PETROLOGY OF THE ROXBORO METAGRANITE, NORTH CAROLINA

by

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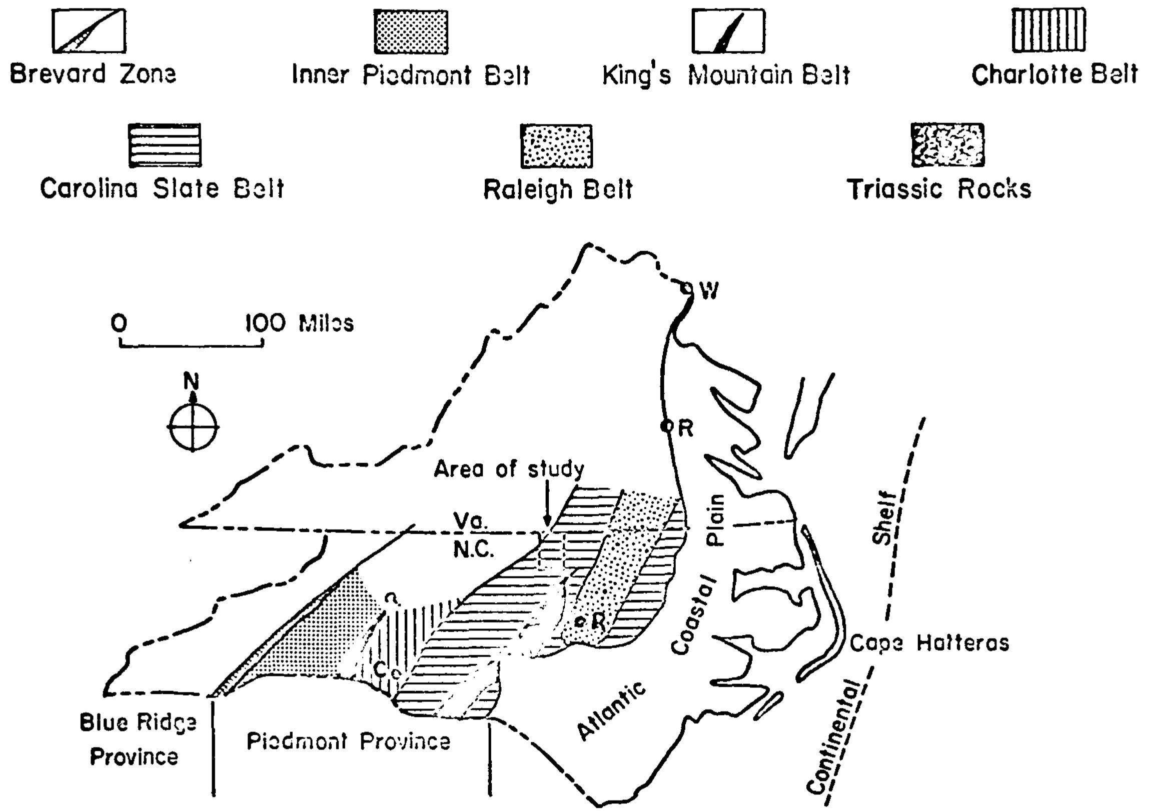
INTRODUCTION

Intensive geologic investigation of the eastern Piedmont of the southern Appalachians has only recently begun (Tobisch and Glover, 1969, 1971; Butler and Ragland, 1969; Fullagar, 1971; Glover and Sinha, 1973; Hadley, 1973; Wagener, 1973). Although some aspects of the geologic history are now known in a general way, much of the data necessary for a more thorough understanding has yet to be gathered. Petrology of the Roxboro metagranite reported herein was investigated as one step in a program of studies of the Carolina slate belt of North Carolina and Virginia now in progress at Virginia Polytechnic Institute and State University. The Roxboro granite (earlier called a granodiorite by Glover and Sinha, 1973) is a premetamorphic pluton located at the Carolina slate belt-Charlotte belt boundary. This paper deals with the eastern portion of the granite which lies in the Roxboro, North Carolina quadrangle (Fig. 1).

Glover and Sinha (1973) have reported that thick sequences of volcanic and epiclastic rocks were deposited in this area during late Precambrian and early Cambrian (?) time. These units were then folded and faulted during the Virgilina deformation and later intruded by the 575 million year old Roxboro granite. Regional metamorphism of the slate belt probably occurred during the Taconic (?) (∿420 m. y.), and/or Acadian (?) (∿350 m. y.) events.

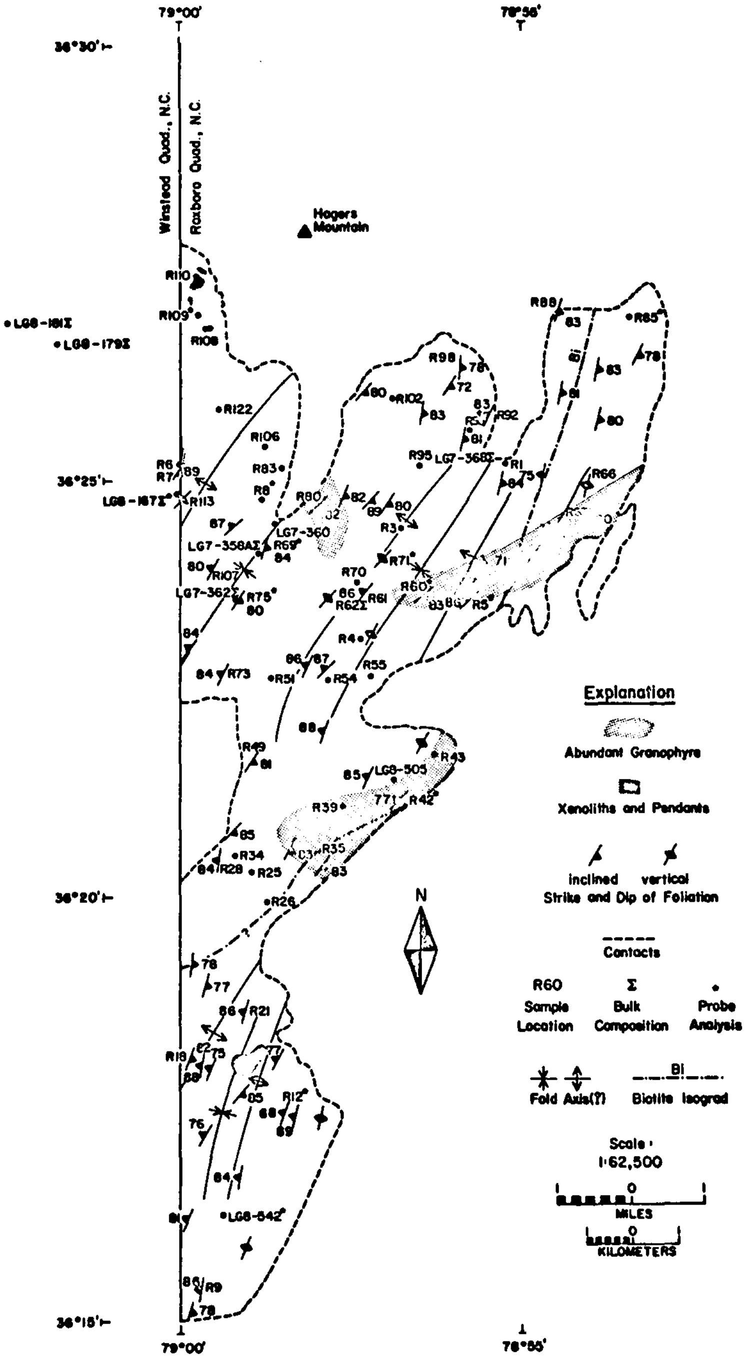
The purpose of this paper is to present a detailed petrologic study of the Roxboro granite. Boundaries of the pluton (Fig. 2)



Geologic Belts of the Piedmont Province

From Glover and Sinha, 1973

Figure 1.



The Roxboro Metagranite, Roxboro Quadrangle, North Carolina

Figure 2.

were mapped earlier by Glover (Glover and Sinha, 1973). Field work included making a representative collection of samples as well as taking structural measurements of rock fabric. In the laboratory, petrographic descriptions, modal analyses of stained thin sections, and microprobe analyses of feldspars and of selected other phases were performed. Bulk rock analyses were prepared by the analytical laboratories of the United States Geological Survey for Glover.

PETROGRAPHY

Modal analyses are shown in Tables 1, 2, and 3 with specimen locations shown in Figure 2. In this section, granitic, alkali-feldspar granitic, and granodioritic facies of the Roxboro pluton are described. Petrography of some dikes, larger xenoliths, and a postmetamorphic granodiorite is included.

Granite

The predominant rock type of the intrusive is a light gray to medium gray, microphaneritic granite (average grain size of groundmass: 0.3-0.8 mm). Phenocrysts of plagioclase (1.0-5.0 mm), quartz (1.0-5.0 mm), perthite (1.0-3.0 mm), and minor allanite are present along with epidote porphyroblasts (0.5-1.8 mm).

The majority of the plagioclase phenocrysts range from subhedral to euhedral, although in some granophyric samples they show very irregular boundaries and embayments suggesting resorption. Myrmekite is rarely present (see Table 1, sample LG7-358A). Plagioclase exhibits both Carlsbad and albite twinning and has been extensively altered to epidote, muscovite, sphene (minor), and fluorite (minor). In some cases, the muscovite grains appear crystallographically oriented. Relict zoning is perhaps indicated by a concentration of alteration products in cores of some of the plagioclase grains (see Fig. 3, plagioclase A). It may be that the clumps of plagioclase grains found in several samples are xenocrysts from some unknown source. Minor amounts of the smaller grains, in addition to rims of

Figure 3. Composite Sketch of Textural Relationships. Diameter of field ∿ 4 mm; A, plagioclase phenocryst with a more sodic, narrow rim and alteration products of muscovite and epidote; B, perthitic rim about plagioclase; C, fractured perthitic rim about quartz; D, strained quartz phenocryst; E, granophyre about perthitic rim of plagioclase; F, stringer of biotite, epidote, sphene, stilpnomelane, and opaque phases; G, originally an igneous biotite, but presently a chlorite with epidote, sphene, and minor strands of relict igneous biotite; H, sprays of stilpnomelane, I, opaque; J, sphene rim about opaque; K, polygonal quartz; L, bent and broken epidote porphyroblast spray.

Table 1

ROXBORO METAGRANITE MODAL ANALYSES

(See Appendix 1 for Sample Descriptions)

	R1	R3	R4	R5	R6	R7	R8	R9	R12
Albite	32.6	28.0	33.30	25.0	36.25	38.6	31.0	29.3	29.3
Microcline	23.0	23.6	28.60	26.0	37.25	30.6	24.0	-	5.3
Quartz	29.0	32.6	30.00	34.6	23.00	26.3	37.6	32.6	32.6
Biotite	5.6	3.3	1.75	2.8	-	0.6	2.6	-	-
Stilpnomelane	1.9	3.0	1.25	6.2	0.50	1.6	M	-	?
Muscovite	1.3	1.0	2.00	2.0	M	0.3	0.3	11.0	18.6
Chlorite	M	0.3	0.30	-	M	-	1.0	3.0	6.3
Amphibole	-	-	-	-	2.25	M	-	-	-
Epidote	6.6	7.6	2.60	2.6	M	1.0	3.6	21.6	5.6
Allanite	M	M	M	M	M	M	M	-	M
Sphene	M	0.3	M	0.6	0.50	M	M	0.3	2.0
Garnet	-	-	-	-	-	-	-	-	-
Apatite (?)	M	M	-	-	-	-	-	M	M
Fluorite	M	-	M	M	M	0.3	M	-	-
Calcite	-	-	-	-	-	-	-	0.3	-
Zircon	M	M	M	-	-	-	M	-	-
Opaques	M	M	M	M	M	0.3	M	1.6	M
Total	100.0	99.7	99.80	99.8	99.75	99.6	100.1	99.7	99.7

Table 1 Continued

	R25	R26	R34C	R35	R39	R42	R43	R49	R51
Albite	35.00	36.0	37.0	41.0	40.3	38.4	32.3	36.0	46.3
Microcline	23.00	24.6	15.3	29.0	23.3	23.8	7.3	33.6	20.3
Quartz	32.50	28.3	21.3	21.6	30.3	29.4	31.6	26.0	25.0
Biotite	0.25	0.3	4.0	M	0.6	M	4.6	M	2.3
Stilpnomelane	1.75	4.3	1.3	3.6	2.0	0.6	M	2.3	1.6
Muscovite	0.25	1.6	6.3	1.3	1.6	2.0	7.6	0.3	M
Chlorite	-	M	M	-	-	0.4	M	M	0.6
Amphibole	-	-	-	-	-	-	-	-	-
Epidote	5.50	3.6	14.0	2.0	1.3	3.4	15.6	0.6	3.3
Allanite	-	M	-	M	-	M	-	M	M
Sphene	M	M	0.3	-	M	1.0	0.3	M	M
Garnet	-	-	-	M	-	-	-	-	-
Apatite (?)	-	-	-	-	-	M	-	-	-
Fluorite	-	-	-	M	-	M	-	-	M
Calcite	-	-	-	-	-	-	-	-	-
Zircon	M	-	M	-	M	M	M	M	M
Opaques	1.75	1.0	0.3	1.3	0.6	1.0	0.3	1.0	M
Total	100.00	99.7	99.8	99.8	100.0	100.0	99.6	99.8	99.4

Table 1 Continued

	R54	R55	R60	R61	R62	R63	R66	R69	R70
Albite	34.50	36.6	37.00	43.6	28.3	25.00	14.6	34.6	32.50
Microcline	36.25	29.0	27.50	23.0	26.0	37.75	-	28.6	23.50
Quartz	26.25	29.3	22.00	20.0	31.0	33.75	46.0	24.6	31.00
Biotite	0.50	M	2.00	1.9	4.0	M	-	3.1	2.50
Stilpnomelane	1.00	1.3	3.50	1.6	2.6	1.50	-	1.6	2.50
Muscovite	1.00	1.6	1.75	M	0.6	M	36.6	1.0	1.25
Chlorite	-	M	M	0.6	M	-	-	0.2	0.50
Amphibole	-	-	-	-	-	-	-	-	-
Epidote	M	0.6	5.75	8.6	6.3	1.00	-	6.0	6.50
Allanite	M	M	M	M	M	-	-	-	M
Sphene	0.50	0.6	0.50	0.3	1.0	M	M	M	M
Garnet	-	-	-	-	-	-	-	-	-
Apatite (?)	-	-	-	M	-	-	-	-	-
Fluorite	M	0.6	-	M	M	M	-	-	M
Calcite	-	M	-	-	-	-	-	-	-
Zircon	M	-	M	M	M	M	M	M	M
Opaques	0.25	0.3	M	0.3	M	1.00	2.6	0.3	M
Total	100.25	99.9	100.00	99.9	99.8	100.00	99.8	100.00	100.25

Table 1 Continued

	R71	R73	R75	R80	R83	R85	R88	R92	R93
Albite	40.3	31.75	32.25	34.3	33.50	28.6	32.0	32.3	32.00
Microcline	19.3	22.75	22.00	38.3	29.75	29.6	22.0	30.3	26.50
Quartz	28.6	28.75	32.50	21.0	27.00	32.6	32.3	29.6	32.75
Biotite	2.4	2.25	3.00	0.4	1.50	0.6	1.0	0.6	0.50
Stilpnomelane	1.6	2.50	0.25	0.8	0.75	1.0	-	1.0	0.75
Muscovite	0.6	0.50	2.25	1.0	0.75	3.6	12.3	3.3	3.25
Chlorite	1.3	0.25	0.50	M	0.25	M	-	0.3	0.25
Amphibole	-	-	-	-	-	-	-	-	-
Epidote	4.3	11.00	7.25	3.3	6.50	2.6	0.3	2.0	3.75
Allanite	M	M	M	M	M	-	-	M	-
Sphene	1.0	M	0.25	0.3	M	M	-	M	M
Garnet	-	-	-	-	-	0.3	-	-	-
Apatite (?)	-	-	-	-	-	-	-	-	-
Fluorite	M	M	-	M	M	-	-	-	M
Calcite	-	-	-	-	-	-	-	-	-
Zircon	-	M	M	-	M	M	M	-	-
Opaques	M	0.25	M	0.3	M	1.0	0.3	M	0.25
Total	99.4	100.00	100.25	99.7	100.00	99.9	100.2	99.4	100.00

