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PETROLOGY OF CORDIERITE- AND ALMANDINE-BEARING GRANITOID PLUTONS OF THE SOUTHERN APPALACHIAN PIEDMONT, U.S.A.

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Abstract

The most distinctive peraluminous granitoid plutons in the southern Appalachians are: (1) the Late Paleozoic Clouds Creek pluton (313 ± 2 *Ma*) in South Carolina, a composite body consisting of biotite and cordierite–biotite monzogranite and granodiorite, and (2) the Precambrian (?) cordierite–biotite granite pluton of Stumpy Point, North Carolina. The cordierite in both plutons is magmatic, with Na_2O contents of up to 1.5 wt. % and Fe/(Fe+Mg) = 0.42–0.52 in the Clouds Creek pluton and 0.56–0.81 in the Stumpy Point pluton. The biotites are siderophyllites with Fe/(Fe+Mg) = 0.65–0.78. Tourmaline, monazite and ilmenite are characteristic accessory minerals. Magnetite, a prominent early phase in the Clouds Creek pluton, was consumed in a subsequent reaction. An inclusion assemblage of almandine ($Alm_{80.3}Py_{10.2}Sp_{4.8}Gr_{4.7}$) + biotite ± cordierite in the Stumpy Point granite and andalusite-bearing autoliths in the Clouds Creek pluton record changing conditions in the magmas. Compared with the typical Late Paleozoic postmetamorphic calc–alkaline granitoid plutons of the region, the Clouds Creek has had more interaction with older crustal rocks rich in aluminum and boron.

Keywords: peraluminous granites, cordierite, almandine, Clouds Creek (South Carolina), Stumpy Point (North Carolina).

Sommaire

Les massifs granitiques hyperalumineux des Appalaches méridionales les plus distinctifs au point de vue minéralogique sont les plutons de Clouds Creek (en Caroline du sud) et de Stumpy Point (Caroline du Nord). Le premier, d'âge Paléozoïque supérieur (313 ± 2 *Ma*) et d'aspect composite, contient des unités granodioritiques et monzogranitiques à biotite et à biotite + cordiérite; le second, d'âge Précambrien(?) consiste en granite à cordiérite + biotite. Dans les deux cas, la cordiérite est primaire, magmatique; elle possède jusqu'à 1.5% de Na_2O (en poids). Son rapport Fe/(Fe + Mg) varie de 0.42 à 0.52 (à Clouds Creek) et de 0.56 à 0.81 (à Stumpy Point). Dans les biotites (plus précisément, des sidérophyllites), ce rapport varie de 0.65 à 0.78. Tourmaline, monazite et ilménite sont les accessoires caractéristiques. La magnétite, phase hâtive importante dans le pluton Clouds Creek, a été détruite par réaction. Une suite d'inclusions à grenat ($Alm_{80.3}Py_{10.2}Sp_{4.8}Gr_{4.7}$) + biotite ± cordiérite (Stumpy Point) et d'autolithes à andalousite (Clouds Creek) illustrent l'évolution du milieu magmatique. Comparé aux intrusions granitiques calco-alcalines postmétamorphiques typiques du Paléozoïque supérieur de la région, le massif de Clouds Creek montre les effets d'une interaction plus poussée avec un socle enrichi en Al et B.

(Traduit par la Rédaction)

Mots-clés: granites hyperalumineux, cordiérite, grenat almandin, Clouds Creek (Caroline du sud), Stumpy Point (Caroline du nord).

Introduction

Speer *et al.* (1980) reported that the Clouds Creek pluton, South Carolina, contains cordierite, but the extent and nature of the cordierite-bearing granitoid rocks were unknown. Subsequent study of the field relations, petrography and mineral chemistry of the Clouds Creek pluton, described in this paper, revealed a prominent facies containing magmatic cordierite. A few other Late Paleozoic, postmetamorphic, coarse grained granitoid plutons of the southern Appalachians are peraluminous, but the Clouds Creek is conspicuous in its distinctive mineralogy and mineral chemistry.

Samples recovered from a drillhole near Stumpy Point, Dare County, North Carolina, examined as part of a study of the crystalline basement underlying the Atlantic Coastal Plain, were found to be almandine + cordierite + biotite granite. Texturally, the rock appears to be postmetamorphic, but a whole-rock, model Rb–Sr isotopic age of 924 ± 24 *Ma* has been reported (Daniels & Zietz 1978). In this article, these two cordierite-bearing granitic plutons in the southern Appalachians are described, although (1) the available data suggest that the rocks at Stumpy Point are *not* the product Late Paleozoic magmatism, and (2) its geological setting is hidden under 1.8 km of Coastal Plain sediments.

