variable REE patterns.

INTRODUCTION

A range of hypotheses has been proposed to explain the origins of mafic and ultramafic rock bodies exposed within the Eastern Blue Ridge province of the southern Appalachians: deep seated magma bodies (Hartley, 1973; Meen,1988), magnesian metamorphic rocks (Swanson, 1980), ultramafic diapirs (Stevens and others, 1974; Yurkovich, 1977), random blocks in a subduction melange (Laccazette and Rast, 1989; Raymond and others, 1989), or fragments of ophiolite sequences (Misra and Keller, 1978; MacElhaney and McSween, 1983; Tenthorey and others, 1996). Amphibolite-granulite facies metamorphism and complex deformation typical of the eastern Blue Ridge province have pervasively modified these mafic/ultramafic rock bodies and obscured many pre-deformational physical relations (Absher and McSween, 1985; Eckert and others, 1989; Tenthorey and others, 1996). Geochemical analysis in conjunction with outcrop- and map-scale field relations allow us to see through the effects of metamorphism, both to ascertain protoliths and to provide indications of tectonic settings. REE systematics have been used to successfully constrain tectonic settings in metamorphosed terranes (Grauch, 1989). With a few exceptions, the REE are not strongly mobilized in H_2O-rich metasomatic fluids (Brookins, 1989); and REE variation patterns have been used for many years to relate suites of rocks and to constrain their tectonic settings.

The relatively large size and lithological complexity of the Buck Creek mafic/ultramafic complex make it an excellent place to establish a basis for REE geochemical characterization. Participants in the 1997 and 1998 NSF-sponsored Buck Creek Research Experiences for Undergraduates (REU) Site research program generated an extensive database of major and

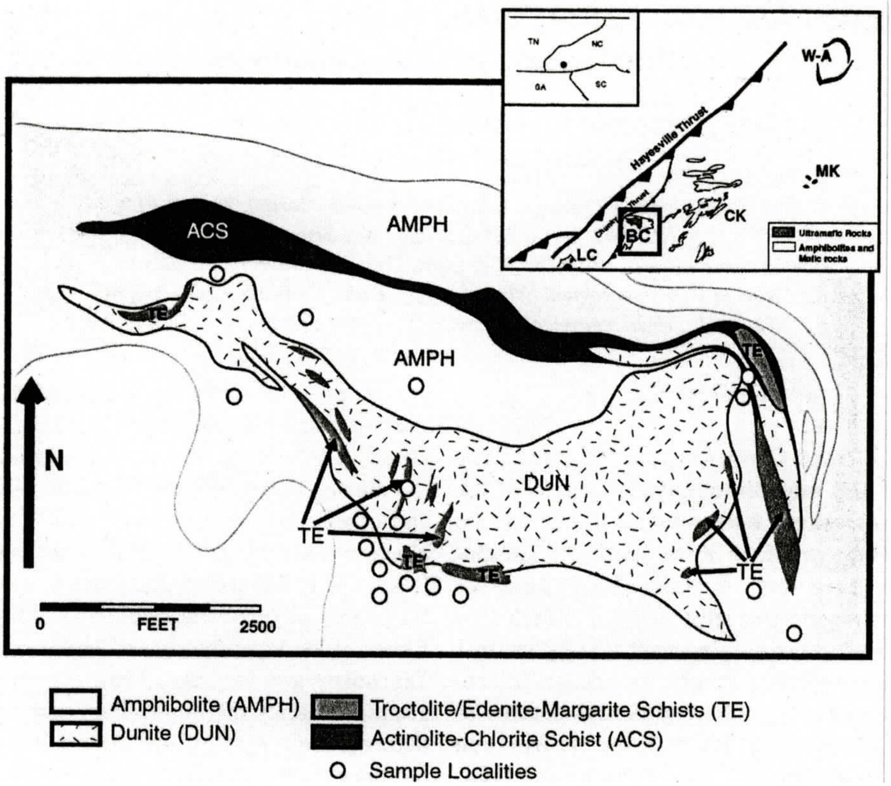

Figure 1: Simplified map of the Buck Creek complex, modified from Hadley (1949), and based on mapping results of 1997 and 1998 REU research working groups (Stonesifer and others, 1998; McCoy and others, 1999), showing the locations of samples for this study. Note that the edenite-margarite schist and anhydrous meta-troctolite units cannot be resolved at the scale of this map. Inset is a schematic regional map noting the positions of the Buck Creek (BC) Lake Chatuge (LC) and Carroll Knob (CK) complexes, as well as the Webster-Addie complex (W-A) and the Moore's Knob dunite (MK) to the east.

trace element compositions for rocks of the Buck Creek complex, constrained by detailed outcrop- and map-scale field observations. These field and geochemical data point to an origin for the Buck Creek complex as a fragment of a layered magmatic sequence, dominated by amphibolite (metabasalt or gabbro) with abundant dunite, and lesser troctolite and other ultramafic assemblages. Post-summer research by some REU participants led to analysis of REE abundances in selected samples from the Buck Creek complex, and from nearby mafic/ultramafic rock bodies. Our results point to genetic affinities among the different lithologic units of the Buck Creek complex, and indicate similarities to other mafic/ultramafic associations of the southeastern Blue Ridge.

SETTING AND PETROLOGIC OVERVIEW OF THE BUCK CREEK COMPLEX

The Buck Creek complex (BC) is made up of metamorphosed mafic and ultramafic rocks, and is located in Clay Co., North Carolina, in the Blue Ridge province of the southern Appalachians (Warner, in this volume; Fig. 1). The BC is the largest of numerous mafic/ultramafic exposures that form a broad chain within the Eastern Blue Ridge province, southeast of the pre-metamorphic Hayesville-Fries fault. The Buck Creek ultramafic rocks have also been described as part of the Chunky Gal Mountain Complex (defined based on extensive exposures of amphibolites, which enclose the ultramafic

Table 1. Bulk Compositions of Typical Buck Creek Lithologies.

	Amphibolites		Troctolites/EMS		Dunite
	High Ti	**Low Ti**	**Troct.**	**EMS**	
Sample	**BC97SM1d**	**BC97SM1b**	**BC97AB6d**	**BC97PG4d**	**BC97JL1b1**
SiO2 (%)	45.85	50.15	48.08	42.19	37.78
Al2O3	14.50	16.20	21.78	20.49	2.72
Fe2O3	13.59	6.39	5.88	6.19	13.08
MnO	0.20	0.12	0.09	0.08	0.16
MgO	9.21	9.27	7.20	19.32	46.07
CaO	13.78	14.29	14.23	9.47	0.34
K2O	0.13	0.15	0.11	0.17	0.01
Na2O	1.75	2.39	2.20	2.83	0.01
TiO2	1.41	0.24	0.21	0.02	0.01
Total	100.42	99.19	99.78	100.75	100.17
LOI (%)	1.75	1.24	0.91	4.49	3.77

rocks at Buck Creek; Fig. 1) (McElhaney and McSween, 1983; McSween and Hatcher, 1985). As the amphibolites and ultramafic lithologies at Buck Creek show both stratigraphic and geochemical relationships, we use the term "Buck Creek complex" to denote both the mafic and ultramafic rocks of the area. The BC rocks are enclosed within late Precambrian to early Paleozoic metamorphosed sediments and volcanics of the Tullalah Falls Formation and Coweeta Group (Eckert and others, 1989, Hatcher and others, 1984; MacElhaney and McSween, 1983).

The BC contains a variety of mafic and ultramafic lithologies, first delineated by Hadley (1949), and recently revised by participants in the NSF-sponsored Buck Creek (REU) Site program (Ryan, Peterson, and others, in prep; Stonesifer and others, 1998; McCoy and others, 1999). The complex includes five distinct map units: dunite, anhydrous meta-troctolite, edenite-margarite schist (metasomatically altered meta-troctolite), actinolite-chlorite schist, and amphibolite, with locally gradational contacts and transitions between units. Geochemically, these map units represent gradations from ultramafic to mafic cumulate protoliths, including dunites, troctolites, gabbros, clinopyroxenites, and anorthosites (Collins and others, 1998; Thomas and others, 1999; Table 1). All of the Buck Creek units have undergone variable hydration during a multistage metamorphic history, with peak conditions reaching ~1.2 GPa and 800-850°C (Tenthorey and others, 1996; Emilio, 1998).

The BC lies in close proximity to two other large complexes of associated mafic and ultramafic rocks: the Lake Chatuge complex, 10 miles to the southwest in NE Georgia, and the Carroll Knob Complex 10 miles ENE in Macon Co, North Carolina (Hartley, 1973; Hatcher and others., 1984; Figure 1, inset). All three of these units include amphibolites coexisting with dunites, metamorphosed gabbros, and/or meta-troctolites. The multilithologic nature of these larger complexes distinguishes them from the small, podiform exposures of dunite +/- minor harzburgite and pyroxenite, such as the Moore's Knob dunite, which are enclosed in Eastern Blue Ridge metasediments of the Ashe Metamorphic Suite (Misra and Keller, 1978; Raymond, 1984; Abbott and Raymond, 1984; Yurkovich and Eckert, 1992). The Webster-Addie dunite, 60 miles northeast of Buck Creek, is a relatively large ring-shaped body that is lithologically similar to the small podiform bodies (Figure 1, inset).

ANALYTICAL METHODS

Samples analyzed for rare earth elements were selected from the 150+ rock samples that were chemically and petrographically characterized during the 1997 and 1998 REU Site Research Program at Buck Creek. We limited our work to BC amphibolites and samples which showed bulk chemical similarities to gabbros/diabases/basalts, partly to ensure that the REE would be at measurable abundances, and also to simplify our inferences to parental magma rare earth contents. Representative mafic rocks from the Lake Chatuge and Carroll Knob complexes were analyzed toward making first-order comparisons among these nearby units. As well, a websterite from the Webster Addie complex, and an orthopyroxenite from the Moore's Knob dunite, were analyzed to assess REE variations among these bodies regionally.

Whole-rock samples were digested via an Na_2CO_3 fluxed-fusion procedure to ensure that all phases (including spinels, corundum, and sapphirine, which are common in many Buck Creek lithologies) would be completely digested. Water-soluble carbonates (and associated Na_4SiO_4) in the fusion cakes were removed by extensive rinsing, leaving carbonate residues that quantitatively retain REE. These residues were dissolved in HNO_3, and diluted at 1000:1. All sample solutions were spiked with the internal standard elements Cs, and Re at the 10 ppb level.

ICP-MS Methods

Most of the REE measurements reported in this study were made via quadrupole ICP-MS using the high-sensitivity Agilent Technologies (formerly HP) 4500 Plus Series 200 ICP-MS instrument in the Department of Marine Sciences on the USF-St. Petersburg campus. Some earlier determinations were made using a VG Elemental PQ2+ ICP-MS, which the Agilent instrument replaced. Oxide and doubly-charged ion interferences were minimal on the Aligent instrument, at less than 1% and 2% of the elemental signal on a 10 ppb Ce solution, so corrections for oxide contributions to signal intensities were found to be unnecessary.

We analyzed the full suite of rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) as well as yttrium, which was compared to our DC plasma spectrometry results on the same samples to assess the quality of our REE digestions. A two-step calibration procedure was used to determine concentrations. First, REE signal intensities were corrected to those of the internal standards. The light REE (La through Eu) were corrected to Cs, and the heavy REE (Eu to Lu) were corrected to Re. Mismatches in corrected Eu intensities were used as an indicator of machine performance, and samples with mismatches were re-analyzed.

