

ULTRAMAFIC BODIES IN THE SOUTHERN APPALACHIANS: A REVIEW

KULA C. MISRA and FRED B. KELLER

Department of Geological Sciences, University of Tennessee,
Knoxville, Tennessee 37916

ABSTRACT. Two chains of alpine-type ultramafic bodies can be distinguished in the southern Appalachians—a well-defined, western, Blue Ridge belt which forms the southern part of a discontinuous chain extending from Newfoundland to Alabama, and an ill-defined eastern belt consisting of scattered bodies in the Piedmont. The ultramafic bodies show close spatial association with metamorphosed mafic volcanics and constitute an integral part of the evolution of the southern Appalachians. The highly altered, sill-like ultramafic bodies in the Albemarle-Nelson belt, Virginia, are probably of the same age as the Catoclin greenschist and appear to be genetically and temporally related to the basaltic volcanism associated with the late Precambrian rift system that marked the initial phase of the Appalachian orogen. The lenticular and predominantly dunite bodies in the rest of the Blue Ridge owe their distribution also to this rifting, but they were emplaced in the upper crust as solid bodies under tectonic stress gradients associated with Taconic deformation. Ultramafic bodies in the Piedmont, especially in the Inner Piedmont belt, are predominantly pre- or syn-metamorphic and may have risen as diapirs above a subduction zone into a back-arc basin. Discrete ultramafic bodies interpreted to be post-metamorphic in age are rare in the Piedmont.

INTRODUCTION

The ultramafic bodies of the Appalachian orogenic belt are of the alpine type, a term introduced by Benson (1926) to include ultramafic rocks of the Alpine ophiolite suite and similar bodies in other orogenic belts. The term is often used to include all peridotite-serpentinite complexes distributed along deformed mountain chains and continental margins. They show tremendous variability in size, mode of occurrence, petrology, degree of serpentinization, contact effects, and temperatures and pressures of equilibration. This led O'Hara (1967) to comment that the special tectonic conditions necessary for their transport and emplacement may be the only feature that alpine-type peridotites have in common. However, they do possess distinctive characteristics that set them apart as a group from concentrically zoned or stratiform (layered) ultramafic (-mafic) complexes (Thayer, 1960, 1967b; Jackson and Thayer, 1972; Taylor, 1967; Chidester and Cady, 1972; Moores, 1973). These characteristics include: (1) irregular to lensoid forms; (2) absence of chilled margins and the general absence of high-temperature contact metamorphic effects; (3) highly magnesian composition of the constituent olivine, pyroxene, and chrome spinel; (4) presence of tectonite fabrics (solid deformation textures) and absence of unequivocal cumulus textures; and (5) presence of podiform chromite.

Thayer (1967b) and Jackson and Thayer (1972) considered the alpine-type complexes to be essentially identical to well-preserved ophiolite assemblages. However, most authors consider ophiolites to be a sub-type of alpine-type complexes (Den Tex, 1969; Wyllie, 1970; Chidester and Cady, 1972; Naldrett, 1973). Two sub-types of alpine-type complexes can be distinguished on the basis of geologic setting:

1. Ophiolites, or ophiolitic bodies, which may occur as:
 - A. Allochthonous sheet-like bodies with thrust contacts, preserving the entire ophiolitic sequence, or only a part of it; or,
 - B. Chaotic blocks in mélange terranes, torn from the front of advancing thrust sheets and incorporated in the subsequently overridden mélange below the thrust;
2. Tectonic or diapiric intrusives, which may occur as relatively small, lenticular bodies in both metamorphosed and unmetamorphosed terranes of sedimentary and volcanic rocks of eugeosynclinal affiliation (this sub-type broadly corresponds to the root-zone peridotites of Den Tex, 1969).

The distinction between the two sub-types is important because of the plate-tectonic significance of the ophiolites. Ophiolites, according to most recent workers, represent fragments of oceanic crust and upper mantle and, therefore, are related to the existence of a former ocean basin and rifting. In the northern and central Appalachians, ophiolites have been documented in Newfoundland (Church and Stevens, 1971; Williams, 1971; Dewey and Bird, 1971; Upadhyay and others, 1971), Southern Quebec (St. Julien, 1972; Laurent, 1975) and Maryland (Crowley, 1976). So far, no ophiolite has definitely been identified in the southern Appalachians, although some of the mafic-ultramafic complexes have been interpreted as ophiolitic mélange (Brown, 1976).

The origin and geodynamic significance of the ultramafic bodies in the southern Appalachians have not been adequately evaluated. Judging from their distribution, however, there can be little doubt that they record an integral part of the evolution of the orogen. Chidester and Cady (1972) and Stevens, Strong, and Kean (1974) have attempted to integrate the ultramafic occurrences in a general way with tectonic scenarios for the Appalachian geosyncline. However, most developmental models proposed for the southern Appalachians (for example, Hatcher, 1972; Odom and Fullagar, 1973) have not critically dealt with the distribution of the ultramafic bodies, though Rankin (1975) related the distribution of ultramafics in Maryland and Virginia in a general fashion to the tectonic evolution of the orogen. The main objective of this paper is to compile and review published data on southern Appalachian ultramafic bodies so that constraints imposed by their distribution and characteristics can be accommodated by future geodynamic models.

GEOLOGIC SETTING

Structural-lithologic belts of the southern Appalachians

Conventionally, the southern Appalachians refer to that portion of the Appalachian orogenic belt extending southwestward from Roanoke, Va. to the Coastal Plain (Rodgers, 1949). However, the ultramafic bodies lying in the northwestern portion of Virginia are also included in the present discussion. The southern Appalachians can be divided into three contrasting physiographic provinces, which approximately coincide with

the geologic strike belts, differing from each other in certain lithologies, structural styles, and grade of metamorphism (King, 1955). These are: (1) Valley and Ridge, (2) Blue Ridge, and (3) Piedmont. The Brevard Zone forms the boundary between the Blue Ridge and the Piedmont. Further subdivision of the Piedmont, based primarily on different grades of metamorphism, include: (A) Inner Piedmont belt, consisting of the Chauga belt and the Mobilized Inner Piedmont (Hatcher, 1972); (B) Kings Mountain belt; (C) Charlotte belt; (D) Carolina Slate belt; (E) Raleigh belt (Parker, 1968); and (F) Pine Mountain belt (Bentley and Neathery, 1970).

Regional distribution of ultramafic complexes

The first comprehensive description of the ultramafic bodies in the Appalachians was given by Pratt and Lewis (1905), who considered them as intrusives related to Ordovician orogeny. Hess (1939, 1955) recognized two parallel chains of ultramafic bodies in the Appalachians, one on either flank of the central axis of most intense deformation. The fairly well defined western chain extends for more than 1100 km, albeit discontinuously, from Newfoundland to Alabama, although this does not necessarily imply a uniform age or origin for all the ultramafic bodies of the chain. This belt includes the ultramafic-mafic complexes of western Newfoundland and the Burlington Peninsula (Kennedy and Phillips, 1971; Williams, 1971), Southern Quebec (St. Julien, 1972; Lamarche, 1972; Laurent, 1975), northwestern New England (Jahns, 1967; Chidester, 1962, 1968), Maryland (Crowley, 1976), and the Blue Ridge belt of the southern Appalachians. The eastern chain is less well defined, except in central Newfoundland, where it is represented by the ultramafic bodies in the southeastern part of the central mobile belt and those of the Gander Lake Zone to the east and southeast of Notre Dame Bay (Stevens, Strong, and Kean, 1974). As has been pointed out by these authors, the chain loses its identity southward, except for isolated bodies in eastern Maine (for example, the Moxie pluton; Espenshade, 1972), but probably reappears in the Piedmont of the southern Appalachians.

The Blue Ridge belt is literally dotted with small bodies of ultramafic rocks; more than 275 have been identified in a belt 500 km long in the Blue Ridge of North Carolina and Georgia (Hunter, 1941). They lie both in the middle Precambrian (1.0 to 1.1 b.y. old) basement complex and in the unconformably superjacent upper Precambrian metasedimentary-metavolcanic sequence and are especially abundant near the central axis of the Blue Ridge belt. The spatial distribution of ultramafic rocks in the Piedmont presents a sharp contrast. There the ultramafics occur as small, isolated bodies irregularly distributed throughout the belt. It is possible that the true picture in the eastern Piedmont is obscured by the cover of Coastal Plain sediments.

Figure 1 shows the distribution of the ultramafic bodies in relation to the geologic belts in the southern Appalachians. The locations and

classification of the ultramafic and mafic bodies shown in this figure have been revised from Larabee's (1966) map to incorporate data from numerous later publications. Other sources for this compilation include: Bentley and Neathery (1970), Brobst (1962), Brown (1969), Butler and Ragland (1969a), Conley and Henika (1973), Espenshade and others (1975), Fullagar (1971), Geologic Map of Georgia (1976), Geologic Map of North Carolina (1958), Geologic Map of Tennessee (1966), Geologic Map of Virginia (1963), Glover and Sinha (1973), Griffin (1969, 1972), Hadley (1973), Hadley and Nelson (1971), Hatcher (1969, 1970, 1974, 1976), Henika (1971), Hermes (1968), Hopkins (1914), Hurst (1973), LeGrand and others (1956), McSween (1970, 1972), Merschat and Wiener (ms), Neathery and Tull (1975), Overstreet and Bell (1965a,b), Ragland and Butler (1972), Rankin (1970, 1975), Rankin, Espenshade, and Neuman (1972), Rankin, Espenshade, and Shaw (1973), Tobisch and Glover (1971), Tull (this issue, p. 442-460), Wagener (1974), and Waskom and Butler (1971).

ULTRAMAFICS OF THE BLUE RIDGE BELT

Distribution and Field Relationships

Albemarle-Nelson belt, Va.—The northeastern end of the Blue Ridge is marked by a very pronounced belt of highly altered ultramafic rocks in northwestern Virginia, the Albemarle-Nelson soapstone belt (Burfoot, 1930), which extends discontinuously from the Madison County-Culpeper County boundary in the north (beyond the limit of fig. 1) to New London, Campbell County, in the south. The belt is mostly less than 1 km in width and consists of several very narrow bands, usually less than 70 m wide and less than 2 km to more than 20 km long, concordant with the foliation in the enclosing Lynchburg Gneiss. Chief members of the ultramafic association, in approximate order of decreasing abundance are: amphibole-chlorite schist ("metapyroxenite" of Burfoot, 1930, and Nelson, 1962); serpentinite, soapstone, and altered peridotite. These rocks are inter-layered and grade into one another (Brown, 1958). Because of extensive alteration it is difficult to determine the petrology of the parent material. From a detailed study of the ultramafic body near Schuyler, Va., Hess (1933) concluded that the parent material consisted of peridotite and picrite (feldspathic peridotite).

The ultramafic rocks of this belt are closely associated with the Catoclin greenstone and with dikes and sills of amphibolite (hornblende gneiss), which occur widely in the Lynchburg Formation. Bloomer and Werner (1955) found the ultramafics, the amphibolites, and the Catoclin to be intergradational, indicating that they were differentiates of a common subcrustal magma. The Catoclin represents flows of tholeiitic basalt (Reed, 1955, 1964), probably associated with continental rifting as a first stage in the development of a spreading plate margin (Blackburn and Brown, 1976). Although it has not been possible to trace an amphibolite dike directly into a flow, these dikes were probably feeders for the Catoclin lava flows, as the calculated original composition of the Catoclin green-

stone is almost identical with that of the amphibolite dikes (Reed and Morgan, 1971). The general arrangement of rock types in and around the Schuyler soapstone body, Virginia, with the ultramafic rocks (now talc-chlorite-tremolite-actinolite-calcite assemblages) at the base and gabbroic (hornblende and actinolite amphibolites) and silicic rocks (quartz-albite-microcline-chlorite-hornblende assemblages) toward the top, is suggestive of *in situ* igneous differentiation (Hess, 1933). Brown (1958) suggested the possibility that the ultramafic bands in the upper part of the Lynchburg may themselves be extrusives. According to him, this would explain their stratigraphic localization regardless of structural position, their concordance with bedding, and their association with the Catoctin extrusives but failure to penetrate rocks which in this area seem to lie conformably above.

Southwest Virginia-northwest North Carolina.—Another concentration of ultramafic bodies occurs in the late Precambrian Ashe and Alligator Back Formations (mostly in the former) of the Blue Ridge, extending from Franklin County, Va., to Watauga County, N.C. A small talc-tremolite body is also found in the Cranberry Gneiss about 16 km northwest of Jefferson, N.C. Rankin, Espenshade, and Shaw (1973) have summarized the general characteristics of these ultramafic bodies. Most of these bodies are small, lens-shaped, and conformable with the foliation of the enclosing rocks. However, the largest of these (about 13 sq km in area) south of Galax, Va., essentially at the contact between the Ashe and the Alligator Back Formations, has a very strong magnetic expression that clearly crosscuts the regional trend. The most common ultramafic rock types are tremolite-chlorite-talc-magnetite and tremolite-chlorite-magnetite schist and gneiss, with or without carbonate and relict olivine. Locally, anthophyllite instead of tremolite may be the dominant amphibole. Serpentine occurs only in minor amounts in the soapstone, usually as coatings on joints and as veins in olivine and tremolite. In addition to the soapstone bodies, which represent intensely altered peridotites, Larabee's (1966) map shows several lenses of harzburgite and dunite enclosed in amphibolite. The Rich Mountain dunite body in North Carolina, with an assemblage olivine (with minor serpentine rims)-enstatite-chlorite-talc-tremolite-magnesite (Hearn and others, 1977), is a typical example.