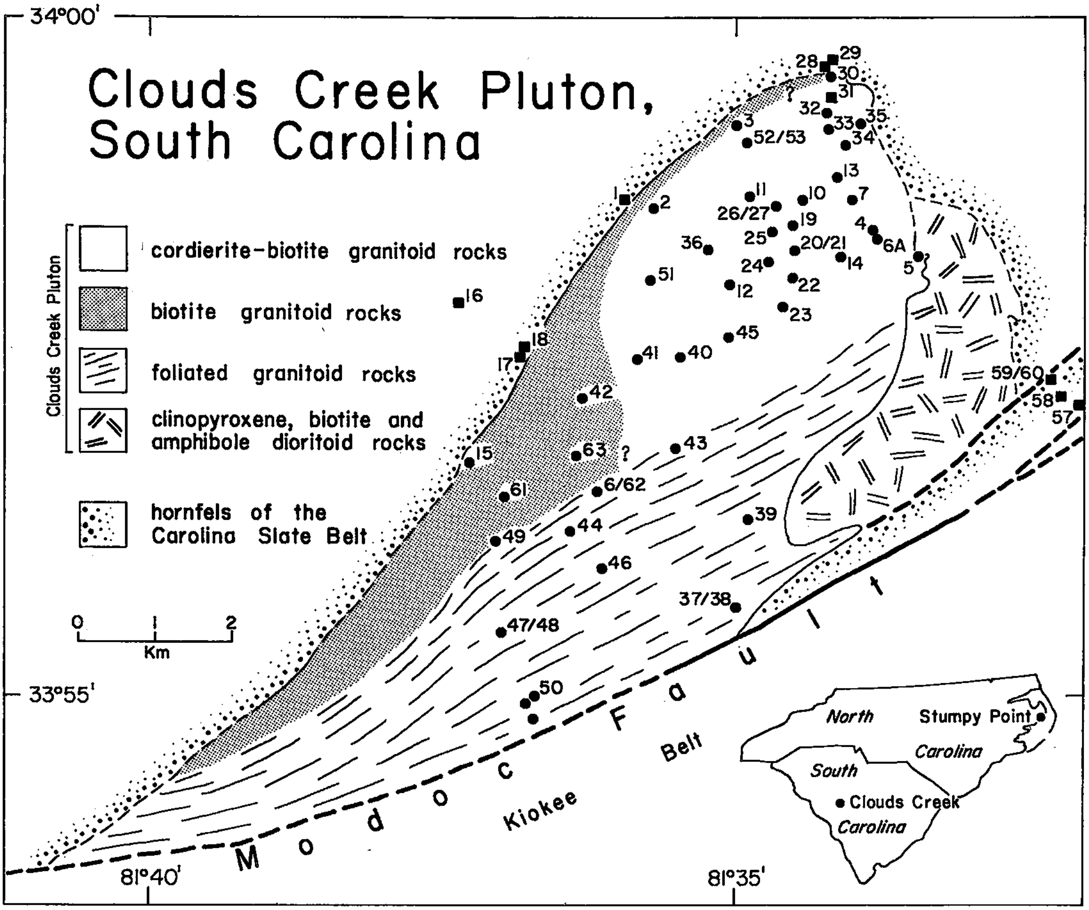

FIG. 1. Map of the Clouds Creek pluton, Saluda County, South Carolina, showing distribution of rock facies (modified from Secor & Snoke 1978, Plate 2) and localities of samples used for microprobe studies, presented in Tables 1 to 12. The index map includes the location of the Stumpy Point almandine + cordierite + biotite granite encountered in the Cities Service Westvaco well 1A, Dare County, North Carolina.

PETROGRAPHY

Clouds Creek pluton

The Clouds Creek pluton crops out in an elongate, elliptical area of approximately 50 km^2 in Saluda County, South Carolina (Fig. 1). It was first mapped as a discrete pluton by Overstreet & Bell (1965a, b). Field relations and the geological setting were reported by Secor & Snoke (1978). Earlier petrographic descriptions are given in Sloan (1908), Watson (1910) and Wagener (1977). Fullagar & Butler (1979) reported a Rb–Sr isotopic age of 313 ± 2 *Ma* with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7099 ± 0.0001. An interpretation of the aeroradioactivity and aeromagnetic survey of the area is given by Daniels (1971).

The Clouds Creek pluton intruded the Carolina slate belt (Fig. 1). Country rocks adjacent to the pluton are metamudstones, metasiltstones and metagreywackes of the Cambrian(?) Richtex Formation. The intrusive contacts are sharp and generally parallel the regional foliation of the country rocks, but are locally discordant. On its southern border, the pluton is bounded by augen gneisses of the Kiokee belt, which are separated from the Clouds Creek by the Modoc fault zone.

The Carolina slate-belt phyllites have undergone contact metamorphism within 0.5 km of the contact. The most evident change is textural. With increasing proximity to the pluton, the rock changes from fine grained phyllite to fine grained granoblastic hornfels spotted with aggregates of muscovite up to 2 mm in diameter. The regional metamorphic assemblage of the Carolina slate-belt phyllites is magnetite + epidote + biotite + phengitic muscovite + albite + quartz. The contact metamorphic assemblage is ilmenite + magnetite + biotite ± chlorite + muscovite + plagioclase (An_{30}) + quartz. Locally, the hornfels is dominated by muscovite + quartz. The texture, mineral assemblage and mineral chemistries of the hornfelses are comparable to the hornfels produced in phyllites of the Carolina slate belt in contact aureoles of other postmetamorphic granitic plutons of the southern Appalachians. The abundance of muscovite-rich rocks in the aureole suggests widespread metasomatism of the hornfels, presumably by the granite.

The Clouds Creek is a composite pluton, which Secor & Snoke (1978) have divided into two parts: (1) a megacrystic granitoid body ranging from massive to gneissic and (2) a heterogeneous mafic complex of biotite–amphibole quartz diorite on the eastern edge of the pluton (Fig. 1). Many of the amphiboles in the mafic complex either are pseudomorphs of earlier pyroxenes or contain clinopyroxene cores, which indicates that the rocks were originally gabbroic. Consanguinity and the age relationship of the two rock types are problematical because of the limited exposure. Only the granitoid rocks are discussed here. The megacrystic granitoid body has three mappable facies: (1) massive, biotite-bearing granitoid rocks, (2) massive, cordierite–biotite-bearing granitoid rocks and (3) foliated biotite- or cordierite–biotite-bearing granitoid rocks (Fig. 1).

The massive, biotite-bearing rocks occur along the western border of the pluton. The area covered by this facies ranges up to 2 km wide and narrows to less than 0.5 km on the northern contact. The massive, cordierite–biotite granitoid facies occupies the core of the northern half of the pluton. The contact between the biotite and cordierite–biotite granitoid facies is gradational. Both facies have the same general appearance in that they are subhedral-inequigranular, coarse grained, blue-grey rocks with blocky, subhedral megacrysts of grey alkali feld-

