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STRUCTURE AND CHEMICAL PETROLOGY OF THREE SOUTHERN APPALACHIAN MAFIC-ULTRAMAFIC COMPLEXES AND THEIR BEARING UPON THE TECTONICS OF EMPLACEMENT AND ORIGIN OF APPALACHIAN ULTRAMAFIC BODIES

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ABSTRACT. Appalachian ultramafic rocks occur in several associations: as isolated pods and small elongate bodies, with or without mafic rocks, in complexly deformed rocks of high metamorphic grade, with mafic rocks in ophiolite sheets, best-preserved in Newfoundland, and as differentiates in mafic plutons. The first two are the most difficult to understand. They constitute the classic "alpine-type peridotite" association and are mostly confined to Hess' belt of Appalachian ultramafic rocks. Most previous studies have attempted to explain their occurrences by focusing specifically on the petrogenesis of the ultramafic rocks. The present study emphasizes their tectonic setting and includes geochemical investigations of associated mafic rocks in three representative complexes from the southern Appalachian Blue Ridge and Piedmont.

Detailed investigations of three large polydeformed upper amphibolite facies mafic-ultramafic bodies reveal associations of ultramafic rocks in varying degrees of alteration with a variety of mafic rocks. Mafic rocks range from amphibolites and garnet amphibolites to metagabbros to hornblende gneisses. There are broad chemical variations in overall compositions, but significantly none plot within the continental basalt association field using several standard element discriminant plots. Detailed geologic mapping suggests that one of the Blue Ridge bodies studied (Laurel Creek) was emplaced along a pre- to syn-metamorphic thrust. Both Blue Ridge bodies were polydeformed and metamorphosed after emplacement. The Gladesville complex exhibits arc affinities and occur southeast of the Towaliga fault, a major suture within the Piedmont thrust sheet.

Isolated ultramafic (and some gabbro) pods (10 cm to 1-3 km) may represent fragments of ophiolitic slices that became dismembered from the body during subsequent ductile deformation and high grade metamorphism. The behavior of ultramafic and coarse cumulate gabbros ranged from that of relatively soft but coherent "punctured basketballs" to competent "watermelon seed" diapirs moving to zones of lower stress. Formation of hydration haloes may have assisted this process. The changes that occur in these bodies, from low to high metamorphic grade and from relatively undeformed to complexly deformed, compound the difficulties in tracing their origins. Geochemical signatures, using "immobile" elements (Ti, Rb, Y), are helpful but many times are still inconclusive partly because even these elements become mobile at higher grade in presence of water. Even where detailed structural studies

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have been made in polydeformed medium to high grade terranes, it still may be impossible to understand completely the history and origin of these complexes.

For most of this century a magnificent argument has gone on between field geologists who have worked on the peridotites of alpine mountains and laboratory investigators of their chemistry . . .

H. H. Hess (1955)

INTRODUCTION

The subject of this paper presents a dilemma to the geologist who chooses to study mafic and ultramafic rocks in the high grade internal parts of orogenic terranes and resolve their fascinating array of complex events. However, this complexity may be so great as to obscure the crucial data that would provide exact solutions to their ultimate origins. The results to be presented herein were derived more from the context of the tectonic and lithostratigraphic settings of these bodies than from specialized studies of a single rock type or suite.

The classic studies by Hess (1939, 1955) were the first that recognized the distributions of ultramafic bodies in the Appalachian orogen. He recognized two major belts of ultramafic rocks, one extending down the western and west-central portions of the orogen and a second more easterly belt. Larrabee (1966) compiled a map showing more accurately where most ultramafic and many mafic bodies are located throughout the United States Appalachians.

More recently Misra and Keller (1978) reviewed the literature and ideas on the ultramafic bodies of the southern Appalachians. Theirs was a comprehensive review which touched upon most of the previous concepts and hypotheses related to the origin of the southern Appalachian ultramafic bodies. These hypotheses range from igneous intrusions to anhydrous assemblages coexisting with hydrous phases thought by Carpenter and Phyfer (1975) to be produced from metamorphism of tectonically emplaced serpentinite bodies. However, it was not the intent of Misra and Keller (1978) to undertake an original study of the ultramafic bodies, nor did they arrive at a new hypothesis to explain their origin. This is not surprising because most of these rocks occur in the medium to high grade terranes.

The purpose here is to present several ideas that have evolved over the past 10 to 12 yrs of detailed studies of several areas in the Piedmont and Blue Ridge of the Carolinas and Georgia. The chemical data and some field data presented herein have been produced recently by investigations of various kinds conducted by the junior authors of this paper.

SETTINGS OF APPALACHIAN ULTRAMAFIC/MAFIC ROCKS

It is relatively easy to recognize and characterize precisely rocks that occur in an essentially unmetamorphosed and undeformed state, such as the well-preserved ophiolites in the Bay of Islands region in Newfoundland (Church and Stevens, 1971; Williams, 1971) or some of the mafic/

ultramafic plutons of the Cordillera (Snoke and others, 1982). The western Newfoundland ophiolites have been preserved because of their almost unique structural setting upon the Appalachian foreland in western Newfoundland where they escaped the rigors of polyphase deformation and metamorphism. Other ophiolitic bodies of the Burlington Peninsula, such as Coachman's Cove and others, were not so fortunate. Were it not for the better preserved examples farther to the west, perhaps these would not have been recognized so early as ophiolites nor would they be as well understood today. Farther south in Quebec are several examples of well-preserved ophiolites, though not as complete as those in western Newfoundland. From Quebec southward, the ultramafic and mafic complexes occur in areas where metamorphic grade is generally higher and the deformation more intense. Their sizes range from very small (< 1 m) (pl. 1) to relatively large (> 1 km). Partly differentiated mafic intrusive bodies with large or small contact aureoles can be recognized. Other southern and central Appalachian ultramafic bodies, which occur within the group of alpine-type ultramafic rocks, have been described by a number of people (for example, Chidester and Cady, 1972; Greenberg, 1976; Crowley, 1976; Yurkovich, 1977; Swanson, 1981). Mafic flows, sills, and dikes also exist in the western parts of the Appalachians (see, for example, Rankin, 1970; Rankin, Espenshade, and Shaw, 1973). However, where the metamorphic grade increases, it is certainly far from easy to differentiate flows from sills and dikes and to separate the intrusives from the others, unless they were emplaced very late in the history of the particular area. Possible ophiolites have been recognized in the eastern Piedmont in the Raleigh belt in North Carolina (Stoddard, Kite, and Moye, 1982; Kite and Stoddard, 1984). These also occur in a medium grade terrane and thus are highly altered and polydeformed. The Lake Chatuge and Shooting Creek mafic/ultramafic complexes in North Georgia and southwestern North Carolina (Hartley, 1973) occur along the Hayesville thrust and partially frame the Brasstown Bald and Shooting Creek windows (Hatcher and others, 1979; Hatcher and Butler, 1979, fig. 41). This is probably the most clear-cut association of mafic and ultramafic rocks with an early thrust in this part of the orogen.

Ophiolitic debris has been recognized in a number of places throughout the Canadian and northern U.S. Appalachians. This debris ranges from sand-size or smaller particles to larger fragments of material which has apparently been derived either erosionally or otherwise from advancing ophiolite sheets thus becoming part of the depositional environment as olistostromal or other detrital material from an ophiolite (Williams, 1977; Williams and Talkington, 1977; Rowley and Kidd, 1981).

