

## **Petrology and geochemistry of metamorphosed ultramafic bodies in a portion of the Blue Ridge of North Carolina and Virginia**

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### **Abstract**

Seventeen metamorphosed ultramafic bodies in the Precambrian Ashe Formation exposed along a northeast-trending belt from near West Jefferson, North Carolina to near Floyd, Virginia in the Blue Ridge, were investigated. The mineral assemblages in individual samples constitute subgroups drawn from the larger group consisting of olivine, enstatite, tremolite, anthophyllite, antigorite, talc, chlorite, magnetite, and dolomite. Although the ultramafic bodies occur in the garnet, staurolite, and kyanite zones recognized in the country rock, no correlation exists between the mineral assemblages in the ultramafic rock and the metamorphic zones. Modal analyses and quantitative chemical analyses for Mg, Al, Ca, Fe, Ni, Mn, Cu, Co, K, and Zn lead to the recognition of two distinct types of metamorphosed ultramafic bodies based on the degree of metasomatic alteration. The metasomatic exchange with the country rock involves the loss of magnesium and nickel and the introduction of aluminum, calcium, iron, manganese, and potassium into the ultramafic bodies. The less altered bodies are more massive and contain relict olivine and rare relict enstatite plus tremolite, anthophyllite, chlorite, and antigorite whereas the more altered bodies are more strongly foliated with abundant tremolite and chlorite and less common relict olivine.

Textural evidence, notably the pseudomorphous partial replacement of tremolite by serpentine, combined with that provided by the geochemical study provides the basis for understanding the recrystallization history and the calculation of mass balance equations. A retrograde hydration of the ultramafic protolith produced the tremolite–chlorite–talc anthophyllite assemblage with relict olivine. In a second stage of this hydration serpentine replaced some of the tremolite and olivine. A later partial dehydration led to the more strongly foliated and, in some places, mylonitized tremolite–chlorite–talc schist or phyllonite.

### **Introduction**

Alpine ultramafic bodies occur throughout the length of the Appalachian Mountains from Quebec to Alabama. These typically peridotitic or dunitic plutons and their serpentinitized equivalents have received considerable attention from petrologists (Misra and Keller, 1978), but a group of metamorphosed and metasomatized ultramafic rocks exposed in the eastern Blue Ridge of North Carolina and Virginia (Fig. 1) have not been investigated in any detailed way. These petrographically rather uncommon rocks were recognized by Keith (1903)

as probably originally ultramafic although they are now largely chlorite–tremolite schists and gneisses and were mapped by Rankin, Espenshade, and Newman (1972) as generally small lens-shaped bodies in the Precambrian Ashe Formation.

The bodies investigated are typically elongate in map view ranging in size from 0.6 km by 0.2 km to 8.0 km by 1.5 km. They are exposed in a northeast trending belt from southwest of West Jefferson in Ashe County, North Carolina to near Floyd in Floyd County, Virginia, a distance of 150 km. A total of fifteen bodies were sampled for petrographic and geochemical study (Table 1).

The study was designed to answer four principal questions. (1) What was the nature of the protolith from which these extensively altered rocks were

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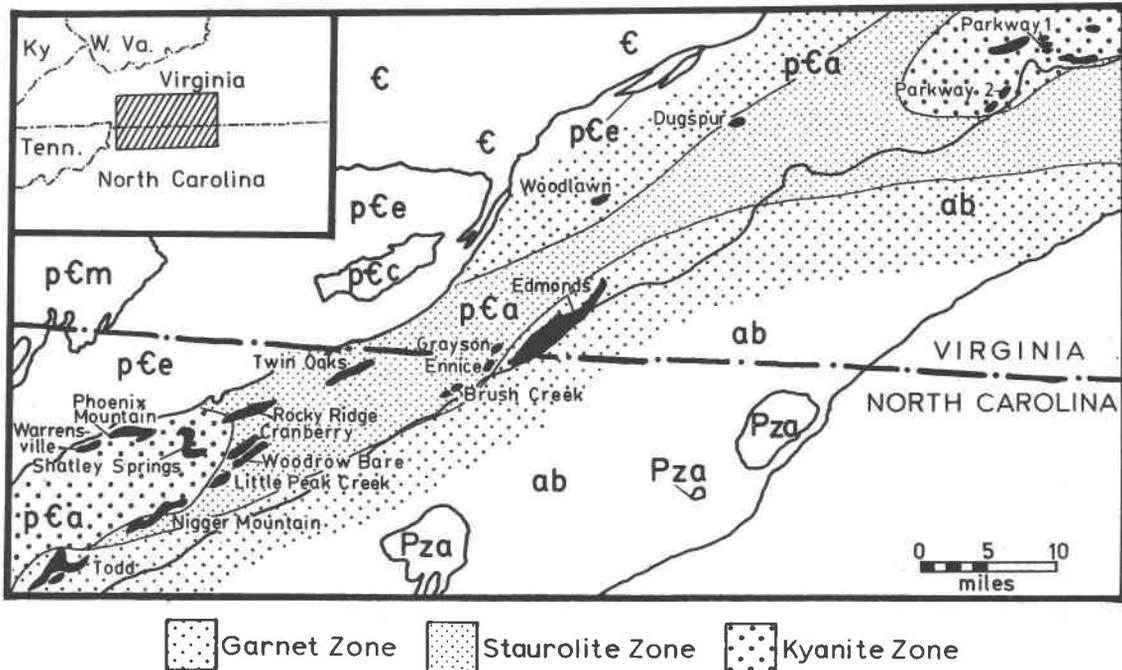


Fig. 1. Location of ultramafic bodies in eastern Blue Ridge in North Carolina and Virginia southeast of Fries fault. pεe—Elk Park Plutonic Group, pεc—Crossnor Plutonic Group, pεa—Ashe Formation, pεm—Mount Rodgers Formation, ab—Alligator Back Formation, ε—Cambrian Sediments, Pza—Spruce Pine Plutonic Group. After Rankin *et al.* (1972). The area of kyanite zone shown in the northeast corner of the map was mapped only as “Amphibolite facies” by Rankin *et al.* (1972).

derived? (2) What relationship exists between the present mineralogy of these rocks and the metamorphic grade of the country rock which changes along the trend of the exposures of ultramafic rock (Fig. 1) from the garnet zone through the staurolite zone to the kyanite zone based on the mapping of Rankin *et al.* (1972). (3) What metasomatic changes have occurred during recrystallization of these rocks based on the present concentrations of the major elements Mg, Fe, Ca, and Al, and the trace elements Mn, Co, Cu, K, Ni, and Zn? (4) What is the recrystallization history of these bodies?

The size, shape, and geologic occurrence of these bodies in deformed Precambrian metasediments and volcanics strongly suggests that they were alpine ultramafic intrusives (as defined by Jackson and Thayer, 1972) and probably emplaced tectonically in a non-liquid state (see Misra and Keller, 1978). What is not clear is whether these rocks were originally harzburgites or dunites, common among the unaltered ultramafic bodies of the Appalachians, or were another ultramafic rock type.

The alteration history of these rocks is undoubtedly complex, involving retrogressive recrystallization from the original ultramafic assemblage plus

chemical mass transfer between the country rock and the ultramafic intrusives. The mineral assemblages of individual specimens are subgroups drawn from the larger suite which comprises olivine, enstatite, tremolite, anthophyllite, chlorite, talc, serpentine, magnetite, and dolomite.

#### Previous investigations

Evans (1977) provided a valuable review of the petrology of metamorphosed peridotites and serpentinites. Trommsdorf and Evans (1974) described the development of mineralogy similar to that observed in this study in ultramafics subjected to alpine regional and contact metamorphism, except that in their study olivine is the dominant mineral rather than tremolite or chlorite.

The textural relationships in the study by Trommsdorf and Evans persuasively demonstrate a prograde metamorphism from serpentinite to peridotite in response to a regional metamorphic episode. As is discussed below, the texture observed in the ultramafic bodies described here is quite different and is not interpreted as indicating a single prograde metamorphism.