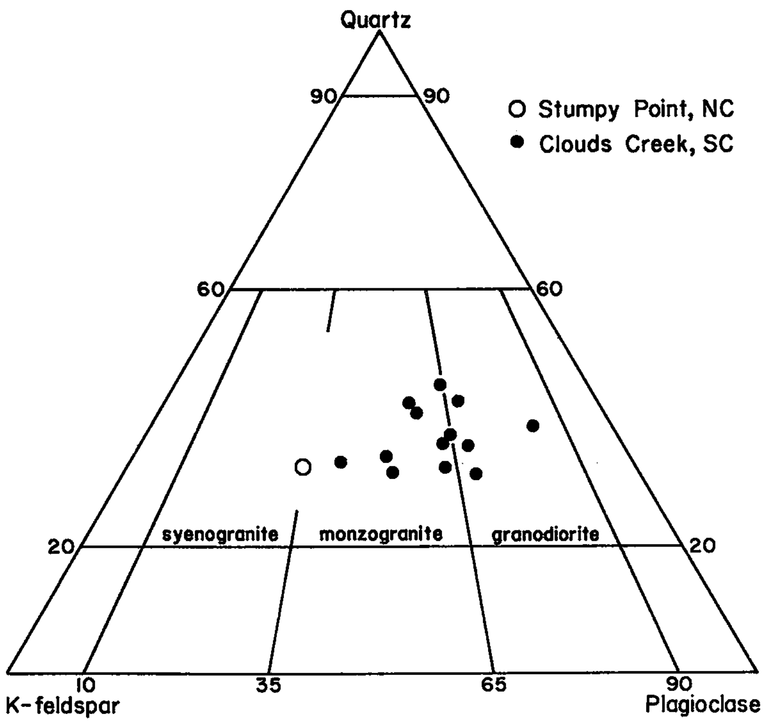

FIG. 2. Modal distribution of quartz, alkali feldspar and plagioclase in the Clouds Creek and Stumpy Point plutons. Rock names are those recommended by the I.U.G.S. subcommission on the Systematics of Igneous Rocks classification.

spar up to 4 cm long. Modal analyses of stained slabs and thin sections show that they are monzogranites and granodiorites with a color index between 9 and 15 (Fig. 2). Near the contacts of the pluton, the massive granitoid facies contains fewer and smaller alkali feldspar megacrysts. This gives the rock a more equigranular appearance. Biotite occurs as subhedral flakes 2 mm or less in size. Commonly, biotite is replaced or rimmed by a finer grained aggregate of recrystallized biotite. Cordierites of the cordierite–biotite granitoid facies are waxy, blue-green, sector-twinned prisms up to 3 mm long and comprise between 1 and 5 modal % of the rock. Accessory epidote, allanite and titanite are largely confined to the biotite granitoid rocks. Ilmenite is the major opaque phase, but magnetite is widespread. Much of the original magnetite has been consumed in subsequent reactions. The former abundance of magnetite is indicated bv skeletons of the exsolved ilmenite. Other primary accessory minerals include apatite, tourmaline, zircon, pyrite, chalcopyrite and monazite. Secondary minerals include chlorite, muscovite, kaolinite, rutile, epidote, calcite and titanite as rims on ilmenite.

Rocks of the foliated granitoid facies occupy the southeastern third of the pluton adjacent to the Modoc fault zone. They are diverse in appearance, varying from gneissic granitic rock, protomvlonite, or porphyroclastic mylonite to a lineated blastomylonite. The foliation is defined by oriented biotite and elongated ovoid feldspar and quartz porphyroclasts. The feldspars are broken in the less-deformed rocks. The deformational effects gradually increase, though not uniformly, towards the Modoc fault. As shown in many outcrops, the deformation was heterogeneous, because augen and lineated gneisses are associated with macroscopically undeformed megacrystic granitoid rocks. The extreme southeastern corner of the pluton is composed of relatively undeformed cordierite–biotite granite (locality 38, Fig. 1). The primary mineralogy of the foliated granitoid facies includes biotite, cordierite, plagioclase, alkali feldspar and quartz, with accessory ilmenite, magnetite, apatite, zircon and pyrite. Secondary minerals contemporaneous with the deformation include rare to abundant epidote and muscovite and subordinate chlorite, titanite, barite and allanite. The primary biotite is commonly recrystallized, with a differing composition, as discussed below. Whether or not cordierite was originally present cannot be determined in every case because of the difficulty in recognizing deformed and pinitized cordierites.

Only two rock analyses have been published for the Clouds Creek pluton. One is a biotite granitoid rock from the Praetor quarry (locality 63, Fig. 1; Sloan 1908); the other is an average of four rock analyses for which locations are not given (Fullagar & Butler 1979). The rocks are corundum-normative, with 3.1 and 3.6 wt. % corundum, and the molar ratio $Al_2O_3/(CaO+Na_2O+K_2O)$ is 1.41 and 1.51, respectively. The Fe/(Fe+Mg) ratios are 0.71 and 0.68.

Several types of enclaves can be distinguished in the Clouds Creek pluton. Xenoliths of rocks from the adjacent Carolina slate belt are the most readily identifiable. They are subangular to rounded and range up to 0.5 m in diameter. They consist of laminated biotite + muscovite + plagioclase + quartz hornfels. These enclaves resemble the hornfelses of the aureole except that they are coarser grained and contain more biotite. Less common in the Clouds Creek pluton are xenoliths of amphibolite and vein quartz.

A second type of enclave consists of melanocratic, microgranular cordierite–biotite granodiorite that contains subhedral phenocrysts of quartz and compositionally and texturally zoned plagioclase up to 2 cm in length. These are rounded enclaves up to 0.25 m in diameter. The groundmass consists of grains up to 2 mm across of biotite + cordierite + plagioclase (An_{29}) + alkali feldspar + quartz. The cordierite is generally subhedral and rimmed either by quartz or by a graphic intergrowth of quartz + cordierite. These composite grains range up to 0.5 cm in diameter. They resemble the graphic intergrowths of cordierite and quartz described by Shibata (1936) and are similarly believed to result from simultaneous crystallization rather than replacement of an earlier phase, as described by Henry (1974) and van Reenen and du Toit (1978) for vermicular quartz + cordierite symplectites. The groundmass of the enclaves is dominated by unoriented laths of plagioclase and biotite, which gives the groundmass a bostonitic texture. Accessory minerals include muscovite, magnetite, ilmenite, apatite and monazite. An additional, scarce poikilitic mineral pseudomorphed by kaolinite has a habit that suggests andalusite. Unlike xenoliths derived from the Carolina slate belt, the mineralogy and mineral compositions of these microgranular enclaves are similar to those of the enclosing granitoid rocks; they differ only in texture and modal abundances. These microgranular enclaves could have several origins: (1) autoliths of an early crystallizing facies, (2) xenoliths that have been subjected to a higher grade of metamorphism and have equilibrated with the enclosing magma, or (3) restites from the site of magma generation.