With these varied possibilities of the origin of mafic and ultramafic bodies, it is not difficult to understand the additional difficulties of working with these materials in high grade polydeformed terranes making the problem seem initially without a solution. Probably the southernmost example in the Appalachians to date using a combination of detailed field work and chemical studies resulted in recognition of the Piney Branch

PLATE 1

Small gabbro nodule enclosed in amphibolite in sillimanite grade rocks of the Central Piedmont northeast of Forsyth, Ga.

ophiolitic complex within the northern Virginia Piedmont (Drake and Morgan, 1981). Here, the rocks are polydeformed and metamorphosed to medium grade. Drake and Morgan met with considerable success by studying the ultramafic and mafic rocks in their regional stratigraphic and structural setting, then conducting detailed structural and petrologic studies of the bodies. We have attempted herein to utilize this technique in the southern Appalachians.

SOUTHERN APPALACHIAN EXAMPLES

Introduction.—Examples from three complexes in the southern Appalachians where detailed geologic mapping, structural studies, and chemical analyses have been made are outlined herein. Sufficient field and laboratory data were collected and integrated to be able to draw conclusions as to the nature and ultimate origin of each of these complexes. The Laurel Creek and Carroll Knob complexes are in the Georgia and North Carolina Blue Ridge respectively, whereas the Gladesville complex is in the Central Piedmont of Georgia (fig. 1).

Field data and setting.—The Laurel Creek mafic/ultramafic complex is a linear body of garnet amphibolite and pods of altered ultramafic rocks within the Tallulah Falls Formation in the Northeast Georgia Blue Ridge (fig. 2). These rocks were metamorphosed to the Barrovian kyanite zone and appear to have been thrust into their present positions along a premetamorphic thrust fault (Petty, ms). Detailed geologic mapping by Petty has revealed that after the rocks of the complex were thrust onto the Tallulah Falls Formation rocks, they were folded several times and transposed during the main prograde metamorphic event. Later, several post-metamorphic structures were superimposed onto the earlier. Mafic and ultramafic rocks of the Laurel Creek complex are associated with mafic rocks of the Tallulah Falls Formation. It is important and relatively easy to distinguish between these rocks both in the field and, as will be demonstrated later, chemically. Tallulah Falls Formation rocks consist of interlayered metagraywackes, muscovite–biotite to aluminous schists, and more feldspathic layered amphibolites. The amphibolites of the Laurel Creek complex are garnet amphibolites containing almandine garnets up to 1 to 2 cm in diameter. No ultramafic rocks are associated with the Tallulah Falls Formation mafic rocks.

The ultramafic rocks of the Laurel Creek complex are mostly soapstones (talc + chlorite + accessories), with the exception of two larger bodies located along the northwest edge of the complex (fig. 2). The larger of the two was originally given the name Laurel Creek ultramafic body and consists of a core of two separated masses of dunite surrounded by serpentinite and soapstone, then a zone of steatite (talc rock) along the contact. Accessory minerals include small zones of chlorite, anthophyllite, and corundum in the Laurel Creek dunite body. The other body consists of highly altered dunite which preserves some unaltered olivine but consists mostly of talc and serpentine. However, the talc is a legitimate middle amphibolite facies mineral and may be in equilibrium with olivine here. The other bodies of soapstone in the complex are made up

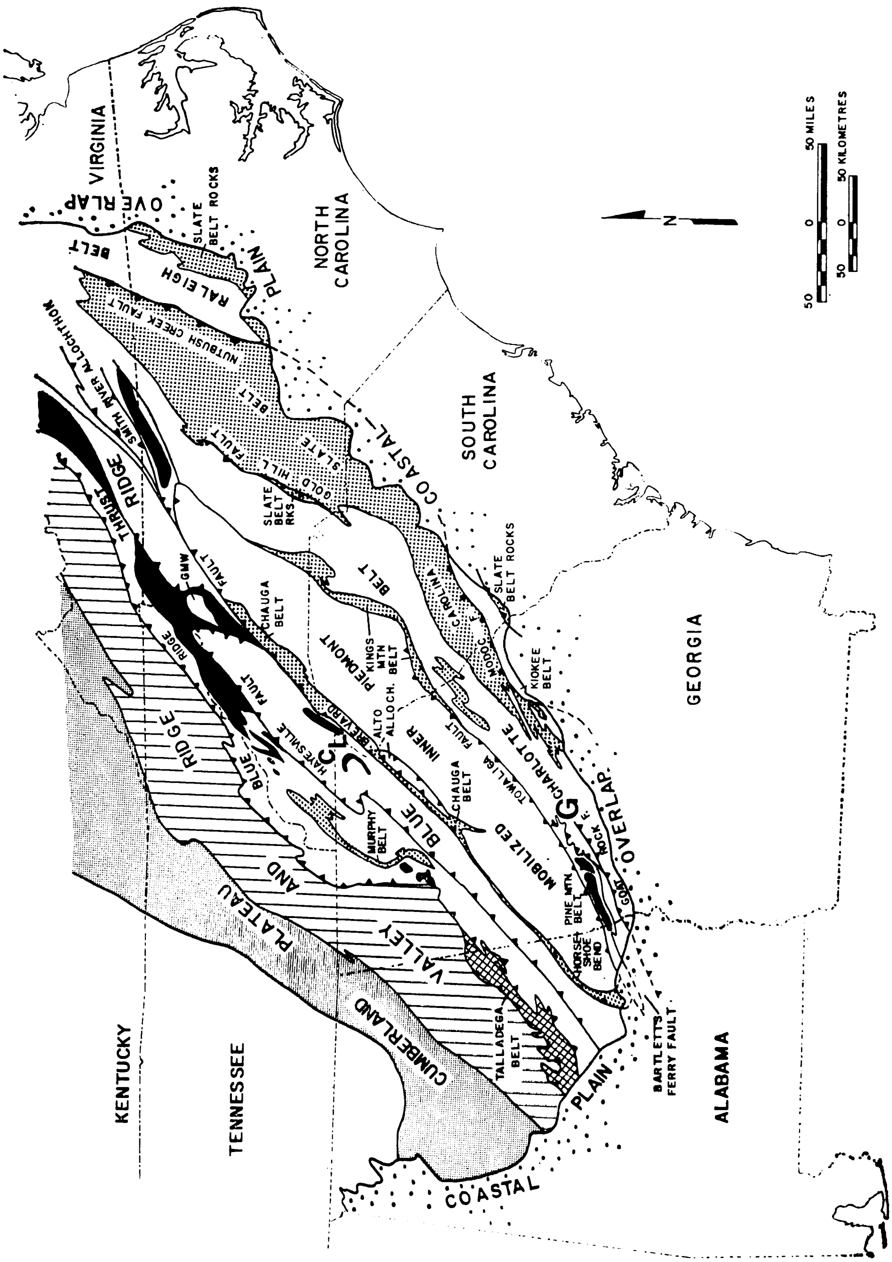

Fig. 1. Map showing the subdivisions of the southern Appalachians and locations of the three mafic-ultramafic complexes discussed herein. Basement rocks are shown in black. C — Carroll Knob complex. L — Laurel Creek complex. G — Gladesville complex.