Table 1 Continued

	R95	R98	R102	R106	R107	R113	R122	LG8-167	LG8-179
Albite	33.00	26.0	26.6	33.0	33.00	37.6	33.3	41.25	32.6
Microcline	25.00	28.3	27.6	21.3	20.50	24.6	22.6	22.25	27.0
Quartz	27.00	38.3	32.6	32.3	34.25	28.6	35.0	30.75	34.0
Biotite	3.60	1.0	3.0	2.6	0.75	1.6	0.6	1.00	0.3
Stilpnomelane	1.40	0.6	0.3	0.6	2.00	0.3	-	1.50	M
Muscovite	2.00	2.0	4.3	2.0	1.75	1.6	1.0	M	1.3
Chlorite	1.00	0.6	0.3	1.3	1.00	0.3	0.6	M	0.6
Amphibole	-	-	-	-	-	-	-	-	-
Epidote	6.50	2.6	4.0	6.3	6.00	4.3	5.6	2.00	4.0
Allanite	M	M	M	M	M	-	-	M	-
Sphene	0.50	0.3	0.6	M	0.25	M	M	0.50	M
Garnet	-	-	-	-	-	-	-	-	-
Apatite (?)	-	-	-	-	-	-	-	-	-
Fluorite	-	M	M	M	0.25	-	-	M	-
Calcite	-	-	-	-	-	-	-	-	-
Zircon	M	M	-	-	M	-	-	M	-
Opaques	M	M	M	0.3	0.25	0.6	1.3	0.75	M
Total	100.00	99.7	99.3	99.7	100.00	99.5	100.0	100.00	99.8

Table 1 Continued

	LG8-181	LG7-358A	LG7-362	LG7-368	LG8-505	LG8-542
Albite	36.0	36.3	28.6	28.0	37.0	27.3
Microcline	30.0	32.3	21.3	28.0	25.3	3.6
Quartz	27.3	26.3	37.0	27.6	32.0	27.6
Biotite	M	3.0	3.6	2.6	M	-
Stilpnomelane	0.3	M	1.0	2.6	2.6	-
Muscovite	2.3	M	2.0	1.3	M	10.8
Chlorite	2.0	M	1.3	0.6	M	8.5
Amphibole	-	-	-	-	-	0.3
Epidote	2.0	2.0	4.6	8.5	2.0	20.4
Allanite	-	-	M	M	M	-
Sphene	-	M	0.3	0.6	0.3	1.0
Garnet	-	-	-	-	-	-
Apatite (?)	-	-	-	-	-	0.3
Fluorite	-	M	M	-	-	-
Calcite	-	-	-	-	-	-
Zircon	M	M	M	M	M	M
Opaques	M	M	0.3	M	1.0	M
Total	99.9	99.9	100.0	99.8	100.2	99.8

phenocrysts cut by the thin section, appear to be less altered than the phenocrysts. Perthitic rims and even perthitic phenocrysts surround much of the plagioclase (Fig. 3, perthite B surrounding plagioclase A). A very minor amount of completely unaltered plagioclase surrounds some of the perthitic grains.

The perthitic feldspars are predominantly anhedral. They appear to have crystallized as one feldspar, subsequently unmixing to produce very sodic and potassic phases (modally, 55-80 percent K-feldspar). Microcline twinning is present but was strained during metamorphism. Compared to plagioclase feldspars, perthite shows only a minor amount of alteration or replacement, and that mainly to stilpnomelane accompanied by very minor amounts of epidote, white mica, and fluorite. Perthitic phenocrysts appear to mold themselves about plagioclase and quartz phenocrysts (Fig. 3).

Quartz underwent a great deal of recrystallization during metamorphism but some phenocrysts still show relict euhedral forms. A minor amount of quartz is embayed. Some large quartz grains show either thin rims of feldspar or feldspar present within fractures in quartz.

The granite varies in texture from highly granophyric to one which shows no granophyre at all. Within the granophyre, intergrown quartz and alkali feldspar form randomly oriented cauliflower-like masses. In any one of these masses, the quartz blebs and the exsolved alkali feldspar (albite + microcline together) will each go extinct simultaneously under crossed nicols. In some cases, feldspar and quartz phenocrysts acted as cores from which the granophyre grew (Fig. 3).

Epidote, biotite, and sphene, along with minor amounts of stilpnomelane, opaques, muscovite, fluorite, or allanite, occur in clumps and stringers (Fig. 3). Green biotite, interpreted as metamorphic in origin, and rare brown biotite (possibly igneous relicts) are present. In some cases, the brown biotite (light reddish brown to dark reddish brown to black) is interleaved with the green biotite (light green to dark green or black). Large clumps of chlorite have partially replaced brown biotite (Fig. 3; Table 1, sample R85). Most of the metamorphic biotite is associated with minor amounts of chlorite and stilpnomelane. Chlorite (light green to dark green) is not uncommonly associated with epidote. Stilpnomelane (light reddish brown to dark reddish brown or black) occurs both as sprays or as individual grains having a needlelike form and is found primarily with perthitic feldspar and to a lesser extent with epidote, chlorite, biotite, opaque minerals (minor), and sphene (minor) (Fig. 3). Allanite commonly has rims of epidote. Inspection of polished sections under reflected light indicates that the opaque phases are magnetite, hematite, ilmenite, and pyrite (minor). Magnetite and ilmenite are locally surrounded by thin rims of sphene (Fig. 3).

Deformation accompanying the major metamorphism produced various degrees of foliation as evidenced by the preferred orientation of stringers of biotite, epidote, sphene, stilpnomelane, chlorite, opaque phases, and muscovite. These stringers are present either at the grain boundaries of feldspar and quartz or in some cases, they cut the grain boundaries. Individual biotite grains within these stringers are randomly oriented, and stilpnomelane sprays regularly cut across the foliation (Fig. 3). The form of these stringers suggests that they were created by the deformation while the random orientation of the individual biotite grains indicates they grew at some later time. The foliation is also shown by preferred orientation of recrystallized polygonal quartz grains and by flattening of quartz phenocrysts (Fig. 3). Many of the strained quartz phenocrysts have polygonal grains at their boundaries (Fig. 3). In some granophyric samples, the originally rounded intergrowths of alkali feldspar and quartz have been compressed so that their long axes are parallel to foliation. Both the plagioclase and perthite show undulose extinction, are bent, and are broken by the deformation (Fig. 3). Some deformation clearly occurred after twinning of the plagioclase. Biotite, epidote (Fig. 3), and chlorite show similar relations.

The southern extension of the pluton differs greatly in appearance from the northern portion. This is partially due to the higher degree of hydration as well as the style of deformation. The southern extension is highly foliated and shows a large amount of local metasomatism. Unlike the northern part, there is only a very minor amount of microcline (0.0-5.6 modal percent), but a large amount of muscovite (10.8-18.6 modal percent) and epidote (up to 21.6 modal percent). Muscovite and epidote, polygonal grains of quartz, and smaller amounts of chlorite and rare pale green amphibole (actinolite ?) occur in stringers defining the foliation. The chlorite (light yellowish green) in the southern extension is only slightly pleochroic, generally associated with the amphibole and epidote.

Alkali-feldspar Granite

The Roxboro granite contains a minor amount of light gray to light pinkish gray alkali-feldspar granite (see Table 1, samples R7, R49, R54, R55, and R63). This facies has a microphaneritic groundmass (average grain size: 0.15-1.0 mm) with phenocrysts of plagioclase (0.8-1.5 mm), perthite or antiperthite (1.0-2.3 mm), quartz (1.0-2.2 mm), allanite, and sphene (?). Epidote porphyroblasts (0.7-1.0 mm) are present. Many of the textural relations and alteration products are similar to that already described for the major granitic facies. Accordingly, this section will concentrate on differences between the alkali-feldspar granite and the granite, or on points of importance to later discussion.

This rock type contains a minor amount of originally more calcic plagioclase (2-11 modal percent of the total feldspar). The average plagioclase, while altering to epidote, muscovite, and minor fluorite as did the plagioclase in the granitic facies, shows much less alteration. Relict zoning within plagioclase is not as pronounced. Plagioclase phenocrysts are surrounded by perthite or antiperthite rims, although rarely some plagioclase grains with few alteration products lie outside of the perthite-antiperthite. Generally, the perthitic or antiperthitic phenocrysts appear either to encircle quartz phenocrysts or to have crystallized simultaneously with the quartz. Modal composition of the perthite-antiperthite grains varies from 40 to 70 percent K-feldspar. Microcline and albitic portions of these grains are now rather strongly segregated and show much less alteration than the plagioclase phenocrysts. This rock type also can contain granophyre.

The alkali-feldspar granite has significantly less biotite and epidote than does the granite (compare samples R49 and R54 to R60 and R62, Table 1). There are stringers of rare amphibole (probably a sodic hornblende based on pleochroism and color) and opaques which are parallel to the foliation (Table 1, sample R6).

Granodiorite

Only two samples of this rock type were found (Table 1, samples R34C and R43). This facies is a medium gray granodiorite with a microphaneritic groundmass (average grain size: 0.7-0.9 mm) and with phenocrysts of plagioclase (2.2-5.5 mm), quartz (1.5 mm), and perthite (1.2 mm). The plagioclase phenocrysts generally show more alteration to epidote and muscovite than phenocrysts in the other rock types. Concentration of alteration products in cores of the plagioclase phenocrysts is marked and presumably indicates the original zoning. This textural feature is even visible in the hand specimen. Plagioclase phenocrysts are surrounded by perthitic rims (60-70 modal percent K-feldspar) and by quartz grains. Quartz and K-rich feldspar appear to mutually interfere and may have begun to crystallize at the same time. Interestingly, altered plagioclase is the sole feldspar within the granophyre of sample R43. In this sample, a minor amount of perthite is molded about the altered plagioclase at the edge of the granophyre. The granodiorite has a larger amount of epidote and biotite than the granite (compare sample R34C to R60, Table 1). Otherwise, all other textural characteristics are similar to the granite facies.

Dikes

Both mafic and felsic dikes cut the Roxboro granite (see Table 2). The felsic dikes range in composition from rhyolite or microgranite to microgranodiorite. However, metamorphism has caused extensive alteration of the mafic dikes so that the original rock type could not easily be determined.

The rhyolitic dikes (Table 2, samples R18, R21, R28) are brownish yellow and range from 2 to 15 feet thick. Phenocrysts of relatively unaltered plagioclase (0.4-2.0 mm), quartz (0.8-2.5 mm), and perthite (minor, 0.5-1.5 mm), as well as epidote porphyroblasts (0.15-0.25 mm) are present. There are small radial structures of interleaved potassium feldspar and quartz in the groundmass which

Table 2

MODAL ANALYSES OF DIKES

(See Appendix 1 for Sample Descriptions)

	R18	R21	R28	R28A	R34E	R62B	R110	LG7-358B	LG7-360
Albite*	39.4	28.3	30.3	M	34.00	10.0	35.50	30.6	35.6
Microcline	20.4	40.3	31.3	-	29.75	-	-	18.0	8.0
Quartz	28.4	25.6	33.3	-	32.75	16.3	-	22.0	25.0
Biotite	-	1.0	0.6	-	M	28.3	M	10.6	10.3
Stilpnomelane	-	-	1.0	-	0.25	-	-	-	-
Chlorite	-	-	M	2.0	M	6.3	-	-	M
Muscovite	-	0.3	0.6	14.3	0.75	-	-	5.6	4.3
Epidote	12.0	4.0	2.0	51.3	1.25	33.3	6.00	11.0	13.6
Allanite	-	-	M	-	-	-	-	-	-
Hornblende	-	-	-	-	-	-	50.00	-	-
Actinolite	-	-	-	31.3	-	-	-	-	-
Garnet	-	-	-	-	M	-	-	-	-
Sphene	-	-	M	1.0	-	5.3	-	1.6	2.6
Rutile	-	-	-	-	-	-	-	M	-
Zircon	-	M	-	-	-	-	M	M	M
Opaques	M	0.3	0.6	M	1.50	0.3	8.00	0.3	0.3
Total	100.2	99.8	99.7	99.9	100.25	99.8	99.50	99.7	99.7

*Albite=Plagioclase for Sample R110

may represent relict spherulites or filled amygdules (Table 2, sample R18). The foliation is shown by the preferred orientation of epidote stringers and narrow zones of polygonal quartz grains.

Some micrograniticand microgranodioritic dikes contain granophyre. The nongranophyric dikes (Table 2, samples LG7-358B and LG7-360) are medium gray while the granophyric dikes (Table 2, sample R34E) are light pinkish gray. All these dikes carry phenocrysts of perthite, quartz, and plagioclase. Epidote porphyroblasts are locally present. Textural relations and alteration products within all these dikes are similar to that described earlier for the granite.

The mafic dikes which cut the Roxboro granite have been almost completely recrystallized by the later major metamorphism. One of these is a light green, fine grained dike (average grain size of groundmass: 0.2-0.3 mm) with an assemblage of epidote, actinolite (porphyroblasts, 0.5-1.0 mm), and muscovite (Table 2, sample R28A). Chlorite grew from the epidote and actinolite and there are large clumps of fine grained muscovite (up to 5.0 mm in diameter). Another dike located in a slightly higher grade region has an assemblage of epidote, biotite, quartz, plagioclase, and chlorite (Table 2, sample R62B). Chlorite grew about biotite, and plagioclase has altered to epidote and muscovite. Foliation is shown by the preferred orientation of the biotite and chlorite.

A post metamorphic diabasic dike is present in the northwestern portion of the Roxboro quadrangle (Table 2, sample R110). The rock consists of hornblende (black groundmass) and white plagioclase phenocrysts (1.8-3.0 mm) which show some alteration to epidote.

Xenoliths and Post Metamorphic Granodiorite

In the northwest portion of the Roxboro quadrangle a post metamorphic granodiorite of unknown dimensions (several corestones have been seen in several locations within a half mile of sample R109), probably intrudes the Roxboro granite. Several large xenoliths (Table 3, samples R108 and R109), of hydrothermally altered rock, which are thought to be from the Hagers mountain body (Glover, personal communication, 1974; see Fig. 2) may be contained within the granodiorite. The intrusion is an equigranular, phaneritic granodiorite (average grain size: 1.0-1.5 mm; Table 3, sample 109A). Its most distinctive feature is the concentrically zoned plagioclase. Microprobe analyses have revealed that the An content oscillates between An_{13} and An_{27} as a traverse is made across a grain. Plagioclase shows only minor alteration to muscovite and epidote. Quartz partially molds itself about the plagioclase while K-feldspar and biotite appear to fill in the spaces between quartz and plagioclase.

A large xenolith (roof pendant ?) in the southern extension has previously been identified by Glover as a block of the felsic and intermediate volcanic rocks (unit II) into which the Roxboro pluton partially intrudes (Glover and Sinha, Fig. 4, 1973).