Stumpy Point pluton

The cordierite–biotite granite from Stumpy Point, Dare County, North Carolina (Fig. 1), is the crystalline basement encountered in the Cities Service Westvaco well no. 1A completed in September 1971. The drillhole is located at 35°39′36″N, 75°46′40″W (Coffey 1977). Basement was encountered at 1862.9 m (6112 ft) and total depth is 1916.6 m (6288 ft). A continuous core sample 10 cm in diameter was taken between 1900.7 (6236 ft) and 1907.7 m (6259 ft). This petrological study is based on six sections of core, each 5 cm long, taken from depths of 6236, 6243, 6248, 6253, 6256 and 6257 feet, which are also the sample numbers.

The Stumpy Point granite is grey-green with an anhedral-inequigranular texture. Most grains are smaller than 7 mm, but subhedral megacrysts of quartz up to 1 cm, plagioclase up to 2.5 cm and alkali feldspar up to 1.5 cm occur locally. A composite modal analysis of 1462 points, located on a 5 x 5 mm grid on stained

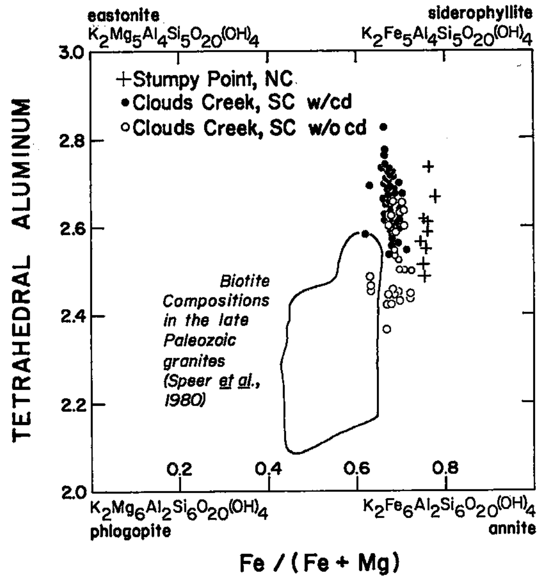

FIG. 3. Biotite compositions from the Clouds Creek and Stumpy Point plutons (Table 1) projected onto the phlogopite–annite–eastonite–siderophyllite field. Solid circles refer to biotites coexisting with cordierite (w/cd); open circles refer to biotites in rocks without cordierite (w/o cd).

TABLE 13. SUMMARY OF MICROPROBE ANALYSES OF THE FERROMAGNESIAN MINERALS: CLOUDS CREEK PLUTON, S. C., AND STUMPY POINT GRANITE, N. C.

	Clouds Creek biotites					Stumpy Point granite
	cordierite-biotite granites		biotite granites		microgranular enclaves	
	original	recrystallized	original	recrystallized		biotite
SiO_2	34.33(0.96)***	35.32(0.66)	34.38(0.41)	35.53(0.61)	34.68(0.68)	34.01(1.31)
TiO_2	3.53(0.95)	1.88(0.52)	2.73(0.39)	1.67(0.62)	3.54(0.56)	2.29(0.99)
Al_2O_3	16.97(0.41)	16.87(0.33)	16.76(0.26)	17.05(0.44)	17.44(0.66)	20.08(1.50)
FeO*	24.36(1.26)	25.42(1.44)	25.80(0.76)	25.37(1.10)	23.51(0.77)	23.80(1.10)
MnO	0.30(0.05)	0.30(0.07)	0.33(0.04)	0.33(0.05)	0.22(0.05)	0.17(0.04)
MgO	6.48(0.45)	6.84(0.58)	6.62(0.35)	6.59(0.53)	6.49(0.46)	4.38(0.23)
CaO	0.01(0.01)	0.02(0.02)	0.08(0.03)	0.04(0.03)	0.03(0.03)	0.06(0.04)
BaO	0.18(0.17)	0.21(0.23)	0.27(0.11)	0.20(0.18)	0.13(0.14)	0.22(0.21)
Na_2O	0.10(0.05)	0.04(0.03)	0.05(0.01)	0.05(0.02)	0.09(0.03)	0.12(0.05)
K_2O	9.72(0.36)	9.69(0.45)	9.49(0.29)	9.66(0.26)	9.71(0.32)	8.86(0.36)
F	0.33(0.23)	0.27(0.12)	0.31(0.08)	0.16(0.16)	0.45(0.13)	0.11(0.11)
Cl	0.13(0.07)	0.13(0.08)	0.17(0.04)	0.10(0.07)	0.16(0.02)	0.04(0.01)
H_2O**	3.65	3.69	3.64	3.75	3.60	3.73
Total	100.08	100.69	100.62	100.50	100.04	97.86
O ≡ F+Cl	0.17	0.14	0.17	0.09	0.22	0.06
Total	99.92	100.55	100.45	100.41	99.82	97.81
Fe/(Fe+Mg)	0.681(0.004)	0.678(0.005)	0.689(0.005)	0.686(0.007)	0.672(0.007)	0.755(0.002)
Number of analyses	43	.10	10	22	16	12

	Clouds Creek cordierites		Stumpy Point granite	
	cd.-bt. granite	microgranular enclave	cordierite	garnet
SiO_2	47.74(0.61)	48.19(0.20)	46.49(1.07)	37.57
TiO_2	0.01(0.02)	0.00(0)	0.00(0)	0.00
Al_2O_3	32.48(0.61)	31.82(0.29)	31.11(0.58)	20.52
FeO*	9.78(0.32)	10.33(0.48)	14.34(1.20)	35.29
MnO	0.50(0.07)	0.51(0.06)	0.36(0.06)	2.10
MgO	6.32(0.34)	6.23(0.38)	3.39(1.07)	2.51
CaO	0.00(0)	0.02(0.02)	0.01(0.01)	1.60
Na_2O	0.69(0.22)	0.66(0.35)	1.12(0.27)	0.00
K_2O	0.00(0)	0.01(0.01)	0.01(0.02)	0.02
Total	97.56	97.79	96.85	99.56
Fe/(Fe+Mg)	0.477	0.494	0.709	0.887
Number of analyses	16	8	8	2