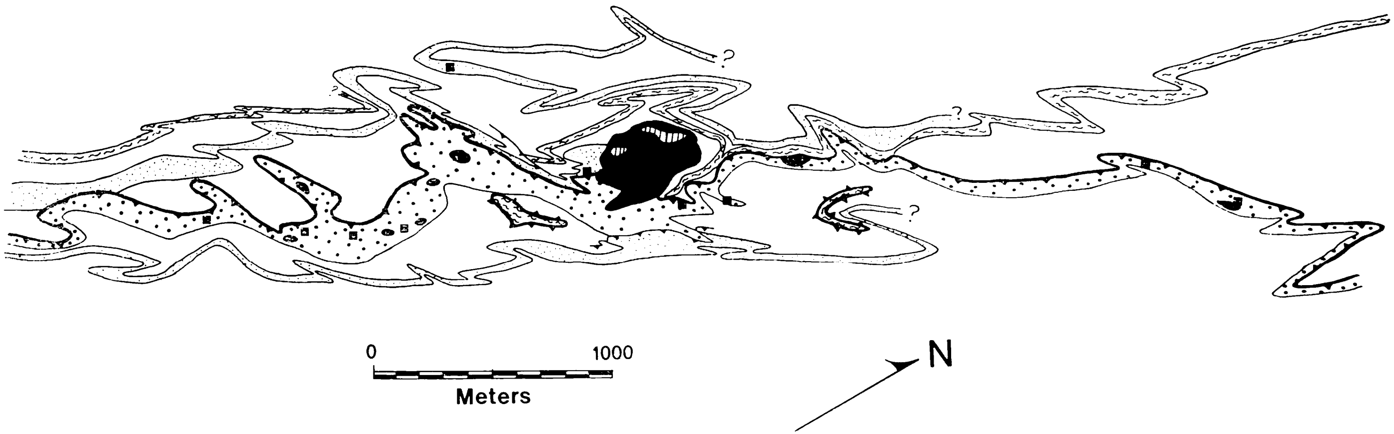

Fig. 2. Detailed geologic map of the Laurel Creek complex in the Satolah 7½ min. quad., northeast Georgia (modified from Petty, 1982). Striped pattern — dunite; black — soapstone; heavy stipple — garnet amphibolite; light stipple — Tallulah Falls amphibolite; wavy line pattern — Garnet Aluminous Schist Member of Tallulah Falls Formation; unpatterned — Tallulah Falls metagraywackes. Black squares are samples for chemical analysis. Three others fall within the large ultramafic body. Exact sample locations available from the authors.

of virtually the same assemblage throughout including talc, chlorite, magnesite, chromite with some minor serpentine.

The Carroll Knob mafic/ultramafic complex (fig. 3) is located in the central Blue Ridge of North Carolina in rocks that probably belong to either the Tallulah Falls Formation or the Coweeta Group (Hatcher, 1979, 1980). Rocks of this complex consist of small amounts of highly altered ultramafic material, presently soapstones (talc + chlorite + accessories), and large volumes of amphibolite with additional masses of medium to very coarse grained metagabbro. The plagioclase in the metagabbro remains only partially altered, whereas all the mafic constituents have been retrograded to amphibolite facies assemblages.

The Carroll Knob complex has also been highly deformed and metamorphosed to probable sillimanite grade assemblages. The emplacement history of this body is less clear than that of the Laurel Creek complex. Its outcrop pattern is a complex fold interference pattern (fig. 3). Cross-cutting relationships were not observed during detailed mapping of the complex. It remains uncertain whether faulting or intrusion is responsible for its emplacement.

The Gladesville complex in Central Georgia represents a third setting of an ultramafic/mafic association in the southern Appalachian orogen. The term Gladesville was first used by Matthews (ms) for the largest gabbro in this complex. We can demonstrate, using field and geochemical relations, that the rocks of the mafic complex, including the Gladesville norite body are all related, and we have chosen to use the name Gladesville for the entire complex. This complex consists of several gabbros and associated amphibolites with only a small amount of altered ultramafic material as thin (< 20 cm) talc–chlorite schist layers. These commonly occur near the contacts. A linear amygdoloidal basalt unit has been mapped as part of this complex. Some of the gabbro bodies range from a meter or less in diameter to the large, Gladesville norite body (fig. 4).

The Gladesville complex gabbros appear on initial examination to have been emplaced after metamorphism. This has doubtlessly been the reason that several earlier studies had considered these gabbros to be late and not related to the adjacent geology (see Matthews, ms; Prather, ms). However, where the contacts of these bodies have been examined, they reveal an obvious polydeformational and premetamorphic history, whereas the internal parts of the bodies appear pristine and preserve original gabbroic textures as well as the primary mineralogy. The reason is probably the relationship between available water along contacts and the lack of water in the interior portions of the bodies. However, detailed geologic mapping suggests that they were integrally related to the associated amphibolites, metagraywackes, and other associated metasedimentary rocks. Contact metamorphic effects are present, but they too are overprinted by metamorphism. Tectonic contacts have not been observed in the Gladesville complex. However, the field relationships and pattern of truncation of rock units along a linear amygdoidal basalt (now altered to amphibolite) and its close proximity to an altered linear ultramafic

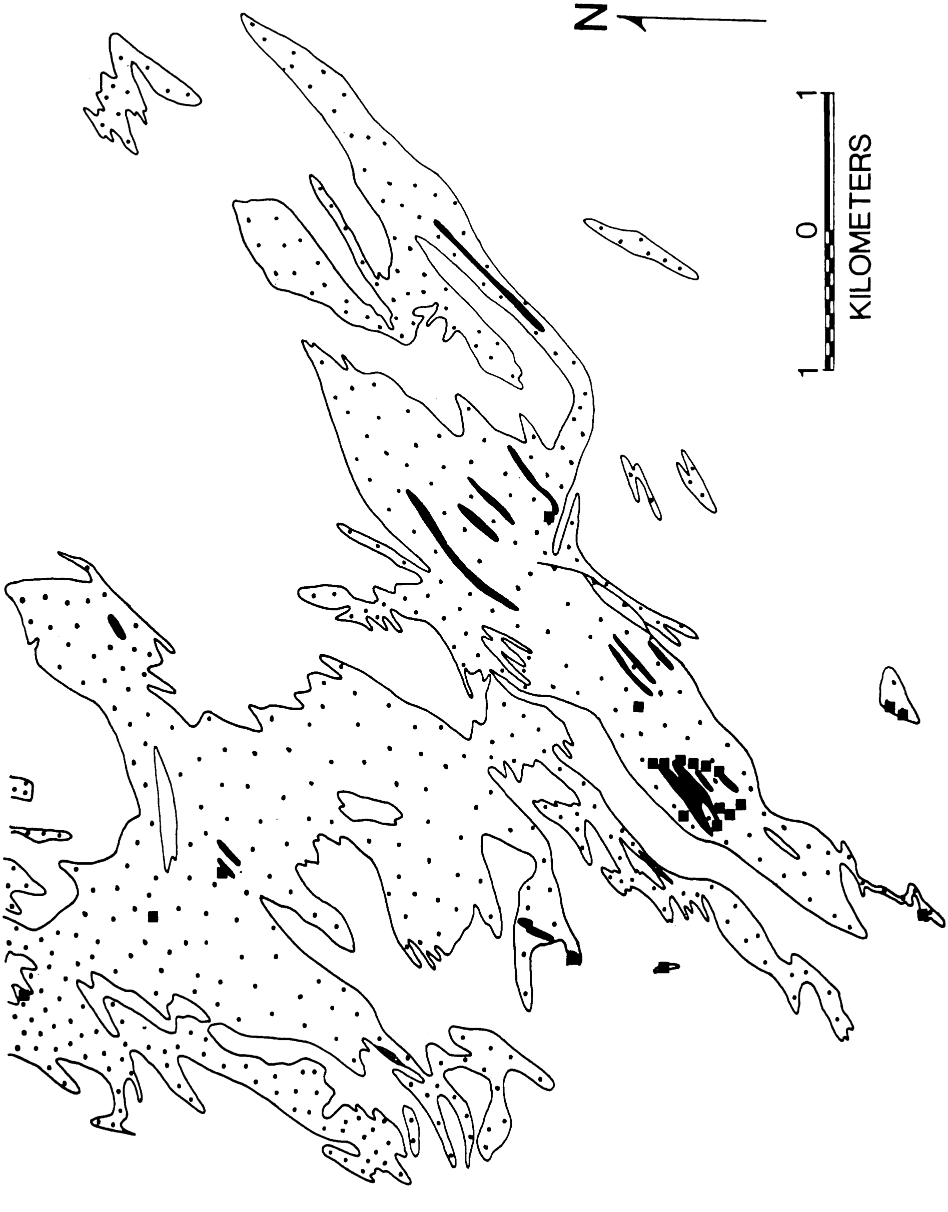

Fig. 3. Detailed geologic map of the Carroll Knob complex, Prentiss 7½ min. quad., North Carolina. Black — ultramafic rocks (mostly soapstones); stipple pattern — gabbro and amphibolite, undivided. Geology from Hatcher (1980). Black squares are chemical analysis sample locations. Some squares in the southern area where most samples were collected represent more than one sample.

