VPI-SU-5104-1
Distribution Category UC-66a

EVALUATION AND TARGETING OF GEOTHERMAL ENERGY RESOURCES IN SOUTH CAROLINA

Progress Report

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Principal Investigators

May 1, 1976 - January 31, 1977

Prepared for Division of Geology,
South Carolina State Development Board

Virginia Polytechnic Institute and State University
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ACKNOWLEDGEMENTS

Henry Bell of the U. S. Geological Survey in Reston, Virginia was extremely helpful in getting the geologic mapping started in South Carolina and supplied advice and unpublished material.

Phil Johnson, Water Resources, Division, U. S. Geological Survey, Columbia, SC, pointed out wells suitable for temperature logging in South Carolina and provided helpful discussions and published material relevant to Coastal Plain sediments. Harry M. Peek and L. A. Register of the Groundwater Section, Department of Natural and Economic Resources, Raleigh, NC, were equally cooperative in North Carolina.

John Wilson of Westvaco and Holt Smith of Catawba Timber Company helped to locate suitable drilling sites. We appreciate the cooperation of these companies in granting us permission to drill on their property.

I. Wendall Marine, Geologist at the Savannah River Plant in South Carolina, discussed the hydrology of Coastal Plain sediments with us and pointed out wells at the Savannah River Plant that might be suitable for our studies. His guidance and constructive comments are gratefully acknowledged. We appreciate the courtesy extended to us by N. Stetson, Manager, Savannah River Operations Office, and other officials of the Energy Research and Development Administration, Savannah River Office, during our visit to the Plant to log the wells.

E. R. Decker, Department of Geology, University of Wyoming, and C. M. Bunker, U. S. Geological Survey, Denver, kindly made preliminary analyses of uranium, thorium, and potassium using gamma-ray spectroscopy.

I. Zietz of the U. S. Geological Survey provided unpublished aeromagnetic data for portions of South Carolina. E. S. Robinson, Department of Geological Sciences, VPI & SU, made preliminary interpretations of aeromagnetic data for the Liberty Hill pluton in South Carolina.

Discussions with M. C. Gilbert, Department of Geological Sciences, VPI & SU, were helpful in the interpretation of the petrology and chemistry of the rock samples.

The Molecular Structures Laboratory in the Department of Geological Sciences, VPI & SU, provided microprobe analyses of selected rock samples.

The technical staff of the Department of Geological Sciences, VPI & SU, provided skill and imagination in the development, installation, and maintenance of instrumentation used for temperature logging, chemical analyses of rocks, and determination of heat generation in rocks. Their contributions to all phases of this program are significant: John Wonderley and Bob Montgomery (geophysics); George Crum (geochemistry); Don Bodell (machinist). Sharon Chiang supervised most of the drafting; Tom Quigley drafted most of the illustrations.

RESEARCH OBJECTIVES

The objective of this research is to develop and apply targeting procedures for the evaluation of low-temperature radiogenically-derived geothermal resources in the eastern United States utilizing geological, geochemical, and geophysical data.

The optimum sites for geothermal development in the tectonically stable eastern United States will probably be associated with areas of relatively high heat flow derived from crustal igneous rocks containing relatively high concentrations of radiogenic heat-producing elements. The storage of commercially exploitable geothermal heat at accessible depths (1-3 km) will also require favorable reservoir conditions in rocks overlying a radiogenic heat source. In order to systematically locate these sites, a methodology employing geological, geochemical, and geophysical prospecting techniques is being developed and applied. The radiogenic distribution within the igneous rocks of various ages and magma types will be determined by a correlation between radioelement composition and the rock's bulk chemistry. Surface sampling and measurements of the radiogenic heat-producing elements are known to be unreliable as they are preferentially removed by ground water, circulation, and weathering. The correlation between the bulk chemistry of the rock (which can be measured reliably from surface samples) and radiogenic heat production is being calibrated by detailed studies at a number of locations in the eastern United States.

Initial studies will develop a methodology for location radiogenic heat sources buried beneath the insulating sedimentary rocks of the Coastal Plain of South Carolina, North Carolina, and Virginia. Additional heat flow and thermal gradient measurements are being made in available deep wells.

INTRODUCTION

This report describes part of a program consisting of several interrelated projects in South Carolina, North Carolina, and Virginia, one Federal funding agency, and one State funding agency. A brief outline of the administrative links between the funding agencies and Virginia Polytechnic Institute and State University (VPI & SU) and the contractual obligations of VPI & SU will help to unify the objectives of the individual projects now underway.

ERDA Contract No. E-(40-1)-5103 to Virginia Polytechnic Institute and State University is the primary source of funding for geologic mapping, surface sampling, drill-site selection, modal analysis, major-element chemical analysis, determination of heat production, thermal conductivity and heat flow, and other aspects of data analysis and interpretation. The primary source of funds for the drilling program in South Carolina was ERDA Contract No. E-(40-1)-5104 with the South Carolina State Development Board (Mr. N. K. Olson, Principal Investigator) which resulted in a drilling subcontract to VPI & SU. Contract E-(40-1)-5104 was granted an extension of time without additional funds to January 31, 1977. This report thus reflects the interaction between two prime contracts which are interdependent.

Since this project interrelates with a program simultaneously authorized for VPI & SU, the drilling effort in South Carolina is closely coordinated with the overall program at VPI & SU. Equipment and personnel provided through the VPI & SU Contract are also part of the effort for the drilling and data interpretation for the work done in South Carolina.

PERSONNEL OF PROGRAM

(May 1, 1976 - January 31, 1977)

Geology and Petrology (South Carolina), Lynn Glover III, Principal Investigator of VPI & SU program

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C. S. Rohrer, Research Specialist
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Administrative Assistant, Patricia C. Sullivan

Secretary, Margie Strickler

Drillers

W. G. Coulson, Core Driller
R. G. Gravley, Driller Helper

DRILLING PROGRAM

Shallow drilling supplemented by surface sampling provides the basic data to evaluate the geothermal potential of radiogenic heat sources. Drilling equipment at Virginia Polytechnic Institute and State University (VPI & SU) includes a Longyear Model 38 wireline core drill with a depth capacity of approximately 3800 feet of AQ core. During the Report Period May 1 - January 31, 1977, drilling funds were provided by a subcontract to VPI & SU by the South Carolina State Development Board.

No problems arose with the drilling operation. One 48-hour shift per week was sufficient to meet contractual obligations and production schedules.

As of January 31, 1977, a total of over 4000 feet was drilled in the Liberty Hill-Kershaw and Winnsboro plutons in South Carolina. This exceeded our anticipated footage during the subcontract period.

The first hole (Ker 1) drilled by VPI & SU was drilled in the Liberty Hill-Kershaw pluton and was located on the basis of geophysical data; the drill site was chosen close to the center of a gravity low.

A total of 4063 feet of core was obtained in South Carolina during the Contract Period May 1, 1976 - January 31, 1977, exceeding our anticipated footage of 2700 feet. The number of samples of core for chemistry and heat production determination is listed below.

Pluton	Chemistry and Heat Production Samples	Total Samples
Liberty Hill, SC		
surface	24	114
Ker 1 (425')	1	5
Ker 2 (420')	5	17
Ker 3 (1334')	13	29
Winnsboro, SC		
surface	36	81
Win 1 (1884')	-	17

A. GEOLOGY (South Carolina)

Lynn Glover III, Principal Investigator
J. A. Speer, Research Associate
S. S. Farrar, Research Associate
S. W. Becker, Research Associate

Operations

Ten man weeks were spent conducting reconnaissance geologic mapping of the Winnsboro plutonic complex and the Liberty Hill pluton during the period 8/3/76 to 10/20/76 (Fig. A1). Moderately detailed mapping was completed during the period 10/20/76 to 11/1/76 in the northern half of the Liberty Hill pluton and in the central, medium-grained phase of the Winnsboro plutonic complex. Additional field work was done on the Winnsboro from 11/11/76 to 11/16/76. The country rocks were mapped and sampled in areas that were considered important to the understanding of the geologic framework and emplacement conditions of the pluton.

Samples collected for chemical analysis were chosen to provide a good geographic distribution and to represent the major rock types recognized in the field. Petrographic descriptions were made from thin and polished sections. Grain mounts of representative amphiboles and biotites were analyzed for major elements by electron microprobe. Modal analyses were performed by point counting. Rocks with an average grain size less than 1 mm were counted in thin section; samples with larger grain sizes were counted on stained rock slabs. Grid intervals used for point counting, ranging from 0.3 to 7.5 mm, were chosen to be consistent with the average grain size. Between 800 and 2000 points were counted for each sample. The rocks were classified on the basis of modal percentages of quartz, alkali feldspar and plagioclase, after Streckeisen (1976).

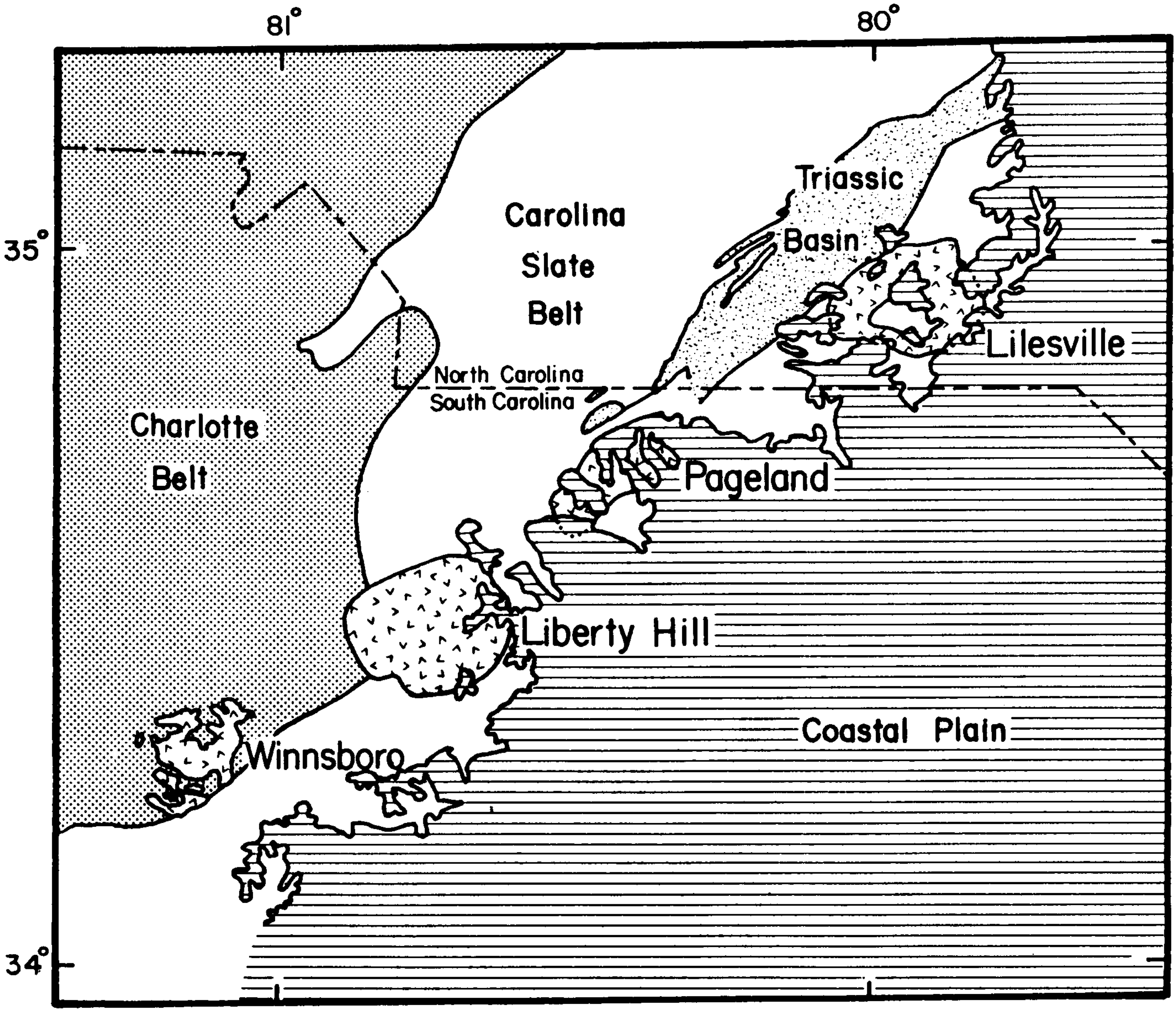


Figure A1. Index map showing locations of the ca. 300 m.y. postmetamorphic granitic plutons in North and South Carolina.

Liberty Hill Pluton
by
J. Alexander Speer and Susan W. Becker

Introduction

The Liberty Hill pluton is the largest of the ca. 300 m.y. unmetamorphosed granitic plutons that occur along the boundary between the Piedmont and the Coastal Plain in Virginia, North Carolina, and South Carolina (Butler and Ragland, 1969; Fullagar, 1971; Wright, Sinha and Glover, 1975). It lies in north-central South Carolina in Kershaw, Lancaster, and Fairfield Counties (Fig. A1).

The Liberty Hill was first described as a discrete pluton by Overstreet and Bell (1956). They determined an age for the pluton of 245 $\pm$ 30 m.y. by lead-alpha dating of zircons. Lead-alpha dating methods are commonly unreliable, however, and a whole-rock Rb/Sr age of 299 $\pm$ 8 m.y., determined by Fullagar (1971), is probably a more accurate date. Reconnaissance mapping of the entire pluton was done by Wagener (1976). Geologic maps of sections of the pluton have been published by Bell *et al.* (1974) and by Shiver (1974). Descriptions of the granitic rocks are given by Sloan (1908), Watson (1910), Butler and Ragland (1969), Wagener and Howell (1973), and Wagener (1976). Gravity data has been collected for the entire pluton by Popenoe and Bell (1974), and magnetic measurements have been made in the eastern third of the pluton (U.S.G.S., 1970).