* Total iron expressed as FeO. ** Calculated to give 24(O,F,Cl,OH). *** Number in parentheses is the standard deviation.

slabs of all samples, shows that the rock is a leucocratic syenogranite (Fig. 2) with quartz = 30.8%, alkali feldspar = 42.9%, plagioclase = 22.2% and a color index of 4.1. Mafic minerals are biotite, cordierite and almandine garnet. Cordierite, which occurs as sector-twinned euhedral to subhedral prisms up to 2 mm long, is extensively altered to chlorite + muscovite. Garnet occurs as anhedral grains 0.1 mm or less in diameter included in some of the larger plagioclase crystals. Biotite occurs as an included phase in plagioclase as well as in the matrix. Accessory minerals include apatite, fluorite, ilmenite, monazite, sphalerite, tourmaline, titanite, uraninite and zircon. Secondary minerals include calcite, chlorite, epidote, muscovite and rutile. The density of the rock is 2.65 g cm^{-1}.

MINERALOGY

Biotite

The biotites in both plutons are pleochroic tan to brown and, where altered, are intergrown with chlorite, muscovite, rutile and alkali feldspar. Results of microprobe analyses (Table 1) show that the biotites lie in the siderophyllite quadrant of the phlogopite–annite–eastonite–siderophyllite projection (Fig. 3). Tables 1 to 12, in which are reported results of microprobe analyses, have been sent to the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Ontario K1A 0S2. A summary of average compositions for the ferromagnesian phases, biotite, cordierite and garnet, is given in Table 13.

In Table 13, averages of the Clouds Creek biotite analyses are grouped into biotites from the cordierite–biotite granites, biotite granites and microgranular enclaves. The rocks in the Clouds Creek pluton locally have undergone postconsolidation recrystallization as a result of subsolidus reactions as well as deformation in the foliated granitic facies. This recrystallization has produced secondary biotite, which forms unoriented, polycrystalline aggregates intergrown with ilmenite and rutile rimming or pseudomorphing the original biotite grain. The compositions of these secondary biotites are distinguished from the original biotites in Table 13. For the Clouds Creek biotites, the average $Fe_{total}/(Fe_{total}+Mg)$ is 0.68. The biotites have compositions uniformly near 0.68 but vary in tetrahedral cation composition, which results in vertical trends in the phlogopite–annite–eastonite–siderophyllite projection (Fig. 3). The least siliceous biotites, those containing the most tetrahedral aluminum, occur in rocks that contain cordierite, namely, the cordierite–biotite granite and microgranular enclaves (Fig. 3, Table 13). The biotites in the biotite granites are more silica-rich, but the most silica-rich are the recrystallized biotites. Another compositional distinction of the recrystallized biotites is their low titanium content. The higher titanium contents of the original biotites produce the intergrown ilmenite and rutile.

The biotites of the Stumpy Point granite are iron-rich; $Fe_{total}/(Fe_{total}+Mg)$ is 0.76. The range of tetrahedral aluminum contents is between 2.48 and 2.73 *per* 24(O,OH,Cl,F) and produces a vertical trend in the biotite quadrilateral (Fig. 3).

The biotites in the Clouds Creek and Stumpy Point plutons are more aluminous and more iron-rich than are biotites of the postmetamorphic, coarse grained granitoid rocks of the southeastern United States (Fig. 3). Biotites without coexisting cordierite in the Clouds Creek pluton overlap the biotite compositional field of these other granitoid rocks. A similar iron and aluminum compositional distinction of biotites coexisting with aluminous minerals has has been noted by de Albuquerque (1973) in sillimanite- and andalusite-bearing granites of northern Portugal and by Clarke *et al.* (1976) in the South Mountain batholith, Nova Scotia. The aluminous nature of these biotites would be anticipated from the coexisting cordierite or aluminum silicates and the presumed aluminum-rich nature of the melt from which they crystallized. In the case of the Clouds Creek pluton, the iron-rich nature of the biotite may be a result of reactions that consumed most of the magnetite.

Cordierite

In the Clouds Creek and Stumpy Point plutons, cordierite constitutes between 1 and 5 modal % of the rocks. It forms subhedral, sector-twinned prisms up to 3 mm long that are generally free of inclusions but locally contain zircon, biotite or opaque minerals. The cordierite is commonly replaced by a bright green, fine grained aggregate of chlorite + muscovite. Less commonly it is replaced by intergrown muscovite and biotite grains that are nearly the size of the original cordierite crystal. In rocks with fresh cordierite, the cordierite is partly replaced by a brown, nearly amorphous material with a composition suggestive of a chlorite + muscovite mixture. This brown material is probably a product of weathering. Results of microprobe analyses of the Clouds Creek cordierite (Tables 2, 13) show an average $Fe_{total}/(Fe_{total}+Mg)$ value of 0.48, with a variation of 0.42 to 0.52. Less than 3 mole % of the Mn end-member is present. The Stumpy Point cordierite is sekaninaite (Tables 2, 13), with an average $Fe_{total}/(Fe_{total}+Mg)$ value of 0.71 but a range of 0.56 to 0.81. Manganese content is less than 2 mole % of the Mn end-member. Unlike the cordierites of the Clouds Creek pluton, compositions of the unaltered sekaninaites from the Stumpy Point granite vary greatly within a single thin-section. No evidence of systematic zoning was found.

The analyses of cordierites have low totals of between 96 and 98% (Tables 2, 13), which suggest the presence of unanalyzed elements. Most of the additional weight is probably contributed by water in the channel sites. The cordierites of the Clouds Creek and Stumpy Point plutons contain up to 1.5 wt. % Na_2O, or 0.3 Na atoms *per* 18 oxygens. The sodium content of cordierites from quartz veins, pegmatites and granites ranges between 0.61 and 3.53 wt. % (Leake 1960, Flood & Shaw 1975). These values are higher than those of metamorphic cordierite, reported to have as high as 0.78 wt. % Na_2O but which have generally less than 0.5 (Leake 1960). The sum Fe + Mg + Mn is low, suggesting that vacancies in sites occupied by Fe + Mg + Mn balance the Na in the channel sites rather than the coupled substitution Na + Be = Al suggested by Schreyer *et al.* (1979).