The close association between the ultramafic rocks and the amphibolites and the fact that many of the ultramafic bodies appear to lie structurally beneath the amphibolites point to a genetic relationship between the two. However, some of the ultramafic lenses lie structurally above the mafic rocks, and still others are not associated with amphibolites at all, suggesting that at least some of the ultramafic bodies were emplaced independently of the amphibolites (Rankin, Espenshade, and Shaw, 1973). The mafic rocks themselves most likely represent metamorphosed basaltic extrusives and coeval shallow intrusives (Rankin, 1970). Corroborating this interpretation are the low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (range 0.7026-0.7087

with an average value 0.706, assuming an age of 600 m.y.) obtained for a series of amphibolite samples from the Ashe Formation (Bottino, 1971).

Western North Carolina.—The greatest concentration of ultramafic bodies in the southern Appalachians is found in the Blue Ridge of North Carolina, especially in the southwestern counties where the bodies are scattered over an area nearly 50 km wide. Their locations and general features have been summarized in the older literature (Lewis, 1896; Pratt and Lewis, 1905), particularly with respect to their economic potential for forsterite (Hunter, 1941), chromite (Hunter, Murdock, and MacCarthy, 1942), vermiculite (Murdock and Hunter, 1946), and asbestos (Conrad and others, 1963). However, detailed published data are limited to only a very small number of these bodies (fig. 1): Frank, Avery County (Bluhm and Zimmerman, 1977); Day Book, Yancey County (Kulp and Brobst, 1954; Phyfer and Carpenter, 1969; Swanson and Raymond, 1976); Micaville-Newdale, Yancey County (Kingsbury and Heimlich, 1977); Bank's Creek, Yancey County (Neuhauser and Carpenter, 1971); Balsam Gap and Dark Ridge, Jackson County (Astwood, Carpenter, and Sharp, 1972); Addie-Webster, Jackson County (Miller, 1953; Ross, Foster and Myers, 1954; Condie and Madison, 1969; Greenberg, 1976); Deposit No. 9, Macon County (Dribus, Heimlich, and Palmer, 1977); Corundum Hill, Macon County (Yurkovich, 1976); and Buck Creek, Clay County (Hadley, 1945; Sailor and Kuntz, 1973).

The individual ultramafic bodies generally are small and lenticular, aligned parallel to the regional foliation. The unique elliptical outcrop pattern of the Addie-Webster body and its locally cross-cutting relationship with the country rocks is due to post-emplacment doming (Miller, 1953; Greenberg, 1976). Dunite is the predominant variety of ultramafic rock in this region, although small bodies of pyroxenite have also been reported. Soapstone bodies are quite common, especially in Yancey and Madison Counties, Serpentinite bodies are notably absent, although partial serpentinization of dunite, particularly along the margins, is characteristic. In general, the ultramafic rocks are massive, but schistose structures are often well developed in the talc-chlorite-serpentine contact zones of individual bodies. Occasionally, the ultramafic bodies show a faint compositional banding due to planar distribution of disseminated chromite (for example, Frank, Balsam Gap, Dark Ridge). The Addie-Webster body is an exception; in this dunite body thin bands composed of concentrations of talc, chlorite, and other secondary minerals are very conspicuous, especially on weathered surfaces, and impart a laminated appearance to the ultramafic rocks.

The host rocks for these ultramafic bodies are interlayered gneisses of varied compositions, mapped as mica gneiss and hornblende gneiss depending on the dominant lithology (Stuckey and Conrad, 1958). The two units essentially correspond to "Carolina Gneiss" and "Roan Gneiss" of Keith (1903). Keith considered the Roan Gneiss to be metamorphosed igneous rocks, intrusive into the Carolina paragneisses. Later, Parker

(1952) and Brobst (1962) argued that the hornblende gneisses represented metamorphosed impure carbonate layers in a sedimentary sequence. This seems unlikely, since very few carbonate rocks are found in the assemblage, and these are not associated with mafic gneisses (Hadley, 1970). According to Hadley, most of the layered gneisses are of mixed volcanic and epiclastic origin, the mafic (amphibolitic) layers representing basaltic flows or shallow intrusives. Rankin (1970) considered the Carolina Gneiss and the Roan Gneiss to be equivalents of clastic and volcanic facies, respectively, of the Ashe Formation.

There is no field evidence to suggest a genetic relationship between the mafic and ultramafic rocks in the area. Although a large number of ultramafic bodies show close spatial association with the hornblende gneiss, many others occur in the mica gneiss independently of the mafic layers. In addition, some ultramafic bodies are also found in what most workers now consider to be basement gneisses of Grenville age (fig. 1; Hadley, 1970; Hadley and Nelson, 1971).

Northern Georgia.—The southwestward continuation of the Blue Ridge ultramafic belt is marked by numerous small bodies in Rabun, Habersham, White, and Lumpkin Counties, Ga. Most of these are confined to a very narrow belt as shown in the Georgia State Geological Map (1976). The southwestward continuation of this belt takes the form of a few scattered bodies of pyroxenite and dunite in Cherokee, Paulding, and Carroll Counties. A number of ultramafic bodies also occur in the vicinity of Lake Chatuge, Towns County, Ga., and Clay County, N.C. A comprehensive account of the ultramafic rocks in Georgia has been given by Hopkins (1914). Two of the occurrences, the Burton Lake and the Laurel Creek dunite bodies, Habersham County, have been described by Hunter (1941). The Lake Chatuge occurrence is the only one that has been described in detail in the recent literature (Hartley, 1973; Hartley and Penley, 1974). Most of these bodies are altered dunites, similar in size, shape, and composition to the dunite bodies in North Carolina. The Lake Chatuge body is a concentrically zoned sill enclosed in orthoamphibolite. It has a dunite core which is surrounded locally by troctolite and gabbro and finally by amphibolite with a gradational boundary. It has been interpreted by the above authors as a sill differentiated from a gabbroic parent magma that carried olivine crystals in suspension.

The geologic setting of the ultramafic bodies in the Georgian Blue Ridge belt is very similar to that in North Carolina, although this may not be apparent due to lack of detailed stratigraphic correlation across the state boundary. In Georgia, the ultramafic rocks occur in the schists and gneisses of the Ashland Group (Hurst, 1973), particularly associated with amphibolites (hornblende gneiss of Crickmay, 1952) of the upper Ashland sequence. Crickmay (1952) considered the hornblende rocks to have originated by intense metamorphism of andesitic igneous rocks intruded as sills (rarely as dikes). Subsequent studies of amphibolites from Haralson, Paulding, Carroll, Cherokee, and Bartow Counties have shown

that they contain amygdaloidal and pillow structures indicative of an extrusive volcanic origin (Hurst, 1955; Hurst and Jones, 1973). The lower part of the Ashland Group is a thick sequence of predominantly meta-sedimentary rocks. Thus, the Ashland Group, a thick sequence of meta-sedimentary and metavolcanic rocks which hosts the ultramafic rocks in the Blue Ridge of Georgia, is similar to the Ashe Formation which hosts the ultramafic bodies in North Carolina and southwest Virginia. On the basis of distribution of amphibolites in the southern Blue Ridge belt, Hurst (1973) has suggested that the Ashland Group in Georgia (and Alabama) is correlative with the Ashe Formation in North Carolina and with the Mount Rogers Formation farther northeast. Jones, Hurst, and Walker (1973) noted that similar low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Cartersville-Villa Rica amphibolites and the Ashland Formation (avg 0.706), reported by Bottino (1971), support the above conclusion, as well as the interpretation that the amphibolites are metamorphosed mafic volcanic rocks of mantle origin. However, the computation of initial ratios in both cases involves the assumption that the amphibolites are 600 m.y. in age.

Hopkins (1914) suggested a common origin for these ultramafic rocks and the associated hornblende gneisses. He postulated that they belonged essentially to the same period of igneous activity, the ultramafics representing the culminating phase; this would account for their occasional cross-cutting relationships with the hornblende gneisses. Not much work seems to have been done subsequently to evaluate this conclusion.

Petrology

Mineralogy.—The peridotites and their alteration products in the Blue Ridge can be classified as dunites, harzburgites (saxonites), pyroxenites (websterites and enstatolites), soapstones, and serpentinites.

Dunite, the predominant variety of peridotite in North Carolina and Georgia, is composed almost entirely of olivine but usually contains a few primary accessory minerals such as enstatite and chrome-rich spinels (chromite and picotite). Locally, clinopyroxene may be important (Iherzolite). In altered dunites, secondary minerals compose 2 to 30 percent of the rock, mainly serpentine, talc, vermiculite, chlorite, and anthophyllite. Other minerals associated with dunites include magnetite, actinolite, phlogopite, garnierite, brucite, magnesite, corundum, spinel, and, occasionally, calcite, tourmaline, and pyrrhotite. Chromite is a common constituent, although it usually forms less than 1 percent of the bulk. It occurs as disseminated crystals in an olivine matrix, as large crystals in talc veins, and as disconnected small lenses and thin veins; well developed octahedral crystals of small to medium sizes are typical. Available analyses indicate that the chromite is characterized by high Al_2O_3 and MgO contents; for example, an analysis of unaltered chromite from the Addie-Webster body shows about 11 percent Al_2O_3 and 10 percent MgO (Miller, 1953). In some cases, chromite is altered at the margins to kammererite, a chlorite with up to 4 percent Cr_2O_3 (Miller, 1953; Dribus and others,

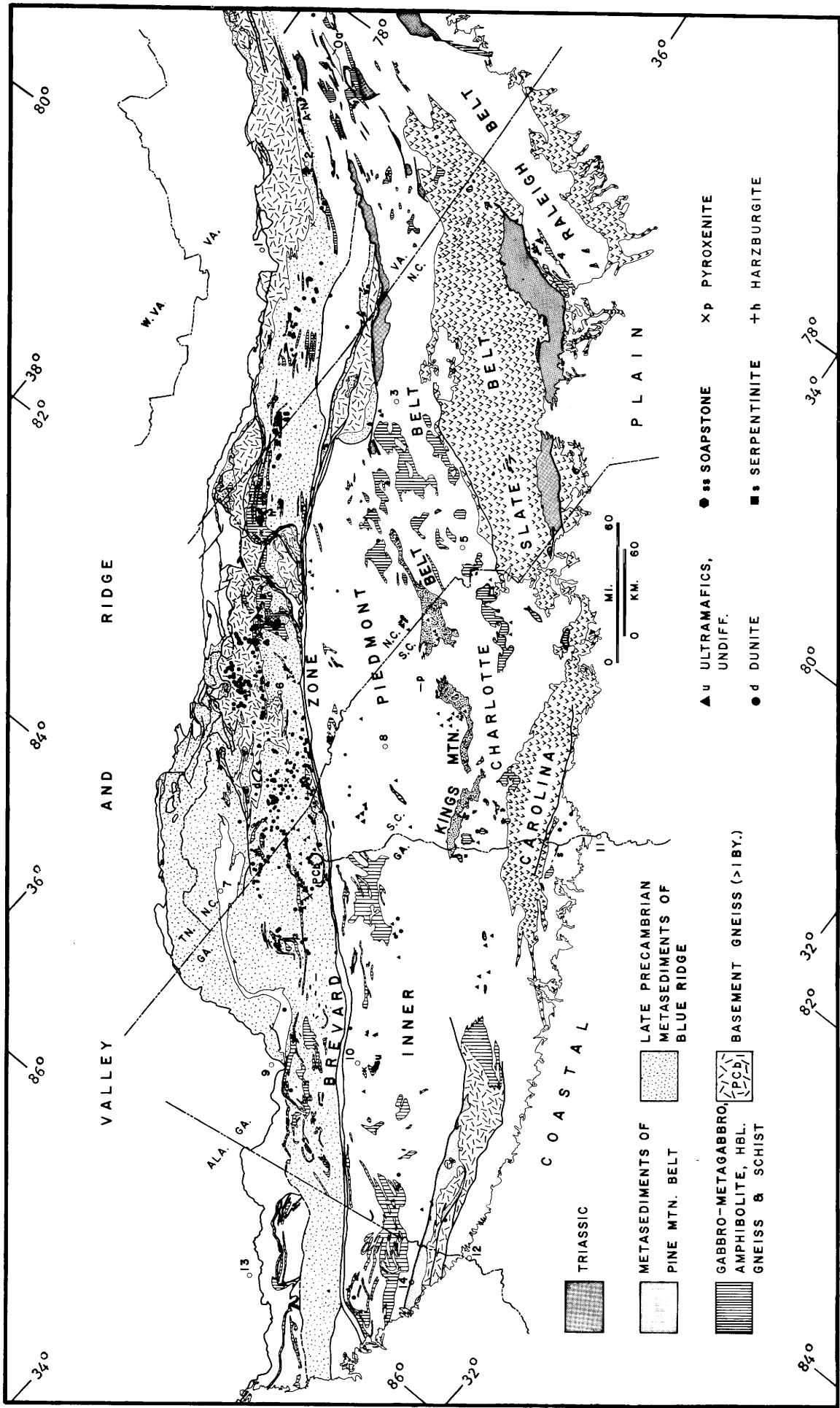


Fig. 1. Geologic map showing distribution of ultramafic and major mafic bodies in the southern Appalachians (modified from Larrabee, 1966). Numbered localities: 1. Roanoke, Va.; 2. Lynchburg, Va.; 3. Winston-Salem, N.C.; 4. Raleigh, N.C.; 5. Charlotte, N.C.; 6. Asheville, N.C.; 7. Murphy, N.C.; 8. Greenville, S.C.; 9. Carversville, Ga.; 10. Atlanta, Ga.; 11. Augusta, Ga.; 12. Columbus, Ga.; 13. Talladega, Ala.; 14. Opelika, Ala. A-N, Albemarle-Nelson belt, Va.; Oa, Ordovician Arvonian Slate in Virginia Piedmont. Sources discussed in text.