In the second calibration step, sample concentrations were calculated against a working curve of gravimetric, matrix-matched REE solutions, all diluted from a stock rare-earth standard solution made with an abundance pattern resembling that of the samples. Calibration solutions included a blank and 5000, 1000, 500, 200 and 100-fold dilutions of the stock standard, yielding REE concentration ranges of 0.4-20 ppb for the LREE and 0.04–2.0 ppb for the lower abundance HREE. Each standard contained 10 ppb of Cs and Re internal standards, and were intensity corrected with the samples.

Detection limits for the REE vary with element, but reproducible measurements were routine at the 1x chondrites (1 x CI) level for all REE, and at ~0.1x CI levels for many of the LREE. Precision for individual analyses based on replicates is ± 10%, but the relative precision among the REE was better, comparable to the precision of our calibration standard solutions (i.e., ± 1%). Accuracy was assessed through replicate measurements of USGS reference material BIR-1. Our values for the LREE were somewhat lower than reported values, but HREE abundances were within ± 10% (Table 2). Yield tests and tests of our calibration solutions convince us of the accuracy of our LREE determinations, which are at 3-5 x CI abundance levels in this standard.

RESULTS AND DISCUSSION

The REE data collected in this study are presented in Table 3, and diagrammatic presentations of our data on "Masuda/Coryell" type chondrite-normalized plots (after Masuda and others, 1973), may be found on Figures 2-6. REE data for BC amphibolites reflect the two different chemical subtypes found by the REU

Table 2. Comparison of REE Data for USGS Reference Material BIR-1.

Element	Recommended	USF ICP-MS
La	0.62	0.49
Ce	1.95	1.88
Pr	0.38	0.34
Nd	2.5	2.19
Sm	1.1	1.04
Eu	0.54	0.49
Gd	1.85	1.70
Tb	0.36	0.34
Dy	2.5	2.51
Tm	0.57	0.57
Er	1.7	1.71
Ho	0.26	0.26
Yb	1.65	1.67
Lu	0.26	0.25

program:

1. Samples with TiO_2 contents greater than 1.0% wt. ("high Ti" amphibolites) show subparallel REE patterns, with modest LREE depletions in most cases ($[La/Sm]_N$ _ 1.3; Table 3; Figure 2). Abundances of the heavy REE range from 10-20 x CI levels, comparable to many tholeiitic basalts and gabbros.
2. Samples with TiO_2 contents less than 1.0% ("low Ti" amphibolites and troctolites) show more variable REE patterns, and range from 1 - 10 x CI levels in the heavy REEs (Table 3; Figure 3,4). A characteristic of most of these samples is a distinct positive "Eu anomaly." Europium exists as both $^{2+}$Eu and $^{3+}$Eu, and $^{2+}$Eu readily substitutes for $^{2+}$Ca in plagioclase feldspar. All of these samples contain abundant modal plagioclase; and some preserve relict primary plagioclase (i.e., "coronal troctolites"; Tenthorey and others, 1996). The chemical compositions of these rocks are consistent with abundant primary plagioclase. Heavy REE in these rocks show largely flat patterns, while the light REE vary from enriched to markedly depleted.
3. $[La/Sm]_N$ ratios in these rocks vary from 0.15 to 2.0, with one extreme value of 4.6 (sample 11C). $[La/Yb]_N$ ratios vary from 0.1 to 3.2.

Sources of REE Variability at Buck Creek

The effects of the regional high-grade metamorphism on the REE systematics is presumed to be minimal, with the REE patterns of metamorphosed rocks reflecting that of their protoliths (Grauch, 1989). The BC amphibolites show REE patterns broadly consistent with basalts/diabases and associated gabbros, but also show some anomalies. The most evident of these are the variable "Ce anomalies" that appear in many of the REE patterns. In the presence of oxidizing metasomatic fluids, Ce will occur partly as Ce^{4+}, and, as has been noted in oceanic settings (Brookins, 1989) Ce^{4+} is readily removed from solution. While marine alteration of ocean crust is known to produce Ce anomalies, in the case of Buck Creek, which has undergone a complex metamorphic history (Emilio, 1998), it seems probable that metasomatic fluids moving through the complex are responsible for Ce redistribution. Ce variability is more evident in the "Low Ti" amphibolites, at lower overall REE contents.

Greater LREE variability in the low Ti BC samples may be partly induced by high-temperature metasomatic interactions. At low REE contents, interactions with CO_2-bearing metasomatic fluids may produce marked enrichments or depletions in the LREE. "U" shaped REE patterns in some ophiolitic dunites are believed to arise via small inputs of fluid borne LREE added to very depleted ultramafic protoliths (McDonough and Frey, 1990). Our strongly LREE enriched ($[La/Sm]_N > 3$) BC samples all have rather low heavy REE contents, and thus may reflect secondary additions of LREE-enhanced fluids, as some of these samples show REE patterns similar in shape to those of the local country rocks (Figure 4). The meta-troctolite sample AB6D has La/Sm _ 0.7, while 11C, a hydrothermally altered meta-troctolite with strongly elevated LREE, and an extreme negative Ce anomaly, has La/SmN of 4.6.

These variations aside, the REE patterns of the different Buck Creek units do not suggest extensive remobilization of the rare earth elements, or pervasive contamination by crustal

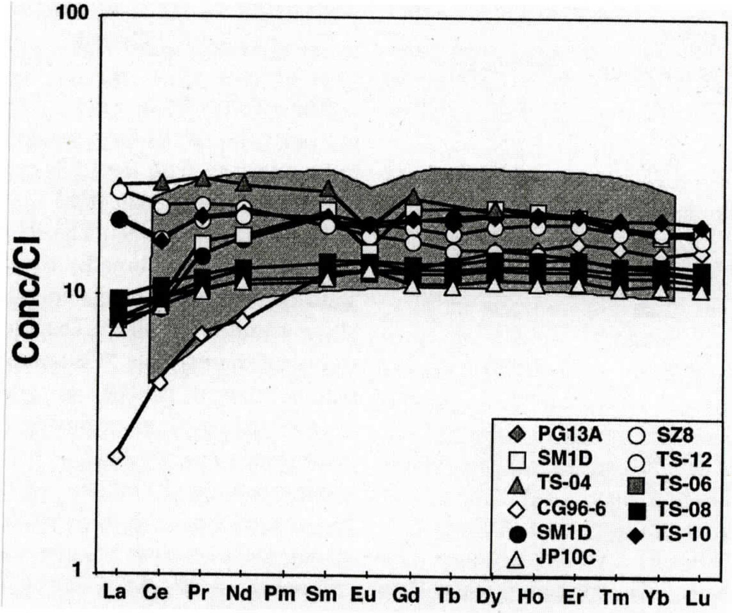

Figure 2: Masuda-Coryell type rare earth diagram (Masuda and others, 1973) of REE data for "high Ti" Buck Creek amphibolites. CI chondrite normalizing values in this and all diagrams are from Taylor and Gorton (1977). Shaded field represents depleted "normal" mid-ocean ridge basalts, based on Bender and others (1984).

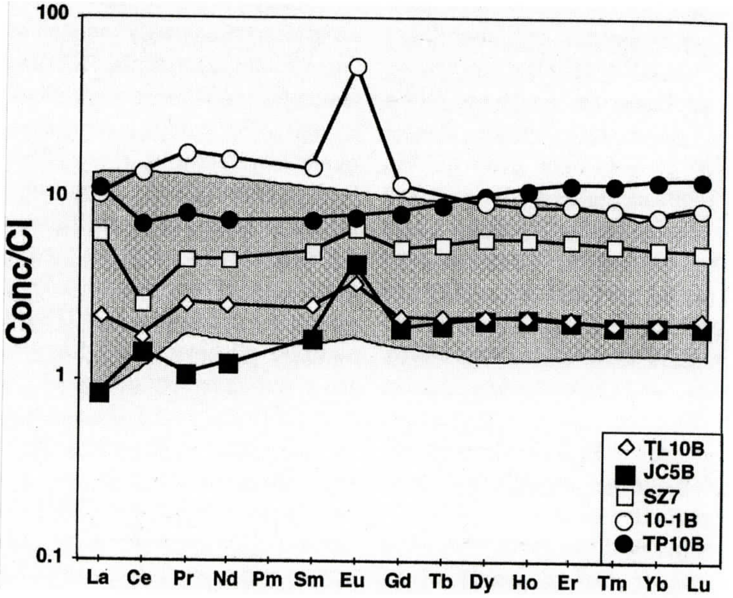

Figure 3: REE data for "low Ti" Buck Creek amphibolites. Shaded field represents cumulate gabbroic rocks from the Balkan-Carpathian ophiolite (Savov and others, in press), a well-preserved, "high Ti" ophiolite complex.

Table 3: Rare Earth Element Data for Buck Creek and other Mafic-Ultramafic Complexes

REEs, ppm	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	“High Ti” Amphibolites													
BC97 TS04	7.54	20.1	3.16	14.8	4.69	1.28	5.90		6.62	1.39	4.04	0.57	3.54	0.55
CG96.6	0.81	3.89	0.87	4.76	2.28		3.33		4.72	1.06	3.23	0.48	2.94	0.47
BC97SM1d	2.48	7.10	1.68	9.45	3.47	1.27	4.79	0.89	6.31	1.39	3.95	0.57	3.55	0.52
BC98SZ8	5.71	12.7	2.24	11.5	3.57	1.31	4.49	0.79	5.65	1.29	3.75	0.55	3.51	0.52
BC97 TS12	7.14	16.5	2.56	12.3	3.44	1.20	4.05	0.69	4.70	1.01	2.87	0.41	2.60	0.38
BC97 TS06	2.95	8.53	1.39	7.48	2.57	0.96	3.38	0.62	4.36	0.96	2.84	0.42	2.70	0.41
BC97 TS10	5.72	12.4	2.30	11.7	3.74	1.33	4.83	0.87	6.21	1.41	4.12	0.61	3.91	0.58
BC97PG13a	2.73	7.65	1.34	7.30	2.45	0.95	3.19	0.58	4.06	0.90	2.64	0.39	2.53	0.38
BC97 JP10c	2.32	7.23	1.23	6.66	2.23	0.90	2.85	0.51	3.60	0.80	2.34	0.34	2.26	0.34
	“Low Ti” Amphibolites													
10-1B	3.17	10.93	2.12	9.75	2.83	3.85	3.07		3.03	0.63	1.89	0.28	1.67	0.28
BC98SZ7	1.94	2.10	0.55	2.69	0.98	0.49	1.38	0.26	1.90	0.42	1.22	0.18	1.12	0.17
BC98TP10b	3.51	5.80	0.99	4.53	1.46	0.57	2.13	0.43	3.30	0.79	2.48	0.39	2.62	0.41
BC98 TL10b	0.68	1.37	0.32	1.51	0.49	0.25	0.57	0.10	0.71	0.16	0.45	0.066	0.43	0.069
BC97 JC5b	0.25	1.14	0.13	0.72	0.33	0.32	0.50	0.10	0.69	0.16	0.45	0.06	0.42	0.06
	Pyroxenite													
BC98 SM11	2.29	4.07	1.38	7.95	3.15	0.87	4.39	0.83	6.16	1.40	3.99	0.57	3.62	0.53
	Troctolites													
BC97 SM1B	2.24	5.47	0.74	3.09	0.71	0.30	0.76	0.12	0.85	0.19	0.52	0.08	0.48	0.07
BC97 AB6D	0.42	1.24	0.14	0.77	0.33	0.32	0.50	0.09	0.66	0.15	0.43	0.06	0.41	0.06
11C	6.53	3.09	1.14	3.31	0.83	0.13	0.68		0.78	0.16	0.47	0.07	0.32	0.07
	Other Complexes													
LCH-gt	1.90	7.60	1.60	8.36	3.23	1.01	4.50	3.20	5.63	1.23	3.52	0.50	3.04	0.48
CK-199	1.07	3.66	0.61	3.54	1.25	0.45	1.55	0.26	1.74	0.38	1.05	0.15	0.94	0.14
CK-299	0.05	0.20	0.03	0.16	0.09	0.06	0.14	0.03	0.22	0.06	0.16	0.03	0.17	0.03
MK OPXite	0.29	1.08	0.14	0.61	0.18	0.05	0.18	0.04	0.28	0.07	0.21	0.04	0.25	0.04
W-A Webst.	0.77	2.25	0.33		0.33		0.25		0.34	0.08	0.25	0.04		0.03

fluids. In particular, the higher concentration amphibolite samples are distinct in their REE patterns from the nearby country rocks, and show abundances and patterns suggestive of mafic igneous protoliths.