Some recent studies of ultramafic rocks in the

Table 1. Division of ultramafic bodies into Todd-type and Edmonds-type

Todd-type bodies	Edmonds-type bodies
(T) Todd	(ED) Edmonds
(W) Warrensville	(GR) Grayson
(NM) Nigger Mountain	(EN) Ennice
(WB) Woodrow Bare	(B) Brush Creek
(L) Little Peak Creek	
(SS) Shatley Springs	
(P) Phoenix Mountain	
(C) Cranberry	
(RR) Rocky Ridge	
(TO) Twin Oaks	
(WL) Woodlawn	
(DG) Dugspur	
(PK) Parkway 1	
(PK) Parkway 2	

Southern Appalachians are pertinent to this investigation. Swanson (1980) described dunite, harzburgite, and orthopyroxenite from two small bodies in the Ashe Formation on Rich Mountain in North Carolina. The metamorphic mineralogy of these rocks included tremolite, talc, and anthophyllite, chlorite, serpentine, and magnesite. Textural relationships indicate the rocks have undergone two, and possibly three, deformations. Swanson concluded that the olivine and pyroxene in these rocks are metamorphic products and not relicts of the primary igneous mineralogy. Although these rocks occur in the Ashe Formation approximately 15 kilometers to the southwest of the belt of ultramafic bodies described here, they are significantly different mineralogically and texturally. Most notably they contain much higher concentrations of olivine and pyroxene and only minor amounts of tremolite and chlorite, the dominant minerals in the ultramafic bodies to the northeast. Additionally, unlike the rocks investigated in this study, they show little or no evidence of metasomatism. They also apparently lack textural evidence indicating relict olivine.

Other recent studies of less altered ultramafic bodies in North Carolina are those of Hahn and Heimlich (1977) and Alcorn and Carpenter (1977).

The rocks in both of these studies have been interpreted as the result of partial serpentinization during or after the emplacement of dunite, but neither has been extensively recrystallized since emplacement.

## Petrology

### General statement

In outcrop these metamorphosed ultramafic bodies are grayish-green with a distinct schistose foliation which typically parallels that of the amphibolite or biotite muscovite gneisses of the Ashe Formation with which they are in contact. The foliation is expressed microscopically by the parallelism of such platy or prismatic minerals as chlorite, tremolite, and talc and the elongation of such non-platy minerals as olivine and dolomite in the foliation plane. In places the foliation planes are deformed into small irregular folds. Larger olivine (up to 5 mm diameter) and some of the less common enstatite crystals are wrapped by the foliation indicating their relict status.

Although all of the rock bodies have a similar megascopic appearance, they can be divided readily into two principal petrographic groups (Table 1) on the basis of mineral association and major and trace element concentrations (Tables 2 and 3). The first group, designated the "Todd-type" after the largest body representative of this group, is characterized by high concentrations of tremolite and chlorite with lesser talc and minor amounts of olivine. The second group is called the "Edmonds-type" because that large body is typical of the group. These bodies are characterized by higher concentrations of olivine, antigorite, anthophyllite, and talc and lesser amounts of tremolite and chlorite. The Todd-type bodies characteristically have lower abundances of magnesium and nickel and higher abundances of calcium, aluminum, manganese, and zinc as compared to the Edmonds-type bodies. Iron is somewhat more abundant in the Todd-type bodies, and the concentration of cobalt is not significantly different in the two types of bodies.

Table 4 contains the point count mineral analysis for each sample with the name of the body from which it was obtained and the metamorphic grade of the country rock. Figure 1 is a map showing the name and location of each of the ultramafic bodies sampled. Figure 2 is a map showing sample locations.

Table 2. Mean values of modal mineral amount by body and type of body

Body	N	Mineral									
		Tr	Ch	Ol	Mg	Car	Antho	Talc	Antig	Lim	En
Todd-type											
Todd	15	50.7	33.8	8.9	2.0	3.4	0.0	0.0	0.0	0.0	0.0
Niger Mountain	15	59.1	29.7	0.9	0.9	2.2	0.2	2.8	0.0	0.5	0.0
Warrensville	4	54.9	30.6	0.1	1.4	12.4	0.3	0.0	0.0	0.4	0.0
Phoenix Mountain	4	64.8	27.6	2.1	0.6	3.2	0.0	0.6	0.0	0.1	0.0
Little Peak Creek	4	76.0	20.7	0.0	0.8	0.3	0.0	0.0	0.0	tr	0.0
Woodrow Bare	4	66.2	30.0	0.6	1.2	0.7	0.0	0.0	0.0	0.4	0.0
Cranberry	3	60.0	23.9	tr	1.7	14.0	0.0	0.0	0.0	0.3	0.0
Shatley Springs	10	61.4	29.1	4.5	2.0	0.3	0.2	0.0	0.0	0.1	0.0
Rocky Ridge	8	61.9	31.1	tr	2.1	3.3	0.0	1.1	0.0	0.0	0.0
Twin Oaks	1	50.6	42.7	0.0	0.7	5.3	0.7	0.0	0.0	0.0	0.0
Parkway	2	46.4	36.6	6.5	4.7	0.5	0.0	6.5	0.0	0.0	tr
Woodlawn	1	44.4	44.6	0.0	tr	9.1	0.0	0.0	0.0	0.0	0.0
	Mean*	56.4	31.7	2.1	1.5	4.5	0.1	3.0	0.0	0.2	tr
Edmonds-type											
Brush Creek	1	68.9	23.5	0.5	2.7	0.0	0.0	0.0	0.0	0.0	0.0
Ennice	3	15.9	29.9	0.0	2.0	14.7	1.3	24.6	0.0	0.0	0.0
Grayson	4	7.7	20.9	19.9	2.8	14.7	12.7	10.9	7.7	0.0	3.3
Edmonds	9	27.9	26.0	21.8	3.3	0.1	1.9	9.1	9.7	0.2	0.0
	Mean*	37.6	25.1	10.6	2.7	7.4	4.0	11.2	2.4	tr	0.8

\*Mean of the mean values of individual bodies, thus slightly different from the true means of the Todd- and Edmonds-type samples.

### Relationship between mineralogy and metamorphic grade

One of the purposes of this study was to examine the relationship between the mineral assemblage in the metamorphosed ultramafic bodies and the metamorphic grade of the country rock in which they were emplaced. Trommsdorf and Evans (1974) described a series of mineral assemblages in Alpine ultramafic rocks which have undergone prograde regional metamorphism from an original serpentine stage. The sequence, applicable to the rocks under study here, is (1) antigorite + talc + tremolite, equivalent to the staurolite-kyanite and lower zones of pelitic rocks; (2) forsterite + talc, equivalent to metamorphism slightly higher than the kyanite zone; (3) forsterite + anthophyllite + tremolite, a somewhat higher grade assemblage; and (4) tremolite + forsterite + enstatite, an assemblage roughly equivalent to the sillimanite zone.

Although these assemblages occur in some of the ultramafic bodies described here, their distribution does not correspond to the metamorphic grade of the country rock as indicated by the isograds mapped (Fig. 1) in the Ashe Formation by Rankin *et al.* (1972). Assemblage (1) occurs in some samples of the Nigger Mountain, Ennice, Grayson, and

Edwards bodies; assemblage (2) in some samples of the Nigger Mountain, Edmonds, Grayson, and Phoenix Mountain bodies; assemblage (3) occurs in some samples of the Nigger Mountain, Waynesville, Grayson, and Edmonds bodies; assemblage (4) occurs in two samples of the Grayson body and one of the Parkway body (Table 4).

