Southeastern Geology: Volume 22, No. 2
May 1981

Edited by: S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

Heron, Jr., S. (1981). Southeastern Geology, Vol. 22 No. 2, May 1981. Permission to re-print granted by Duncan Heron via Steve Hageman, Professor of Geology, Dept. of Geological & Environmental Sciences, Appalachian State University.

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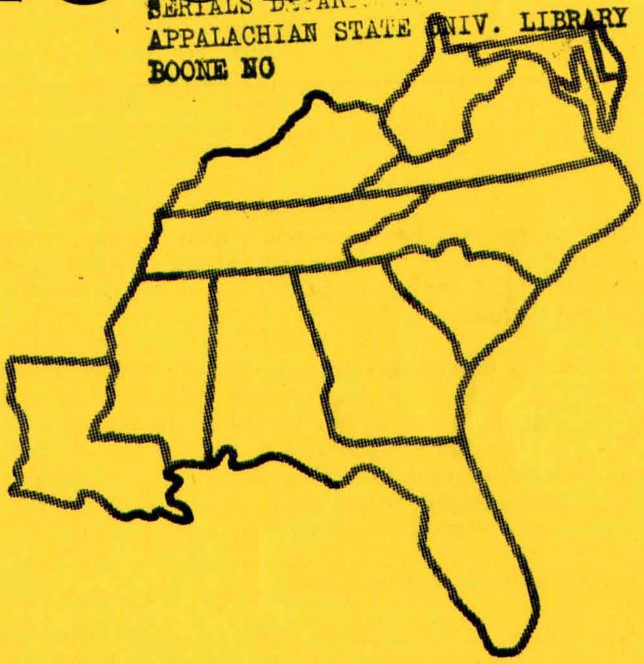

PUBLISHED AT DUKE UNIVERSITY DURHAM, NORTH CAROLINA

VOL.22. NO.2 MAY, 1981

SOUTHEASTERN GEOLOGY

PUBLISHED QUARTERLY

AT

DUKE UNIVERSITY

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SOUTHEASTERN GEOLOGY

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MINERALOGY AND PETROLOGY OF THE DAY BOOK DUNITE AND ASSOCIATED ROCKS, WESTERN NORTH CAROLINA

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ABSTRACT

Results of mapping and petrographic and electron microprobe analyses show the Day Book dunite to be a typical body of alpine ultramafic rock surrounded by regionally metamorphosed rocks of the Blue Ridge thrust sheet. The dunite is predominately olivine with minor amounts of chromian spinel and orthopyroxene. A variety of metamorphic minerals are found in the dunite including talc, tremolite, anthophyllite, chlorite, serpentine and magnesite. The country rocks consist of amphibolite (hornblende + plagioclase + quartz + sphene + garnet; or hornblende + plagioclase + quartz + clinopyroxene + sphene) and interlayered mica gneiss (quartz + plagioclase + biotite + white mica ± garnet ± staurolite ± kyanite ± chlorite). Intrusive into the dunite and the country rocks are white mica and garnet-bearing granodiorite pegmatites. Pegmatite contacts crosscut the regional foliation. Contacts between the dunite and country rocks and pegmatite are characterized by a metasomatic reaction zone consisting of essentially monomineralic bands of anthophyllite (if the rock is pegmatite or mica gneiss) talc and vermiculite or chlorite (if the country rock is amphibolite).

Electron microprobe analyses of olivine, chromian spinel and chlorite do not reveal any compositional zoning. Olivine compositions range from Fo_{92-95}. Chromian spinels have compositional trends similar to those found in other alpine ultramafic rocks. Temperatures, calculated from co-existing olivine and chromian spinel, range from 1070^{o} to $1184^{o}C$ and average $1141^{o}C$--results similar to those from other alpine ultramafics. However, much of the chromian spinel is associated with a chromian-bearing chlorite (kämmererite) that is apparently an alteration product of the spinel. Therefore, the significance of the calculated temperatures is thus open to some question.

Metamorphism of the dunite is indicated by the abundance of metamorphic minerals both in veins and within the dunite. The dunite is cut by a series of veins that are apparently related to the pegmatites. Many of the same texturally stable mineral assemblages are found in both the veins and the dunite and include; tremolite + talc + forsterite, talc + anthophyllite + forsterite, tremolite + talc +anthophyllite, tremolite + anthophyllite + forsterite, and talc + forsterite + magnesite. The assemblage talc + anthophyllite + magnesite was only found within the veins, whereas the assemblages involving orthopyroxene (talc + forsterite + orthopyroxene and tremolite + forsterite + orthophyroxene) are confined to the dunite. Many of the amphiboles show partial to complete replacement by talc. Mineral assemblages in the dunite and in the veins are consistent with the middle amphibolite grade of regional metamorphism ($550-650^{o}C$, 5-6 kb) observed in the country rock. Analysis of the mineral assemblage in light of experimental work in the system $MgO-SiO_2-H_2O-CO_2$ shows that the fluid phase which accompanied the metamorphism became more enriched in H_2O with time. This is consistent with the change in fluid composition during the crystallization of a granitic magma. Metamorphism of the country rocks and the dunite was apparently contemporaneous with pegmatite intrusion. Serpentine, found as both fracture fillings and coronas surrounding other silicates, is a late-stage alteration product that is unrelated to any metamorphic event observed in the country rocks.

Evidence of recrystallization in the dunite is found in the olivine fabric. A

porphyroclastic texture with large, irregular, deformed olivine grains surrounded by fine-grained, undeformed, polygonal matrix characterizes the dunite. The polygonal texture has grain boundaries that meet at 120° triple junctions and is clearly the result of annealing after formation of the large deformed olivines.

At least three different episodes of crystallization have left their imprint on the Day Book dunite. An initial phase involved the formation of the large olivine porphyroblasts. A second period coincided with the peak of regional metamorphism and pegmatite intrusion and formed the polygonal olivine texture. The third phase of recrystallization is related to the serpentinization of the ultramafic. If anything is to be learned about the intrusion of the dunite into the crust or its subsequent emplacement into the Blue Ridge, the polygonal olivine fabric is not the place to look for clues.

INTRODUCTION

Alpine ultramafic rocks are dunites and peridotites (or their serpentinized equivalents) that occur as linear belts within or parallel to the axial region of mountain belts (Hess, 1955; Mores & MacGregor, 1972). Contacts between the ultramafic rocks and country rocks usually do not show any effects of contact metamorphism and are generally concordant with regional structures. Mineralogically, alpine ultramafic rocks are composed of magnesium-rich olivine, pyroxene, and subordinate amounts of chromian spinel. Textures of the ultramafic rocks suggest recrystallization, especially of olivine (Raleigh, 1965).

Alpine ultramafic rocks found in regionally metamorphosed terranes such as the Appalachians, are generally conformable to the regional foliation. Mineral assemblages in these ultramafic rocks indicate a P-T of equilibration similar to the surrounding metamorphic rocks (Moores and MacGregor, 1972). Aditionally, many of these bodies show textural evidence for recrystallization. Interpretation of the history of alpine ultramafic rocks is difficult due to the masking effect of the regional metamorphism. Moores and MacGregor (1972) have suggested that these ultramafic rocks may represent melanges or overthrust sheets that have been metamorphosed subsequent to emplacement.

Ultramafics of the Southern Appalachians

Within the Appalachian Mountains, hundreds of small bodies of ultramafic rock define two narrow belts that parallel the structural trends from Newfoundland to Alabama (Larabee, 1966). In North Carolina, one group of ultramafic rocks occurs in the allochthonous Blue Ridge thrust sheet and a second group is located in the Piedmont Province (Fig. 1). On a smaller scale, individual bodies are conformable to the foliation of the country rock. Petrology of the ultramafics varies from relatively unaltered dunite and peridotite to completely altered serpentinites. Misra and Keller (1978) have summarized much of the data on ultramafic rocks from the Southern Appalachian Mountains.

Ultramafic rocks in North Carolina are the source of a number of mineral resources including olivine, chromite, vermiculite, and asbestos (commonly anthophyllite) (Hunter, 1941; Hunter, et al., 1942; Murdock and Hunter, 1946; Conrad et al., 1963). Pegmatitic granitic rocks, often found intruding the ultramafic rocks, have reacted with the dunites and peridotites to produce some of the vermiculite and asbestos (Kulp and Brobst, 1954) and corundum (Pratt and Lewis, 1905).

Several studies of ultramafic rock bodies in the North Carolina portion of the Blue Ridge Province have been concerned mainly with petrofabric analysis of olivines or the mineralogy of a particular phase. Astwood (et al., 1972) studied the optical orientation of polygonal olivine in two ultramafic bodies in southwestern North Carolina and did not find any preferred orientation. Other ultramafic bodies in the North Carolina Blue Ridge do show preferred orientation of olivine microfabrics and these structures suggest syntectonic recrystallization (Greengerg, 1976; Bluhm and Zimmerman, 1977; Dribus et al., 1977). Some of the North Carolina ultramafics show

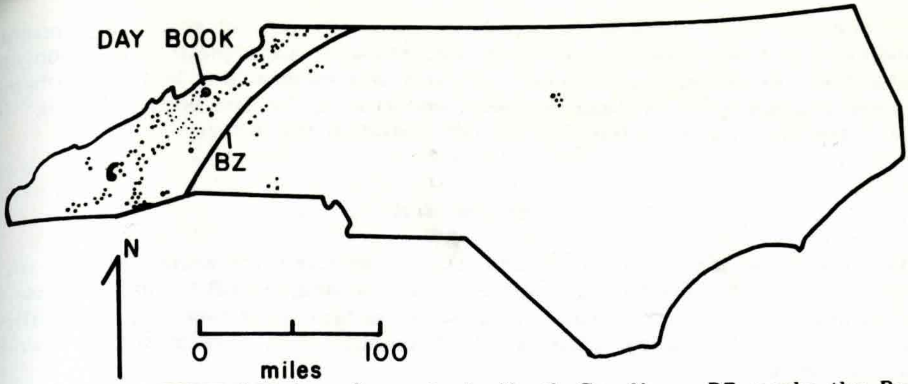

Figure 1. Distribution of ultramafic rocks in North Carolina. BZ marks the Brevard Zone and divides Ultramafics in the Blue Ridge (to the west) from ultramafics in the Piedmont.

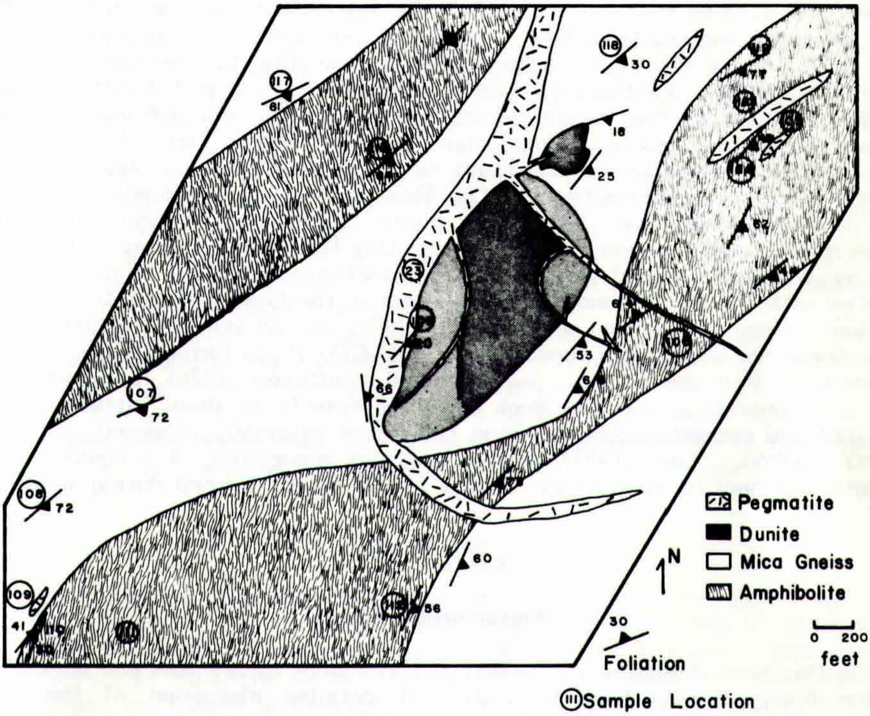

Figure 2. Geologic map of the Day Book dunite. Numbers in circles are samples locations referred to in Tables 1 and 2.

significant serpentinization that apparently took place *in situ* (Neuhauser and Carpenter, 1971) as a constant or variable (Madison and Condie, 1969) volume process. Olivine from the ultramafics has a near constant composition of $Fo_{92.5}$ (Carpenter and Phyfer, 1975). Chromite compositions follow the same trend shown by other alpine ultramafics (Fletcher and Carpenter, 1972; Swanson and Whittkopp, 1976), but some of the massive varieties show affinities for chromian-spinels from layered intrusions (Carpenter and Fletcher, 1979).

As much of the work done in ultramafics in the Southern Appalachians has been topical in nature, i.e., individual studies have concentrated on topics such as petrofabric analysis or petrology, it is difficult to develop a complete geologic history for individual bodies or the ultramafic belt as whole from the scattered, limited data available. The purpose of this paper is to present as complete a description of a representative ultramafic body as is possible with presently available data. In so doing

I have included some previously published data in an attempt to present a comprehensive analysis. Some information important to a complete description of an ultramafic body including a petrofabric analysis and mineral and bulk rock chemical analyses are not complete or have not been undertaken, for the body selected. It is hoped that the remaining studies will be completed in the future.

Previous Work

The Day Book dunite (Figs. 1 and 2) was selected for study because of the excellent exposures afforded by an active olivine mining operation and because this body is familiar to many geologists. This dunite is typical of many of ultramafics in the Blue Ridge belt and various aspects have been studied by several different workers at different times.

Several papers that discuss the economic minerals associated with the ultramafic rocks in North Carolina mention the Day Book deposit. Hunter (1941) described the olivine and presented a map of the Day Book deposit. Analyses of chromian spinel from Day Book are given by Hunter (et al., 1942), Bentzen (1970) and Carpenter and Fletcher (1979). Murdock and Hunter (1946) mention the vermiculite at Day Book and Kulp and Brobst (1954) ascribed the development of vermiculite to metasomatic alteration between the dunite and intruding granitic pegmatites. Kulp and Brobst also presented bulk rock analyses of the dunite, weathered pegmatite, and metasomatic products, along with a much improved geologic map of the ultramafic body. Lack of a contact aureole and the distribution of transition metals in bulk rock samples led Phyfer and Carpenter (1969) to conclude that the Day Book dunite was emplaced as a crystal mush or as a serpentinite that dehydrated during subsequent thermal metamorphism. Election microprobe analyses of olivine from Day Book show a compositional range of $Fo_{92.0-92.6}$ (Carpenter and Phyfer, 1975). McCormick (1975) studied the chlorite associated with the olivine and chromian spinel in the Day Book dunite and concluded it was kämmererite. Swanson and Raymond (1976) studied veins in the Day Book dunite and concluded the veins were formed from H_2O-CO_2 fluids formed during the intrusion of pegmatites into the dunite. Swanson and Whittkopp (1976) feel that, based on setting and mineralogy, the Day Book dunite represents an alpine ultramafic that was dehydrated and recrystallized following the model originally proposed by Phyfer and Carpenter (1969). Tien (1977) reported on the occurrence of aragonite, dolomite, magnesite and huntite as fracture fillings in the dunite formed during weathering.

COUNTRY ROCKS

Metamorphic Rocks

The Day Book dunite is surrounded on three sides by gneisses and amphibolites of the Blue Ridge thrust sheet (Fig. 2). A detailed discussion of the structural complexities is beyond the scope of this report, but minor structural features observed in the area are consistent with the multi-deformational history of the Blue Ridge outlined by Butler (1973).

The predominate metamorphic rock is a biotite gneiss. Within the biotite gneiss more aluminous layers and lenses have been metamorphosed to kyanite gneiss. Layers of kyanite gneiss range in thickness from a few millimeters to tens of meters and are discontinuous along the strike of the regional foliation. Amphibolites occur as layers and as occasional blocks surrounded by biotite gneiss. The thickness of individual amphibolite layers also varies along strike.

Mineral assemblages in the metamorphic rocks are given in Table 1. Diagnostic mineral assemblages in the pelitic bulk compositions include quartz + plagioclase + white mica + biotite + garnet + staurolite + kyanite + chlorite, whereas the assemblage hornblende + plagioclase + quartz ± garnet + sphene and hornblende + clinopyroxene + plagioclase + quartz + sphene characterize the amphibolites. These assemblages are indicative of a medium grade (Winkler, 1976) or the middle amphibolite facies (Turner, 1968) of regional metamorphism. Differences in mineral assemblages in the micaceous

Table 1. Mineralogy of the Country Rocks.

Sample Number[1]	% Flds[2]	% Qtz	% Amph	% Epid	% Gar	% Sph	% Cpx	% Opa	% Ky	% Sta	% Wm	% Biot
Mica Gneiss												
103	29.5	20.5	---	---	1.7	---	---	2.1	---	2.1	17.9	26.2
106	38.0	14.0	---	---	3.9	---	---	0.5	12.9	---	4.5	26.2
108	51.7	16.2	---	1.2	tr	---	---	---	---	---	tr	30.9
110	61.9	8.5	---	---	1.0	---	---	0.7	5.6	---	5.6	16.7
118	41.4	28.5	---	---	---	---	---	---	---	---	0.2	29.9
Amphibolite												
100	3.2	4.1	54.9	34.6	tr	3.2	---	---	---	---	---	---
102	14.9	8.2	72.5	---	---	4.4	---	---	---	---	---	---
110	13.0	8.1	76.6	1.0	---	1.3	---	---	---	---	---	---
111	15.1	10.3	67.2	5.9	---	1.5	---	---	---	---	---	---
112	20.2	4.0	50.9	23.2	---	0.9	0.8	---	---	---	---	---
116	26.3	6.3	63.8	0.9	tr	1.7	---	1.0	---	---	---	tr
119	27.4	9.7	58.9	2.7	---	1.1	---	0.2	---	---	---	---
121	12.9	10.9	51.4	17.7	---	2.8	3.3	---	---	---	---	---
122	18.0	7.9	53.9	17.2	---	3.0	---	---	---	---	---	---

Flds-feldspar, Qtz-quartz, Amph-hornblende, Epid-epidote, Gar-garnet, Sph-sphene, Cpx-clinopyroxene, Opa-opaque, Ky-kyanite, Sta-staurolite, Wm-white mica, Biot-biotite, tr-trace amount.

[1] Location given on Figure 2.
[2] For amphibolites, all of the feldspar is plagioclase.

rocks or the amphibolites are due to differences in bulk compositions rather than local gradients in pressure-temperature. Contacts between the country rocks and the dunite are characterized by a metasomatic reaction zone where magnesium from the dunite has combined with silica, aluminum, potassium and water from the country rocks to produce a series of essentially monomineralic bands. Immediately adjacent to the dunite is a zone of anthophyllite with long, fibrous crystals oriented perpendicular to the contact with the country rock. Much of the anthophyllite has been replaced by talc that still retains the fibrous habit of the anthophyllite. The next zone located successively outward from the dunite consists of talc. Finally, immediately adjacent to the country rock, there is a zone of either vermiculite (if the country rock is mica gneiss) or chlorite (if the country rock is amphibolite).

Country rocks around the dunite have been assigned to the Ashe Formation by Butler (1973). Elsewhere in the Blue Ridge, Rankin (1973) equates the amphibolite and mica gneiss of the Ashe Formation to metamorphosed basalt and graywacke, respectively. Blocks of amphibolite up to 5 m in length are found within the mica gneiss. Mapping on a larger scale may show that the amphibolites of Fig. 2 are also blocks surrounded by gneiss as suggested by Swanson and Whittkopp (1976).

Igneous Rocks

Intrusive into the metamorphic rocks and the dunite are quartz monzonite-granodiorite pegmatites (Fig. 2). Pegmatitic rocks found within the ultramafic bodies are weathered to kaolinite plus quartz, but the pegmatitic texture is still preserved. The large pegmatite along the western margin of the ultramafic and the dikes within the country rock are fresher and consist of perthitic alkali feldspar, quartz, plagioclase, muscovite, and garnet. Modal analyses of the pegmatites are given in Table 2 along with a chemical analysis of a weathered pegmatite from Kulp and Brobst (1954).

Pegmatites show two different relations with the country rocks. Most of the dikes are conformable to the regional foliation, whereas a few dikes associated with the ultramafic body cross-cut the metamorphic foliation (Fig. 2). Within the ultramafic body, pegmatites follow joints (Figs. 3 and 4), the trend of which cross-cuts the regional foliation.

Some of the pegmatites within the country rocks are crudely zoned. The margins are medium-grained (1-5 mm) quartz monzonite. Quartz with large crystals of muscovite (to 25 cm) is found in the core of the pegmatite bodies. Some of the pegmatite bodies were mined for muscovite during World War II.