Relationships Between BC “High Ti” and “Low Ti” Rocks

The rare-earth element systematics of the “high Ti” and “low Ti” Buck Creek amphibolites are consistent with associated basalt/diabases and cumulate gabbros, respectively, as found in ophiolite associations. The “high Ti” amphibolites possess REE patterns similar to ocean floor basalts both in terms of overall REE abundances and pattern shape. The origins of the “Low Ti” amphibolite patterns are somewhat more complicated. These samples have lower overall REE contents and are clearly more susceptible to metasomatic disturbance. However, these rocks show strong positive Eu anomalies, which complement the modest negative Eu anomalies observed in many of the “high Ti” samples; and relatively flat patterns in the heavy REE. We interpret these samples as representing a range of mafic cumulate protoliths. The markedly lower TiO_2 contents of these samples supports this interpretation, as do their more variable Mg/Al and Ca/Al ratios (Collins and others, 1998). The chemical variations in these rocks probably reflect variations in the proportion of four igneous components: plagioclase, clinopyroxene, olivine crystals,

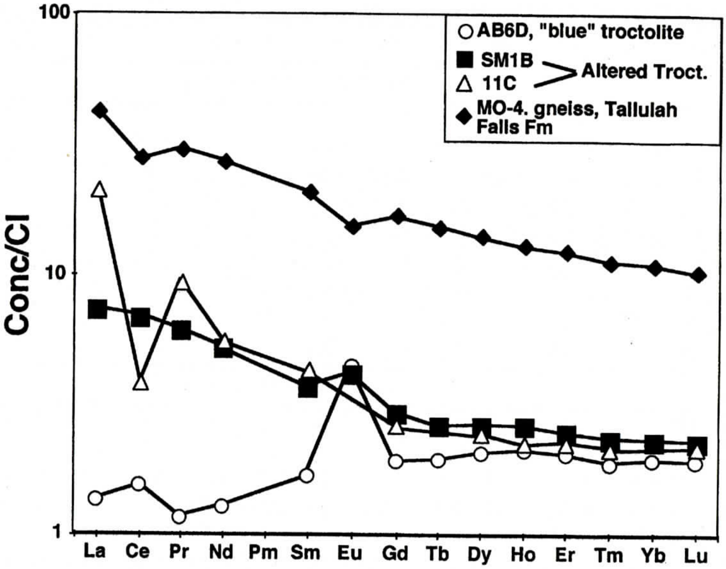

Figure 4: Comparison of REE data for metasomatically altered Buck Creek edenite-margarite schists 11C and SM-1B and for the unaltered "blue" metatroctolite AB6D. Shown for comparison is the REE pattern of MO-4, a pelitic gneiss from the surrounding Tallulah Falls formation.

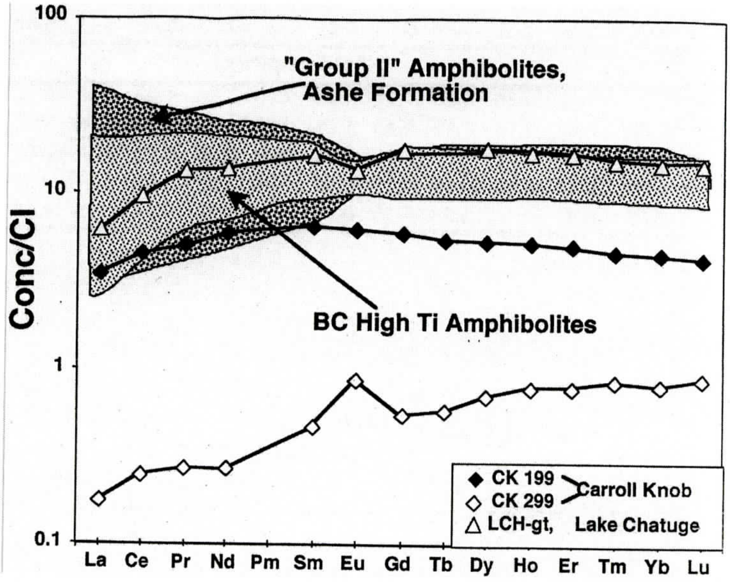

Figure 5: Overlay of the range for Buck Creek "High Ti" amphibolites on the field for depleted "Group II" amphibolites from Misra and Conte (1991), along with REE patterns for a garnet pyroxenite from the Lake Chatuge complex (Meen 1988; Dallmeyer 1974), and two amphibolitic samples from the Carroll Knob mafic complex (see Hatcher and others, 1984).

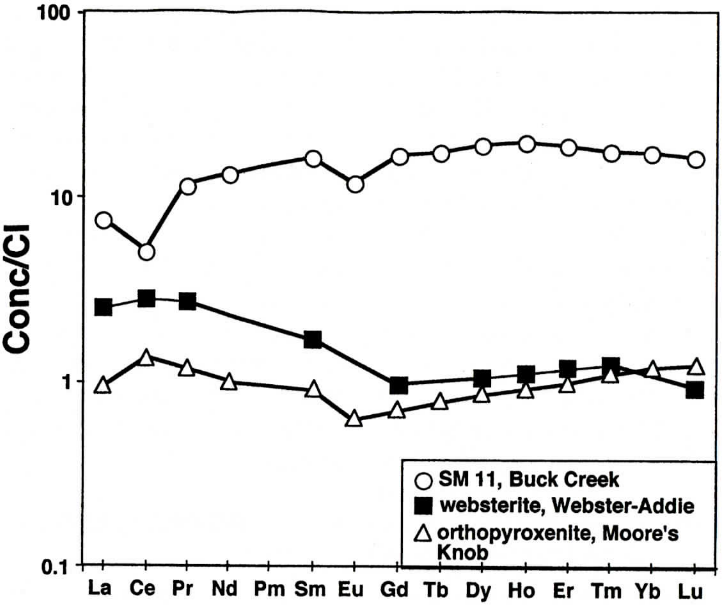

Figure 6: Comparison of REE data for pyroxenites from the Webster-Addie and Moore's Knob ultramafic bodies to sample SM-11, a massive clinopyroxenite from the Buck Creek complex.

and small (but in some cases significant) amounts of intercumulus melt. Prominent, positive Eu anomalies indicate the presence of primary, accumulated plagioclase. The relatively flat HREE patterns shown by most these rocks are consistent with the presence of significant amounts of clinopyroxene, similar in composition to sample SM–11, an augitic clinopyroxenite found in the complex (Figure 6). Sample 10-1B has an overall REE pattern and rare earth abundance levels similar to the "high Ti" amphibolites, but also includes a prominent positive Eu anomaly (Figure 3). This combination of features, along with an intermediate TiO_2 content (0.62% wt) points to a melt containing significant accumulated plagioclase, as might occur if plagioclase flotation were occurring in a mafic magma chamber.

Overall, the BC amphibolites and troctolites show REE systematics consistent with a suite of associated gabbroic and cumulate rocks, as might be found in the "oceanic", high TiO_2 class of ophiolites (Serri, 1981; Savov and others, in press). The LREE depleted character of our "high Ti" BC samples are similar to those of rocks from mid-oceanic or distal back-arc settings. This interpretation is consistent with inferences made from the bulk chemical variations of all the Buck Creek lithologies by Collins and others (1998), and with past studies of BC amphibolites (i.e., MacElhaney and McSween, 1983).

Comparisons to Other Blue Ridge Mafic and Ultramafic Rocks

The "high Ti" Buck Creek amphibolites show similar REE abundances and REE patterns to "Group II" amphibolites from the Ashe Metamorphic Suite (Misra and Conte 1991). No Buck Creek mafic rocks we have analyzed exceed 2.0% wt TiO_2, and so they are chemically distinct from Group III Ashe Metamorphic Suite amphibolites, which have TiO_2 contents >3.0%, and REE patterns that reflect an enriched mantle source (Misra and Conte, 1991). Our "low Ti" amphibolites show the same range in overall REE contents as the Group I amphibolites from the Ashe Metamorphic Suite, although the poorer detection limits for INAA data make a comparison of REE patterns problematic.

Among nearby mafic-ultramafic bodies, the Buck Creek complex bears considerable lithologic similarity to the Lake Chatuge complex, as both include meta-troctolites and amphibolites, and record similar metamorphic histories (i.e., Hartley, 1973; Dallmeyer, 1974; Meen, 1988; Tenthorey and others, 1996; Emilio, 1998). A sample of garnet pyroxenite from the Lake Chatuge complex with a major element composition similar to BC "high Ti" amphibolites displays a similar REE pattern (Figure 5a). This observation concurs with Nd isotopic results for BC and Lake Chatuge that indicate comparably LREE depleted mantle source regions (Shaw and Wasserburg, 1984)

The Carroll Knob Complex, which lies ENE of Buck Creek (Figure 1 inset), includes abundant amphibolites enclosing small lenses of dunite and rare meta-troctolites (Hatcher and others, 1984). Carroll Knob amphibolite and meta-troctolite samples both show LREE depleted patterns, but at lower abundance levels than at Buck Creek. While the LREE-depleted nature of the Carroll Knob rocks point to a chemically similar mantle source, the petrogenesis of this unit as compared to Buck Creek is unclear. Hatcher and others (1984) suggest that the Carroll Knob protoliths may have formed in an oceanic or arc setting.

Pyroxenites from the Webster-Addie and the Moore's Knob dunite, which lie well east of Buck Creek (Figure 1 inset; Condie and Madison, 1969; Yurkovich and Eckert, 1992) show overall low REE abundances and slightly "U" shaped rare earth patterns. These types of patterns are more typical of residual, mantle-derived ultramafic rocks (McDonough and Frey, 1989), and thus reflect a very different history than the rocks at Buck Creek. Whether these different patterns point to a different mantle source is unclear, as metasomatic enhancement of the LREE is possible. However, Nd isotopic data that exists for Webster-Addie are consistent with a modestly LREE enriched source region (i.e., εNd=-1; Shaw and Wasserburg, 1984).