1976). The olivines are characteristically highly magnesian, making these dunites potentially suitable for production of refractories and various magnesium compounds. Recent petrographic studies of several dunite bodies in western North Carolina (Carpenter and Phyfer, 1975; Swanson and Raymond, 1976; Dribus and others, 1976) have shown that the composition of the olivine is remarkably uniform (average $\sim \text{Fo}_{92}$) within an individual body and between different bodies. This pattern of consistent olivine composition and the lack of detectable compositional zoning in individual olivine crystals suggest that the olivines have been recrystallized.

Harzburgite is very similar in mineralogy to dunite, except that it contains, in addition to olivine, significant amounts of enstatite and bronzite, usually as well developed prisms disseminated among olivine. Individual bodies of harzburgite are rather rare; typically it occurs as a petrographic variant of dunite.

Pyroxenite occurs as a minor constituent of larger peridotitic bodies (Frank and Corundum Hill, N.C.) and occasionally as separate lenses (Jackson and Transylvania Counties, N.C.; Cherokee County, Ga.). As discussed above, the sill-like ultramafic bodies in the Albemarle-Nelson belt, Va., may have been feldspathic peridotites, not pyroxenites as described by some authors. Typically, the pyroxenite is an orthopyroxenite, composed mainly of interlocking enstatite crystals that enclose irregular masses and individual grains of olivine (usually less than 10 percent), magnetite, and chromite. The enstatite usually shows alteration to fibrous anthophyllite, talc, and minor chlorite. Websterite, so named after its type occurrence in the Webster ultramafic body, is a diopside-bronzite rock of very restricted occurrence.

Soapstone, or talc-rich rock with varying amounts of amphibole and chlorite, is widespread in the Blue Ridge. It is a hydrothermal alteration product of pyroxenites and dunites, and so pockets of soapstone with gradational boundaries are common in most peridotite bodies. In many cases, almost complete alteration of the peridotites has produced soapstone bodies.

Although olivine in these peridotites invariably shows some alteration to serpentine, serpentinite bodies are not as common in the Blue Ridge as they are in Pennsylvania, New Jersey, and Maryland. However, most of the larger dunite bodies in the Blue Ridge belt contain marginal alteration zones of serpentinite (serpentinized dunite) that more or less concentrically surround cores of relatively unaltered, granular dunite (Hunter, 1941; Brobst, 1962; Dribus and others, 1976).

Alteration.—Alteration of the southern Appalachian ultramafics can be related to four main processes: (1) serpentinization, (2) amphibolization, (3) steatization, and (4) chloritization. Serpentinization and steatization are the most widespread alterations and, in fact, are present to some extent in all the ultramafic bodies. Amphibolization and chloritization are more local in their development. These alterations are hydrothermal in the sense that they require the presence of H_2O , or H_2O and CO_2 . The

textures produced by these alterations have been described by Hopkins (1914) and Conrad and others (1963).

Serpentinization still is a poorly understood process. The problem of serpentinization reactions has been discussed by many authors (Thayer, 1966, 1967a; Johannes, 1968, 1969; Condie and Madison, 1969; Martin, 1971) and will not be reviewed here. Another problem pertains to the timing of serpentinization: whether it was *in situ* (Neuhauser and Carpenter, 1971; Neuhauser, 1973; Swanson and Raymond, 1976) or took place prior to the emplacement of the peridotites (Astwood, Carpenter, and Sharp, 1972; Hearn and others, 1977). The presence of a serpentinized border zone in most of the Blue Ridge peridotite bodies can be explained either way, but the sheared nature of the serpentine at their margins suggests that serpentinization mainly occurred prior to emplacement. This is consistent with the hypothesis of solid-state emplacement of mantle peridotite (discussed below). The serpentinization probably continued after emplacement during regional metamorphism, producing only marginal alteration of olivine in the core regions of larger dunite bodies and converting some of the smaller dunite bodies almost completely into serpentinites, although some of these may have been emplaced as serpentinites. At least one later, minor period of serpentinization is suggested by the presence of serpentine-bearing veins cutting across peridotite bodies and serpentine coatings on joint and fracture planes.

Amphibolization is represented most commonly by the development of anthophyllite at the expense of olivine and orthopyroxene. The occurrence of long, undeformed anthophyllite prisms that show no preferred orientation but cut across olivine grains and serpentine-filled fractures suggests that amphibolization took place later than the emplacement of the peridotites and the *in situ* serpentinization.

Talc may be derived from amphibole, especially the non-aluminous varieties such as anthophyllite, orthopyroxene, olivine, and serpentine. The age relationship between serpentinization and steatization is not clear. Talc occurs with serpentine as foliated masses in the border zone of many peridotites (Stose and Stose, 1957), in veins associated with serpentine and anthophyllite, and even as an alteration product of serpentine (Burfoot, 1930; Brown, 1958), suggesting that there may be as many as three generations of talc.

Chlorite is mostly found in the border zone of peridotites and is predominantly an alteration product of olivine and orthopyroxene. Well-developed schistosity in some chlorite-rich portions suggests the development of chlorite during regional deformation. As pointed out by Trommsdorff and Evans (1972), in ultramafic assemblages chlorite is stable up to sillimanite-grade metamorphism.

Contact Relationships

Most of the ultramafic bodies are elongated parallel to the foliation of the enclosing gneisses and schists. This does not necessarily indicate a concordant contact, because the foliation may be an axial-plane folia-

tion (Neuhauser and Carpenter, 1971). Also, some ultramafic bodies are distinctly discordant, at least locally, to country rock foliation. Actual contacts against country rocks are usually obscured under soil cover. Where observed, the contacts are sharp and devoid of any recognizable contact effects such as chilled borders or thermal aureoles. Fault contacts have been suggested for many of the ultramafic bodies in North Carolina; for example, Holcombe (Hunter, 1941), Frank (Bluhm and Zimmerman, 1977), Addie-Webster (Miller, 1953). A common feature of many contacts is the presence of a thin (several cm to 1 m or more wide) alteration zone, characterized by the presence of talc, chlorite, and vermiculite, with or without minor amounts of serpentine. This alteration zone may show deformation features such as shearing, flaser dunite, strained porphyroclasts, and lineated chromite (Dribus, Heimlich, and Palmer, 1977).

Fabric

Generally, the ultramafic bodies are massive and lack conspicuous mesoscopic structures. In a few bodies such as Frank, Balsam Gap, Dark Ridge, Addie-Webster, and Buck Creek, a weak compositional banding (primary foliation) defined by planar distribution of pyroxene and chromite is discernible. Occasionally, folded seams of chromite are also found in dunites. These structures are discordant to the foliation of the country rocks (Bluhm and Zimmerman, 1977; Astwood, Carpenter, and Sharp, 1972; Sailor and Kuntz, 1973). Brittle deformation features such as fractures and shear zones are usually the only mesoscopic structures that are correlatable between the ultramafics and the country rocks.

Dribus and others (1976) have summarized the textures of several dunite bodies in North Carolina; this description is generally applicable to all dunites in the Blue Ridge belt (for example, Hearn and others, 1977; Kingsbury and Heimlich, 1977). The relatively unaltered dunites show two characteristic types of anhedral olivine: scattered, augen-shaped porphyroclasts with irregular outlines, surrounded by a mosaic of smaller polygonal grains. The porphyroclasts usually show plastic deformation features (Raleigh, 1968) such as undulatory extinction, often in the form of kink bands in individual olivine grains. The polygonal grains are typically unstrained, and they often show straight grain boundaries and triple junctions with boundary angles close to 120°, suggesting annealing recrystallization of the olivine aggregates (Ragan, 1969). Occasionally, as in the Frank body, flattened olivine and pyroxene grains mark a penetrative foliation that is parallel to the compositional banding. Persistence of strained porphyroclasts, the general lack of penetrative foliation, and the presence of mosaic aggregates of olivine with a variety of grain shapes and sizes, curved boundaries, unequal dihedral angles, and quadruple points are indicative of incomplete recrystallization (Nicolas and others, 1971). Undulose extinction in some recrystallized olivine grains and granulation of olivine grains, often along shear zones, indicate cataclastic deformation without recrystallization.

Although petrofabric analysis of constituent olivine and orthopyroxene can provide vital clues to the understanding of the emplacement history of ultramafic bodies (Den Tex, 1969; Lappin, 1971), only preliminary petrofabric data for olivine are available for a few of the dunite bodies in the Blue Ridge belt. The olivine in the Frank and the Buck Creek bodies shows strong $X = [010]$ maxima normal to the primary foliation in dunite, and $Y = [001]$ and $Z = [100]$ form diffuse maxima in a girdle parallel to the foliation or normal to X (Bluhm and Zimmerman, 1977; Sailor and Kuntz, 1973). According to Greenberg (1976), in the Addie-Webster dunite the olivine fabric is characterized by strong $Y = [001]$ maxima plunging steeply in the primary dunite foliation, whereas the dunite sample from the Addie body used by Avé Lallemant (1975) for deformation experiments shows a less pronounced preferred orientation, the strongest element in the fabric being a Z -maximum and a girdle. In both the above cases, the microfabrics do not correlate with the fabric of the country rocks. On the other hand, the olivine fabric in deposit no. 9 dunite consists of a strong $Z = [100]$ maximum, which is parallel to the axial trend of the enclosing anticline (Dribus, Heimlich, and Palmer, 1977).

These olivine preferred orientations are relatively strong and lack positive correlation with the shape anisotropy of the olivine grains. These features argue against their development by igneous processes such as magmatic flow during crystal-mush intrusion or gravitational settling of olivine from a stagnant magma, because olivine preferred orientations formed by these processes are typically weak and are controlled by crystal habit (Jackson, 1961; Den Tex, 1969). In fact, there is little doubt now that the observed olivine fabrics are caused by solid-state deformation, although there is no agreement regarding the mechanism of the orienting process.

The strong X -maxima of the Frank dunite is the most common olivine fabric among alpine-type peridotites. Almost identical olivine fabrics have been produced by experimental deformation of natural and synthetic dunite samples at temperatures above 1000°C (Avé Lallemant and Carter, 1970; Avé Lallemant, 1975; Nicolas, Boudier, and Boullier, 1973). However, Avé Lallemant and Carter (1970) have argued that, with the low strain rates expected under upper mantle conditions, syntectonic crystallization may take place at temperatures as low as 500°C . Thus, if the Frank dunite body represents upper mantle material, its olivine fabric could have formed by solid-state deformation either in the upper mantle or in the lower crust, before it reached its present position in the upper crust.

Departures from the typical X -maxima fabric in alpine-type peridotites may be due to variations in temperature and strain rate during recrystallization (which in turn determine the slip system operating during deformation), incomplete recrystallization, and overprint of later regional deformation. Lappin (1967) found significant differences between the fabric of strained, large olivine grains and unstrained, mosaic-type

olivine grains in the alpine-type dunite samples studied by him. Data presented by Avé Lallemant (1975, fig. 2) show that the olivine fabric (Y-maximum) of the Addie dunite sample partially recrystallized under triaxial compression tests was significantly different from the completely recrystallized fabric (X-maxima), and that both these fabrics were different from the fabric of the starting material (Z-maximum) which itself seems to have been modified by regional metamorphism.

Astwood, Carpenter, and Sharp (1972) found no statistically significant lattice preferred orientation of olivine in the Dark Ridge and Balsam Gap dunitites. This is unusual for alpine-type dunitites, although they believe that rigorous applications of statistical tests to published fabric data would turn out more examples of this type of fabric. According to them, this fabric resulted from dehydration of serpentinite (Carpenter and Phyfer, 1969) in a low-strain environment during regional deformation.