Along the contact between the pegmatitic rocks and the dunite bodies is an extensive metasomatic reaction zone. Width of the reaction zone is directly proportional to the width of the pegmatite mass. The reaction zone represents a movement of silica, aluminum, potassium, and H_2O from the granitic magma toward

Table 2. Modal[1] and Chemical Composition of Day Book Pegmatites.

	100*	23*
Quartz	32.6	31.7
Plagioclase	49.2	31.2
K-Feldspar	15.8	35.1
Other+	2.4	2.0

+Includes garnet and white mica.

*Sample locations given on Figure 2.

Kulp and Brobst (1954)	
SiO_2	55.66
Al_2O_3	25.05
Fe_2O_3	1.62
FeO	0.45
MgO	2.00
CaO	4.89
Na_2O	4.51
K_2O	0.61
H_2O	1.09
H_2O^+	3.09

[1] Based on point counting (5.0 mm. between points) stained slabs (Laniz et.al., 1964) of pegmatite. Total area analyzed was in excess of 600 sq. cm.

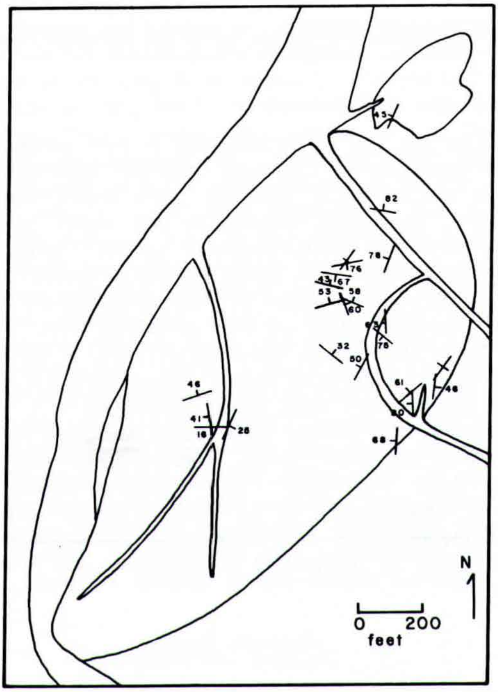

Figure 3. Attitudes of serpentine-filled fractures in the dunite.

the dunite body and movement of magnesium from the ultramafic body toward the pegmatitic body. Mineralogically, this chemical zonation is reflected by vermiculite adjacent to the pegmatite, followed by talc and anthophyllite (Fig. 5). Vermiculite apparently represents weathered phlogopite (Kulp and Brobst, 1954). As mentioned previously, pegmatites in the dunite are deeply weathered. Compositional data on the pegmatites supports the model of desilicification (Kulp and Brobst, 1954). Work is currently in progress to develop a diffusion model for the pegmatite-dunite contacts.

MINERALOGY AND PETROLOGY OF THE DUNITE

The Day Book dunite (Fig. 2) consists of two bodies separated by a small septa of mica gneiss. All of the dunite is lithologically similar, consisting of the primary minerals olivine, orthopyroxene and accessory chromian spinel. Color of the dunite ranges from pale green in less a altered rock to olive black with increasing serpentinization. Within the dunite the degree of serpentinization generally increases toward the contact with the country rock and the pegmatite. The dunite is fine-

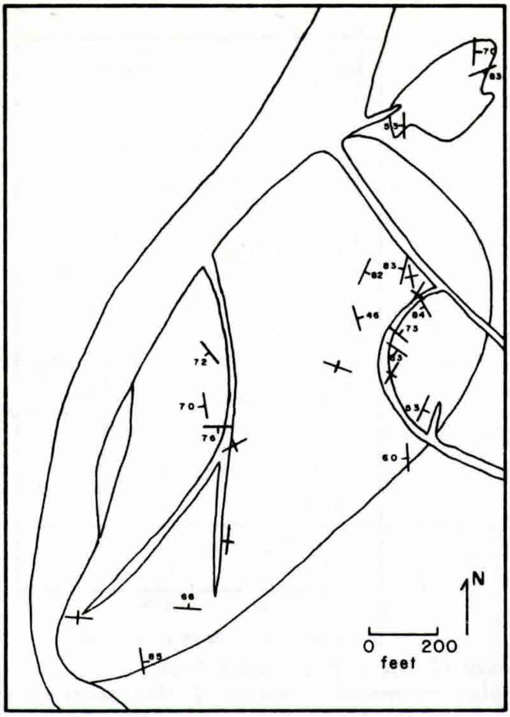

Figure 4. Attitudes of veins in the dunite.

grained with an average olivine grain size of 0.2 mm. A metasomatic reaction zone characterizes the contact between the dunite and the country rock and is a common feature in the ultramafic rocks of the region (Conrad et al., 1963).

A planar orientation of chromian spinel layers and pods is the only definite foliation observable in the dunite in the field (Fig. 6). Layers vary from irregular concentrations of a few chromite grains less than 1 cm in thickness to layers 30 cm wide composed almost entirely of chromian spinel. The thickest layer was mined during World War I (Hunter et al., 1942). Observations of chromian spinel foliations are generally restricted to the excellent exposures along the quarry walls. Pods of chromite also weakley define a foliation. The pods observed *in situ* during this study are less than 20 cm in greatest dimension, but blocks in the quarry rubble suggest that pods up to 3 m across occur in the dunite. Attitudes of chromian spinel layering define two trends within the dunite (Fig. 6). One set of attitudes is approximately parallel to the margin of the ultramafic while a second set is at right angle to the first set. In places the chromian spinel layering is folded into isoclinal folds with an amplitudes of 5-20 cm.

Two different types of shear fractures filled with serpentinization products cut the dunite bodies (Fig. 3 and 4). Shear zones vary in thickness from 0.2-2 m. Mineral assemblages of the shear zones are different in each of the bodies. In the smaller mass of dunite, a shear zone is filled with long-fiber chrysotile (?). The larger dunite body has a shear zone 1-2 m wide filled with brecciated, partially serpentinized fragments of dunite. In addition to serpentine this zone contains chalcedony, nickel silicates, and a variety of carbonate minerals formed as weathering products (Tien, 1977). It has not been possible to trace shear zones from the dunite into the country rock, but crosscutting relations suggest the shear zones were formed after the last metamorphic event.

Joints are common in both of the dunite bodies (Figs. 3 and 4). Dunite adjacent to the joints is serpentinized and the joint surfaces are covered with serpentine and magnetite. Attitudes of joints show the same pattern as the chromian spinel layering. One set follows the trend of the dunite bodies and the regional foliation, whereas a second set is perpendicular to this trend (Figs. 3 and 4). In some instances, pegmatite

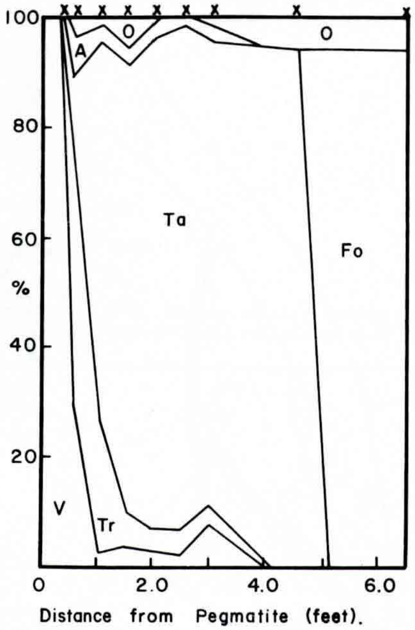

Figure 5. Mineralogy of the contact zone between pegmatite and dunite at point 93 (Fig. 7) as determined by model analyses of thin sections from localities shown by crosses on the top of the diagram. V is vermiculite, Tr is tremolite, Ta is talc, Fo is olivine, A is anthophyllite and O represents the sum of chlorite + serpentine + opaques.

Table 3. Mineralogy of Veins in the Day Book Dunite.

	Minerals Present								Texturally Stable Mineral Assemblages					
Sample Number	Ta	Fo	Ch	M	Tr	S	Antho	Opaque	Tr+Ta +Fo	Ta+Fo +Antho	Tr+Ta +Antho	Ta+M +Antho	Ta+Fp +M	Tr+Fo +Antho
4	M	tr	m			tr	tr		X	X	X			
10	M	tr	m		M	m	m		X	X	X			X
21A*	M	m	M		tr	m				X				
21B*	M	m	m		m	tr			X					
38	M	M	M			m								
58	M	tr	m			tr	M			X	X			
63-A*	M	m	m		m	tr	tr		X		X			
63-B*	M	m	tr			m		tr						
65	M	m	tr		M	tr	m		X	X	X			
69	M	m	m	tr	m	tr							X	
71B*	tr	m	tr	tr	M	tr	m			X		X		
84A*	M	M	m		tr	M	tr							
84B*	M	M	m		m	m	M							
84C*	m	M	m		m	tr	m							
90A*	tr	m	M		m	tr			X					
90B*	m	m	M		m	tr			X					
90C*	M	m	m		m	tr	tr			X	X			
92	M	m	m		tr	tr	tr			X	X			
93	M		M			tr								
94A*	tr	m	M		tr	tr	tr		X	X				
94B*	M	tr	m			tr								
94C*	M	tr	m			m								
94D*	M		tr			m								
94E*	tr	tr	M	m	M		tr					X	X	
94F*	m	m	m		M	tr								
94G*	M	M	m		m	tr	tr			X				
94H*	M	tr	M	m		tr				X			X	
94I*	M	tr	tr	M	tr	m		tr						
94J*	M	m	tr		m	m	tr			X				

M = major constituent, m = minor constituent, tr = trace amount
*Letters after sample number indicates multiple samples from the same outcrop
Ta = talc, Fo = olivine, Ch = chlorite, M = magnesite, Tr - tremolite, S = serpentine, Antho = anthophyllite,
Opaque includes chromian spinel and magnetite.

bodies and associated veins have intruded the dunite along joints.

The mineral assemblages of the veins are similar to metasomatic zones betwen pegmatite and dunite, but additionally the veins contain local segregations of

Table 4. Composition of the Day Book Dunite.

	A	B	C	D
SiO_2	40.67	40.93	40.86	42.40
Al_2O_3	0.75	1.32		
Cr_2O_3	0.32	--	2.18	1.06
TiO_2	0.01	--		
Fe_2O_3	1.15	7.60	7.66	8.62
FeO	6.56			
MgO	48.77	48.77	49.31	45.92
CaO	0.00	0.19	0.00	0.00
Na_2O	0.00	0.13	--	--
K_2O	0.03			
H_2O	0.08			
H_2O^+	1.38	1.09	0.63	1.23
CO_2	0.12			
NiO	0.31	--	--	--
MnO	0.12	--	--	--
Total	100.27	100.13	100.64	99.23

A - dunite (Kulp and Brobst, 1954)
B - average of five commercial olivine shipments (Hunter, 1941)
C - dunite; 95% olivine, 2% chromian spinel, 2% talc, 1% chlorite (Hunter, 1941)
D - saxonite; 83% olivine, 10% tremolite, 5% chlorite, 2% chromian spinel plus traces of orthopyroxene, talc and antigorite (Hunter, 1941)

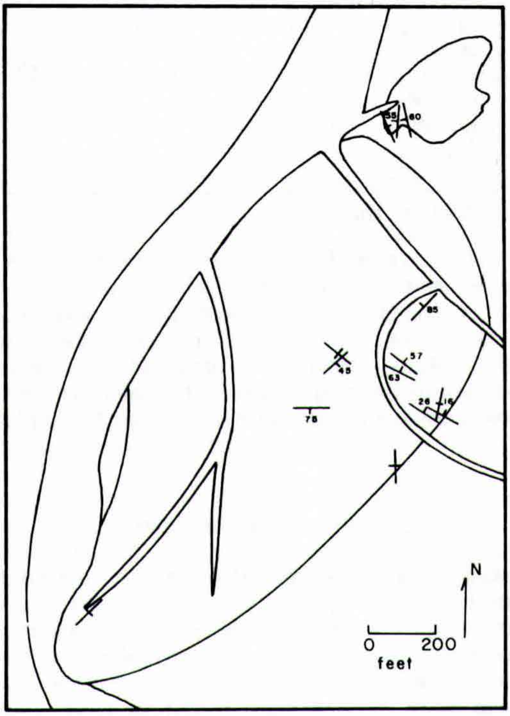

Figure 6. Attitudes of chromian spinel layers in the dunite.

magnesite. Much of the magnesite is coarse-grained with individual crystals up to 20 cm. Texturally stable mineral assemblages are found in different locations. Table 3 gives the plotted mineral assemblages found in the veins and the sample locations are in Figure 7.

Bulk Composition

The chemical compositions of the Day Book dunite, given in Table 4 are those reported by Hunter (1941) and Kulp and Brobst (1954). Note that one analysis represents an average of five commercial olivine shipments from the quarry and this

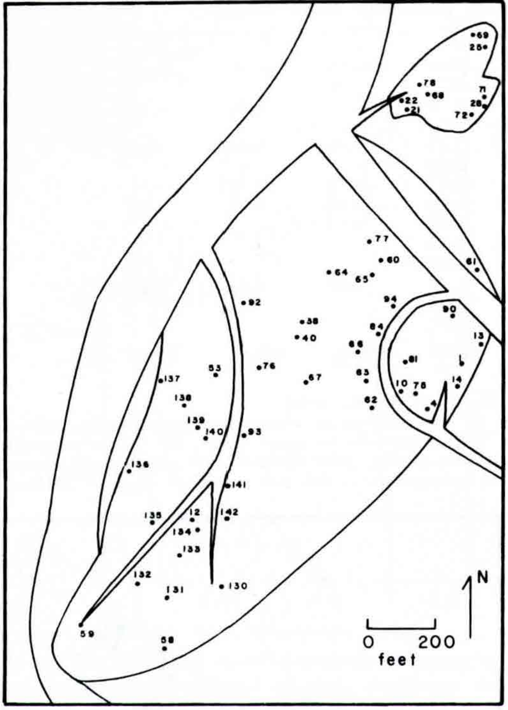

Figure 7. Sample localities in the dunite.

average is probably the best value for the fresh dunite at Day Book.

All of the analyzed samples contain small amounts of serpentine, chlorite, and chromian spinel. Water in the analyses is found in the serpentine or in other hydrous phases such as talc, chlorite, or tremolite. Chromian spinel and chlorite are the only abundant phases that contain significant amounts of aluminum and chromium. Tremolite is the only calcium-bearing phase in the analyzed samples. The abundances of other components (such as magnesium or nickel) can be explained by the abundance of olivine.

Methods of Analysis

Mineral compositions were determined with an Applied Research Laboratories EMX-SM electron beam microprobe. Analyses were made on at least five different parts of several different grains per sample with an excitation potential of 15 kv. Compositional zoning was not found in any of the minerals. Raw data were corrected following the method Bence and Albee (1968). For the spinels, an estimate of ferrous-ferric content was made using a technique modified from Carmichael (1967). This technique, when applied to standards determined by wet chemistry, gives ferrous-ferric contents similar to those measured by wet chemistry. Mineral identification was checked by X-ray diffraction.

Modal analyses were done on standard thin sections for dunite and on slabs of pegmatite that were stained to distinguish plagioclase and alkali feldspar. Point spacing in the dunite analyses was 1 mm and 500 to 600 points were counter per sample. The extreme variability of the modal mineralogy of the dunite on even the handspecimen scale made determination of more points impractical.

Anhydrous Minerals

Olivine: By far the most abundant mineral in the ultramafic rock is olivine which ranges from approximately 80 to 99 modal per cent and averages about 95 percent.

Table 5. Composition of Olivine.

	A	B	C	D	E	F	G	H	I	J
SiO_2	42.34	42.05	41.99	41.79	41.59	41.26	40.94	40.43	40.74	40.88
MgO	53.73	53.42	53.45	52.41	52.34	51.91	49.70	50.17	50.19	49.96
FeO	4.37	4.48	4.58	6.42	6.41	6.31	7.78	7.27	7.12	7.15
NiO	0.53	0.53	0.53	0.40	0.42	0.41	0.44	0.43	0.40	0.43
MnO	0.06	0.06	0.06	0.09	0.09	0.09	0.11	0.10	0.10	0.10
Total	101.03	100.54	100.61	101.11	100.85	99.98	98.97	98.40	98.55	98.52
ions in Structural formula										
Si	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mg	1.90	1.90	1.90	1.87	1.87	1.86	1.82	1.84	1.84	1.83
Fe	0.09	0.09	0.09	0.13	0.13	0.13	0.01	0.01	0.01	0.01
Ni	0.01	0.01	0.01	<0.01	<0.01	0.01	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	<0.01	<0.01	<0.01				
%Fo	95	95	95	94	94	93	92	93	93	93

A-C olivine associated with chromian spinel E-G of Table 6.
D-F olivine 6 associated with chromian spinel A-D of Table 6.
G-J from Carpenter and Phyfer (1975)

Most of the olivine forms a mosaic of equant polygonal grains that meet at approximately 120^{o} triple junctions. These olivine crystals do not show kink bands or undulatory extinction and the grain size ranges from 0.05 to 2 mm and averages 0.2 mm. Within this fine grained matrix of olivine there are larger olivine grains that range up to 29 cm in length. The larger olivine grains show kink bands, undulatory extinction, and have irregular boundaries where they contact the mosaic of smaller crystals. Such a texture, larger deformed grains surrounded by a polygonal matrix, is termed porphyroclastic and is thought to represent a metamorphic texture (Pike and Schwarzman, 1977). Chemical compositions and structural formula of olivine from the Day Book dunite are given in Table 5. Olivine from the Day Book dunite does not show any compositional zoning. Individual olivine grains are homogeneous. Additionally, no significant variation in olivine composition exists within the dunite body (Carpenter and Phyfer, 1975). Compositional differences shown in Table 5 are apparently the result of different analytical facilities and data reduction procedures.

Day Book olivine compositions are typical of the high-magnesium olivines from alpine ultramafic rocks (Moores and MacGregor, 1972). The high-magnesium content and restricted range of compositions of olivine in alpine ultramafic rocks contrast with the wider compositonal range (including more iron-rich varieties) of olivines from stratiform ultramafic rocks. Similar magnesium-rich olivine compsitions are found in the alpine ultramafic rocks of active tectonic belts (Challis, 1965; Loney et al., 1971) and older mountain systems, such as the Appalachians.

Chromian Spinel: Chromian spinel, which occurs as an accessory phase in the Day Book dunite, generally makes up less than one percent of the rock. Local layers and pods are dominately chromian spinel. Subhedral to euhedal octahedra characterize the chromian spinel in the dunite. Often the chromian spinel is surrounded by kämmererite, a chromian chlorite.

The chemical compositions of chromian spinels from the Day Book dunite are given in Table 6. Iron in the electron microprobe analyses was determined as total iron and the amount of FeO and Fe_2O_3 was calculated based on a method modified from Carmichael (1967).

Chromian spinels from the Day Book dunite show a relatively large range of compositions in comparison to olivine. The range in composition is due largely to differences in cation ratios of $Cr/(Cr+Al+Fe^{+3})$ and to a lesser extent $Mg/(Mg+Fe^{+2})$. This compositional difference is shown on Figure 8 along with data for the chromian spinels from the Burro Mountain peridotite, a typical alpine-type ultramafic from the Coast Ranges of California (Loney et. al., 1971). Chromian spinels from the Day Book dunite show the same compoitional trend as typical alpine-type ultramafics. One chromian spinel does not fall on the typical alpine-ultramafic trend. This is a chip sample across a chromian spinel layer that was analyzed by wet chemistry (Hunter, et al., 1942). The different composition may reflect a difference in the analytical method. Alternatively, this abhorrent chromian spinel may be part of a different compositional trend.

Fletcher and Carpenter (1972) suggest that chromian spinels from the Day Book

Table 6. Composition of Chromian Spinel.