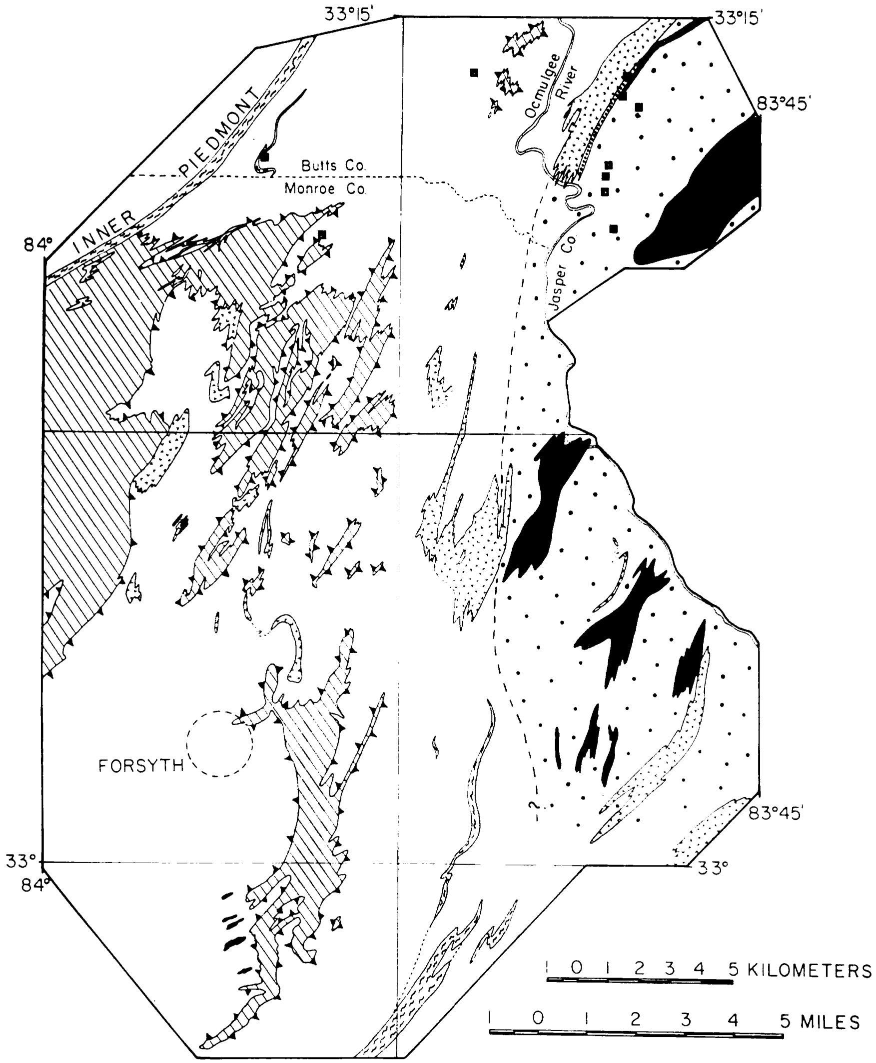

Fig. 4. Detailed geologic map of the east end of the Pine Mountain belt and the Gladesville complex. Striped pattern — Grenville basement rocks; black — ultramafic rocks and gabbro; random rooftop pattern — granitoids; densely dotted area in northeast part of map — amygdaloidal basalt (deformed); wavy pattern — post-metamorphic mylonites (Towaliga and Goat Rock faults). Sparsely dotted area is the Gladesville complex. Black squares are chemical analysis sample locations. Exact locations may be obtained from the authors.

TABLE 1

A. Chemical data from Laurel Creek mafic-ultramafic complex

	Garnet amphibolite LC-95†	Garnet amphibolite LC-179B†	Garnet amphibolite LC-152	Garnet amphibolite LC-138	Garnet amphibolite LC-240†	Garnet amphibolite LC-239B†	Garnet amphibolite LC-137†	Garnet amphibolite LC-161†	Tallulah Falls amphibolite LC-140	Tallulah Falls amphibolite LC-14
Laurel Creek amphibolites Major element analyses (wt %)										
SiO_2	49.89	47.15	51.20	48.61	49.14	50.12	59.79	48.61	51.93	52.69
Al_2O_3	14.36	14.23	15.21	14.48	9.01	6.34	10.77	12.47	16.05	12.08
Fe_2O_3*	12.24	13.49	13.03	12.88	15.50	15.13	12.88	13.58	11.01	12.03
MgO	12.86	10.64	7.60	7.40	15.05	19.73	10.32	12.80	8.64	7.73
CaO	10.28	10.97	10.62	9.59	6.72	5.45	10.63	10.17	9.48	10.05
Na_2O	0.53	0.94	0.83	1.51	1.23	0.44	1.44	1.29	0.73	0.94
K_2O	0.17	0.20	0.27	0.47	0.07	0.05	0.50	0.16	0.19	0.24
TiO_2	0.54	1.93	1.54	2.29	0.41	0.52	1.96	1.38	0.85	1.25
P_2O_5	0.11	—	0.21	—	0.23	0.05	0.27	0.13	0.27	0.25
MnO	0.18	0.19	0.18	0.17	0.18	0.22	0.18	0.18	0.18	0.19
TOTAL	101.5%	100.3%	100.9%	98.0%	98.0%	98.6%	99.7%	100.8%	101.0%	98.0%
Laurel Creek amphibolites Trace elements (ppm)										
Rb	0.2	5.6	0.2	tr	tr	0.8	tr	1.3	2.5	3.2
Sr	271.4	264.0	199.5	192.7	116.5	101.0	158.9	129.3	192.6	234.1
Zr	37.4	54.7	72.1	233.0	58.5	44.2	119.1	43.5	115.7	103.8
Y	20.4	19.9	27.9	33.7	27.1	24.3	39.6	19.6	28.1	35.3
Ni	112.0	72.0	148.0	79.0	303.0	313.0	750.0	270.0	135.0	283.0
Ba	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Nb	tr	10.8	10.9	14.0	8.6	10.3	9.2	4.9	2.7	8.6
Cu	320.0	145.0	97.0	115.0	83.0	99.0	105.0	111.0	118.0	200.0
Cr	520.0	158.0	270.0	118.0	80.0	130.0	240.0	295.0	160.0	24.0
V	220.0	330.0	135.0	29.5	273.0	238.0	200.0	510.0	133.0	435.0

† Analyses not used in Pearce or Pearce and Cann diagrams.