Table 3

MISCELLANEOUS MODAL ANALYSES

(See Appendix 1 for Sample Descriptions)

	R108A	R109	R109A
Plagioclase	-	-	49.00
K-feldspar	-	-	12.75
Quartz	79.6	64.0	27.00
Biotite	-	-	6.25
Muscovite	10.0	3.6	2.25
Epidote	?	-	2.00
Clinozoisite	-	31.0	-
Zircon	m	m	m
Chloritoid	1.4	-	-
Topaz	1.0	-	-
Opaque	8.0	1.3	0.50
Total	100.0	99.9	99.75

STRUCTURAL GEOLOGY

The Roxboro granite intrudes the Virgilina synclinorium which was created by the Virgilinian late Precambrian or early Cambrian deformational event. A slaty cleavage and the preferred orientation of the stringers of biotite, epidote, muscovite, and chlorite in the Roxboro pluton were apparently developed during the major middle Paleozoic metamorphism as the trends inside the pluton and in the surrounding host rock are similar (Glover and Sinha, 1973). Attitudes of foliation and slaty cleavage were measured and are shown together on the map as one feature (Fig. 2). The pattern of foliation suggests fanning possibly related to folding of the pluton. At the northern boundary of the pluton, these folds (?) appear to be coextensive with known folds in the country rock, where their wavelength is decreased (Glover, personal communication, 1974). This suggests that the pluton is not as tightly deformed as the country rock.

CHEMICAL RELATIONSHIPS

Bulk Rock Chemistry

Seven bulk rock analyses and their norms are shown in Table 4. Butler and Ragland (1969) have identified two chemically distinct magmatic trends in the metamorphosed intrusions of the Piedmont of North Carolina and South Carolina. These are the West Farrington and the Salisbury and metavolcanic trends.

The calc-alkaline West Farrington trend is defined from chemical analyses of the western stock of the Farrington complex (Butler and Ragland, 1969). This stock has been described by Wagener (1965) and Wagener and others (1969) as a concentrically zoned pluton in which the composition gradually changes from a gabbro at the edge to a leucogranodiorite near the center. Butler and Ragland (1969) have defined the metavolcanic trend or its intrusive equivalent, the Salisbury trend, from chemical analyses of metavolcanic and associated dike rocks from the Carolina slate belt. However, the work of Hills and Butler (1968) and Fullager and others (1971) indicate that the Salisbury pluton is more than 100 m. y. younger than the metavolcanics so that the Salisbury and metavolcanic trends, while sensibly the same, are in fact probably unrelated (see Glover and Sinha, p. 242-243, 1973, for a discussion of age relations in the Carolina slate belt).

Plots by Butler and Ragland (1969) illustrate the differences between these magmatic trends. Their relationship to the Roxboro

Table 4

ROXBORO GRANITE

Chemical Analyses[1]

	LG7-368	LG7-362	LG7-358A	LG8-179	LG8-167	R62[2]	LG8-181
SiO_2	73.20	73.50	72.60	75.70	76.60	75.70	76.00
Al_2O_3	13.50	13.40	13.80	13.40	12.30	12.30	12.80
Fe_2O_3	1.10	1.00	1.50	0.49	0.77	1.20	0.50
FeO	1.20	1.30	1.80	0.72	0.70	1.50	0.56
MgO	0.29	0.59	0.19	0.10	0.05	0.23	0.16
CaO	1.20	1.30	1.50	0.61	0.57	1.30	0.66
Na_2O	4.40	4.40	4.90	3.80	4.30	3.30	3.80
K_2O	3.60	3.70	3.00	4.40	4.40	3.20	4.10
MnO	0.09	0.14	0.15	0.04	0.07	0.11	0.12
TiO_2	0.20	0.20	0.47	0.11	0.10	0.22	0.10
P_2O_5	0.02	0.00	0.00	0.02	0.00	0.04	0.00
CO_2	0.02	0.01	0.01	0.01	0.02	<0.05	0.02
H_2O^+	0.83	0.85	0.73	0.63	0.52	0.76	0.67
H_2O^-	0.08	0.04	0.03	0.03	0.08	0.07	0.02
Total	99.73	100.43	100.68	100.06	100.48	99.98	99.51

Table 4 Continued

C.I.P.W. Norms, Weight Percent[3]

	LG7-368	LG7-362	LG7-358A	LG8-179	LG8-167	R62	LG8-181
Q	30.42	29.53	28.55	35.01	33.53	40.65	36.30
Or	21.28	21.87	17.73	26.00	26.00	18.91	24.23
Ab	37.23	37.23	41.46	32.16	36.39	27.92	32.16
An	5.70	5.89	6.80	2.83	1.27	5.87	3.15
Di	0.00	0.41	0.50	0.00	1.25	0.00	0.00
Hy	1.85	2.76	1.79	1.06	0.09	2.18	1.07
Mt	1.59	1.45	2.17	0.71	1.12	1.74	0.72
Il	0.38	0.38	0.89	0.21	0.19	0.42	0.19
Ap	0.05	0.00	0.00	0.05	0.00	0.09	0.00
Cc	0.05	0.02	0.02	0.02	0.05	0.11	0.05
C	0.28	0.00	0.00	1.35	0.00	1.26	0.96
Total	98.83	99.54	99.91	99.40	99.89	99.15	98.83

[1] Chemical Analyses performed by United States Geological Survey; Leonard Shapiro, Project Leader

[2] R62 equals LG9-515.

[3] Calculated using a program obtained from F. Chayes.

pluton is shown in Figures 4, 5, and 6. The Roxboro appears to lie along the metavolcanic trend in these plots.

Mineral Chemistry

Although very little if any change has occurred in the bulk rock chemistry of this intrusion, as indicated by the similarity in the 7 bulk rock analyses and the absence of any profound chemical changes near the boundaries of the pluton, textural relationships suggest that the igneous mineral compositions have been greatly modified by new mineral growth during regional metamorphism of the Carolina slate belt. Individual alkali feldspar grains show a great deal of segregation into albitic and K-feldspar rich phases. Electron microprobe studies of the alkali feldspar show that the exsolved portions are nearly pure albite and microcline (Fig. 7). The originally calcic plagioclase phenocrysts have been altered to a very albitic plagioclase (Fig. 8) plus large amounts of epidote and muscovite. Such feldspar compositions are characteristic of greenschist facies conditions.

Single crystal X-ray measurements of the γ^* angle of chemically analyzed plagioclase grains (see Table 5) were combined with the γ^* versus composition plot of Doman and others (1965) in order to determine the structural state of the plagioclase. Even though the X-ray photographs showed streaked spots indicating the strained nature of the plagioclase crystals, it was confirmed that low albite is present.

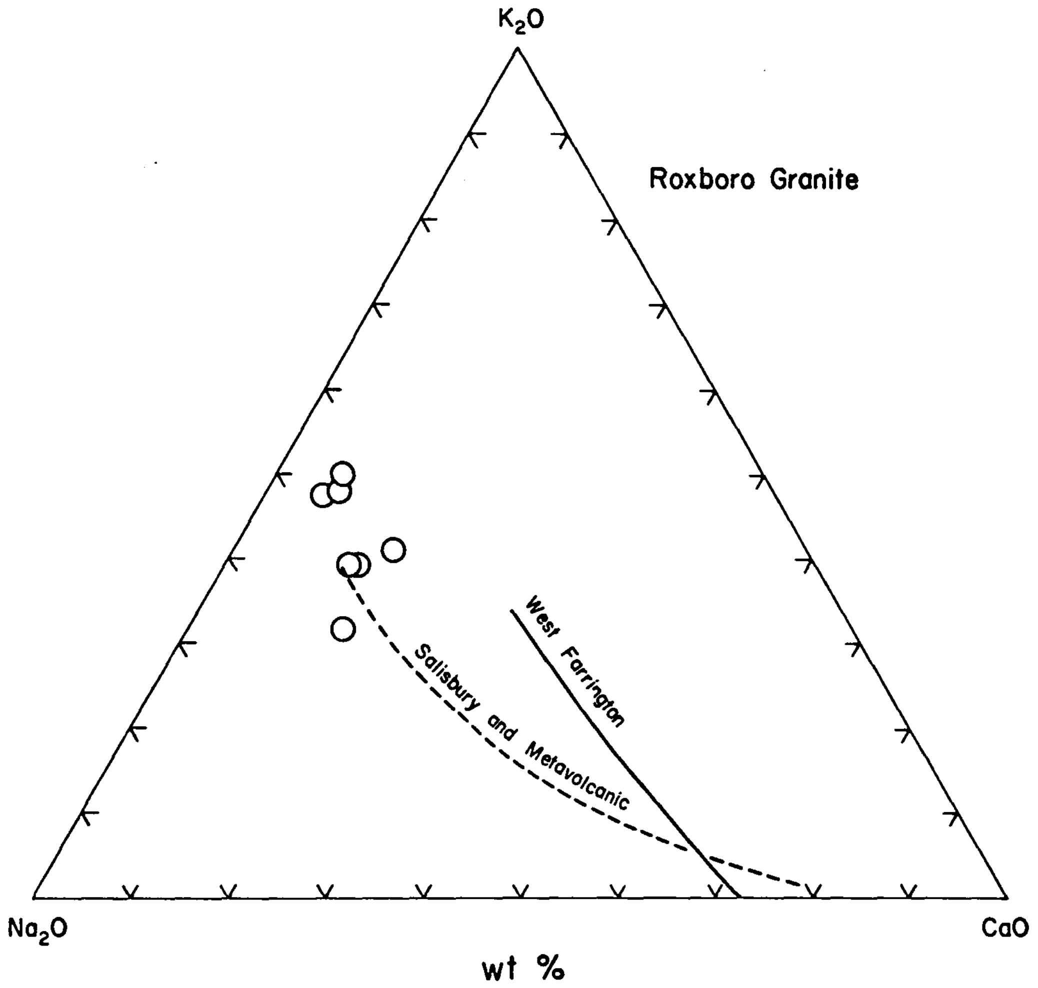


Figure 4. $CaO-K_2O-Na_2O$ Diagram: Comparison of the bulk chemistry of the Roxboro metagranite with magmatic trends recognized by Butler and Ragland (1969) in the southeastern Appalachian Piedmont.

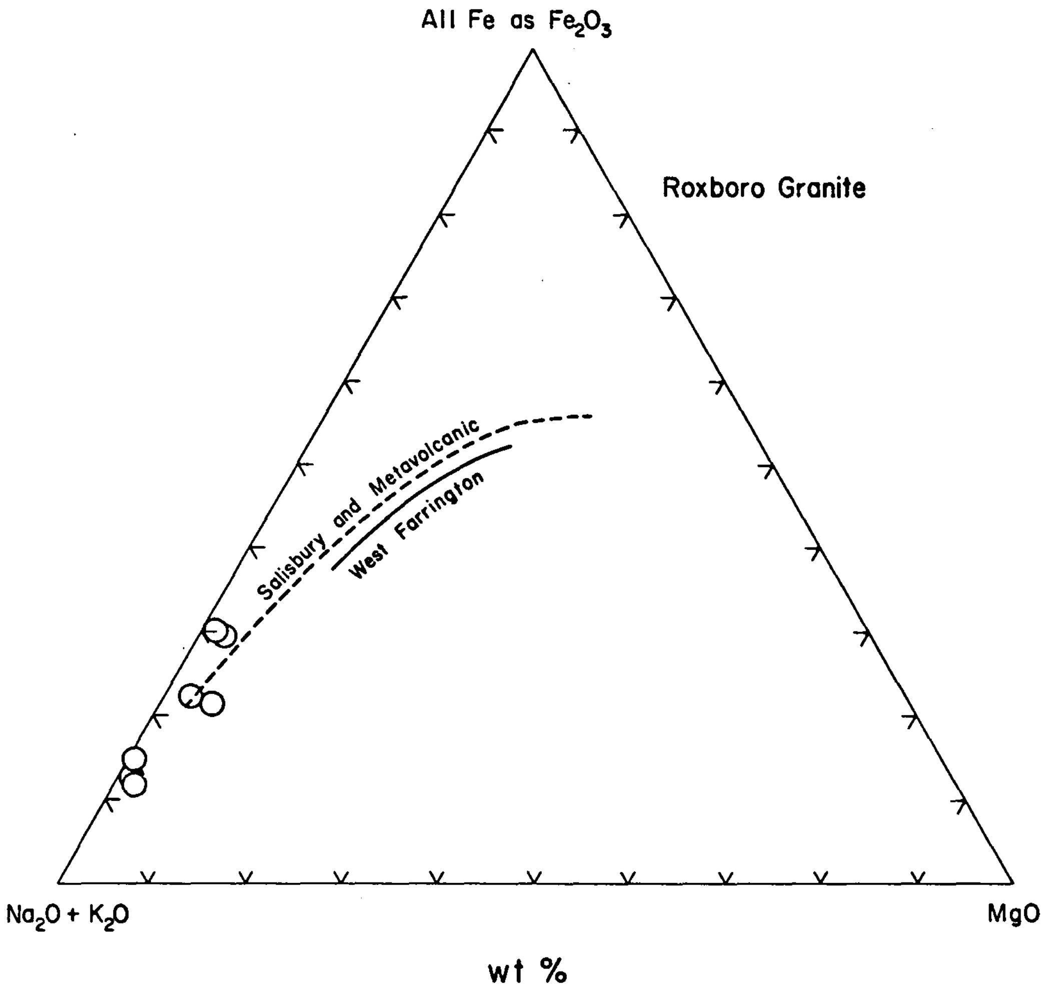


Figure 5. MgO-Total Fe as Fe_2O_3-Total Alkalis Diagram: Comparison of the bulk chemistry of the Roxboro metagranite with magmatic trends recognized by Butler and Ragland (1969).

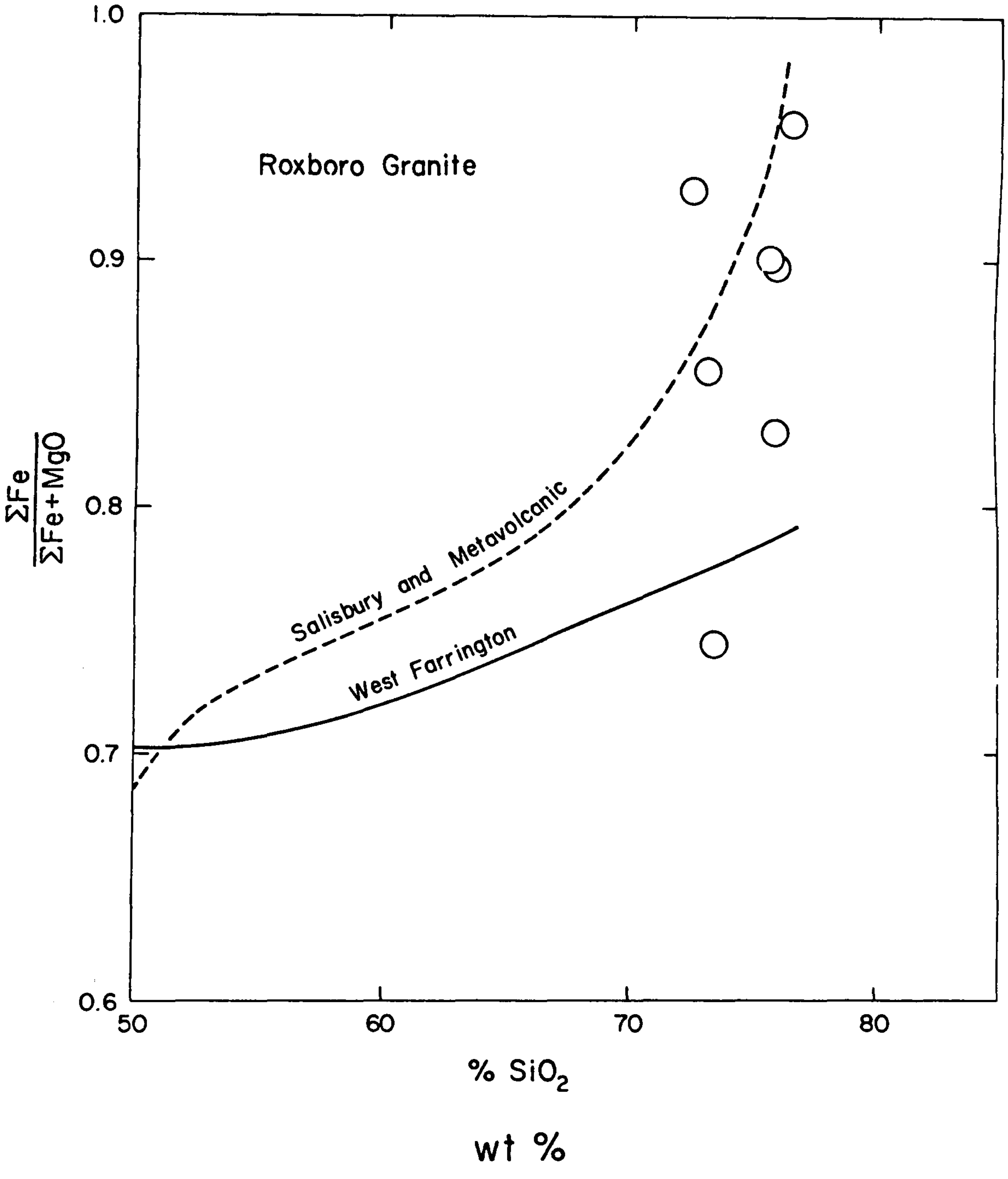


Figure 6. Ratio of Total Fe to Total Fe + Mg Versus SiO_2 Diagram: Comparison of the bulk chemistry of the Roxboro metagranite with magmatic trends recognized by Butler and Ragland (1969).