General Geology

The Liberty Hill pluton comprises three texturally distinct phases. The predominant phase (Lhc) consists of very coarse biotite-amphibole granite

EXPLANATION

MAP UNITS

Tku	*Tertiary and Cretaceous Coastal Plain deposits*, undifferentiated.
╂d	*Diabase dikes*, mostly Triassic in age. Field checked from magnetic data; dotted where concealed.
	Contact aureole of the Liberty Hill pluton.
Lhp Lhc Lhi Lhf	*Liberty Hill pluton*, consisting of a porphyritic border phase (Lhp), pink to white coarse-grained biotite-amphibole granite and quartz monzonite (Lhc) commonly intruded (Lhi) by dikes and small plugs of fine-grained granite (Lhf).
	Gabbro norite: *Dutchmans Creek Gabbro* of McSween (1972).
gg	Gneissic granite: *Great Falls granite of Fullagar* (1971) and Pleasant Hill Granite of Shiver (1974).
Csa Csv	*Carolina Slate Belt:* metamorphic rocks in the greenschist and amphibolite facies; originally argillites, tuffaceous argillite, and graywacke (Csa) and felsic and mafic volcaniclastic rock and volcanic flows (Csv).

	Contact, dashed where inferred and dotted where concealed
50	Strike and dip of foliation
20	Strike and dip of igneous lamination
30	Strike and dip of xenoliths
S699	Sample locality
⊕ Ker I	Drill hole
⚒	Quarry

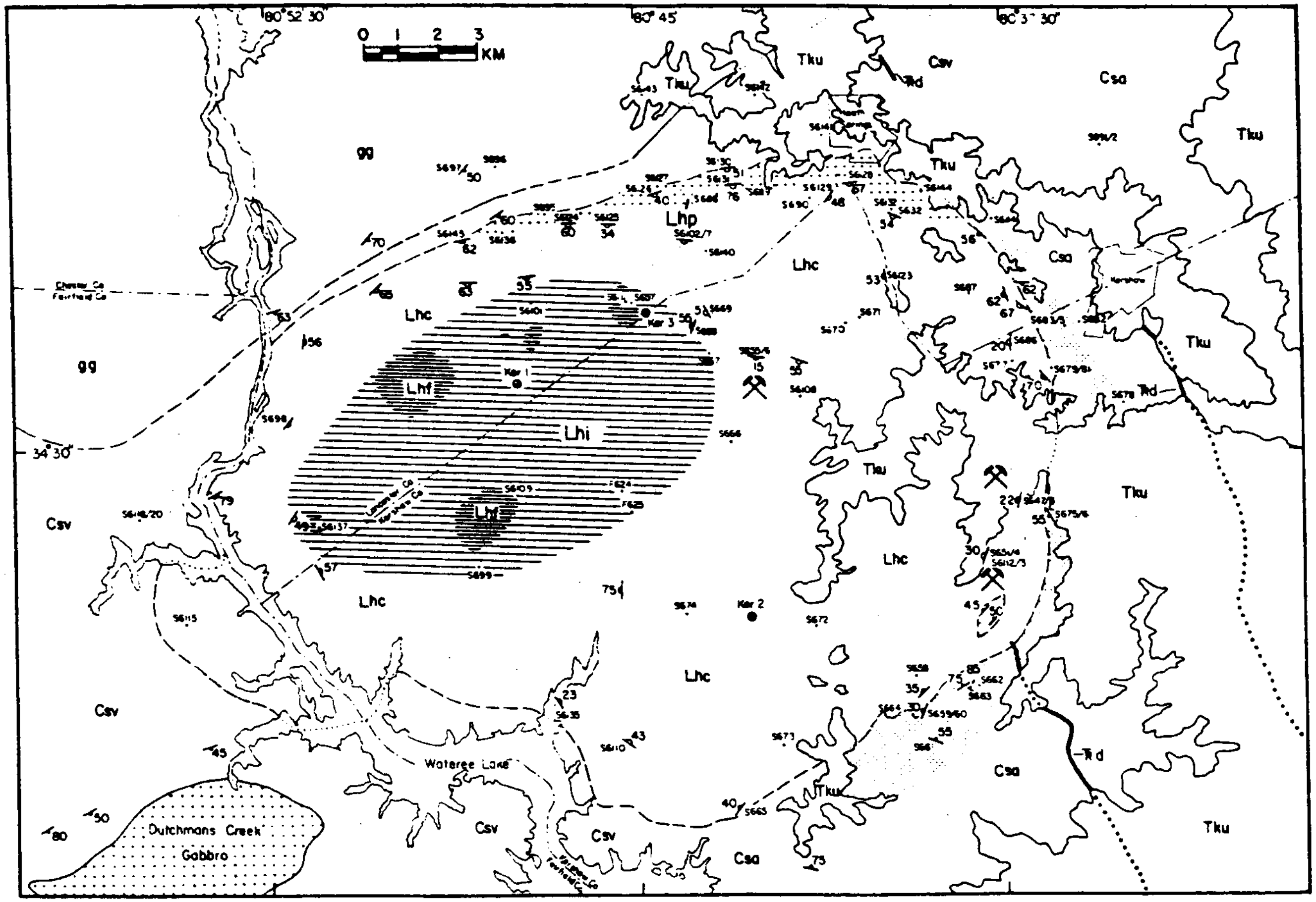


Figure A2. Geologic map of the Liberty Hill pluton, South Carolina.

and quartz monzonite. The second phase, which occurs along the northern margin of the pluton, consists of a porphyritic border phase (Lhp). It contains alkali feldspar phenocrysts up to 10 cm long in a groundmass that is similar to the very coarse phase. This porphyritic border phase is separated from the main pluton by a structurally conformable screen of hornfels. No evidence suggesting the relative ages of these two phases was observed in the field. The third and youngest phase (Lhf), represented in Figure A2 by the closely spaced horizontal lines, is fine- to medium-grained biotite granite which intruded the western part of the pluton in the form of large dikes or plugs. Between the areas of fine-grained granite (Lhf), the coarse-grained granite (Lhc), represented in Figure A2 by the widely spaced horizontal lines, has been intruded by varying amounts of the fine-grained granite (Lhi). Rare aplite dikes and muscovite-bearing pegmatites occur throughout the pluton.

An igneous lamination, defined by the alignment of tabular alkali feldspar crystals, is common throughout the pluton. The lamination parallels the orientation of tabular xenoliths of country rock. The alignment of the xenoliths and feldspar grains is more strongly developed near the margin of the pluton than towards the center. The dip of the foliation is moderate, defining the shape of an irregular funnel (Fig. A2). The nearly circular pluton is structurally discordant to the northeasternly trending regional structure. During intrusion, it deformed the adjacent country rock so that the foliation of the country rock adjacent to the contact is now conformable to the foliation and margins of the pluton. This warping of the structure in the country rock, combined with the presence of numerous and usually large xenoliths of country rock, suggests that forceful injection, as well as stoping, was important in the emplacement of the Liberty Hill pluton. In addition, the very coarse grain size, which continues to the contact, suggests that the granite was largely crystalline when emplaced.

Numerous outcrops of diabase occur in both the country rock and the Liberty Hill pluton. Only those which could be traced for some distance are shown in Figure A2. Some diabase dike traces shown in Figure A2 were plotted from magnetic surveys (U.S.G.S., 1970) and were field checked. Other strong northwesterly trending anomalies have yet to be checked in the field. Diabase outcrops and boulder fields not associated with predominant magnetic anomalies probably represent very small dikes.

Petrography of the Liberty Hill Pluton

The coarse-grained rocks of the main pluton (Lhc) and the porphyritic border phases (Lhp) are modally leucocratic granites and quartz monzonites (color index of 2 to 10), with biotite and amphibole (Table A1, Fig. A2). Varieties containing biotite as the only mafic mineral are rare. The coarse grain size prevents the rock from having a uniform color in hand specimen. Instead, the color of each mineral is evident: pink or white alkali feldspar, greenish white plagioclase, grey quartz, and dark mafic minerals. The texture is hypidiomorphic granular, commonly with a discernable feldspar foliation.

Tabular, subhedral, pink or white alkali feldspar is the most conspicuous mineral because of its large size, usually 0.5 to 5.0 cm, and locally as much

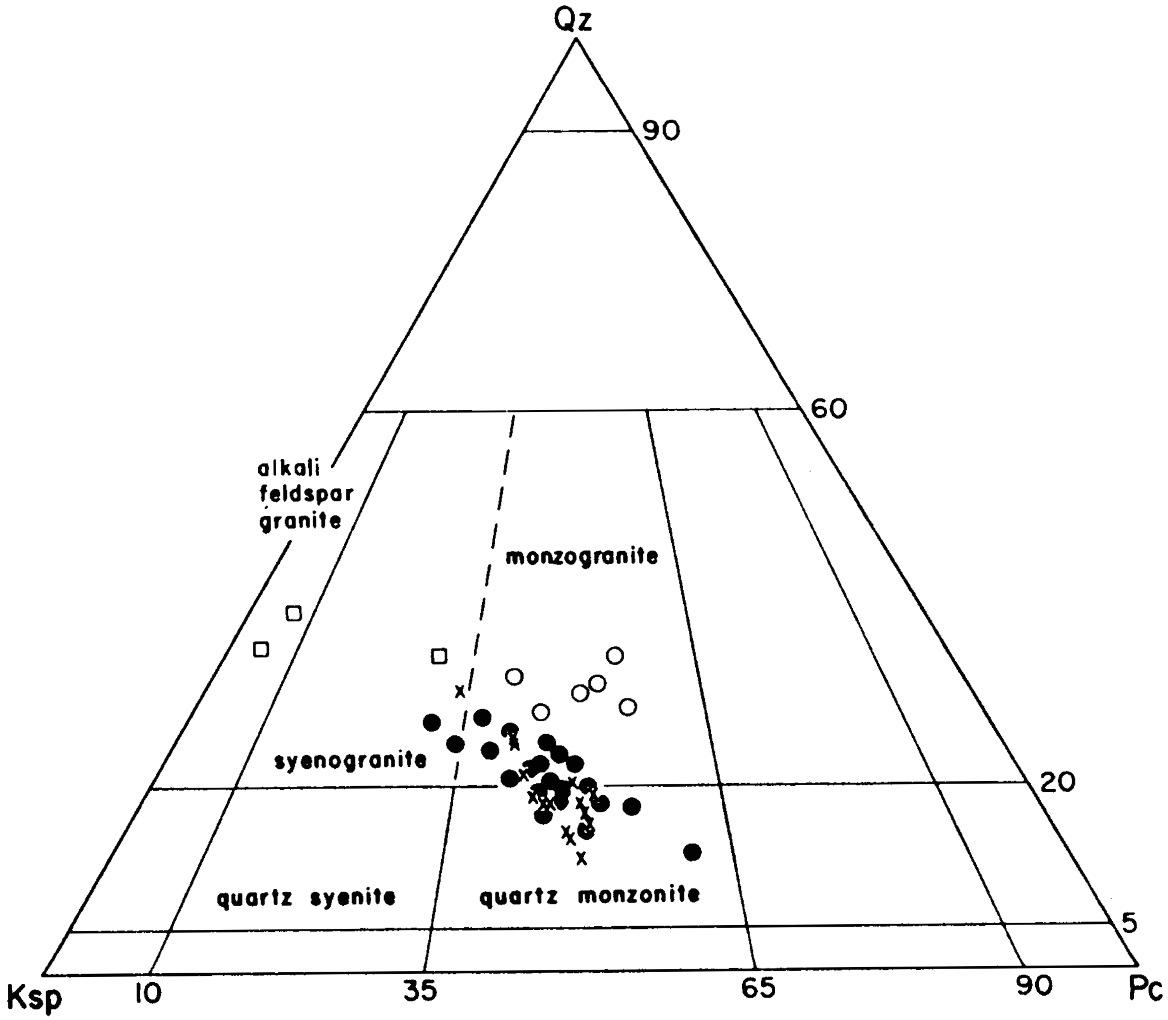


Fig. A3. Triangular diagram of modal volume percent of alkali feldspar (Ksp), plagioclase (Pc), and quartz (Qz) for samples from the Liberty Hill drill cores (Ker-1,-2,-3) (x), and surface samples (□, ○, and ●).