Inspection of Figure 1, the regional map of these bodies, shows no correspondence between the occurrence of these assemblages and indicated metamorphic grade of the country rock perhaps because the temperature range recorded in the pelitic rocks was too narrow to be reflected in the ultramafic bodies. Moreover, there is no systematic geographic distribution of these assemblages regardless of the grade of the country rock and in several cases assemblages representing different grades occur in the same body. We conclude that the observed mineral distribution does not reflect a prograde regional metamorphism of serpentinite, but a two-stage retrogressive recrystallization of a dunite or harzburgite protolith. Observations which support this assertion will be described in subsequent sections of the paper, but critical to this conclusion is the occurrence of antigorite pseudomorphs after tremolite (Fig. 3). Whether the tremolite, olivine, and chlorite crystallized simultaneously or sequen-

Table 3. Mean values of chemical data by body and type of body

Body	N	Weight percent					ppm					
		MgO	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe	MnO	Co	Cu	K	Mn	Ni	Zn
Todd-type												
Todd	8	22.13	5.74	5.53	9.25	0.20	124	107	75	1520	1052	104
Niger Mountain	7	22.96	5.85	4.09	9.00	0.21	110	89	62	1620	1129	120
Phoenix Mountain	2	20.26	7.10	6.79	8.45	0.20	89	33	457	1494	905	113
Little Peak Creek	2	20.35	9.00	7.93	10.40	0.24	138	38	262	1875	735	103
Woodrow Bare	2	22.41	6.12	3.35	9.50	0.23	129	60	69	1800	1245	148
Cranberry	2	22.50	4.84	5.34	10.04	0.22	143	63	41	1693	880	107
Shatley Springs	3	26.72	5.97	2.27	10.50	0.19	127	100	56	1480	1170	116
Rocky Ridge	4	22.49	7.66	5.93	9.42	0.19	114	125	66	1458	1010	94
Twin Oaks	1	16.93	7.54	11.05	8.27	0.18	117	151	104	1367	1040	95
Parkway	3	18.84	5.55	6.68	9.18	0.21	104	235	518	1646	876	101
Woodlawn	2	24.03	8.43	4.91	9.82	0.22	116	40	45	1470	945	78
Mean*		21.78	6.71	5.81	9.44	0.21	119	95	160	1585	1099	107
Edmonds-type												
Brush Creek	1	23.38	2.74	0.08	5.32	0.09	119	10	22	697	1910	42
Ennice	2	27.04	3.61	3.20	6.85	0.13	102	24	26	955	1510	61
Grayson	2	41.31	1.02	.66	7.20	0.08	139	39	43	674	2220	52
Edmonds	10	33.10	3.26	3.51	6.39	0.12	117	71	63	1092	1836	62
Mean*		31.22	2.66	1.86	6.44	0.11	119	36	39	855	1619	54

\* Mean of the mean values of the individual bodies, thus slightly different from the true mean of Todd- and Edmonds-type samples.

tially, it is quite evident that serpentinization followed rather than preceded their crystallization. The relict nature of the olivine is strongly suggested where small anhedral olivine crystals with optical continuity are separated by interstitial serpentine (Fig. 3).

#### Mineralogy and texture

*Olivine.* Relict olivine is present in both Edmonds- and Todd-type bodies although it is more common and occurs as somewhat larger crystals in the Edmonds-type samples. In the less recrystallized Edmonds-type samples individual crystals of

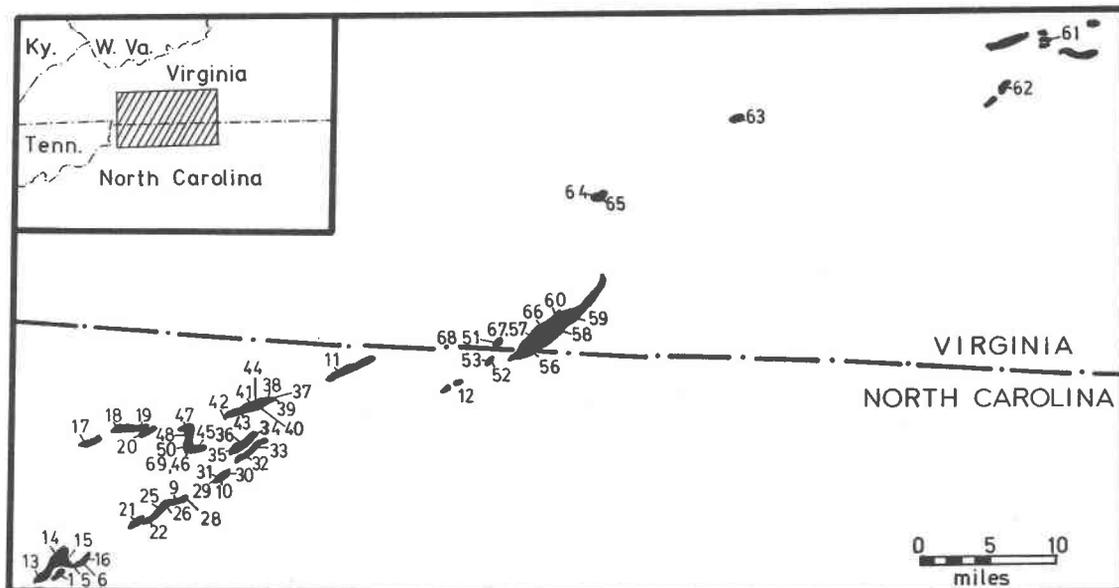


Fig. 2. Map of sample locations. See Figure 1 for name and geologic position of individual bodies.

Table 4. Mineralogical data derived from point count analysis of samples from the ultramafic bodies in North Carolina and Virginia

Sample number	Mineral										
	Tremolite	Chlorite	Olivine	Magnetite	Carbonate	Anthophyllite	Talc	Antigorite	Limonite	Enstatite	Meta. zone
T 5	42.6	33.1	18.2	3.3	1.8	0.0	0.0	0.0	0.0	0.0	G
T 6	60.8	35.9	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	G
T 13-b	28.9	25.6	38.6	4.5	2.1	0.0	0.0	0.0	0.0	0.0	G
T 13-d	35.5	49.7	12.6	1.9	0.3	0.0	0.0	0.0	0.0	0.0	G
T 13-1	58.9	33.6	0.0	1.0	0.0	0.0	4.5	0.0	0.0	0.0	G
T 14-b	57.9	37.9	0.0	1.6	5.8	0.0	0.0	0.0	0.0	0.0	G
T 15-b	61.2	31.6	0.0	1.1	3.8	0.0	0.0	0.0	0.0	0.0	G
T 16-d	46.3	28.3	19.5	1.1	4.0	0.0	0.0	0.0	0.0	0.0	G
T 16-a	65.6	29.4	0.0	1.2	0.6	0.0	0.0	0.0	0.0	0.0	G
T 2	49.4	33.0	0.0	1.0	11.6	0.0	0.0	0.0	0.0	0.0	G
NM 21-b	43.4	37.1	3.1	0.6	2.0	2.0	9.0	0.0	0.0	0.0	S
NM 21-c	61.8	36.5	0.0	1.6	0.0	0.0	0.0	0.0	0.1	0.0	S
NM 21-d	55.3	44.3	0.0	1.0	0.0	0.0	0.0	0.0	2.3	0.0	S
NM 21-e	56.4	28.0	0.0	0.5	4.5	0.0	10.4	0.0	0.0	0.0	S
NM 21-f	51.9	45.9	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	S
NM 21-g	66.5	29.1	2.2	0.6	0.5	0.2	0.0	0.6	0.0	0.0	S
NM 7	67.6	16.6	0.0	0.2	4.2	6.0	1.2	0.0	2.2	0.0	S
NM 24	58.7	37.2	0.0	1.8	0.0	0.0	0.0	0.0	1.3	0.0	S
NM 22	72.2	17.0	0.0	0.5	10.2	0.0	0.0	0.0	0.0	0.0	S
NM 23	56.0	28.7	6.1	0.8	0.0	0.0	7.2	0.0	0.7	0.0	S
NM 25-a	56.6	30.4	2.0	1.2	6.4	0.0	3.4	0.0	0.0	0.0	S
NM 25-b	61.5	36.9	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	S
NM 26-b	53.8	31.6	0.0	1.3	0.2	0.0	10.6	0.0	0.0	0.0	K
NM 26	60.8	35.3	2.0	1.2	0.0	0.0	0.0	0.0	0.7	0.0	S
NM 9	63.9	28.7	0.0	0.2	4.5	0.0	0.0	0.0	0.0	0.0	K
W 17-XA	66.4	13.6	0.0	1.2	18.7	0.0	0.0	0.0	0.2	0.0	K
W 17-X	32.7	40.1	0.0	1.0	26.2	0.0	0.0	0.0	0.0	0.0	K
W 17-1	59.9	30.9	0.4	2.2	4.4	1.1	0.0	0.0	1.1	0.0	K
W 17-2	60.6	37.7	0.0	1.2	0.1	0.0	0.0	0.0	0.4	0.0	K
P 18-a	66.0	31.8	0.0	0.2	0.6	0.0	0.0	0.0	0.0	0.0	K
P 18-b	62.1	32.9	0.8	0.8	0.0	0.0	2.4	0.0	0.0	0.0	K
P 20-u	86.6	13.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	K
P 20-a	44.3	32.1	7.4	1.2	13.2	0.0	0.0	0.0	0.0	0.0	K

olivine are fractured with serpentine occurring in the fractures. Anthophyllite and tremolite have replaced olivine and are in turn partially replaced by serpentine (Fig. 3). In the Todd-type bodies olivine occurs as smaller fragmented clusters which are elongated in the foliation. Here olivine does not occur with serpentine but commonly occurs with chlorite which is located in the pressure shadows formed by the olivine clusters, as well as in the foliation. The presence of chlorite in the pressure shadows of olivine attests to the secondary origin of the chlorite with respect to olivine and the relict nature of the olivine.