	A	B	C	D	E	F	G	H	I	J
Cr_2O_3	62.43	62.82	62.34	62.03	58.88	58.86	58.78	44.20	55.5	57.2
Al_2O_3	5.98	6.80	5.98	5.24	12.72	11.80	12.68	21.30	--	--
Fe_2O_3*	4.57	3.43	4.24	5.04	2.32	2.66	2.46	20.05	19.6	20.0
FeO	19.30	18.97	20.32	19.50	14.31	14.51	14.21			
MgO	9.13	9.43	8.15	8.75	13.07	12.69	13.21	14.48	--	--
MnO	0.16	0.56	0.60	0.62	0.45	0.46	0.46	--	--	--
Total	101.57	102.01	102.14	101.18	101.75	100.98	101.80	100.03	75.10	77.20
ions in formula +										
Cr	13.16	13.16	13.21	13.18	11.75	11.90	11.73	--	--	--
Al	1.88	2.12	1.89	1.69	3.79	3.56	3.77	--	--	--
Fe^{+3}	0.92	0.68	0.86	1.04	0.44	0.51	0.47	--	--	--
Fe^{+2}	4.30	4.20	4.67	4.45	3.02	3.10	3.00	--	--	--
Mg	3.63	3.73	3.26	3.56	4.92	4.84	4.94	--	--	--
Mn	0.14	0.13	0.14	0.14	0.10	0.10	0.10	--	--	--
εR^{+3}	15.96	15.96	15.96	15.91	15.98	15.97	15.97	--	--	--
$(Cr/Cr+Al+Fe^{+3})$	0.82	0.82	0.83	0.83	0.74	0.75	0.73	--	--	--
$(Al/Cr+Al+Fe^{+3})$	0.12	0.13	0.12	0.11	0.24	0.22	0.24	--	--	--
$(Fe^{3}/Cr+Al+Fe^{+3})$	0.06	0.04	0.05	0.07	0.03	0.03	0.03	--	--	--
εR^{+2}	8.07	8.06	8.10	8.15	8.04	8.04	8.04	--	--	--
$(Mg/Mg+Fe^{+2})$	0.46	0.47	0.41	0.44	0.62	0.61	0.62	--	--	--
$(Fe^{+2}/Fe^{+2}+Fe^{+3})$	0.82	0.86	0.84	0.81	0.87	0.86	0.86	--	--	--

	K	L	M	N	O	P	Q	R	S	T
Cr_2O_3	60.55	61.84	57.20	58.49	66.55	60.23	61.00	59.07	61.62	60.86
Al_2O_3	5.24	7.63	4.56	10.08	5.29	3.11	7.51	10.54	7.63	9.68
Fe_2O_3 FeO	26.39	21.87	29.18	20.86	19.69	28.45	20.52	18.32	19.56	16.68
MgO	6.87	8.51	7.81	10.13	9.24	8.17	10.77	11.43	11.93	12.38
MnO	0.38	0.44	0.43	0.43	00.35	0.50	0.30	0.35	0.30	0.37
Total	99.52	100.35	99.40	100.10	101.18	100.59	100.23	99.80	101.17	100.07
ions in formula$^+$										
Cr	13.25	13.14	12.45	12.18	14.12	13.02	12.77	12.21	12.69	12.54
Al	1.71	2.42	1.48	3.13	1.67	1.00	2.34	3.25	2.34	2.98
Fe^{+3}	1.01	0.41	1.98	0.64	0.18	1.93	0.84	0.51	0.92	0.45
Fe^{+2}	5.09	4.50	4.70	3.93	4.22	4.55	3.68	3.47	3.31	3.18
Mg	2.83	3.41	3.20	3.98	3.70	3.33	4.25	4.46	4.61	4.74
Mn	0.09	0.10	0.10	0.10	0.08	0.12	0.07	0.08	0.07	0.08
R^{+3}	15.97	15.97	15.91	15.95	15.97	15.95	15.95	15.97	15.95	15.97
$(Cr/Cr+Al+Fe^{+3})$	0.83	0.82	0.79	0.76	0.89	0.82	0.80	0.77	0.79	0.78
$(Al/Cr+Al+Fe^{+3})$	0.11	0.15	0.09	0.20	0.10	0.06	0.15	0.20	0.15	0.19
$(Fe^{+3}/Cr+Al+Fe^{+3})$	0.06	0.03	0.12	0.04	0.01	0.12	0.05	0.03	0.06	0.03
R^{+2}	8.01	8.01	8.00	8.01	8.00	8.00	8.00	8.01	7.99	8.00
$(Mg/Mg+Fe^{+2})$	0.36	0.43	0.41	0.50	0.47	0.42	0.54	0.56	0.58	0.60
$(Fe^{+2}/Fe^{+2}+Fe^{+3})$	0.83	0.92	0.70	0.86	0.96	0.70	0.81	0.87	0.78	0.88

K-T From Carpnter and Fletcher,(1979)

	U	V	W	X	Y	Z	AA	BB	CC	DD
Cr_2O_3	61.07	60.23	61.12	61.43	60.78	60.18	59.97	60.54	60.54	60.64
Al_2O_3	10.20	10.75	10.20	9.99	9.68	9.35	10.30	10.93	10.15	10.45
Fe_2O_3 FeO	15.47	16.03	16.05	16.21	17.66	17.30	16.65	15.70	17.72	16.52
MgO	12.97	13.29	12.95	12.50	12.39	12.28	12.76	13.20	11.53	12.64
MnO	0.26	0.36	0.34	0.32	0.32	0.31	0.28	0.30	0.38	0.33
Total	100.08	100.79	100.71	100.50	100.89	99.48	100.07	100.75	100.40	100.68
ions in formula$^+$										
Cr	12.48	12.17	12.42	12.50	12.40	12.46	12.26	12.24	12.46	12.34
Al	3.10	3.24	3.09	3.03	2.94	2.88	3.14	3.30	3.11	3.17
Fe^{+3}	0.37	0.54	0.47	0.45	0.62	0.66	0.56	0.43	0.40	0.46
Fe^{+2}	2.95	2.86	2.98	3.03	3.17	3.12	3.02	2.91	3.44	3.07
Mg	4.99	5.06	4.96	4.80	4.77	4.79	4.92	5.03	4.47	4.85
Mn	0.06	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.08	0.07
R^{+3}	15.95	15.95	15.98	15.98	15.96	16.00	15.96	15.97	15.97	15.97
$(Cr/Cr+Al+Fe^{+3})$	0.79	0.77	0.78	0.78	0.78	0.78	0.76	0.76	0.78	0.77
$(Al/Cr+Al+Fe^{+3})$	0.19	0.20	0.19	0.19	0.18	0.18	0.20	0.21	0.19	0.20
$(Fe^{+3}/Cr+Al+Fe^{+3})$	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03
R^{+2}	8.00	8.00	8.01	7.90	8.01	7.98	8.00	8.00	7.98	7.99
$(Mg/Mg+Fe^{+2})$	0.63	0.64	0.62	0.61	0.60	0.61	0.62	0.63	0.57	0.61
$(Fe^{+2}/Fe^{+2}+Fe^{+3})$	0.89	0.84	0.86	0.87	0.84	0.83	0.84	0.87	0.90	0.87

U-DD From Carpenter and Fletcher (1979)

A-D Sample 22, desseminated chromian spinel, associated with olivine A-C of Table 5.
E-G Podiform chromian spinel from quarry rubble, associated with olivine D-F of Table 5.
H- From Hunter, Murdoc, and MacCarthy (1942)
I&J - From Bentzen (1970)
*Calculated from Fe_{total} = FeO based on the method of Carmichael (1967)
$^+$Based on 32 oxygen atoms

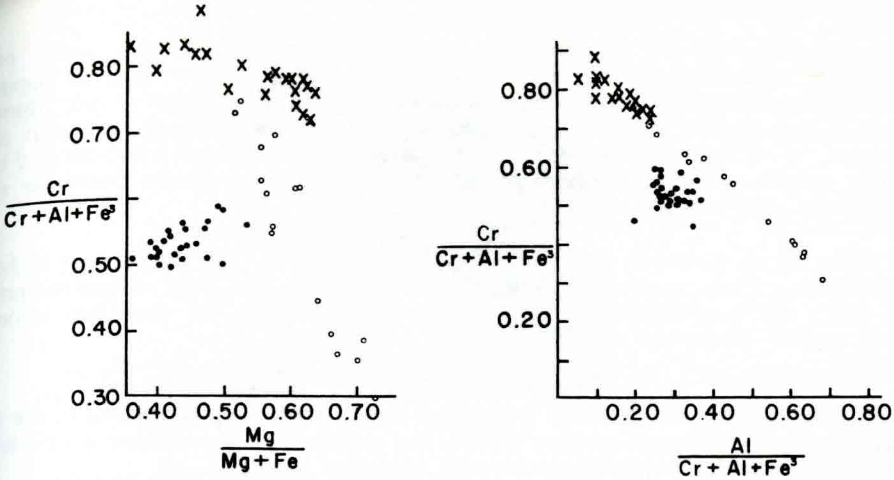

Figure 8. Comparison of chromian spinel compositions from Day Book (X's), Burro Mt. peridotite (open circles; Loney, et al., 1971) and Stillwater complex (closed circles; Jackson, 1969).

Table 7. Composition of Chlorite.

	A	B	C	D	E
SiO_2	31.47	32.59	32.79	32.87	34.29
Al_2O_3	15.64	13.03	13.11	13.43	12.22
Cr_2O_3	2.82	3.78	4.07	3.80	6.39
FeO	1.72	1.41	1.40	1.43	1.33
MgO	31.95	32.85	32.54	32.76	33.82
MnO	0.01	0.01	0.01	0.01	0.01
CaO	--	--	--	--	0.02
NiO	0.27	0.22	0.21	0.22	0.43
Na_2O	--	--	--	--	0.08
K_2O	--	--	--	--	0.01
H_2O	--	--	--	--	12.56
Total	83.88	83.89	84.13	84.52	101.16

A-D associated with podiform chromian spinel (E-G, Table 6) and olivine (D-F, Table 5).
E - from McCormick (1975)

dunite show two compositional trends. One trend of disseminated grains parallels the Burro Mountain trend on a MgO/RO vs. Cr_2O_3/R_2O_3 plot while massive chromian spinels from the pods define a trend described as a constant Cr_2O_3/R_2O_3 ratio with a variable MgO/RO ratio similar to chromian spinels from stratiform ultramafic complexes, such as the Stillwater Complex. Fletcher and Carpenter (1972) believe that this difference in chromian spinel compositions is due to partial recrystallization, wherein disseminated chromian spinels recrystallized during regional metamorphism while the massive pods of chromian spinel escaped the metamorphism. A difference in composition between chromian spinels with different textures was not confirmed in the present study (Figure 8, Table 6).

Analyses of disseminated and massive chromian spinel from several ultramafic bodies in western North Carolina do not show any significant difference between the different textural varieties (Carpenter and Fletcher, 1979). Trends described by Fletcher and Carpenter (1972) for the chromian spinels from the Day Book dunite are not apparent from the data of Carpenter and Fletcher (1979) as shown in Figure 8. Disseminated and massive chromian spinels compositions from the Day Book dunite follow the trend defined by chromian spinels of the alpine-type ultramafic bodies.

Associated with the chromian spinel is a chromian chlorite, kämmererite. This chlorite is found along the margins of both disseminated and massive (podiform) chromian spinel grains. Textural relations (Fig. 9) suggest that the kämmererite formed from the chromian spinel during metamorphism.

Compositions of the kämmererite from the Day Book dunite are given in Table 7. The chlorites are enriched in aluminum and magnesium relative to the associated chromian spinel. Presumably disseminated chromian spinels would be more susceptible to recrystallization than the massive chromian spinels. Indeed, many of the disseminated chromian spinels are mantled by epitaxial kämmererite suggesting recrystallization of these spinels accompanied by a loss of magnesium and aluminum. However, kämmererite is also associated with the more massive chromian spinels (McCormick, 1975) and this together with the single compositional trend defined by the Day Book samples (Fig. 8) suggests both disseminated and massive chromian spinels reequilibrated with the kämmererite.

Cation Distribution Between Olivine and Chromian Spinel. The distribution of Mg and Fe^{+2} between coexisting olivine and chromian spinel may be used as geothermometer (Irvine, 1965; Jackson, 1969). The exchange reactions for the chromian spinel end members can be combined to give

$$Fe^{+2}Si_{0.5}O_4 + Mg(Cr_{\alpha}Al_{\beta}Fe_{\delta}^{+3})_2O_4 = MgSi_{0.5}O_4 + Fe^{+2}(Cr_{\alpha}Al_{\beta}Fe_{\delta}^{+3})_2O_4 \qquad (1)$$

where $\alpha + \beta + \delta = 1$ and represent the mole fractions of the trivalent cations in the spinel. Following Irvine (1965) and Jackson (1969), the equilibrium distribution coefficient for the exchange reaction between olivine and chromian spinel is

$$Kd = \frac{X_{Mg}^{ol} \quad X_{Fe^{+2}}^{chr}}{X_{Fe^{+2}}^{ol} \quad X_{Mg}^{chr}} \qquad (2)$$

where X_{Mg}^{ol} and $X_{Fe^{+2}}^{ol}$ are the mole tractions of the olivine end members $FeSi_{0.5}O_2$ and $MgSi_{0.5}O_2$, X_{Mg}^{chr} and $X_{Fe^{+2}}^{chr}$ are the mole fractions of $Mg(Cr_{\alpha}Al_{\beta}Fe_{\delta})_2O_4$ and $Fe(Cr_{\alpha}Al_{\beta}Fe_{\delta})_2O_4$ in chromian spinel. Jackson (1969) has compiled the standard Gibbs free energy data for the end members of the olivine-chromian spinel series and derived a geothermometer based on coexisting olivine and chromian spinel as given by

$$\frac{T^{o} = 5580\alpha + 1018\beta - 1720\delta + 2400}{0.90\alpha + 2.56\beta - 3.08\delta - 1.47 + 1.987 \ \ln Kd} \qquad (3)$$

with T in degrees Kelvin α, β and δ defined by equation (1) and Kd defined in equation (2). Substitution of this value along with the composition of trivalent cations in the olivine and chromian spinel into equation (3) yields an estimate of the temperature of equilibration of the olivine and spinel. Temperature of crystallization obtained from this equation for coexisting olivine and chromian spinel from the Day Book dunite range from 1070 to 1184°C with an average of 1141°C. Jackson (1969) tabulates the uncertainties in the standard free energy measurements in the olivine and chromian spinel series and estimates a uncertainty in temperatures measured with equation (6) of ± 300°C. Clearly the variation of temperatures calculated for the Day Book dunite is not significant.

An alternative approach to $Mg\text{-}Fe^{+2}$ distribution between olivine and coexisting chromian spinel is given by Irvine (1965). The technique used thermodynamic data to calculate "equipotential surfaces" which represent theoretical equilibrium compositions for coexisting olivine and chromian spinel. Comparison of natural samples to the theoretical results gives an indication of attinment of equilibrium between olivine and chromian spinel (Loney et al., 1971).

Distribution of the analyzed olivine-chromian spinels from the Day Book dunite show a fairly close agreement to the calculated equipotential lines (Fig. 10). However, all of the values fall below the equipotential line that corresponds to the olivine in the samples. In other words, the chromian spinels from the Day Book dunite coexist with more Mg-rich olivine than predicted from the thermodynamic calculations of Irvine (1965). A certain amount of scatter is common the equipotential plots (Loney et al., 1971), but the scatter is random and not the systematic pattern shown on Figure 10. Several possibilities may explain the compositional pattern shown on Figure 10, for example, the olivine may have been enriched in Mg, the chromian spinel may have been depleted in Cr or Mg. However, the association of kämmererite with the chromian spinel (Fig. 9) discussed previously suggests the formation of this Mg-rich chlorite (Table 7) depleted the spinel in Mg thus explaining the pattern observed on Figure 10. Formation of kämmererite also requires other components from the spinel (such as Al and Cr, Table 7), but the high Mg-content of the chlorite relative to these other components shows the greatest effect on chromian spinel compositions accompanying chlorite formation will be a decrease in the Mg-content. The pattern on Figure 10

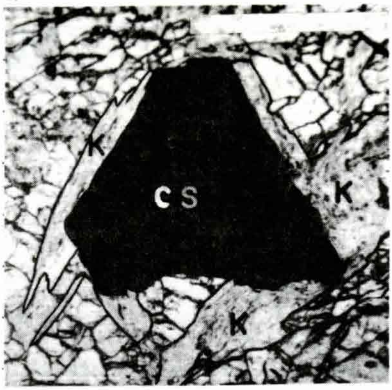

Figure 9. Photomicrograph of chromian spinel (CS) with kämmerite overgrowth (K). White bar is 1.0 mm.

Table 8. Mineralogy of the Day Book Dunite.

Sample Number	%Fo	%Opx	% Opaque	%S	%Ta	%Ch	%Tr	% Antho	Tr+Ta +Fo	Ta+Fo +Antho	Tr+Ta +Antho	Tr+Fo+ Antho	Ta+Fo +Opx	Tr+Fo +Opx	Fo+Ta+ M	Tr+Ta +Opx
1	83	1	1	1	11	3	2	1	X							
13	95		1	3		1										
25	91	1	tr	1	1	3	2	1					X	X		X
38	80	tr	tr	14	5	1							X			
53	64	tr	1	29	5	1		1					X		X	
58	92		1	1	5	1	1		X	X	X					
59A*	98		1	tr	2	1										
59B*	95		1	1	1	1	1									
60A*	84	tr	1	2	10	3	tr	1	X				X			
60B*	81		1	4	7	6	1	1	X							
61	67	tr	1	26	4	2	tr	tr					X			
62	87	tr	2	11	tr	1										
63	86		1	5	4	1	2	2	X			X				
64	89		tr	8	1	1	1		X							
66	85	tr	tr	4	4	4	1	2	X				X			X
67	82		tr	1	10	2	2	1	X							
68	78		1	3	12	3	tr	3		X						
69	73		tr	6	10	6	2	2			X				X	
71	82	3	tr	1		12	1						X			
72	75		1	23	1	1										
76	91	tr	tr	2	18	5	3	2								
77	89	4	tr	2	1	2	3	1						X		
78	97		1	2	1	1	1									
81	90	tr	1	4	2	2	2	4	X	X						
90	70	1	tr	2	18	5	3	2	X	X						
92	89	tr	2	tr	5	2	1	tr		X			X			
130	80	1	tr	10	9	1	1									
131	90		1	1	7	1	1		X							
132	99		1	1		1										
133	84		1	1	12	2	1	tr	X	X	X					
134	92		2	5		1	tr									
135	85		1	1	11	2	1		X							
136	62		1	30	6	1	1		X							
137	65	13	1	8	4	6	4		X			X				
138	83		tr	3	10	3	1	tr	X		X					
139	91		1	1	4	4	1		X							
140	95		1	1	2	1										
141	86		1	2	9	1	2	1	X		X					
142	72		1	2	22	4	4									

suggests disequilibrium between the chromian spinel and olivine from the Day Book dunite, probably related to the formation of chlorite from the spinel. In light of this, the significance of the temperatures calculated from equation (3) based on an equilibrium coexistence of olivine and chromian spinel is open to discussion.

Orthopyroxene: Distribution of small amounts of fine-grained (generally less than 1 mm), subhedral enstatite (Table 8) does not form any apparent pattern in the dunite. Much of the orthopyroxene is included within the porphyroclastic olivine texture. However, in some samples, orthopyroxenes form grains up to 5 mm in maximum dimension with irregular grain boundaries similar to the olivine porphyroblasts. The orthopyroxene has a low birefrigence, parallel extinction and is not pleochroic. Enstatite is texturally stable with several of the metamorphic minerals including talc, tremolite and chlorite.

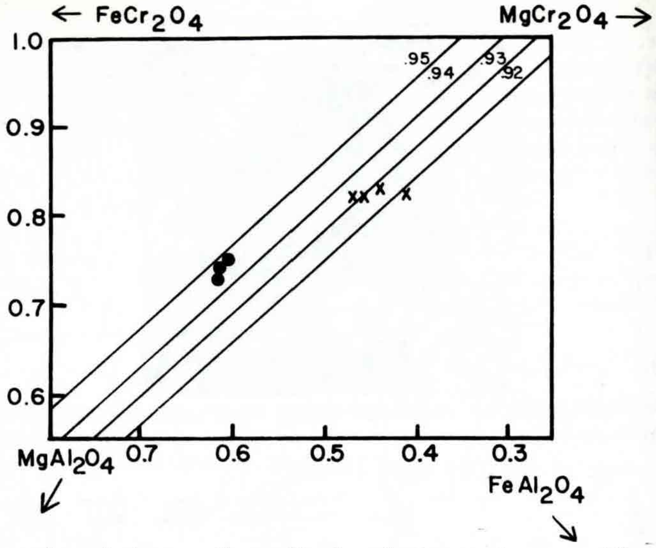

Figure 10. Comparison between theoretical and observed compositions of olivine and chromian spinel in the Day Book dunite. Lines are intersections of theoretical $Mg-Fe^{+2}$ equipotential surfaces for olivine with cation fractions of Mg of 0.95, 0.94, 0.93 and 0.92 at $1200^{o}C$. Crosses represent olivine with an average cation fraction of Mg of 0.935 (D-F, Table 5) and dots represent olivine with an average cation fraction of Mg of 0.955 (A-C, Table 5), different data points represent different chromian spinel grains within the samples.

Volatile-Bearing Minerals

Talc, chlorite serpentine, tremolite, anthophyllite, and magnesite are all found as metamorphic products within the dunite. Modal amounts of these minerals vary greatly over relatively small areas and values listed in Table 8 should only be regarded as an estimate of a variable population. All of these minerals contain a volatile component (either H_2O or CO_2) and the variability of the modal mineralogy is probably related to the fluid distribution during the metamorphism. The abundance of volatilte-bearing phases increases greatly near the veins and pegmatites that transect the dunite bodies.