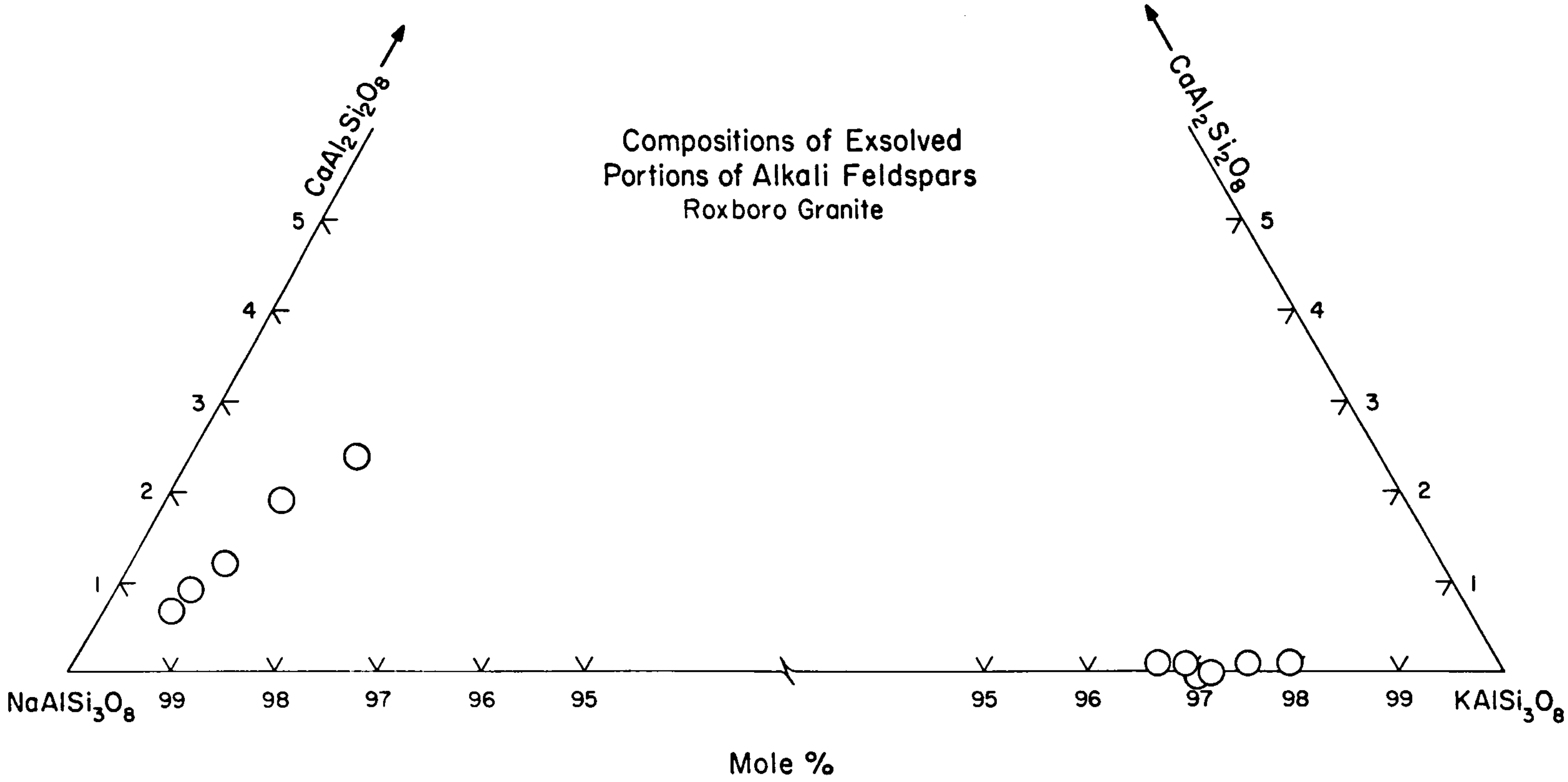

Compositions of Exsolved
Portions of Alkali Feldspars
Roxboro Granite
$CaAl_2Si_2O_8$
$CaAl_2Si_2O_8$
1
2
3
4
5
1
2
3
4
5
$NaAlSi_3O_8$
99
98
97
96
95
95
96
97
98
99
$KAlSi_3O_8$
Mole %

Figure 7.

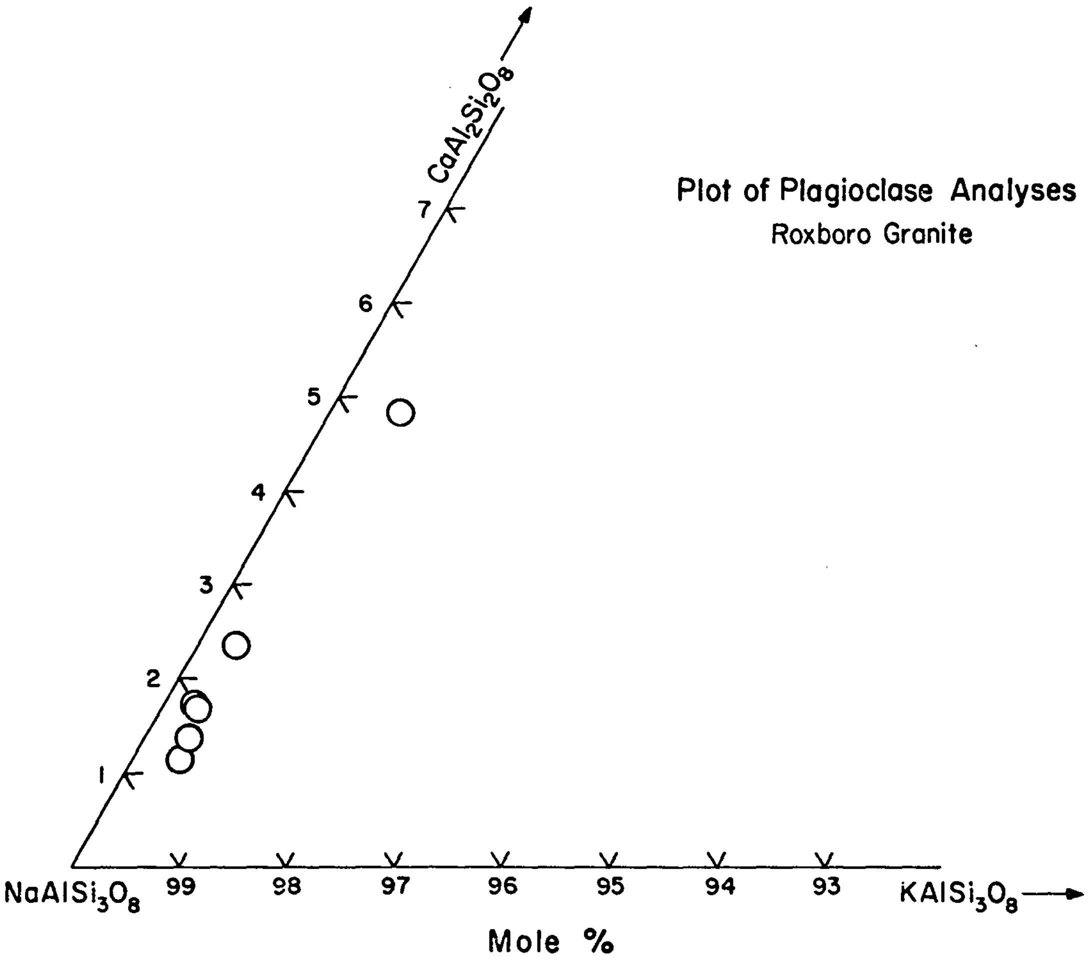

Plot of Plagioclase Analyses
Roxboro Granite
CaAl$_2$Si$_2$O$_8$
7
6
5
4
3
2
1
NaAlSi$_3$O$_8$
99
98
97
96
95
94
93
KAlSi$_3$O$_8$
Mole %

Figure 8.

Table 5

SINGLE CRYSTAL DATA

FOR

SELECTED PLAGIOCLASE GRAINS FROM LG8-167[1]

Average Composition: $Ab_{97.3}An_{2.4}Or_{0.4}$

1) 90° 25' = γ^*
2) 90° 10' = γ^*
3) 90° 15' = γ^*
4) 90° 23' = γ^*

[1] Due to strain the γ^* values are ±10'.

Partial analyses (Table 6) were made in order to confirm the petrographic identification of several minerals and to detect possible compositional variations. Chlorite in the southern portion of the pluton is noticably more Mg-rich than the chlorite of the northern portion (compare sample R12 to R60, Table 6). Epidote porphyroblasts are more Fe-rich than the smaller epidote grains residing in plagioclase. Although no ferric-ferrous ratios are available for the stilpnomelane, it appears optically as a ferristilpnomelane (Hutton, 1938). Additional analyses showed that the white mica was a low sodium muscovite and that biotite coexisting with fluorite contains 0.4-0.5 weight percent fluorine (sample R8).

Table 6

PARTIAL ANALYSES OF SELECTED MINERALS

(See Appendix 3 for Description of Samples)

Biotites

				wt %	
Sample			K	Fe	Mg
R8			8.2	22.1	2.3
R60	Grain 3		7.9	22.3	1.7
R60	Grain 6	Position 1	8.1	21.6	1.7
R60	Grain 6	Position 2	8.2	21.8	1.8
R60	Grain 7		7.6	22.0	1.7
R85	Grain 1	Position 1	7.5	21.2	2.2
R85	Grain 1	Position 2A	6.2	21.0	2.5
R85	Grain 1	Position 2B	2.9	23.5	2.9
R85	Grain 2		2.1	20.2	2.5
R85	Grain 5	Position 1	2.5	22.3	2.9
R85	Grain 5	Position 2	2.7	22.7	3.0
R85	Grain 7		7.0	20.6	2.4

Chlorite

				wt %	
Sample			Ca	Fe	Mg
R12	Grain 1	Position 1	0.0	16.8	7.5
R12	Grain 1	Position 2	0.0	16.4	7.9
R12	Grain 1	Position 3	0.0	17.0	7.2
				wt %	
			K	Fe	Mg
R60	Grain 1A		0.0	29.2	2.1
R60	Grain 1B		0.0	29.7	2.0
R60	Grain 8		0.0	30.1	2.1
R85	Grain 4		0.0	27.7	2.9
R85	Grain 8		0.0	28.7	2.7

Table 6 Continued

Stilpnomelane

Sample			K	wt % Fe	Mg
R60	Grain 2	Position 1	1.6	23.5	1.2
R60	Grain 2	Position 2	1.4	23.5	1.1
R60	Grain 5	Position 1	1.3	24.1	1.2
R60	Grain 5	Position 2	1.2	23.3	1.1
R85	Grain 6		1.0	20.4	1.6
R85	Grain 9		0.8	19.9	1.6

Epidote

Sample		K	wt % Fe	Al
R60	Grain 4	0.0	9.2	13.2
R60	Grain 9	0.0	6.9	14.8

Muscovite

Sample		K	wt % Ca	Na
R71		9.2	0.0	0.1
R75	Grain 1	9.1	0.0	0.2
R75	Grain 2	9.1	0.0	0.1
R93	Grain 6	9.1	0.0	0.1
R93	Grain 7	9.3	0.0	0.1

CLASSIFICATION

Attempting to arrive at the classification of a metamorphosed pluton on the basis of its original igneous character is a difficult task. One method which has been used is a comparison of bulk rock analyses with the average chemical compositions of different rock types (for example, Nockolds, 1954). But this approach fails to distinguish among many important petrologic characteristics useful in ascertaining original geologic setting. In this study, a combination of modal and chemical analyses was used to try to reconstruct the original igneous mineralogy. Under the classification system recommended by the I. U. G. S. Subcommission of Systematics of Igneous Rocks (1973), the pluton located at Roxboro, North Carolina was dominantly a granite. This rock originally consisted of about 30 modal percent quartz with the majority of samples having a ratio of plagioclase (plagioclase of the classification = plagioclase > An_5 = altered plagioclase of this study) to total feldspar between 0.26 and 0.56 (see Table 7). Amounts of original mafic minerals could not be determined because of low grade metamorphic effects. However, normative analyses suggest that this intrusion would plot around the leucogranite-granite boundary. This pluton is here formally named the Roxboro Metagranite.

Table 7

ORIGINAL FELDSPAR MODAL ANALYSES

Sample	Plagioclase[1]	Albite[2]	K-feldspar[3]
R1	56.3	17.0	26.6
R5	36.0	23.0	41.0
R6	9.0	39.3	51.6
R25	51.5	21.0	27.5
R34C	69.0	11.0	20.0
R49	3.5	54.0	42.5
R61	54.0	13.0	33.0
R62	49.3	19.0	31.6
R63	2.0	32.0	66.0
R69	44.6	16.6	38.6
R70	38.0	26.0	36.0
R73	46.0	18.5	35.5
R80	11.0	40.5	48.5
R85	26.5	26.5	47.0
R92	43.6	19.6	36.6
R93	26.5	31.0	42.5
R95	49.0	10.0	41.0
R98	33.0	15.5	51.5
R107	44.5	20.0	35.5
LG7-368	45.5	12.0	42.5

[1] Plagioclase - altered plagioclase grains, original igneous composition > An_5

[2] Albite - in perthite, very minor albite grains and rims, original igneous composition < An_5

[3] K-feldspar - in perthite

METAMORPHIC ASSEMBLAGES

The Roxboro granite was first reequilibrated under greenschist facies conditions characteristic of the Barrovian style of regional metamorphism (kyanite-sillimanite, or high P high T facies series of Miyashiro (1961)). Later, either during the waning of the main episode, or during a separate low temperature heating, further recrystallization occurred. Three metamorphic assemblages can be discerned which are principally related to the main metamorphic event:

1. Quartz + low albite + epidote + muscovite + chlorite ± microcline ± actinolite (?)
2. Low albite + microcline + quartz + muscovite + epidote + stilpnomelane ± chlorite ± garnet
3. Low albite + quartz + microcline + epidote + biotite + muscovite + stilpnomelane ± chlorite ± hornblende (?) ± garnet

Although assemblages (1) and (2) probably represent the same grade, (3) is clearly higher grade than the other two and establishes an increase in grade to the northwest consistent with the regional setting (Tobisch and Glover, 1969). Mapping of a biotite isograd (Fig. 2) across the Roxboro granite was complicated by the presence of relict igneous biotite. Although metamorphic biotite also shows minor alteration to stilpnomelane and chlorite, relict igneous biotite commonly shows much larger amounts of alteration to these phases.