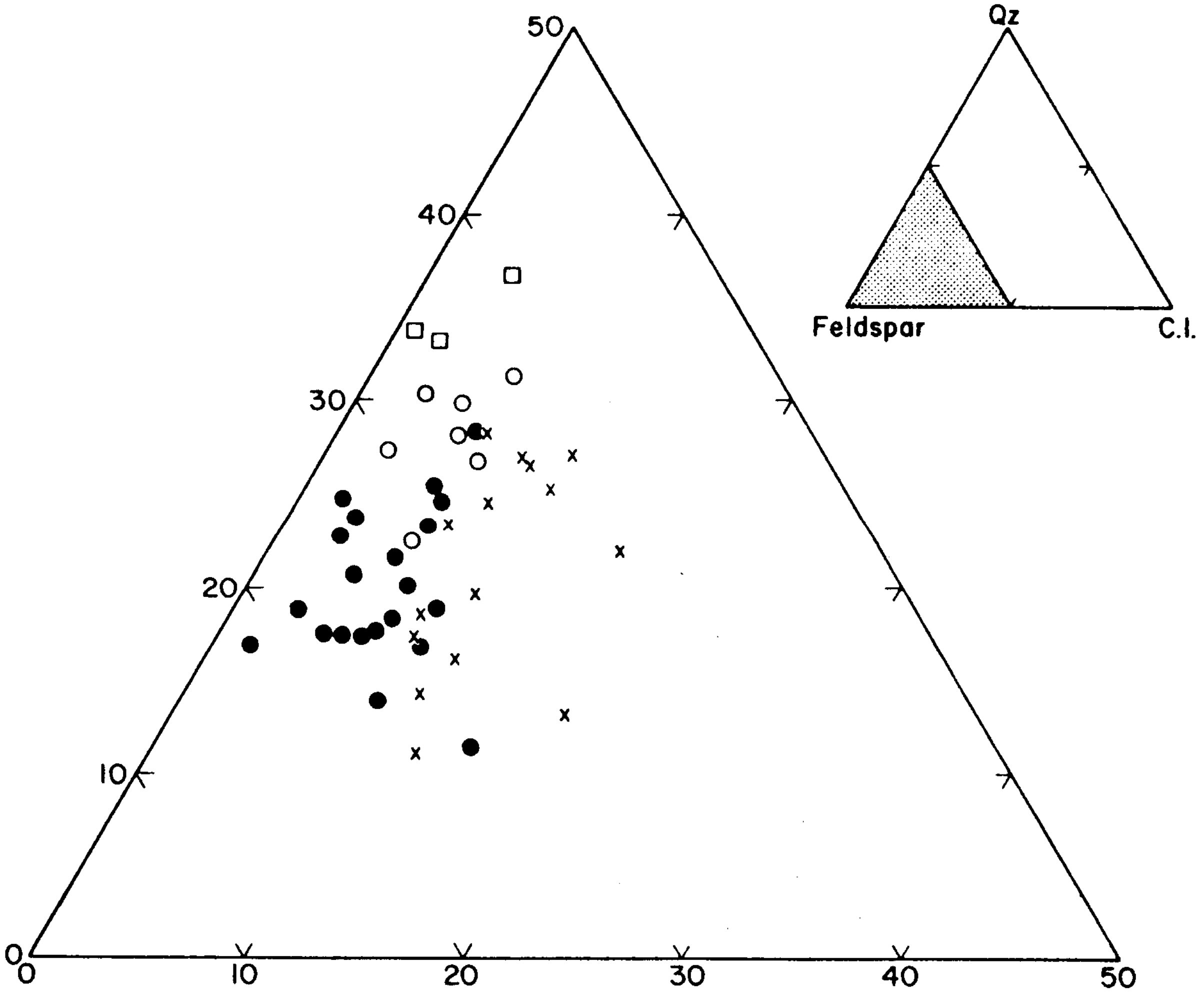


Fig. A4. Modal data for the Liberty Hill drill cores (X) and surface samples (□, ○, and ●) plotted on triangular diagram showing volume percent total feldspar, color index (C.I.), and quartz (Qz).

as 10 cm in the marginal phase. The feldspar is macro- and microperthite exhibiting both primary growth twins, dominantly Carlsbad twins, and albite and pericline inversion twins. Locally the alkali feldspar is poikilitic with oriented inclusions of plagioclase, quartz, biotite, and magnetite. These inclusions, together with differences in extinction angle of the feldspar, define an oscillatory zoning. Plagioclase grains are smaller (less than 1.5 cm), subhedral, and white with a greenish tint because of saussuritization. Optical compositional determinations by the a-normal method (Smith, 1974) show that the plagioclase is oligoclase having normal oscillatory zoning, with cores of An_{28-32} and rims of An_{18-12}. On some grains, a discontinuous rim of albite is present, usually associated with myrmekite. Rapikivi texture is widespread and accentuated by the color difference between the plagioclase and alkali feldspar. Biotite, the dominant mafic mineral, is 5 mm or less in size. It is pleochroic dark brown to tan. Microprobe analyses (Table A2) show that the biotite has an Fe/Fe+Mg ratio uniformly near 0.6, and a low aluminum content, indicating that it is rich in the annite component. Amphibole occurs as euhedral to subhedral prismatic crystals up to 0.5 cm long. They have the pleochroic formula: X = yellow brown; Y = yellow green; Z = blue green, and are often twinned on (100). Microprobe analyses (Table A3) show that they are ferrohornblendes. They plot near the ferrotschermakitic hornblende field (Leake, 1968), with an Fe/Fe+Mg ratio near 0.6 and a silicon content in the half unit cell formula of 6.67 to 6.56. Primary accessory minerals include allanite, zircon, apatite, titanite, monazite (?), magnetite, pyrite, chalcopyrite, bornite, molybdenite, uraninite, pyrrhotite, fluorite, ilmenite, and xenotime. Titanite is the most abundant accessory mineral; large allanites, up to 5 mm long, are the most spectacular, with their zoning and surrounding radiation cracks. Secondary minerals include epidote, chlorite, calcite, white mica, albite, and hematite.

The fine- to medium-grained rocks (Lhf), which occur as plugs and dikes that intrude the very coarse Liberty Hill, are modally leucocratic granites, (Figs. A3,A4, Table A1). They are more quartz rich than the coarse-grained phase and have a uniform grey color when fresh. This finer grained phase commonly contains xenoliths of the coarse-grained phase. Xenocrysts of alkali feldspar, plagioclase, quartz, and biotite from the coarse-grained phase, which are broken or mantled by reaction rims, are also present.

The alkali feldspar is anhedral and 2 mm or less in size. It is microcline microperthite with Carlsbad growth twins, and albite and pericline inversion twins. Plagioclase is subhedral and less than 1 mm in size. Optical compositional determinations by the a-normal method (Smith, 1974) show that the plagioclase crystals have normal oscillatory zoning profiles from cores of An_{22-18} to rims of An_0. Plagioclase crystals with saussuritized cores have developed reverse zoning with depletion of calcium from the altered plagioclase. The sole mafic mineral is a pleochroic brown to tan biotite, which in many cases is altered entirely to chlorite. Muscovite, calcite, and colorless clinozoisite are developed in saussuritized plagioclase.

In addition to the difference in grain size between (1) the coarse, and (2) the medium- to fine-grained phases of the Liberty Hill pluton, differences in several textural and mineralogical features are apparent. The coarse-grained phase is an amphibole-biotite monzogranite or quartz monzonite, whereas the fine- to medium-grained phase is a biotite monzogranite. Titanite is a prominent and abundant accessory mineral in the coarse-grained phase, but it is absent from the finer. The plagioclase is more sodic in the fine-grained phase. The subhedral to euhedral alkali feldspars in the coarse-grained phase (Lhc) suggest that it was an early crystallizing phase. The opposite appears to be true for the anhedral alkali feldspars for the fine-grained rocks (Lhf). Extensive saussuritization and chloritization is developed only in the fine-grained phase (Lhf) and is absent in the enclosing coarse-grained phase (Lhc). This indicates an increased amount of autometamorphism after consolidation of the fine-grained phase (Lhf), and, perhaps, a difference in the residual fluid composition of the two phases. A late regional metamorphic overprint would be expected to affect both rock types similarly.

The aplite dike rocks are characterized by very low (<4.0%) modal amounts of mafics or plagioclase and by fine grain size. They are either syenogranites or alkali feldspar granites (Fig. A3, Table A1); texturally, they are xenomorphic granular. Sample S6-66 is a graphic intergrowth of quartz and alkali feldspar. Plagioclase contains two broad compositional zones, cores of An_{17-20} and rims of An_0. The mafic content is primarily composed of biotite and magnetite. The pegmatites are alkali feldspar granites with grain sizes on the order of 2 to 4 cm, and they contain muscovite from 1 to 2 cm in size.

Rocks of the Contact Aureole and Xenoliths of the Liberty Hill Pluton

The Carolina slate belt bordering the eastern part of the Liberty Hill pluton consists of argillites (Csa) regionally metamorphosed in the greenschist facies. On the western margin, rocks of the Carolina slate belt are felsic and intermediate volcanic lavas and pyroclastic rocks (Csv), and dikes which have been metamorphosed in the greenschist facies and possibly as high as the lower amphibolite facies. Contact metamorphism by the Liberty Hill pluton produced a contact aureole as much as 1.5 km wide in the argillites. The rocks are fine-grained, black hornfels with 1-4 mm porphyroblasts of cordierite, biotite, and garnet. Original compositional banding of 1-10 mm is fairly common. The metamorphosed argillite shows a strong magnetic anomaly (U.S.G.S., 1970). The volcanic rocks show only slight contact metamorphic effects so that the contact aureole is not evident in the field or on the magnetic map. Both the argillite and volcanic rocks occur as xenoliths in the Liberty Hill pluton.

The mineral assemblages of the hornfels in the contact aureole and xenoliths are diverse, reflecting a wide range in composition of the original country rocks. Only the frequently occurring assemblages are summarized here. Argillite xenoliths have mineral assemblages characteristic of the pyroxene hornfels facies:

(1) orthopyroxene-cordierite-biotite-K feldspar-plagioclase-quartz

(2) orthopyroxene-cordierite-garnet-biotite-K feldspar-plagioclase-quartz

and hornblende hornfels facies:

(1) garnet-cordierite-biotite-K feldspar-plagioclase-quartz.

The highest grade metamorphic mineral assemblages in the contact aureole are characteristic of the hornblende hornfels facies:

(1) garnet-cordierite-biotite-K feldspar-plagioclase-quartz

(2) andalusite-cordierite-biotite-K feldspar-plagioclase-quartz.

The metamorphic grade decreases to the muscovite hornfels facies with the assemblages:

(1) cordierite-biotite-muscovite-K feldspar-plagioclase-quartz

(2) chlorite-biotite-muscovite-plagioclase-quartz.

The outer part of the aureole grades into the earlier greenschist facies of regional metamorphism. An insufficient number of volcanic hornfelses have been examined to give detailed mineral assemblage changes. In general, with increasing metamorphic grade, epidote and chlorite give way to amphibole, and, in one case, clinopyroxene. The volcanics also lose their original textures with increasing metamorphic grade in the contact aureole.

Until compositional data on coexisting mineral phases are obtained, only an approximation can be made of the pressure conditions of emplacement of the Liberty Hill pluton. The general sequence of assemblages suggests that total pressure was less than 5.1 kb, but more than 3.0 kb. The development of the pyroxene-hornfels facies in enclaves of a granitic rock is uncommon and indicates that the magma was either hot, dry, or both. In any case, the pyroxene-hornfels facies indicates a minimum temperature of 650-700°C. The outer edge of the aureole was probably at temperatures less than 500°C.

Shear Fractures and Fissure Veins

Shear fractures and fissure veins are rarely observed in surface outcrops, but are commonly encountered in the three drill holes. Shear zones are a maximum of 8 meters thick and exhibit slickensides and brecciation. The granitic rocks in these zones are dark red in color, spotted by bright green chlorite and epidote. The greenschist facies mineral assemblage of the shear zones is more pervasive than that of the autometamorphism of the fine-grained rocks. It is unlike and represents too high pressure and temperature for the weathering processes leading to the production of saprolite. The amount of displacement along the shears is unknown but probably small.

Fissure zones up to 3 cm thick occur in curving networks. Movement, if any, was completed before vein filling. The most common vein minerals are calcite, laumontite, fluorite, pyrite, and an unidentified zeolite. Open fissures observed at sample locality S6-121, the Flat Rock Quarry of the Kershaw Granite Company, contained the assemblage: chlorite-alkali feldspar-quartz-calcite-fluorite-chalcopyrite-pyrite.

Table A1. Modal data for the Liberty Hill pluton.

Sample	quartz	plagioclase	K-feldspar	Color Index[1]	biotite	accessories[2]	muscovite	epidote	alteration
Coarse-grained rocks:									
S6-47	22.7	32.9	37.8	6.5					
S6-54	25.9	25.4	41.7	6.9					
S6-56	17.7	34.5	42.6	5.2					
S6-58	24.5	25.5	46.8	3.2					
S6-65	25.5	29.4	42.7	2.4					
S6-69	20.6	31.2	40.6	7.6					
S6-71[3]	17.4	37.0	43.8	1.7					
S6-73	25.6	21.0	46.5	6.9					
S6-74[3]	19.4	35.7	41.7	3.2					
S6-86	23.8	31.4	37.7	7.1					
S6-87	18.0	33.3	41.7	7.1					
S6-88	18.7	33.9	39.5	7.9					
S6-89	17.8	35.3	41.0	5.8					
S6-90	22.3	34.6	37.0	6.1					
S6-98	11.4	44.8	28.5	15.3					
S6-110	23.5	27.9	45.2	3.4					
S6-132	14.3	38.1	38.2	9.4					
S6-135	20.9	32.2	41.8	5.0					
F6-24	18.4	37.0	36.9	7.8					
F6-25	17.0	37.4	35.6	10.0					
Ker 1-135/145	38.3	21.6	43.3	6.8					
Ker 2-1.5/11	19.1	29.1	42.0	9.8					
Fine-grained rocks:									
S6-57	27.2	36.4	28.9	-	5.9	0.6	-	tr	0.8
S6-67	29.8	33.2	31.3	-	3.2	0.2	1.7	0.5	tr
S6-99	31.2	26.5	39.3	-	3.0	tr	-	tr	tr
S6-100[3]	31.8	33.1	28.1	-	6.9	tr	-	tr	tr
S6-101	28.0	37.2	31.9	-	2.0	0.3	0.4	tr	0.1
S6-111	28.8	32.5	32.7	-	4.9	0.7	0.3	tr	tr
Aplites:									
S6-51	37.4	3.9	54.9	-	3.6	tr	-	-	-
S6-66	34.5	3.1	62.2	-	-	0.2	-	-	-
S6-77	33.9	18.8	45.2	-	0.9	1.1	-	-	-

[1] primarily biotite and amphibole.

[2] includes allanite, zircon, apatite, titanite, monazite, magnetite, pyrite, chalcopyrite, bornite, and molybdenite.

[3] xenocrystic rocks, fine-grained matrix with xenocrysts from the coarse-grained phase.

Table A2. Microprobe analyses of Liberty Hill biotites.