CONCLUSIONS

The REE systematics of rocks from the Buck Creek mafic/ultramafic complex largely preserve igneous protolith signatures. The REE patterns of "high-Ti" BC amphibolites are similar to mid-ocean basalts, while those of "low-Ti" amphibolites are consistent with mafic cumulate rocks. The REE systematics of BC amphibolites indicate the complex was once part of an oceanic crustal section. BC amphbolites show similar REE signatures to Group I and Group II amphibolites in the Ashe Metamorphic Suite, and to mafic rocks from the Lake Chatuge complex. Other mafic and ultramafic rocks that have been examined in the Blue Ridge, as compared to BC, may reflect different evolutionary histories, or different mantle sources.

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MINERALOGY AND GEOCHEMISTRY OF METAMORPHOSED ULTRAMAFIC ROCKS IN THE CENTRAL PIEDMONT PROVINCE OF VIRGINIA

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ABSTRACT

We report new field and petrographic observations, and whole-rock major and trace element compositions for small metamorphosed ultramafic rock bodies that occur across a narrow region of the central Piedmont Province of Virginia. A variety of rock types is present, including chlorite-amphibole schist (the most dominant type), carbonate-chlorite-talc schist, chlorite-talc schist, talc schist, chlorite schist, and muscovite-chlorite rock (altered country rock). Some chlorite-amphibole rocks contain hornblende, in addition to retrograde actinolite and chlorite. All ultramafic rocks have relatively high Mg# (73.1-91.7), but display a wide range (on an anhydrous basis) in SiO_2 (31 to 63 wt.%), Al_2O_3 (1-22 wt.%), and CaO (0.1-9.5 wt.%). Most rocks contain relatively high concentrations of Ni (up to 1986 ppm) and Cr (up to 3000 ppm). On primitive mantle-normalized transition element plots, all chlorite-amphibole schists show similar flat patterns with troughs at Cr and Ni, whereas patterns for the other rock types are variable. Chlorite-amphibole schists and a carbonate-chlorite-talc schist display a wide range of rare-earth element (REE) concentrations, and chondrite-normalized pattern shapes that range from light REE-enriched to flat to slightly light-REE depleted. Most have a negative Eu-anomaly, and two samples show prominent negative Ce-anomalies. Some rock types clearly represent fragments of metasomatic alteration zones between ultramafic rock and country rock. The origin of the chlorite-amphibole schists is less certain. They may represent metamorphosed amphibole-bearing peridotites, or they originated via extensive metasomatic exchange with country rock. The proximity of all occurrences to a melange zone is consistent with tectonic rather than intrusive emplacement.

INTRODUCTION

Small bodies of ultramafic rock are widespread throughout the Piedmont Province of the central and southern Appalachians (Misra and Keller, 1978). The paucity of information on these rocks noted by Misra and Keller in 1978 prompted a symposium in 1987 devoted to ultramafic occurrences in the Appalachian Piedmont, which resulted in a Geological Society of America Special Paper (Mittwede and Stoddard, 1989). Notably absent from that volume were any studies of ultramafic rocks from the Piedmont of Virginia, and no such studies have been published in the intervening years. Drake and Morgan (1981) and Pavlides (1989) reported observations and data on a few occurrences in the contexts of their studies on the Piney Branch ophiolite complex and melange in northern Virginia, respectively, but the focus of these investigations was primarily tectonic rather than petrologic. Thus, most ultramafic bodies in the Piedmont of Virginia have not been studied beyond the mapping stage, and the pre-

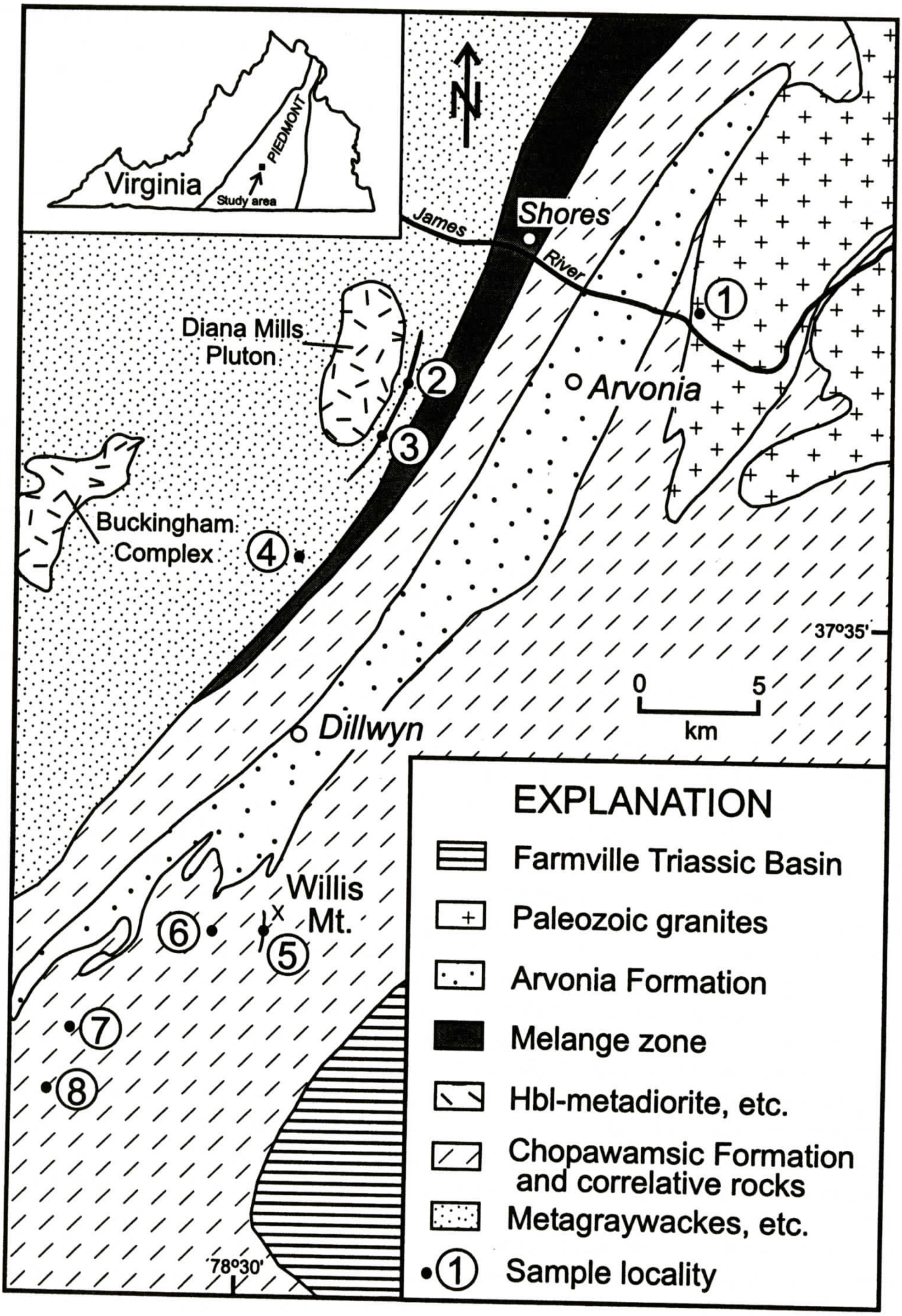

Figure 1. Geologic sketch map of the study area, simplified from the geologic map of Virginia (Virginia Division of Mineral Resources, 1993), with additions based on the maps of Brown (1969) and Marr (1980a,b). The latter maps should be consulted for more detailed illustrations of the ultramafic rock locations. Localities 2, 3, and 5 occur within elongate, thin lenses, represented by black on the map. The other localities are smaller than the black location dots.

cise nature of these rocks and their petrogenesis are not well understood.

The present investigation represents an initial attempt to characterize some of the occurrences in Virginia by focusing on several small metamorphosed bodies located in the central Piedmont Zone (Hibbard and Samson, 1995), primarily in Buckingham County, VA (Figure 1). This area was chosen because it has been mapped in detail (Brown, 1969; Marr, 1980a,b), and numerous rocks of apparent ultramafic character (e.g., "talc-tremolite schist") appear on existing maps. The purposes of this paper are to: 1) report on the field setting, mineralogy, and whole-rock compositions of these rocks; 2) highlight some of the interpretive challenges presented by these occurrences; and 3) speculate on their regional significance. This project was designed as a reconnaissance study, but it provides a frame of reference for future, more comprehensive investigations.

GEOLOGIC SETTING

All of the ultramafic rocks of this study occur in proximity to a melange zone that was initially recognized by Brown (1976, 1986; Brown and Pavlides, 1981). In the immediate area, it has been informally referred to as the Shores melange, for exposures near Shores Station on the James River (Figure 1). This melange is now considered part of the Mine Run complex of Pavlides (1989), which consists of several melange zones that are more extensive further to the north in Virginia. It is formally referred to as melange zone III on the current geologic map of Virginia (Virginia Division of Mineral Resources, 1993). This melange consists of numerous exotic blocks of amphibolite, greenstone, and ultramafic rock in a complexly deformed matrix of magnetite-rich metagraywacke (Brown, 1986). Such melanges are thought to have formed in a back-arc basin that separated a volcanic arc to the east (i.e., the Chopawamsic Formation) from the continent to the west (Bland and Brown, 1977; Brown, 1986; Pavlides, 1989). As such, this melange, along with associated ultramafic rocks, marks a significant tectonic boundary within the Piedmont Zone.

West of the melange zone are the oldest rocks (of uncertain, but probable late Precambrian to Cambrian age) in the study area. The dominant rock type is chlorite-quartz-muscovite schist, inferred to represent metamorphosed graywacke (Brown, 1969). Also included in this unit are a variety of metamorphosed volcanic rocks, including greenstones and metadacitic rocks. These rocks were previously considered part of the Candler Formation (Ern, 1968; Marr, 1980b), but this formation is now confined to rocks west of the Mountain Run fault in the Blue Ridge Province (Virginia Division of Mineral Resources, 1993). Evans (1984) referred to these rocks in the study area as the Hardware metagraywacke, but the unit currently has no formal stratigraphic name. These rocks form a part of the Potomac Terrane, as defined by Drake (1985), which has been designated a "disrupted" terrane by Horton and others (1989).

Several plutonic bodies of mafic to ultramafic composition occur within the metagraywacke unit west of the Shores melange, including the Diana Mills pluton and the Buckingham Complex (Figure 1). These bodies contain a variety of rocks including hornblende metadiorite, hornblendite, amphibolite, metaperidotite, and serpentinite (Ern, 1968; Henika, 1969; Brown, 1969). Brown (1969) originally interpreted the Diana Mills pluton to be intrusive into surrounding metagraywacke, but Brown and Pavlides (1981) reinterpreted the body as a tectonically emplaced exotic block.

Mafic and felsic metavolcanic rocks of the Chopawamsic Formation occur east of the melange zone. The Chopawamsic Formation forms a major part of the central Virginia volcanic-plutonic belt of Pavlides (1981), who interpreted it as an island arc. Although the Chopawamsic has been considered late Precambrian to Cambrian in age by previous investigators, Coler and others (2000) recently determined U-Pb zircon ages of ~470 Ma on felsic volcanic rocks near the study area. These ages indicate that the Chopawamsic, at least in this area, is middle Ordovician.