The fabric data discussed here are consistent with the interpretation of most workers that the ultramafic bodies in the Blue Ridge of North Carolina and Georgia were emplaced prior to or during the major episode of regional deformation. Deformational structures formed by plastic flow such as olivine preferred orientation, kink bands, folded chromite seams, and penetrative foliation must have developed prior to emplacement because they show no correlation with the fabric of the country rocks. The compositional banding probably developed by segregation during plastic flow. Post-emplacement fabrics include the cataclastic textures in olivine, modifications of olivine preferred orientation patterns, and other structures such as shearing and foliation in border zones that can be correlated with similar structures in the country rocks produced by regional deformation. The general concordance of the ultramafic bodies with the regional foliation suggests that they were probably emplaced after the first stage of folding of the country rocks.

Age Relations

No radiometric dates are available for the ultramafics, either in the Blue Ridge or in the Piedmont. Thus, their relative ages must be inferred from their geologic settings and associations.

Several features of the ultramafics of the Albemarle-Nelson belt in Virginia indicate that they may be distinct from those in the remainder of the Blue Ridge. These include: (1) the presence of a feldspathic facies, (2) development of tremolite and actinolite as the dominant amphiboles instead of anthophyllite, (3) paucity of chromite, (4) prevalence of linear rather than lenticular shapes, and (5) possibility of a genetic link with the associated amphibolites. These ultramafics are localized within the upper part of the Lynchburg Formation and are also associated with the Catoclin greenstone. If the ultramafics are extrusives or hypabyssal intrusives related to Catoclin volcanism (Brown, 1958), they are approximately of the same age as the Catoclin. Rankin and others (1969) report an age of 820 m.y. from zircons in felsic volcanics of the Catoclin, pro-

viding a maximum age for the ultramafics. To the authors' knowledge no ultramafics in this area have been reported from rocks younger than the Catocin, so that the age of the overlying Evington Group (Lower Cambrian?) may be considered a minimum age for the ultramafics.

The ultramafics in the remainder of the Blue Ridge belt appear to be of a different age. In southwest Virginia and western North Carolina they intrude portions of the late Precambrian stratified sequence, indicating that they are late Precambrian or younger in age. From a consideration of structural and fabric data (discussed earlier), almost all recent investigators have concluded that the ultramafic bodies were emplaced prior to or during the major episode of regional metamorphism and deformation. Butler (1972, 1973), Dallmeyer (1975), and other workers have argued, primarily on the basis of K-Ar dating techniques, that Blue Ridge regional metamorphism occurred at least 450 m.y. ago. In many localities ultramafic rocks are crosscut by pegmatites of the Spruce-Pine type which are broadly synchronous with the effects of mid-Paleozoic metamorphism, variously dated as 350 to 450 m.y. throughout the southern Appalachians (Long, Kulp, and Eckelman, 1959; Overstreet and Bell, 1965b; Fullagar, 1971; Butler and Ragland, 1969a; Butler, 1973). Although ultramafic rocks predate the granite and pegmatites in the Blue Ridge, their distribution along with granitic and pegmatitic bodies near the thermal axis (kyanite and sillimanite zones) of metamorphism in the Blue Ridge suggests that the ultramafic emplacement is related in some manner to this regional metamorphic event (Carpenter, 1970). This conclusion appears consistent with an Ordovician (Taconic) age for their emplacement, as proposed by Pratt and Lewis (1905), Hess (1955), and Stuckey (1965).

Hatcher (1971) suggested a Paleozoic age for the ultramafics in the Tallulah Falls Formation and the Coweeta Group in Rabun and Habersham Counties, Ga. He (Hatcher, 1973, 1974, 1976) also noted the similarity in the stratigraphic position and lithologies of the Tallulah Falls-Coweeta and Ashe-Alligator Back sequences and thus suggested a late Precambrian age for the Tallulah Falls Formation. The continuity of a belt of amphibolites in the Ashland group of Georgia, the Tallulah Falls Formation, and the Ashe led Hurst (1973) to suggest a late Precambrian age for the Ashland. If the Ashland is at least in part correlative with the Ashe, then the occurrence of ultramafics along the Ashland-Tallulah Falls-Ashe belt, within the kyanite and sillimanite zones of metamorphism (Hurst, 1973, fig. 8), indicates a geologic setting for the Georgia ultramafics similar to that in western North Carolina. This suggests an Ordovician age for these bodies, as well.

Origin and Emplacement

Proposed hypotheses for the origin of alpine-type ultramafic bodies have been elegantly summarized by Wyllie (1969, 1970) and need not be reviewed here. The present discussion is limited to those hypotheses that may be relevant to the Blue Ridge ultramafics.

The peridotites of the Blue Ridge belt are characterized by low-temperature emplacement (within the stability field of serpentine, probably less than 500°C), as shown by complete lack of thermal metamorphism at their contacts. This rules out the possibility of their crystallization from peridotitic melt, which can exist only at high temperatures (Bowen and Tuttle, 1949; Clark and Fyfe, 1961; Kitahara, Takenouchi, and Kennedy, 1966).

Another consistent feature of the ultramafic bodies of the Blue Ridge belt is their close association with amphibolites. Sørensen (1967) suggested that peridotite and garnet peridotite bodies, when enclosed in amphibolite, could be products of metamorphic differentiation in zones of stress concentration. Such an origin is unlikely for the Blue Ridge ultramafics, because they lack structural control and show sharp contacts against amphibolites. Also, ultramafics enclosed in amphibolites appear no different from those enclosed in mica gneisses.

As discussed earlier, the amphibolites probably represent metamorphosed basaltic flows and coeval shallow intrusives. It is conceivable that the associated ultramafic rocks are cumulates of a differentiating basaltic magma, similar to the ultramafic cumulates in mafic layered intrusions. Hess (1933) suggested that the ultramafic body near Schuyler, Va., was probably formed by *in situ* differentiation of picritic magma. In the Blue Ridge, the best documented example of a mafic-ultramafic complex ascribable to crystallization of a basaltic magma appears to be the Lake Chatuge sill, Ga. (Hartley, 1973; Hartley and Penley, 1974). There, the low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7023-0.7068) of all the components of the complex — dunite, olivine gabbro, troctolite, and amphibolite — indicate a common upper mantle source (Jones, Hartley, and Walker, 1973), and flowage differentiation appears to be a reasonable explanation for the concentric zoning. However, these two bodies can hardly be considered typical of the Blue Ridge belt. We have pointed out the distinctiveness of the Albemarle-Nelson belt ultramafics, and Thayer has also expressed doubt about the alpine nature of the Lake Chatuge sill (personal commun., cited in Hartley and Penley, 1974).

There is little evidence to suggest contemporaneous emplacement of the ultramafic bodies and amphibolites elsewhere in the Blue Ridge. Their spatial relationship in North Carolina suggests that at least some of the ultramafics must have been emplaced independently of the amphibolites of the Ashe Formation (Rankin, Espenshade, and Shaw, 1973). However, this does not necessarily preclude a genetic relationship between them. One can postulate that the ultramafic rocks were formed by accumulation from a basaltic magma at depth, that the residual liquid was expelled as volcanic materials and intercalated with sediments in the geosynclinal section, and that the ultramafic cumulates were tectonically emplaced at higher crustal levels during a subsequent orogeny (Chidester, 1968). The ultramafics, then, would be associated, but not exclusively, with the amphibolites (mafic volcanics) inasmuch as they constitute a part of the eugeosynclinal sequence. Such a mechanism is supported by

recent experimental data of Green and Ringwood (1964) and Tilley and Yoder (1964). They showed that at high pressure the initial high-temperature crystallization product from a picritic or olivine tholeiitic magma would be of peridotitic composition, and the residual liquid of alkali basaltic or olivine-poor composition depending on the depth of differentiation. Depending on the time and distance of migration, such a crystalline peridotite mass may be emplaced at high temperature as suggested for Lizard, Cornwall (Green, 1967), or at low temperature as suggested for peridotites in northwestern New England (Chidester, 1968). Presence of compositional banding in peridotite, interpreted as a cumulus fabric, is often considered reliable evidence for such an origin, although similar banding could develop during partial melting of primary mantle material accompanied by differential elutriation of suspended crystals in a mobile crystal-liquid system (Ringwood, 1975, p. 96) or even by metamorphic differentiation. Thus, the real test of this hypothesis must rest on proving a genetic relationship between the associated mafic and ultramafic rocks.

The major objection to a genetic relationship between the ultramafics and the mafics as implied by the above hypothesis arises from the incompatibility of strontium isotope ratios between the alpine-type peridotites and mafic volcanics on a world-wide scale. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the alpine-type peridotites (0.707-0.725, avg 0.711) are consistently higher than those in oceanic basalts, suggesting that the two mantle-derived materials could not be genetically related (Stueber and Murthy, 1966; Bonatti, 1971; Bonatti, Honnorez, and Ferrara, 1970). Stueber and Murthy (1966) proposed that alpine-type ultramafics originate from a relatively Rb-enriched residual peridotitic layer in the upper mantle which, as proposed by Birch (1965), was formed during the primitive differentiation of the Earth. Clark and Ringwood (1964) had proposed a similar model, in which a thick (~ 100 km) layer of residual ultramafic mantle exists below the continents but is thin or absent below the oceans. However, Bonatti (1971) and Bonatti, Honnorez, and Ferrara (1970) have argued that either a continuous layer or blocks of ancient, residual, alpine-type peridotite must exist also in the oceanic mantle, overlying "normal" mantle which is the source material for oceanic basalts.

A residual peridotitic layer in the upper mantle appears to be a reasonable source for alpine-type ultramafics, but its applicability to the Blue Ridge ultramafics cannot be accepted on the basis of the limited available data. In five western North Carolina ultramafic bodies studied by Stueber (1969), the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are within the range of values for alpine-type peridotites (see Bonatti, 1971, fig. 1) and higher than the range of values reported for the Blue Ridge belt amphibolites (Bottino, 1971; Jones, Hurst, and Walker, 1973). However, according to Stueber (1969), the relatively wide variations in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios on a local scale and lack of isochron relationships suggest that the high ratios are probably due to introduction of radiogenic strontium during regional metamorphism and thus bear no direct relationship to the source of the ultra-

mafics. Evidently, more data are needed to test this interpretation, and we hope collection of strontium isotopic data will form an integral part of future studies on mafic and ultramafic rocks in the southern Appalachians. For the present, alternate models that imply a genetic relationship between the ultramafics and the associated mafics must be retained as viable possibilities, at least as far as the Blue Ridge belt is concerned. One such model, which considers the ultramafics to be accumulates from a basaltic magma, was discussed earlier. Another possibility is that the ultramafic materials represent the refractory residuum of partially melted garnet lherzolite or pyrolitic upper mantle, the composition of the residuum and the complementary liquid being determined by the degree of partial melting and the depth of segregation of the liquid (Ringwood, 1975, p. 146-157).

Whether alpine-type ultramafics represent fragments of upper mantle or accumulates from a basaltic magma, most authors consider them to have been emplaced in the upper crust as solid bodies (Bowen and Tuttle, 1949; De Roever, 1957; Ragan, 1967; Jahns, 1967; Green, 1967; Chidester, 1968; Den Tex, 1969). The major problem in the solid-state emplacement of an ultramafic body lies in accounting for its upward transport. At deeper levels, the upward movement of a peridotite body probably takes place by plastic flow (Bowen and Tuttle, 1949; Hess, 1955); at shallower levels the movement is believed to take place under a tectonic stress gradient and is facilitated by serpentinization and weakening of the border zone due to high fluid pressures generated at the contact of the relatively hot peridotite with wet sediments (Raleigh, 1967; Jahns, 1967; Chidester, 1968). Hess (1955) considered that at shallow depths the ultramafics move as fault-bounded blocks or slices without internal flow, but forceful diapiric intrusion should be possible if the pore pressure at the hot peridotite-wet sediment contact equals or exceeds the overburden pressure.

According to most workers, the ultramafics in the Blue Ridge belt were tectonically emplaced as cold, solid peridotite bodies (Conrad and others, 1963; Sailor and Kuntz, 1973; Yurkovich, 1976; Bluhm and Zimmerman, 1977; Dribus, Heimlich, and Palmer, 1977; Kingsbury and Heimlich, 1977). Evidence for this conclusion includes: (1) absence of thermal metamorphism at contacts, (2) presence of tectonite olivine fabric unrelated to the fabric of the country rocks, and (3) serpentinization and shearing at the margins of the peridotite bodies.

Carpenter and Phyfer (1969) advocated that most of the Appalachian ultramafics were emplaced as solid serpentinite bodies and were partially dehydrated during subsequent metamorphism to form olivine-rich rocks. Solid-state emplacement of serpentinite bodies is well documented in the literature (for example, Jahns, 1967), and the feasibility of serpentine dehydration has been demonstrated by several workers (King and others, 1967; Scarfe and Wyllie, 1967; Johannes, 1968). However, features such as the presence of a dunite core with large olivine crystals, the tectonite fabric of olivine, and the lack of textures which would suggest formation

of olivine from serpentine argue against the general applicability of the dehydration hypothesis to the Blue Ridge ultramafics.

ULTRAMAFICS OF THE PIEDMONT REGION

Distribution

Much less is known about the ultramafic rocks of the Piedmont compared to those of the Blue Ridge. Numerous brief references to small ultramafic bodies can be found in various local and areal reports or in regional compilations of economic prospects (for example, Sloan, 1908; Hopkins, 1914), but detailed studies are conspicuously absent from the literature, no doubt in part because of the generally poor exposure of these bodies. Therefore treatment of these bodies in this paper is limited to descriptions of their occurrences and associations and inferences of their relative ages based upon regional constraints.