Feldspars

The alkali feldspars in the Clouds Creek and Stumpy Point plutons are microcline microperthites. Results of microprobe analyses (Table 3) show that the exsolved phases of the alkali feldspars are nearly end-member compositions, at least as sodic and potassic as Ab_{98} and Or_{93}, respectively. The perthites in the Clouds Creek rocks are uniformly distributed string perthites up to 0.02 mm long and 0.001 mm wide. They are smaller than the perthites in other coarse grained granitoid plutons in the southeastern United States and permit a better estimate of the bulk composition of the alkali feldspar megacrysts: $Or_{75.8}Ab_{23.8}An_{0.3}Cn_{0.3}$.

The plagioclases of the Clouds Creek and Stumpy Point plutons have normal oscillatory zoning of An_{34} to An_{11}, with locally developed discontinuous rims of An_1. The sodic andesine and oligoclase have potassium feldspar contents of Or_{2-5} (Table 3), which is higher than the values of Or_1 or less in plagioclases of the coarse-grained granitoid rocks of the southern Appalachians (Speer *et al.* 1980). The plagioclases are locally altered to white mica + epidote + quartz ± calcite.

Garnet

The garnets of the Stumpy Point granite occur as clusters of 2 to 4 grains in the plagioclase. They are anhedral and range up to 0.25 mm in in diameter. Results of microprobe analyses (Tables 4, 13) show that they are almandine: $Alm_{80.3}Py_{10.2}Sp_{4.8}Gr_{4.7}$. These garnets differ from those in the other coarse grained granitoid plutons of the southern Appalachians, which are spessartine–almandine solid solutions in which the spessartine component exceeds 50% (Speer *et al.* 1980); however, the Stone Mountain pluton in Georgia is reported to contain an almandine-rich garnet (Whitney *et al.* 1976).

Accessory minerals

Ilmenite is at present the most abundant oxide mineral in the Clouds Creek and Stumpy Point rocks. The ilmenites are ilmenite–pyrophanite solid solutions with a small amount of the hematite component (Table 5). Ilmenites in the Clouds Creek granitoid facies range in composition from $(Mn_{0.117}Fe^{2+}_{0.951})(Fe^{3+}_{0.064}Ti_{0.936})O_3$ to $(Mn_{0.269}Fe^{2+}_{0.739})(Fe^{3+}_{0.020}Ti_{0.980})O_3$. Ilmenites in the microgranular enclaves are less manganiferous, with $Mn_{0.07}$, as are the ilmenites in the Stumpy Point granite. Titanites in the Clouds Creek pluton have variable compositions (Table 6), with substitution for TiO_2 ranging from 7.1 wt. % Fe_2O_3 to 5.2 wt. % Al_2O_3. Fluorine content is high: 1.4 to 2.3 wt. % F. Anhedral, pleochroic blue-brown tourmaline occurs in the aplite dykes and cordierite-bearing granitoid rocks of the Clouds Creek pluton. Anhedral tourmaline, color-zoned brown to green and attaining 1.5 mm in diameter, occurs in the Stumpy Point granite. Results of microprobe analyses (Table 7) show the tourmalines to be intermediate members of the series hydroxyl dravite–schorl, with $Fe_{total}/(Fe_{total}+Mg)$ between 0.5 and 0.6 and with Ca/(Ca+Na) less than 0.06. These plutons and the Stone Mountain pluton in Georgia are the only postmetamorphic granitoid plutons in the southern Appalachians known to contain tourmaline as an accessory phase. Colorless apatites are ubiquitous in the Clouds Creek and Stumpy Point plutons. Microprobe results (Table 8) show them to be fluorapatites with less than 0.2 wt. % substitution by Cl. A Cabearing thorium phosphate (brabantite or brockite?) was found in the Clouds Creek pluton.

Other secondary minerals

Secondary minerals in the Clouds Creek and Stumpy Point plutons include (in addition to the recrystallized biotite) chlorite, epidote, muscovite, rutile, ilmenite, kaolinite and calcite. The chlorites occur as alteration products of biotite and cordierite. Results of microprobe analyses of the Clouds Creek chlorites (Table 9) show them to be ripidolites and brunsvigites according to the classification of Hey (1954), with $Fe_{total}/(Fe_{total}+Mg)$ between 0.51 and 0.66. Chlorites in the Stumpy Point granite have a wider compositional range: $Fe_{total}/(Fe_{total}+Mg)$ is between 0.37 and 0.71 and tetrahedral silicon between 2.7 and 3.5 (Table 9).

Epidote occurs in all rock types of the Clouds Creek and Stumpy Point plutons as a product of saussuritization of plagioclase or in intergrowths with biotite. Epidote is rarer in the cordierite-bearing rocks, but locally euhedral crystals form in the chlorite + muscovite replacements of cordierite. Microprobe results for the Clouds Creek epidote (Table 10) show a range in composition between $Ps_{29.7}$ and $Ps_{14.8}$, with a manganese content between $Pt_{0.09}$ and $Pt_{1.6}$. Epidotes are normally colorless to pale green. Brown epidotes, which occur either as zones in otherwise colorless grains or as separate crystals, are solid solutions toward allanite, with up to 25% of the Ca replaced by rare-earth elements.

Muscovite occurs as anhedral flakes, 1 mm or smaller, intergrown with biotite, in saussuritized plagioclase, in altered cordierite and as vein fillings in fractured feldspars. Results of microprobe analyses (Table 11) show that the Clouds Creek white micas are phengitic, with an average Si content of 6.20 (range 5.70 to 6.45) atoms *per* 24(O,OH,F). Average Fe and Mg contents are 0.31 (range 0.10 to 0.57) and 0.16 (range 0.10 to 0.38) atoms. F content is less than 0.17. The muscovites are relatively sodic, with Na/(Na+K) ranging between 0.02 and 0.11 and with an average of 0.07. Compositions of the Stumpy Point muscovites (Table 11) are similar to those of the Clouds Creek white micas, with Si contents between 6.24 and 6.30, Fe contents between 0.14 and 0.17 and Mg contents between 0.11 and 0.15. F content is less than 0.09, and Na/(Na+K) is between 0.09 and 0.11.