Chemical and optical data obtained by Laskowski and Scotford (1980) from an Edmonds-type sample (0-25) indicate that the olivine composition is 88.5 mol% forsterite, this value being based on atomic absorption analyses of mineral separates. This same sample contains only 737 ppm Ca. The  $2V$  is  $+88^\circ$  and the  $n_D \beta$  is 1.672 for this specimen. The optical data of two samples of olivine from Todd-type

rocks indicate compositions of 90 and 91 mol% forsterite.

*Antigorite.* The serpentine mineral is identified as antigorite on the basis of its X-ray diffraction pattern. No unique lizardite peaks were observed and four typical antigorite peaks are present (Borg and Smith, 1979). Antigorite has partially replaced olivine in some Edmonds-type rocks and also has replaced tremolite resulting in partial pseudomorphs of serpentine after tremolite (Fig. 3). It also appears to have replaced chlorite in a few samples. It is absent in Todd-type bodies.

*Tremolite.* Tremolite is common in both types of ultramafic bodies. In the more massive Edmonds-type rocks its prismatic crystals are completely unoriented producing a jack-straw texture. In those Edmonds-type rocks which have been lightly sheared with a relatively widely spaced fracture foliation, the tremolite laths are shredded at their terminations and have been rotated into parallelism with the foliation. In some places where the basal

Table 4. (continued)

Sample number	Mineral										Meta. zone
	Tremolite	Chlorite	Olivine	Magnetite	Carbonate	Anthophyllite	Talc	Antigorite	Limonite	Enstatite	
L 29-b	99.1	0.0	0.0	0.0	0.0	tr	0.0	0.0	tr	0.0	S
L 30	74.5	23.9	0.0	0.3	1.3	0.0	0.0	0.0	0.0	0.0	S
L 10	68.7	25.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	S
L 31	61.7	34.2	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	S
WB 32-c	62.0	33.4	0.0	0.8	0.2	0.0	0.0	0.0	0.0	0.0	S
WB 33-a	66.8	28.5	0.0	1.5	2.2	0.0	0.0	0.0	0.0	0.0	S
WB 33-b	66.9	26.6	2.4	1.9	0.2	0.0	0.0	0.0	1.7	0.0	S
WB 36	67.9	31.4	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	S
C 35	54.6	36.7	0.0	2.1	6.6	0.0	0.0	0.0	0.0	0.0	S
C 34-a	68.1	12.4	0.0	1.5	16.9	0.0	0.0	0.0	0.3	0.0	S
C 34-b	57.3	22.7	tr	1.5	18.5	0.0	0.0	0.0	0.0	0.0	S
SS 47-a	70.2	21.8	0.0	1.0	0.0	0.0	7.1	0.0	0.0	0.0	K
SS 47-b	86.0	9.0	0.0	1.4	0.0	1.0	0.0	0.0	0.0	0.0	K
SS 50	63.6	27.5	1.0	0.5	1.1	1.0	0.0	0.0	0.0	0.0	K
SS 48	63.9	28.8	2.5	0.5	0.0	0.0	0.0	0.0	0.3	0.0	K
SS 48-a	67.4	24.4	4.6	1.3	0.0	0.0	0.0	0.0	0.0	0.0	K
SS 45-a	66.9	30.8	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	K
SS 45-b	51.9	45.6	0.0	1.0	0.0	0.0	0.0	0.0	1.0	0.0	K
SS 46	58.8	31.2	5.5	4.0	0.5	0.0	0.0	0.0	0.0	0.0	K
SS 46-d	49.3	29.5	18.0	2.8	0.2	0.0	0.0	0.0	0.0	0.0	K
SS 69-a	36.1	42.6	13.4	7.1	1.0	0.0	0.0	0.0	0.0	0.0	K
RR 43	52.0	34.6	0.0	0.3	12.8	0.0	0.0	0.0	0.0	0.0	K
RR 42-b	71.1	28.1	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	K
RR 44	66.4	29.0	0.0	0.5	0.1	0.0	0.0	0.0	0.0	0.0	S
RR 41	65.2	31.4	0.0	1.1	1.6	0.0	0.0	0.0	0.0	0.0	S
RR 40-b	59.5	34.9	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	S
RR 37-a	60.1	27.1	0.0	0.3	1.7	0.0	9.1	0.0	0.0	0.0	S
RR 39	62.3	36.0	0.0	1.5	0.2	0.0	0.0	0.0	0.0	0.0	S
RR 38-b	58.5	36.7	0.0	2.7	2.1	0.0	0.0	0.0	0.0	0.0	S
TO 11	50.6	42.7	0.0	0.7	5.3	0.7	0.0	0.0	0.0	0.0	S
B 12-a	68.9	23.5	0.5	2.7	0.0	0.0	0.0	0.0	0.0	0.0	S
EN 53-b	42.3	42.4	0.0	1.9	7.7	0.0	5.8	0.0	0.0	0.0	S
EN 53-a	41.9	36.6	0.0	3.7	13.1	0.0	4.7	0.0	0.0	0.0	S
EN 52	0.0	10.9	0.0	0.5	23.2	3.8	62.6	0.0	0.0	0.0	S

sections are subparallel with the plane of the thin section, the drag of chlorite and antigorite crystals at their contacts with the larger tremolite basal sections gives the impression of rotation or "snow ball" texture (Fig. 4). Tremolite has replaced olivine, rare enstatite, and in a few places shows evidence suggesting it has replaced chlorite (Fig. 5). In Todd-type bodies the tremolite laths are aligned parallel to the foliation plane in many samples. In others the tremolite crystals have been shredded and deformed in response to later shearing producing a phyllonitic texture. In some well-sheared rocks the larger tremolite crystals constitute porphyroclasts in a matrix of smaller chlorite and tremolite prismatic crystals.

*Anthophyllite.* Anthophyllite, distinguished from cumingtonite by its parallel extinction and lack of twinning, is present in some Edmonds-type samples where its occurrence is similar to that of tremolite.

It is rare in Todd-type rocks. Some crystals show a prismatic habit whereas others are fibrous.

*Chlorite.* Chlorite is common in both types of ultramafic bodies. It is colorless or faintly green-tan pleochoric and has a small extinction angle suggesting clinocllore. It occurs as a matrix mineral replacing olivine in the less recrystallized Edmonds-type bodies or is concentrated in the foliation planes in those Edmonds-type samples having foliation. In a few samples it is concentrated in small veinlets. It appears to have a wide range of temperature stability as it also occurs abundantly in the Todd-type tremolite phyllonites. Chlorite occurs in the pressure shadows of relict olivine phenoclasts in some Todd-type samples. A few chlorite crystals are cross cut by tremolite laths suggesting a paragenetic sequence: chlorite-tremolite (Fig. 5). However, it is probable the chlorite was stable throughout the recrystallization and deformation history of these

Table 4. (continued)

Sample number	Mineral										
	Tremolite	Chlorite	Olivine	Magnetite	Carbonate	Anthophyllite	Talc	Antigorite	Limonite	Enstatite	Meta. zone
GR 51-a	4.7	32.1	18.1	1.2	10.3	30.2	1.1	tr	2.0	0.0	S
GR 51-b	15.2	12.0	2.1	0.9	40.0	tr	29.6	0.0	0.0	0.0	S
GR 51-c	6.0	27.2	23.2	9.1	1.0	10.7	0.0	22.8	0.0	tr	S
GR 68	4.8	12.1	36.2	tr	7.6	0.0	13.0	8.2	0.0	13.1	S
ED 56-a	82.8	1.5	0.0	5.4	0.0	10.0	0.0	0.0	0.0	0.0	G
ED 56-c	2.6	16.7	48.9	1.3	0.6	4.2	17.4	8.0	0.0	0.0	G
ED 57-a	21.1	65.4	10.2	3.2	0.0	0.0	0.0	0.0	0.0	0.0	G
ED 57-b	50.2	43.6	1.6	2.6	0.0	0.0	2.0	0.0	0.0	0.0	G
ED 58-a	1.8	9.3	30.7	0.3	0.0	tr	13.9	44.8	0.0	0.0	G
ED 59	0.0	25.0	55.4	1.0	0.2	0.8	7.2	9.1	1.3	0.0	G
ED 60-b	8.8	28.7	15.7	2.8	0.0	tr	41.2	1.7	0.6	0.0	G
ED 66-a	21.4	13.1	33.6	6.0	0.0	2.0	tr	23.6	0.0	0.0	G
ED 67-a	62.7	30.3	0.0	7.1	0.0	0.0	0.0	0.0	0.0	0.0	G
PK 62	54.0	31.9	0.0	3.2	0.0	0.0	11.1	0.0	0.0	0.0	G
PK 61-b	38.8	41.2	13.1	6.2	1.0	0.0	0.0	0.0	0.0	tr	G
WL 65	44.4	44.6	0.0	tr	9.1	0.0	0.0	0.0	0.0	0.0	G