B. Major element analyses of Laurel Creek ultramafics

Major elements (wt%)	LC-242† Dunite	LC-56† Dunite	LC-34† Dunite	LC-142† Dunite	LC-4C† Dunite	LC-2† Dunite
SiO_2	49.85	38.37	46.76	51.83	41.79	47.66
Al_2O_3	2.66	1.78	1.66	2.90	1.67	6.22
Fe_2O_3*	10.38	15.51	8.89	17.43	10.92	17.34
MgO	32.20	41.98	39.93	21.71	38.91	16.99
CaO	0.24	0.15	0.13	1.44	0.32	5.49
Na_2O	2.71	2.73	2.77	2.77	2.68	3.07
K_2O	0.06	0.06	0.06	0.06	0.06	0.06
TiO_2	0.05	tr	tr	0.28	tr	0.25
P_2O_5	0.18	0.17	0.19	0.20	0.18	0.32
MnO	0.11	0.12	0.11	0.13	0.12	0.13
TOTAL	98.44%	100.87%	100.68%	98.75%	96.65%	97.53%

† Analyses not used in Pearce or Pearce and Cann diagrams.

mass (soapstone) require tectonic emplacement of at least parts of the Gladesville complex.

Some granitic bodies in this area also appear related to the Gladesville complex. Several highly deformed layered feldspar–quartz (± biotite or hornblende) rocks interlayered with some of the amphibolitic and other mafic rocks within the mafic complex are probably interlayered felsic volcanic rocks. Some deformed granites may also be related, but this is impossible to determine without more complete exposure. Other felsic materials, such as pegmatites, cut across the gabbros in places, and pegmatites serve as an economic source of feldspar in the area. The ages of the Gladesville complex rocks are unknown, except to say that they are premetamorphic. Odom, Hatcher, and Hooper (1982) have concluded metamorphism occurred at least 350 my ago.

Chemical petrology.—The study of major elements and their relationships to protolith materials within highly deformed, metamorphosed, and altered mafic-ultramafic rocks is a difficult task. The alkalies, some of the alkaline earths, and other elements become mobile under conditions of amphibolite facies metamorphism (Allegre and Michard, 1973). This problem, added to the compositional variations produced by fractionation trends, mixing, and other primary igneous processes should answer the question of whether chemical analyses of medium- to high-grade mafic rocks should be used. However, we feel that meaningful conclusions may be drawn from analyses of metamorphosed mafic rocks, provided sufficient care is exercised in sampling, sample preparation, and analysis, and if major element comparisons are carefully integrated with comparisons utilizing immobile elements from the same rocks. These conclusions must also be combined with those from field, structural, and petrographic studies to provide the best possible conclusions.

Samples for this study were collected to assure that they are both representative and composed of fresh material. Samples of rocks making up large percentages of the bodies were sampled, along with representative samples from the volumetrically small portions.

Geochemical data from samples from the three complexes described above (tables 1, 2, and 3) were obtained using standard X-ray fluorescence methods and accepted U.S. Geological Survey and National Bureau of Standards standards. Although some X-ray fluorescence analyses are reported to four significant figures, replicate analyses indicate that accuracy of this technique is good only to three significant figures. Additional discussion of analytical techniques may be found in Petty (ms). Analyses of Cr, V, Ni, and Cu could not be obtained on the X-ray fluorescence unit available for the study and were determined by emission spectroscopy. Standard discrimination diagrams were plotted for major elements using the discrimination function technique of Pearce (1976). Scatter of points is probably the result of element mobility at high grade, with some contribution from analytical error.

Cann (1970) and Pearce and Cann (1973) have shown that Ti, Y, Zr, and Nb are relatively immobile during metamorphism. Sr is immobile into greenschist facies conditions (Pearce and Cann, 1973). Additionally, element mobilities are probably strongly dependent upon availability of water in the system at the time of metamorphism. Discrimination diagrams using these immobile elements and the incompatible element Cr have been devised to determine the tectonic setting of non-cumulative basaltic rocks with (CaO + MgO) between 12 and 20 percent (Pearce and Cann, 1973; Pearce, 1979). That this sum does not fall between 12 and 20 percent does not mean the rocks are cumulates. We have plotted our data from the three complexes, removing those analyses in which (CaO + MgO) did not fall within the 12 to 20 percent range, in the discrimination diagrams Ti/100 versus Zr versus Y × 3 (and Sr/2) (fig. 5), Zr/Y versus Zr (fig. 6), as well as plots of TiO_2 versus Zr and Cr versus Y which are not included here.

All discrimination plots yield the same conclusion, that none of the mafic rocks in any of the three complexes studied possess continental or "within plate" affinities. However, the very few analyses of Tallulah Falls Formation amphibolites near the Laurel Creek complex (table 1) do possess continental affinities, indicating a fundamental difference between the mafic complex rocks and the mafic rocks within the sedimentary sequence.

Analyses of mafic rocks from the Carroll Knob and Laurel Creek complexes, with few exceptions, fall within the oceanic and/or island arc fields. Samples from the Gladesville complex plot in fields related to arc lavas (figs. 6 and 7).

F_1 versus F_2 and F_2 versus F_3 discriminant function variation diagrams (fig. 7) for major elements (Pearce, 1976) have been plotted using data from the three complexes. Despite the potential mobility problems, these diagrams again suggest that the mafic rocks of all the complexes were generated in either an ocean floor or arc environment.

The most significant and least equivocable conclusion that may be drawn from these data is that the mafic rocks of the Carroll Knob, Laurel Creek, and Gladesville complexes probably originated in a noncontinental environment. It is difficult to pinpoint exactly in which environment they were produced, either ocean floor or arc.

Table 2
Chemical data from Carroll Knob mafic-ultramafic complex

	Metagabbro P-972†	Metagabbro P-634	Metagabbro P-966B†	Metagabbro P-1164	Amphibolite P-973†	Metagabbro P-962	Metagabbro P-968A†	Metagabbro P-682C†	Amphibolite P-986E†	Metagabbro P-966A†	Amphibolite P-989	Metagabbro P-682B†
Carroll Knob Major element analyses (wt %)												
SiO_2	44.79	52.64	48.98	50.06	49.14	53.38	48.39	52.75	49.82	50.10	51.78	48.66
Al_2O_3	13.36	11.6	16.28	15.70	13.99	16.30	22.09	14.68	14.69	16.88	12.72	10.33
Fe_2O_3*	15.23	12.98	10.44	10.75	11.90	11.06	9.30	9.93	9.98	8.56	12.26	11.95
MgO	7.82	6.83	10.78	7.33	11.22	7.47	8.89	5.94	8.94	9.47	7.72	11.11
CaO	12.29	9.83	13.95	11.31	13.13	10.85	13.56	17.11	12.40	14.30	9.98	11.48
Na_2O_3	1.03	1.83	0.99	2.70	1.11	1.29	1.13	0.97	2.01	1.98	2.15	2.10
K_2O	0.21	0.80	0.08	0.55	0.68	0.07	0.19	0.15	0.21	0.06	0.46	0.42
TiO_2	2.82	1.54	0.18	1.01	0.36	0.34	0.12	0.07	0.34	0.11	3.11	1.55
P_2O_5	0.26	0.25	0.11	0.26	0.09	0.14	0.11	0.15	0.25	0.11	0.27	0.26
MnO	0.18	0.17	0.16	0.16	0.17	0.17	0.16	0.16	0.16	0.15	0.15	0.15
TOTAL	97.99%	98.47%	101.88%	100.33%	101.77%	101.06%	101.93%	101.91%	98.80%	101.90%	100.60%	98.00%
Carroll Knob Trace elements (ppm)												
Rb	7.1	2.0	1.6	2.6	1.8	tr	1.6	tr	16.4	18.9	16.7	1.5
Sr	128.5	162.6	138.9	490.0	125.9	151.0	300.5	940.5	141.5	133.7	370.2	132.5
Zr	40.6	105.7	38.8	298.7	39.9	49.8	36.8	tr	43.3	42.1	131.3	80.2
Y	20.9	37.2	20.1	47.8	21.6	23.6	17.9	46.4	12.5	22.8	33.4	47.3
Ni	<10.0	250.0	<10.0	226.0	<10.0	334.0	230.0	<10.0	295.0	<10.0	<10.0	230.0
Ba	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Nb	7.1	8.5	9.0	13.6	0.6	18.9	1.8	27.2	9.0	11.5	19.8	11.4
Cu	17.0	90.0	10.0	57.0	45.0	88.0	77.0	10.0	68.0	49.0	110.0	115.0
Cr	24.0	300.0	260.0	106.0	122.0	198.0	325.0	94.0	165.0	167.0	105.0	430.0
V	<10.0	300.0	150.0	<10.0	97.0	195.0	243.0	<10.0	243.0	153.0	300.0	363.0

† Analyses not used in Pearce or Pearce and Cann diagrams.