Additional secondary minerals include rutile, which occurs as oriented rods in chloritized biotites, and ilmenite, which occurs as intergrowths in recrystallized biotites. Kaolinite(?) replaces a mineral thought to have been andalusite in the microgranular enclaves of the Clouds Creek pluton. Compositions of the kaolinite(?) are given in Table 12. Calcite occurs as a product of plagioclase saussuritization and is intergrown with biotite and epidote.

Discussion

The assemblage cordierite + biotite in the Clouds Creek and Stumpy Point plutons is believed to be magmatic and to have crystallized at the conditions of final emplacement. This conclusion is based on the euhedral shapes of the cordierites, their sodium contents and the aluminous compositions of the coexisting biotites, as compared with biotites in cordierite-free granitoid rocks both in the Clouds Creek and other postmetamorphic plutons of the southern Appalachians. In the Clouds Creek pluton, the widespread occurrence of cordierite-bearing granitoid rocks isolated within a border zone of biotite granitoid rocks makes it unlikely that cordierite xenocrysts or aluminous hornfels xenoliths from the adjacent Carolina slate belt were incorporated to produce the cordierite. A border zone lacking cordierite also suggests that the pluton has not become peraluminous by alkali loss to the immediate country rocks.

Crystallization of the Clouds Creek and Stumpy Point magmas was completed on the cordierite–biotite liquidus boundary. The cordierite + biotite crystallization assemblage is consistent with conditions for any of the regions below *ng3* (Fig. 4a) using the liquidus topology of Abbott & Clarke (1979). The intermediate to iron-rich composition of the AFM assemblage suggests conditions in the lower part of this pressure interval. Because neither garnet nor aluminum silicate was encountered during progressive crystallization, the biotite–cordierite crystallization assemblage suggests the topology of region *cef* (Fig. 4a). But the compositions of coexisting biotite–cordierite pairs (Fig. 4b) do not show sufficient chemical evolution to limit conditions of crystallization to the *cef* topology. The inclusions of almandine and biotite in the Stumpy Point plagioclases suggest that garnet + biotite was the crystallization assemblage during an earlier period in the history of the magma. Evolution from an almandine + biotite ± cordierite assemblage to a more magnesian cordierite + biotite assemblage can be achieved by a change in the AFM topology, indicating a drop in temperature, pressure, or both (Fig. 4a). Crystallization would have occurred somewhere along the path labeled Stumpy Point in Figure 4a. If the kaolinite in the microgranular enclaves of the Clouds Creek pluton is interpreted as a pseudomorph of andalusite, these enclaves would have crystallized with the assemblage andalusite + cordierite + biotite. This assemblage represents P–T conditions of regions *emng* or *ecjm* in Figure 4a, and the microgranular enclaves represent possible equilibria at pressures greater than the final level of emplacement.

The almandine garnets in the Stumpy Point granite have compositions comparable to the 2–6 mol % grossular and 2–10 mol % spessartine garnets in the silicic volcanic and plutonic rocks of eastern Australia (Green 1977). Based on experimental work, Green concluded that these garnets crystallized from a silicic magma at pressures of 5–7 kbar and are not stable at pressures of less than 4 kbar for aluminosilicate-free compositions. However, Clemens & Wall (1981) found that in their experiments, almandine garnet is stable to much lower pressures in a granitic melt. Lack of garnet in the Stumpy Point granite, not encountered as inclusions in plagioclase, indicates that the peritectic reaction garnet = cordierite + liquid (Abbott & Clarke 1979) consumed the matrix garnet during ascent and cooling of the magma (Fig. 4a). Preservation of garnets in the Australian rocks resulted from rapid quenching in the volcanic rocks and development of spessartine-rich rims on garnets in the plutonic rocks (Green 1977, Flood & Shaw 1977).

Final crystallization of the Clouds Creek and Stumpy Point magmas at conditions of region *cef* of Figure 4a would have several implications: (1) the plutons were emplaced at a relatively shallow level in the crust, probably between 1 and 2.5 kbar (Fig. 4a). This interval is a minimum estimate of emplacement pressure because the granites violate some of the assumptions used to construct Figure 4a: they have intermediate compositions of iron–magnesium phases, and the cordierite may behave as a hydrous phase (Newton & Wood 1979, Kurepin 1979). (2) These magmas would have had a