G = Garnet; S = Staurolite; K = Kyanite; T = Todd; NM = Nigger Mountain; W = Warrensville; P = Phoenix Mountain; L = Little Peak Creek; WB = Woodrow Bare; C = Cranberry; SS = Shatley Springs; RR = Rocky Ridge; TO = Twin Oaks; EN = Ennice; GR = Grayson; ED = Edmonds; PK = Parkway-1; WL = Woodlawn; B = Brush Creek.

rocks as it clearly replaces olivine but is present in the fracture foliation of the most sheared Todd-type bodies. Also, its occurrence in the pressure shadows around tremolite indicates that in those places it post-dates that mineral.

Microprobe analyses by William Zhong (pers. comm.) of chlorite samples separated from specimens used in this study show a distinct difference between the compositions of three chlorite samples taken from Edmonds-type rocks and eight taken from Todd-type rocks. The mean major element weight percentages of these two types of chlorites

are as follows: Mg 22.19 for Edmonds versus 16.85 for Todd; Fe 3.16 for Edmonds versus 8.98 for Todd; Al 6.28 for Edmonds versus 8.41 for Todd; Si 14.47 for Edmonds versus 12.51 for Todd. There is little difference in Cr concentration between the two types of samples; 0.48% for Edmonds and 0.43 for Todd.

**Talc.** Talc is more common in the Edmonds-type rocks but occurs in both types. It is most commonly a matrix mineral not aligned with respect to a foliation or fracture planes.

**Dolomite.** Dolomite ( $\omega = 1.691$ ,  $\epsilon = 1.548$ ) occurs widely but is rarely more than an accessory mineral. It typically cross-cuts the foliation or appears to have replaced other minerals, suggesting a late stage crystallization.

**Enstatite.** Relict enstatite occurs in a few Edmonds-type samples where it has been replaced by antigorite, anthophyllite, or tremolite. The measured  $2V$  of  $+82^\circ$  indicates a composition of about  $En_{91}Fs_9$ .

### Textural interpretation

Mineral occurrence and textural fabric allow an interpretation of the crystallization history. These rocks have undergone two principal stages of recrystallization which appear to have been approximately synchronous with two deformation episodes. An initial retrograde hydration during ductile

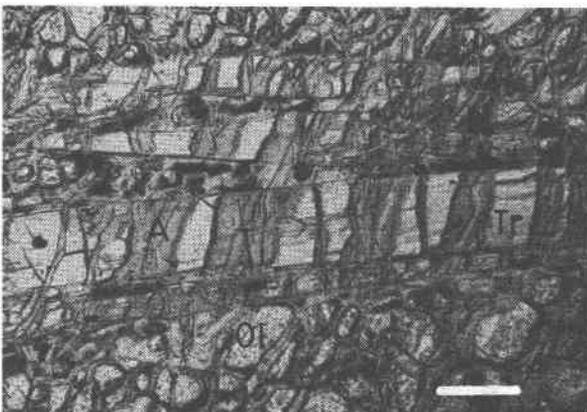


Fig. 3. Prismatic tremolite (Tr) crystal with pseudomorphous replacement by antigorite (A). Relict olivine (O1) partially replaced by antigorite (A). Bar = 0.025 mm. Edmonds-type.

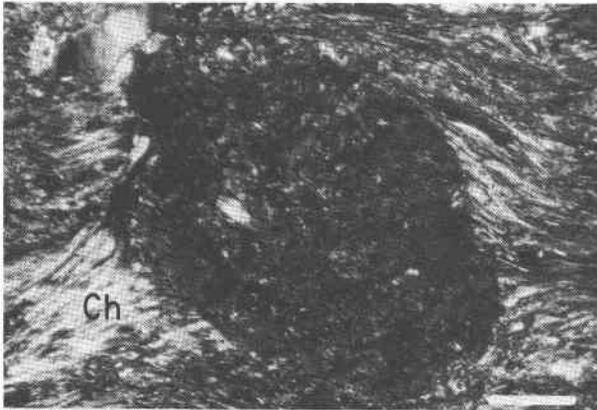


Fig. 4. "Snowball" basal section of tremolite (Tr) with finer chlorite (Ch) in pressure shadow. Bar = 0.025 mm. Todd-type.

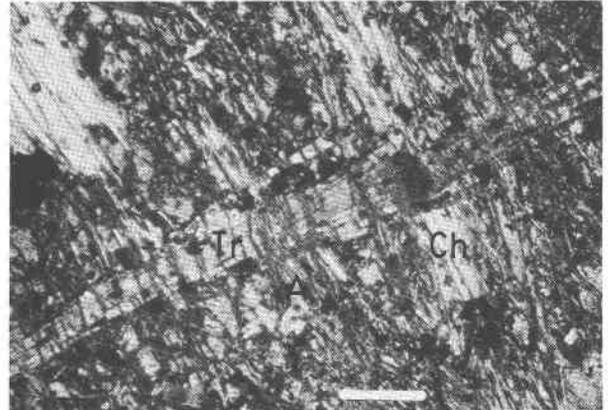


Fig. 5. Tremolite (Tr) crystal cutting chlorite (Ch) and being cut by antigorite (A). Bar = 0.05 mm. Todd-type.

deformation was followed by a progressive dehydration during a brittle deformation. The Edmonds-type bodies have been affected principally by the first stage whereas the Todd-type bodies show the effects of both stages.

The peridotite protolith has not been preserved but the least altered of the Edmonds-type rocks contain olivine and enstatite which have been partially replaced by chlorite, talc, anthophyllite, and dolomite. Tremolite replaced some of the olivine, and in turn was replaced by antigorite which also replaced some of the remaining olivine along fractures (Fig. 3). These rocks were only slightly affected by a ductile deformation which caused a poor alignment of tremolite blades and chlorite plates in some specimens whereas others remain unaffected and exhibit a jack-straw texture. The retrograde recrystallization began with the peridotite protolith assemblage of olivine and enstatite being partially replaced by tremolite and chlorite and to a lesser extent by talc and dolomite. The final event in this sequence was the partial serpentinization of the tremolite and remaining olivine.

The second stage, a dehydration and cataclasis accompanying a brittle shearing deformation, is best seen in the Todd-type samples. There is a gradation in the degree of shearing from rocks with widely spaced shear fractures in which large tremolite porphyroclasts were partially shredded and rotated into parallelism with the shear planes, to phyllonites composed almost entirely of smaller tremolite fragments and chlorite plates strongly oriented in the fracture foliation. The perfection of the preferred orientation of the tremolite and chlorite is proportional to the closeness of the spacing of

the fractures. Typically large porphyroclasts of tremolite remain surrounded by deflected foliation bands of finer tremolite and chlorite. Small relict olivine phenoclasts persist in many of these phyllonites attesting to the ultramafic protolith of these rocks.

The crystallization sequence in the second stage begins with the tremolite-rich rocks containing some chlorite and minor talc, olivine, serpentine, and chlorite. As the tremolite was shredded by shearing deformation, additional chlorite formed in the foliation and in pressure shadows. Some dolomite replaced both of these minerals after the shearing episode. Talc is present but not common in these rocks and serpentine is absent. Magnetite, a product of the olivine serpentinization, persists from the first stage and minor iron oxide has formed in some shear fractures.