	1	2	3	4	5
SiO_2	36.07	36.23	35.43	36.00	35.77
Al_2O_3	13.59	14.17	13.58	13.75	13.58
FeO	25.71	25.70	26.10	26.04	25.36
TiO_2	4.29	3.96	4.13	4.03	3.77
MnO	0.42	0.48	0.51	0.45	0.49
CaO	0.0	0.0	0.0	0.0	0.0
MgO	9.93	9.44	9.62	10.58	10.43
Na_2O	0.07	0.09	0.11	0.09	0.08
K_2O	8.29	7.80	8.28	8.27	8.17
H_2O	3.94	3.94	3.90	3.97	3.91
Sum	102.31	101.81	101.66	103.18	101.56

number of cations based on 24 oxygens

	1		2		3		4		5	
Si	5.486	7.922	5.516	8.000	5.448	7.909	5.437	7.884	5.477	7.927
Al	2.436		2.484		2.461		2.447		2.450	
Al	0.0		0.058		0.0		0.0		0.0	
Ti	0.491		0.453		0.478		0.458		0.434	
Fe	3.270	6.066	3.272	5.987	3.356	6.105	3.289	6.186	3.247	6.125
Mn	0.054		0.062		0.066		0.058		0.064	
Mg	2.251		2.142		2.205		2.382		2.380	
Ca	0.0		0.0		0.0		0.0		0.0	
Na	0.021	1.629	0.027	1.541	0.033	1.657	0.026	1.619	0.024	1.619
K	1.608		1.515		1.624		1.593		1.596	
H	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
F/FM		0.596		0.609		0.608		0.584		0.582

[1]F6-25, Liberty Hill

[2]F6-24, Liberty Hill

[3]S6-54, Liberty Hill

[4]S6-86, Liberty Hill

[5]S6-88, Liberty Hill

Table A3. Microprobe analyses of Liberty Hill amphiboles.

	1		2		3		4	
SiO_2	43.00		42.16		42.37		43.00	
Al_2O_3	7.50		8.47		8.38		8.41	
FeO	22.18		23.21		24.75		22.22	
TiO_2	1.83		2.06		1.23		1.97	
MnO	0.69		0.75		0.94		0.67	
CaO	10.74		10.48		10.88		10.73	
MgO	9.19		8.21		7.66		9.14	
Na_2O	2.00		2.05		2.23		2.19	
K_2O	0.0		0.0		0.0		0.0	
H_2O	1.93		1.93		1.93		1.96	
Sum	99.06		99.32		100.37		100.29	
			number of cations based on 24 oxygens					
Si	6.669	8.000	6.557	8.000	6.578	8.000	6.583	8.000
Al	1.331		1.443		1.422		1.417	
Al	0.040		0.109		0.112		0.101	
Ti	0.213		0.241		0.144		0.227	
Fe	2.877	5.346	3.019	5.370	3.214	5.365	2.845	5.345
Mg	2.125		1.903		1.773		2.086	
Mn	0.091		0.099		0.124		0.087	
Na	0.601		0.618		0.671		0.650	
Ca	1.785	2.386	1.746	2.364	1.810	2.481	1.760	2.410
K	0.0		0.0		0.0		0.0	
H	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
F/FM		0.583		0.621		0.653		0.584

[1]F6-24, Liberty Hill

[2]F6-25, Liberty Hill

[3]S6-54, Liberty Hill

[4]S6-86, Liberty Hill

Petrography of the Liberty Hill Drill Cores

J. Alexander Speer

Three holes have been drilled in the Liberty Hill pluton; locations are shown in Fig. A2. Core samples from these holes are petrographically similar in most respects to the surface samples and can be characterized by rock descriptions included in the first report.

Lithologic logs for drill holes Ker 2 and Ker 3 are illustrated in Figs. A5 and A6. Two types of granite are encountered in the drill cores: coarse-grained granite cut by large dikes of a fine-grained granitic phase, a maximum of 130 feet in vertical height. Xenoliths and xenocrysts from the coarse-grained granite occur within the margins of these fine-grained dikes. Small (1-5 cm) mafic clots, consisting largely of biotite and amphibole, are found in the coarse-grained granite. Amphiboles with pyroxene cores, which are otherwise rarely seen, usually occur in these clots. Several large hornfels xenoliths, up to 45 ft. in vertical height, were encountered. Thin dikes of aplite and muscovite-quartz-alkaki feldspar are ubiquitous.

Modes of samples selected for chemical analysis and measurement of heat production are listed in Table A4. On the quartz-alkali feldspar - plagioclase diagram (Fig. A3), the modes fall within the field defined by the surface samples. The drill hole specimens, however, are notably different from the surface samples in that they have a uniformly higher color index (Fig. A4). This phenomenon may be a result of the more rapid weathering of the more mafic granite. Surface sampling therefore probably results in a disproportionate number of more felsic samples. The difference in composition between the surface and subsurface samples indicates that the granite is more mafic in composition than would have been postulated from the surface samples alone.

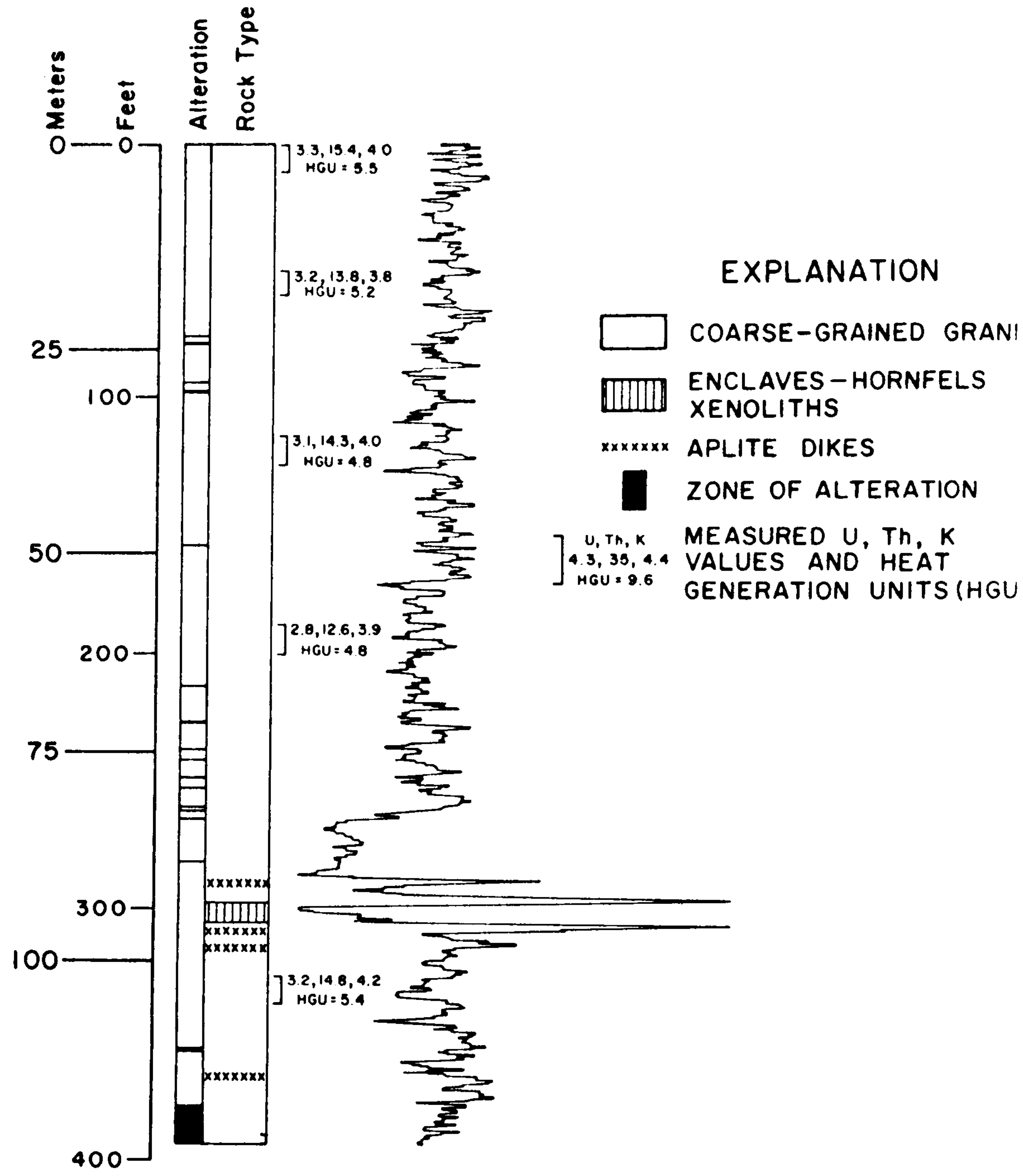
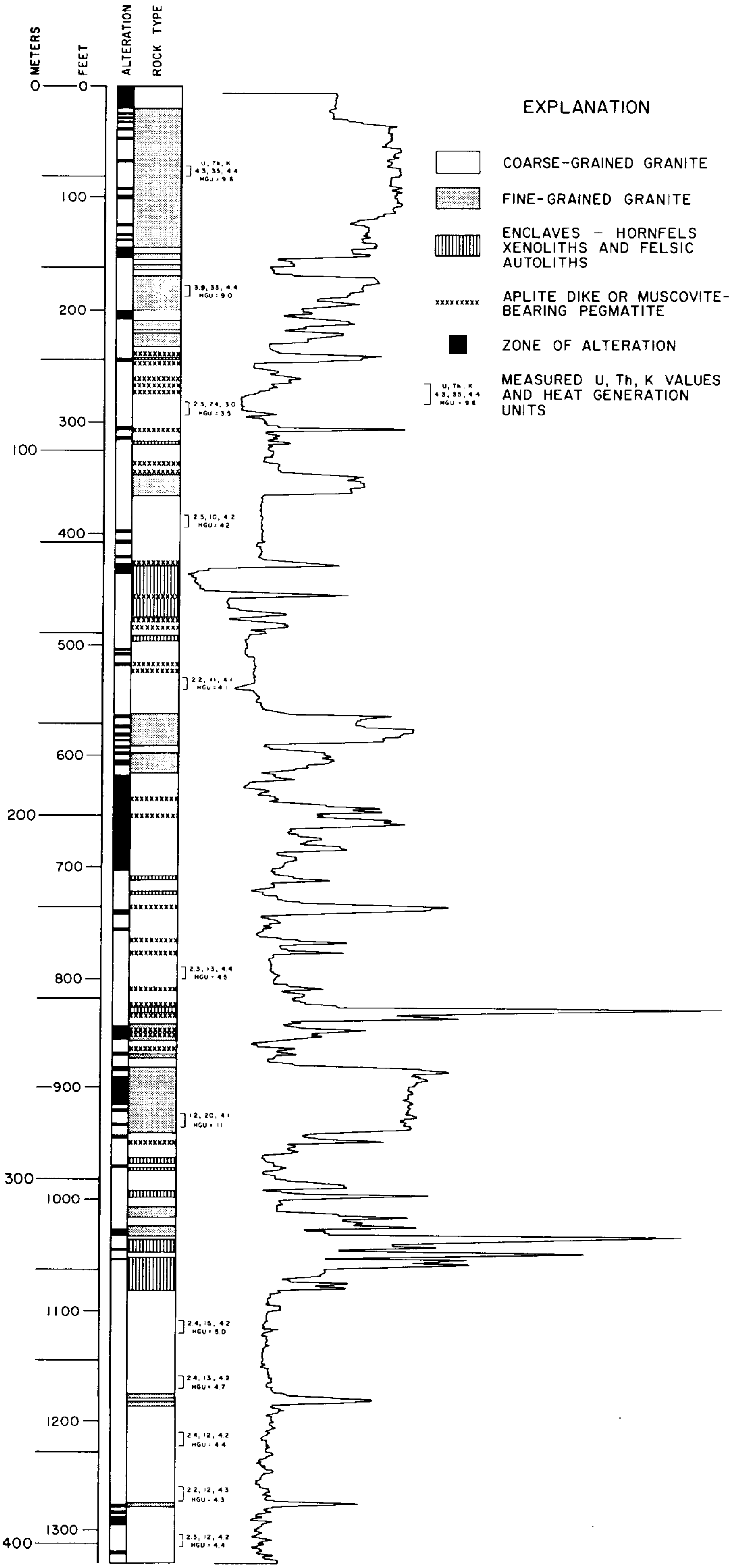


Fig. A5. Lithologic log of drill hole Ker 2, with corresponding alteration and gamma ray spectrometer log. Radioactivity measurements increase to the right.

Following page: Fig. A6. Lithologic log of drill hole Ker 3, with corresponding alteration and gamma ray spectrometer log. Radioactivity measurements increase to the right.


METERS
FEET
ALTERATION
ROCK TYPE
EXPLANATION
COARSE-GRAINED GRANITE
FINE-GRAINED GRANITE
ENCLAVES - HORNFELS XENOLITHS AND FELSIC AUTOLITHS
APLITE DIKE OR MUSCOVITE-BEARING PEGMATITE
ZONE OF ALTERATION
MEASURED U, Th, K VALUES AND HEAT GENERATION UNITS

The mineralogy of the hornfels xenoliths is similar to that of the surface hornfels samples. Mineral assemblages indicate metamorphic conditions of the amphibole and pyroxene hornfels facies. Two mineral assemblages of the pyroxene hornfels facies were found:

*Ker 3 - 1074.2	Orthopyroxene-garnet-cordierite-biotite-K feldspar-plagioclase-quartz
Ker 3 - 472 and Ker 3 - 465	Orthopyroxene-clinopyroxene-plagioclase-quartz-garnet

These are the only observed occurrences of orthopyroxene with garnet + cordierite or clinopyroxene in the xenoliths. Its presence confirms the conclusion, derived from other assemblages (see previous section), that the granite was emplaced at an unusually high temperature. Compositions of the coexisting orthopyroxene + clinopyroxene and garnet + cordierite coexisting with orthopyroxene can be used to determine their temperature and pressure of formation.

Some xenoliths are cut by a number of muscovite-bearing granitic dikes, 1-2 cm wide. The adjacent hornfels also contains muscovite, indicating a locally fluid-rich environment. These granitic dikes may represent either partial melts of the xenoliths, or invading fluid-rich residual melts derived from the enclosing granite.