Younger rocks in the study area include the metasediments (slate, schist, and quartzite) of the Upper Ordovician Arvonia Formation (Figure 1), which lie unconformably above the Chopawamsic, and two Paleozoic granitic plutons to the northeast. Mesozoic sedimentary rocks occur in the Farmville basin to the southeast, and numerous diabase dikes of Triassic to Jurassic age cross the area (not shown on Figure 1).

ANALYTICAL METHODS

All samples were analyzed for major element oxides and trace elements by X-ray fluorescence (XRF) analysis at Washington University in St. Louis, using methods described by Couture and others (1993) and Couture and Dymek (1996). A subset of samples (primarily chlorite-amphibole schists) was also analyzed for the rare-earth and other selected trace elements by instrumental neutron activation (INA) analysis at Washington University, using procedures described by Korotev (1987a,b). Several elements were determined by both methods on this sample subset, and the agreement between the two methods is generally excellent. All XRF determinations are reported, but only those elements determined solely by INA are reported for the analyzed subset. One exception is Cr, for which the INA values may be more accurate. Mineral compositions were determined with a JEOL-733 electron microprobe, equipped with Advanced MicroBeam Inc. automation, at Washington University. X-ray matrix corrections were based on a modified Armstrong (1988) CITZAF routine.

DESCRIPTION OF LOCALITIES

The ultramafic rocks of this study (Figure 1) occur within metagraywacke (localities 2, 3, and 4), or mafic rocks (now amphibole or biotite gneisses) of the Chopawamsic Formation (localities 1, 5, 6, 7, and 8). All of the localities appear either on the geologic maps of Brown (1969) or Marr (1980a,b), except for locality 7, which was discovered during this study. Brief descriptions of these localities are provided here, along with a listing of the individual samples from each locality. The most typical rock type is a medium-grained, dark green schist. Most occurrences are small (a few meters across) and consist of discontinuous outcrops or scattered loose boulders. Contacts with enclosing rocks typically are not visible, and the nature of the exposure makes it difficult to evaluate spatial relations among rock types within a given locality. Fortunately, the ultramafic rocks are somewhat more resistant to weathering than the surrounding rocks, and it was possible in most cases to extract relatively fresh rock for further investigation. Listed here are only those samples for which modal or geochemical data appear in this paper, but additional samples from some localities were examined petrographically. Locality 1 (samples 003, 004, 039), southeast of the village of Bremo Bluff, is a small, long-abandoned soapstone quarry (Brown, 1969), now completely overgrown. Several rock types are present here, but only loose blocks could be sampled. Amphibolite and felsic metavolcanic(?) schist also occur near this quarry, but the locality is surrounded by granite (Figure 1). Thus, locality 1 may represent a local screen of older country rock (David Spears, Virginia Division of Mineral Resources, personal communication). Locality 2 (samples 013, 029) is a rusty-weathering roadcut in what was mapped by Brown (1969) as an extensive lens of ultramafic rock east of the Diana Mills pluton (Figure 1). Locality 3 (sample 035), further south within this same lens, consists of several small (~1 m across) outcrops or loose blocks. Locality 4 (sample 009) is a low roadcut primarily in greenish brown metasedimentary schist. The ultramafic rock is a lens of pale gray talc schist less than a meter wide. Locality 5 (samples 021, 023), southwest of the Willis Mountain kyanite quartzite mine (Figure 1), is within one of the better-exposed lenses of ultramafic rock in the area. Outcrops and boulders are semi-continuous along the west side of Route 15 here for about 2 km, and the maximum width of the lens as mapped by Marr (1980a) is about 50 m. Localities 6 (BC-18), 7 (BC-13), and 8 (BC-19) are all similar, and consist of low outcrops or loose boulders exposed along roads or shallow slopes. Outcrops of amphibole gneiss of the

Table 1. Modal mineralogy of ultramafic and related rocks.

Sample	**BC-13**	**BC-18**	**BC-19**	**003**	**021**	**023**	**035**	**039**	**009**	**004**	**013**
Locality	**7**	**6**	**8**	**1**	**5**	**5**	**3**	**1**	**4**	**1**	**2**
Rock type*	**CAS**	**CAS**	**CAS**	**CAS**	**CAS**	**CAS**	**CAS**	**CCTS**	**TS**	**CS**	**CS**
Ca-amphibole	63.8	86.8	69.5	79.0	48.5	61.0	81.8	tr	--	--	--
chlorite	34.8	12.9	27.5	13.0	51.2	38.2	18.2	20.3	--	98.0	96.6
talc	--	--	--	7.0	--	0.7	--	63.0	93.4	1.5	--
serpentine	--	--	--	--	--	--	--	--	6.1	--	--
sphene	--	--	--	--	--	--	tr	--	--	--	2.6
carbonate	--	--	1.3	--	--	--	--	14.1	--	--	--
rutile	--	0.3	--	--	--	--	tr	--	--	--	0.8
magnetite	1.4	--	1.6	1.0	0.3	--	--	2.6	0.4	0.5	--
ilmenite	tr	--	--	--	--	0.1	--	--	--	--	--
pyrite	--	--	--	--	--	--	tr	tr	--	--	--
zircon	--	--	--	--	--	--	--	--	--	--	tr
apatite	--	tr	tr	--	--	--	--	--	--	--	--
plagioclase	--	tr	--	--	--	--	--	--	--	--	--

*Abbreviations in this and other tables: CAS=chlorite-amphibole schist; CCTS=carbonate-chlorite-talc schist; TS=talc schist; CS=chlorite schist

tr = observed but not counted

Chopawamsic Formation typically occur in close proximity (within a few tens of meters) to these latter occurrences.

PETROGRAPHY AND MINERAL COMPOSITIONS

In this study we have recognized a variety of rock types, and named them on the basis of their dominant minerals. These include chlorite-amphibole schist, carbonate-chlorite-talc schist, talc schist, chlorite schist, and muscovite-chlorite rock. Proportions of these minerals in the various samples are listed in Table 1. Modes, determined by point counting a single thin section from each sample, are based on approximately 1000 points each. Mineral compositions have not been investigated comprehensively, but several amphibole grains in each sample were analyzed in addition to a few grains of chlorite. These compositions are noted in the following petrographic descriptions, but not tabulated in this paper. The identity of some phases was also clarified with an energy dispersive spectrometer (EDS) on the microprobe.

Chlorite-amphibole schist

This rock type is the most common in the study area. These rocks are dominated by Ca-amphibole and chlorite, with amphibole being more abundant in most cases (Table 1). Amphibole grains range in shape from blocky to bladed to needle-like, and in size from less than 1 mm up to ~ 4mm long. In many cases, grains have highly ragged edges because of moderate to severe replacement by chlorite. Most grains are colorless or pleochroic in shades of pale green. Many individual grains show distinct compositional domains, which appear as patchy zones of different color (colorless vs. green) or as distinct green cores and colorless rims. Typically, the green zones also contain abundant, small grains of exsolved Fe-Ti oxide. The colorless to very pale green areas are actinolitic in composition, whereas the more highly colored zones vary from tschermakitic hornblende to magnesio-hornblende to magnesio-hastingsitic hornblende (nomenclature of Leake, 1978). Sample BC-18 is unique in being dominated by tschermakitic hornblende, typically with ~15 wt.% Al_2O_3, and this sample might be more properly classified as a hornblendite. Values of X_{Mg} in all samples range from 0.70 to 0.90, with hornblende consistently displaying more Fe-rich compositions than actinolite. Most grains contain negligible to low amounts of TiO_2 and Cr_2O_3 (<0.2 wt.% of each), but those in sample

BC-18 contain up to 0.50 wt.% TiO_2. Fluorine and chlorine were not detected in most cases.

Chlorite occurs as colorless to pale green masses, with grain lengths ranging up to about 2 mm. Chlorite has extensively replaced many amphibole grains along grain margins and cleavage planes, and in some cases all that remains are isolated "islands" of optically continuous amphibole in a matrix of chlorite. Values of X_{Mg} range in all samples (including the other rock types) from 0.78 to 0.84, and Al_2O_3 from 18.4 to 22.6 wt.%. Most grains contain small amounts of Cr_2O_3 (up to 1 wt.% in 003) and NiO (typically <0.2 wt.%).

Subhedral to euhedral grains of magnetite up to ~1 mm across occur in minor amounts in several samples. Much of this is Cr-magnetite, based on EDS spectra. Other minor to trace phases that occur in one or more samples include talc, carbonate (dolomite based on EDS spectra), ilmenite, pyrite, rutile, titanite, and apatite. One small grain of plagioclase was found in sample BC-18.

Carbonate-chlorite-talc schist

Found only at locality 1, this rock is dominated by somewhat randomly oriented talc flakes that are typically <0.5 mm long. Chlorite and carbonate (dolomite based on EDS spectra) are intergrown with talc, although some carbonate grains (0.1-0.5 mm across) locally occur in elongate polycrystalline clusters. Magnetite is dispersed throughout the section as sub- to euhedral grains from 0.1-0.25 mm across. A few small (<0.25 mm across) grains of Ca-amphibole are present. A similar rock type that lacks carbonate (chlorite-talc schist) was found at two localities (1 and 3), but not investigated further.

Talc schist

This rock occurs only at locality 4. It consists primarily of abundant fine- to medium-grained talc flakes typically 0.1-0.5 mm long, which show some preferred orientation. Patches of somewhat fibrous serpentine occur throughout the thin section, and this is the only rock investigated that contains serpentine. Anhedral to subhedral grains of magnetite are typically <0.25 mm across.

Chlorite schist

Nearly pure chlorite schist was found at two localities. Sample 004 contains distinctly aligned chlorite laths $\leq$0.5 mm long, a minor amount of talc, and several larger grains of euhedral magnetite up to 2 mm across. Sample 013 is similar, but zones with aligned chlorite grains are interspersed with zones of more randomly oriented grains. In contrast to sample 004, 013 contains additional anhedral grains of titanite and rutile (<0.25 mm across), reflecting a more Ti-rich bulk composition (see below). It also contains trace amounts of zircon. Chlorite in both of these samples is pleochroic from nearly colorless to pale green.

Muscovite-chlorite rock

This dark green, fine-grained rock occurs only at locality 3, and despite the abundance of sheet silicates, it is not prominently schistose. Randomly oriented chlorite and muscovite are the only abundant minerals, with chlorite predominating. Minor magnetite and ilmenite are present, along with trace amounts of quartz and zircon. Brown (1969) suggested that this rock may represent highly metasomatized country rock associated with the large ultramafic lens in this area. The bulk composition of this rock, described below, is consistent with this interpretation.

CHEMICAL COMPOSITIONS

Major and trace element compositions of all samples (determined by XRF) are listed in Table 2, and trace elements in the subset of samples analyzed by INA are listed in Table 3. The abundance of H_2O- or CO_2-bearing minerals in all samples is reflected in moderate to high loss on ignition (LOI) values, ranging from 2.2 up to an extreme of 12 wt.% in the carbonate-chlorite-talc schist. These values are plotted vs. measured wt.% SiO_2 in Figure 2a. Given these high LOI values, samples can be compared in a

Table 2. Whole-rock major and trace element compositions of ultramafic and related rocks determined by X-ray fluorescence (major elements in weight percent, trace elements in parts per million).