Dunite: At least three varieties of phyllosilicates are associated with the dunite. Talc forms anhedral grains that reach several centimeters in their largest dimension and occurs in the dunite and as an important constituent of talc schist associated with the pegmatites. Talc is found in textural equilibrium with olivine and orthopyroxene plus many of the other metamorphic minerals in the dunite (Table 8). In many cases, talc is found replacing anthophyllite along cleavage planes, resulting in talc with a fibrous habit. Chlorite found in the dunite is light brown in color and does not show pleochroism. The chlorite forms subhedral to anhedral grains up to a centimeter across in the dunite and epitaxial overgrowths occur on chromian spinel. Analyses of the chlorite (Table 7) show the material to be kämmererite. Serpentine forms coronas around olivine grains in the dunite. As the amount of serpentine increases, the color of the dunite changes from light green to black. The serpentine is younger than other metamorphic minerals such as talc or tremolite, as indicated by cross-cutting relations and local replacement of these minerals by serpentine.

Tremolite and anthophyllite are found in the Day Book dunite as euhedral to subhedral crystals up to four centimeters long (Table 8). Tremolite forms blade-like crystals with an inclined extinction. Anthophyllite occurs in acicular masses with parallel extinction. Some tremolite crystals show an overgrowth of anthophyllite. These overgrowths on tremolite may be magnesiocummingtonite rather than anthophyllite (Evans, 1977; Whitney, personal communication, 1977). Both of these amphiboles are also found in the contact zone between the pegmatitic rocks and the dunite (Fig. 5).

Table 9. Composition of Magnetite.

TiO_2	0.04
Al_2O_3	0.01
Cr_2O_3	0.00
Fe_2O_3*	64.58
FeO	34.45
MnO	0.04
MgO	0.22
NiO	0.00
Total	99.34

Sample from a serpentine-filled fracture at location 63 on Figure 2.
*Calculated from Fe_{total} = FeO based on the method of Carmichael (1967).

Other metamorphic minerals found in the dunite are confined to zones of extensive alteration and include magnetite and magnesite. In dunite that shows extensive serpentinization, octahedra of magnetite to 0.5 mm are found with the serpentine. Magnesite is found in some dunite samples and is associated with extensive development of talc and amphiboles. The carbonate forms anhedral grains up to 4 cm across which shows good rhombohedral cleavage and a very high relief.

Veins: The mineralogy of the veins is very similar to that of the dunite, but the modes vary considerably between dunite and veins. The modes of the veins are dominated by talc, but also include subordinate amounts of tremolite, anthophyllite, olivine, magnesite, serpentine and chlorite. The veins show crude zonation from a olivine-amphibole margins to talc ± magnesite interiors. Many of the veins do not contain magnesite, but when magnesite is present, it is found in the central portion of the veins.

The veins and dunite also differ in grain size. Minerals in the veins are coarser-grained than their counterparts in the dunite. For example, magnesite in the veins forms crystals up to 20 cm across whereas the largest magnesite crystal found in the dunite is 4 cm in maximum dimension. The dominance of fluid-bearing phases and the coarser grain size in the veins suggests formation in more fluid-rich evironment than the bulk of the dunite.

Joint and Shear-Zone Fillings: A third group of metamorphic minerals is found as joint coatings and fracture fillings that cross-cut the dunite and its associated veins. The most common minerals in these fractures are serpentines. Long fiber, white asbestiform serpentine fills a shear zone in the smaller of the two dunite bodies (Fig. 3). Another shear zone in the larger dunite mass contains serpentine, magnetite, and chalcedony. Joint surfaces in the dunite are also coated with serpentine, chalcedony, aragonite and magnetite (Table 9). Tien (1977) described fracture fllings of aragonite, dolomite, magnesite and huntite from the Day Book dunite formed during weathering. With the exception of aragonite, which forms radiating clusters with crystals up to 2 cm long, the carbonates are all fine-grained and in this respect differ from the coarse-grained magnesite found in the veins.

PETROGENESIS OF THE DUNITE

Primary Features

Few of the structural, mineralogic or petrologic features of the Day Book dunite can be uniquely related to either the initial intrusion, tectonic emplacement or subsequent deformation of the ultramafic body. Concentration of chromian spinel into layers and pods most likely represents a primary magmatic feature. Carpnter and Fletcher (1979) argue that the chromian spinels from pods in Southern Appalachian ultramafics yield compositional trends consistent with magmatic crystallization, while disseminated chromian spinel appears to have suffered subsolidus recrystallization. Results of the present study suggest that both disseminated and massive chromian spinel from the Day Book dunite define a single compositional trend related to recrystallization. Thus, the structure of the layered chromian spinel at Day Book appears to be a primary feature of magmatic crystallization, but the compositon has been modified by post-magmatic recrystallization perhaps associated with the folding of the chromian spinel layers.

Dominance of olivine, chromian spinel, and enstatite in the dunite (Table 8) might be used as an argument for a primary magmatic origin of the ultramafic rock. However, other clearly metamorphic minerals such as talc, tremolite and chlorite are also common in the dunite and the significance of modal mineralogy is thus open to question. Tremolite is a very common, Ca-bearing phase in the dunite, suggesting that a Ca-bearing magmatic mineral may have been originaly present in the dunite. Considering the abundance of olivine and the calcium content of the dunite (as evidenced by the presence of tremolite and the dunite bulk compositon, Table 4), original magmatic mineralogy of the dunite is best approximated by olivine + orthopyroxene + clinopyroxene + chromian spinel.

Textural relations of olivine in ultramafic rocks from the Southern Appalachians have been attributed, at least in part, to crystallization and recrystallization in the mantle (Sailor and Kuntz, 1972; Bluhm and Zimmerman, 1977; Hahn and Hemlich, 1977). Olivine in many of the ultramafics occurs as coarse to very coarse-grained porphyroblasts with kink bands and irregular grain boundaries surrounded by a fine-grained granoblastic polygonal fabric of undeformed olivine. The olivine porphyroblasts are thought to represent a relic texture, whereas the finer-grained polygonal grains are clearly a recrystallization texture (Spry, 1969). To the authors' knowledge all of the petrofabric studies on olivine from the Southern Appalachians have utilized these polygonal recrystallization textures and have not distinguished between different types of textures in petrofabric analyses. Thus, the significance of such studies is questionable. Clearly the fabric measured is a recrystallization texture, but where did this recrystallization take place? Did it occur deep in the mantle, near the magmatic source, in the mantle during diapiric rise, in the crust during emplacement or is the texture the result of some subsequent metamorphic epsiode that took place after the emplacement of the ultramafic body in the crust? The complex textures found in the ultramafics seems to argue for recrystallization during more than one deformation (Bluhm and Zimmerman, 1977). However, until petrofabric analyses of texturally different coexisting olivines are combined with detailed structural studies of the surrounding country rocks, it will be very difficult to distinguish between mantle emplacement or post emplacement recrystallization textures in the ultramafic rocks.

The presence of large olivine porphyroblasts does indicate a relict texture, but a relic of what? The general argument is that these large deformed grains represent mantle-derived material, deformed during emplacement, which escaped recrystallization (Misra and Keller, 1978). However, work with metamorphic olivine has shown that large porphyroblasts of olivine can be developed during the prograde metamorphism of low grade ultramafic rocks (Evans and Trommsdorff, 1974; Vance and Dungan, 1977). It thus appears possible that these porphyroblasts may represent olivine formed during prograde metamorphism and that the granoblastic-polygonal olivine could represent recrystallization during cooling or during a subsequent metamorphic event. In contrast to this interpretation, Lappin (1967) found that olivine porphyroblasts and granoblastic-polygonal olivine in ultramafic rocks from Norway had significantly different fabrics and he argued against a prograde-retrograde metamorphic origin for the two olivine textures. Clearly, more work is needed on olivine petrofabrics from the Southern Appalachians, before a primary or secondary origin can be ascribed to these textures.

Metamorphism of the Day Book Dunite

Ultramafic rocks at Day Book have been metamorphosed as indicated by the abundance of metamorphic minerals in the dunite (Table 8), textural equilibrium between the metamorphic minerals, and the granoblastic-polygonal olivine fabric developed by recrystallization. The homogeneity of the dunite texture and minerals (no zoning was detected either optically or in the microprobe analyses), together with the repeated occurrence of rather simple mineral assemblages (forsterite + talc + tremolite, Table 8 for example) strongly argues for attainment of equilibrium during metamorphism of the Day book dunite (Evans and Trommsdorf, 1970). The

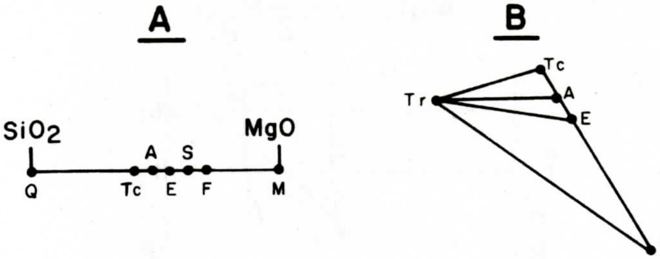

Figure 11. Compositional relations in the volatile-free portion of the system MgO-SiO_2-H_2O-CO_2 (A) and a portion of the system CaO-MgO-SiO_2 (B). Phases shown include quartz (Q), talc (Tc), anthophyllite (A), orthopyroxene (E), serpentine (S), olivine (F). magnesite (M), and tremolite (Tr).

metamorphism appears to have been, with the exception of the volatile components H_2O, CO_2, and O_2, isochemical as evidenced by the dominance of SiO_2-poor (i.e., forsterite-bearing) assemblages in the dunite. An obvious exception to this argument for isochemical metamorphism is the monomineralic metasomatic contact zones associated with the country rock and pegmatite contacts.

The bulk composition of the dunite, plus the relatively simple mineral compositions, permits a close comparison to the synthetic system MgO-SiO_2-H_2O-CO_2 or, for the tremolite-bearing assemblages, with the system CaO-MgO-SiO_2-H_2O (Evans and Trommsdorf, 1974; and Evans, 1977). Most reactions involving Mg-rich silicates in these ultramafic systems are changed little in P-T-X_{fluid} space by the presence of small amounts of FeO (Evans and Trommsdorff, 1970; Winkler, 1976). Thus the small amounts of iron in the Day Book dunite (Table 4) should have little effect on conclusions based on the Fe-free system. The presence of Al_2O_3 in ultramafic systems will result in the formation of an Mg-rich chlorite in all but the highest grades of metamorphism (Winkler, 1976). Evans (1977) has treated the Al-bearing phase separately from the phases in the system CaO-MgO-SiO_2, thus taking advantage of simple triangular geometry in the volatile-free system. Considering the ubiquitous occurrence of chlorite in both the veins (Table 3) and the dunite (Table 8) at Day Book, a similar approach will be used in this paper. The resulting geometrical representations for phases observed in the Day Book dunite in the systems MgO-SiO_2 and CaO-MgO-SiO_2 are shown in Figure 11.

Evans and Trommsdorff (1974) have developed a model based on petrographic and experimental studies for the metamorphism of ultramafic rocks in the system MgO-SiO_2-H_2O-CO_2 and a portion of their model is reproduced here at Figure 12. The two isobaric T-X_{fluid} sections (P_3 and P_4) best represent the P-T conditions during the metamorphism of the Day Book dunite because a number of the three-phase univariant assemblages represented on these isobaric sections are also found in the dunite and in the veins. The critical assemblages (Table 10) are located around the MFAT invariant point at P_4 and around the FEAT and MFET invariant points at P_3. Actually only the assemblage TEF is unique to P_3 suggesting that pressure during metamorphism of the Day Book dunite was closer to P_4 than to P_3. The passage of the reaction EAT through the invariant point MFET generates a new invariant point MFAT as the pressure decreases from P_3 to P_4. The association of three of the critical assemblages (Table 10) with the new invariant point together with one assemblage (TEF) unique to the old invariant point, suggests the metamorphism occurred at pressures near the crossing of MFET by EAT. At such a pressure all of the observed critical assemblages in the system MgO-SiO_2-H_2O-CO_2 (Table 10) would be stable or slightly metastable. Occurrence of metastable assemblages may then be explained as retrograde assemblages, by slight variations in fluid composition or by the influence of FeO on the system.

Discussion of the stability relations of tremolite-bearing assemblages must be treated in terms of the system CaO-MgO-SiO_2-H_2O. Evans (1977) has developed an excellent model for the metamorphism of ultramafic rocks in this system and the following discussion will be largely based on his work. Critical tremolite-bearing mineral assemblages are given in Table 11 and Figure 13. As in the case of the MgO-

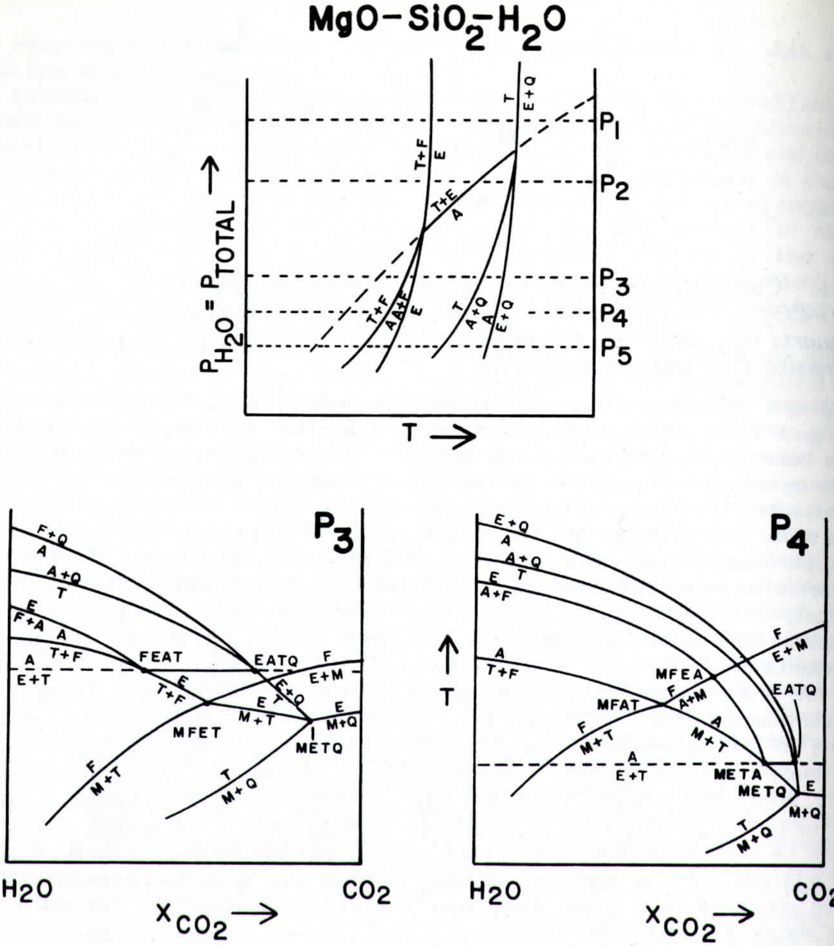

Figure 12. Phase relations in a portion of the system MgO-SiO$_2$-H$_2$O-CO$_2$ (Evans and Trommsdorff, 1974b).

Table 10. Occurrence of Key Mineral Assemblages in the System MgO-SiO$_2$-H$_2$O-CO$_2$.

	Ta+Fo +M	Ta+Fo +Opx	Ta+Fo+ Antho	Ta+M+ Antho
Veins	3	0	12	2
Dunite	2	9	6	0

SiO$_2$-H$_2$O-CO$_2$ system, similar mineral assemblages are found in both the dunite and the veins, the major difference being in the relative amounts of the phases present (Tables 3 and 8). The assemblage tremolite + anthophyllite + enstatite was not noted in any of the samples, but this may be due to a sampling problem related to the overall scarcity of enstatite rather than a gap in the bulk compositions of the ultramafic rock.

Metamorphic assemblages (Tables 3 and 8) and critical mineral assemblages used to define metamorphic reactions (Tables 9 and 10) in the dunite and the veins found in the dunite are very similar. Assemblages that contain enstatite are unique to the dunite, as this phase is not found in the veins. The similarity of mineral assemblages in the dunite and the veins suggests the metamorphism of the dunite and the formation of the veins was the result of contemporaneous recrystallization at the same temperature, pressure, and fluid composition. Veins probably served as channels for the fluid that accompanied recrystallization of the dunite. In some cases, veins can be traced from the metasomatic reaction zone surrounding pegmatites, directly into the dunite. The veins contain a higher modal proportion of volatile-bearing phases than the

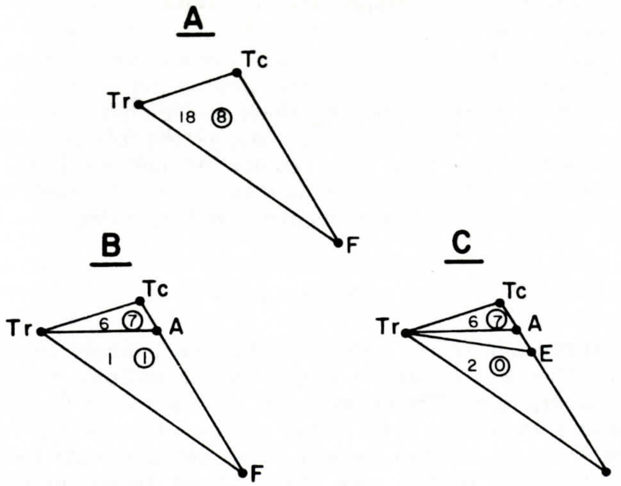

Figure 13. Occurrences of mineral assemblages in a portion of the triangle CaO-MgO-SiO_2 in the dunite and associated veins (circled). All assemblages include chlorite.

Table 11. Occurrence of Key Mineral Assemblages in the System CaO-MgO-SiO_2-H_2O.

	Tr+Ta +Fo	Tr+Ta+ Antho	Tr+Fo+ Antho	Tr+Fo +Opx	Tr+Ta +Opx
Veins	8	7	1	0	0
Dunite	18	6	1	2	2

dunite (Tables 3 and 8) because of a higher original fluid content.

Variation of mineral assemblages within the veins and dunite is most likely due to local variations in bulk composition (particularly in the fluid phase) rather than gradients in pressure and/or temperature within the dunite. Figure 12 illustrates how small changes in the mole percent of CO_2 in the fluid phase (X_{CO_2}) can change mineral assemblages. For example, at pressures corresponding to P_4 and temperatures slightly less than the MFAT invariant point, a variation of 10-20 mole percent CO_2 can result in the following stable mineral assemblages: anthophyllite + magnesite, anthophyllite + talc, talc + quartz, anthophyllite + magnesite + talc, talc + magnesite, magnesite + talc + forsterite, magnesite + forsterite and talc + forsterite. Another effect of changing fluid composition is the steatization of tremolite and anthophyllite. Individual amphibole crystals commonly show partial to total replacement by talc. Within the contact zone between the pegmatites and the dunite, much of the talc has a fibrous structure that is thought to result from replacement of anthophyllite by talc. Reduction of CO_2 activity in the vapor can result in the isothermal breakdown of anthophyllite as shown on Figure 12 at P_4 (reactions T+F=A and M+T=A). The common steatization of anthophyllite in the Day Book dunite suggests that the composition of the vapor phase in the ultramafic rock became more enriched in H_2O during the course of the metamorphism. The effect of variation in volatile-free bulk composition is shown in Figure 11. Occurrence of the assemblages tremolite + talc + anthophyllite or tremolite + forsterite + anthophyllite is controlled by the bulk composition and not by any variation in temperature or pressure.

Mineral assemblages in the Day Book dunite and surrounding country rocks indicate recrystallization under conditions corresponding to medium grade (Winkler, 1976) or the middle amphibolite facies of regional metamorphism (Turner, 1968; Evans, 1977). Estimates of pressure and temperature based on mineral assemblages in pelitic rocks yield 550-650°C and 5 to 6 Kb (Winkler, 1976).

Serpentine is found throughout the dunite and associated veins (Tables 3 and 8) as both fracture fillings (Fig. 3) and coronas surrounding Mg-silicates. Textural and structural relations clearly indicate the serpentinization is younger than the major metamorphism that recrystallized the dunite. Fluids that accompany serpentinization are H_2O-rich and serpentine is unstable even in the presence of small amounts of CO_2 (Johannes, 1969). Thus, the early period of talc-tremolite-anthophyllite- magnesite-chlorite metamorphism with its relatively CO_2-rich fluid is different from the serpentinization event, not only in terms of timing, but also in terms of fluid composition. Serpentinization is a low grade metamorphic process. Indeed, some workers believe serpentinization occurs in the weathering environment (Barnes, et al., 1969). Some of the shear zones in the Day Book dunite contain springs with associated thin coatings of chalcedony and serpentine--suggesting active serpentinization. The country rocks surrounding the Day Book dunite do not show any evidence of the retrograde metamorphism that might be related to serpentinization, thus supporting the argument for very low grade local development of serpentine.