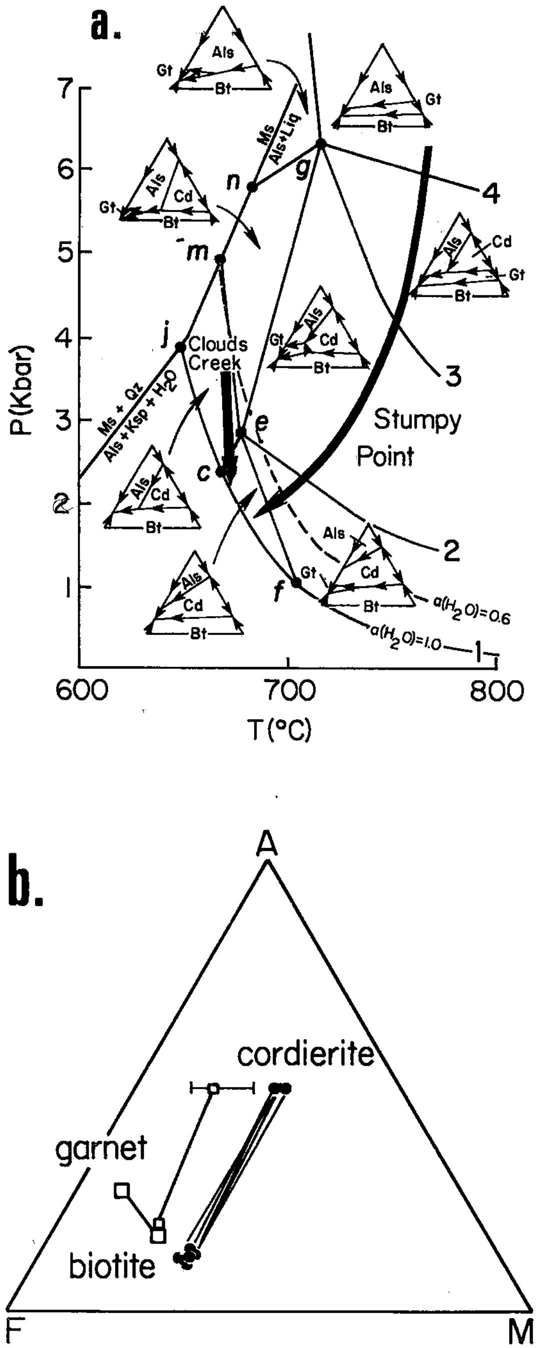

FIG. 4a. Regions of distinct AFM liquidus topologies in P–T space, from Abbott & Clarke (1979). The Clouds Creek and Stumpy Point plutons completed their crystallization on the cordierite–biotite liquidus boundary without encountering either garnet or an aluminum silicate. An inclusion assemblage of almandine + biotite with or without cordierite in the Stumpy Point granite suggests crystallization somewhere along the P–T path labeled Stumpy Point. The andalusite(?) + cordierite + biotite assemblage in enclaves of the Clouds Creek pluton suggests the Clouds Creek path. 4b. AFM projection from alkali feldspar for biotite, cordierite and garnet in the Clouds Creek pluton, S.C. (solid circles) and Stumpy Point, N.C. (open squares).

high partial pressure of water. This is reflected in the more extensive deuteric alteration of the Clouds Creek and Stumpy Point rocks compared with other postmetamorphic granitoid plutons in the southern Appalachians. In addition, fluid expelled from the crystallizing Clouds Creek magma could account for the probable retrogression in its contact aureole. (3) Figure 4a suggests that the muscovite in these cordierite-bearing rocks is not a magmatic phase, in accordance with the textural observations indicating that the muscovite is secondary. However, the rare biotite + muscovite pseudomorphs of cordierite may have crystallized at the four-phase peritectic reaction cordierite + liquid = biotite + muscovite suggested by Abbott & Clarke (1979).

The Clouds Creek and Stumpy Point plutons are mineralogically the most distinctive granitoid rocks in the southern Appalachians because of their cordierite. The Stumpy Point granite occurs in the region of a large, negative gravity anomaly where the rocks encountered beneath the Atlantic Coastal Plain are granites, biotite gneisses and schists (Denison *et al.* 1967, Daniels & Zietz 1978). It is included in the Hatteras belt of Daniels & Zietz. The Stumpy Point granite has a model whole-rock Rb–Sr isotopic age of 924 ± 40 *Ma* (Daniels & Zietz 1978). Isotopic ages of other rocks in the Hatteras belt range from Precambrian to Paleozoic (granites); the metamorphic rocks are Paleozoic (Denison *et al.* 1967, Daniels & Zietz 1978). The Stumpy Point granite does not appear to have undergone deformation.

The Late Paleozoic magmatic event, of which the Clouds Creek pluton was a part, produced chiefly rather uniform biotite or amphibole–biotite granites, the petrography, mineralogy and chemistry of which are typically calc–alkaline (Speer *et al.* 1980, Fullagar & Butler 1979). Locally the rocks can be slightly peraluminous, containing an aluminous biotite as the only mafic mineral. Many plutons evolved more aluminous compositions, distinguished by the presence of aluminous biotite + muscovite ± spessartine garnets. These more strongly peraluminous rocks are volumetrically minor facies of composite plutons. Late-stage, finer grained biotite + muscovite ± spessartine granitoid dykes and stocks intruding earlier biotite and amphibole + biotite granites provide the most common occurrences of the strongly peraluminous rocks in these postmetamorphic plutons. Less common is a garnet-bearing facies such as that on the northwestern corner of the Siloam pluton, Georgia (Speer *et al.* 1980). These Late Paleozoic granites exhibit characteristics of the I-type or magnetite-series granites (Chappell & White 1974, Ishihara 1977). They commonly contain hornblende and, more rarely, clinopyroxene. The biotites have intermediate Fe/(Fe+Mg) values (Speer *et al.* 1980). Prominent accessory minerals include magnetite, titanite and allanite. A vein-disseminated, molybdenum–copper-type mineralization is evident in several plutons (Speer 1978, Speer *et al.* 1980). The initial $^{87}Sr/^{86}Sr$ ratios are less than 0.706, with a range of 0.7024 to 0.7052 (Fullagar & Butler 1979). Values of $\delta^{18}O$ show a range of 5 to 9‰ relative to SMOW (Wenner *et al.* 1977, 1978).

In contrast, some of the Late Paleozoic granitic plutons are composed entirely of peraluminous rocks, such as at Clouds Creek and Stone Mountain (Georgia). These plutons, unlike the others, show characteristics of S-type or ilmenite-series granites. They contain either muscovite, cordierite or garnet. The biotite is more aluminous and iron-rich than the biotites in I-type granites. Common accessory minerals are monazite, ilmenite and tourmaline. The initial $^{87}Sr/^{86}Sr$ ratios are greater than 0.706: Clouds Creek pluton 0.7099(1) (Fullagar & Butler 1979), Stone Mountain 0.7250(5) (Whitney *et al.* 1976). The Stone Mountain pluton is enriched in ^{18}O, with $\delta^{18}O$ values greater than 11 (Wenner *et al.* 1978).

The features of the I-type granites suggest a magmatic source containing an insignificant contribution from older crustal material; the source region may be the upper mantle or a crustal source formed not much before generation of the melt. The features of the Clouds Creek and Stone Mountain plutons suggest that the source region consisted of older, more aluminum- and boron-rich crustal rocks as compared with the source region for the I-type, Late Paleozoic granites. The contrasting types of granites indicate the heterogeneity of the source regions of the Late Paleozoic magmatic event.

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