Sample	BC-13	BC-18	BC-19	003	021	023	035	039	004	013	009	029
Locality	7	6	8	1	5	5	3	1	1	2	4	2
Rock type	CAS	CAS	CAS	CAS	CAS	CAS	CAS	CCTS	CS	CS	TS	MC§
SiO_2	42.86	43.83	43.96	50.19	41.37	44.60	45.92	39.69	27.23	27.44	60.54	33.89
TiO_2	0.30	0.67	0.26	0.11	0.25	0.37	0.44	0.12	0.37	2.52	0.00	2.57
Al_2O_3	9.22	13.85	7.55	5.45	10.95	9.34	8.76	4.07	19.93	19.48	0.82	23.37
Fe_2O_3(T)	12.36	11.99	10.66	10.23	11.78	12.35	10.41	13.56	15.88	14.81	5.19	21.62
MnO	0.23	0.21	0.15	0.23	0.17	0.28	0.19	0.17	0.11	0.20	0.06	0.26
MgO	22.05	16.58	22.99	21.36	22.71	22.85	19.85	23.96	25.25	24.09	28.78	7.01
CaO	6.88	8.04	7.99	8.02	5.75	4.72	9.02	5.77	0.05	0.73	0.01	0.01
Na_2O	0.19	1.20	0.19	0.50	0.39	0.38	0.60	0.02	0.21	0.00	0.09	0.34
K_2O	0.03	0.09	0.04	0.03	0.03	0.03	0.22	0.00	0.01	0.00	0.00	3.72
P_2O_5	0.08	0.06	0.01	0.01	0.01	0.02	0.08	0.00	0.02	0.06	0.03	0.00
LOI	5.17	2.20	4.50	2.56	5.51	4.38	3.05	12.00	10.60	10.45	3.60	6.69
Total	99.37	98.72	98.30	98.69	98.92	99.32	98.54	99.36	99.66	99.78	99.12	99.48
Mg#*	78.0	73.2	81.1	80.6	79.3	78.6	79.1	77.8	76.0	76.4	91.7	39.2
Sn	<6.0	<4.0	<7.0	<11.4	<12	<11.4	<4.0	<3.8	<3.8	<12	<3.5	<6.9
Nb	2.1	<2.8	<2.7	<4.2	<2.0	<2.3	<4.2	<1.4	<1.5	14.8	<1.2	13.7
Zr	51.9	34.4	9.5	<4.8	12.9	17.8	61.9	<4.8	6.4	130	<1.2	289
Y	8.2	15.1	9.8	7.5	6.5	24.5	24.1	<2.6	<2.2	109	<1.6	18.7
Sr	10.8	65.5	19.1	<4.8	5.2	5.4	67.9	25.0	<1.6	<1.6	<1.2	51.9
Rb	<1.8	<1.8	<2.7	<1.8	<1.8	<1.8	<5.4	<2.3	<1.8	<1.8	<1.5	95.7
Pb	<5.2	<5.4	<8.4	<5.2	<5.4	<5.4	<5.9	<6.3	<7.1	<5.7	<4.9	<19.8
Ga	7.1	11.4	7.3	<5.4	8.6	8.8	9.7	<5.4	13.8	26.2	<3.6	46.1
Zn	192	124	66.9	66.9	70.7	99.8	148	63.7	133	179	157	368
Ni	440	496	984	620	900	949	609	778	285	622	1986	200
V	89.1	154	141	116	102	122	149	112	157	353	17.4	314
Cr	1039	649	3001	2898	2122	2391	1915	2678	2667	389	1970	247
Ba	<18.2	<14.2	243	18.9	<12.6	166	19.9	14.6	<10.4	<13.2	<21.3	1603
Co	92.6	78.9	98.6	87.6	102	108	70.8	107	108	119	73.5	45.3
Mo	n.d.	n.d.	n.d.	<2.9	<3.2	<1.6	<2.1	<2.1	<2.3	<1.6	<1.9	<2.0
As	n.d.	n.d.	n.d.	<7.0	<8.6	<6.2	<7.3	<6.9	<7.5	<6.2	<7.6	<7.8

§ MC = muscovite-chlorite rock

* Mg# = atomic 100 x Mg/(Mg+Fe)

n.d. = not determined

more straightforward way on the basis of recalculated anhydrous compositions. In addition, the anhydrous compositions are undoubtedly more similar to those of the igneous protoliths. Apart from 2a, all variation diagrams in Figure 2 were constructed using these anhydrous compositions. Comparison of Figures 2a and 2b (for example) provides an indication of the magnitude of the increase in SiO_2 (which shows the most change) resulting from recalculation. Plotting recalculated anhydrous compositions does not result in any significant change in the relative distribution of data points. The following descriptions are based on the recalculated results. The muscovite-chlorite rock is distinct from the other samples, and its major element characteristics are summarized separately below.

Values of SiO_2 show a wide range from 30.6 to 63.4 wt.%. All rocks contain ≥21 wt.% MgO, with the exception of sample BC-18, which contains 17.2 wt.% (Figure 2b). Levels of

Table 3. Trace elements in selected samples of chlorite-amphibole schist and a carbonate-chlorite-talc schist determined by INA analysis (all in parts per million).

Sample	BC-13	003	021	023	035	039
Locality	7	1	5	5	3	1
Rock type	CAS	CAS	CAS	CAS	CAS	CCTS
Sc	28.5	30.4	16.33	19	36.2	21.3
Cr	945	2740	1845	2210	1735	2630
Br	<0.7	<0.19	<0.3	<0.5	<0.9	<0.22
Sb	<0.05	0.025	<0.04	<0.09	0.07	<0.05
Cs	<0.11	<0.09	<0.15	<0.20	<0.3	<0.12
La	10.89	0.538	0.939	19.32	31.5	0.656
Ce	17.8	0.9	1.7	6.8	21.1	1.4
Nd	8.8	<3	<8	16.4	28	<6
Sm	2.08	0.553	0.636	3.8	5.35	0.093
Eu	0.358	0.122	0.222	1.12	1.25	0.01
Tb	0.297	0.155	0.159	0.797	0.8	0.024
Yb	0.67	0.746	0.651	2.53	1.71	0.095
Lu	0.104	0.111	0.101	0.357	0.256	0.016
Hf	1.59	0.064	0.4	0.59	1.82	0.08
Ta	0.168	<0.04	<0.07	<0.1	0.18	<0.08
W	<3	<0.5	<1.4	<1.9	1.3	<0.6
Au	<5	<1.2	<1.8	<4	<4	23.5
Th	2.010	0.095	0.137	0.180	2.610	0.060
U	0.48	<0.12	<0.16	<0.18	0.41	<0.11

Fe_2O_3(T) span a wide range from 5.4 to 17.8 wt.% (Figure 2c), but all rocks have relatively high Mg# (73.2 to 91.7; Table 2). The chlorite schists are characterized by low SiO_2 and high Al_2O_3 (Figure 2d), with compositions similar to pure chlorite. The talc schist has a composition resembling that of pure talc. All chlorite-amphibole schists and the carbonate-chlorite-talc schist are compositionally similar, clustering together on most diagrams. They are distinct from all other rocks in their higher amounts of CaO (5.0-9.5 wt.%; Figure 2e), but they also contain significant Al_2O_3 (4.7 to 14.4 wt.%; Figure 2d). However, CaO and Al_2O_3 are highly variable in this group of samples, and the two oxides are not correlated. Levels of TiO_2 are low (<0.7 wt.%) in all rocks except chlorite schist sample 013, which contains 2.8 wt.% (Figure 2f). Values of Na_2O are typically low (<0.6 wt.%), but sample BC-18 is an exception with 1.2 wt.%. All samples contain very low K_2O(<0.2wt.%).

The muscovite-chlorite rock differs from all others in containing much lower MgO, but higher Fe_2O_3(T), Al_2O_3, and much higher K_2O (4.0 wt.%). However, its TiO_2-content is similar to that of chlorite schist sample 013, which comes from the same locality (2).

Most samples contain low to very low amounts of all large ion lithophile trace elements (Rb, Ba, Sr). Chlorite-amphibole schist samples BC-19 and 023 contain significantly higher Ba (243 and 166 ppm, respectively) than the other samples, which may be present in the amphibole. Concentrations of Sn, Nb, Pb, Mo, and As are below detection limits in most cases. Levels of Ga are low, but correlate well with Al_2O_3. Chlorite schist sample 013 and the muscovite-chlorite rock (029) show some exceptions to these generalizations. Both contain higher Nb and Ga, and 013 is highly enriched in Y (109 ppm), which probably is present in titanite. In addition, sample 029 contains high Rb (96 ppm), and very high Ba (1603 ppm), consistent with its high K_2O.

Concentrations of most ferromagnesian trace elements and Zr do not show a strong correlation with MgO (not plotted), which either re-

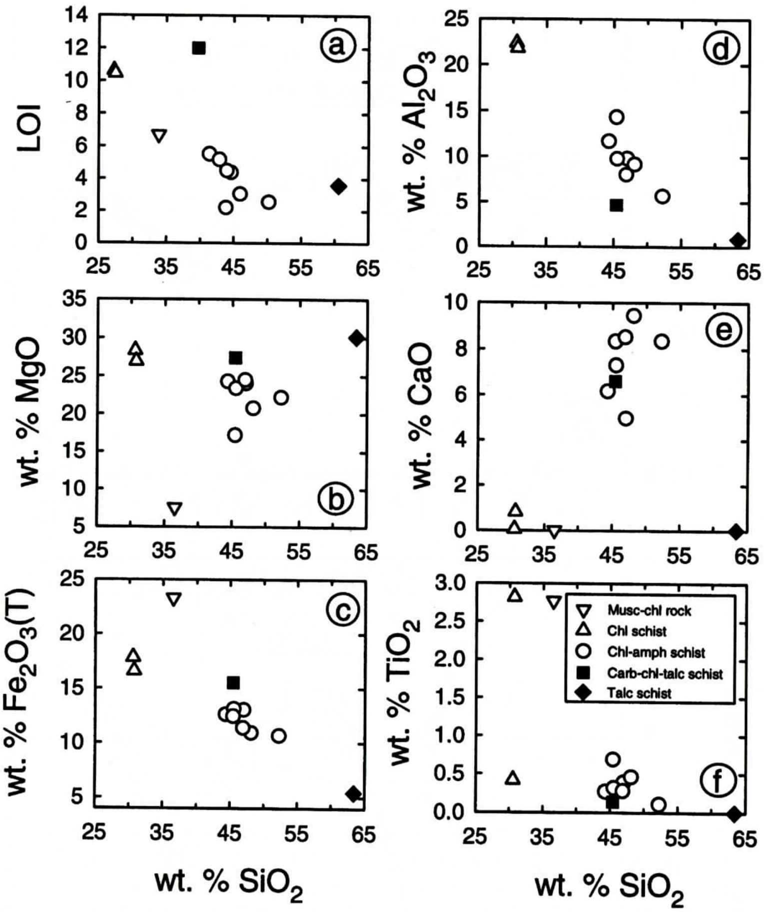

Figure 2. Selected major element compositions of the rocks of this study illustrated on silica variation diagrams. Compositions are plotted as determined on (a) SiO_2 vs. LOI. On all other diagrams, recalculated anhydrous compositions are plotted.

flects their dominance in low-MgO phases (e.g., zircon, magnetite) or their distribution in multiple MgO-bearing phases in different proportions. The muscovite-chlorite rock is distinct from all other samples in being enriched in Zr, Zn, and V, but depleted in Ni, Cr, and Co. The chlorite schist from this same locality (2) shows some similar enrichments (Zr, V) and depletions (Cr). The higher V in these two rocks is consistent with their much higher TiO_2 (Table 2).