The texture of the rocks under investigation here contrasts sharply with that described by Evans and Trommsdorf (1970) in metamorphosed ultramafic rocks in the Alps. The Alpine rocks contain a discernible foliation but are characterized by mosaic textures involving olivine, tremolite, anthophyllite, antigorite, and enstatite. These textures are correctly interpreted as representing equilibrium assemblages in a prograde recrystallization of serpentinite. Such textural arrangements are not present in the rocks under study here, nor are the overgrowth textures reported by Trommsdorf and Evans (1974) indicating a prograde origin of tremolite and olivine present. Rather, the textural relationships in the present rocks indicate a secondary origin of the serpentine and relict olivine and enstatite.

Table 5. Analyses of USGS standard PCC-1

	PCC-1					
	Flanagan		PCC-1 this study			
	(1973)					
Weight percent						
MgO	43.18	42.16	42.49	42.33	43.32	42.24
Al <sub>2</sub> O <sub>3</sub>	0.74	0.76	0.77	0.77	0.85	----
CaO	0.51	0.52	0.51	0.52	0.52	0.48
Fe <sub>2</sub> O <sub>3</sub>	2.85	ND	ND	ND	ND	ND
FeO	5.24	ND	ND	ND	ND	ND
Total Fe as Fe <sub>2</sub> O <sub>3</sub>	8.35	8.02	8.20	8.31	8.34	8.39
K <sub>2</sub> O	0.004	0.004	0.004	0.003	0.003	0.004
ppm						
Co	112	113	115	110	108	112
Cu	11	17	13	19	9	15
Mn	959	975	975	930	950	952
Ni	2339	2390	2300	2325	2320	2160
Zn	36	38	38	36	36	35

Comment should be made on the possibility that the Edmonds- and Todd-type bodies represent two contrasting groups of ultramafic occurrences with separate protoliths and post-emplacement histories rather than rocks with the same protolith but representing separate stages of the same post-emplacement history as assumed in the above discussion. Observations which favor the single protolith history are: (1) both groups of bodies occur in the same stratigraphic unit (the Ashe Formation) and lie approximately along the same structural trend; (2) both tend to be elongated in the prominent S<sub>1</sub> foliation trend; (3) a few samples from Edmonds-type bodies are chemically and mineralogically similar to Todd-type samples; (4) Todd-type samples commonly contain relict olivine and porphyroclasts of tremolite—minerals characteristic of the less recrystallized Edmonds-type rocks.

The cause of the observed difference in degree of alteration of the two types of bodies is not self-evident but is possibly attributable to differences in permeability, with the typically smaller more sheared Todd-type bodies being more permeable to hydrothermal fluids.

#### Geochemistry of the metamorphosed ultramafic bodies

##### Analytical methods, accuracy, and results

Sixty-one samples were analyzed by atomic absorption spectrophotometry for Mg, Al, Ca, Fe,

Mn, Co, Cu, K, Ni, and Zn. Accuracy of the analyses was evaluated by determining elemental composition of the USGS standard PCC-1. With every run of four to eight rock samples, a standard was analyzed along with a contamination blank. Before continuing analyses of unknown ultramafic rocks, elemental analysis of the standard PCC-1 had to be within an acceptable range and the contamination blank was required to be low compared to standard working solutions. Analyses of PCC-1 are listed in Table 5 with the accepted values as stated by Flanagan (1973). Values for Mn, Zn, Ca, Ni, and Co are within three percent (of the amount present) of the accepted value. The trace elements Cu and K had higher errors, but this was a result of their low abundances.

The precision of the analyses was determined through duplicate analyses of pairs of samples. Reproducibility of at least five percent of the amount present was obtained for all elements except K, Ca, and Fe. Commonly 1–3 percent precision was achieved. From the iron analyses it appears that the powders used for analyses were not completely homogeneous. This is also the case with the analyses of calcium. For potassium most values were reproducible to 25 percent of the amount present. Duplicate analyses of the standard PCC-1 showed good reproducibility for all elements.

Table 6 shows the chemical analytical results obtained by sample and by body.

##### Elemental distribution

The mean values quoted in this section are the means of all samples or the means of Todd- or Edmonds-type samples and differ slightly from the mean values shown on Table 2 which are means of the mean values of individual ultramafic bodies.

**Magnesium.** The mean magnesia content for all the rocks analyzed is 25.59 weight percent MgO, with a range from 14.77 to 42.45 percent. The Edmonds-type samples have higher magnesia content (33.38% mean MgO) than the Todd-type samples (22.38% mean MgO). The Todd-type samples are low in Mg compared to the average for all ultramafic rocks as reported by Turekian and Wedepohl (1961, Table 1). Based on a literature search, it appears that an average of 38–40% MgO is probable for alpine-type peridotites. Thus, the rocks under study are abnormally low in magnesium when compared to alpine-type peridotites.

**Iron.** The distribution of iron reflects the division of Todd-type and Edmonds-type ultramafic bodies. The Edmonds-type have lower (6.11% mean) but

more varied iron (4.03–10.20% Fe) concentrations than the Todd-type (9.13% mean, 7.93–11.40% range). The mean for all samples is 8.30% Fe which is slightly lower than the average (9.38% Fe) reported by Turekian and Wedepohl (1961, Table 1) for all ultramafic rocks. Probably the higher concentration of iron in the Todd-type samples reflects the metasomatic loss of magnesium from Fe–Mg minerals in these bodies.

*Aluminum.* The distribution of alumina shows that the Edmonds-Type samples have lower mean concentrations (3.11%  $\text{Al}_2\text{O}_3$ ) than the Todd-type samples (6.28%  $\text{Al}_2\text{O}_3$ ) and that the Todd-type have higher concentrations of aluminum than the average of peridotites of 3.99%  $\text{Al}_2\text{O}_3$  reported by Wedepohl (1969).

Most samples analyzed in this study have very high aluminum concentrations compared to alpine-type harzburgites which dominate the alpine ultramafics of the Appalachians, although some of the Edmonds-type samples have aluminum concentrations that compare to typical alpine harzburgites. It is thus probable that all of the Todd-type and some of the Edmonds-type samples have been enriched in aluminum. As no garnet pseudomorphs or relicts of feldspar have been observed, the aluminum must be of metasomatic origin derived from the country rock.

*Calcium.* The mean calcium content as CaO for all rocks analyzed is 4.55%. The Edmonds-type samples show a larger variation (0.94–11.87% CaO) and a lower mean (2.86%) than the Todd-type samples (2.75–11.47% and 5.19%). It is clear that the Edmonds-type samples have generally lower concentrations of calcium, although three samples (66c, 56a, 53a) show much higher calcium than the typical Todd-type sample.

Wedepohl (1969) reported that the average peridotite contains 3.46% CaO. Compared to this value the Todd-type samples appear to represent rocks enriched in calcium and the Edmonds-type those depleted in calcium. It must be kept in mind that the average peridotite includes garnet-rich varieties which would tend to increase the calcium content compared to the average alpine-type harzburgite.

Clinopyroxene accounts for most of the calcium in fresh alpine ultramafics. In view of the large amount of calcium in most of the samples for this study, a wehrlitic peridotite, garnet wehrlite, or pyroxenite composition is necessitated if the calcium is considered primary. However, as the rocks studied are not fresh ultramafics and contain almost no relict pyroxene, a metasomatic source for the

calcium is favored. The negative correlation of calcium with magnesium of  $-0.669$  ( $P = 0.0001$ ) and the positive correlation with tremolite of  $0.576$  ( $P = 0.0002$ ) and the low concentration of calcium in the olivine suggest that calcium was introduced and was incorporated into the tremolite as magnesium was removed.

*Nickel.* The mean nickel content for all the ultramafics analyzed is 1238 ppm. The Todd-type samples range from 540 to 1680 ppm and have a mean content of 1053 ppm. The Edmonds-type samples have a wider range (461 to 2660 ppm) and a higher mean (1730 ppm). If the few Edmonds-type samples, probably altered, with the very low nickel concentrations are not considered the mean would be much higher.

Turekian and Wedepohl (1961) reported an average nickel content for ultramafic rocks of 2000 ppm Ni. Goles (1967) revised this estimate to 1500 ppm Ni. A positive correlation ( $0.811$ ,  $P = 0.0001$ ) found in the present study between nickel and magnesium, the positive correlation with olivine ( $0.570$ ,  $P = 0.0002$ ), and the negative correlation with iron ( $-0.348$ ,  $P = 0.0301$ ) are consistent with observations made by Vogt (1923) and Stueber and Goles (1967).