TABLE 2 (continued)

	Amphibolite P-967†	Metadiorite P-434C	Metadiorite P-1485	Amphibolite P-686D†	Amphibolite P-587†	Amphibolite P-686B†	Metagabbro P-968B†	Amphibolite P-588†	Metagabbro P-682A†	Metagabbro P-974†	Metagabbro P-513	Metadiorite P-434B
SiO_2	48.53	60.23	63.29	46.38	47.55	46.20	44.98	46.70	44.50	45.87	46.38	63.08
Al_2O_3	14.98	10.31	12.57	15.53	17.93	22.57	28.94	16.73	8.16	23.61	11.24	11.66
Fe_2O_3*	12.04	9.58	7.88	4.75	6.94	4.16	4.18	8.76	16.15	4.82	18.70	10.02
MgO	9.75	2.19	2.58	17.22	11.88	9.11	4.75	10.22	14.63	9.89	6.06	2.82
CaO	14.15	15.46	7.61	15.55	14.18	16.13	15.95	14.55	11.22	13.02	11.35	7.17
Na_2O_3	1.08	1.44	3.35	1.36	1.38	1.32	1.62	1.33	2.08	1.61	1.52	2.71
K_2O	0.07	0.13	0.52	0.06	0.06	0.06	0.07	0.07	0.34	0.08	0.32	0.60
TiO_2	0.41	0.41	1.15	0.07	0.09	0.04	0.03	0.16	1.55	0.03	2.70	1.41
P_2O_5	0.10	0.25	0.21	0.07	0.07	0.07	0.07	0.06	0.07	0.06	0.41	0.24
MnO	0.17	0.11	0.10	0.10	0.11	0.09	0.11	0.11	0.12	0.10	0.11	0.11
TOTAL	101.30%	100.11%	99.66%	101.09%	100.19%	99.75%	100.70%	98.75%	99.19%	99.09%	98.79%	99.82%
Rb	tr	tr	8.0	6.6	4.4	9.2	6.3	4.7	7.7	8.3	3.0	1.0
Sr	135.7	400.6	313.1	134.9	132.6	146.8	212.7	136.1	143.3	148.5	159.2	239.0
Zr	41.4	136.0	840.1	40.5	40.6	45.2	40.1	45.0	74.1	43.5	886.2	533.0
Y	19.7	53.4	74.5	22.7	21.5	16.8	20.8	24.4	51.1	25.8	70.8	52.5
Ni	<10.0	300.0	294.0	<10.0	227.0	<10.0	293.0	<10.0	418.0	225.0	192.0	<10.0
Ba	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Nb	10.9	24.0	22.4	4.9	4.8	11.5	tr	14.9	7.8	13.1	29.1	tr
Cu	110.0	57.0	45.0	90.0	44.0	36.0	57.0	90.0	90.0	44.0	44.0	75.0
Cr	235.0	94.0	147.0	170.0	320.0	110.0	227.0	275.0	283.0	183.0	265.0	170.0
V	323.0	<10.0	<10.0	243.0	98.0	<10.0	185.0	300.0	243.0	43.0	67.0	<10.0

TABLE 2 (continued)

	Metagabbro P-965	Metagabbro P-975†	Amphibolite P-686A†	Metagabbro P-970†	Metagabbro P-434A†
SiO_2	46.48	47.44	46.54	48.11	47.31
Al_2O_3	16.91	15.52	11.85	18.05	18.43
Fe_2O_3*	11.08	9.31	5.37	5.75	7.00
MgO	9.51	12.58	21.11	11.01	11.98
CaO	3.13	12.06	15.24	15.78	13.86
Na_2O_3	1.73	1.39	1.45	1.54	1.52
K_2O	0.07	0.09	0.02	0.03	0.05
TiO_2	0.17	0.10	0.07	0.10	0.06
P_2O_5	0.06	0.20	0.06	0.06	0.06
MnO	0.10	0.11	0.10	0.10	0.11
TOTAL	99.24%	99.13%	101.81%	100.53%	100.38%

Rb	tr	9.0	8.1	3.4	11.5
Sr	127.5	119.2	128.3	125.8	152.4
Zr	46.4	44.7	44.0	35.4	40.6
Y	14.9	20.8	26.3	7.0	22.0
Ni	<10.0	223.0	10.0	460.0	394.0
Ba	<10.0	<10.0	<10.0	<10.0	<10.0
Nb	29.8	27.4	17.2	tr	tr
Cu	90.0	25.0	37.0	44.0	125.0
Cr	170.0	<10.0	<10.0	82.0	235.0
V	243.0	<10.0	108.0	185.0	113.0

DISCUSSION

Mafic/ultramafic complexes and isolated mafic or ultramafic bodies occur in a variety of settings within the Appalachian orogen. They range from demonstrable ophiolites to ophiolitic debris to plutons. Studies of the type conducted herein of mafic/ultramafic complexes in medium to high grade terranes elsewhere in the Appalachians (for example, Crowley, 1976; Drake and Morgan, 1981) yield similar results to ours. These bodies were all derived in noncontinental environments, probably in the late Precambrian Iapetus Ocean or as part of a more outboard terrane (see Williams and Hatcher, 1982).

Appalachian mafic and ultramafic rocks have been emplaced in a variety of settings. Those that have been subjected to deformational and metamorphic overprints must be considered in the context of the overall evolution of the mountain chain and the setting in which they presently reside. Their post-igneous emplacement history may involve a complex variety of events of thrusting, folding, and multiple events of penetrative strain. These must be properly addressed before their histories may be properly resolved.

An interesting comparison may be made with examples of intermediate to ultramafic plutons in the Klamath and western Sierra Nevada Mountains (Snoke and others, 1982), where the rocks are not as complexly