Natural gamma-ray logs were made of drill holes Ker 2 (Fig. A5) and Ker 3 (Fig. A6). Gamma rays measured are emitted principally from K^{40} and from U and Th and their daughter products. The daughter products may not be in equilibrium with their parent isotopes so that the gamma-ray readings may not represent U and Th contents along the length of the log. However, heat production determinations for powdered core samples (Figs. A5 and A6) do show a good correlation with the gamma-ray log. The coarse-grained granite, which has an average heat production of 5.01 HGU

*Samples are labeled by drill hole number and depth or depth interval (feet).

Table A4. Modal Data for Drill Holes in the Liberty Hill Pluton.

Drill Hole	Depth	Quartz	K-feldspar	Plagioclase	Color Index
Ker 1	135/145	28.3	43.3	21.6	6.8
Ker 2	1.5/11	19.2	42.1	29.1	9.7
	53.5/59.7	16.6	37.4	36.2	9.8
	118.1/128.5	16.9	39.5	34.3	9.3
	194/204	17.2	36.1	35.3	11.4
	334/344	15.4	36.7	36.9	11.0
Ker 3	284/294	21.9	36.9	26.7	16.1
	384/394	14.5	40.1	37.1	8.7
	530/540	12.9	36.1	32.9	17.9
	784/794	23.3	40.1	29.1	7.4
	1110/1120	18.6	37.7	35.0	8.7
	1140.2/1150.7	14.4	37.1	37.6	11.0
	1160/1170	17.2	41.2	32.5	9.1
	1210/1220	19.5	39.7	30.0	10.7
	1260/1270	16.0	39.5	32.8	11.7
	1304/1314	11.0	39.0	37.8	12.1

(30 samples), gives lower gamma log readings than the fine-grained granitic dikes, which have an average heat production of 9.33 H.G.U. (8 samples). The aplite dikes and muscovite-bearing pegmatites have gamma ray spikes with magnitudes similar to or greater than those of the fine-grained granite. One heat production value determined for an aplite is 10.5 H.G.U.

Radiation levels within the xenoliths, as recorded by the gamma ray spectrometer, are variable. For xenoliths Ker 2- 302/315 and Ker 3- 430/476, the readings are lower than for the coarse-grained granite. The xenolith from Ker 3- 1038/1083 produces a highly erratic response. This xenolith is cut by a number of thin granitic dikes which probably cause the high spikes of Figure A6.

Nearly all spikes on the two gamma ray logs are associated with fine-grained granitic dikes, aplites, or pegmatites. The peak at Ker 3 - 302 is not associated with any of the above rock types, but occurs at an interface between hornfels and coarse granite. A thin section of this contact shows a number of small grains of xenotime (YPO_4). Large radiation damage halos surround the grains, suggesting that the mineral is more radioactive than any other phase present except uraninite. The concentration of xenotime along the top of the xenolith probably causes the observed spike.

Magnetic Modeling of the Liberty Hill Pluton and its Contact Aureole with Comments on the Mineralogy of Magnetic Phases

John Dunbar, J. Alexander Speer, and Susan W. Becker

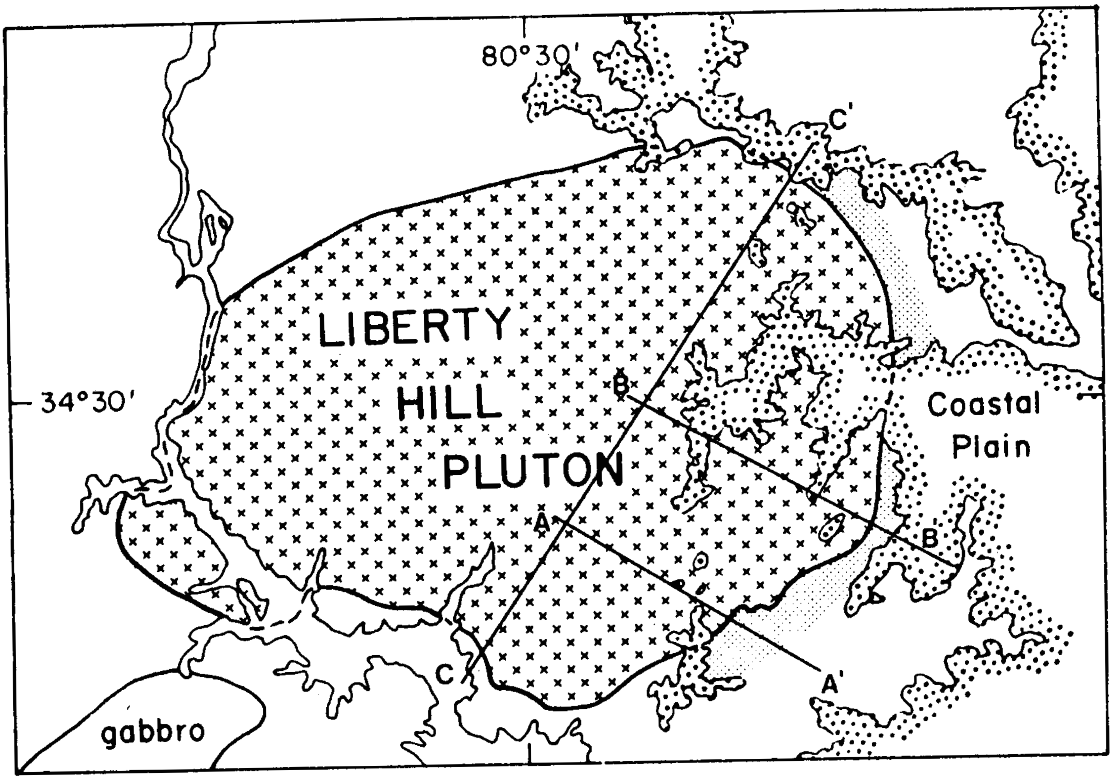
Introduction

The Liberty Hill pluton and its contact aureole have a readily recognizable expression on the aeromagnetic map of the Camden-Kershaw area (U.S.G.S., 1970, reproduced in part in Fig. A7b). The pluton is associated with a uniform magnetic high, 300 gammas greater than the approximately 700 gamma regional magnetic field of the Carolina slate belt. This high falls off sharply at the northern and eastern edges of the pluton, but decreases more gradually over the southern margin. The contact aureole shows a 400 gamma magnetic high 2 km wide on the eastern rim of the pluton, where the aureole is developed in the Carolina slate belt argillites.

The north-northwest trending magnetic linears are expressions of diabase dikes, and a magnetic high, which appears in the southwest corner of Fig. A7b, is caused by the Dutchman's Creek gabbro.

Magnetic Modeling

A model for the shape of the Liberty Hill pluton was derived from the magnetic data of Fig. A7b. The procedure used, based on Talwani's method of computing profiles over bodies of infinite length (Talwani and Heirtzler, 1964), is not especially well-suited to bodies with circular outcrop patterns, but should provide a first-order approximation of the pluton's shape. Magnetic profiles were computed from starting models based only on geologic information. The computed profiles were then compared to the observed magnetic profiles (Fig. A7b), and the pluton model was modified to improve the agreement between the computed and observed profiles.



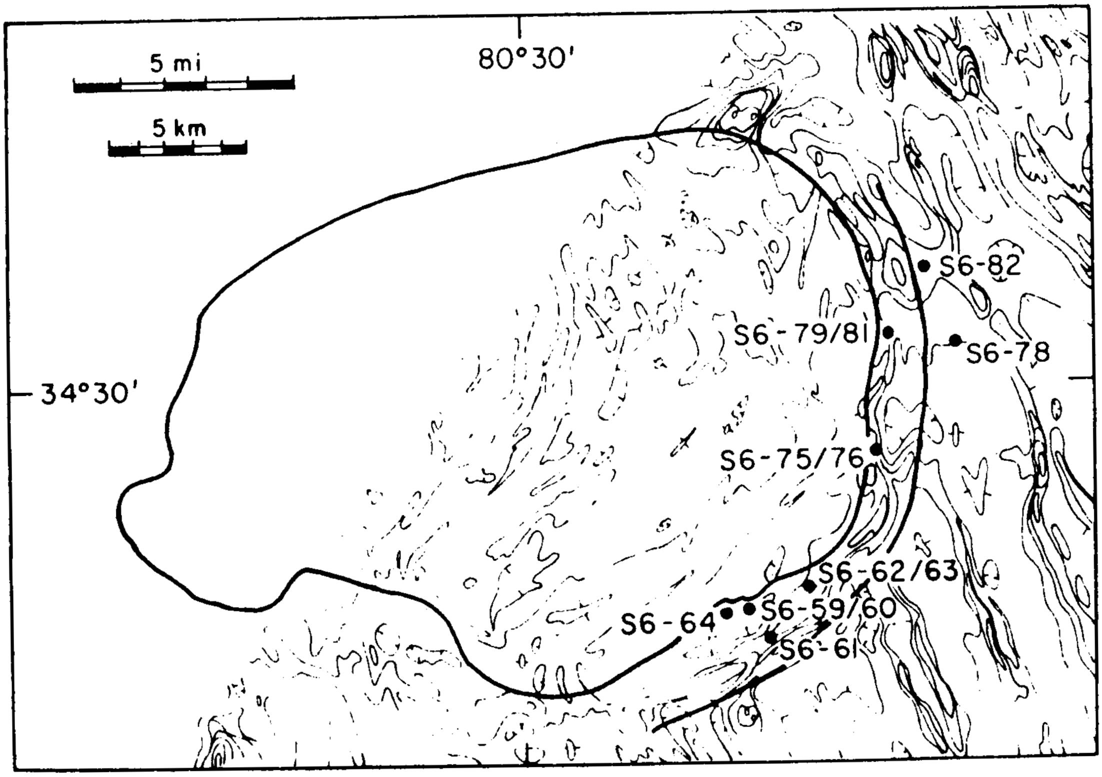


Fig. A7. (a) Geologic map of the Liberty Hill pluton, showing section lines used for magnetic modeling.

(b) Aeromagnetic map of the eastern half of the Liberty Hill pluton and contact aureole with locations of hornfels samples. From aeromagnetic map of the Kershaw-Camden area, SC (USGS, 1970).

Magnetic susceptibility measurements of the two major granite types of the pluton are shown in Table A5. For modeling purposes, it was assumed that the pluton is a homogeneous body with a susceptibility of 0.001cgs. The hornfels of the metamorphic aureole was found to have highly variable susceptibilities; the values used are shown in the profiles (Figs. A8, A9, A10). The volcaniclastic units in contact with the pluton on the north and south appear to have uniformly low susceptibility. Susceptibilities, measured by Waskom (1970), of various units of the country rock surrounding the Lilesville pluton, similar to rocks bordering the Liberty Hill pluton, are shown in Table A5.

In this model, the metamorphic aureole is represented by thin shells of material of different susceptibilities, running within the argillite parallel to the surface of the pluton. The shells extend laterally along the face of the pluton and end at the contact with the volcaniclastic units, in which the aureole is not developed. The depth to which the shells extend was arbitrarily chosen. The volcaniclastic rocks and the parent material of the aureole, the argillites, were assumed to have no susceptibility.

Results

The models shown in Figs. A8, A9 and A10 correspond to section lines in Fig. A7a. Along lines A-A' and B-B', the dip of the granite/country rock interface is shallow, so that near the margin of the pluton the shapes of the computed profiles are well constrained, and are not affected by the depth to which the granite extends.

The behavior of the southern part of section C-C' is similar to the behavior of A-A' and B-B'. In the northern part, however, the granite dips steeply, so that the dip is not well constrained, and the shape of

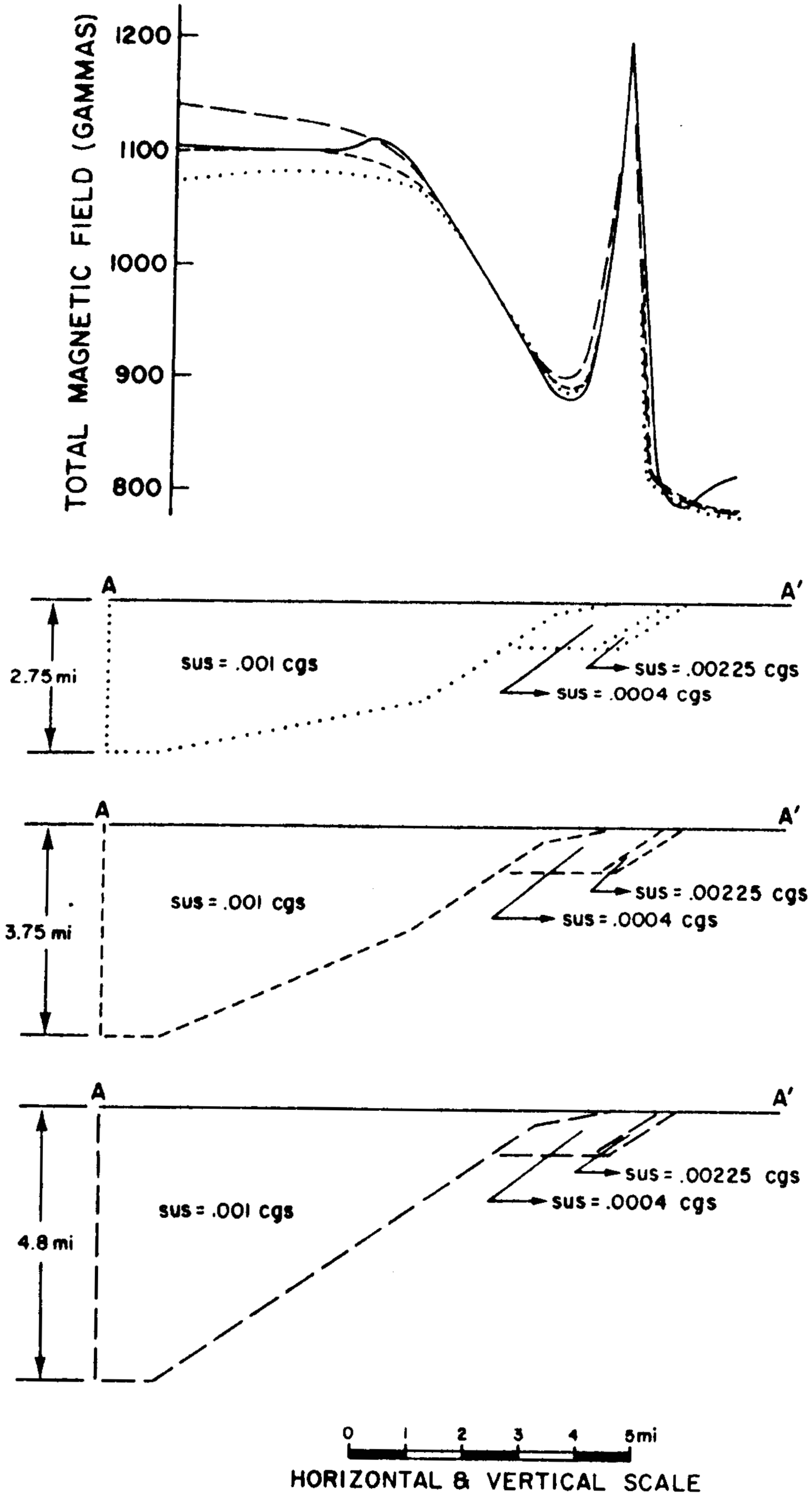


Fig. A8. Three models of the Liberty Hill pluton along the section A-A' and their calculated magnetic profiles compared to the observed magnetic profile (solid line). The strike of the A-A' section is N42W (N137E). Each model is extended to the northwest (left) 10 miles.