In Virginia, isolated occurrences include a small lens of pyroxenite in the northwest corner of Goochland County (beyond the limit of fig. 1; see Brown, 1937) and sill-like bodies of altered ultramafic rocks associated with the Diana Mills Pluton (hornblende gabbro), Buckingham County (Brown, 1969). In Goochland County, the pyroxenite is apparently intrusive into the Columbia Granite and is altered to soapstone along the borders. The sill-like bodies in Buckingham County occur in the metagraywackes of the Evington Group and are composed mainly of actinolite-chlorite schist, with minor amounts of soapstone and serpentinite. Both chlorite and talc appear to have been derived, at least in part, from actinolite. Much of the talc and antigorite, however, occurs as small rounded masses which probably were olivine. Magnetite and minor amounts of chromite occur as accessories. Except for the greater proportion of chromite, these bodies seem to be mineralogically similar to ultramafic bodies in the Albemarle-Nelson belt and probably represent altered peridotites. Recently, Brown (1976) has interpreted the Evington Group metagraywacke as a tectonic *mélange* formed during subduction, some or all of the mafic and ultramafic rocks, including the Diana Mills Pluton, constituting exotic blocks folded into the metagraywacke. Other small pockets of soapstone associated with hornblende metagabbros in the Virginia Piedmont may represent local pyroxene-rich differentiates.

In the Piedmont of the Carolinas and Georgia, ultramafic rocks occur in close association with amphibolites (including hornblende gneisses and schists). The amphibolites consist predominantly of metamorphosed mafic lavas and tuffs (with some intercalated graywacke, tuffaceous argillite, and calcareous sediments) and contain numerous dikes of basalt, andesite, diorite, gabbro, pyroxenite, and probably dunite, some of which probably were feeders for the mafic lavas. Ultramafic rocks also occur associated with some of the gabbroic intrusives but mostly either as irregularly distributed, minor petrographic variants (troctolite, picrite, pyroxenite, with up to 51 percent modal olivine), or as olivine- and pyroxene-rich layers of local extent that can be attributed to flowage differentiation (Butler and Ragland, 1969a). Griffin (1972) noted the oc-

currence of a small ultramafic body (chloritized pyroxenite or hornblendite) enclosed in gabbroic rock, south of the Calhoun Falls gabbro in McCormick County, S.C. However, occurrences of such discrete ultramafic bodies in gabbroic plutons are rare in the Piedmont. According to Overstreet and Bell (1965a), hornblendite, one of the principal rock types of their gabbro-pyroxenite-norite unit in South Carolina, was probably derived from peridotite. This, however, remains to be established from detailed petrologic studies.

Small lenses of altered ultramafic rocks occur throughout the Inner Piedmont belt. Griffin (1969) recognized two types in South Carolina: altered dunite and magnesian schist, both of which occur in amphibolites, gabbros, and biotite gneisses and schists. Dunite bodies typically alter to talc and anthophyllite, whereas alteration products in magnesian schist mainly consist of cummingtonite and clinocllore. Narrow zones of serpentinite and soapstone enclosed in amphibolite are also found in this belt, as in Anderson County, S.C. (Griffin, 1972). These bodies are conformable with the local foliation of the country rocks, although the internal foliation in some is discordant (Griffin, 1969). Elongate and apparently folded bodies of pyroxenite and soapstone in hornblende gneiss occur in Cherokee County, S.C. (Keith and Sterrett, 1931). In the Inner Piedmont belt of Alabama and Georgia (Dadeville belt of Adams, 1933), pyroxenite and soapstone bodies occur in close association with folded bands of amphibolite (Ropes Creek amphibolite of Bentley and Neathery, 1970). Neathery (1968) has described the association in the Smith Mountain complex in eastern Tallapoosa County, Ala. The ultramafics are rounded inclusions, a few centimeters to greater than 1 m in diameter, composed primarily of enstatite, hypersthene, bronzite, and their altered equivalents, and occur in sharply defined bands a few meters to more than 300 m in length within the amphibolites. They are altered to fibrous masses of talc and anthophyllite inward from their margins and are cut by numerous veins of talc-anthophyllite, with minor amounts of serpentine or tremolite. Their unique mode of occurrence as strata-bound zones of inclusions in deformed amphibolite indicates that these bodies were coeval with the formation of the amphibolite protoliths. According to Neathery (1968), they may represent igneous differentiates of mafic flows or intrusives, or flows or sills in volcanoclastic sediments, or alpine-type intrusions associated with earlier deformation. Clark (1973) has described an assemblage of mafic and ultramafic rocks (the Seroyer Branch complex) in southwestern Chambers County, Ala. Discordant pyroxenite dikes along the margin of the complex are interpreted by him to have formed as ultramafic crystal mush intruded from the pyroxenite core of the complex.

In Wake County, N.C., a swarm of about two dozen lenticular bodies of serpentine, soapstone, and other ultramafic rocks lie about midway between Raleigh and Henderson, along the western margin of the Raleigh belt (Parker, 1968). Individual lenses range in outcrop length from a few hundred meters to about 5 km, lying in a belt of high-rank mica and

hornblende gneisses and schists characterized by garnet and kyanite. They are conformable to the local and regional foliation in their position, but the few actual exposures of their contacts are so deformed that original relations are uncertain. Primary olivine and pyroxene remain now only as relics, and the rocks consist chiefly of variable proportions of serpentine, amphiboles, talc, and chlorite (Dickey, ms). Gravity data (Mann, 1962) suggest that no large ultramafic body exists at high levels in the crust along this belt (Parker, 1968). Spence and Carpenter (1976) have suggested that the ultramafic and mafic bodies of Wake County may represent dismembered ophiolite sequences, which may be stratigraphically overlain by the quartzites and quartz pebble conglomerates of the Raleigh belt.

Age Relations

Butler and Ragland (1969a) divided the intrusive rocks of the Piedmont into two groups: pre- and syn-metamorphic intrusions and post-metamorphic intrusions. The great majority of the ultramafic bodies in the Piedmont, especially those in the Inner Piedmont belt, appear to belong to the older group, as shown by their concordant geometry and intense alteration. Radiometric age data from post-metamorphic intrusives in the Piedmont place rough limits on the minimum age of metamorphism and thus provide a reference age for the ultramafic bodies. Kish and Fullagar (1977) report a Rb-Sr age of 350 m.y. for the post-metamorphic Cherryville quartz monzonite in North Carolina. This may be considered a minimum age for the regional metamorphism and therefore for the pre-metamorphic ultramafic bodies. Fullagar (1971), however, has argued that post-metamorphic syenites (Mount Carmel and Concord bodies) associated with the younger gabbro belt are at least 385 m.y. old (K-Ar age for Mount Carmel diorite reported by Medlin, 1969) and may be as old as 400 m.y. The Lowrys granite pluton in North Carolina, considered by Butler and Ragland (1969a) to be post-metamorphic, yields a Rb-Sr age of 407 m.y. (Fullagar, 1971). It thus appears that the pre-metamorphic ultramafics may be older than about 400 m.y.

An upper age limit for these ultramafic bodies is far more difficult to establish. Pre-metamorphic granodiorite of the Hatcher complex in Virginia yields a Rb-Sr age of about 595 m.y. (Fullagar, 1971). The Henderson Gneiss, thought by some workers to be intrusive into older Inner Piedmont rocks, yields an age of 535 m.y. (Odom and Fullagar, 1973). Preliminary work by Kish and Fullagar (1977) indicates that the Toluca quartz monzonite probably bears a similar age. Thus large areas of the country rocks of the Inner Piedmont intruded by these granitic rocks are at least Cambrian in age and conceivably may be older, judging from the numerous late Precambrian ages derived from volcanogenic rocks of the Carolina Slate belt (Fullagar, 1971; Glover and others, 1971; Black and Fullagar, 1976). A maximum age for the earlier ultramafics—assuming that they are all related to the same event—could range from late Precambrian to early Paleozoic.

According to Butler and Ragland (1969a), the olivine- and pyroxene-rich cumulates in some of the younger gabbroic intrusives constitute the only post-metamorphic ultramafic rocks in the Piedmont. However, several ultramafic bodies of possible post-metamorphic age have been reported. These include peridotite bodies in Cleveland County, N.C. (Overstreet and Bell, 1965a), a dike-like body of serpentinite in Greenwood County, S.C. (McSween, 1972), an altered pyroxenite body enclosed in gabbroic rocks, McCormick County, S.C. (Griffin, 1972), and a pyroxenite body exposed along an irregular contact with hornblende gneiss and amphibolite in Green County, Ga. (Medlin and Hurst, 1967). If indeed they are post-metamorphic intrusions, the age of the regional metamorphism provides a maximum age for these bodies. Some of the younger gabbroic intrusives (for example, the Pee Dee gabbro, Waskom and Butler, 1971; the Coronaca norite, McSween, 1970) appear to intrude the associated granites, which are very similar to the post-metamorphic Liberty Hill pluton (306 m.y., Butler and Ragland, 1969a). Thus, the post-metamorphic ultramafic bodies may be as young as 300 m.y., or even younger. Their minimum age cannot be ascertained from the available data.

TECTONIC IMPLICATIONS

Any viable geodynamic model proposed for the southern Appalachians must address itself to the differences in the geologic settings and relative ages of ultramafic bodies in this segment of the orogen. Within such a context the various plate-tectonic models proposed for this region are examined below.

Most workers now agree with Wilson (1966) that the initial phase of development of the Appalachian orogen was marked by an episode of late Precambrian rifting to form a Proto-Atlantic ocean. The western edge of this initial rift in the southern Appalachians is now marked by a sequence of metamorphosed igneous and volcanogenic sedimentary rocks of the Catoctin, Ashe, Mount Rogers, and Grandfather Mountain Formations and the Crossnore Plutonic-Volcanic Group, stretching from southern Pennsylvania to western North Carolina. The bimodal character of these igneous suites and the peralkaline affinity of their felsic members suggest a divergent plate-boundary setting for this igneous activity (Rankin, 1975, 1976). From a detailed study of the chemistry of the Catoctin greenstones and the associated mafic intrusives, Blackburn and Brown (1976) concluded that the Catoctin series represents tholeiites associated with continental rifting. If the proposed correlation of the Ashland-Tallulah Falls sequence with the Ashe is correct, then a similar late Precambrian tectonic setting appears reasonable also for Georgia and Alabama. In the southern Appalachians, the lack of oceanic crust points to an ensialic rifting, whereas the presence of ophiolitic sequences in Newfoundland, Quebec, and Maryland suggests that the northward extension of this rifting was probably ensimatic.

We have stressed earlier the close spatial association of the Blue Ridge ultramafic bodies with the upper Precambrian mafic igneous rocks

along the western edge of the crystalline Appalachians. This led Rankin (1975) to suggest that the distribution of the ultramafics is largely controlled by the trough of the late Precambrian-early Paleozoic rift system. The distinctive features of the Albemarle-Nelson belt ultramafics raise the possibility that they may be genetically and temporally related to the basaltic volcanism of the rift system. For the rest of the ultramafic bodies in the Blue Ridge, there is no evidence to suggest that they were coeval with the mafic volcanics. The common but not exclusive association of these ultramafic bodies with the mafic volcanics and their solid state emplacement during compressional events can be best accounted for by a two-stage process — an initial mobilization of upper mantle material to lower crustal levels under tensional stresses associated with rifting and a later emplacement as solid peridotite bodies in the upper crust under tectonic stress gradients established during Taconic deformation. The solid peridotite may represent refractory residuum of partially melted mantle material, or igneous cumulates of the basaltic liquid, or a fragment of the Rb-enriched differentiated mantle. The answer to this problem must await detailed petrologic and isotopic data on the ultramafics and the associated mafics.

The Piedmont presents a much less coherent picture. Available evidence indicates that rocks of the Carolina Slate belt and portions of the Charlotte belt represent an island arc which developed in the late Precambrian through early Paleozoic east of the present Blue Ridge anticlinorium (Butler and Ragland, 1969b; Odom and Fullagar, 1973; Fullagar and Butler, 1977). The arc was welded to the North American craton during a later collisional event. Several geodynamic models have been proposed to explain the topology of the craton-arc assemblage before collision and the manner in which the arc subsequently collided with the craton (Hatcher, 1972; Odom and Fullagar, 1973; Rankin, 1975; Crowley, 1976; Bland and Brown, 1977). Clearly, an acceptable model must account for the distribution of the pre-metamorphic ultramafics in the Piedmont, but lack of adequate data limits the usefulness of this constraint at present in evaluating alternative plate-tectonic models. If the premetamorphic ultramafic bodies represent solid-state intrusions into wet geosynclinal sediments, they may have been mobilized into either a dominantly continental crust and sediment cover during westward subduction beneath the arc (Hatcher, 1972) or an ensimatic back-arc basin, which was later closed by eastward subduction beneath the arc (Bland and Brown, 1977). In the former case, the ultramafics would be emplaced in two stages, similar to that proposed for the Blue Ridge: initial emplacement in lower crustal levels during late Precambrian rifting and subsequent upward mobilization during subduction. In the latter case, the ultramafics rising as diapirs above the subduction zone (Karig, 1971) would be a direct consequence of the subduction beneath the arc. According to Dewey (1976), the close association of ophiolites with rocks of volcanic-arc affinities, as in Maryland (Crowley, 1976), suggests a back-arc origin, although the sequence of events leading to collision may develop

in a number of ways. Rankin (1975) favors a model in which diamictite-like facies of the Smith River allochthon, the Inner Piedmont, and the ophiolitic terrain of Maryland represent *mélange* associated with obduction (presumably east-dipping) of ophiolite, which was later transported westward over the Pine Mountain, Sauratown Mountains, and Baltimore-Washington anticlinoria along a deeper "hard-rock" thrust. Bland and Brown's (1977) model, in which the Evington Group with the associated ultramafics represent *mélange* in a back-arc setting, is similar. If the back-arc model is correct, then a likely scenario would involve (A) west-dipping subduction beneath the arc with formation of a back-arc basin and diapiric intrusion of peridotites as suggested by Karig (1971), followed by (B) closure of the marginal basin by eastward subduction of the marginal basin beneath the arc, leading to arc-craton collision. Westward subduction along the east side of the craton-arc assemblage would be reestablished after the collision.