The chlorite-amphibole schists and carbonate-chlorite-talc schist contain similar amounts of Zn, V, Ni (440-980 ppm), and Co. Most contain high Cr (1039-3001 ppm by XRF), apart from BC-18 which contains 649 ppm. Chlorite schist sample 004 (locality 2) also contains similar levels of these elements, although Ni is low at only 249 ppm. The talc schist contains more than twice as much Ni (1986 ppm) as chlorite-amphibole schists, but contains similar amounts of Cr. Otherwise, concentrations of Cr and Ni are positively correlated, albeit with considerable scatter (not plotted). The subset of samples analyzed by INA shows levels of Sc that vary by a factor of two, from 16 to 36 ppm.

Concentrations of all transition elements are illustrated on primitive mantle-normalized plots on Figure 3, where samples are grouped by rock type. The overall similarity of the chlorite-amphibole schists and the carbonate-chlorite-talc schist is clear from Figure 3a. These samples

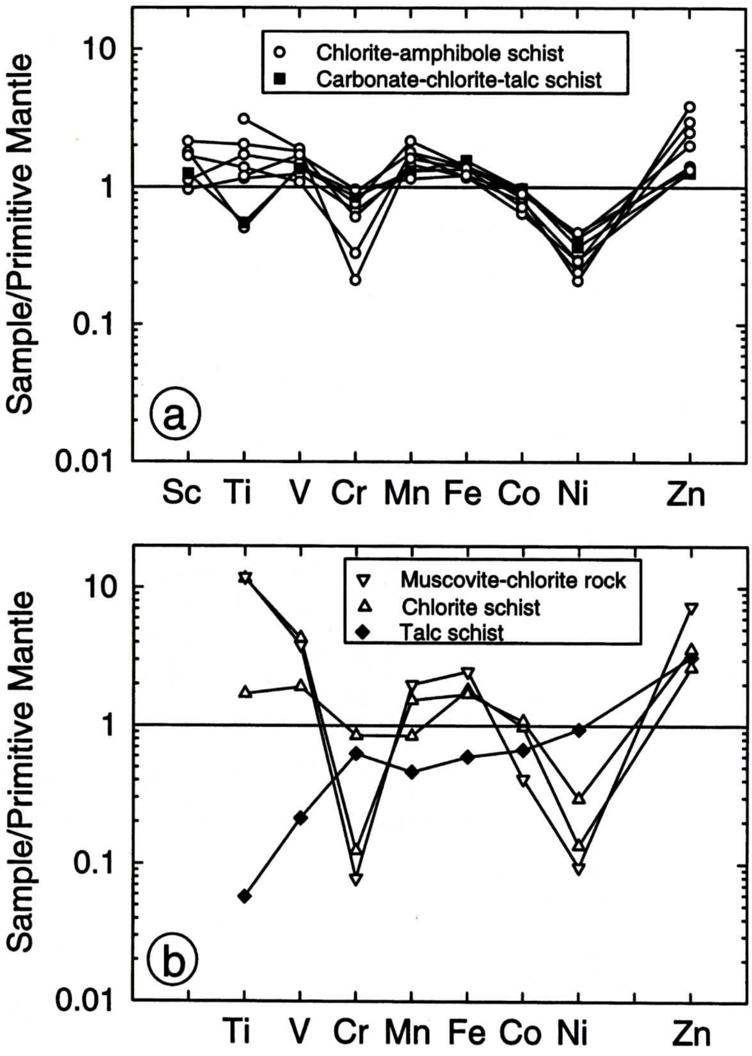

Figure 3. Abundances of transition elements in chlorite-amphibole schists and carbonate-chlorite-talc schist (a) and other rocks (b), normalized to primitive mantle values of Jagoutz and others (1979), with Sc value from Sun (1982).

show relatively flat patterns with moderate to deep troughs at Cr and Ni, and elevated Zn in some cases. Titanium shows slight enrichment in some samples, and slight depletion in others. The other samples show variable patterns, as illustrated on Figure 3b. The talc schist pattern is distinct from all others in having an overall positive slope, and levels of all elements are slightly to considerably below primitive mantle values, apart from Ni and Zn. Chlorite schist sample 004 has a pattern that is similar to some of the chlorite-amphibole schists, but with a more pronounced trough at Ni. The muscovite-chlorite rock (013) and chlorite schist (029) from locality 2 show nearly identical patterns for most elements.

Rare earth element (REE) concentrations in five chlorite-amphibole schists and the carbonate-chlorite-talc schist show a wide range, and display a diversity of chondrite-normalized patterns (Figure 4), despite their similar major and transition element compositions. Two samples (035, 023) are enriched in all REE relative to the others, and display light-REE enriched patterns

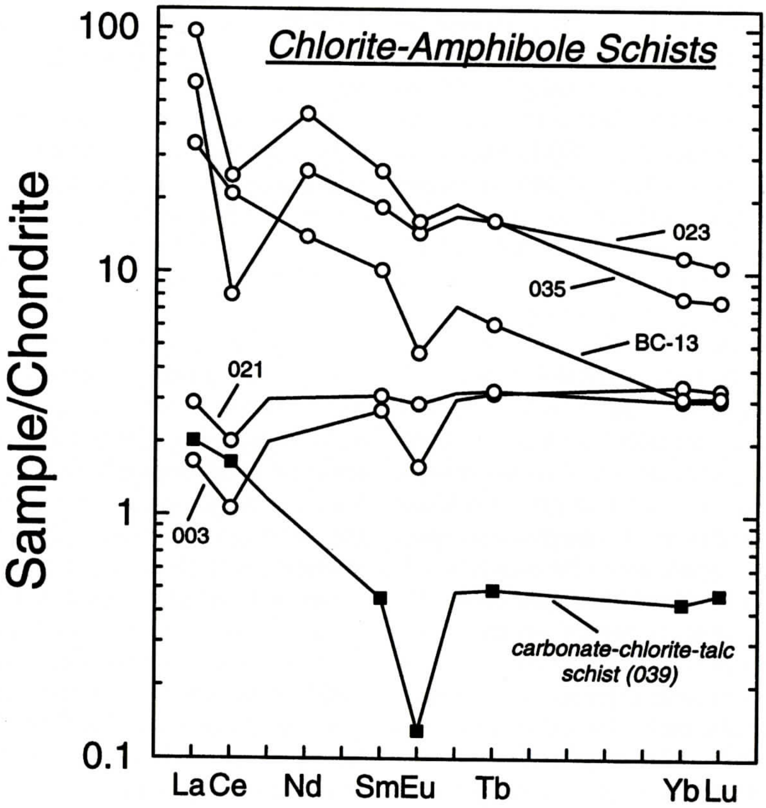

Figure 4. Chondrite-normalized rare-earth element abundances in selected chlorite-amphibole schists and carbonate-chlorite-talc schist. Normalizing values are those of Anders and Ebihara (1982) multiplied by 1.38, which represents a least-squares best fit to the earlier chondrite composite of Haskin and others (1968) (R. Korotev, personal communication). Nd values for 021, 003, and 039 are not plotted because of poor accuracy, and the patterns were constructed by interpolating a value for Pr between La and Sm.

with prominent negative Ce-anomalies. Sample BC-13 shows a similar fractionated pattern, but lacks a Ce-anomaly. Samples 021 and 003 have lower concentrations of all REE, and show relatively flat (021) to slightly light-REE depleted (003) patterns. The carbonate-chlorite-talc schist contains significantly lower amounts of the middle- and heavy-REE. All samples display negative Eu-anomalies that range from slight to pronounced. All samples analyzed by INA show a good positive correlation between Yb and Y. Thus, the Y values determined by XRF for the remainder of the samples should provide a reasonable indication of their levels of heavy-REE.

DISCUSSION

Conditions of Metamorphism

Brown (1969) and Marr (1980a,b) noted an increase in metamorphic grade across this area approximately from northwest to southeast. To the northwest, graywackes preserve greenschist assemblages dominated by quartz, muscovite, and chlorite. Interlayered greenstones contain chlorite, epidote, and actinolite. To the southeast, schists of the Arvonia Formation first display biotite porphyroblasts, followed by biotite + garnet. Brown (1969) reported sparse staurolite just east of a garnet isograd that he drew across the Dillwyn 15' quadrangle (extending approximately from locality 1 through Dillwyn and beyond on Figure 1). Kyanite is abundant in the kyanite-quartzites of this area, and kyanite ± fibrolitic sillimanite occurs locally within aluminous portions of the Chopawamsic Formation ~3 km southeast of Willis Mountain (Cochrane, 1986). Cochrane (1986) determined peak metamorphic conditions in the vicinity of Willis Mountain to be ~600°C and ~6.5 kb. Thus, several lines of evidence indicate that metamorphic grade ranges from greenschist to amphibolite facies across the study area.

The ultramafic localities crudely straddle this greenschist to amphibolite transition. Specifically, localities 2 through 4 are associated with lower grade (greenschist) host rocks, whereas localities 1 and 5 through 8 are primarily within amphibolite. However, the progressive change in metamorphic grade across the area is not obviously reflected in the ultramafic rocks. The preserved assemblages, particularly those dominated by Ca-amphibole and chlorite, are unlike those in more typical examples of metamorphosed ultramafic rocks. Thus, direct comparisons with other studies (e.g., Evans, 1977) on rocks containing serpentine, tremolite, forsterite, enstatite, talc, etc. are not possible. Tremolite-actinolite and chlorite are stable minerals in ultramafic rocks to upper amphibolite to granulite facies conditions, depending on X_{Mg} (Bucher and Frey, 1994), and thus provide no clear insight to peak metamorphic conditions.

The assemblage talc + antigorite (assuming antigorite is the serpentine mineral) in the talc schist is stable over a wide range of temperatures and pressures, but at least provides an upper temperature limit of ~570°C (Bucher and Frey, 1994).

The presence of hornblende in most chlorite-amphibole schists may reflect an earlier episode of metamorphism under amphibolite facies conditions. In those samples that contain two Ca-amphiboles, it is clear that actinolite formed as a reaction product from hornblende. If the hornblende originated during an amphibolite facies event, its presence in rocks within the greenschist facies metagraywackes (e.g., locality 3) suggests that some of the ultramafic rock bodies are not isofacial with their local host rocks. Nonetheless, the textures exhibited by actinolite and chlorite in the ultramafic rocks are consistent with greenschist facies overprinting.

An alternative interpretation for the presence of hornblende in these rocks is that it reflects an original hornblende-bearing protolith. Some discussion of this idea is presented below.

Origin of Various Rock Types

The diversity of rock types in the study area implies that a variety of protoliths and processes were involved in their origin. No unaltered ultramafic rocks (e.g., peridotite) are present, and none are mineralogically simple serpentinites. Furthermore, the transition element plots (Figure 3) indicate that none of them represent unmodified primitive mantle material. Their current mineralogical and compositional characteristics may reflect the combined effects of igneous crystal fractionation or accumulation, multiple metamorphic events, and significant metasomatic alteration. Interpretation of the origin of some rock types is relatively straightforward, but others present a considerable challenge.