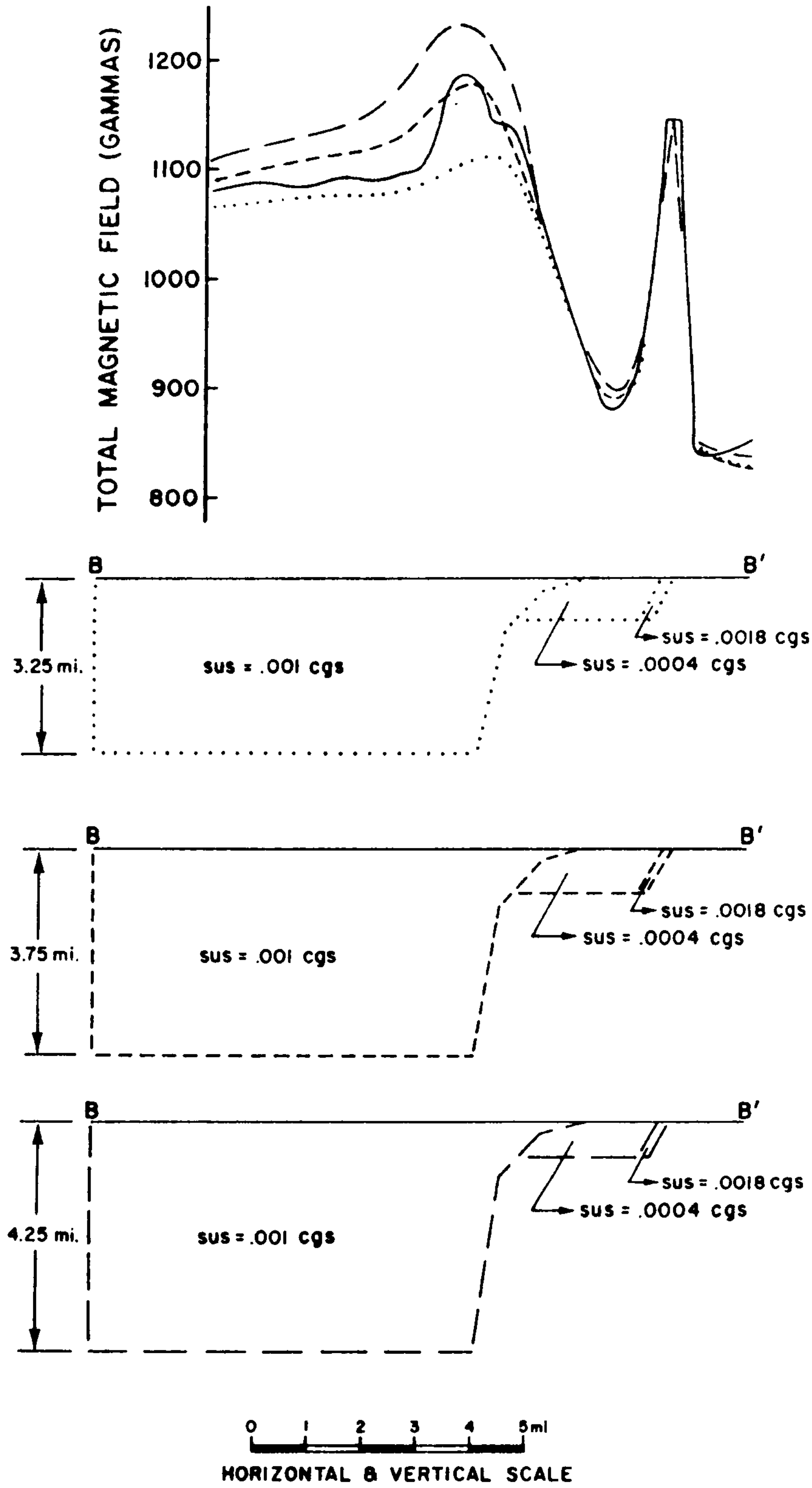


Fig. A9. Three models of the Liberty Hill pluton along the section B-B' and their calculated magnetic profiles compared to the observed magnetic profile (solid line). The strike of the B-B' section is N52W (N125E). Each model is extended to the northwest (left) 10 miles.

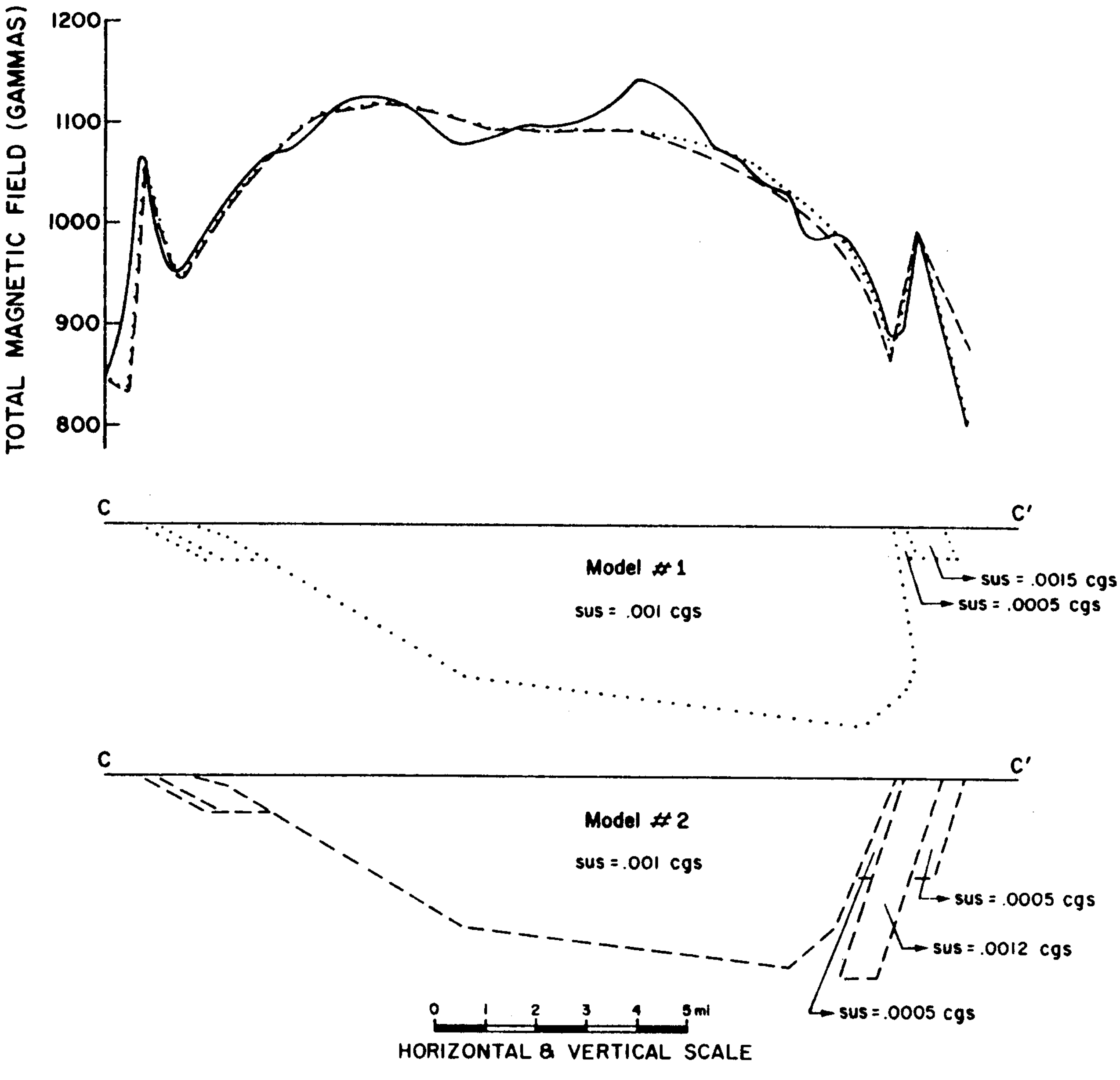


Fig. A10. Two models of the Liberty Hill pluton along the section C-C' and their calculated magnetic profiles compared to the observed magnetic profile (solid line). The strike of the C-C' section is N33E. Model #2 incorporates a diabase dike of susceptibility = 0.0012 cgs.

Table A5. Susceptibilities of Rocks of the Liberty Hill Pluton and the Carolina Slate Belt.

Rock Type	No. Samples	Mean Susceptibility (10^{-4} cgs)	Range of Susceptibility (10^{-4} cgs)
Coarse-grained granite (Lhc)	10	10.7	
Fine-grained granite (Lhf)	10	9.75	
Values from Waskom (1970, Table 3).			
Granite	30	5.6	0-12.7
Argillite	6	2.3	0- 2.5
Mica gneiss	4	7.0	1.4- 9.1
Mica schist	4	1.3	0- 3.3
Felsic volcanic	3	0.3	0- 0.9

the profile is strongly dependent on the depth to which the granite extends. In addition, a diabase dike runs tangential to the pluton in this area. Because the thickness of the granite, the dip of the granite/country rock interface, and the nature of the diabase dike all influence one area of the profile, there is little control over any of these parameters. A wide range of granite depths and dips could be made to agree with the observed field by varying the shape and susceptibility of the dike. For reasonable dike models, however, the range of the dip of the granite contact varies between 70° inward and 80° outward.

Conclusion

The general shape of the eastern half of the Liberty Hill pluton, as defined by the models discussed above, is shown in Fig. A11. The pluton appears to be asymmetrical: in the south and southeast, the granite-country rock interface dips inward at 20° to 40°; in the north, the interface is nearly vertical to a depth of about 21,000 feet. From this point, a relatively flat bottom slopes gently upward toward the south.

Comparison of the Magnetic Model to Gravity and Geologic Data

The model derived from the magnetic data for the shape of the Liberty Hill pluton agrees well with a model based on gravity studies, derived by Bell and Popenoe (1976). In their model (Fig. A12), also, the pluton is asymmetric, dipping steeply inward on the north and west, and sloping more gently inward on the south and east. In addition, they suggest that the pluton is bounded on the northwest by a normal fault that is an extension of the faults bounding the Triassic Wadesboro basin (Bell and Popenoe, 1976, Fig. 3).

Geologic data supports the two mathematical models. In the granite,

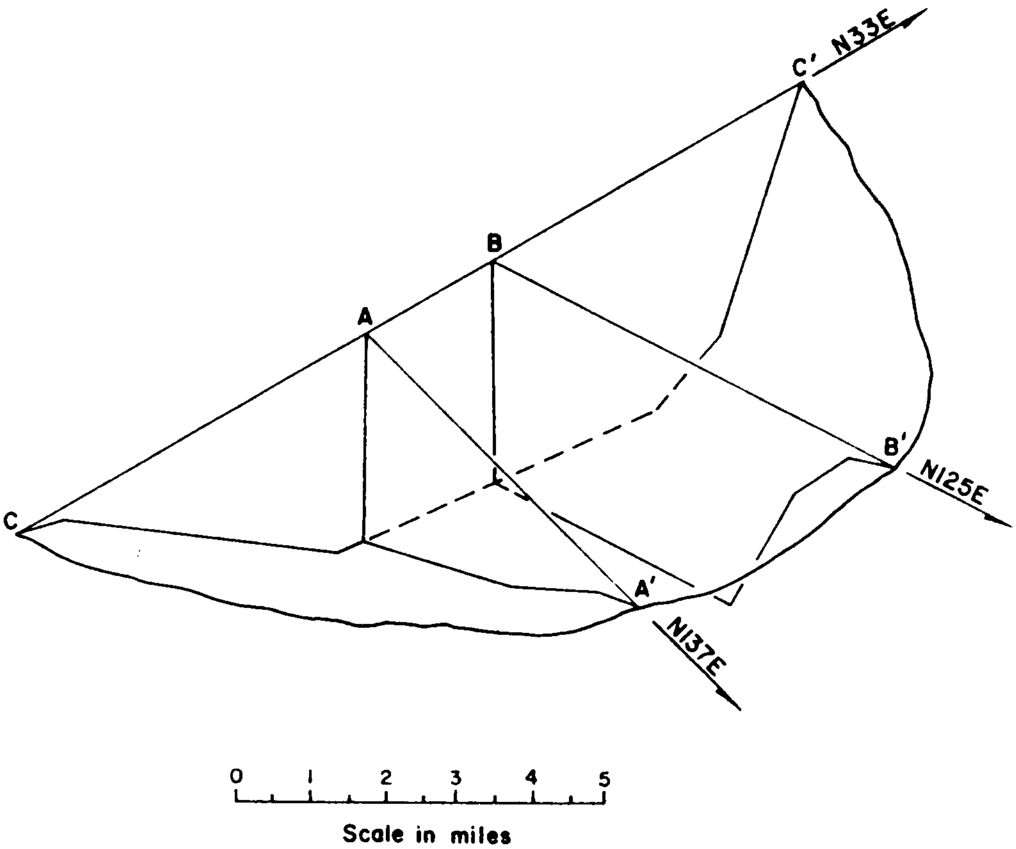


Fig. A11. Model for the shape of the eastern half of the Liberty Hill pluton, derived from profiles illustrated in Figs. A8, A9, and A10.