Partial electron microprobe analyses of relict igneous biotite showed a marked decrease of potassium compared to the stoichiometric amount (compare sample R85 to R60, Table 6). Relict igneous biotite is generally more deformed whereas metamorphic biotite occurs as clean, well developed grains forming stringers partially defining foliation.

Assemblage (1) occurs in the southern extension of the pluton which is highly foliated. Foliation is defined by oriented stringers of epidote, muscovite, chlorite, actinolite (?), and polygonal quartz. Original plagioclase is highly altered to epidote, muscovite, sphene, calcite (minor), and albite of less than An_5 (Fig. 8). Only small amounts of microcline are present, most having been transformed to muscovite (compare modes, R12 and R1, Table 1). Chlorite grew from the actinolite (?) and epidote. Some chlorite and actinolite (?) grains within the stringers are not parallel to the foliation suggesting that they grew after the deformational phase accompanying regional metamorphism. Assemblage (2), found north of the locality of sample R21 carries stilpnomelane which occurs in sprays about perthite, epidote, relict igneous biotite, chlorite, and opaque minerals. Chlorite grew from relict igneous biotite and epidote (?). Also present in several samples are very small garnets, presumably spessartine-rich (Table 1, sample R35) and thus compatible with low grade metamorphic conditions.

A biotite isograd marks the appearance of zone 3. It is important to note that chlorite apparently grew from metamorphic biotite and epidote, and that stilpnomelane grew from perthite, epidote, metamorphic biotite, chlorite, and opaque minerals. In the petrographic section, it was suggested that some new mineral growth took place after the deformational event accompanying the main regional metamorphism. Because some chlorite has grown from metamorphic biotite, and sprays of stilpnomelane cut across the foliation and occur ubiquitously throughout the extent of assemblages (2) and (3), a second, less intense and lower grade metamorphism may have affected the pluton. Presently all K-rich feldspar is nearly pure microcline ($\sim Or_{97}$) with essentially no An content. All plagioclase is nearly pure low albite (Ab_{97-99}). The extreme compositions of the feldspar, showing no appreciable change in composition across the area, are also indicative of a late reequilibration, perhaps coinciding with growth of stilpnomelane.

ORIGINAL IGNEOUS MINERALOGY

Study of the original igneous mineralogy and its interpretation is complicated by the low grade regional metamorphism which caused a redistribution of elements among relict phases accompanied by addition of several new phases. Deformation promoted the recrystallization of quartz into small polygonal grains. However, enough of the original igneous texture is preserved to allow an interpretation of the igneous history of the intrusion.

The original igneous mineralogy probably consisted primarily of plagioclase (oligioclase or andesine, some zoned), monoclinic alkali feldspar (orthoclase or sanidine), high quartz and possibly even tridymite, and biotite. Possible accessory mineral phases included sphene (?), zircon, ilmenite, or magnetite. Minor amounts of fluorite, allanite, and epidote may have been formed by hydrothermal solutions on cooling.

Although an accurate description of the crystallization of the magma is difficult, the order of crystallization, an estimate of the composition of the first crystals, and the final composition of the liquid may be ascertained. Subhedral to euhedral plagioclase phenocrysts are commonly surrounded by perthitic rims and phenocrysts, which also mold themselves about quartz phenocrysts. Quartz locally appears to surround plagioclase, but this relationship is problematic in many samples because of the large amount of recrystallized quartz.

Even though substantial amounts of recrystallization have occurred, diamond-shaped phenocrysts of quartz can still be found. Minor resorption of plagioclase and quartz has been noted. Perthitic feldspar is generally anhedral and locally shows "cross-hatched" twinning (combination of albite and pericline twinning). Presence of this type of twinning indicates that alkali feldspar crystallized as monoclinic (that is orthoclase or sanidine) and was later inverted to triclinic (that is microcline) (Laves, 1950). Because of the low grade metamorphism, only a few relict biotite grains remain making their position in the order of crystallization unclear although probably late. Some of the epidote porphyroblasts are interpretated as late hydrothermal products formed during the cooling of the pluton while others are probably related to the later metamorphism. In any case, they are not part of the main igneous history. Textural relationships thus suggest that the order of crystallization was plagioclase, quartz and then K-rich feldspar. The exact compositional path along which the magma crystallized can be explained by either of two models discussed further on. For purposes of analysis, the normative feldspar compositions can be used as an average composition of all the feldspars (Fig. 9).

From modal analyses made within the grain boundaries of individual altered plagioclase phenocrysts (present composition: $Ab_{98.0}An_{1.6}Or_{0.5}$, mole percent), the original igneous compositions were estimated and plotted on the feldspar ternary diagram shown in Figure 9. An

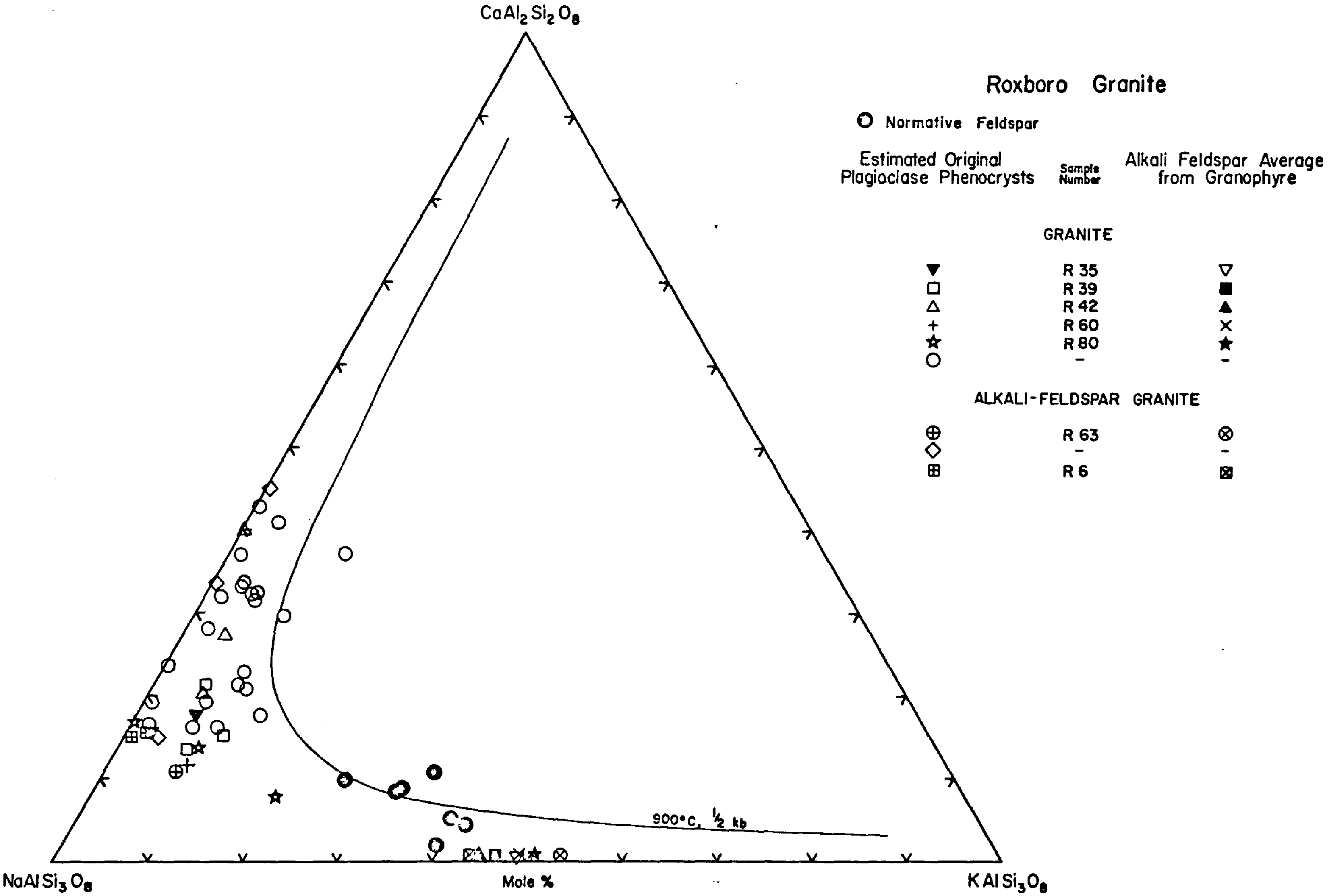


Figure 9. $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$ Plot of Normative, Estimated Plagioclase Phenocryst, and Granophyric Feldspar Compositions: 900°C, $^1/_2$ kb solvus isotherm after Seck (1971).

underlying assumption is that all calcium present in the rock was originally contained in feldspar. As an average of about 25 percent of modal epidote is present outside the feldspar grains as large porphyroblasts or with stringers of biotite, some calcium has left the feldspar. Thus, the original plagioclase would likely have had a higher An content than the average value of this plot, a crude estimate being An_{25} to An_{40}.

The last liquid to crystallize is represented by granophyre, which is not everywhere present in the pluton (see Fig. 2). Granophyric texture is similar to graphic intergrowths developed on quenching magnetite-pyrrhotite melts of the Fe-S-O system (Naldrett, 1969). By analogy, the intergrowths of alkali feldspar and quartz were presumably caused by rapid quenching of the magma. One way to accomplish this might be the release of volatiles from a volcanic vent. Modal analyses of granophyre were made on thin sections which contain a great abundance of this feature. Fifty counts were made on ten different areas of granophyre in each sample. An average of the ten areas was used as the modal analysis of the granophyre. By combining the average compositions of the albite and microcline phases ($Ab_{97.5}An_{1.5}Or_{1.0}$ and $Ab_{2.5}An_{0.1}Or_{97.4}$, weight percent) in the granophyre as determined by use of the electron microprobe, with the modes of the granophyre, an estimate of the final liquid composition was ascertained (Fig. 10). The electron microprobe was also used to analyze these intergrowths of alkali feldspar and quartz. Each

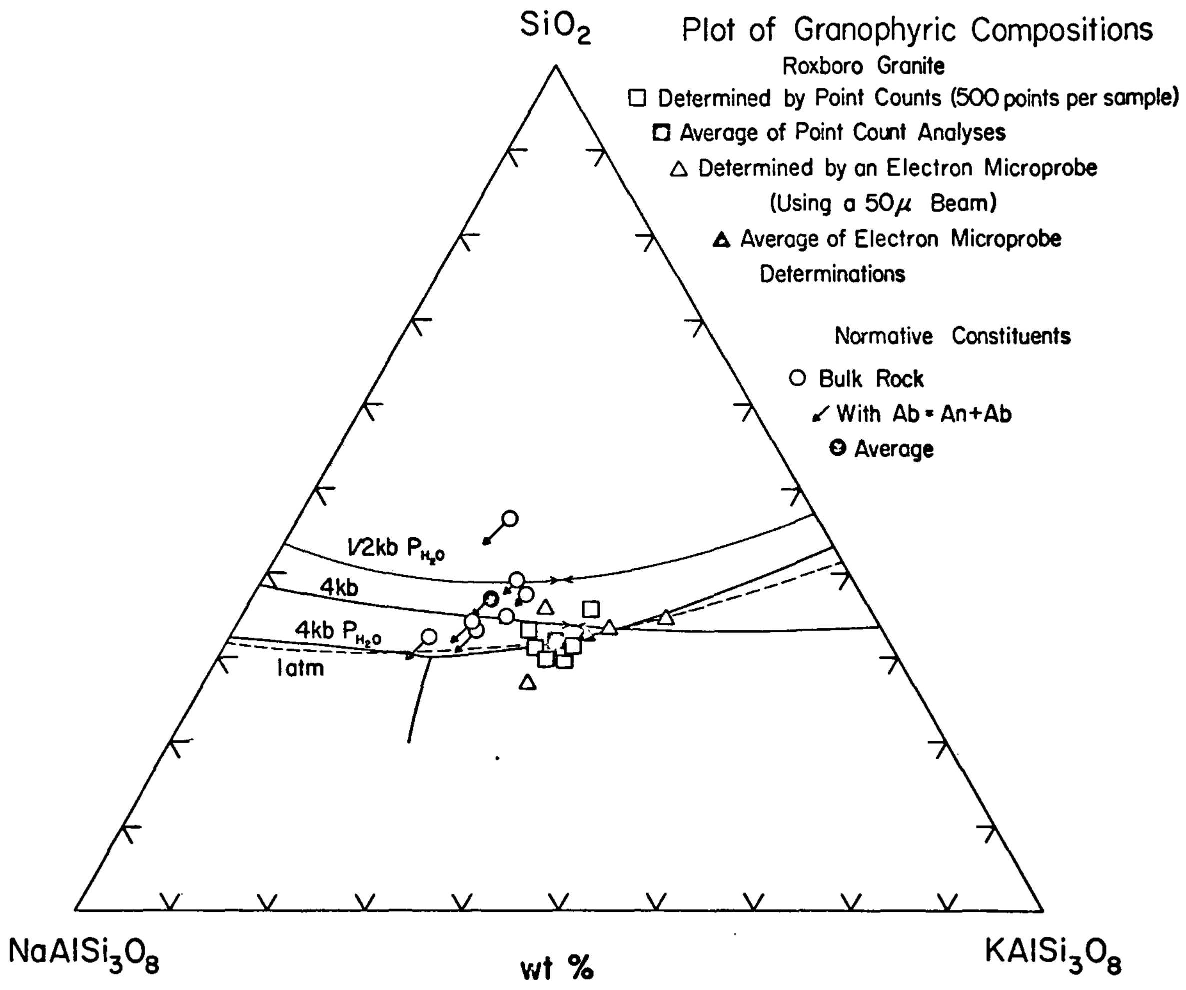


Figure 10. Liquidus boundary curves shown are: $^1/_2$ kbar P_{H_2O} curve after Tuttle and Bowen (1958), 1 atm curve after Schairer (1950), 4 kbar and 4 kbar P_{H_2O} curves after Steiner and others (1974).

analysis consisted of analyzing an area of approximately 10,000 square microns with a large beam of approximately 50 microns diameter. Many uncertainties are associated with the determination of the granophyric compositions. Among these are metasomatic action during low grade regional metamorphism which has probably caused some redistribution of elements during reequilibration of the mineral phases. This effect was minimized by only determining compositions in samples which contained the most granophyre. Since deformation has produced a minor flattening of the intergrowths, a slight bias in the determination is possible but this effect should be minor. The fact that the two different approaches noted above yielded similar values suggests a close approach to the correct composition (Fig. 10).