CONCLUSIONS

Mineral assemblages, textures and field relations indicate the Day Book dunite is an alpine ultramafic that was emplaced in graywackes and basalts prior to amphibolite grade regional metamorphism. Chromian spinel and olivine compositions from the Day Book body are similar to values from other alpine ultramafics. The absence of a contact aureole or other associated igneous rock also demonstrates the alpine nature of the ultramafic body. Country rock distributions shown in Figure 2 suggest a protolith with alternating, irregular layers of basaltic and clastic sedimentary rocks. Banding of thin layered amphibolites has been ascribed to metamorphic differentiation (Orville, 1969), but the scale involved at Day Book is too large to be explained by ion migration. On an outcrop scale, blocks of amphibolite from 3 cm to 5 m are found to be surrounded by more pelitic material. These structural relations may have resulted from polyphase folding accompanied by shearing or they may represent a metamorphic terrain in which protoliths of clastic sediment surrounded blocks of basalt--a rock distribution suggestive of a melange terrain (Raymond, 1977).

Regional metamorphism of the ultramafic and surrounding rocks has produced mineral assemblages corresponding to the middle amphibolite facies, 550-650°C and 5-6 kb. Such temperatures, in this pressure range closely approximate the solidus temperature for the Spruce Pine pegmatites (P.M. Fenn, personal communication, 1978). It is possible that the metamorphism of the dunite and country rock was also accompanied by pegmatite intrusion. Minerals found in the contact zone between the pegmatite and the dunite are the same (with the exception of vermiculite) as the minerals found in the dunite and the veins. Orientation of the veins (Fig. 4) suggests a genetic relation between the H_2O-CO_2 fluid that invaded the ultramafic and the pegmatites and, locally, veins can be traced from the pegmatites into the dunite.

Granitic magmas that contain an H_2O-CO_2 fluid phase initially evolve a vapor phase with a relatively high CO_2 content, but as crystallization of the magma proceeds the vapor becomes more enriched in H_2O (Holloway, 1975; Swanson, 1979). In granitic melts, H_2O is more soluble than CO_2, thus H_2O is fractioned into the granitic liquid, while CO_2 will be concentrated in the vapor phase. As the melt crystallized, H_2O is gradually expelled from the melt and added to the vapor phase, thus enriching the vapor in H_2O.

At Day Book, pegmatite intrusion was apparently accompanied by a relatively CO_2-rich vapor that moved into the dunite along fractures and produced the anthophyllite and magnesite-bearing assemblages. As the granitic magma crystallized, the fluid became more H_2O-rich, resulting in the replacement of anthophyllite and tremolite by talc. Textural relations suggest that magnesite and anthophyllite crystallized early in the ultramafic rocks, whereas talc formed later, thus supporting the argument for H_2O-enrichment in the vapor phase as a function of time.

Serpentinization of the Day Book dunite is a comparatively recent event, unrelated to the amphibolite grade regional metamorphism. Serpentine minerals are confined to fracture fillings or grain boundaries and do not show stable textural relations with any other Mg-silicates. Stability relations of the serpentine minerals suggest formation in an H_2O-rich environment at low temperatures, perhaps seven in the zone of weathering. Textures and phase equilibria results show the serpentinization post dates the major metamorphism of the Day Book dunite and surrounding country rocks.

Alpine ultramafic rocks found as conformable bodies in regionally metamorphosed terrains, such as the Day Book dunite in the Blue Ridge of western North Caolina, have clearly suffered polyphase deformation and recrystallization. Textural and mineralogic data indicate the ultramafics have been recrystallized during regonal metamorphism and subsequently altered by serpentinization. Trying to unravel the emplacement history of such recrystallized rock is very difficult. The ultimate origin of these rocks is probably diapiric upwelling or intrusion from the mantle into the crust--few workers would argue this (Moores and MacGregor, 1972). However, the emplacement of these rocks into their present positions in the crust is a matter of some controversy (Misra and Keller, 1978). Whatever the emplacement mechanisms for the ultramafics, the data necessary to evaluate the models will not be found in the dominant polygonal olivine fabric that is clearly the result of recrystallization. Large, deformed olivine grains offer the best chance for olivine petrofabric data that bears on the question of emplacement mechanisms. However, without a detailed structural study of the surrounding country rocks, the significance of such data is still open to question. Study of the geologic history of these recrystallized ultramafics is a complex problem whose solution requires detailed petrologic and structural analysis of the ultramafics and enclosing country rocks.

ACKNOWLEDGEMENTS

This project would not have been possible without the full and complete cooperation of the quarry operators at Day Book, Northwest Carolina Olivine and in particular Doug Wiseman, the plant manager. Electron microproble analyses were done by Raymond W. Whittkopp at the University of California at Davis. Cost of thin section preparation for this project was provided by research grants from the University of North Carolina at Charlotte (1975-75) and Appalachian State University (1976-1977; 1978-1979). The author wishes to thank his good friend Loren Raymond for support during the field work and for many stimulating discussions on Appalachian geology. Loren Raymond and John Carpenter reviewed an earlier version of the manuscript and made many useful suggestions.

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AN IGNEOUS ORIGIN FOR THE HENDERSON AUGEN GNEISS, WESTERN NORTH CAROLINA: EVIDENCE FROM ZIRCON MORPHOLOGY

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ABSTRACT

Zircon morphological studies were conducted on six samples collected from two belts of the Henderson augen gneiss cropping out in western North Carolina. Length/breadth ratios for suites from both belts were compared using the non-parametric Mann-Whitney U test. Based on the U test, zircon suites within each belt represent a single population (with one exception). U test comparison of zircon populations between the belts suggests that there are subtle but real differences. Mode maxima from length/breadth frequency plots, elongation ratios, and the reduced major axes plots indicate an igneous origin for both belts of augen gneiss. Volume frequency plots indicate, based on the lack of dispersion within each suite, an igneous origin for four zircon suites when compared with the Lilesville Pluton.

INTRODUCTION

There has been considerable debate concerning the origin of the Henderson Gneiss. Keith (1903, 1905 and 1907) originally mapped the unit cropping out northwest and southeast of the Brevard Zone and defined it as the Henderson Granite. He interpreted the unit to be igneous in origin. Reed (1964) renamed the lithologies as the Henderson Gneiss and restricted its occurrence to outcrops southeast of the Brevard Zone, along the western edge of the Inner Piedmont throughout the southern Appalachians. Cazeau (1967) and Hatcher (1970) mapped portions of the Henderson Gneiss in South Carolina and interpreted it to be of metasedimentary origin. Odom and Fullagar (1973) inferred an igneous origin for the Henderson Gneiss based on correlative radiometric age determinations.

Zircon suites were studied from the Henderson Gneiss in conjunction with geologic mapping in western North Carolina. Samples were located from within the Bat Cave, Fruitland (Lemmon, 1973; Lemmon and Dunn, 1973a, 1973b) and the Hendersonville (Lemmon, unpublished data) 7-1/2 minute geologic quadrangles (Figure 1). In the map area the Henderson Gneiss was subdivided and mapped as an augen gneiss (Єag) and a biotite granitic gneiss (OSgg). Six zircon suites from the augen gneiss were analyzed and compared. Two suites from the Lilesville Pluton cropping out in Anson and Richmond Counties, and a sedimentary suite (TGS) from the Texasgulf, Inc. phosphate plant in Beaufort County, North Carolina are included for comparisons. Over 1700 data pair are involved in this study.

The purposes of the study are: 1) to determine the origin of the Henderson augen gneiss based on zircon morphology; 2) to compare zircon suites collected by random sampling from the augen gneiss; 3) to compare suites from the augen gneiss to zircon suites from the Lilesville Pluton and a sedimentary suite (TGS).

PREVIOUS WORK

Articles dealing with zircon morphology and its application to petrogenetic problems are numerous (Poldervaart, 1955 and 1956; Alper and Poldervaart, 1957; Larson and Poldervaart, 1957; Eckelmann and Poldervaart, 1957; Ragland, 1969; Byerly

Department of Agriculture, Science and Education Administration-Agricultural Research, Oxford, Mississippi, in cooperation with the Vicksburg District of the U. S. Corps of Engineers, Department of the Army. Paul Hawks, Ray Frederking, Bill Reynolds, Charles Thompson, Whitney Autin and Wutti Uttamo skillfully helped log samples and Maxine Nelson and Donald Main provided valuable assistance in the laboratory.

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STRUCTURE CONTOUR MAP OF BASEMENT BELOW NORTH CAROLINA COASTAL PLAIN AND CONTINENTAL SHELF

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ABSTRACT

A structure contour map of the basement surface below the North Carolina Coastal Plain and continental shelf has been prepared from existing basement well and seismic data. This map results from work performed as part of a U.S. Department of Energy-funded project to evaluate geothermal energy potential in the Atlantic Coastal Plain.

As shown by the structure contours, the basement surface is not simple. Large scale features, including the Cape Fear Arch, a major northwest-trending basement flexure in southern North Carolina, and a sharp increase in the dip of the basement surface along a north-northeast trend at approximately the -1500 foot contour northeast of the Cape Fear Arch are defined. The basement structure contour map was used to predict basement depths for eight holes drilled as part of the Virginia Polytechnic Institute and State University (VPI&SU) - Department of Energy (DOE) project; predictions were accurate to within 2 per cent of true depths.

INTRODUCTION

For the past several years, a DOE-funded program exploring the potential for low-temperature geothermal resources in the Atlantic Coastal Plain has been underway at VPI&SU (Costain, 1979; Glover, 1979). Exploration is based upon a model predicting high heat flow from granitic plutons in the crystalline basement below the Atlantic Coastal Plain. According to the model, such plutons would contain anomalously high amounts of radioactive elements relative to surrounding country rock; radioactive decay would produce heat which would be retained in deep acquifers due to the insulating capability of the overlying Coastal Plain sediments. Analysis of this model requires a knowledge of both the thickness of the Coastal Plain sequence and the lithology of the basement below the Coastal Plain. Therefore, an attempt was made to compile all available information regarding these two parameters. For this compilation, "basement" has been defined to include all crystalline rocks of the buried Piedmont as well as volcanic and sedimentary rocks confined to buried Triassic/Jurassic basins. Overlying Coastal Plain sediments are of Cretaceous and younger age, with the exception of deep Coastal Plain sediments of possibly Upper Jurassic age near Cape Hatteras (Mattick et.al., 1974).

Information regarding the Coastal Plain basement was obtained primarily through a review of professional journals, oil and gas drilling reports, U.S.G.S. publications, and state geological survey publications. State survey geologists also provided supplemental data, and additional data were obtained from several test holes drilled to basement as part of the VPI & SU-DOE geothermal project.

NORTH CAROLINA BASEMENT DATA

The compilation of basement data includes four hundred fifty wells drilled to

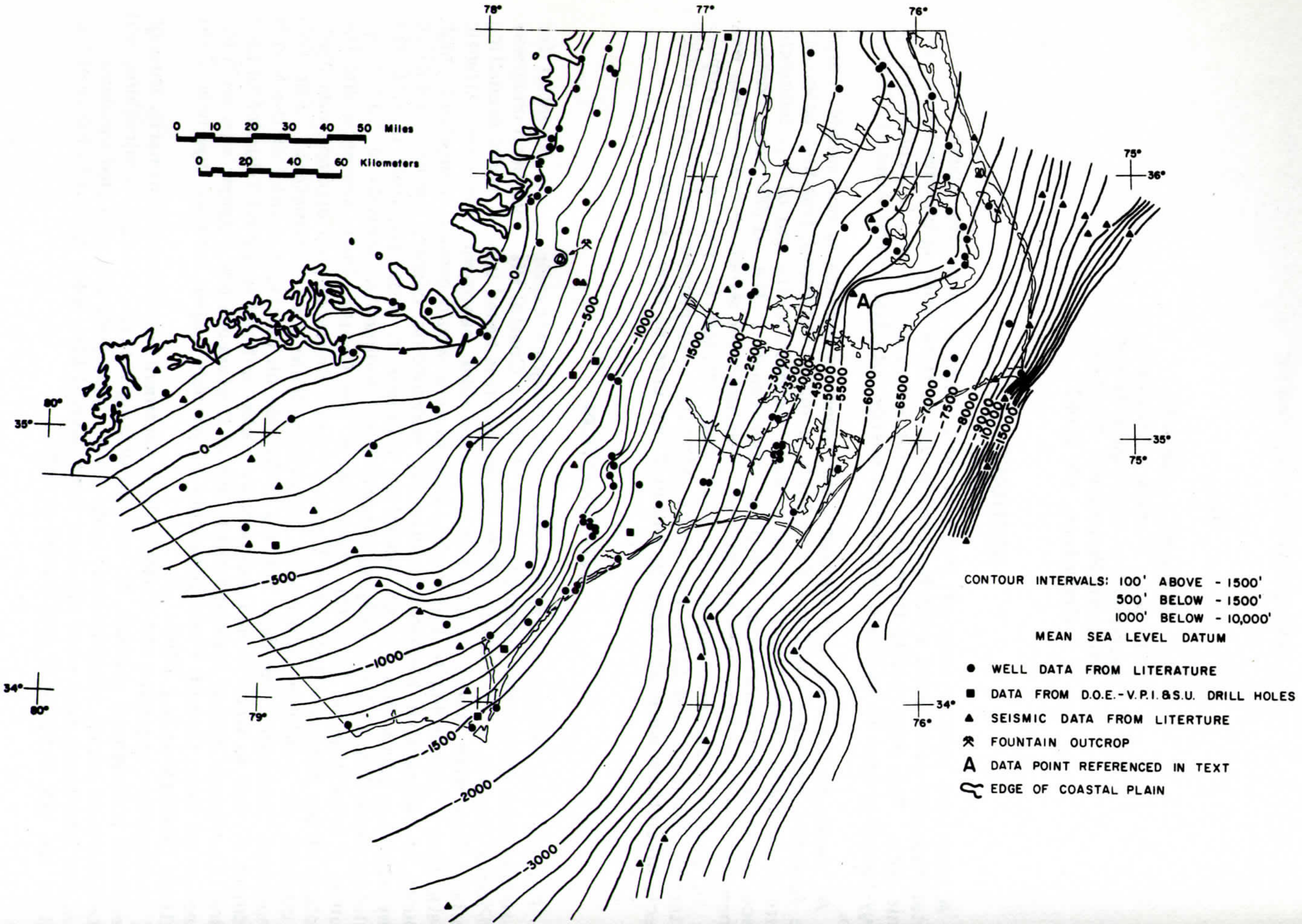

Figure 1. Structure Contour Map of the Basement Surface Below North Carolina Coastal Plain and Continental Shelf.

basement in North Carolina, mostly near the thin western edge of the Coastal Plain. Depth to the top of basement was obtained for one hundred fifty of the wells. Appendix I summarizes pertinent information regarding these wells. Additionally, data regarding depths to basement in the North Carolina Coastal Plain are available from published reports of seismic refraction investigations in North Carolina (Skeels, 1950; Bonini and Woollard, 1960). Appendix II lists data on thirty-two seismic refraction lines obtained during these investigations. Information on depth to basement on the continental shelf is available from several sources (Hersey, et. al., 1959; Dowling, 1968; Klitgord and Behrendt, 1979; Grow and Markl, 1977; King, 1980). Data points obtained from these sources are also listed in Appendix II.

Figure 1 is a structure contour map constructed from the data included in Appendix I and Appendix II. Because most of the data in the tables were derived from reports listing English measure units, data in the appendices and figure are presented in such units. The map presented here updates earlier maps by Spangler (1950); Bonini and Woollard, (1960); Dennison et al., (1967); Flawn, (1967); Maher, (1971); Brown et al., (1972).

Several features of the North Carolina basement surface are apparent from Figure 1. The Cape Fear Arch, a subsurface topographic high which has been recognized for nearly a century (Dall and Harris, 1892; Stephenson, 1926; Mansfield, 1927; Prouty, 1936; Cooke, 1936; Richards, 1945, 1947, 1948; Straley and Richards, 1950; Berry, 1951; LeGrand, 1955; Ferenczi, 1960), is well defined, as is a sharp increase in basement slope which occurs at approximately -1500' on the basement northeast of the Cape Fear Arch. This change in basement slope occurs along a north-northeast trend, parallel to Appalachian structural trends west of the Coastal Plain. To the west of this break, the basement slope is approximately 30'/mile (5.7m/km or .3^{o}), increasing abruptly to approximately 100'/mile (18.9 m/km or 1.1^{o}) at the break in slope. This break in basement slope was previously recognized by Prouty (1946) and by Berry, (1948). A greater steepening of the basement slope is apparent at the -10,000' contour below the continental shelf off Cape Hatteras. The basement slope here assumes a gradient of approximately 850'/mile (160 m/km or 9.1^{o}). Figure 1 also indicates an embayment on the basement surface west of Cape Hatteras. It should be noted that seismic point A (Figure 1) is the sole control point for this embayment. This configuration was noted by Bonini and Woollard (1960) who felt that such a basement structure was real.

The basement surface appears to be a somewhat irregular surface, with local relief of 50-100', as evidenced by sharp jogs in contours, particularly where data points are clustered. An outcrop of basement rocks near Fountain in Pitt County (Figure 1), approximately twenty miles from the western edge of the Coastal Plain, indicates local basement relief in excess of 200'.

The contour map was constructed to aid in estimating basement depths for VPI & SU geothermal drill holes in the Coastal Plain of North Carolina. Estimates derived from this map proved reasonably accurate for eight holes drilled between late 1978 and early 1980 (Figure 1). Depths to basement at these locations were all within 1-2' of predicted depths. These drill holes were all less than 2000' deep; somewhat less accuracy might be expected in areas where the Coastal Plain sediments are thicker and the basement dip is correspondingly steeper or in areas where control data are sparse.

APPLICATIONS

The revised structure contour map presented here is a valuable tool for those who require reliable estimates of the thickness of the Coastal Plain sediments in North Carolina. Such estimates are a necessary prerequisite to the evaluation of the geothermal resource potential of deep Coastal Plain aquifers as well as the evaluation of basement "hot dry rock" prospects, a geothermal technique presently being developed by the Los Alamos Scientific Laboratory (Energy Research and Development Authority, 1977). The map may also aid in evaluating oil and gas potential in deeper parts of the Coastal Plain and continental shelf and may also be of use in hydrologic and water resources studies of the North Carolina Coastal Plain.

ACKNOWLEDGEMENTS

This work was performed as part of Department of Energy contract #ET- 78-C-05-5658 to J. K. Costain, Lynn Glover, III, and A. K. Sinha. The writer would like to express his appreciation to Lynn Glover, III, J. A. Speer, S. S. Farrar, and K. C. King for their critical review of the manuscript.

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Appendix I: Wells drilled to basement in North Carolina Coastal Plain for which depths to top of basement are known. Reference numbers refer to sources listed at end of text.