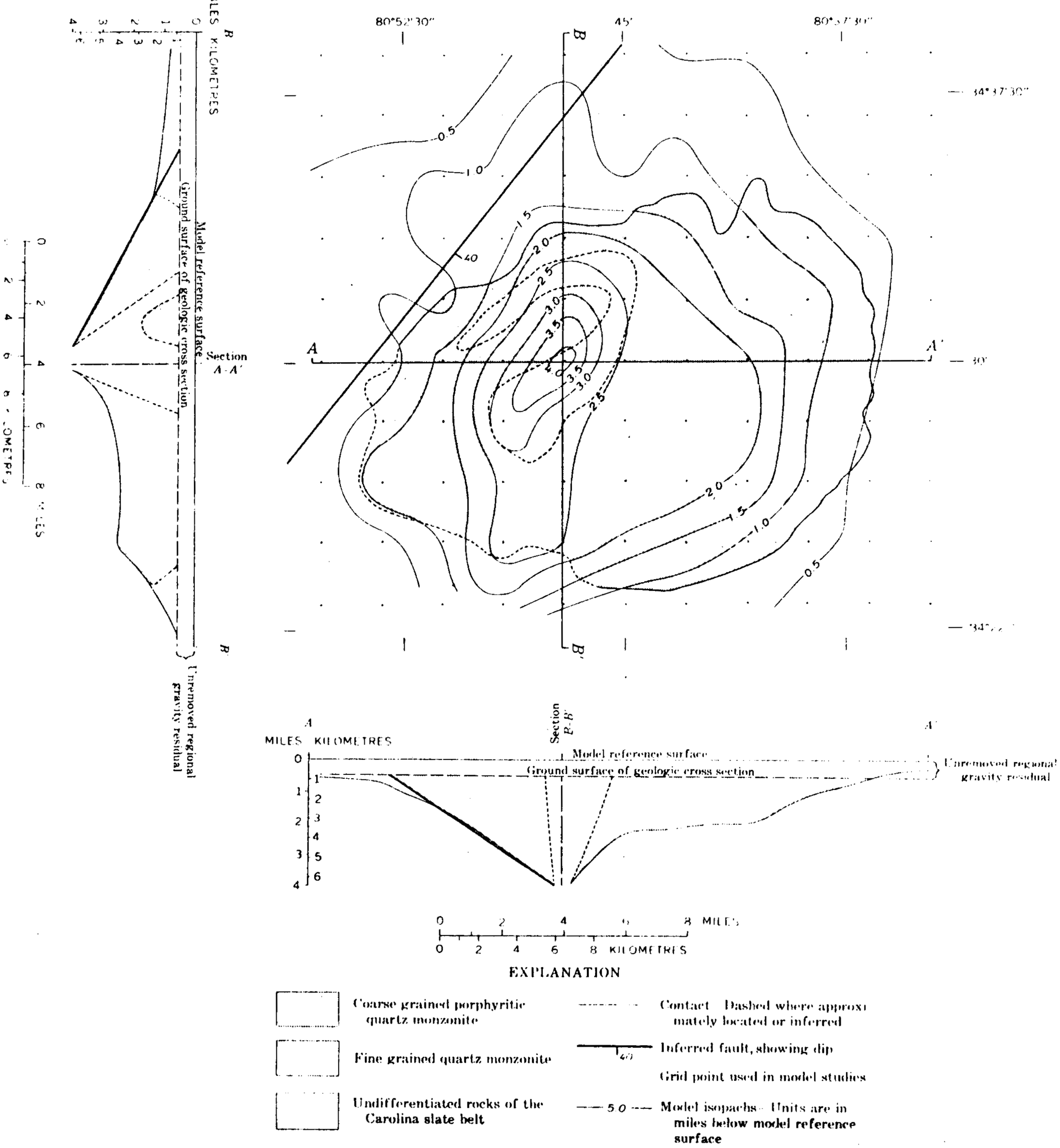


Fig. A12. **Model of the shape of the Liberty Hill pluton derived from gravity data by Bell and Popenoe (1976).**

tabular enclaves and potassium feldspar crystals are aligned parallel to the outer contact of the pluton and dip inward, defining an asymmetric funnel shape (Fig. A2).

Magnetic Mineralogy of the Granite and Country Rocks

An aeromagnetic map shows the relative magnetic susceptibilities of the lithologic units in an area and the magnetic susceptibility of a rock is primarily a function of the volume percentage of magnetite.

In the Liberty Hill pluton, the coarse-grained phase contains up to 2 modal volume percent magnetite and ilmenite. Sulfides are generally rare. The fine-grained phase, which has little exposure in the area covered by the magnetic map, contains magnetite and equal or greater amounts of ilmenite in modal volume amounts less than 1%. The differences in the percentage and mineralogy of the opaque phases between the coarse and the fine-grained rocks should create contrasting magnetic susceptibilities. This may account in part for the magnetic anomalies of $\pm$ 40 gammas within the pluton (Fig. 7b).

The opaque mineralogy of the granites causes high magnetic susceptibilities in these rocks relative to the Carolina slate belt rocks, in which the only oxides observed are hematite and limonite. Magnetite and ilmenite have been identified by x-ray from other Carolina slate belt argillites (Sundelius, 1970; Randazzo, 1972), but if present in the rocks surrounding the Liberty Hill pluton, they are minor in amount.

The contact metamorphic aureole of the Liberty Hill pluton exhibits strong magnetic anomaly (Fig. A7b). Bell *et al*. (1974) attribute this high magnetic anomaly to large amounts of magnetite in the hornfels. Study of the opaque mineralogy shows that ilmenite is also an important oxide mineral. Opaques in the hornfels are coarser grained than those in the argillite, because of metamorphic recrystallization, but the increase in magnetic susceptibility from the argillite to the hornfels requires an increase in the amount of magnetic minerals in the hornfels. Magnetite can be produced by the reduction of less magnetic hematite and limonite with increasing metamorphic grade (increasing T, decreasing f_{O_2}). The formation of additional ilmenite is hampered by the lack of any identified titanium-bearing phase other than ilmenite in the argillites. However, very fine-grained detrital titanite, rutile, or their cryptocrystalline alteration products (leucoxene), as yet undetected, could be involved in the following reactions:

rutile and hematite $\rightleftharpoons$ ilmenite
titanite and hematite $\rightleftharpoons$ ilmenite and calcite and quartz
hematite and leucoxene $\rightleftharpoons$ ilmenite

Additional iron and titanium oxides could be produced by reactions of iron silicates in the low grade, regionally metamorphosed argillites in response to increasing metamorphic grade in the aureole. The white micas of the argillites, for example, may be phengites, which with increasing metamorphic grade react to produce a purer muscovite, iron oxides, and alkali feldspar. Other possibilities include decomposition of the iron-rich chlorite and epidote.

The above reactions that produce magnetite and ilmenite coincide with the beginning of the muscovite hornfels facies. Opaque minerals are generally rare in the country rocks except for samples in this facies (Table A10). The magnetic anomaly is largely associated with the muscovite hornfels facies and disappears with the beginning of the amphibole hornfels facies of the inner aureole.

The disappearance of the oxides and the magnetic anomaly close to the pluton is thus a result of continuous metamorphic reactions that occur with increasing metamorphic grade. The appearance of cordierite at the beginning of the muscovite hornfels facies is probably a result of the idealized reaction:

$$\text{muscovite} + \text{chlorite} + \text{quartz} \rightleftharpoons \text{cordierite} + \text{biotite} + H_2O$$

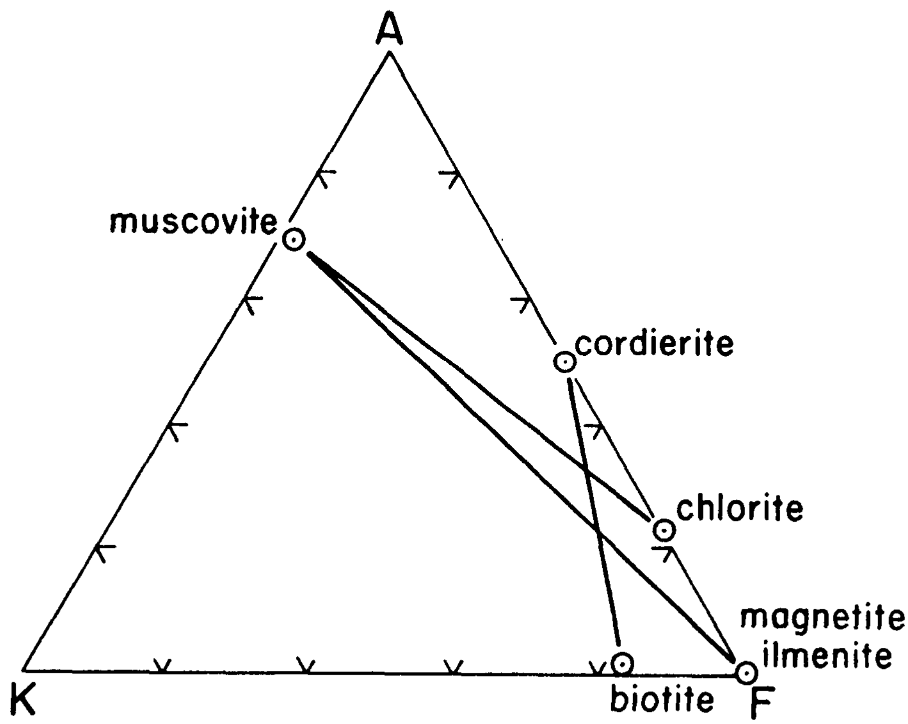
When the reaction has gone to completion by exhausting the supply of chlorite (Figure A13), the production of cordierite and biotite can continue with the consumption of iron oxides. This takes place by a reaction of the type:

$$\text{muscovite} + \text{Fe-oxides} + \text{quartz} \rightleftharpoons \text{cordierite} + \text{biotite} + H_2O$$

which probably begins to take place at the axis of the magnetic high. This reaction will continue until one of the reactants is exhausted or until muscovite + quartz becomes unstable, producing Al_2SiO_5 + K-feldspar. The persistance of small amounts of oxides (mostly ilmenite) in the high grade rocks, and the scarcity of aluminosilicates, suggest that it is the disappearance of muscovite that halts the reaction.

The lower magnetic field of the inner aureole is most easily seen in the southeast quadrant (Figure A7b), where the zones of both the magnetic high and inner magnetic low are wide. To the north the anomalies become narrower and are closer to the granite. This geometry is a result of the increase in dip of the contact between the granite and country rock from south to north, as discussed above (p.A-34).

Hornfels xenoliths in the Liberty Hill pluton have very little magnetic susceptibility, as suggested by qualitative measurements of magnetic susceptibility and the rarity of magnetic minerals noted in polished sections. The silicate mineral assemblages indicate that the xenoliths are in the amphibole and pyroxene hornfels facies. At these high grades,



$A = Al_2O_3 + Fe_2O_3 - (Na_2O + K_2O + CaO)$

$F = FeO + MnO + MgO$

$K = K_2O$

Fig. A13. AFM diagram showing the topology of reactions that occur with increasing metamorphic grade in the Liberty Hill contact aureole: ms + chl + qtz = bt + cd + H_2O, and ms + Fe-oxide + qtz = cd + bt + H_2O.

the reactions consuming Fe-oxides would have occurred, as in the inner aureole, depleting the xenoliths of magnetic minerals. An effect of the magnetic low of the xenoliths is apparent on the aeromagnetic map, where a low magnetic anomaly is centered over a large mapped xenolith in the southeast quadrant of the pluton (Fig. A7b). These non-magnetic xenoliths probably account in large part for the concentric magnetic anomalies within the pluton.

Shape and Orientation of the Pluton

Geologic, magnetic and gravity models of the Liberty Hill pluton indicate that its shape is similar to an asymmetric funnel. On the north, the pluton dips steeply inward at 60° - 90°, whereas it dips inward at only 30° on the south (Fig. A14a). Several explanations could account for the asymmetric nature of the pluton.

The rocks along the northern margin of the pluton may have acted as a resistant barrier to outward flow as the magma was enlarging its chamber during emplacement (Fig. A14b). On the north, the two units in contact with the granite are the Great Falls metagranite and the Carolina slate belt metavolcanics. Although the Great Falls metagranite could have acted as a resistant unit, it is unlikely that the metavolcanics would have acted similarly, because equivalent rock types crop out along the southern contact, where the dip of the granite contact is shallow and no "damming" action occurred.

Bell and Popenoe (1976) suggest that a Triassic reverse fault, dipping 40° to the southeast, bounds the northwest margin of the pluton (Fig. A14c), causing the steep dip of the contact between the granite and the country rock. The presence of the fault does not explain the steep contact along the northeast side of the pluton, and, more importantly, it fails to account for the steep dip of the igneous layering in the northern part of the pluton.