The first model (see Fig. 11, crystallization path o-p-q-i) involves the fractional crystallization of the magma and a crystal path which does not intersect the ternary feldspar solvus. In this case, the first crystals to appear are plagioclase (oligoclase or andesine) which were later accompanied by quartz. The estimated Or content of the plagioclase phenocrysts is too low if the crystal path were to have reached the solvus (2 coexisting feldspars), as can be seen by reference to the 900°C solvus isotherm, but compatible with a model where only one feldspar has crystallized (see Fig. 9). During crystallization, the plagioclase became less calcic as is indicated by relict zoning shown by concentration of alteration products in cores of some phenocrysts. Consistent with this, some of the small plagioclase appears less altered than the larger

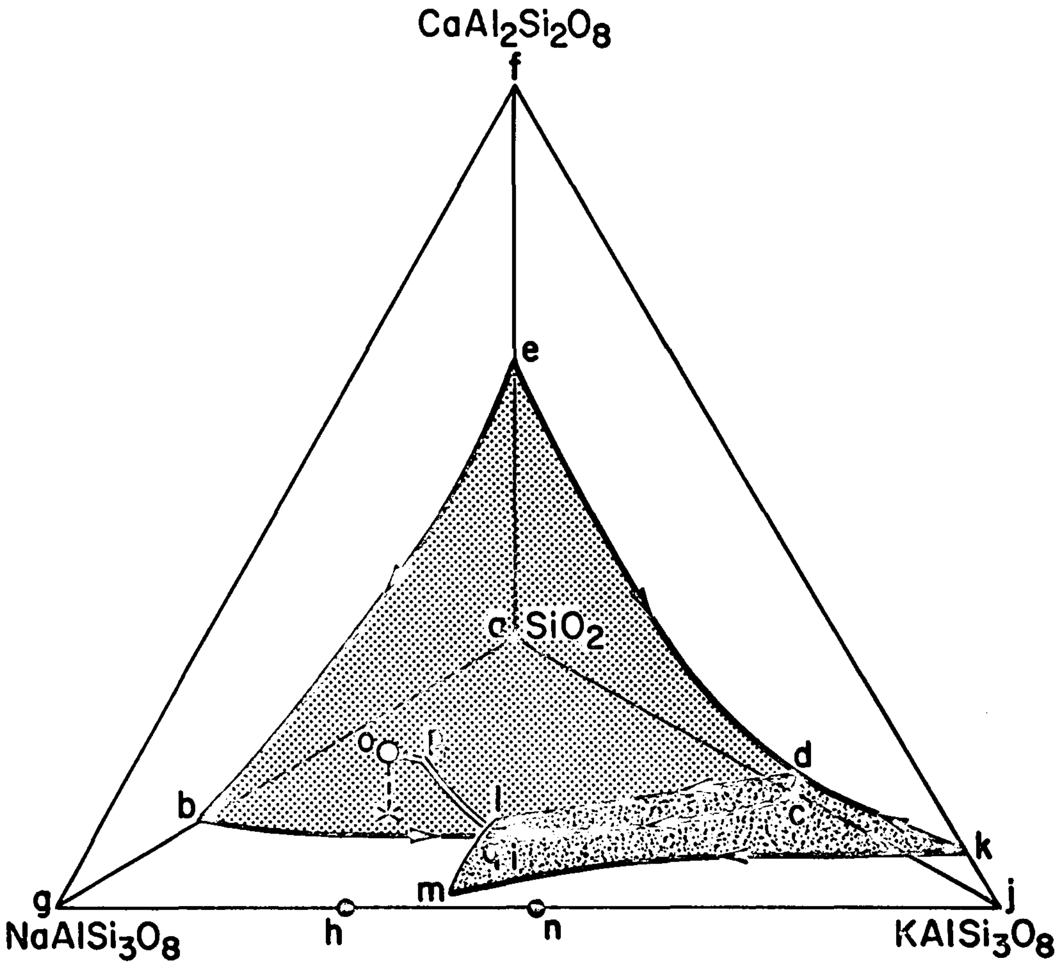


Figure 11. Schematic $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 Liquidus Diagram: After data in Schairer and Bowen (1947), Franco and Schairer (1951), Schairer (1957), and James and Hamilton (1969). Path o-p-q-i is a possible crystallization path as discussed in the text.

phenocrysts. Textural relationships suggest that the presently altered plagioclase stopped crystallizing before the perthitic feldspar began to crystallize because the small altered plagioclase is partially surrounded by perthite. Quartz and perthitic feldspar continued to crystallize until the body solidified, and where present the granophyre would represent the last liquid. Feldspar within granophyre plots on the K-feldspar side of the thermal trough in the ternary feldspar system, having 43 to 54 mole percent Or component. In order to obtain these granophyric feldspar compositions from this magma, fractional crystallization would be required. Restraints placed on this system by the initial bulk composition and by the permitted crystallization path make it impossible to obtain an alkali feldspar much richer in Or component than that observed in the granophyre. In conflict with this model, perthitic feldspar, separate from that in granophyre, ranges between 52 and 77 mole percent Or. Enrichment of the alkali feldspar in potassium during metamorphism is one explanation for such a range of compositions.

The second model is the fractional crystallization of the magma in which the crystal path intersects the ternary feldspar solvus during later stages of the crystallization history. As in the first case, plagioclase (oligioclase or andesine) is the first to crystallize and is later followed by quartz. Plagioclase would become less calcic as crystallization proceeds. When the liquid path intersects the boundary curve (surface) between the K-feldspar and plagioclase feldspar fields, the crystal path intersects the ternary solvus allowing albitic plagioclase and quartz to be accompanied by a potassium-rich feldspar. Albitic feldspar has crystallized in minor amounts as rims about the originally more calcic plagioclase as well as about a few of the perthitic grains. This is the main evidence for the crystallization of two coexisting feldspars. The potassium feldspar would initially have a high Or content thus offering an explanation for the estimated original amount of Or (52 to 77 mole percent) in the perthite. As crystallization of these three phases continued, compositions of the albitic and potassic rich phases would approach a common composition. Therefore, by the time that the granophyre was produced, the two feldspars only varied slightly in composition or even had become one, the liquid having passed the critical end point (Stewart and Roseboom, 1962), making it impossible to observe differences, particularly after the low grade metamorphic reequilibration.

Textures observed in the Roxboro granite are best explained by one of the fractional crystallization models. Equilibrium crystallization would require that crystals be in equilibrium with melt throughout the crystallization history. However, there is abundant evidence to the contrary. For example, the presence of zoned plagioclase phenocrysts and plagioclase of original composition between An_{25} and An_{40}, which would not be compatible with a granitic melt during the later stages of equilibrium crystallization, argue for fractional crystallization. Other evidence for this is that some phenocrysts of perthite are richer in Or component than alkali feldspar in granophyre of the same sample. Molding of alkali feldspar (now perthite) about plagioclase phenocrysts is also another characteristic of fractional crystallization.

PETROGENESIS

Estimated P-T Conditions of Emplacement

If the granophyre truly represents the last liquid to crystallize in the pluton, then its composition limits the possible conditions under which the Roxboro granite was finally emplaced. Because the granophyre is almost wholly composed of alkali feldspar and quartz, its composition can be plotted directly in the $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 system (Fig. 10). As a reference, normative compositions and their averages are also shown. At first glance, the normative average appears to lie in the primary crystallization field of quartz, thus contradicting textural observations which suggested that plagioclase was first to crystallize. However, this composition represents a point which has been projected onto the Ab-Or-quartz face of the quarternary system $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 (Fig. 11). In this system the primary crystallization field of plagioclase greatly expands with increasing An content (for example see James and Hamilton, 1969) making the quarternary system compatible with the textural observations of the previous section. The very minor amounts of epidote in the granophyric feldspar probably indicate that the original An content was initially very low. By reference to Figure 10 the following conditions of emplacement are possible: $P_{Total} = P_{H_2O} = 4$ kbar (H_2O satuated conditions), dry at P_{Total} of 4 to 5 kbar, and dry at P_{Total} of up to about 350 bars. The faults and merits of each will now be discussed.

At $P_{Total} = P_{H_2O} = 4$ kbar the composition of the liquidus at its lowest temperature, where quartz + sodic plagioclase + K-feldspar coexist, is far removed from where the granophyre actually plots. If this intrusion had crystallized under these conditions, the order of crystallization would have restricted the composition of the final liquid to plot at the "ternary" eutectic of the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2. In this case, coexistence of 2 feldspars should be clearly evident in the rocks. Finally, since the average granophyric composition lies on the quartz-K-feldspar boundary curve of this 4 kbar wet system, some other environment of emplacement is required to explain the observed texture and composition.

Another model of the environment of emplacement is that the pluton was dry at $P_{Total} = 4$ to 5 kbar. The average composition of the granophyre plots just below the 4 kbar curve of Steiner and others (1974). Since experimental data at moderate pressure in the dry ternary system, $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 are not presently available, experiments by Luth (1969) on the binary systems $NaAlSi_3O_8$-SiO_2 and $KAlSi_3O_8$-SiO_2 were used to estimate the slight variations in this ternary system about the 4 kbar curve. It was observed that the primary crystallization field of quartz expands gradually with increasing pressure. However, these pressures correspond to depths of the order of 12 to 15 km. At this level in the earth's crust, it would seem to be very difficult if not impossible to produce the amount of granophyre associated with this intrusion. This textural feature is more characteristic of quick cooling at generally shallow depths of emplacement. In addition, at depth of 12 to 15 km, regional temperatures would have probably been high enough to produce a low grade metamorphic reequilibration of the country rock, but there is no evidence of a metamorphic event at this crustal level at the time of emplacement (Glover and Sinha, 1973). Further, if crystallization had occurred at these high pressures, there would have been an improbably larger amount of sediment present in this area of the Carolina slate belt at the time of intrusion than is preserved today. The presently exposed thickness of the slate belt volcanics is at least 7 km and this would require a minimum of 19 km. Such thicknesses are possible but not probable (Glover, personal communication, 1974).

The third and probably most favorable environment of emplacement would be under almost "dry" conditions at very low pressures with perhaps a P_{Total} of up to about 350 bars. The average granophyric composition plots in the vicinity of the one atmosphere curve of Schairer (1950). However, if one considers the probable uncertainties inherent in this determination a slightly higher pressure is also acceptable. Because experimental data for the anhydrous system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 is lacking for pressures of several hundred bars, estimates of how the tridymite-alkali feldspar boundary curve changes with pressure were taken from Luth (1969). In the system $NaAlSi_3O_8$-SiO_2, the binary eutectic moves from 31.8 weight percent SiO_2, at one atmosphere to about 42-43 weight percent SiO_2 at one kilobar. The binary eutectic of the system $KAlSi_3O_8$-SiO_2 changes from about 41.7 weight percent SiO_2 at one atmosphere to about 43 weight percent SiO_2 at about 600 bars. Thus, in approximating the movement of the tridymite-alkali feldspar boundary curve with increasing pressure, an estimated pressure of up to about 350 bars is compatible with the observations. Melting experiments of Tuttle and Bowen (1958) of anhydrous synthetic granites at one atmosphere show that melting begins at about 960°C. Schairer (1950) suggests that at one atmosphere the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 has a minimum on the boundary curve. However, no minimum is shown by Schairer because of the very sluggish crystallization of the compositions in the vicinity of the boundary curve. With increasing pressure and increasing An content (James and Hamilton, 1969), the melting temperature of granite increases, however with increasing H_2O content, the melting temperatures are drastically lowered (Tuttle and Bowen, 1958). Assuming as a rough approximation that these two kinds of effects offset each other, the temperature at which crystallization was completed in the Roxboro granite can be assumed in the vicinity of 950°C.

Textural and field relations are also compatible with this latter interpretation. The presence of granophyre suggests that the liquid was quenched very rapidly during crystallization of the pluton. This is most likely to occur in shallow level intrusions, where some volatiles can be released through volcanic vents. The presence of granophyre in restricted areas of this intrusion suggests that several vents may have been present (see Fig. 2). The absence of pegmatitic dikes within the pluton also suggests that it was mostly hot and dry, with H_2O-solubility being exceeded only near the very end of crystallization. Glover (personal communication, 1974) has observed only a very minor amount of contact metamorphic effects in the surrounding country rock, which is in agreement with observations made by Tuttle and Bowen (1958). They suggest that even though hypersolvus granites crystallize at higher temperatures, the more H_2O-rich, lower temperature magmas of the subsolvus granites commonly show more profound contact metamorphic effects. The presence of a minor amount of relict euhedral quartz phenocrysts, a characteristic of rhyolites, pitchstones, and quartz porphyries, also suggest a shallow level of intrusion (Deer and others, p. 352, 1966). There is an absence of cataclastic textures which would have been suggestive of violent volcanic erruptions. This is compatible with the rather dry conditions postulated for this pluton, since it is the presence of abundant volatiles which produces violent volcanic activity. It is not known if there were any volcanic rocks associated with this pluton since erosion has removed all the younger stratagraphic units (Glover and Sinha, 1973). The presence of granophyre in only about 30 percent of the samples is perhaps less than would be expected from a pluton of this shallow a depth although low water content may be a factor. Field mapping by Glover indicates that the Roxboro granite intruded the faulted west limb of the Virgilina synclinorium.

Because of the complex structural relationships and erosion, it is impossible to reconstruct the amount of overburden on stratigraphic grounds alone. Crystallization of this magma may have begun at much greater depths, but as a whole, the final emplacement of a very H_2O-poor magma at low pressure appears compatible with the majority of observed textural, field, and mineralogical relationships.

Estimated P-T Conditions of Metamorphism

The best estimate of the environment of the main regional metamorphism comes from the Hagers mountain area approximately 3 km north of the pluton (see Fig. 2). Tobisch and Glover (1969) have reported the assemblage: kyanite-quartz-chloritoid-pyrophyllite. However, pyrophyllite formed from the kyanite and quartz (Glover, personal communication, 1974), either as the area cooled after the regional metamorphism or during a later, less intense, thermal high as suggested earlier for stilpnomelane growth. The P-T relationships of the aluminum silicates presented by Richardson and others (1969) combined with the pyrophyllite ----> Al_2SiO_5 + quartz curve of Kerrick (1968) and chloritoid + Al_2SiO_5 ----> staurolite + quartz curve of Richardson (1968) can be used to place rough limits on the metamorphic conditions. The kyanite-quartz-chloritoid assemblage is not stable over 540°C and would probably require 3 to 4-1/2 kbar. The formation of pyrophyllite has an upper temperature limit of 425°C and would probably require a minimum of 2 to 3-1/2 kbar, although this is recording a later event. Because the Hagers mountain area is higher metamorphic grade (garnet zone), and the isograds seem to swing to the west approaching the pluton (Tobisch and Glover, 1969), P-T conditions for regional metamorphism of the northern portion of the Roxboro metagranite would have been less than those mentioned above. If we assume about 400-450°C for the main metamorphism, then the biotite (0.4-0.5 weight percent F) coexisting with fluorite might have been in equilibrium with a fluid phase whose log f_{H_2O}/f_{HF} was about 4 to 5 (Munoz and Ludington, 1974).

Temperature estimates of metamorphism determined from compositions of exsolved phases within perthite can not clearly be related to the main regional metamorphism because of later, or retrograde effects. Both chlorite and biotite zones are recognized in the pluton. However, no shift of composition in the exsolved alkali feldspars has been observed with increasing metamorphic grade. Comparison of the observed compositions with the alkali feldspar solvus at 2.5 kbar (Luth and others, 1973) indicates temperatures of less than 300°C, probably more nearly 250°C. The presence of ferristilpnomelane can also be used to indicate the nature of the last recrystallization. Brown (1967) has performed experiments on ferristilpnomelane from low grade metamorphic rocks of eastern Otago, New Zealand. Although ferristilpnomelane from the Roxboro metagranite and that from the New Zealand greenschists may not be compositionally the same, a crude correlation can be assumed. At a P_{H_2O} of 3 kbar and 230°C ferristilpnomelane is unstable and breaks down into hematite or goethite plus an unknown phase. This suggests, as does the temperature estimate from the perthite and from pyrophyllite forming from kyanite + quartz, along with textural relationships of the stilpnomelane, that this area has partially reequilibrated under less intense conditions than those realized during the peak of the major regional metamorphic event.

CONCLUSIONS

The intrusion located at Roxboro, North Carolina is a chemically rather uniform granitic body having a minor amount of alkali-feldspar granitic and granodioritic facies. It was probably emplaced at very low pressures, perhaps around 350 bars total pressure with a relatively low P_{H_2O}, at a temperature of about 950°C. Concentrations of granophyre in the pluton may represent subvent areas. Some epidote grew from minor hydrothermal activity on cooling. During Taconic (?) and/or Acadian (?) time, this pluton was metamorphosed at a minimum pressure of about 3 kbar and a temperature of around 400°C. Deformation occurred during metamorphism forming a foliation defined by stringers of mainly biotite and epidote. Recrystallization continued after major deformation as shown by random orientation of individual biotite grains. Either during further cooling, or a later low grade event, stilpnomelane grew pervasively throughout the northern portion of the pluton and alkali feldspars reached extreme compositions. No deformation accompanied the last recrystallization.