An alternative to the above model has been proposed by Odom and Fullagar (1973) and Fullagar and Butler (1977), in which an open ocean basin between the craton and the arc is closed along an east-dipping subduction zone beneath the arc. This leads to arc-craton collision, followed by westward-dipping subduction along the east side of the welded assemblage. This model is more attractive in its relative simplicity — only one reversal of arc polarity is implied — but does not readily account for the distribution of the pre-metamorphic ultramafics in the Piedmont.

Following arc-continent collision, westward-dipping subduction beneath the edge of the craton-arc assemblage is required to account for the post-metamorphic plutons of the eastern Piedmont (Fullagar and Butler, 1977). Continued convergence between the African and North American plates would ultimately lead to continental collision along a suture, now likely buried beneath Coastal Plain sediments.

Much of the discussion presented above is of necessity speculative in nature. Admittedly, our understanding of the southern Appalachians is still in an embryonic state. A clearer picture can only be obtained by continued investigation and the debate that new data stimulates.

ACKNOWLEDGMENTS

The authors wish to acknowledge the thorough reviews by J. Robert Butler and Harry Y. McSween, Jr., and the careful editing of Kenneth R. Walker. Their comments greatly improved this paper. Leonard S. Wiener and Carl E. Merschat graciously provided unpublished map data for southwestern North Carolina. We also thank Oscar E. Gilbert for discussion concerning aspects of Piedmont geology in Alabama and Georgia, and Dietrich Roeder for discussions on southern Appalachian geodynamics. All errors of interpretation or omission, however, are our own.

REFERENCES

- Adams, G. I., 1933, General geology of the crystallines of Alabama: *Jour. Geology*, v. 41, p. 159-173.
Astwood, P. M., Carpenter, J. R., and Sharp, W. E., 1972, A petrofabric study of the Dark Ridge and Balsam Gap dunites, Jackson County, North Carolina: *Southeastern Geology*, v. 14, p. 183-194.

- Avé Lallemant, H. G., 1975, Mechanisms of preferred orientations of olivine in tectonite peridotite: *Geology*, v. 3, p. 653-656.
- Avé Lallemant, H. G., and Carter, N. L., 1970, Syntectonic recrystallization of olivine and modes of flow in the upper mantle: *Geol. Soc. America Bull.*, v. 81, p. 2203-2220.
- Benson, W. N., 1926, The tectonic conditions accompanying the intrusion of basic and ultrabasic plutonic rocks: *Natl. Acad. Sci. Mem.*, v. 19, mem. 1, 90 p.
- Bentley, R. D., and Neathery, T. L., 1970, Geology of the Brevard Fault zone and related rocks of the Inner Piedmont of Alabama: University, Ala., Alabama Geol. Soc. Guidebook, 8th Ann. Field Trip, p. 1-80.
- Birch, F., 1965, Speculations on the earth's thermal history: *Geol. Soc. America Bull.*, v. 76, p. 133-154.
- Black, W. W., and Fullager, P. D., 1976, Avalonian ages of metavolcanics and plutons of the Carolina slate belt near Chapel Hill, North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 8, p. 136.
- Blackburn, W. H., and Brown, W. R., 1976, Petrochemical evidence relating the Catocin volcanic series to late Precambrian continental separation [abs.]: *Geol. Soc. America Abs. with Programs*, v. 8, p. 136-137.
- Bland, A. E., and Brown, W. R., 1977, Evington Group (?) of the Arvonnia district, Virginia: rear arc sedimentation and volcanism [abs.]: *Geol. Soc. America Abs. with Programs*, v. 9, p. 120-121.
- Bloomer, R. O. and Werner, H. J., 1955, Geology of the Blue Ridge region in central Virginia: *Geol. Soc. America Bull.*, v. 66, p. 579-608.
- Bluhm, C. T., and Zimmerman, J., Jr., 1977, Structure of the Frank ultramafic tectonite, Avery County, North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 9, p. 181.
- Bonatti, E., 1971, Ancient continental mantle beneath oceanic ridges: *Jour. Geophys. Research*, v. 76, p. 133-154.
- Bonatti, E., Honnorez, J., and Ferrara, G., 1970, Equatorial mid-Atlantic ridge: Petrologic and Sr isotopic evidence for an alpine-type assemblage: *Earth Planetary Sci. Letters*, v. 9, p. 247-256.
- Bottino, M. L., 1971, Rb, Sr, and Sr isotope measurements of amphibolites from the Ashe Formation, North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 3, p. 297.
- Bowen, N. L., and Tuttle, O. F., 1949, The system MgO-SiO₂-H₂O: *Geol. Soc. America Bull.*, v. 60, p. 439-460.
- Brobst, D. A., 1962, Geology of the Spruce Pine District, Avery, Mitchell, and Yancey Counties, North Carolina: U.S. Geol. Survey Bull. 1122-A, 26 p.
- Brown, C. B., 1937, Outline of the geology and mineral resources of Goochland County, Virginia: Virginia Geol. Survey Bull., v. 48, 68 p.
- Brown, W. R., 1958, Geology and mineral resources of the Lynchburg Quadrangle, Virginia: Virginia Div. Mineral Resources Bull. 74, 99 p.
- 1969, Geology of the Dillwyn Quadrangle, Virginia: Virginia Div. Mineral Resources Rept. Inv. 10, 77 p.
- 1976, Tectonic melange (?) in the Arvonnia Slate district of Virginia [abs.]: *Geol. Soc. America Abs. with Programs*, v. 8, p. 142.
- Burfoot, J. D., 1930, The origin of the talc and soapstone deposits of Virginia: *Econ. Geology*, v. 25, p. 805-826.
- Butler, J. R., 1972, Age of Paleozoic metamorphism in the Carolinas, Georgia, and Tennessee Southern Appalachians: *Am. Jour. Sci.*, v. 272, p. 319-333.
- 1973, Paleozoic deformation and metamorphism in part of the Blue Ridge thrust sheet, North Carolina: *Am. Jour. Sci.*, v. 273-A, p. 72-88.
- Butler, J. R., and Ragland, P. C., 1969a, A petrochemical survey of the plutonic intrusions in the Piedmont, southeastern Appalachians, U.S.A.: *Contr. Mineralogy Petrology*, v. 24, p. 164-190.
- 1969b, Petrology and chemistry of meta-igneous rocks in the Albemarle area, North Carolina Slate belt: *Am. Jour. Sci.*, v. 267, p. 700-726.
- Carpenter, J. R., and Phyfer, D. W., 1969, Proposed origin for the alpine type ultramafics of the Appalachians [abs.]: *Geol. Soc. America Abs. with Programs*, v. 1, p. 216-263.
- 1975, Olivine compositions from southern Appalachian ultramafics: *Southeastern Geology*, v. 16, p. 169-172.
- Carpenter, R. H., 1970, Metamorphic history of the Blue Ridge Province of Tennessee and North Carolina: *Geol. Soc. America Bull.*, v. 81, p. 749-762.

- Chidester, A. H., 1962, Petrology and geochemistry of selected talc-bearing ultramafic rocks and adjacent country rocks in north-central Vermont: U.S. Geol. Survey Prof. Paper 345, 107 p.
- 1968, Evolution of the ultramafic complexes of northwestern New England, in Zen, E-an, White, W. S., and Hadley, J. B., eds., *Studies of Appalachian Geology—northern and maritime*: New York, Intersci. Publishers, p. 343-354.
- Chidester, A. H., and Cady, W. M., 1972, Origin and emplacement of alpine-type ultramafic rocks: *Nature Phys. Sci.*, v. 240, p. 27-31.
- Church, W. R., and Stevens, R. K., 1971, Early Paleozoic ophiolite complexes of Newfoundland Appalachians as mantle-ocean crust sequences: *Jour. Geophys. Research*, v. 76, p. 1212-1222.
- Clark, J. R., 1973, Petrology and geochemistry of the Seroyer Branch mafic-ultramafic complex, Chambers County, Alabama [abs.]: *Geol. Soc. America Abs. with Programs*, v. 5, no. 5, p. 387.
- Clark, R. H., and Fyfe, W. S., 1961, Ultrabasic liquids: *Nature*, v. 191, p. 158-159.
- Clark, S. P., and Ringwood, A. E., 1964, Density distribution and constitution of the mantle: *Jour. Geophysics*, v. 2, p. 35-88.
- Condie, K. C., and Madison, J. A., 1969, Compositional and volume changes accompanying progressive serpentinization of dunites from the Webster-Addie ultramafic body, North Carolina: *Am. Mineralogist*, v. 54, p. 1173-1179.
- Conley, J. F., and Henika, W. S., 1973, Geology of the Snow Creek, Martinsville East, Price, and Spray quadrangles, Virginia: Virginia Div. Mineral Resources Rept. Inv. 33, 71 p.
- Conrad, S. G., Wilson, W. F., Allen, E. P., and Wright, T. J., 1963, Anthophyllite asbestos in North Carolina: North Carolina Div. Mineral Resources Bull. 77, 61 p.
- Crickmay, G. W., 1952, Geology of the crystalline rocks of Georgia: Georgia Dept. Mines, Mining, and Geology Bull. 58, 54 p.
- Crowley, W. P., 1976, The geology of the crystalline rocks near Baltimore and its bearing on the evolution of the eastern Maryland Piedmont: Maryland Geol. Survey Rept. Inv. 27, 40 p.
- Dallmeyer, R. D., 1975, Incremental $^{40}\text{Ar}/^{39}\text{Ar}$ ages of biotite and hornblende from retrograded basement gneisses of the southern Blue Ridge: Their bearing on the age of Paleozoic metamorphism: *Am. Jour. Sci.*, v. 275, p. 444-460.
- Den Tex, E., 1969, Origin of ultramafic rocks, their tectonic setting and history: A contribution to the discussion of the paper "The origin of ultramafic and ultrabasic rocks" by P. J. Wyllie: *Tectonophysics*, v. 7, p. 457-488.
- De Roever, W. P., 1957, Sind die Alpinotypen Peridotitmassen vielleicht tektonisch verfrachtete Bruchstücke der Peridotitschale?: *Geol. Rundschau*, v. 46, p. 137-146.
- Dewey, J. F., 1976, Ophiolite obduction: *Tectonophysics*, v. 31, p. 93-120.
- Dewey, J. F., and Bird, J. M., 1971, Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland: *Jour. Geophys. Research*, v. 76, p. 3197-3207.
- Dickey, J. B., ms, 1963, Geology of Barton Creek area, northern Wake County, North Carolina: M.S. thesis, North Carolina State College of The University of North Carolina at Raleigh, Dept. Mineral Industries, 55 p.
- Dribus, J. R., Godson, W. L., Hahn, K. R., Kammer, T. W., Lawton, D. L., Pesch, H. G., Schick, J. T., and Tata, S. S., 1976, Comparative petrography of some alpine ultramafic plutons in western North Carolina: Norman, Okla., The Compass of Sigma Gamma Epsilon, v. 53, p. 33-45.
- Dribus, J. R., Heimlich, R. A., and Palmer, D. F., 1977, Petrology and petrofabric analysis of the deposit No. 9 dunite, Macon County, North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 9, p. 135.
- Espenshade, G. H., 1972, Geology of the Moxie pluton in the Mooshead Lake-Jo-Mary Mountain area, Piscataquis County, Maine: U.S. Geol. Survey Bull. 1340, 40 p.
- Espenshade, G. H., Rankin, D. W., Shaw, K. W., and Neuman, R. B., 1975, Geologic map of the east half of the Winston-Salem quadrangle, North Carolina-Virginia: U.S. Geol. Survey Misc. Geol. Inv. Map I-709B, scale 1:250,000.
- Fullagar, P. D., 1971, Age and origin of plutonic intrusions in the Piedmont of the southeastern Appalachians: *Geol. Soc. America Bull.*, v. 82, p. 2845-2862.
- Fullagar, P. D., and Butler, J. R., 1977, Carolinas corridor geotraverse and the evolution of the southern Appalachians [abs.]: *Geol. Soc. America Abs. with Programs*, v. 9, p. 137.
- Fullagar, P. D. and Odom, A. L., 1973, Geochronology of Precambrian gneisses in the Blue Ridge Province of northwestern North Carolina and adjacent parts of Virginia and Tennessee: *Geol. Soc. America Bull.*, v. 84, p. 3065-3080.