COUNTY	WELL NAME (OWNER)	OPERATOR	LATITUDE	LONGITUDE	DATE DRILLED	TOTAL DEPTH (FEET)	SURFACE ELEVATION (FEET)	DEPTH TO BASEMENT (FEET)	BASEMENT ELEVATION (FEET)	REFERENCES
Beaufort	Rodman #1	Coastal Plains Oil	35°32.8'	76°46.8'	1963	2012	16	1980	-1964	5,21
	West Dismal #1	Coastal Plains Oil	35°39.0'	76°48.2'	1963	1938	34*	1930	-1896	5,21
	Rodman #2	Coastal Plains Oil	35°34.0'	76°45.8'	1963	2120	18*	2107	-2089	5,16
	Z. Ratcliff #1	Coastal Plains Oil	35°35.8'	76°48.2'	1963	1966	18*	1963	-1945	5,16
Bertie	Cowand #1	Coastal States Oil	36°00.9'	76°46.3'	1969	1570	35*	1510	-1475	5,21
Bladen	Corbett #1	Am. Mining & Develop.	34°26.1'	78°16.5'	1959	765	23	690	- 667	5,16,21
Brunswick	Fort Caswell	W. H. Gray Bros.	33°53.3'	78°02.0'	1907	1543	10	1540	-1530	6,16,19,24
	Calabash	No. Carolina State	33°53.6'	78°35.3'		1335	48	1333	-1285	6,11
	Skipper #1	Coastal States Oil	34°17.0'	78°09.0'	1969	1010	47*	1000	- 953	5,21
	D.O.E.-C.P. #14A	Gruy Federal	33°56.9'	78°00.0'	1979	1864	25*	1554	-1529	
Camden	DuGrandlee-Forman #1	Urice Drill.	36°25.2'	76°10.0'	1953	6421	16	3520	-3504	5,6,16,21,26
	Weyerhaeuser #1	E. F. Blair	36°24.7'	76°10.5'	1965	3741	8	2822	-2814	1,5,6,7,21
Carteret	Laughton #1	F. L. Karston	34°45.7'	76°45.5'	1945	4044	17	4030	-4013	5,6,16,21,25
	Guy M.Carraway #1	Carolina Petroleum Co.	34°57.1'	76°38.5'	1946	4069	15	4054	-4039	5,6,16,21,25
	Nita Carraway # 1	Carolina Petroleum Co.	34°55.8'	76°38.1'	1946	4126	15	4120	-4105	5,6,16,21
	D. H. Phillips #1	Carolina Petroleum Co.	34°58.8'	76°39.0'	1946	3964	13	3946	-3933	5,6,21,25
	H. B. Salter #1	Carolina Petroleum Co.	34°57.3'	76°39.6'	1946	3963	13	3955	-3942	5,6,16,21,25
	John Wallace #1	Carolina Petroleum Co.	34°58.8'	76°38.0'	1946	4024	11	4020	-4009	5,6,16,21,25
	Bayland Corp. #1	Coastal Plains Oil	34°53.9'	76°22.0'	1961	5609	18	5570	-5552	5,6,16,21
	Huntley-Davis #1	Coastal Plains Oil	34°43.8'	76°34.5'	1961	4965	17	4955	-4938	5,6,16,21
	Elliot #1	Carr & Schmidt	34°48.2'	76°49.8'	1973	3441	22*	3396	-3374	5,21
	Atlantic Beach Corp #1	Carr & Schmidt	34°42.3'	76°44.4'	1974	4092	9	4088	-4079	5,21
Craven	Great Lakes #2	Great Lakes Drill.	34°51.0'	76°58.8'	1925	2404	30	2318	-2288	5,6,10,16,17,18,21,24
	C. Bryan #1	Carolina Petroleum Co.	34°50.9'	76°57.9'	1947	2435	15	2408	-2393	5,6,16,21,25
	Graham Merritt	State of No. Carolina	35°13.4'	77°25.4'	1979	1090	50*	980	- 930	27
	Peter Havfich	State of No. Carolina	35°12.4'	77°23.5'	1979	1194	60*	1154	-1054	27
Cumberland	Fayetteville Ice & Mfg.		35°02.9'	78°53.3'		265	106	220	- 114	9
		J. M. Wright	35°02.9'	78°53.3'		237	100	192	- 92	9
Currituck	Twiford #1	E. F. Blair	36°18.2'	75°55.5'	1965	4553	10	4526	-4516	1,5,6,7,21
	Kellog #1	Rapp Oil Co.	36°07.0'	75°51.2'	1969	5140	16	5071	-5055	5,21
Dare	Esso #1-Hatteras Light	Standard Oil of N. J.	35°15.0'	75°31.8'	1946	10054	24	9878	-9854	5,6,16,21,30,31
	Mobil#1-Pamlico Sound	Socony-Mobil Oil	35°59.9'	75°52.0'	1965	5255	19	5165	-5146	1,5,6,16,21
	Mobil #2-Pamlico Sound	Socony-Mobil Oil	35°26.2'	75°34.6'	1965	8381	24	8360	-8336	1,5,6,16,21
	Marshall Collins #1	E. F. Blair	35°53.0'	75°40.3'	1965	6291	2	6268	-6266	1,5,6,7,21
	West Va. Pulp & Paper #1	E. F. Blair	35°51.8'	75°55.5'	1965	5144	5	5124	-5119	1,5,6,21
	Westvaco #1A	Cities Service	35°39.6'	75°46.7'	1971	6288			-6112	5,6,21
	Westvaco #2A	Cities Service	35°51.8'	75°51.1'	1971	5817			-5409	5,6,21
	First Colony Farms #1	Cities Service	35°48.3'	75°47.8'	1974	5582	10	5540	-5530	5,6,21
	First Colony Farms #2A	Cities Service	35°56.6'	75°52.3'	1974	5260	19	5228	-5209	5,6,21
	Westvaco #2	Gentles	35°45.3'	75°46.4'	1973	6079	5*	6062	-6057	5,21
	Westvaco #3	Gentles	35°41.4'	75°46.8'	1973	5823	3	5812?	-5809	5,21
Duplin	Jones #1	Coastal States Oil	34°55.7'	78°03.8'	1969	596	105*	580	- 475	5,21
Edgecombe	Town of Tarboro	Snyder Pump & Well	35°53.7'	77°32.5'	1899	349	50	328	- 278	6,16,19,24
	Town of Pinetops	Va. Well & Machinery Co.	35°47.3'	77°38.5'	1925	446	100	342	- 242	6,19,20
	Bricks Rural Life School	Va. Well & Machinery Co.	36°08.3'	77°42.7'		326	80*	48	+ 32	20
	East Carolina Training School	Heater Well Co.	35°59.3'	77°46.0'		86	80*	50	+ 30	20
	Meadowbrook Dairy	Heater Well Co.	35°55.2'	77°46.3'		131	95*	100	- 5	20
	G. W. Bradley	R. L. Jones	35°56.7'	77°43.4'		120	65*	120	- 55	20
	B.C. Pittman	R. L. Jones	36°06.1'	77°40.1'		130	125*	130	- 5	20
	Rocky Mount Ice & Fuel Co.		35°53.6'	77°48.1'		754	120	200	- 80	9
	RM-1	VPI&SU	36°02.2'	77°45.4'	1980	413	90*	112	- 22	

Appendix I: Continued

COUNTY	WELL NAME (OWNER)	OPERATOR	LATITUDE	LONGITUDE	DATE DRILLED	TOTAL DEPTH (FEET)	SURFACE ELEVATION (FEET)	DEPTH TO BASEMENT (FEET)	BASEMENT ELEVATION (FEET)	REFERENCES
Gates	Weyerhaeuser #1	S. E. Cullinan Drill.	36°26.0'	76°30.0'	1971	2139	22	2110	-2088	5,6,21
	D.O.E.-DO#1	VPI & SU	36°31.9'	76°52.7'	1978	1351	25*	1023	- 998	
Halifax	Tillery School #1	Heater Well Co.	36°14.7'	77°29.9'		325	70	205	- 135	6,20
	Town of Halifax	Carolina Drill. & Equip. Co.	36°19.9'	77°35.9'		135	125*	110	+ 15	20
	Town of Halifax	Carolina Drill. & Equip. Co.	36°19.9'	77°35.9'		285	125*	110	+ 15	20
	Town of Enfield	Va. Machine & Well Co.	36°10.8'	77°40.2'		350	105*	125	- 20	20
	Town of Scotland Neck	Snyder Pump & Well Co.	36°07.6'	77°25.3'		507	100*	349	- 249	20
			36°19.9'	77°35.9'		270	100	40	- 60	9
	Enfield Grade School		36°10.8'	77°40.2'		115	100	90	- 10	9
	Town of Enfield		36°10.8'	77°40.2'		200	100	109	- 9	9
Harnett	Erwin Cotton Mills		35°19.4'	78°40.6'		502	170	143	+ 27	9,28
	Town of Dunn		35°18.6'	78°36.4'		434	208	90	+ 118	9,28
Hertford	Edgar Bazemore #1	Pam-Beau Drill. Co.	36°19.0'	76°49.0'	1949	1278			-1235	5,6,16,21
Hoke	No. Carolina Sanitorium #1	Heater Well Co.	35°03.5'	79°19.0'	1954	401	510	380	+ 130	4,6
Hyde	Mobil #3 Palmico Sound	Mobil Oil Corp.	35°18.4'	75°49.8'	1965	7314	24	7260	-7236	1,5,6,7,21
	Socony-Mobil-State #3	Socony Mobil Oil	35°15.0'	75°52.0'		7266	0*	7220	-7220	7,16
Johnston	W. D. Avera		35°28.3'	78°16.2'		185	175	30	+ 145	9
	W. D. Avera		35°28.3'	78°16.2'		90	175	20	+ 155	9
	W. D. Avera		35°28.3'	78°16.2'		92	175	30	+ 145	9
	W. D. Avera		35°28.3'	78°16.2'		70	175	20	+ 155	9
	W. D. Avera		35°28.3'	78°16.2'		300	175	70	+ 105	9
	W. D. Avera		35°28.3'	78°16.2'		300	175	70	+ 105	9
	W. E. Edgerton		35.28.3'	78°16.2'		168	173	26	+ 147	9
	Navassa Guano Co.		35°28.3'	78°16.2'		238	175	20	+ 155	9
	Selma Knitting Mills		35°28.3'	78°16.2'		140	175	30	+ 145	9
	W. B. Johnson		35°30.2'	78°25.6'		150	200	55	+ 145	9
			35°29.2'?	78°22.5'?		63	150	45	+ 105	9
	Smithfield Cotton Mills		35°29.2'?	78°22.5'?		150	150	20	+ 130	9
			35°29.2'?	78°22.5'?		125	150	60	+ 90	9
	Town of Smithfield		35°29.2'?	78°22.5'?		106	150	20	+ 130	9
	Oil Mill		35°30.7'	78°14.9'		101	160	40	+ 120	9
	Oliver, Godwin, & Lynch		35°30.7'	78°14.9'		110	160	40	+ 120	9
	Town of Pinelevel		35°30.7'	78°14.9'		104	160	37	+ 123	9
	Selma Cotton Mills		35°28.3'	78°16.2'		168	175	165?	+ 10?	9
	Town of Kenley		35°35.4'	78°06.4'		100	204	23	+ 181	9
Jones	Hofmann Forest #2	Peter Henderson	34°56.3'	77°24.5'	1960	1239?	65*	1228?	-1163	5,6,21
Lenoir	Town of LaGrange	Layne-Atlantic Co.	35°18.1'	77°47.3'	1952	404	105	392	- 287	4,6,16
	D.O.E.-C.P. #16A	Gruy Federal	35°14.2'	77°35.4'	1978	721	50*	680	- 630	
	R. Johnson, Jr.	State of No. Carolina/VPI&SU	35°17.0'	77°29.8'	1979-80	1131	20*	759	- 739	27
Moore	Steam Pumping Plant		35°07.9'	79°28.5'		730	520	197	+ 323	9,28
Nash	Town of Whitakers	Heater Well Co.	36°06.2'	77°42.8'		82	115*	69	+ 46	20
	Town of Whitakers	Va. Machinery & Well Co.	36°06.2'	77°42.8'		405	115*	135	- 20	20
	Town of Battleboro	White Well Co.	36°03.0'	77°45.2'		250	118*	165	- 47	20
New Hanover	Fort Fisher #1	No. Carolina Oil & Gas	33°58.4'	77°55.2'	1966	1558	9	1545	-1536	5,6,21
	City of Wilmington	Clarendon Water Works	34°15.0'	77°57.0'	1399	1330	9	1109	-1100	6,16,19,21,24
	J. H. Foy #1	Coastal States Oil	34°18.1'	77°47.0'	1969	1306			-1267	5
	D.O.E.-C.P. #14	Gruy Federal	34°12.0'	77°53.4'	1979	1280	30*	1263	-1233	
Northampton	Seaboard School	O. L. Truby	36°29.0'	77°26.5'		265	130	230	- 100	6,20
	State Prison Camp	Heater Well Co.	36°24.2'	77°26.2'	1912?	296			- 176	6,20
	Thomas Gregory		36°26.7'	77°33.9'		505	140*	145	- 5	22
	Town of Jackson	Layne-Atlantic Co.	36°23.3'	77°24.9'	1940?	260	90	260	- 170	9,19,20
Onslow	Cadco #1	International Paper	34°32.8'	77°33.0'	1950	1497	30	1449	-1419	5,6,16,20
	Seay-Hofmann Forest #1	Bryant Seay	34°54.0'	77°23.8'	1959	1433	52	1420	-1368	5,6,9,16,21
	Hofmann Forest #3	Peter Henderson	34°49.5'	77°23.9'	1960	1328	35*	1310?	-1275?	5,6,16,21
	International Paper #2	No. Carolina Oil & Gas	34°39.7'	77°28.9'	1967	1402	57*	1390?	-1333?	5,6,21
	Baucom #1	No. Carolina Oil & Gas	34°40.3'	77°30.3'	1967	1414	57	1412	-1355	5,6,21
	Evans #1	No. Carolina Oil & Gas	34°41.5'	77°30.5'	1967	1370	40*	1365	-1325?	5,6,21
	Cadco #2	International Paper	34°38.0'	77°29.9'	1950	1493	52*	1343	-1291	5,9,16,21
	Burton-Hofmann Forest #1	E. T. Burton	34°50.0'	77°16.7'	1953	1570	44	1560	-1516	5,16,21
	Seay-Hofmann Forest #2	Bryant Seay	34°51.9'	77°24.8'	1959	1337	32	1335	-1303	5,9,16,21
	James #1	No. Carolina Oil & Gas	34°42.0'	77°32.0'	1966	1254	47	1247	-1200	5,21
	International Paper #1	No. Carolina Oil & Gas	34°39.5'	77°28.8'	1966	1286	60*	1247?	-1187?	5,21
	Sheppard #1	No. Carolina Oil & Gas	34°41.8'	77°32.3'	1966	1276	50	1273	-1223	5,21
	Justice #1	No. Carolina OIl & Gas	34°33.0'	77°22.5'	1966	1681	11	1669	-1658	5,21
	L. Parker #1	Colonial Oil & Gas	34°45.4'	77°11.6'	1970	2009	32	1807	-1775	5,21
	D.O.E.-C.P. #15	Gruy Federal	34°39.0'	77°19.0'	1979	1954	25*	1675	-1650	
Pamlico	N.C. Pulpwood #1	Carolina Petroleum	35°04.6'	76°39.0'	1947	3667	11	3658	-3647	5,6,16,21,25
	Atlas Plywood #1	Carolina Petroleum	35°05.3'	76°40.6'	1947	3425	8	3414	-3406	5,6,16,21,25
Pasquotank	Hoerner-Waldorf #1	S. E. Cullinan	36°20.0'	76°22.0'	1971	2715	91?	2690?	-2599	5,6,21
Pender	Keith #1	Am. Mining & Develop.	34°26.8'	78°11.8'	1959	720	23	695	- 672	5,6,21
	Cowan #1	No. Carolina Oil & Gas	34°40.5'	77°42.5'	1966	1004	34	990	- 956	5,21
	Batts #1	No. Carolina Oil & Gas	34°26.8'	77°33.8'	1966	1493	28	1480	-1452	5,21
	Batts #2	No. Carolina Oil & Gas	34°26.0'	77°33.8'	1966	1462	11	1456	-1445	5,21
	McMillan #1	No. Carolina Oil & Gas	34°25.7'	77°37.1'	1966	1431	15*	1410	-1395	5,21
	Lea #1	No. Carolina Oil & Gas	34°22.6'	77°44.0'	1966	1255	37	1250	-1213	5,21
	G. Meeks #1	Coastal States Oil	34°31.0'	77°47.0'	1969	940	25*	910	- 885	5,21
Pitt	Town of Farmville	Layne-Atlantic Co.	35°35.5'	77°35.0'	1937	472	80	465	- 385	6,9,16,19,24
Richmond	W. R. Bonsal		34°53.0'	79°42.0'		425	375	200	+ 175	9
Robeson	Lum-1	VPI&SU	34°34.2'	78°56.0'	1979	1274	106*	490	- 384	
Sampson	Town of Roseboro	Layne-Atlantic	34°57.5'	78°30.5'	1955	420	134	353	- 219	4.6.16
	Henry Vann #1	Heater Well Co.	35°06.0'	78°13.3'	1955	271	166	245	- 79	4,6,16
Scotland	U.S. Army	Va. Machinery & Well Co.	34°46.7'	79°22.7'	1942	448	210	363	- 153	6,19,24
Tyrrell	Westvaco #2	Exchange Oil & Gas	35°53.6'	76°09.6'	1971	4198	26	3908	-3882	5,6,21
	Westvaco #1	Exchange Oil & Gas	35°47.9'	76°12.3'	1971	4242			-4064	5,6,21
	Westvaco #3	Exchange Oil & Gas	35°43.0'	76°06.3'	1971	4859	21	4755	-4734	5,21
	Whitehurst #1	R. DeKay	35°48.3'	76°20.7'	1971	3564	7*	3547	-3540?	5,21
	White #1	Kit Develop. Co.	35°44.8'	76°08.9'	1972	4315	3*	4300	-4297	5,21
Washington	Furbee #1	Davidson Oil	35°43.5'	76°37.5'	1951	2693	17	2690	-2673	5,21
Wayne	City of Goldsboro	Layne-Atlantic Co.	35°23.3'	77°59.7'	1950	133	75	93	- 18	4,6,16
	Borden Mfg. Co.		35°23.3'	77°59.7'		307	110	268	- 158	9
	Goldsboro Ice Co.		35°23.3'	77°59.7'		266	110	175	- 75	9
	State Hospital		35°23.7'	78°01.4'		570	100	100	0	9
	J. D. Davis		35°32.6'	77°58.6'		140	144	90	+ 54	9
	Fremont Oil Mill		35°32.6'	77°58.6'		190	140	105	+ 35	9
	Town of Fremont		35°32.6'	77°58.5'		175	145	100	+ 45	9,23
	W. T. Turlington		35°32.6'	77°58.6'		126	144	100	+ 44	9
Wilson	Dr. A. B. Williams	Heater Well Co.	35°44.5'	77°45.0'	1942	335	123	245	- 122?	6,16,19,20,24
	Town of Elm City	Va. Machinery & Well Co.	35°48.4'	77°51.7'		187	130*	74	+ 56	20
	Wilson Country Club	C. W. Norton	35°40.6'	77°55.4'		125	80*	3?	+ 72	20

* Surface elevation estimated from topographic map.

Appendix II: Seismic refraction and reflection data from North Carolina Coastal Plain and continental shelf, from which depths to top of basement have been calculated. Reference numbers refer to sources listed at end of text.

COUNTY	LATITUDE	LONGITUDE	DATE	DEPTH TO BASEMENT (FEET)	SURFACE ELEVATION (FEET)	BASEMENT ELEVATION (FEET)	REFERENCES
Beaufort	35°34.0'	76°53.4'	1945	1830	36	-1794	3,29
Bladen	34°26.1'	78°28.0'	1952-53	850	85	- 765	3
	34°33.7'	78°34.9'	1952-53	604	112	- 492	3
	34°42.3'	78°46.6'	1952-53	385	140	- 245	3
Brunswick	34°02.5'	78°03.2'	1952-53	1380	43	-1337	3
	34°12.7'	78°05.5'	1952-53	1125	68	-1057	3
Columbus	34°20.0'	78°16.9'	1952-53	1045	60	- 985	3
Craven	34°56.8'	76°54.4'	1945	2725	25	-2700	3,29
Currituck and Camden	36°21.4'	76°08.0'	1945	3080	8	-3072	3,29
Dare	35°13.8'	75°38.8'	1945	8578	6	-8572	3,29
	35°26.0'	75°30.4'	1945	9000	0	-9000	3,29
	35°49.5'	75°50.6'	1945	5460	8	-5452	3,29
	36°00.9'	75°42.8'	1945	5720	9	-5711	3,29
	36°08.9'	75°44.6'	1945	5260	4	-5256	3,29
Harnett	35°25.0'	78°58.2'	1952-53	50	395	+ 345	3
Hoke	34°59.9'	79°13.2'	1952-53	170	216	+ 46	3
Hyde	35°33.3'	76°18.1'	1945	5795	5	-5790	3,29
Johnson	35°19.2'	78°23.2'	1952-53	193	190	- 3	3
Moore	35°06.8'	79°23.3'	1952-53	238	460	+ 222	3
	35°13.2'	79°31.1'	1952-53	190	565	+ 375	3
Onslow	34°54.4'	77°35.0'	1945	1120	60	-1060	3,29
Pamlico	35°13.0'	76°51.1'	1945	2300	25	-2275	3,29
Perquimanns and Chowan	36°05.9'	76°32.7'	1945	2130	15	-2115	3,29
Pitt	35°35.6'	77°32.8'	1945	420	73	- 347	3,29
Richmond	35°04.0'	79°47.6'	1952-53	168	509	+ 341	3
Robeson	34°47.9'	78°56.1'	1952-53	294	166	- 128	3
	34°53.6'	79°03.9'	1952-53	360	203	- 157	3
	34°34.3'	79°04.0'	1952-53	530	142	- 388	3
Sampson	34°55.9'	78°31.7'	1952-53	405	114	- 291	3
	35°06.9'	78°14.6'	1952-53	334	172	- 162	3
Tyrrell	35°50.0'	76°13.1'	1945	4177	12	-4165	3,29
Wayne	35°17.2'	78°03.2'	1952-53	255	168	- 87	3,29
OFFSHORE:	33°24.0'	77°15.0'	1965	5479	0	- 5479	8
	33°29.8'	77°08.5'	1965	6004	0	- 6004	8
	34°02.6'	76°28.0'	1965	8333	0	- 8333	8
	34°18.3'	76°12.0'	1965	10367	0	-10367	8
	34°12.5'	76°34.0'	1965	8923	0	- 8923	8
	34°20.0'	76°57.0'	1965	4823	0	- 4823	8
	34°23.9'	77°03.5'	1965	3510	0	- 3510	8
	34°11. '	76°59.5'	1954	3806	0	- 3806	13
	33°14. '	78°12. '	1954	2822	0	- 2822	13
	33°52. '	76°58. '	1954	4823	0	- 4823	13
	35°47. '	75°12. '	1954	10630	0	-10630	13
	34°37.2'	75°46.4'	1974	16930	0	-16,930	12
	34°54.1'	75°40.6'	1974	14075	0	-14075	12
	35°09.6'	75°35.5'	1974	11350	0	-11350	12
	35°55.6'	75°25.4'	1977	7715	0	- 7715	15
	35°53.4'	75°19.3'	1977	9100	0	- 9100	15
	35°51.2'	75°13.2'	1977	9755	0	- 9755	15
	35°49.0'	75°07.0'	1977	10785	0	-10785	15
	35°46.8'	75°00.9'	1977	14595	0	-14595	15

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PETROGRAPHY OF THE GRANITIC BASEMENT BENEATH THE COASTAL PLAIN, GATES COUNTY, NORTH CAROLINA

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ABSTRACT

A 1-inch diameter hole located in the center of a large gravity anomaly in Gates County, North Carolina, was drilled through the Coastal Plain sediments to basement. Crystalline basement was encountered at 323 m, and 87.5 m of continuous core was recovered. The basement rock, herein named the Dort Granite, is an amphibole-biotite granite which has been cut by two episodes of brittle fracture.