The southern Piedmont of the Appalachian mountain system remains one of the most complex and least understood areas of regional geology of the United States. Therefore, detailed field work, petrographic studies and the application of relevant experimental data are extremely important in unraveling relationships revealed by these rocks.

LITERATURE CITED

Boone, G. M., and Wheeler, E. P., 1968, Staining for cordierite and feldspars in thin section: Am. Mineralogist, v. 53, p. 327-331.

Brown, E. H., 1967, The greenschist facies in part of eastern Otago, New Zealand: Contr. Mineralogy and Petrology, v. 14, p. 259-292.

Butler, J. R., and Ragland, P. C., 1969, A petrochemical survey of plutonic intrusions in Piedmont, southeastern Appalachians, U.S.A.: Contr. Mineralogy and Petrology, v. 24, p. 164-190.

Deer, W. A., Howie, R. A., and Zussman, J., 1966, An introduction to the rock-forming minerals: New York, John Wiley and Sons, Inc., 528 p.

Doman, R. C., Cinnamon, C. G., and Bailey, S. W., 1965, Structural discontinuities in the plagioclase feldspar series: Am. Mineralogist, v. 50, p. 724-740.

Franco, R. R., and Schairer, J. F., 1951, Liquidus temperatures in mixtures of the feldspars of soda, potash, and lime: Jour. Geology, v. 59, p. 259-267.

Fullagar, P. D., 1971, Age and origin of plutonic intrusions in the Piedmont of the southeastern Appalachians: Geol. Soc. America Bull., v. 82, 2845-2862.

Fullagar, P. D., Lemmon, R. E., and Ragland, P. C., 1971, Petrochemical and geochronological studies of plutonic rocks in the southern Appalachians: I. The Salisbury pluton: Geol. Soc. America Bull., v. 82, p. 409-415.

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 (Cooper volume), p. 234-251.

Hadley, J. B., 1973, Igneous rocks of the Oxford area, Granville county, North Carolina: Am. Jour. Sci., v. 273-A (Cooper volume), p. 217-233.

Hills, F. A., and Butler, J. R., 1969, Rubidium-strontium dates for some rhyolites from the Carolina slate belt of the North Carolina Piedmont: Geol. Soc. America, Abs. for 1968, Spec. Paper 121, p. 445.

Hutton, C. O., 1938, The stilpnomelane group of minerals: Mineralog. Mag., v. 25, p. 172-206.

I. U. G. S. Subcommission of Systematics of Igneous Rocks, 1973, Plutonic rocks, classification and nomenclature: Geotimes, v. 18, no. 10, p. 26-30.

James, R. S., and Hamilton, D. L., 1969, Phase relations in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-SiO_2 at 1 kilobar water vapour pressure: Contr. Mineralogy and Petrology, v. 21, p. 111-141.

Kerrick, D. M., 1968, Experiments on the upper stability limit of pyrophyllite at 1.8 kilobars and 3.9 kilobars water pressure: Am. Jour. Sci., v. 266, p. 204-214.

Laves, F., 1950, The lattice and twinning of microcline and other potash feldspars: Jour. Geology, v. 58, p. 548-571.

Luth, W. C., 1969, The systems $NaAlSi_3O_8$-SiO_2 and $KAlSi_3O_8$-SiO_2 to 20 kb and the relationship between H_2O content, P_{H_2O}, and P_{Total} in granitic magmas: Am. Jour. Sci., v. 267-A (Schairer volume), p. 325-341.

Luth, W. C., Martin, R. F., and Fenn, P. M., 1973, Peralkaline alkali feldspar solvi, in MacKenzie, W. S., and Zussman, J., (eds.), Proc. N. A. T. O. Advanced Studies Institute on Feldspars: Manchester, Manchester Univ. Press, p. 297-312.

Miyashiro, A., 1961, Evolution of metamorphic belts: Jour. Petrology, v. 2, p. 277-311.

Munoz, J. L., and Ludington, S. D., 1974, Fluoride-hydroxyl exchange in biotite: Am. Jour. Sci., v. 274, p. 396-413.

Naldrett, A. J., 1969, A portion of the system Fe-S-O between 900 and 1080°C and its application to sulfide ore magmas: Jour. Petrology, v. 10, p. 171-201.

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geol. Soc. America Bull., v. 65, p. 1007-1032.

Richardson, S. W., 1968, Staurolite stability in a part of the system Fe-Al-Si-O-H: Jour. Petrology, v. 9, p. 467-488.

Richardson, S. W., Gilbert, M. C., and Bell, P. M., 1969, Experimental determination of kyanite-andulusite and andulusite-sillimanite equilibria; the aluminum silicate triple point: Am. Jour. Sci., v. 267, p. 259-272.

Rucklidge, J., and Gasparrini, E. L., 1969, EMPADR VII-Specifications of a computer program for processing electron microprobe analytical data: Dept. Geol., Univ. Toronto.

Schairer, J. F., 1950, The alkali-feldspar join in the system $NaAlSiO_4$-$KAlSiO_4$-SiO_2: Jour. Geology, v. 58, p. 512-517.

Schairer, J. F., 1957, Melting relations of the common rock forming oxides: Jour. Ceram. Soc., v. 40, p. 215-235.

Schairer, J. F., and Bowen, N. L., 1947, The system anorthite-leucite-silica: Bull. Comm. geol. Finlande, No. 140, p. 67-87.

Seck, H. A., 1971, Koexistierende alkalifeldspäte und plagiocklase im system $NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-H_2O bei temperaturen von 650°C bis 900°C: N. Jb. Miner. Abh., v. 115, no. 3, p. 315-345.

Steiner, J. C., Jahns, R. H., and Luth, W. C., 1974, Crystallization of alkali feldspars and quartz in the haplogranite system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O at 4 kbar: Geol. Soc. America Bull., (in press).

Stewart, D. B., and Roseboom, E. H., Jr., 1962, Lower temperature terminations of the three-phase region plagioclase-alkali feldspar-liquid: Jour. Petrology, v. 3, p. 280-315.

Tobisch, O. T., and Glover, L., III, 1969, Metamorphic changes across part of the Carolina slate belt-Charlotte belt boundary, North Carolina and Virginia: U. S. Geol. Survey Prof. Paper 650-C, p. C1-C7.

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.

Tuttle, O. F., and Bowen, N. L., 1958, Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O: Geol. Soc. America Mem. 74, 153 p.

Wagener, H. D., 1965, Areal modal variation in the Farrington igneous complex, Chatham and Orange counties, North Carolina: Southeastern Geology, v. 6, p. 49-77.

Wagener, H. D., 1973, Petrology of adamellites, granites and related metamorphic rocks of the Winnsboro quadrangle, South Carolina: The Citadel: Monograph Series, no. X, 75 p.

Wagener, H. D., Ragland, P. C., and Billings, G. K., 1969, Chemical fractionation in the Farrington igneous complex, North Carolina: Geol. Soc. America, Abs. for 1968, Spec. Paper 121, p. 472.

APPENDIX 1. SAMPLE DESCRIPTIONS

R1: Microphaneritic granite, phenocrysts of plagioclase, quartz, and perthite, no granophyre, moderately foliated.

R3: Microphaneritic granite (groundmass: 0.5-1.0 mm), medium gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, weakly foliated.

R4: Microphaneritic granite (groundmass: 0.15-0.3 mm), light pinkish gray, phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, no granophyre, weakly foliated.

R5: Microphaneritic granite (groundmass :0.15-0.4 mm), light gray, phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, moderate amount of granophyre, strongly foliated.

R6: Microphaneritic alkali-feldspar granite, light reddish gray phenocrysts of plagioclase, quartz, and perthite, large allanite, sphene, and fluorite grains are also present, abundant granophyre, weakly foliated.

R7: Microphaneritic alkali-feldspar granite (groundmass: 0.2-0.3 mm), light gray, phenocrysts of plagioclase, quartz, and perthite, large allanite (possible late hydrothermal product), moderate amount of granophyre, moderate foliation.

R8: Microphaneritic granite, light gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, weakly foliated.

R9: Granite or granodiorite (?), medium greenish gray, phenocrysts of quartz, and plagioclase, highly altered, no granophyre, strongly foliated.

R12: Granite or granodiorite (?), medium gray, phenocrysts of plagioclase, quartz, and K-feldspar, highly altered, no granophyre, moderately foliated.

R18: Rhyolite dike, brownish yellow, phenocrysts of quartz and plagioclase, porphyroblasts of epidote, moderately foliated.

R21: Rhyolite dike, brownish yellow, phenocrysts of plagioclase, porphyroblasts of epidote, strongly foliated.

R25: Microphaneritic granite, light gray, equigranular, sparse phenocrysts of plagioclase, quartz, and perthite (very minor), no granophyre, no foliation.

R26: Microphaneritic granite, medium gray, equigranular, sparse phenocrysts of plagioclase, perthite, and quartz, no granophyre, no foliation.

R28: Rhyolitic dike, phenocrysts of plagioclase, quartz, perthite, and opague minerals, porphyroblasts of epidote, euhedral to subhedral diamond shaped quartz phenocrysts, minor resorbed quartz, minor foliation.

R28A: Mafic dike, (groundmass: 0.2-0.3 mm), light green, porphyroblasts of actinolite (?), large clumps (up to 5 mm) of fine grained muscovite, entirely metamorphic, no foliation.

R34C: Microphaneritic granodiorite (groundmass: 0.7-0.9 mm), medium gray, phenocrysts of plagioclase, quartz, and minor perthite, no granophyre, no foliation.

R34E: Microgranitic dike, light pinkish gray, phenocrysts of plagioclase (minor), perthite, and quartz, abundant granophyre, no foliation.

R35: Microphaneritic granite (groundmass: 0.1-0.3 mm), light whitish gray, phenocrysts of plagioclase, quartz, and perthite (minor), porphyroblasts of epidote, abundant granophyre, weakly foliated.

R39: Microphaneritic granite, light pinkish gray, phenocrysts of plagioclase, quartz, and perthite (minor), porphyroblasts of epidote, abundant granophyre, weakly foliated.

R42: Microphaneritic granite, light whitish gray, phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, abundant granophyre, moderately foliated.

R43: Microphaneritic granodiorite, grayish green, phenocrysts of plagioclase, quartz, and perthite, abundant granophyre shown by plagioclase and quartz, weakly foliated.

R49: Microphaneritic alkali-feldspar granite, light brownish gray, phenocrysts of antiperthite, quartz and plagioclase (minor), no granophyre, weakly foliated.

R51: Microphaneritic granite (groundmass: 0.2-0.4 mm), medium gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, moderately foliated.

R54: Microphaneritic alkali-feldspar granite (groundmass: 0.2-0.5 mm), light pinkish gray, phenocrysts of plagioclase, perthite, quartz, and minor albite (not altered, about the perthite), no granophyre, weakly foliated.

R55: Phaneritic alkali-feldspar granite, phenocrysts of quartz, perthite, and plagioclase, minor albite about perthite (slightly altered), no granophyre, no foliation.

R60: Microphaneritic granite (groundmass: 0.3-0.6 mm), medium gray, phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, moderate amount of granophyre, moderately foliated.

R61: Microphaneritic granite (groundmass: 0.4-0.6 mm), medium gray, phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, minor granophyre, moderately foliated.

R62: Microphaneritic granite (groundmass: 0.3-0.6 mm), medium gray, phenocrysts of plagioclase, perthite, and quartz, porphyroblasts of epidote, minor granophyre, moderately foliated.

R62B: Mafic Dike (groundmass: 0.05-0.2 mm), greenish gray, phenocrysts of plagioclase, large sphenes, strongly foliated.

R63: Microphaneritic alkali-feldspar granite, light whitish gray, phenocrysts of perthite, quartz, and plagioclase (minor), porphyroblasts of epidote, and large masses and sprays of stilpnomelane, some albitic rims about the perthite, abundant granophyre, no foliation.

R66: Sheared granite (?), light whitish gray, phenocrysts of plagioclase and quartz, no granophyre, strongly foliated.

R69: Microphaneritic granite (groundmass: 0.3-1.0 mm), medium gray, phenocrysts of plagioclase, perthite, and quartz, no granophyre, moderately foliated.

R70: Microphaneritic granite, medium gray, phenocrysts of plagioclase, perthite, and quartz, porphyroblasts of epidote, minor granophyre, moderately foliated.

R71: Microphaneritic granite, medium gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, weakly foliated.

R73: Microphaneritic granite (groundmass: 0.5-0.7 mm), phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, no granophyre, moderately foliated.

R75: Microphaneritic granite (groundmass: 0.4-0.6 mm), phenocrysts of plagioclase, quartz, and perthite, no granophyre, moderately foliated.

R80: Microphaneritic granite, light reddish gray, phenocrysts of plagioclase, perthite, and quartz, porphyroblasts of epidote and fluorite (?), minor amount of albitic plagioclase surrounding perthites, abundant granophyre, weakly foliated.

R83: Microphaneritic granite (groundmass: 0.3-0.7 mm), light gray, phenocrysts of plagioclase, perthite, and quartz, porphyroblasts of epidote and allanite, no granophyre, moderately foliated.

R85: Microphaneritic granite (groundmass: 0.7-1.0 mm), light pinkish gray, phenocrysts of plagioclase, perthite, and quartz, large chlorite replacing relict igneous biotite, no granophyre, weakly foliated.

R88: Aphanitic-microphaneritic granite porphyry, contact zone, light gray, phenocrysts of plagioclase and quartz, no granophyre, strongly foliated.

R92: Microphaneritic granite (groundmass: 0.7-1.0 mm), light whitish gray, phenocrysts of plagioclase, quartz, perthite, and sphene (?), porphyroblasts of epidote, no granophyre, moderately foliated.

R93: Microphaneritic granite, light pinkish gray, phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, no granophyre, weakly foliated.

R95: Microphaneritic granite (groundmass: 0.5-0.6 mm), medium gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, moderately foliated.

R98: Microphaneritic granite (groundmass: 0.5-1.0 mm), medium gray, phenocrysts of plagioclase, perthite, and quartz, no granophyre, moderately foliated.

R102: Microphaneritic granite (groundmass: 0.5-0.7 mm), light gray, phenocrysts of plagioclase, perthite, and quartz, porphyroblasts of epidote, no granophyre, moderately foliated.

R106: Microphaneritic granite (groundmass: 0.5-1.0 mm), light gray, phenocrysts of plagioclase, perthite, and quartz, porphyroblasts of epidote, no granophyre, moderately foliated.

R107: Microphaneritic granite (groundmass: 0.5-0.7 mm), light gray, phenocrysts of plagioclase, perthite, and quartz, porphyroblasts of epidote, no granophyre, moderately foliated.

R108A: Hydrothermally altered xenolith, possibly originally a quartzite which may show graded bedding.

R109: Hydrothermally altered xenolith, clinozoisite is aleigned in stringers.

R109A: Post metamorphic phaneritic granodiorite, equigranular, (1.0-1.5 mm), plagioclase shows concentric zoning.

R110: Post metamorphic diabase dike, black with white plagioclase phenocrysts.

R113: Microphaneritic granite (groundmass: 0.2-0.4 mm), light gray, phenocrysts of plagioclase, quartz (?), and perthite, no granophyre, moderately foliated.

R122: Microphaneritic granite (groundmass: 0.7-1.0 mm), light pinkish gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, weakly foliated.

LG8-167: Microphaneritic alkali-feldspar granite (groundmass: 0.15-0.30 mm), light pinkish gray, phenocrysts of plagioclase, quartz, and antiperthite, minor granophyre, weakly foliated.

LG8-179: Microphaneritic-phaneritic granite (groundmass: 0.7-1.5 mm), light gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, weakly foliated (?).

LG8-181: Microphaneritic-phaneritic granite (groundmass: 0.7-1.2 mm), light pinkish gray, phenocrysts of plagioclase, perthite, and quartz, no granophyre, weakly foliated (?).