TABLE 3
Chemical analyses of Gladesville complex rocks

	Amphibolite 16/IS/R.H.	Amphibolite 317/BE/R.H.	Amphibolite 354/BE/R.H.	Amphibolite 120/BE/R.H.	Amphibolite 277/BE/J.W.	Amphibolite 123/IS/R.H.	Amphibolite 352/BE/R.H.†	Amygdaloidal amphibolite 388/BE/R.H.†	Amphibolite 479/BE/J.W.	Chlorite schist 349/BE/J.W.†	Metamelagabbro 453/BE/R.H.†
SiO_2	57.79	57.02	56.23	54.59	51.60	50.89	50.49	50.42	48.16	46.06	44.35
Al_2O_3	13.81	15.10	14.20	11.35	12.06	13.27	14.24	14.34	19.56	14.16	5.44
Fe_2O_3*	8.66	12.12	10.44	12.50	14.89	12.21	7.13	6.66	11.49	11.49	12.98
MgO	3.60	3.15	3.45	4.67	3.91	6.64	9.06	9.08	4.13	16.09	19.38
CaO	11.32	10.02	8.61	12.21	9.19	10.61	13.38	13.75	12.97	9.17	11.65
Na_2O	2.44	2.22	3.59	2.09	3.15	3.20	2.61	2.39	2.39	3.00	1.80
K_2O	0.32	0.45	0.39	0.33	0.61	0.08	0.36	0.33	0.22	0.29	0.20
TiO_2	0.44	0.88	0.94	1.63	1.31	1.07	0.53	0.39	0.87	0.65	0.25
P_2O_5	0.15	0.28	0.24	0.27	0.21	0.17	0.18	0.13	0.13	0.15	0.13
MnO	0.21	0.20	0.22	0.22	0.22	0.16	0.14	0.12	0.14	0.16	0.18
S. total	98.74	100.44	98.31	98.86	97.15	98.30	98.12	97.61	100.06	101.77	96.36
L.O.I.	0.53	0.33	1.50	0.46	1.33	0.82	1.03	0.63	0.33	0.05	0.70
TOTAL	99.27%	100.77%	99.81%	99.32%	98.48%	99.12%	99.15%	98.24%	100.39%	101.82%	97.06%
Mo	2.0	0.9	1.1	1.0	1.7	0.8	1.2	1.9	1.0	0.7	
Nb	N.D.	17	19	N.D.	N.D.	N.D.	6.3	25	N.D.	18.7	
Zr	58	75	81	114	62	104	75.7	60	42	63	
Y	26.7	28.8	28.0	33.8	31.0	25.3	28.6	28.0	20.4	23.4	
Sr	126	238	353	153	259	190	234	216	332	423	
Rb	2.6	8.5	4.5	25.4	11.3	6.8	9.8	7.0	8.7	7.1	
Ba	116	337	154	259	233	137	223	138	158	148	

† Analyses not used in Pearce or Pearce and Cann diagrams.
Trace element concentrations in ppm.

deformed and metamorphosed as the examples cited here. Also, these rocks are easily related to a mid-Mesozoic arc complex.

Ophiolite sheets and mafic intrusives may look very much alike after undergoing polyphase deformation and medium to high grade metamorphism. They may be dismembered by folding and boudinage, faulting, or otherwise producing small pods and fragments that resemble ophiolitic debris (fig. 8). These small bodies (up to 1-2 km) may behave as soft but coherent "punctured basketballs" or competent "watermelon seeds" during ductile deformation, thus accounting for the isolated and podiform shapes of a number of mafic bodies and alpine-type ultramafic bodies. The presence of water doubtlessly would assist this process by causing hydration reactions to occur along the outer edges of these bodies converting primary materials with largely equant properties to a sheath of amphiboles and layer silicate minerals. This would enhance the ability of the mass to move under stress, particularly if additional unreacted water is present.

The solution to the problem is to utilize a multidisciplinary approach to the study of mafic and ultramafic bodies in medium to high grade terranes. This is probably the only way that we will be able ultimately to understand the origins of most of the altered mafic and ultramafic bodies in the Appalachians and other orogens.

CONCLUSIONS

1. Detailed field structural and stratigraphic studies, coupled with elemental analyses of samples, provide the necessary background data for interpretation of the complex histories of Appalachian mafic and ultramafic rocks.

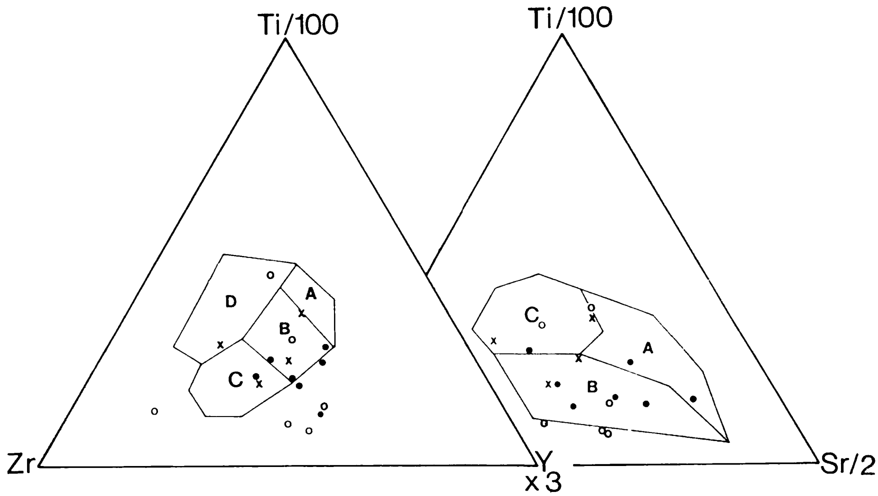

Fig. 5. Ti–Zr–Y and Ti–Zr–Sr discrimination diagrams (Pearce and Cann, 1973). In the Ti–Zr–Y diagram, A + B = low potassium tholeiites, C + B = calcalkaline basalt, B = ocean floor basalt, and D = within plate basalt. In the Ti–Zr–Sr diagram, A = low potassium tholeiites, B = calcalkaline basalt, and C = ocean floor basalt. o's — Carroll Knob complex; x's — Laurel Creek complex; dots — Gladesville complex.

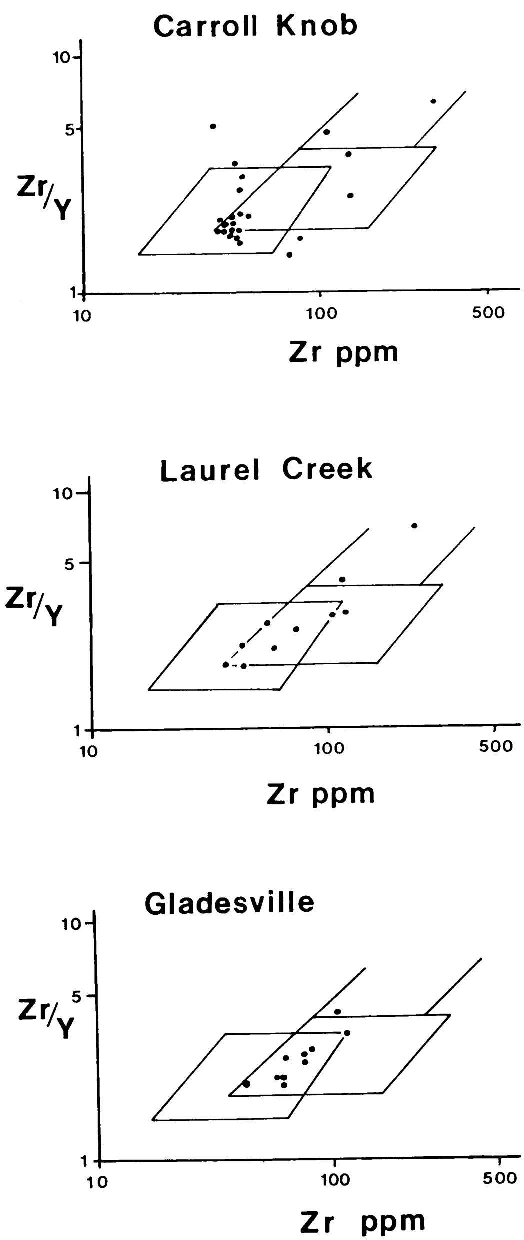

Fig. 6. Zr/Y versus Zr discrimination diagrams (Pearce and Cann, 1973) for mafic rocks from the three complexes. The lower left box in each diagram is the field for island arc tholeiites, the middle box is mid-ocean ridge basalts, and the upper right box is the within plate basalts.