The Todd-type ultramafics have lower nickel contents than peridotites and dunites, but higher concentrations than pyroxenites. Most of the Edmonds-type samples have nickel concentrations similar to dunites and typical alpine peridotites or harzburgites. This distribution can best be explained by a metasomatic model where nickel tends to follow magnesium as it is removed from the ultramafic body. This type of variation in nickel concentrations in metasomatic environments for ultramafic rocks was demonstrated by Curtis and Brown (1971).

*Cobalt.* No easily observable differences exist between the Todd-type and Edmonds-type samples with respect to the distributions of cobalt, although it is possible that contamination with cobalt in the tungsten carbide grinding elements has affected the values obtained. The mean cobalt content for all samples is 118 ppm, as it is separately for the Todd-type and Edmonds-type samples. This value is very near the 110 ppm average reported by Goles (1967) for ultramafic rocks.

*Manganese.* Manganese concentrations largely separate the rocks analyzed into Todd- and Edmonds-types. The mean concentration is 1358 ppm for all analyzed samples. The Todd-type samples range from 973 to 1960 ppm Mn and have a 1566

Table 6. Analyses of ultramafic rocks

Sample number	Weight percent					ppm					
	MgO	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe	MnO	Co	Cu	K	Mn	Ni	Zn
T 2	25.43	5.19	5.93	7.93	0.17	112	146	26	1347	1145	93
T 16-a	24.40	5.70	3.19	9.60	0.19	132	230	42	1460	1190	95
T 13-d	14.77	4.92	7.32	8.29	0.18	133	71	73	1390	990	120
T 13-b	26.73	5.37	4.34	9.48	0.20	146	110	70	1576	1170	137
T 14-b	14.94	8.23	6.86	8.56	0.21	100	81	223	1603	680	157
T 15-b	15.77	5.89	7.06	8.91	0.19	110	95	59	1520	1140	121
T 5	23.13	5.16	3.82	9.86	0.21	143	50	53	1637	1070	105
T 6	31.58	6.18	5.75	11.40	0.21	112	69	54	1624	1030	122
NM 7	25.58	4.88	4.35	8.79	0.22	114	27	26	1680	1430	117
NM 9	23.57	5.86	4.57	8.80	0.19	104	98	68	1460	1080	132
NM 21-e	23.85	5.86	5.57	9.36	0.20	112	179	72	1513	1100	110
NM 21-g	21.69	6.16	3.17	9.18	0.25	98	57	106	1947	900	133
NM 22	16.77	4.73	4.48	8.17	0.20	107	58	67	1550	1100	84
NM 25-a	26.17	5.51	3.10	9.42	0.19	120	87	33	1510	1260	147
NM 26	23.09	7.92	3.36	9.28	0.22	118	109	65	1683	1030	114
P 18-b	23.96	4.87	3.48	8.74	0.19	105	39	42	1458	1270	122
P 19-a	24.62	5.43	3.91	8.69	0.18	110	76	44	1387	1230	114
P 20	16.56	9.33	10.10	8.15	0.20	75	27	857	1530	540	103
SS 45-b	23.71	7.41	3.11	11.31	0.21	118	73	54	1637	1130	ND
SS 46	25.19	5.56	4.75	8.03	0.20	132	86	60	1515	1040	106
SS 47-b	22.44	5.03	4.52	8.60	0.24	103	129	59	1890	880	120
SS 69-a	28.61	5.79	0.45	9.46	0.17	143	91	ND	1323	1038	100
SS 69-b	27.86	4.70	3.24	10.73	0.19	120	135	58	1479	1343	131
RR 38-b	22.49	7.24	6.21	8.96	0.16	123	305	31	1247	1350	81
RR 39	20.42	10.21	6.23	9.45	0.23	105	131	67	1750	860	104
RR 41	26.37	4.87	2.91	10.31	0.24	112	81	17	1828	1285	ND
RR 42-b	23.24	7.32	6.76	8.12	0.19	106	11	102	1450	930	85
RR 43	23.82	5.88	4.51	11.16	0.18	121	51	64	1383	900	104
ED 56-a	22.99	0.88	11.57	4.03	0.14	61	5	111	1084	580	29
ED 57-a	33.62	3.09	2.33	10.20	0.21	180	133	30	1624	2030	92
ED 58-a	40.09	0.99	0.10	5.63	0.12	119	14	27	904	2340	55
ED 59	38.60	1.87	0.04	6.88	0.13	177	12	34	1044	2350	67
ED 60-b	33.86	2.61	1.97	5.47	0.13	121	35	32	983	1800	59
ED 66-a	39.55	1.86	1.17	6.07	0.13	115	71	21	973	2125	45

ppm mean. The Edmonds-type samples range from 397 to 1624 ppm Mn and have a mean of 950 ppm. Most of the Edmonds-type samples have manganese contents similar to the average of ultramafics as reported by Goles (1967), but most Todd-type samples show concentrations higher than this average value of 1040 ppm.

It has been reported by Livingston (1976) and by Curtiss and Brown (1971) that manganese concentrations increase during metasomatism of ultramafic bodies, which is consistent with observed manganese distribution in the rocks investigated here. The metasomatized Todd-type samples show higher manganese concentrations than the less altered Edmonds-type samples. This transfer of manganese into the ultramafics is supported by a positive correlation between manganese and the principal mineralogical product of metasomatism, tremolite (correlation coefficient 0.605,  $P = 0.0001$ ). Microprobe analyses show no Mn present in the chlorite (William Zhong, pers. comm.).

*Zinc.* The means for zinc content of the Edmonds- and Todd-type samples show a distinct difference between these two groups. The average zinc content for all ultramafics analyzed is 96 ppm. The mean for 38 Todd-type samples is 111 ppm with a range of 45 to 157 ppm Zn. The mean for the Edmonds-type samples is 57 ppm and the range is 29 to 110 ppm. This mean is comparable to that for ultramafic rocks of 50 ppm Zn (Turekian and Wedepohl, 1961). Vinogradov (1962) reported 30 ppm as an average for ultramafic rocks. It thus appears that the Todd-type ultramafic rocks have been somewhat enriched in zinc compared to the Edmonds-type.

*Copper.* The division of samples into two groups based on copper content is not as straightforward as it is for the other elements. There is a large overlap in copper concentrations between Todd- and Edmonds-type samples although the latter tend to have somewhat lower copper concentrations. The mean copper content for all samples is 81 ppm. The

Table 6. (continued)

Sample number	Weight percent					ppm					
	MgO	Al <sub>2</sub> O <sub>3</sub>	CaO	Fe	MnO	Co	Cu	K	Mn	Ni	Zn
ED 66-b	39.10	1.46	2.03	5.65	0.10	109	137	20	760	1985	37
ED 66-c	22.36	4.22	11.87	4.41	0.12	59	19	260	965	550	34
ED 67-a	33.40	3.42	3.90	4.31	0.14	103	202	33	1062	2360	110
ED 67-b	31.51	12.18	0.18	5.94	0.12	123	25	19	899	461	58
L 10	18.87	10.92	11.47	10.40	0.25	158	32	451	1960	590	102
L 30	21.83	5.47	4.38	10.40	0.23	118	44	72	1790	880	104
TO 11	16.93	7.54	11.05	8.27	0.18	117	151	104	1367	1040	95
B 12-a	23.38	2.74	0.08	5.32	0.09	119	10	22	697	1910	42
EN 52	29.47	1.85	0.11	4.24	0.05	92	5	15	397	1970	30
EN 53-a	24.71	5.37	6.30	9.13	0.20	112	43	37	1513	1050	ND
WB 32-c	20.75	5.81	3.95	9.17	0.21	126	6	91	1650	970	152
WB 33-b	24.07	6.42	2.75	9.84	0.25	133	114	46	1950	1520	143
C 34-b	23.96	4.81	6.74	10.20	0.24	159	30	40	1865	770	111
C 35	21.03	4.87	3.93	9.88	0.20	126	95	41	1520	1060	103
GR 51-a	40.17	1.02	0.31	9.30	0.09	173	20	41	727	2660	61
GR 68	41.45	ND	1.00	5.08	0.08	104	58	41	620	1780	43
WL 65	24.01	7.71	5.09	9.79	0.19	113	55	45	973	1200	45
WL 64	24.05	9.16	4.74	9.84	0.25	118	25	ND	1967	690	111
DG 63-b	23.34	5.59	6.31	9.71	0.16	108	93	45	1253	890	100
PK 62	23.71	ND	5.07	8.40	0.15	83	194	35	1200	725	89
PK 61-b	24.18	5.55	4.51	9.69	0.23	143	428	ND	1767	1680	101
PK 61-c	8.62	ND	10.45	9.45	0.25	84	84	1000	1970	225	113