LG7-358A: Microphaneritic granite (groundmass: 0.2-0.3 mm), light gray, phenocrysts of plagioclase, quartz, and perthite, porphyroblasts of epidote, no granophyre, moderately foliated.

LG7-358B: Microgranite dike (groundmass: 0.05-0.20 mm), medium gray, phenocrysts of plagioclase, perthite (mostly K-feldspar component), and quartz (?), porphyroblasts epidote, no granophyre, strongly foliated.

LG7-360: Microgranodioritic dike (groundmass: 0.1-0.5 mm), medium gray, phenocrysts of plagioclase, and quartz, porphyroblasts of epidote, no granophyre, moderately foliated.

LG7-362: Microphaneritic granite, phenocrysts of plagioclase, quartz, and perthite, no granophyre, moderately foliated.

LG7-368: Microphaneritic granite, medium gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, no foliation.

LG8-505: Microphaneritic granite (groundmass: 0.3-0.6 mm), pinkish gray, phenocrysts of plagioclase, quartz, and perthite, no granophyre, weakly foliated.

LG8-542: Granite or granodiorite (?), grayish white, phenocrysts of plagioclase and quartz, porphyroblasts of epidote, highly altered, no granophyre, moderately foliated.

APPENDIX 2. FELDSPAR ANALYSES.

Microprobe Analyses of Exsolved Portions of Alkali Feldspar

			mole%	
Sample		Ab	Or	An
R5	Microcline	3.2	96.6	0.1
R42	Albite	98.4	0.7	0.9
	Microcline	2.8	97.2	0.0
R69	Albite	96.0	1.6	2.4
	Microcline	2.0	97.8	0.1
R71	Albite	97.0	1.1	1.9
	Microcline	2.4	97.5	0.1
LG8-167	Albite	98.7	0.6	0.6
	Microcline	3.0	96.9	0.1
LG8-542	Albite	97.9	0.9	1.2
	Microcline	2.8	97.1	0.0

Microprobe Analyses of the Plagioclase

		mole%	
Sample	Ab	Or	An
R60	98.2	0.4	1.3
R71	98.0	0.3	1.8
R75	97.9	0.4	1.7
R93	98.4	0.4	1.1
LG8-167	97.3	0.4	2.4
LG8-542	94.5	0.6	4.8

APPENDIX 2 CONTINUED

Plagioclase Analyses from the Post Metamorphic Granodiorite

R109A

	Mole%		
Sample	Ab	Or	An
Grain 1 Position 1	80.7	0.5	18.8
Grain 1 Position 2	78.0	0.5	21.6
(Step Scan across grain) in 20 micron steps	81.5	0.3	18.2
	81.5	0.2	18.3
	81.2	0.4	18.4
	80.0	0.3	19.6
	75.6	0.4	24.0
	-	-	-
	82.4	0.2	17.4
	75.5	0.4	24.1
	76.5	0.5	23.0
	74.2	0.5	25.4
	72.7	0.6	26.7
	-	-	-
	78.3	0.3	21.4
	-	-	-
	86.4	0.2	13.4
	81.8	0.4	17.8
	79.9	0.2	19.9
	78.1	0.3	21.6
	80.0	0.9	19.1
	79.5	0.5	20.0
	78.0	0.3	21.7
	75.2	0.3	24.5
	-	-	-
	-	-	-
	78.1	1.7	20.1
	-	-	-

APPENDIX 2 CONTINUED

Sample	Ab	Or	An
	80.2	0.2	19.6
	-	-	-
	74.2	0.3	25.5
	73.7	0.4	25.9
	72.7	0.6	26.7
	78.2	0.3	21.5
	-	-	-
	-	-	-
	79.1	0.2	20.7
	78.1	0.5	21.5
	-	-	-
	-	-	-
	79.3	0.4	20.2
	79.7	0.6	19.7
Grain 1 Position 3	78.9	0.3	20.8
Grain 1 Position 4	73.7	0.3	25.9
Grain 1 Position 5	78.2	0.7	21.2
Grain 1 Position 6	78.4	0.4	21.3
Grain 2 Position 1	78.0	0.4	21.5
Grain 2 Position 2	76.6	0.6	22.8
Grain 2 Position 3	81.2	0.5	18.4
Grain 2 Position 4	80.5	0.5	18.9
Grain 3 Position 1	80.8	0.5	18.7
Grain 3 Position 3	81.8	0.5	17.7
Grain 3 Position 4	75.0	1.4	23.6
Grain 3 Position 5	74.3	0.3	25.4
(Step Scan across Grain) in 20 micron steps	78.2	0.2	21.6
	76.3	0.6	23.1
	74.2	0.4	25.4
	-	-	-

APPENDIX 2 CONTINUED

Sample	Ab	Or	An
	73.8	0.4	25.8
	81.2	0.4	18.4
	73.2	0.6	26.2
	74.5	0.7	24.8
	85.3	0.2	14.5
	80.3	0.4	19.3
	-	-	-
	77.2	0.5	22.3
	78.4	0.3	21.3
	74.5	0.5	25.0
Grain 4 Position 2	79.9	0.4	19.7
Grain 4 Position 4	81.0	0.4	18.5

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*The - mark represents a point in the step scan where the analysis was not acceptable.

APPENDIX 3. DESCRIPTION OF MINERALS PARTIALLY ANALYZED

R8:	Green biotite is surrounded by fluorite.
R12 Grain 1:	Light yellowish green-light green chlorite surrounded by quartz.
R60 Grain 1:	Green chlorite with a couple of stilpnomelane needles growing from it.
R60 Grain 2:	Reddish brown stilpnomelane spray at grain boundary between a plagioclase and a perthitic grain.
R60 Grain 3:	Green biotite lying on its 001 face.
R60 Grain 4:	Clear-light greenish tinted epidote porphyroblast.
R60 Grain 5:	Reddish brown stilpnomelane spray having minor, small opaque grains within them.
R60 Grain 6:	Light yellowish green-dark brownish green biotite in stringer with epidote.
R60 Grain 7:	Light yellowish green-dark brownish green biotite.
R60 Grain 8:	Light yellowish green-dark green chlorite growing from an epidote porphyroblast.
R60 Grain 9:	Epidote grain as an alteration product of plagioclase.
R71:	Muscovite alteration of plagioclase.
R75 Grain 1:	Muscovite alteration of plagioclase.
R75 Grain 2:	Muscovite alteration of plagioclase.
R85 Grain 1:	Yellowish green-black biotite with sphene inclusions.
R85 Grain 2:	Light yellowish green tint-brownish green biotite which appears to be altering to chlorite.

APPENDIX 3 CONTINUED

R85 Grain 4: Green chlorite with sphene and possible zircon (?) inclusions.

R85 Grain 5: Light yellowish green-reddish brown biotite with epidote and sphene.

R85 Grain 6: Reddish brown stilpnomelane sprays which contain opaque grains.

R85 Grain 7: Green-dark green biotite which appears to be altering to chlorite.

R85 Grain 8: Green chlorite with minor sphene inclusions.

R85 Grain 9: Yellowish brown-reddish brown stilpnomelane spray.

R93 Grain 6: Muscovite alteration of plagioclase.

R93 Grain 7: Stringer of muscovite.

APPENDIX 4. ESTIMATED ORIGINAL PLAGIOCLASE COMPOSITIONS

		mole %	
Sample	Ab	Or	An
R1	74.6	9.3	16.1
	74.2	6.4	19.4
	62.9	5.7	31.3
	68.3	8.9	22.8
R3	63.5	3.4	33.1
	60.7	9.7	29.5
	62.7	5.1	32.2
R6	82.1	2.3	15.6
	84.0	1.0	15.0
R12	50.5	12.3	37.2
R25	55.7	3.4	40.9
	62.1	5.5	32.4
	63.1	3.5	33.4
R35	76.2	6.3	17.5
	81.9	2.7	15.4
R39	73.3	5.6	21.1
	74.4	10.4	15.2
	79.2	7.4	13.5
R42	74.0	5.7	20.3
	59.7	0.2	40.0
	68.5	4.3	27.2
R54	81.8	5.9	12.3
	82.0	4.4	13.5
R55	71.6	7.2	21.2
R60	80.0	11.6	8.3
R62	61.6	1.5	36.9
	69.6	2.4	28.0
R63	81.5	7.6	10.9

APPENDIX 4 CONTINUED

Sample	mole % Ab	Or	An
R69	81.6	1.9	16.5
	69.1	13.2	17.7
	76.0	0.3	23.7
	79.7	1.0	19.3
R71	56.8	0.3	42.9
	66.3	1.9	31.8
	69.7	9.0	21.2
R80	82.9	0.3	16.8
	72.6	19.8	7.6
	77.8	8.6	13.6
R98	77.1	6.6	16.3
	69.1	10.1	20.8
LG8-167	54.8	0.2	45.0
	81.2	3.8	15.0
	66.2	0.3	33.6

APPENDIX 5. EPIDOTE POINT COUNT

Sample	In Feldspar	Outside Feldspar in Stringers and Porphyroblasts
R1	75	25
R3	85	15
R12	59	41
R25	91	9
R42	83	17
R62	80	20
R69	65	35
R71	90	10
R98	68	32
LG8-167	56	44

APPENDIX 6. GRANOPHYRIC FELDSPAR COMPOSITIONS[1,2]

Sample	Mole %		
	Ab	Or	An
R6	55.7	43.5	0.8
R35	50.4	48.8	0.7
R39	53.0	46.3	0.7
R42	54.5	44.8	0.7
R42[3]	44.7	54.4	0.9
R60	50.4	48.9	0.8
R63	46.1	53.2	0.6
R80	48.9	50.4	0.8

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1. Determined from modal analyses of chemically analyzed feldspars in the granophyre. The very minor amount of epidote present within the granophyre was not included in the modal analyses.

2. If two feldspars crystallized in the granophyre, these values would represent an average composition.

3. Average feldspar composition within the granophyre as determined from electron microprobe analyses using an open beam (50 microns in diameter).

APPENDIX 7. GRANOPHYRIC COMPOSITIONS

		Wt %	
Sample	Ab	Or	Quartz
A. Determined from modal analyses			
R6	36.5	30.3	33.2
R35	34.7	35.7	29.6
R39	36.4	33.8	29.8
R42	36.7	32.0	31.2
R60	33.9	34.9	31.2
R63	28.9	35.4	35.7
R80	32.7	35.9	31.4
Average	34.3	34.0	31.7
B. Determined by an electron microprobe (using a 50 micron beam)			
R42	33.3	30.7	36.0
	39.7	33.3	27.0
	28.0	38.4	33.6
	21.8	43.8	34.4
Average	30.7	36.6	32.7

APPENDIX 8. PROCEDURES

Staining Procedure

Thin sections were stained for both K-feldspar and plagioclase using sodium cobaltinitrite and amaranth. The method of staining was similar to that of Boone and Wheeler (1968) except that the final rinse was made with ethyl alcohol instead of water to prevent amaranth from being dissolved. With this procedure, plagioclase with an An content of one mole percent was successfully stained.

Probe Analyses and Procedure

An ARL-SEM electron microprobe was used to chemically analyze the feldspars and to confirm the identification of several other minerals. The EMPADR VII program by Rucklidge and Gasparrini (1969) was used to reduce the feldspar data by apportioning aluminium and silicon stoichiometrically. The analyzing crystals were LiF for K and Ca, and RAP for Na, in every case using the Kα wavelengths. Operating conditions were 15 kilovolts, 0.15μ amp beam current, 1.00μ sec dead time, and 150μ amp emission current. Standards were Tiburon albite (assumed stoichiometric), anorthite (assumed stoichiometric), and orthoclase (0.85% Na, 9.83% Al, 30.08% Si, 12.39% K, 0.73% Ba, 46.12% O, weight percent), all obtained by courtesy of P. H. Ribbe.

The feldspars were analyzed at 3 to 4 points on each of 3 to 4 grains per sample using photographs and sketches to locate the position of the analysis. A small beam (7-10 microns) was used to probe a small portion of the sample. In order to determine the compositions of the perthitic phases, analyses were only made on the most potassium-rich (microcline) and the most sodium-rich (albite) areas. An intermediate value was disregarded as indicating that the beam had overlapped a phase boundary.

Partial analyses of biotite, epidote, stilpnomelane, chlorite, and muscovite were made. Raw data from the electron microprobe were corrected only for background and then compared to the standards neglecting other corrections. The beam size was about 5 microns. A biotite surrounded by fluorite was analyzed for fluorine using the fluorite as a standard.

Single Crystal X-ray Methods

A Charles Supper precession camera was used to obtain photographs for structural state analyses on four plagioclase grains from a single sample. Both copper and molybdenum Kα radiation was used. After analyzing the plagioclase with an electron microprobe, the crystals were mounted perpendicular to the 010 cleavage, allowing γ^* to be measured from a hk0 level precession photograph. The γ^* versus mole percent anorthite plot of Doman and others (1965) was used to determine the structural state.

Approximation of the Original Plagioclase Compositions

Modal analyses, which are good estimates of a volume percent were made of individual altered plagioclase phenocrysts. The mineral phases which are included in these analyses are plagioclase ($Ab_{98.0}An_{1.6}Or_{0.5}$, mole percent), epidote or clinozoisite, muscovite, fluorite (very minor), and sphene (very minor).

The volumes of the phases present were converted to moles and the following reactions were used to approximate amounts of anorthite and orthoclase which could be formed from their alteration products.

$$2CaAl_2Si_2O_8 + {}^1/_2\,H_2O \rightleftarrows Ca_2Al_3Si_3O_{12}(OH) + SiO_2 + {}^1/_2\,Al_2O_3$$

(Anorthite) (Clinozoisite)

$$KAlSi_3O_8 + Al_2O_3 + H_2O \rightleftarrows KAl_3Si_3O_{10}(OH)_2$$

(Orthoclase) (Muscovite)

$$3CaAl_2Si_2O_8 + 3FeTiO_3 + {}^1/_2\,O_2 \rightleftarrows 3CaTiSiO_5 + Fe_3O_4 + 3SiO_2 + 3Al_2O_3$$

(Anorthite) (Ilmenite) (Sphene) (Magnetite)

$$CaAl_2Si_2O_8 + F_2 \rightleftarrows CaF_2 + Al_2O_3 + 2SiO_2 + {}^1/_2O_2$$

(Anorthite) (Fluorite)

The metamorphic composition of the plagioclase was taken into consideration when these approximations were made.

PETROLOGY OF THE ROXBORO METAGRANITE, NORTH CAROLINA

by

David F. Briggs

(ABSTRACT)

The intrusion located at Roxboro, North Carolina is predominantly a light gray to medium gray, microphaneritic granite, now metamorphosed. Phenocrysts of plagioclase, quartz, and perthite are accompanied by porphyroblasts of epidote. Relict igneous textural relationships suggest two possible fractional crystallization models, in which the order of crystallization was plagioclase, quartz, and then K-rich feldspar. A crude approximation of the original plagioclase phenocryst An content ranges between An_{25} to An_{40}. An estimate of the granophyric composition reveals that the pluton was emplaced under almost "dry" conditions with a P_{Total} of about 350 bars and a temperature in the vicinity of 950°C. Some epidote porphyroblasts grew during minor hydrothermal activity on cooling. During the middle Paleozoic, this granitic intrusion was metamorphosed at a minimum pressure of about 3 kbar and a temperature of around 400°C. A foliation, as shown by stringers of mainly biotite and epidote, was produced by the deformational phase accompanying the regional metamorphism. All K-rich feldspar is nearly pure microcline ($\sim Or_{97}$) and all plagioclase is nearly low albite (An_{97-99}). Such feldspar compositions accompanied by the late growth of ferristilpnomelane suggest that the Roxboro metagranite has reequilibrated under less intense conditions than those realized during the peak of the major regional metamorphic event.