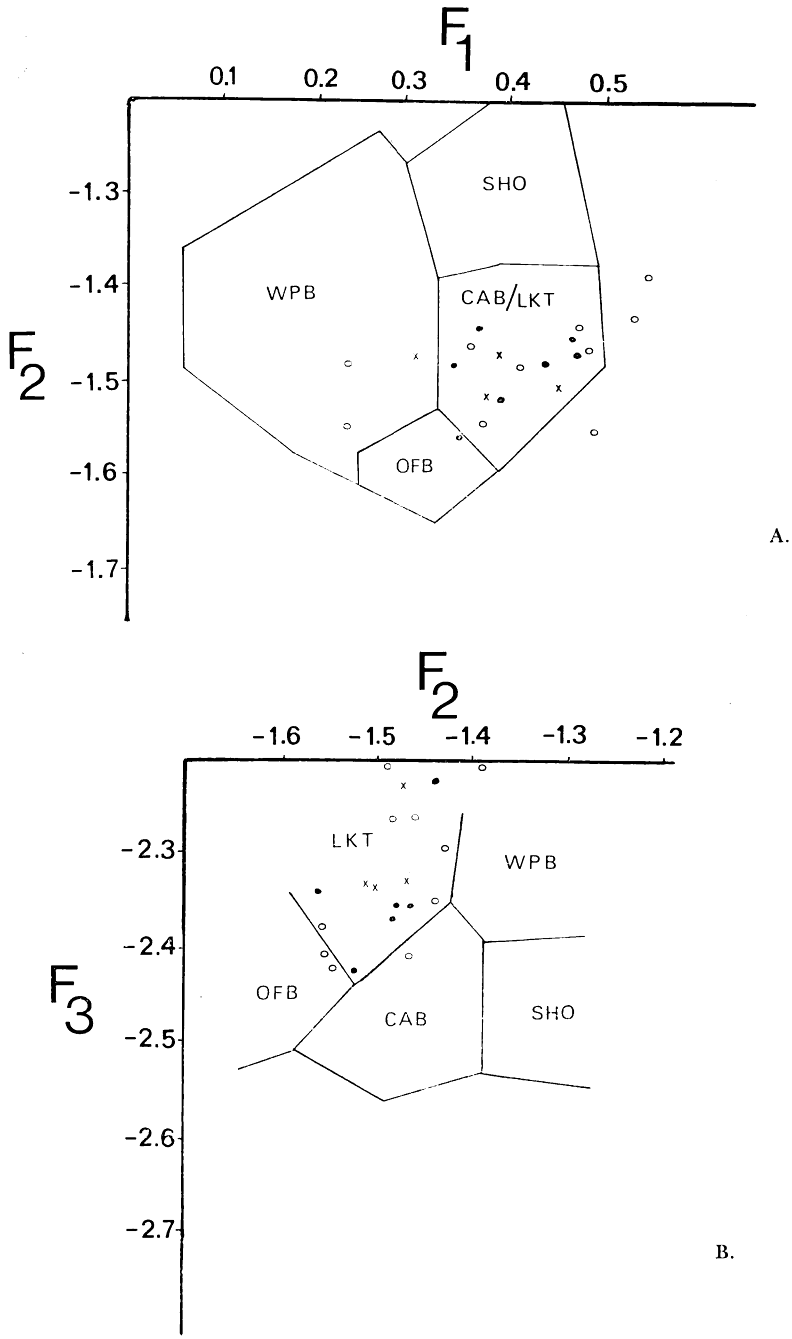

Fig. 7. F_1 versus F_2 (A) and F_2 versus F_3 (B) major element discriminant diagrams (Pearce, 1976) for mafic rocks from the Carroll Knob (circles), Laurel Creek (x's), and Gladesville (dots) complexes.

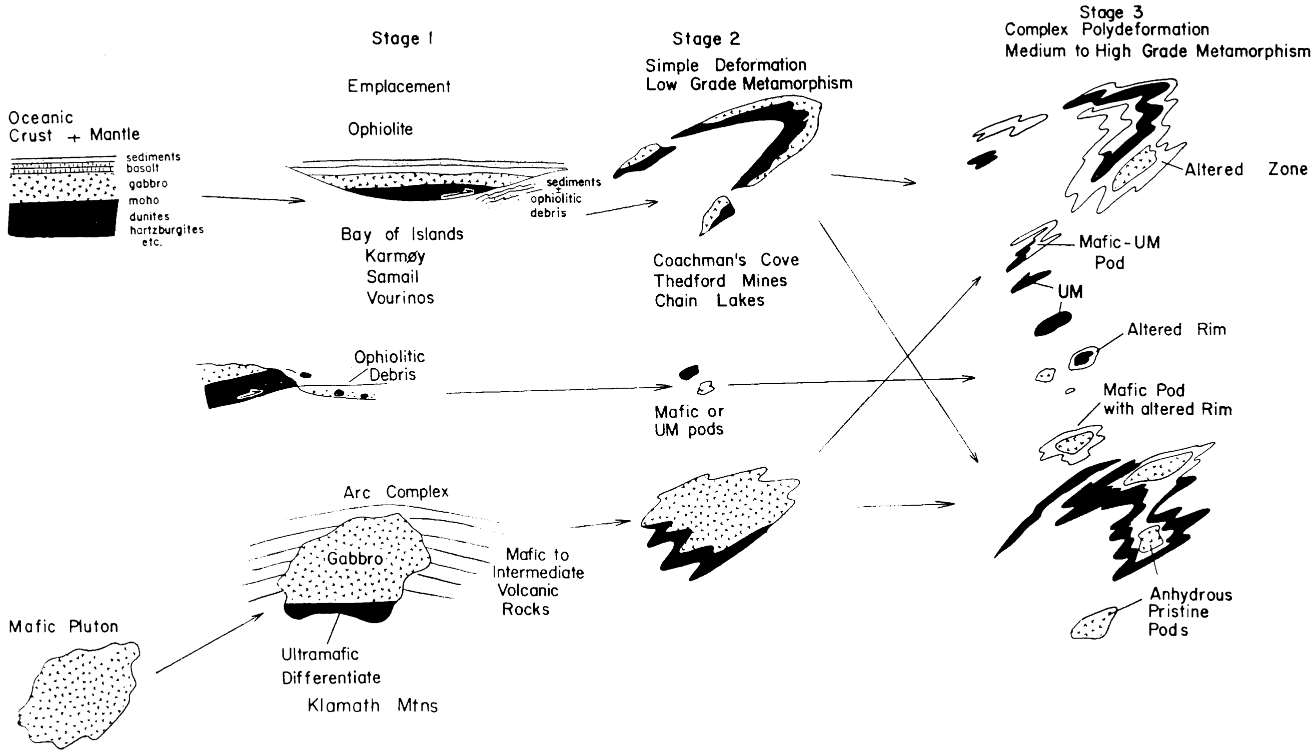

Fig. 8. Diagram showing the possible subsequent histories for mafic and ultramafic rocks from a simple emplacement as primary igneous bodies through several stages of deformation and varying degrees of metamorphism.

2. Study of three southern Appalachian examples, the Carroll Knob, Laurel Creek, and Gladesville complexes, demonstrates that all had a non-continental origin, and at least one, the Laurel Creek complex, was probably an ophiolite. The Carroll Knob complex may have been an ophiolite but could also have been a complex pluton, and the Gladesville complex was likely part of a mafic arc complex.

3. Elemental data, when plotted on standard discriminant diagrams, strongly suggest none of these complexes was produced in a continental environment.

4. Ophiolites and complex mafic plutons may appear similar following intense deformation and metamorphism. Furthermore, they may be tectonically dismembered into small fragments that resemble ophiolitic debris. These small bodies may be moved as resistant "punctured basketballs" and "watermelon seeds" during ductile deformation so that they become isolated from the larger body from which they were derived. Water probably aids the process.

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