INTRODUCTION

Approximately thirty syn-and post-metamorphic plutons (Fullagar and Butler, 1979) crop out of the southeastern U.S. Piedmont in a belt trending northeast from Georgia to Virginia. Most of the granitoid plutons in the exposed Piedmont produce closed, nearly circular gravity lows (Popenoe and Bell, 1974; Glover, 1963; Cogbill, 1977). Gravity surveys over the Coastal Plain in eastern North Carolina and Virginia have outlined similar gravity anomalies (Dept. of Defense, 1976), suggesting that additional granitoids underlie the Coastal Plain sediments. One of the most prominent gravity "lows" (-20 mgal) is located astride the North Carolina-Virginia border near the community of Dort, in Gates County, North Carolina (Fig. 1). As part of a study of granites in the southeastern Piedmont, a 1-inch diameter hole was drilled to basement near the center of the anomaly near Dort. Basement was encountered at 323.0 m; 87.5 m of continuous core was recovered from the top of the crystalline basement rocks, to a depth of 410.5 m.

LITHOLOGY

The rock recovered from the basement is a gray, coarse-grained amphibole-biotite granite, herein named the Dort Granite. Minerals visible in hand specimen include subhedral, pale pink K-feldspar, 0.5-2.0 cm long; subhedral to anhedral plagioclase up to 1.5 c.m. long; quartz grains up to 1.0 cm long; and biotite flakes, 0.1-0.5 cm across. Color index (C.I.) ranges from 8 to 15. Most plagioclase grains are saussuritized and tinged pale green. In a few segments of the core, the alignment of biotite and K-feldspar defines a moderately to steeply dipping foliation which varies from weak to strong.

Locally the granite is cut by small (1-5 cm) pegmatite and aplite dikes composed of quartz, plagioclase, and alkali feldspar. Near the bottom of the core, several mafic clots up to 20 cm across are included in the granite. The rock recovered from the core shows varying intensities of alteration and brittle fracture (Fig. 2).

PETROGRAPHY

In thin section, K-feldspar appears as microperthitic microcline clouded red-brown. According to microprobe analyses, bulk compositions average $An_0Ab_8Or_{92}$. Plagioclase is unzoned and has an average composition of $An_{20}Ab_{79}Or_1$; it shows both

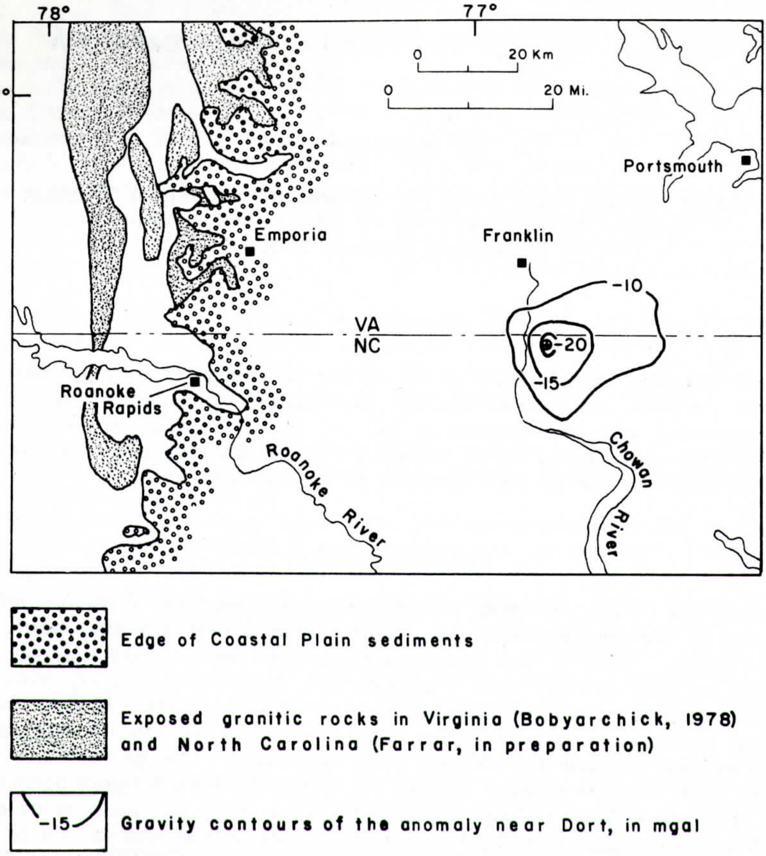

Figure 1. Location map for Drill Hole DO-1 showing gravity anomaly (Dept. of Defense, 1976) and nearest outcrop of the Petersburg Granite (Farrar, in preparation).

Carlsbad and albite twinning. The plagioclase is generally saussuritized to epidote ± chlorite ± carbonate ± white mica. In most grains, the epidote is strongly concentrated near the center of the feldspar, suggesting that the original plagioclase was normally zoned. Quartz grains have undulose extinction; myrmekite occurs locally.

Biotite is pleochroic tan to dark brown or dark olive green. Compositions (Table I) plot near the center of biotite compositions determined for postmetamorphic plutons in the exposed Piedmont (Fig. 3a; Speer et al., 1980). Chlorite has partially replaced biotite in even relatively unaltered rocks, and epidote occurs along the cleavage planes of scattered biotite grains. Anhedral amphibole comprises about 1% of the fresh samples (e.g. DO-1114); it does not occur in many parts of the core because of the extensive alteration. The amphibole in pleochroic: X = tan, Y = yellow-green, Z = blue-green, with 2V approximately 65°. Following the nomenclature of Leake (1978), it is a potassian ferroan pargasitic hornblende (Table I). The analyses plot within the cluster of analyses of amphiboles from postmetamorphic granites in the southeastern U.S. (Fig. 3b) (Speer, et al., 1980).

Primary accessory minerals include titanite (Fig. 4a), apatite, opaques, zircon, and allanite. Some titanite grains enclose a corroded opaque grain, suggesting that a portion of the titanite formed by a reaction that consumed oxides. In all but the freshest samples, titanite is partially altered to carbonate + rutile + quartz. Allanite, which is commonly altered, occurs as zoned, prismatic crystals up to 0.3 cm long.

Secondary minerals comprise chlorite, epidote, and calcite. Epidote, the most abundant, is optically negative with 2V = 80-85°, and r > v; it is pleochroic colorless to yellow-green. The chlorite (Table I) can be classified as a pycnochlorite (Hey, 1954).

TABLE 1. Microprobe Analyses

	1	2	3	4	5	6	7	8	9	10
SiO_2	41.9	40.7	29.0	28.7	36.7	37.2	37.4	35.9	37.7	37.2
TiO_2	0.5	0.5	0.0	0.0	1.7	1.6	1.7	1.6	1.8	1.8
Al_2O_3	11.1	11.5	18.1	18.7	14.9	15.7	15.6	15.5	15.1	15.2
FeO^*	22.1	22.5	21.4	21.7	22.2	21.5	21.8	20.7	22.3	21.8
MgO	7.3	7.3	18.0	18.2	10.5	11.0	10.8	10.7	10.1	9.9
MnO	0.4	0.5	0.8	0.7	0.3	0.3	0.3	0.4	0.3	0.3
CaO	11.1	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Na_2O	1.7	1.9	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
K_2O	1.6	1.7	0.1	0.0	9.8	9.9	9.8	9.5	9.7	9.8
H_2O^{**}	1.9	1.9	11.6	11.7	3.9	4.0	4.0	3.9	4.0	3.9
Sum	99.6	99.6	99.0	99.7	100.1	101.3	101.5	98.3	101.0	100.0
Si	6.49	6.35	3.00	2.94	5.64	5.62	5.64	5.58	5.71	5.70
Al_t	1.51	1.65	1.00	1.06	2.36	2.38	2.36	2.42	2.29	2.30
	8.00	8.00	4.00	4.00	8.00	8.00	8.00	8.00	8.00	8.00
Al_o	0.52	0.47	1.20	1.20	0.34	0.41	0.41	0.42	0.41	0.44
Ti	0.06	0.06	0.00	0.00	0.20	0.18	0.19	0.19	0.21	0.21
Fe	2.86	2.94	1.85	1.86	2.85	2.71	2.75	2.70	2.83	2.80
Mg	1.68	1.70	2.77	2.79	2.41	2.48	2.43	2.49	2.29	2.27
Mn	0.06	0.06	0.07	0.06	0.04	0.04	0.04	0.05	0.04	0.04
	5.18	5.23	5.89	5.91	5.84	5.82	5.82	5.85	5.78	5.76
Ca	1.84	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.52	0.56	0.00	0.00	0.02	0.04	0.03	0.03	0.02	0.04
K	0.31	0.33	0.01	0.00	1.91	1.91	1.89	1.87	1.89	1.92
	2.67	2.75	0.01	0.00	1.93	1.95	1.92	1.90	1.91	1.96
O	24.00	24.00	18.00	18.00	24.00	24.00	24.00	24.00	24.00	24.00

1,2 Amphibole, DO1-1114
3,4 Chlorite DO1-1114
5-10 Biotite, DO1-1114
* All Fe as FeO
** H_2O calculated

TABLE II. Modes of samples from DO-1

	DO1-1075	DO1-1079	DO1-1114
Quartz	28.8	27.9	33.1
K-feldspar	22.5	17.2	18.4
Plagioclase	39.0	39.9	33.6
Biotite + chlorite	8.9	12.6	13.2
Amphibole	-	-	0.3
Epidote	0.4	0.2	tr
Titanite	0.4	2.2	1.1
Opaques	tr	tr	0.2
Accessories	tr	tr	0.1
no. points	1450	1450	1450

The texture of the granite is allotriomorphic inequigranular. Few grains are euhedral or subhedral; most have embayed and irregular edges, and some are bordered by fine-grained mosaics of quartz and feldspar (Fig. 4b).

Modal analyses of representative samples are shown in Table II; in Streckeisen's (1976) classification, the rocks plot along the monzogranite-granodiorite boundary.

The mineralogy of the mafic clots is the same as that of the granite, with greater amounts of dark minerals, and C.I. about 40. Biotite is present in higher proportions than amphibole. Most mafic clots are finer grained than the granite, with the grain size of the major minerals ranging from 0.1 to 1.0 cm.

FRACTURE FILLINGS

The granite in the core is cut by numerous veins of at least two generations. First generation veins are steeply dipping and filled (0.1-1.0 cm wide) with calcite +

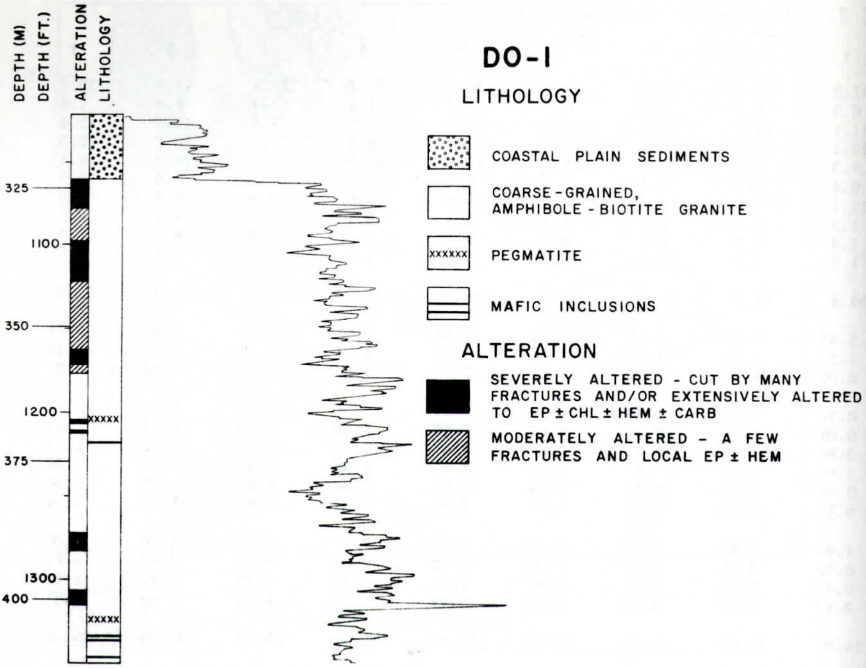

Figure 2. Lithologic and gamma logs of DO-1.

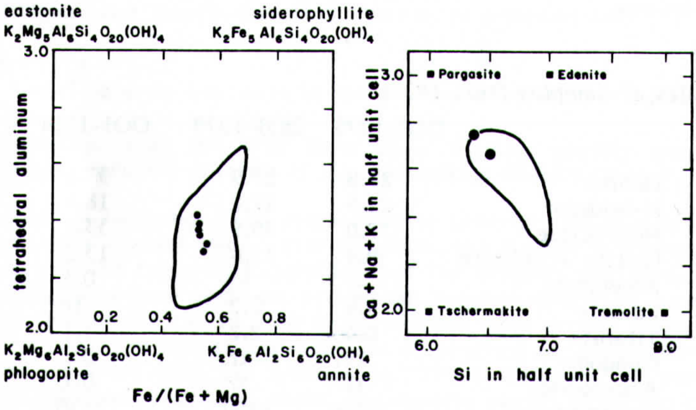

Figure 3. (a) Plot of analyses of biotite from the Dort Granite; and (b) amphibole analyses. In each diagram, the lines enclose compositions of the respective phases in post-metamorphic granites in the exposed southeastern Piedmont (Speer, et. al., 1980).

epidote ± chlorite. In one sample (DO-1122), a few chlorite crystals contain grains of blue fluorite.

In the vicinity of the first generation veins, the granite is green and friable for a distance of 10 to 20 cm from the fracture. Where the core is cut by numerous veins, the green color may continue over a distance of more than a meter. Thin sections show that the pervasive green color is caused by the presence of abundant epidote and chlorite, which entirely replace biotite and amphibole. Titanite grains, with euhedral outlines still distinct, are completely altered to turbid mats containing clots of opaque minerals. Saussuritization is extensively developed in plagioclase, and calcite is the most abundant saussuritization product.

Second generation veins cuts and clearly postdate those of the first. They are horizontal, and filled with calcite alone (0.1-0.2 cm). No alteration is apparent in the adjacent granite.

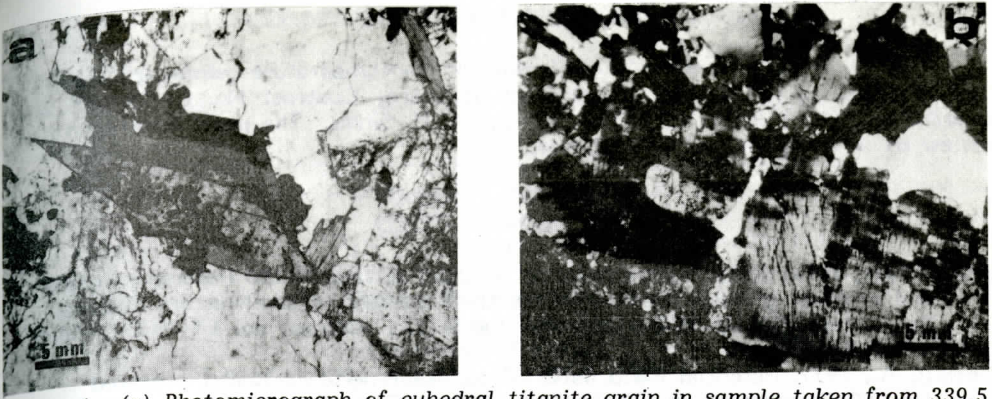

Figure 4. (a) Photomicrograph of euhedral titanite grain in sample taken from 339.5 m. The titanite is bordered by biotite, magnetite, K-feldspar, and quartz. (b) Photomicrograph (X-Nicols) of large microcline grain bordered by recrystallized mosaic of quartz + K-feldspar.

DEFORMATION

Several petrographic features of the Dort granite suggest that it was mildly deformed during or after intrusion. Quartz grains have undulose extinction and show development of subgrain boundaries. Large quartz and feldspar grains are bordered by a crystal hash of fine-grained quartz and feldspar. These fine-grained mosaics appear to have recrystallized during or after deformation, while the granite was still fairly hot, because the fine-grained crystals commonly have sutured grain boundaries, and meet at angles of 120°.

The granite was subsequently subjected to two periods of brittle deformation. During the first episode, steep fractures formed, and hydrothermal fluids rich in $CO_2 + H_2 + F_2$ circulated through the fractures. The fluids produced a mineral assemblage of calcite $\pm$ epidote $\pm$ chlorite $\pm$ fluorite in the fractures, and epidote + chlorite + calcite in the granite. During the second episode the granite was fractured along nearly horizontal planes. CO_2-rich fluids filled the fractures with calcite, but had little effect on the granite mineralogy.

COMPARISON TO THE PETERSBURG GRANITE

In mineralogy, mode, and grain size, the Dort Granite closely resembles the Petersburg Granite, which crops out as close as 65 km to the northwest (Farrar, in preparation) (Fig.1). In both granites, biotite is the dominant mafic mineral; amphibole occurs in minor amounts in both the Dort Granite and some phases of the Petersburg Granite. The Petersburg Granite also shows primary textures, similar to those of the Dort Granite, that are indicative of slight recrystallization following mild deformation (Bobyarchick, 1978).

CONCLUSIONS

The basement rock encountered in a drill hole in Gates County, North Carolina, is a coarse-grained granite which resembles petrographically the syntectonic (Bobyarchick, 1978) Petersburg Granite. The similarity of the two granites suggests that some lithologies in the exposed Piedmont also occur to the east under Coastal Plain sediments. In addition, the recovery of granite from a drill hole centered on a pronounced gravity low suggests that gravity data can be used as an indication of the nature of the basement rocks beneath Coastal Plain sediments.

ACKNOWLEDGEMENTS

This paper stems from an investigation of low-temperature geotheraml resources that is supported by the U.S. Department of Energy Contract No. ET-78-C-05-5648 awarded to J. K. Costain, L. Glover, III, and A. K. Sinha. The paper benefitted from review by J. A. Speer and S. S. Farrar.

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CHLORAPATITE FROM NORTHERN VIRGINIA:
THE FIRST OCCURRENCE IN THE UNITED STATES

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ABSTRACT

Chlorapatite occurs in the Fairfax trap quarry at Centreville, Fairfax County, and in the Bull Run trap quarry, Loudon County. Both quarries are in Triassic diabase. The euhedral to subhedral stubby prismatic crystals vary from 1 mm to 40 mm long, and are cloudy white to light greenish-gray. The crystal morphology and optical data are given. Chemical analyses, especially for specimens from the Fairfax quarry, indicate a fluorian-hydroxylian chlorapatite. X-ray diffraction powder data are presented and discussed, and it is shown the mineral can be separated from the related species on the basis of these data. Single crystal X-ray studies indicate hexagonal symmetry in contrast to the monoclinic symmetry of some natural and synthetic chlorapatite.

INTRODUCTION

Although chlorapatite, $Ca_5(PO_4)_3Cl$, is listed in nearly every mineralogy textbook as a well-known apatite species, it is not generally realized that the mineral is very rare. It has been reported from Norway (Hendricks and others, 1932; Morton and Catanzaro, 1964), Japan (Seto, 1932; Harada, 1938), Canada (Hounslow and Chao, 1970), India (Babu, 1972), and in some stony meteorites (Shannon and Larsen, 1925). Studies of an apatite-rich vein in a specimen of diabase from the well-known Fairfax trap quarry at Centreville, Fairfax County, Virginia, have recently shown the mineral to be chlorapatite. After this discovery small euhedral chlorapatite crystals from the Bull Run trap quarry in Loudon County, Virginia, were also identified.