- Georgia Geological Survey, 1976, Geologic Map of Georgia: Atlanta, Ga., Georgia Geol. Survey, 1:500,000.
- Glover, Lynn, III, and Sinha, A. K., 1973, The Virgilina deformation: a late Precambrian to early Cambrian (?) orogenic event in the central Piedmont of Virginia and North Carolina: *Am. Jour. Sci.*, v. 273-A, p. 234-251.
- Glover, Lynn, III, Sinha, A. K., Higgins, M. W., and Kirk, W. S., 1971, U-Pb dating of Carolina slate belt and Charlotte belt rocks, Virgilina district, Virginia and North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 3, p. 313.
- Green, D. H., 1967, High-temperature peridotite intrusions, in Wyllie, P. J., ed., *Ultramafic and related rocks*: New York, John Wiley and Sons, p. 212-222.
- Green, D. H., and Ringwood, A. E., 1964, Fractionation of basalt magmas at high pressures: *Nature*, v. 201, p. 1276-1279.
- Greenberg, J. K., 1976, The alpine ultramafic problem in the southern Appalachians: the Webster-Addie dunite [abs.]: *Geol. Soc. America Abs. with Programs*, v. 8, p. 185.
- Griffin, V. S., Jr., 1969, Migmatitic Inner Piedmont belt of northwestern South Carolina: *South Carolina State Devel. Board Div. Geology Geol. Notes*, v. 13, p. 87-104.
- 1972, Progress report on a geologic study in Abbeville and McCormick Counties, South Carolina: *South Carolina State Devel. Board Div. Geology Geol. Notes*, v. 16, p. 59-78.
- Hadley, J. B., 1945, A preliminary report on corundum deposits in the Buck Creek peridotite, Clay County, North Carolina: *U.S. Geol. Survey Bull.* 948-E, p. 103-128.
- 1970, The Ocoee Series and its possible correlatives, in Fisher, G. W., and others eds., *Studies of Appalachian Geology—central and southern*: New York, Intersci. Publishers, p. 247-259.
- 1973, Igneous rocks of the Oxford area, Granville County, North Carolina: *Am. Jour. Sci.*, v. 273-A, p. 217-233.
- Hadley, J. B., and Nelson, A. E., 1971, Geologic map of the Knoxville quadrangle, North Carolina, Tennessee, and South Carolina: *U.S. Geol. Survey Misc. Geol. Inv. Map I-654*, 1:250,000.
- Hartley, M. E., III, 1973, Ultramafic and related rocks in the vicinity of Lake Chatuge: *Georgia Geol. Survey Bull.*, 85, 61 p.
- Hartley, M. E., III, and Penley, H. M., 1974, The Lake Chatuge Sill outlining the Brasstown antiform: *Georgia Geol. Soc. Guidebook* 13, 27 p.
- Hatcher, R. D., Jr., 1969, Stratigraphy, petrology, and structure of the low rank belt and part of the Blue Ridge of northwesternmost South Carolina: *South Carolina State Devel. Board Div. Geology Geol. Notes*, v. 13, p. 105-141.
- 1970, Geology of the Long Creek soapstone body, Oconee County, South Carolina: *South Carolina State Devel. Bd. Div. Geology Geol. Notes*, v. 14, p. 49-55.
- 1971, The geology of Rabun and Habersham counties, Georgia: *Georgia Geol. Survey Bull.* 83, 48 p.
- 1972, Developmental model for the southern Appalachians: *Geol. Soc. America Bull.*, v. 83, p. 2735-2760.
- 1973, Basement versus cover rocks in the Blue Ridge of northeast Georgia, northwestern South Carolina, and adjacent North Carolina: *Am. Jour. Sci.*, v. 273, p. 671-685.
- 1974, An introduction to the Blue Ridge tectonic history of northeast Georgia: *Georgia Geol. Soc. Guidebook* 13-A, 60 p.
- 1976, Introduction to the geology of the eastern Blue Ridge of the Carolinas and Georgia: *Carolina Geol. Soc. Field Trip Guidebook*, 53 p.
- Hearn, F., Heron, S. D., III, Schumaker, D., and Swanson, S. E., 1977, Petrology of the Rich Mountain alpine ultramafic, Watauga Co., North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 9, p. 147-148.
- Henika, W. S., 1971, Geology of the Bassett quadrangle, Virginia: *Virginia Div. Mineral Resources Rept.* Inv. 16, 43 p.
- Hermes, O. D., 1968, Petrology of the Mecklenburg gabbro-metagabbro complex, North Carolina: *Contr. Mineralogy Petrology*, v. 18, p. 270-294.
- Hess, H. H., 1933, Hydrothermal metamorphism of an ultrabasic intrusive at Schuyler, Virginia: *Am. Jour. Sci.*, 5th ser., v. 26, p. 377-408.
- 1939, Island arcs, gravity anomalies and serpentine intrusions: *Internat. Geol. Cong. Moscow 1937, Rept.* 17, v. 2, p. 263-283.
- 1955, Serpentine, orogeny, and epeirogeny: *Geol. Soc. America Spec. Paper* 62, p. 391-408.
- Hopkins, O. B., 1914, Asbestos, talc and soapstone deposits of Georgia: *Georgia Geol. Survey Bull.* 29, 319 p.

- Hunter, C. E., 1941, Forsterite olivine deposits of North Carolina and Georgia: North Carolina Div. Mineral Resources Bull. 41, 117 p.
- Hunter, C. E., Murdock, T. G., and MacCarthy, G. R., 1942, Chromite deposits of North Carolina: North Carolina Div. Mineral Resources Bull. 42, 39 p.
- Hurst, V. J., 1955, New evidence of volcanism in Georgia [abs.]: Georgia Acad. Sci. Bull., v. 13, p. 57.
- 1973, Geology of the southern Blue Ridge belt: Am. Jour. Sci., v. 273, p. 643-670.
- Hurst, V. J., and Jones, L. M., 1973, Origin of amphibolites in the Cartersville-Villa Rica area, Georgia: Geol. Soc. America Bull., v. 84, p. 905-912.
- Jackson, E. D., 1961, Primary textures and mineral associations in the ultramafic zone of the Stillwater Complex, Montana: U.S. Geol. Survey Prof. Paper 358, 106 p.
- Jackson, E. D., and Thayer, T. P., 1972, Some criteria for distinguishing between stratiform, concentric and alpine peridotite-gabbro complexes: Internat. Geol. Cong., 24th, Montreal 1972, Sec. 2, p. 289-296.
- Jahns, R. H., 1967, Serpentinities of the Roxbury District, Vermont, in Wyllie, P. J., ed., Ultramafic and related rocks: New York, John Wiley & Sons, p. 137-167.
- Johannes, W., 1968, Experimental investigation of the reaction forsterite + H_2O = serpentine + brucite: Contr. Mineralogy Petrology, v. 19, p. 309-315.
- 1969, An experimental investigation of the system $\text{MgO-SiO}_2\text{-H}_2\text{O-CO}_2$: Am. Jour. Sci., v. 267, p. 1083-1104.
- Jones, L. M., Hartley, M. E., III, and Walker, R. L., 1973, Strontium isotope composition of alpine-type ultramafic rocks in the Lake Chatuge district, Georgia-North Carolina: Contr. Mineralogy Petrology, v. 38, p. 321-327.
- Jones, L. M., Hurst, V. J., and Walker, R. L., 1973, Strontium isotope composition of amphibolite of the Cartersville-Villa Rica District, Georgia: Geol. Soc. America Bull., v. 84, p. 913-918.
- Karig, D. E., 1971, Origin and development of marginal basins in the western Pacific: Jour. Geophys. Research, v. 76, p. 2542-2561.
- Keith, A., 1903, Description of the Cranberry quadrangle (N.C.-Tenn.): U.S. Geol. Survey Geol. Atlas, Folio 116, 10 p.
- Keith, A., and Sterrett, D. B., 1931, Description of the Gaffney and Kings Mountain quadrangles, South Carolina-North Carolina: U.S. Geol. Survey Geol. Atlas, Folio 222, 13 p.
- Kennedy, M. J., and Phillips, W. E., 1971, Ultramafic rocks of Burlington Peninsula, Newfoundland: Geol. Assoc. Canada Proc., v. 24, p. 35-46.
- King, E. G., Barny, R., Weller, W. W., and Pankratz, L. B., 1967, Thermodynamic properties of forsterite and serpentine: U.S. Bur. Mine Rept. Inv. 6962.
- King, P. B., 1955, A geologic section across the southern Appalachians: an outline of the geology in the segment of Tennessee, North Carolina, and South Carolina, in Russell, R. J., ed., Guides to southeastern geology: Boulder, Colo., Geol. Soc. America, p. 332-373.
- Kingsbury, R. H., and Heimlich, R. A., 1977, Petrology of a dunite pluton near Mica-ville, North Carolina [abs.]: Geol. Soc. America Abs. with Programs, v. 9, p. 154-155.
- Kish, S. A., and Fullagar, P. D., 1977, Plutonic history of the Inner Piedmont near Shelby, North Carolina [abs.]: Geol. Soc. America Abs. with Programs, v. 9, p. 155.
- Kitahara, S., Takenouchi, S., and Kennedy, G. C., 1966, Phase relations in the system $\text{MgO-SiO}_2\text{-H}_2\text{O}$ at high temperatures and pressures: Am. Jour. Sci., v. 264, p. 223-233.
- Kulp, J. L., and Brobst, D. A., 1954, Notes on the dunite and the geochemistry of vermiculite at the Day Book dunite deposit, Yancey County, North Carolina: Econ. Geology, v. 49, p. 211-220.
- Lamarche, R. Y., 1972, Ophiolites of southern Quebec, in The Ancient Lithosphere: Ottawa, Dept. Energy, Mines and Resources, Earth Physics Br., Pub. 42, pt. 3, p. 65-99.
- Lappin, M. A., 1967, Structural and petrofabric studies of the dunites of Almklovdaalen, Nordfjord, Norway, in Wyllie, P. J., ed., Ultramafic and related rocks: New York, John Wiley & Sons, p. 183-190.
- 1971, The petrofabric orientation of olivine and seismic anisotropy of the mantle: Jour. Geology, v. 79, p. 730-740.
- Larrabee, D. M., 1966, Map showing distribution of ultramafic and intrusive mafic rocks from northern New Jersey to eastern Alabama: U.S. Geol. Survey Misc. Geologic Inv. Map I-476, 1:500,000.