Several rock types appear to represent fragments of metasomatic alteration zones associated with the metamorphism of serpentinites. Such zones are common at the contact between serpentinite or soapstone bodies and adjacent country rock, and have been described from many localities, including elsewhere in the Appalachians (e.g., Phillips and Hess, 1936; Chidester, 1962; Jahns, 1967; Sanford, 1982). Sanford (1982) provided a generalized description of these zones, which are typically characterized by the following sequence: ultramafic assemblage (antigorite in the greenschist facies) → talc + carbonate → talc → Ca-amphibole + chlorite → chlorite ("blackwall") → transitional country rock → country rock. Sanford (1982) argued that the original contact between ultramafic rock and country rock was at the Ca-amphibole + chlorite/chlorite contact in most cases.

The bulk compositions of all samples are plotted on a MgO+FeO (FmO)-SiO_2-Al_2O_3 ternary diagram in Figure 5, which is useful for

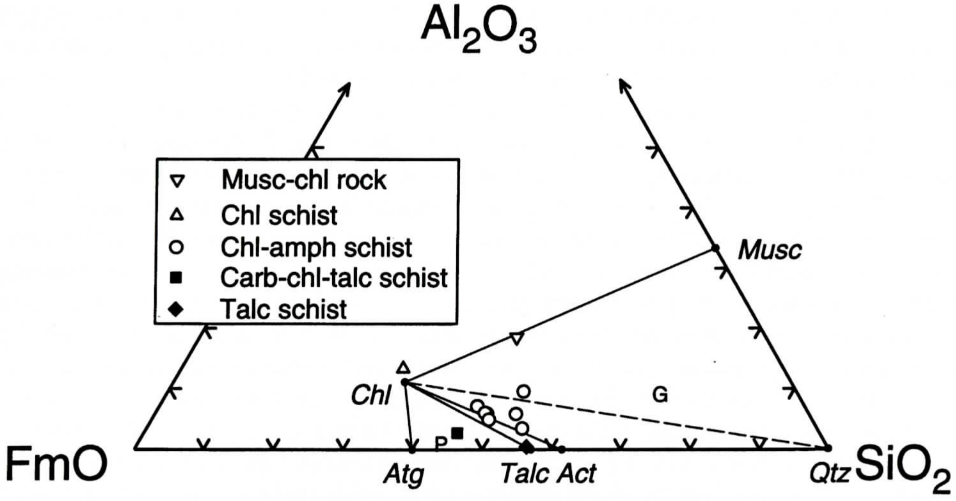

Figure 5. Bulk compositions of analyzed rocks plotted on the MgO+FeO (FmO)-SiO_2-Al_2O_3 ternary. Locations of end-member antigorite, talc, actinolite, chlorite (clinochlore), muscovite, and quartz are included for reference, as are positions of possible graywacke (G) and peridotite (P) protoliths.

considering the metasomatic changes that produced these rocks. A similar diagram was presented by Brady (1977) in a theoretical study of metasomatic zoning in metamorphic rocks. A typical graywacke country rock (G) would plot in the quartz-muscovite-chlorite field. As reasoned by Brady (1977), loss of silica to adjacent ultramafic rock could readily result in a muscovite-chlorite rock, as exemplified by sample 029. The overall major and trace element characteristics of this sample, as described above, are consistent with it representing altered country rock. The chlorite schists must represent rocks that lost major amounts of silica as well as other components such as K_2O, Na_2O, and CaO; these rocks are clearly analogous to chlorite "blackwalls" described elsewhere. Chlorite schist sample 013 and the muscovite-chlorite rock are from the same locality, and share several characteristics (e.g., high TiO_2 and Zr) indicating derivation from a similar country rock protolith. The relatively high Ni (622 ppm) and Mg# in this chlorite schist probably reflect some diffusion of Ni and Mg from nearby ultramafic rock, although this rock is not evident in the sampled roadcut. Chlorite schist sample 004 (locality 1), on the other hand, has a transition element pattern like that of chlorite-amphibole schist (Figure 3), and contains very high Cr (2667 ppm). Conceivably, it could represent a "blackwall" derived in part from ultramafic rock, although it has low Ni.

The talc schist sample 009 (locality 4) could have been produced by simple Si addition to pre-existing serpentinite (Figure 5). This rock is distinct from all others in its very high Mg# (91.7) and Ni (1986 ppm), but much lower Al, Ti, V. The talc schist is the only rock of this study that clearly appears to have been derived from a broadly dunitic to harzburgitic protolith (P on Figure 5).

From Figure 5 it is apparent that rocks dominated by talc + chlorite could have been produced from country rock (by Si loss coupled with Mg gain) or serpentinite (by gain of Si and Al). Talc-chlorite rocks were found in this study (localities 1 and 3), but not analyzed. The carbonate-chlorite-talc schist (039) from locality 1 could represent serpentinite modified by addition of Si, Al, and Ca, together with a CO_2-bearing fluid. This rock is similar to the chlorite-amphibole schists with respect to major elements (Figure 2) and trace transition elements (Figure 3a). Thus, these rocks may have originated in a similar fashion, with the differences reflecting contrasting fluid compositions.

Although the chlorite-amphibole schists are the most common rocks encountered in this study, their origin is the most difficult to decipher. Similar rocks have been described from several other localities in the central and southern Appalachians, and there appear to be two schools of thought regarding their petrogenesis. In some cases, isochemical metamorphism has been assumed (or defended), and a variety of protoliths suggested including plagioclase peridotite, hornblende peridotite, lherzolite, or pyroxenite (Hess, 1933; Warner and others 1986, 1989; Hooper and Hatcher, 1989). In a regional investigation that encompassed the current study area, Duke (1983) suggested that such rocks represent meta-komatiites. Alternatively, similar rocks elsewhere have been viewed as the products of extensive metasomatic alteration, such that the current bulk compositions are not those of the protolith (Drake and Morgan, 1981; Mittwede and Zupan, 1985; Scotford and Williams, 1983).

The chlorite-amphibole schists of this study may be the products of extreme metasomatism, and some samples are clearly associated in the field with other examples of probable metasomatic rocks. For example, sample 003 occurs with chlorite schist ("blackwall"), chlorite-talc schist, the carbonate-chlorite-talc schist (039), and presumably soapstone (given its location in the abandoned quarry). Several additional observations are also consistent with a metasomatic origin. The dominant chlorite + Ca-amphibole assemblage in these rocks is observed in numerous examples of metasomatized reaction zones in other ultramafic bodies (Sanford, 1982). Such zones obviously require diffusion of Si, Ca, and Al (and probably Fe) from country rock into the ultramafic body, concomitant with loss of Mg. In addition, a logical extension of the theoretical treatment of Brady (1977) is that such metasomatic alteration of serpentinite could indeed result in a chlorite-actinolite rock, which can be seen in Figure 6. Curtis and Brown (1969) also reasoned that small ultramafic bodies could be ultimately metasomatized to chlorite-actinolite rocks, which they also observed in the field. These rocks also contain variable amounts of calcium and aluminum, but the two are not correlated. Thus, the rocks cannot represent addition of a single Al-Ca phase of fixed composition to olivine. In addition, apart from a crude positive correlation with Ti, aluminum shows no correlation with any other pyroxene- or amphibole-compatible trace element (e.g., Sc, Y, Yb).

Despite the evidence marshalled above, a metasomatic origin for all chlorite-amphibole schists is problematic for several reasons. First, their broadly similar major element compositions would require remarkably similar extents of elemental diffusion from adjacent country rocks (which also vary in composition). Second, the largest body of chlorite-amphibole schist in this study (locality 5) is several tens of meters wide, and it appears to be mineralogically similar throughout. In metasomatic reaction zones described elsewhere, the chlorite-actinolite zone is no more than a meter thick, and typically much narrower (Sanford, 1982). This observation provides some indication of the probable limits of Al diffusion during metasomatic processes. Thus, the size of some bodies in our study area may preclude an origin by metasomatism. Finally, there seems to be no obvious reason why the ultramafic rocks of this particular area would be susceptible to such extensive metasomatism.

Assuming that the chlorite-amphibole schists of this study underwent isochemical metamorphism, some broad constraints can be placed on the nature of their protolith. The moderate to high amounts of aluminum and calcium in these rocks rule out the possibility of typical dunitic, lherzolitic or pyroxenitic protoliths. On the other hand, the normative mineralogy of all samples is consistent with a variety of plagioclase-bearing ultramafic protoliths including harzburgites, lherzolites, or wehrlites, with the amount of normative feldspar ranging from 18 (sample 003) to 44% (sample BC-18). However, such plagioclase-bearing protoliths are considered unlikely for several reasons. First, there is no correlation between the amount of normative feldspar and any other plagioclase-sensitive element such as Sr, Eu, or the Eu-anomaly. Second, Sr is typically very low in all samples, even in the sample with the highest normative feldspar. Finally, all samples analyzed by INA display a slight to pronounced negative Eu-anomaly. On the other hand, hornblende-bearing to hornblende-rich ultramafic rocks could contain the requisite aluminum and calcium. The concentrations of these two elements are not expected to correlate in hornblende (because of the nature of Al-substitutions), which could account for the lack of correlation between aluminum and calcium in the rock compositions. Such protoliths might also help to explain the current, amphibole-rich nature of some samples (particularly BC-18), as well as the presence of hornblende cores in many grains. Hornblende-bearing mafic to ultramafic rocks do occur in the nearby Diana Mills pluton and Buckingham Complex (Figure 1), providing some support for this interpretation.

The REE-patterns (Figure 4) provide no obvious evidence for the presence of hornblende in the protolith. However, the REE-patterns vary widely, even among samples from the same body which otherwise have similar major element compositions (021 and 023). This variability in REE concentration and patterns may be an indication of original heterogeneity, or of significant REE mobility. The pronounced negative Ce-anomalies in samples 023 and 035 are surely an indication of some mobility, either of Ce (seawater alteration?) or possibly La.

Despite the uncertainties presented by the REE compositions, the similar transition element patterns of these samples (Figure 3) suggest that the rocks clearly had similar protoliths, assuming immobility of these elements. These patterns are more consistent with pyroxene- or amphibole-bearing ultramafic protoliths rather than simple dunite. Thus, the compositional heterogeneities displayed by these rocks probably reflect real variations in original mineralogy, perhaps coupled with variations in the extent of metasomatic alteration.

Regional Significance

It is clear that metamorphosed ultramafic rocks are a minor, but widespread component of the local bedrock. Given the uncertainties in protolith mineralogy, and the lack of focused mapping, it seems unproductive at this point to speculate on the status of such rocks as true ophiolite fragments. Nonetheless, the proximity of all occurrences to a melange zone provides strong support for their emplacement as tectonic slivers, rather than as intrusive masses. The regional distribution of such rocks away from the immediate study area is unknown. It is possible that their abundance here may be atypical, and linked to the specific setting near a melange (which has been interpreted as a terrane boundary). In fact, these occurrences may be an indication that the melange zone is wider here than previously recognized. More detailed geologic mapping in the Piedmont, particularly to the east, is required to address this issue. On the other hand, some occurrences here are clearly associated with amphibolitic rocks of the Chopawamsic Formation, suggesting at least the possibility that these mafic and ultramafic rocks are magmatically related. This hypothesis can be addressed through additional mapping in conjunction with comprehensive geochemical studies.

We emphasize again the reconnaissance nature of the present study. Further investigations of other occurrences in the area, coupled with more systematic sampling of the larger, and better-exposed bodies (e.g., locality 5) may provide considerable insights into lingering questions regarding protolith mineralogy and composition.

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