Both quarries are in Triassic diabase outcrops which are only two of many similar localities in northern Virginia. Because these Triassic rocks are tectonically and genetically related to many similar occurrences scattered across New Jersey, Pennsylvania, Maryland, Virginia, and North Carolina, further study may show chlorapatite is widespread in this geologic environment. However, it should be noted here that tiny apatite crystals recovered from a pink feldspar-rich vein in diabase from a similar exposure near Goose Creek, Virginia, yielded X-ray data typical of fluorapatite. Also recent surveys of New Jersey trap quarries (Peters, Peters, and Weber, 1978; and Sassen, 1978) have not recorded the presence of apatite. Mason (1960) did note apatite from the Palisades sill, a New Jersey diabase intrusive, but did not indicate the species.

The general mineralogy of the Fairfax quarry was described by Medici (1972) while that of the Bull Run quarry was described by Freeland (1979).

DESCRIPTION OF THE CHLORAPATITE

Specimens from the Fairfax quarry have a vitreous to greasy luster and consist of translucent light greenish-gray chlorapatite in the crystal cores with opaque white alteration zones of fluorapatite along the crystal margins and internal fractures. The largest crystal observed measures 4 cm by 1.5 cm, although crystals measuring from 3 mm to 10 mm are more common. The crystals vary from euhedral to subhedral. Goniometric and X-ray studies of one relatively small crystal showed a combination of second order prisms, a (11$\bar{2}$0), and smaller first order prisms, m (10$\bar{1}$0). Although on this imperfect crystal other faces were absent (some broken off), cleavage planes parallel to c (0001) and m (10$\bar{1}$0) were detected. The indices of refraction are e = 1.650 (third decimal estimated) and o = 1.653. The specific gravity of the chlorapatite from Fairfax is 3.17.

These chlorapatite crystals occur in a vein in diabase where they compete for space with crystals of a black to greenish-black pyroxene, which according to X-ray studies is close to the diopside end of the diopside-hedenbergite series. These subhedral crystals average 1 cm across. Minor amounts of bornite are also in the vein. Small radiating needles of green amphibole are associated with the margins of some of the chlorapatite crystals. The original vein was at least 1 cm wide, but the specimen available for study was broken so only the contact with one wall was observable. Between the chlorapatite-pyroxene vein and the dark gray medium-grained diabase matrix rock is a lighter gray transition zone (1 cm wide) rich in white plagioclase. Although the species was not indicated, apatite crystals have been reported previously at this deposit (Dietrich, 1970; Medici, 1972).

The chlorapatite from Bull Run occurs as vitreous, stubby, euhedral crystals which vary from cloudy white to clear grayish. All the crystals studied are less than 1 mm across, usually between 0.50 and 0.75 mm. Goniometric measurements were made of several specimens. The largest forms are c (0001) and m (10$\bar{1}$0) followed by x (10$\bar{1}$1) and a (11$\bar{2}$0). The angle, measured from the perpendiculars to c (0001) and x (10$\bar{1}$1), varies from $39^\circ 23'$ (3 sharp faces) on one crystal to $39^\circ 35'$ (1 sharp face) on a second specimen, indicating c/a ratios of 0.711 and 0.716 respectively. These data correlate well with the c/a ratio expected for chlorapatite (0.7041) which is smaller than those for fluorapatite (0.7346) and hydroxyl-apatite (0.7305), calculated from the data of Young and Elliott (1966). Measurements of the indices of refraction yielded the following in which the third decimal is estimated: e = 1.643, o = 1.647. The specific gravity was not determined for the Bull Run chlorapatite because the few available crystals are laced with inclusions and attached minerals, and are very small.

The chlorapatite crystals from the Bull Run quarry occur either singly or are intergrown with each other. They are intermixed with loosely aggregated, matted asbestiform white amphibole, dark green to black amphibole needles, fine-grained platy to spherulitic green chlorite, euhedral white plagioclase plates, wedge-shaped amber-colored titanite, and clear datolite crystals. Many of the apatite crystals have grown around and incorporated dark amphibole needles. The minerals in this association have recently been described by Freeland (1979).

X-RAY DIFFRACTION DATA

The X-ray diffraction powder data given in Table 1 represent the averaged values from five diffractometer traces of translucent unaltered chlorapatite from Fairfax. The reflection angles were obtained with a goniometer scanning of one quarter degree 2θ per minute (nickel-filtered copper radiation). Accuracy was checked using a silicon standard and fluorapatite from Durango, Mexico with known parameters (Young and others, 1969). The precision reported as the standard deviation was 0.05° 2θ (or 0.004 A in the region of the strongest reflections). In order to index the powder data, all possible reflections allowed by the $P6_3/m$ space group were calculated through 1.20 A. The unit cell a = 9.53, c = 6.86, determined from our powder data, was used in the calculations. No appreciable differences were observed for the Bull Run specimens.

Examination of diffraction data indicated there is significant zoning in the chlorapatite from Fairfax. Since the a dimension is the most sensitive to variations in chlorine, fluorine, and hydroxyl content (Table 2), diffractometer traces from the powder of a compositionally-zoned crystal should manifest a-dependent peaks which are broader relative to the c-dependent peaks. The Fairfax chlorapatite reflections dependent upon the a parameter (i. e. h00 and hk0) show significant broadening and in

Table 1. X-Ray Data for Chlorapatite from Fairfax quarry (nickel filtered copper radiation).

hkl	d calculated (Å)	d observed (Å)	I
100	8.25	8.26	11
101	5.28	5.29	8
110	4.765	4.774	2
200	4.127	4.129	6
111	3.914	3.912	8
201	3.536	3.542	5
002	3.430	3.434	69
102	3.167	3.169	15
210	3.119	3.122	11
121	2.840	2.840	95
112	2.784	2.779	100
300	2.751	2.750	63
202	2.638	2.633	50
301	2.553	2.556	3
310	2.289	2.292	26
311	2.171	2.169	14
302	2.146	2.148	6
400	2.063	2.066	8
203	2.000	2.000	5
222	1.957	1.957	51
312	1.904	1.905	15
320	1.893	1.895	12
213	1.844	1.842	59
321	1.825	1.824	14
410	1.801	1.800	9
402	1.768	1.768	17
303	1.759	1.758	6
004	1.715	1.717	8
104	1.679	1.677	1
322	1.658	1.656	5
313	1.618	1.616	18
420	1.560	1.557	1
403, 421	1.532, 1.521	1.529	7
214	1.503	1.500	11
502	1.487	1.487	6
323, 304	1.458, 1.455	1.455	14
511	1.449	1.451	35
332	1.441	1.443	9
215	1.256	1.255	8
414, 611	1.242, 1.238	1.240	9

the case of $(30\bar{0})$, there are actually several closely spaced reflections. Reflections dependent upon the c parameter are generally narrow. The smallest shifts in the a parameter occur within the translucent and apparently unaltered cores of the apatite crystals. There exists a larger deviation between the unit cells of the translucent portion and the opaque portion.

In order to verify these conclusions about the translucent and opaque portions, numerous X-ray diffraction powder films were prepared using cameras of 11.46 cm diameter (nickel-filtered copper radiation). Only a small quantity of mineral is required in this technique, and this can be selected from specific zones within the crystals. Films obtained from the opaque altered areas are visually different from those obtained from the translucent chlorapatite, and the interplanar spacings of the opaque zone are much closer to fluor-hydroxyl-apatite than chlorapatite.

Because Canadian chlorapatite (Hounslow and Chao, 1970) and synthetic chlorapatite (Prener, 1967) have been found to be monoclinic with space group $P2_1/a$, a single crystal X-ray study was made of the Virginian specimens to check their

Table 2. Comparative Physical Data for Apatite.

	a(A)	c(A)	c/a	e	o	Specific Gravity
Synthetic Chlorapatite	9.634[1]	6.783[1]	0.7041	1.6675[2]	1.6684[2]	3.172[4]
Synthetic Hydroxyl-apatite	9.442[1]	6.883[1]	0.7305	1.664[3]	1.651[3]	3.152[4]
Synthetic Fluorapatite	9.364[1]	6.879[1]	0.7346	1.630[2]	1.6325[2]	3.212[4]
Unaltered Chlorapatite from Fairfax quarry	9.53	6.86	0.7198	1.650	1.653	3.17
Chlorapatite from Bull Run quarry	---	---	0.7135	1.643	1.647	---

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[1] Young and Elliot (1966)
[2] Palache and others (1951)
[3] Mitchell and others (1943), optical data for nearly pure natural hydroxyl-apatite
[4] Calculated

Table 3. Chemical Data for Fairfax Apatite - Major Elements.

	Chlorapatite, Unaltered Crystal Core	Fluorapatite, Altered Crystal Rim	Theoretical $Ca_5(PO_4)_3(Cl,F,OH)$[2]
CaO	54.87%	52.83%	55.38%
P_2O_5	40.62	39.95	42.06
Cl_2	3.22	2.02	2.33
F_2	0.84	1.95	1.25
H_2O[1]	0.50	0.25	0.56
Total	100.05	97.00	101.58
O = Cl,F	1.08	1.28	1.58
Corrected Total	98.97	95.72	100.00

[1] H_2O determined by difference as OH necessary to fill monovalent site.
[2] Cl:F:OH = 1:1:1, Palache and others (1951)

symmetry. Rotation and Weissenberg (showing a* and c*) photographs were made of several crystals representing both localities. Superlattice reflections, like those reported for the Canadian chlorapatite, were not observed so it is concluded the Virginian material is hexagonal.

CHEMICAL DATA

The major elements in the apatite from Fairfax were determined by wet chemical analyses, however, the chlorapatite from Bull Run was not analyzed due to the small quantities of impure material available. Mineral grains to be analyzed were sorted under the microscope to minimize impurities. The specimens were powdered and oven dried (105° C) to remove adsorbed water. Each sample (100-200 mg) was weighed and dissolved in 10% nitric acid. Dissolution was carried out in plastic beakers and samples were stored in plastic bottles to avoid loss of fluorine by reaction with silica glass. Dilution of samples to constant volume was performed rapidly to avoid loss of HF volatiles. Calcium was determined by standard atomic absorption spectrophotometric techniques including use of lanthanum as a complexation and ionization buffer and a deuterium arc to compensate for scattering. Phosphate analyses were performed according to the Standard E.P.A. technique (Environmental Protection Agency, 1974), i.e., the single-reagent molybdenum blue method. Chloride and fluoride were analyzed with specific ion electrodes by the calibrated electrode technique of Duff and Stuart

(1971) and Evans and others (1970) and by the standard additions method of Burton (1971). A 1.5 M sodium citrate solution mixed 1:1 with unknowns and standards was used both to normalize ionic strengths and to prevent interferences due to complexation. Edmund (1969) demonstrated the superiority of sodium citrate over the conventional ionic strength-complexation buffers. When using specific ion probes, better accuracy is attained if the standards have the same concentrations of dissolution acid, calcium, and phosphate as the unknowns even if a very strong ionic strength buffer is used. Reagent-grade, halogen-free $CaHPO_4$ dissolved in 10% nitric acid was used to provide the proper matrix for the standards. The sodium citrate also buffered the pH into the proper range (5-7) for fluoride analysis. As done by Walters and Luth (1969), water was determined by difference as OH necessary to fill the monovalent structural site because of the difficulty and unreliability of most methods available for water determination. Apatite must be heated above 1400° C to remove all structural water and it is not known how much halogen and CO_2 are lost simultaneously. The precision of the data for major elements in Table 3 is better than 2.5% as relative standard deviation. The chemical data in Table 3 are of the same chlorapatite for which X-ray data are reported in Table 1. Accuracy for the major elements was checked by analyzing fluorapatite from Mexico (Young and others, 1969) along with our samples. The chemical formulas of the apatite from Fairfax in Table 4 were calculated assuming exactly three phosphate anions and no significant contribution from the minor elements. Minor and trace elements, determined by semiquantitative spectrographic analysis, are reported in Table 5.

DISCUSSION

The chemical data clearly indicate that chlorine is the dominant anion in the monovalent structural site for the greenish translucent portion of the mineral. Thus the mineral from Fairfax is considered to be chlorapatite even though only 48% of the possible sites are filled by chlorine. Analyses of other chlorapatite crystals from Fairfax indicate chlorine fills between 50% and 62% of the chlorine sites. The chlorine content apparently varies with the proximity of the analyzed grains to the chlorine-rich cores of the zoned crystals. Therefore whether the criterion for chlorapatite is $Cl > (OH + F)$ or $Cl > OH$ and $Cl > F$, the cores of the Fairfax crystals can be accepted as fluorian-hydroxylian chlorapatite.

The white portions of the chlorapatite have the composition of chlorian fluorapatite. These same white zones occur along internal fractures in the crystals. This relationship indicates a paragenetic sequence for the minerals in the vein. After the intrusion of the diabase, the chlorapatite-diopside vein was deposited along a joint. Subsequently the host rock was deformed sufficiently to fracture the chlorapatite crystals and then apparently a fluorine-bearing solution partially replaced the chlorine and hydroxyl in the apatite yielding a zoned crystal. The chlorine and hydroxyl depletion relative to the core demonstrates the preference of the monovalent site for fluorine.

Apparently zoning from chlorapatite to fluorapatite is a unique feature of the Fairfax quarry. Two of the other four terrestrial occurrences for chlorapatite, Japan and Norway, have crystals of chlorapatite which are altered externally to hydroxylapatite (Harada, 1938; Morton and Catanzaro, 1964).

The calcium and phosphate analyses indicate there is very little deviation from stoichiometry in the apatite from Fairfax. The slight excess of calcium relative to phosphate may indicate very minor substitution of silicate, vanadate, or carbonate for phosphate. Indeed the spectrographic analysis (Table 5) verified the presence of some vanadate and silicate. The spectrographic analysis also reveals the presence of minor amounts of many elements which are known to substitute for calcium the apatite structure, i.e., Mn, Na, Sr, Y, Yb, La, Nd, and Ce. However, the possibility that some of the minor and trace elements may be from inclusions, perhaps diopside or actinolite, cannot be completely discounted. Considering the minor elements, it is understood why the major element analyses total a little less than 100% (Table 3).

The X-ray data show that the chlorapatite from Fairfax has a unit cell ($\underline{a}$ = 9.53, $\underline{c}$ = 6.86) intermediate between chlorapatite and fluor-hydroxyl-apatite (Table 2). The

Table 4. Chemical Formulas of Fairfax Apatities[1].

	Chlorapatite, Unaltered Crystal Core	Fluorapatite, Altered Crystal Rim	Theoretical $Ca_5(PO_4)_3(Cl,F,OH)$
Ca^{2+}	5.13	5.02	5.00
PO_4^{3-}	3.00	3.00	3.00
Cl^{1-}	0.48	0.30	0.33
F^{1-}	0.23	0.55	0.33
OH^{1-}	0.29	0.15	0.33

[1] Based on $PO_4 = 3.0$

Table 5. Semiquantitative Chemical Data for Fairfax Apatite - Minor Elements.

	Chlorapatite Unaltered Crystal Core		Chlorapatite Unaltered Crystal Core
SiO_2	0.75%	TiO_2	0.005
Fe_2O_3	0.25	SrO	0.05
Al_2O_3	0.30	BaO	< 0.001
MgO	0.15	Y_2O_3	0.025
MnO	0.05	Yb_2O_3	0.002
V_2O_5	0.03	La_2O_3	0.08
CuO	0.001	Nd_2O_3	0.05
Na_2O	0.05	Ce_2O_3	0.15
		Total	1.944

intermediate composition inferred from the X-ray data agrees well with the chemical data. The cell for the chlorapatite from Fairfax is similar to the cell determined by Hendricks and others (1932) for chlorapatite from Norway (a = 9.52, c = 6.85) with chlorine filling 64% of the monovalent sites. Harada and others (1971) reported a Japanese chlorian hydroxyl-apatite with 33% of the monovalent sites filled by chlorine. The apatite from Japan has a unit cell (a = 9.49, c = 6.85) which is fairly close. Other natural chlorapatites have a unit cell much closer to synthetic chlorapatite because of their higher chlorine content. It should be noted, however, that X-ray data for natural apatite can provide only a semiquantitative indication of the chlorine content, because a large variety of ions can substitute for calcium, phosphate, and/or chlorine.

When X-ray diffraction powder films of the specimens from Fairfax were initially examined it was obvious the mineral was an apatite, but not the common fluorapatite species. A study of the data using the Hull-Davey (1921) chart showed the mineral to have a c/a ratio of approximately 0.71, significantly smaller than the ratios for fluorapatite (0.7346) and hydroxyl-apatite (0.7305). The spatial relationships, on the chart and the films, between the following three groups of reflections are especially sensitive to variations in the c/a ratio and were found to be good indicators of the apatite species: 102 and 210; 121, 112 and 300; and 402, 303 and 004. In chlorapatite the 102 and 210 reflections are nearly indistinguishable (almost superimposed) while there is a definite separation of them in fluorapatite and hydroxyl-apatite. Also in chlorapatite 121 is somewhat separated in position from the closely juxtaposed 112 and 300 pair, while in fluorapatite and hydroxyl-apatite 121 and 112 form a close pair somewhat separated from 300. Finally in chlorapatite the 402-303 doublet and 004 are much more widely spaced than in fluorapatite and hydroxyl-apatite. With pictures from powder diffraction films, Wallaeys and Chaudron (1950) illustrated the gradation in the spatial relationships of reflections for a series of six synthetic members of the chlorapatite-fluorapatite series. Walters and Luth (1969) also emphasize the usefulness of unit cell dimensions for differentiating the apatite species.

The hexagonal symmetry revealed by the single crystal photographs is expected for chlorapatite with the composition of the specimen from Fairfax. Prener (1967), from studies of synthetic chlorapatite crystals, observed that the pure substance is monoclinic at room temperatures and transforms to the hexagonal from between 185° and 210° C. When it is cooled, the transition is reversible. However, the higher symmetry hexagonal form is easily stabilized by the substitution of small amounts of hydroxyl (Young and Elliot, 1966) and fluorine anions (Prener, 1967), thus explaining the reason natural chlorapatite is usually hexagonal. In studies of synthetic fluor-chlorapatite Prener (1967) concluded that the hexagonal form becomes stable above a certain atomic ratio of F/(F+Cl) somewhere between 0.16 and 0.36. Hounslow and Chao (1970), supporting Prener's (1967) general conclusions, suggested the lower figure of 0.16 is very close to the transitional composition; and further suggested the transition from hexagonal to monoclinic occurs when 82% to 91% of the monovalent sites are filled with chlorine. The chlorapatite from Fairfax has between 48% and 62% chlorine occupancy in the monovalent site, well into the hexagonal range. The chlorapatite from Bull Run is also hexagonal but its c/a ratio suggests that the substitution for chlorine is less extensive and therefore the substance may approach the maximum chlorine content allowed in hexagonal chlorapatite.

The indices of refraction for chlorapatites from Fairfax and Bull Run are closer to the values reported for hydroxyl-apatite than synthetic chlorapatite (Table 2). However, the Virginian chlorapatite indices are close to those reported by Seto (1932), $\underline{e}$ = 1.651 and $\underline{o}$ = 0.657, for Japanese chlorapatite with chlorine filling 62% of the monovalent positions. It is not surprising that the Virginian and Japanese chlorapatites should have indices close to hydroxyl-apatite because of their high fluorine content. Hydroxyl-apatite has indices of refraction intermediate between fluorapatite and chlorapatite (Table 2). Consequently fluorian chlorapatite should have indices which fall close to hydroxyl-apatite indices.

The chlorapatites from Fairfax and Japan (Seto, 1932; Harada, 1938) share the distinction of being the most chlorine deficient of the natural chlorapatites, i.e., the chlorapatite from Fairfax has 48% to 62% chlorine occupancy of the chlorine positions and the chlorapatite from Japan has 55% to 62% occupancy. As such, these minerals come closest to fulfilling the prediction of Hendricks and others (1932) that there may exist a natural phase with the composition $Ca_{10}(PO_4)_6FCl$ in which there is a statistical ordering of chlorine and fluorine atoms. This hypothetical mineral would bear the same relationship to chlorapatite and fluorapatite that dolomite bears to calcite and magnesite. However, no evidence for such a phase with lower symmetry has been noted.

ACKNOWLEDGMENTS

The writers wish to express their appreciation to Mr. and Mrs. Elmer L. Hensley of Centreville, Virginia, for bringing the apatite from the Fairfax quarry to their attention, and for supplying the specimen used in this study. Mr. Howard R.Freeland of Richmond, Virginia, kindly allowed us to study his specimens from Bull Run.

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