- Laurent, R., 1975, Occurrences and origin of the ophiolites of Southern Quebec, Northern Appalachians: *Canadian Jour. Earth Sci.*, v. 12, p. 443-455.
- Le Grand, H. E., Furcron, A. S., Carter, R. F., and Lendo, A. C., 1956, Geology and ground-water resources of central-east Georgia: *Georgia Geol. Survey Bull.* 64, 174 p.
- Lewis, J. V., 1896, Corundum and the basic magnesian rocks of Western North Carolina: *North Carolina Geol. Survey Bull.* 11, 107 p.
- Long, L. E., Kulp, J. L., and Eckelmann, F. D., 1959, Chronology of major metamorphic events in the southeastern United States: *Am. Jour. Sci.*, v. 257, p. 585-603.
- Mann, V. I., 1962, Bouguer gravity map of North Carolina: *Southeastern Geology*, v. 3, p. 207-220.
- Martin, B., 1971, Some comments on the processes of serpentinization from experimental and other work: *Geol. Soc. Australia Spec. Pub.* 3, p. 301-310.
- McSween, H. Y., Jr., 1970, Petrology of Charlotte and Kings Mountain belt rocks in northern Greenwood County, South Carolina: *South Carolina State Devel. Board Div. Geology Geol. Notes*, v. 14, p. 57-84.
- 1972, An investigation of the Dutchman's Creek gabbro, Fairfield County, South Carolina: *South Carolina Devel. Board Div. Geology Geol. Notes*, v. 16, p. 19-42.
- Medlin, J. H., 1969, Petrology of two mafic igneous complexes in the South Carolina Piedmont [abs.]: *Geol. Soc. America Abs. with Programs*, v. 1, p. 52.
- Medlin, J. H., and Hurst, V. J., 1967, Geology and mineral resources of the Bethesda Church area, Greene County, Georgia: *Georgia Geol. Survey Inf. Circ.* 35, 29 p.
- Merschat, C. E., and Wiener, L. S., ms, 1975, Provisional geologic map of the Ocoee Supergroup, southwestern North Carolina and southeastern Tennessee: *North Carolina Div. Mineral Resources Open File Map*, 1:500,000.
- Miller, R. M., 1953, The Webster-Addie ultramafic ring, Jackson County, North Carolina, and secondary alteration of its chromite: *Am. Mineralogist*, v. 38, p. 1134-1147.
- Moores, E. M., 1973, Geotectonic significance of ultramafic rocks: *Earth Sci. Rev.*, v. 9, p. 241-258.
- Murdock, T. C., and Hunter, C. E., 1946, The vermiculite deposits of North Carolina: *North Carolina Div. Mineral Resources Bull.* 50, 44 p.
- Naldrett, A. J., 1973, Nickel sulphide deposits—their classification and genesis, with special emphasis on deposits of volcanic association: *Canadian Mining Metall. Trans.*, v. LXXVI, p. 183-201.
- Neathery, T. L., 1968, Talc and anthophyllite asbestos deposits in Tallapoosa and Chambers counties, Alabama: *Alabama Geol. Survey Bull.* 90, 98 p.
- Neathery, T. L., and Tull, J. F., eds., 1975, Geologic profiles of the northern Alabama Piedmont: *University, Ala., Alabama Geol. Soc. Guidebook*, 13th Ann. Field Trip, 174 p.
- Nelson, W. A., 1962, Geology and mineral resources of Albemarle County: *Virginia Div. Mineral Resources Bull.* 77, 92 p.
- Neuhauser, K. R., 1973, A structural analysis of several alpine-type ultramafics [abs.]: *Geol. Soc. America Abs. with Programs*, v. 5, p. 424.
- Neuhauser, K. R., and Carpenter, J. R., 1971, A structural and petrographic analysis of the Bank's Creek (North Carolina) serpentinite: *Southeastern Geology*, v. 13, p. 151-165.
- Nicholls, I. A., and Ringwood, A. E., 1973, Effect of water on olivine stability in tholeiites and the production of silica saturated magmas in the island-arc environment: *Jour. Geology*, v. 81, p. 285-300.
- Nicolas, A., Bouchez, J. L., Boudier, F., and Mercier, J. C., 1971, Textures, structures and fabrics due to solid state flow in some European lherzolites: *Tectonophysics*, v. 12, p. 55-86.
- Nicolas, A., Boudier, E., and Boullier, A. M., 1973, Mechanisms of flow in naturally and experimentally deformed peridotites: *Am. Jour. Sci.*, v. 273, p. 853-876.
- North Carolina Geological Survey, 1958, Geologic Map of North Carolina: Raleigh, N.C., North Carolina Division of Mineral Resources, 1:500,000.
- Odom, A. L., and Fullagar, P. D., 1973, Geochronologic and tectonic relationships between the Inner Piedmont, Brevard Zone, and Blue Ridge belts, North Carolina: *Am. Jour. Sci.*, v. 273-A, p. 133-149.
- O'Hara, M. J., 1967, Mineral paragenesis in ultrabasic rocks, in Wyllie, P. J., ed., *Ultramafic and related rocks*: New York, John Wiley & Sons, p. 393-403.
- Overstreet, W. C., and Bell, H., III, 1965a, Geologic map of the crystalline rocks of South Carolina: *U.S. Geol. Survey Misc. Geol. Inv. Map* I-413, scale 1:250,000.
- 1965b, The crystalline rocks of South Carolina: *U.S. Geol. Survey Bull.* 1183, 126 p.

- Parker, J. M., III, 1952, Geology and structure of part of the Spruce Pine district, North Carolina: North Carolina Div. Mineral Resources Bull., v. 65, 26 p.
- 1968, Structure of easternmost North Carolina Piedmont: Southeastern Geology, v. 9, p. 117-131.
- Phyfer, D. W., and Carpenter, J. R., 1969, Geochemistry and petrology of the Day Book (NC) dunite [abs.]: Geol. Soc. America Abs. with Programs: v. 1, p. 62-63.
- Pratt, J. H., and Lewis, J. V., 1905, Corundum and the peridotites of western North Carolina: North Carolina Geol. Survey Bull. 1, 440 p.
- Ragan, D. M., 1967, The Twin Sisters dunite, Washington, *in* Wyllie, P. J., ed., Ultramafic and related rocks: New York, John Wiley & Sons, p. 160-167.
- 1969, Olivine recrystallization textures: Mineralog. Mag., v. 37, p. 238-240.
- Ragland, P. C. and Butler, J. R., 1972, Crystallization of the West Farrington pluton, North Carolina, U.S.A.: Jour. Petrology, v. 13, p. 381-404.
- Raleigh, C. B., 1967, Experimental deformation of ultramafic rocks and minerals, *in* Wyllie, P. J., ed., Ultramafic and related rocks: New York, John Wiley & Sons, p. 191-199.
- 1968, Mechanism of plastic deformation of olivine: Jour. Geophys. Research, v. 73, p. 5391-5406.
- Rankin, D. W., 1970, Stratigraphy and structure of Precambrian rocks in northwestern North Carolina, *in* Fisher, G. W., and others, eds., Studies of Appalachian Geology—central and southern: New York, Intersci. Publishers, p. 227-245.
- 1975, The continental margin of eastern North America in the southern Appalachians: The opening and closing of the Proto-Atlantic ocean: Am. Jour. Sci., v. 275-A, p. 298-336.
- 1976, Compositional variation of upper Precambrian and Cambrian metamorphosed basalt across the Blue-Green-Long axis of the U.S. Appalachians [abs.]: Geol. Soc. America Abs. with Programs, v. 8, p. 251.
- Rankin, D. W., Espenshade, G. H., and Neuman, R. B., 1972, Geologic map of the west half of the Winston-Salem quadrangle, N.C., Va., Tenn.: U.S. Geol. Survey Misc. Geol. Inv. Map I-709A, scale 1:250,000.
- Rankin, D. W., Espenshade, G. H., and Shaw, K. W., 1973, Stratigraphy and structure of the metamorphic belt in northwestern North Carolina and southwestern Virginia: a study from the Blue Ridge across the Brevard Fault zone to the Sauratown Mountains anticlinorium: Am. Jour. Sci., v. 273-A, p. 1-40.
- Rankin, D. W., Stern, T. W., Reed, J. C., Jr., and Newell, M. F., 1969, Zircon ages of felsic volcanic rocks in the Upper Precambrian of the Blue Ridge, Appalachian Mountains: Science, v. 166, p. 741-744.
- Reed, J. C., Jr., 1955, Catoclin Formation near Luray, Virginia: Geol. Soc. America Bull., v. 66, p. 871-896.
- 1964, Chemistry of greenstone of the Catoclin Formation in the Blue Ridge of central Virginia: U.S. Geol. Survey Prof. Paper 501-C, p. C69-C73.
- Reed, J. C., Jr., and Morgan, B. A., 1971, Chemical alteration and spilitization of the Catoclin greenstones, Shenandoah National Park, Virginia: Jour. Geology, v. 79, p. 526-548.
- Ringwood, A. E., 1975, Composition and petrology of the earth's mantle: N.Y., McGraw-Hill, 618 p.
- Rodgers, John, 1949, Evolution of thought on structure of middle and southern Appalachians: Am. Assoc. Petroleum Geologists Bull., v. 33, p. 1643-1654.
- Ross, C. S., Foster, M. D., and Myers, A. T., 1954, Origin of dunites and olivine-rich inclusions in basaltic rocks: Am. Mineralogist, v. 39, p. 693-737.
- Sailor, R. V., and Kuntz, M. A., 1973, Petrofabric and textural evidence for syntectonic recrystallization of the Buck Creek dunite, North Carolina [abs.]: Geol. Soc. America Abs. with Programs, v. 5, p. 791-792.
- Scarle, C. M., and Wyllie, P. J., 1967, Experimental redetermination of the upper stability limit of serpentine up to 3-kb pressure [abs.]: Am. Geophys. Union Trans., v. 48, p. 225.
- Sloan, E., 1908, Catalogue of the mineral localities of South Carolina: South Carolina Geol. Survey Bull. 2, ser. IV, 505 p.
- Sørensen, H., 1967, Metamorphic and metasomatic processes in the formation of ultramafic rocks, *in* Wyllie, P. J., ed., Ultramafic and related rocks: New York, John Wiley & Sons, p. 204-212.
- Spence, W. H., and Carpenter, P. A., III, 1976, Metallogenic zonation and a model for the development of the Piedmont of eastern North Carolina [abs.]: Geol. Soc. America Abs. with Programs, v. 8, p. 273-274.

- St. Julien, P., 1972, Appalachian structure and stratigraphy, Quebec: Internat. Geol. Cong., 24th, Montreal 1972, Field Excursion A56-C56, Guidebook, 35 p.
- Stevens, R. K., Strong, D. F., and Kean, B. F., 1974, Do some eastern Appalachian ultramafic rocks represent mantle diapirs produced above a subduction zone?: *Geology*, v. 2, p. 175-178.
- Stose, A. J., and Stose, G. W., 1957, Geology and mineral resources of the Gossan Lead District and adjacent areas in Virginia: Virginia Div. Mineral Resources Bull. 72, 233 p.
- Stuckey, J. L., 1965, North Carolina: its geology and mineral resources: North Carolina Div. Mineral Resources Econ. Paper, 550 p.
- Stuckey, J. L., and Conrad, S. G., 1958, Explanatory text for geologic map of North Carolina: North Carolina Dept. Cons. Devel. Bull. No. 71, 51 p.
- Stueber, A. M., 1969, Abundances of K, Rb, Sr and Sr isotopes in ultramafic rocks and minerals from western North Carolina: *Geochim. et Cosmochim. Acta*, v. 33, p. 543-553.
- Stueber, A. M., and Murthy, V. R., 1966, Strontium isotope and alkali element abundances in ultramafic rocks: *Geochim. et Cosmochim. Acta*, v. 30, p. 1243-1259.
- Swanson, S. E., and Raymond, L. A., 1976, Alteration of the Day Book dunite, Spruce Pine district, Western North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 8, p. 282.
- Taylor, H. P., Jr., 1967, The zoned ultramafic complexes of southeastern Alaska, in Wyllie, P. J., ed., *Ultramafic and related rocks*: New York, John Wiley & Sons, p. 97-121.
- Tennessee Geological Survey, 1966, Geologic Map of Tennessee (East sheet): Nashville, Tenn., Tennessee Div. Geology, 1:250,000.
- Thayer, T. P., 1960, Some critical differences between alpine-type and stratiform peridotite-gabbro complexes: Internat. Geol. Cong., 21st, Norden 1960, Rept., pt. 13, p. 247-259.
- 1966, Serpentinization considered as a constant metasomatic process: *Am. Mineralogist*, v. 51, p. 685-710.
- 1967a, Serpentinization considered as a constant metasomatic process: A reply: *Am. Mineralogist*, v. 52, p. 549-553.
- 1967b, Chemical and structural relations of ultramafic and feldspathic rocks in alpine intrusive complexes, in Wyllie, P. J., ed., *Ultramafic and related rocks*: New York, John Wiley & Sons, p. 222-239.
- Tilley, C. E., and Yoder, H. S., 1964, Pyroxene fractionation in mafic magma at high pressures and its bearing on basalt genesis: *Carnegie Inst. Washington Year Book* 63, p. 114-120.
- Tobisch, O. T., and Glover, L., III, 1971, Nappe formation in part of the southern Appalachian Piedmont: *Geol. Soc. America Bull.*, v. 82, p. 2209-2230.
- Trommsdorff, V., and Evans, B. W., 1972, Progressive metamorphism of antigorite schist in the Bergell tonalite aureole (Italy): *Am. Jour. Sci.*, v. 272, p. 423-437.
- Tull, J. F., 1978, Structural development of the Alabama Piedmont northwest of the Brevard zone: *Am. Jour. Sci.*, v. 278, p. 442-460.
- Upadhyay, J. D., Dewey, J. F., and Neale, E. R. W., 1971, The Betts Cove ophiolite complex, Newfoundland: Appalachian oceanic crust and mantle: *Geol. Assoc. Canada Proc.*, v. 24, p. 27-34.
- Virginia Geological Survey, 1963, Geologic Map of Virginia: Charlottesville, Va., Virginia Div. Mineral Resources, 1:500,000.
- Wagner, H. D., 1974, The York-Chester gabbro-metagabbro-amphibolite complex: *South Carolina Devel. Bd. Geol. Notes*, v. 18, p. 1-3.
- Waskom, J. D., and Butler, J. R., 1971, Geology and gravity of the Lilesville granite batholith, North Carolina: *Geol. Soc. America Bull.*, v. 82, p. 2827-2844.
- Williams, H., 1971, Mafic ultramafic complexes in western Newfoundland Appalachians and the evidence for their transportation: A review and interim report: *Geol. Assoc. Canada Proc.*, v. 24, No. 1, p. 9-25.
- Wilson, J. T., 1966, Did the Atlantic close and then reopen?: *Nature*, v. 211, p. 676-681.
- Wyllie, P. J., 1969, The origin of ultramafic and ultrabasic rocks: *Tectonophysics*, v. 7, p. 437-455.
- 1970, Ultramafic rocks and the upper mantle: *Mineralog. Soc. America Spec. Paper* 3, p. 3-32.
- Yurkovich, S. P., 1976, Petrology of the Corundum Hill alpine peridotite, Macon County, North Carolina [abs.]: *Geol. Soc. America Abs. with Programs*, v. 8, p. 306.