T = Todd; NM = Nigger Mountain; P = Phoenix Mountain; L = Little Peak Creek; WB = Woodrow Bare; C = Cranberry; SS = Shatley Springs; RR = Rocky Ridge; TO = Twin Oaks; EN = Ennice; GR = Grayson; ED = Edmonds; PK = Parkway-1; WL = Woodlawn; B = Brushy Creek; DG = Dugspur.

mean copper content for the Todd-type samples is 92 ppm with a range of 6 to 230 ppm. The range of the Edmonds-type samples is similar to the Todd-type (5 to 202 ppm), but that mean copper content is lower (53 ppm). All of these values are high compared with averages for ultramafic rocks of 10, 20, and 30 ppm as reported by Turekian and Wedepohl (1961), Vinogradov (1962), and Goles (1967) respectively.

**Potassium.** There is no clear distribution of potassium between the Edmonds- and Todd-type samples although most samples with low potassium are of the Edmonds-type. The mean potassium concentration for all ultramafics analyzed is 81 ppm. The Todd-type samples have a mean of 94 ppm and a range of 17 to 857 ppm. The Edmonds-type samples have a mean of 50 ppm and a range of 15 to 260 ppm. As potassium may enter ultramafic rocks during metasomatism it is interesting to note that the samples containing more than 200 ppm K (14b, 20, 10, and 66c) on the basis of major element concentrations are among those altered metasomatically to the greatest extent. It is also important

to note that sample 20, which contains the highest potassium concentrations (857 ppm), was located within one foot of the contact with country rock.

Carswell *et al.* (1974) and Curtis and Brown (1969) demonstrated that potassium enters ultramafic bodies from solutions derived from the country rock in quantities which are a function of country rock composition, but in amounts smaller than those of calcium or aluminum. Thus if potassium enters the ultramafic along with aluminum and calcium, these elements should show positive correlations. Conversely, as potassium enters the ultramafics, magnesium moves toward the country rock, and therefore correlation between potassium and magnesium should show a negative correlation. These correlation coefficients are indeed observed: K vs. Al = 0.510 ( $P = 0.0009$ ), K vs. Ca = 0.553 ( $P = 0.0003$ ), and K vs. Mg =  $-0.369$  ( $P = 0.0207$ ).

#### Mineral reactions and metasomatism

A sequence of mineral reactions and metasomatic exchanges which describes the evolution of these bodies from the protolith ultramafic rock to the



eastern Blue Ridge as post-kinematic, thus somewhat later than the  $S_1$  foliation.

Although a pre-emplacment age for the first stage retrograde hydration of the ultramafic protolith cannot be ruled out, the presence of the  $S_1$  foliation in even the Edmonds-type bodies, which is expressed by the preferred orientation of chlorite and tremolite, strongly suggests that these reactions are post-emplacment and reasonably represent a partial reestablishment of equilibrium in the pressure, temperature, and water environment of regional metamorphism in comparison to that of the higher intensity environment of the upper mantle. The second stage hydration reaction causing the partial serpentinization of olivine and tremolite is tentatively assignable to the metamorphic regime which followed the peak of taconic metamorphism (Hatcher, 1978, Fig. C). The dehydration stage of the sequence which was accompanied by shearing is then possibly correlative with the Acadian(?) ( $375 \pm m.y.$ ) greenschist metamorphism and brittle deformation associated with the  $F_3$  folding (Hatcher, 1978).

As pointed out by Rankin, Espenshade, and Shaw (1973), these ultramafic bodies typically occur on the northwest side of the amphibolite layers in the Ashe Formation although some occur on the southeast side and some are independent of the amphibolite outcrops. This association suggests a genetic relationship and perhaps an ophiolitic association. Whether or not this is valid, a tectonic emplacement of these ultramafic bodies seems most likely. Hatcher (1978) theorized that thrusts initiated in the unstable sea floor brought oceanic crust and mantle, including the mafic and ultramafic rocks of the eastern Blue Ridge, into the sedimentary pile during the closing of a marginal sea in Middle to Late Cambrian.

The nature and history of the protolith before its probable tectonic emplacement is an important but difficult question. It may have progressed through a prograde deserpentinization cycle before the retrograde events described in this study. Whether or not an earlier deserpentinization has occurred, we favor a history involving emplacement of enstatite-bearing dunite from an ophiolite source. The projected major element chemistry of the protolith based on this study is characterized by low calcium concentration. This is typical of dunite and harzburgite from ophiolite metamorphic peridotite complexes according to chemical data provided by Coleman (1977, Tables 1, 2, 3, and 4) and contrasts

with the high calcium abundances characteristic of lherzolites or cumulate ultramafic rocks from ophiolites. This suggests a source from the base of the ophiolite sequence below the cumulate peridotite and mafic members of the sequence.

### Conclusions

Analysis of the mineralogical and geochemical data, together with textural information, indicates that the ultramafic bodies investigated can be divided into two distinct groups, the more recrystallized and metasomatized Todd-type and the less altered Edmonds-type. The contrasting character of these two types of bodies reflects differing degrees of alteration of the original protolith, probably a dunite which contained a small amount of enstatite.

Textural evidence is important in understanding the sequence of mineral reactions which converted the protolith to the tremolite-chlorite-talc schist of the Todd-type bodies. In the less altered Edmonds-type rocks primary olivine and uncommon primary enstatite have been replaced by tremolite, chlorite, talc, and anthophyllite. In a second hydration stage, there was pseudomorphous replacement of some of the tremolite by antigorite, which also replaced some olivine (Fig. 3). These observations support the conclusion that the recrystallization sequence did not begin with serpentinization as has been reported in other areas. The lack of antigorite in the Todd-type samples and the mylonitic texture of many of these samples indicate a second major stage in the recrystallization was one of partial dehydration and cataclasis.

An examination of the abundance data for Mg, Al, Ca, Fe, Ni, Mn, Cu, Co, K, and Zn obtained from analyses of these rocks allows conclusions to be drawn concerning the movement of these elements during metasomatism. Assuming, for reasons detailed earlier, that the two types of ultramafic bodies investigated represent different degrees of metasomatic alteration of the protolith, the exchange of these elements between the ultramafic bodies and the country rock can be described. There is strong evidence that Mg and Ni have been removed from the ultramafic rocks and that Al has been added. It is probable, though less well demonstrated, that Ca, Fe, Mn, and K entered the ultramafic bodies and that Co was removed. The movement, if any, of Zn and Cu could not be determined.

A statement of the recrystallization sequence in terms of calculated mass balance reactions can be made using constraints provided by the geochemi-

cal, mineralogical, and textural information. An initial retrograde hydration converted the protolith, probably a dunite with some enstatite, into altered rocks of the Edmonds-type by the hydration of olivine and enstatite producing tremolite, chlorite, talc, and anthophyllite with the addition of Si, Al, Ca, and the loss of Mg leaving some relict olivine and enstatite. In a later stage of this hydration, serpentine (antigorite) was the product of the hydration of some of the olivine and tremolite, with the addition of Mg and loss of Ca.

The final step in the recrystallization sequence was a dehydration accompanied by brittle deformation which destroyed the serpentine and increased the concentration of tremolite, with the addition of Ca and loss of Mg. The net chemical change between the protolith of the more altered Todd-type rocks was one of loss of Mg and addition of Al and Ca as indicated by the geochemical study.

The possible relationship between this recrystallization sequence and the tectonic and metamorphic history of the eastern Blue Ridge is subject to speculation. If the reasonable assumption is made that these ultramafic bodies were emplaced tectonically into the Ashe Formation, retrograde hydration could have occurred during the Taconic metamorphism as a non-equilibrium adjustment to the lower  $P$ - $T$  conditions of regional metamorphism. The later dehydration may be associated with the  $350 \pm$  m.y. old (Acadian?) greenschist facies metamorphism and brittle deformation.

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