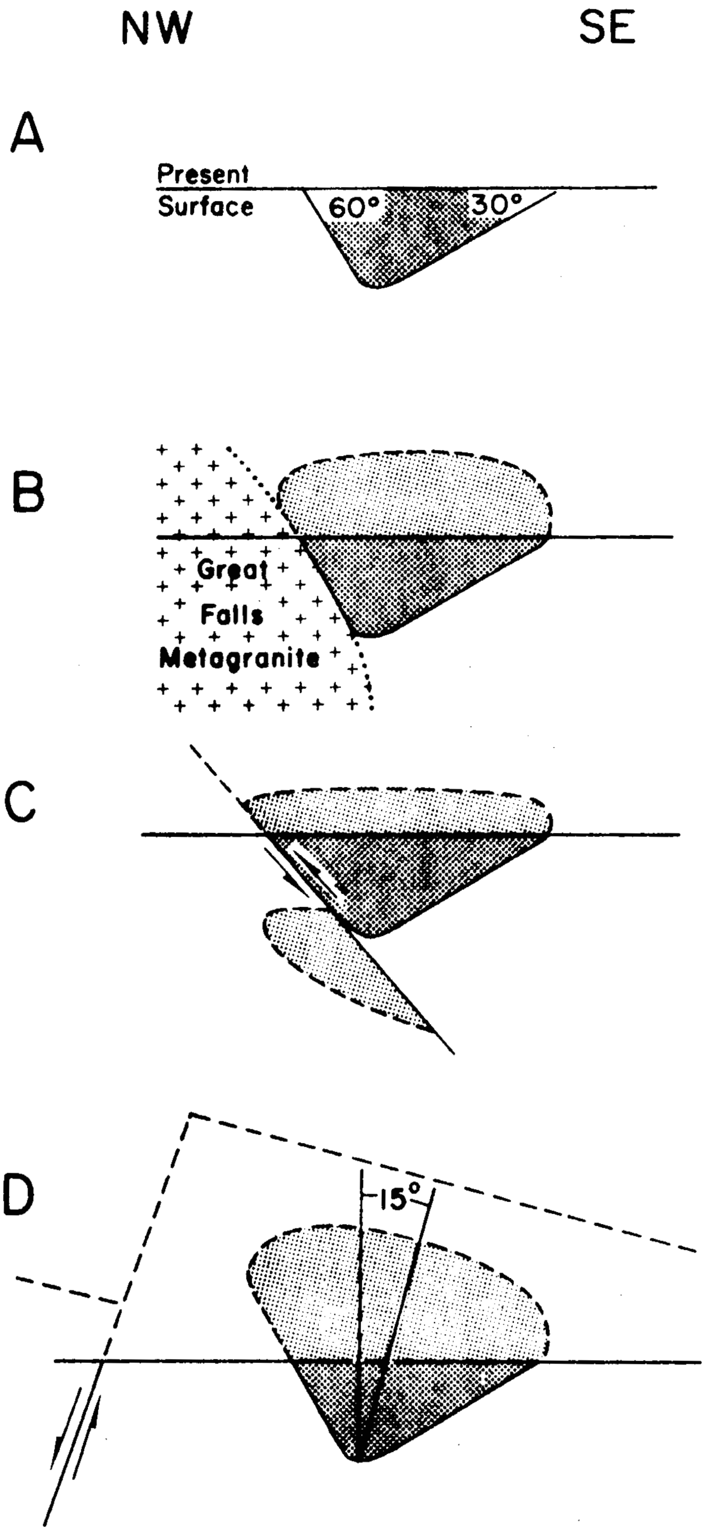


Fig. A14. Models for derivation of the shape of the Liberty Hill pluton: (a) observed asymmetrical shape; (b) resistant rock units limited northward expansion, causing steep dip on that side; (c) faulting along northwest margin truncated the pluton; (d) the pluton was rotated by Triassic normal faulting.

The asymmetry of the Liberty Hill pluton could also be caused by rotation. A 15° rotation about a southwest-northeast axis through its center would bring the pluton to its present orientation. This movement could be achieved by block faulting along a normal fault to the northwest (Fig. A14d). The presence of a normal fault is likely, because the southeastern borders of the nearby Wadesboro and Deep River Triassic Basins are high angle, northeast trending, normal faults which dip to the northwest (Randazzo and Copeland, 1976). If continued along strike, these faults would pass to the northwest of the Liberty Hill pluton.

The amount of displacement along the faults bounding the basins appears to be adequate to produce a 15° rotation. The minimum thickness of the Wadesboro Basin, determined in a gravity study by Mann and Zablocki (1961), is 3800 ft. Estimates of the maximum thickness of sediments in the Triassic basins are as great as 10,000 ft. (Reinemund, 1955). Displacements near this order of magnitude would be sufficient for a 15° rotation.

The rotation of the Liberty Hill pluton by normal faulting associated with the formation of nearby Triassic basins appears to be the most reasonable explanation for the asymmetry of the shape of the pluton.

Winnsboro Plutonic Complex
by

Stewart S. Farrar and Susan W. Becker

General Geology

The Winnsboro complex is composed of two plutons. The Rion pluton, a medium-grained biotite monzogranite, constitutes the central portion of the complex. The Winnsboro pluton, composed of medium- to coarse-grained granite, quartz syenite, and quartz monzonite, occurs as a series of large lenticular, partially connected bodies surrounding the Rion monzogranite.

Detailed reconnaissance mapping and sampling of the complex has been conducted by H. D. Wagener (1970, 1973). Most of the complex lies within the Charlotte belt, whereas the southern border is in contact with the Carolina slate belt (Wagener, 1970). The contacts between the granite and country rock, as shown in Figure A15, are, for the most part, those of Wagener (1970), modified in detail by this investigation.

Structure and Enclaves

An igneous foliation defined by a planar orientation of mafic minerals and feldspar is common near the borders of lenses of the Winnsboro pluton, but it is rarely visible in the Rion pluton. Enclaves in these plutons include xenoliths of country rock and possible autoliths of the plutons. Xenoliths of biotite-quartz-plagioclase gneiss, amphibolite, quartzite, quartz-muscovite-sillimanite schist, and granitic gneiss are common in the Winnsboro pluton, and within the margin of the Rion pluton. The interior of the Rion pluton contains only scarce, small and rounded amphibolitic and leucogranitic enclaves which may be autoliths.

EXPLANATION

MAP UNITS

PERMIAN AND CARBONIFEROUS

RION PLUTON

rm	Medium grained biotite monzogranite
rf	Fine-medium grained biotite monzogranite

WINNSBORO PLUTON

wg	Biotite-hornblende granite, quartz syenite, and quartz monzonite, C. I. < 10
wgm	Biotite-hornblende monzogranite, C. I. > 10
wgk	Biotite-hornblende syenogranite and quartz syenite, K-feldspar rich

gb	Gabbronorite

UPPER PRECAMBRIAN AND PALEOZOIC

Csu	Carolina slate belt undifferentiated metamorphic rocks
Csug	Mixed granite and Csu
Cbu	Charlotte belt undifferentiated metamorphic rocks
Cba	Charlotte belt amphibolite
Cbug	Mixed granite and Cbu

SYMBOLS

- Contact, dashed where inferred
- 50 — Strike and dip of foliation
- 20 — Strike and dip of igneous lamination
- 30 — Strike and dip of xenoliths
- Sample locality

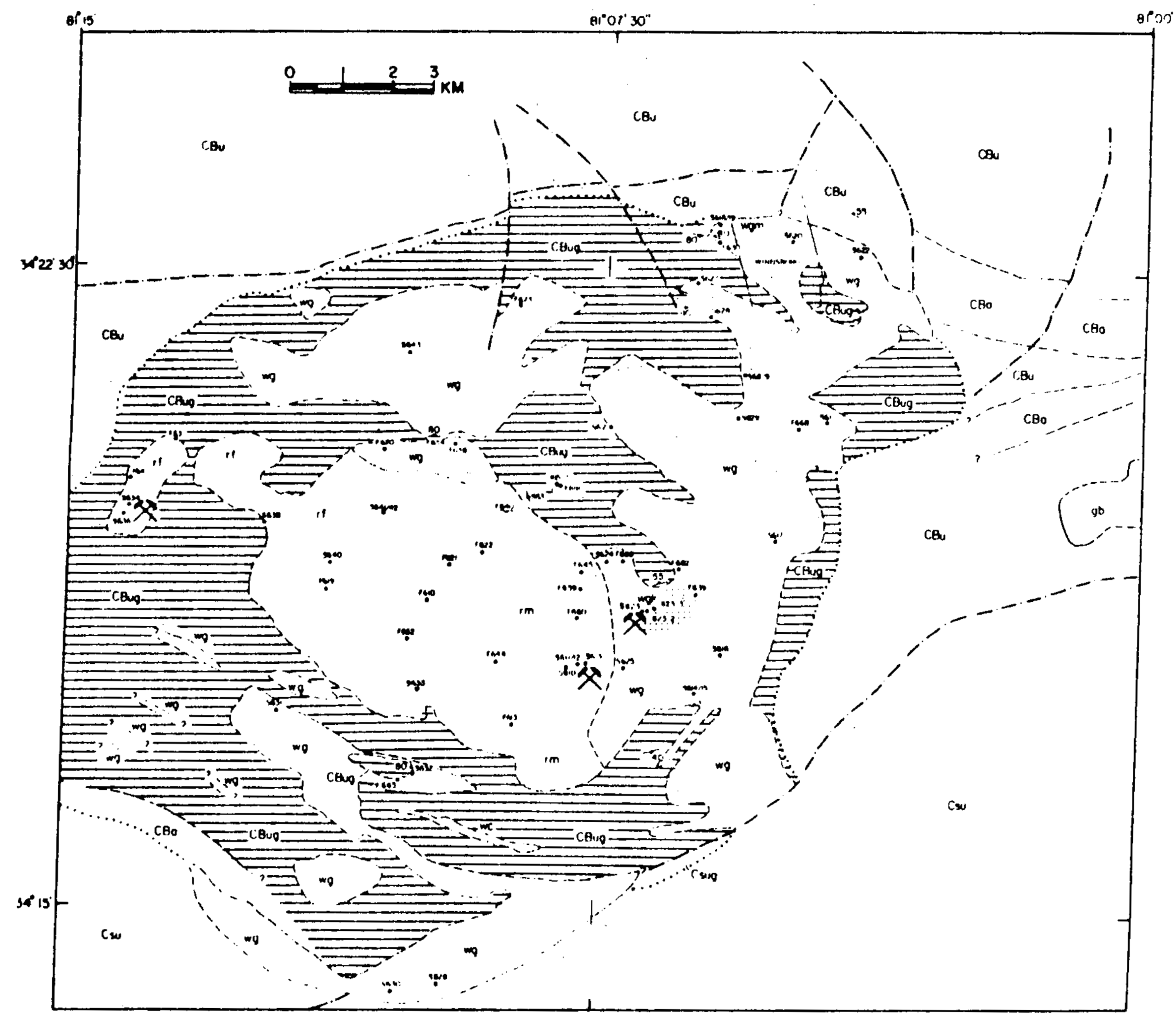


Fig. A5. Geologic map of the Winnsboro plutonic complex, South Carolina.

Attitudes of the igneous foliation parallel the planar orientations of the enclaves, and they are, for the most part, conformable with the dominant foliation in the surrounding metamorphic country rocks (foliation data is from Wagener, 1970). The overall pattern for the complex is a generally funnel-shaped steep to nearly vertical inward dip. Structural data is very incomplete at this time.

Around most of its circumference, the Rion pluton is separated from the Winnsboro pluton by a screen of country rock. The two plutons may be in contact along parts of the northern and southern border of the Rion pluton, but lack of outcrop leaves the possibility of a country rock screen there also.

Mineralogy and Petrology

The Rion pluton is a medium-grained biotite monzogranite (Fig.A16) contains microcline, plagioclase, quartz, and biotite, with the primary accessory minerals zircon, apatite, allanite, titanite, magnetite, and scarce fluorite and molybdenite. Secondary minerals include chlorite, epidote, muscovite-sericite, and minor calcite. Subhedral microcline (0.4-1.0 cm) is consistently slightly larger than the other major minerals (0.2-0.4 cm). The microcline is film or string microperthite. Zoning in the plagioclase is normal oscillatory zoning, with cores of calcic oligoclase grading outward to sodic oligoclase, usually with a discontinuous albite rim. Biotite is pleochroic yellow-brown to olive green.

Secondary minerals are found in most samples. Chlorite replaces biotite, muscovite-sericite replaces plagioclase, and epidote, common in the saussuritized cores of plagioclase, also occurs as possible late-crystallizing magmatic grains. Saussuritization has caused reverse zoning in some plagioclase cores.

Modal analyses of the Rion pluton, presented as Table A6, are represented in Figs. A16 and A17. Rion rocks plot as a relatively tight cluster in the monzogranite field (Fig. A16) and are generally leucocratic (Fig. A17).

The Winnsboro pluton consists of medium- to coarse-grained hornblende-biotite granite, quartz syenite, and quartz monzonite. The mineralogy of these rocks is more varied than that of the Rion granite. The rocks contain varying proportions of microcline, plagioclase, quartz, biotite, hornblende, and accessory titanite, magnetite, chalcopyrite, pyrite, zircon, apatite, allanite, and scarce fluorite. Secondary minerals include chlorite (usually after biotite), and epidote, sericite-muscovite, and calcite, all found in saussuritized plagioclase.

As in the Rion pluton, microcline is the largest mineral, averaging 0.5 to 1 cm long, with a maximum of about 1.5 cm. In contrast to the Rion microperthite, the Winnsboro microcline is macroperthitic with vein, patch, and combinations of perthitic textures. Plagioclase varies in composition (as measured by the 'α normal' method) from calcic oligoclase to albite, and is only slightly zoned, although the more calcic plagioclase usually has a discontinuous albite rim. Biotite is present in all samples, and is pleochroic dark brown to light brown. Hornblende, present in most samples, is pleochroic; X = yellow-brown, Y = olive green, Z = dark green. Compositions of both biotite and hornblende vary within the Winnsboro pluton (see microprobe analyses, Tables A7 and A8).

Modal analyses of Winnsboro rocks are given in Table A6 and illustrated in Figs. A18 and A19. The Winnsboro rocks have a much wider modal variation

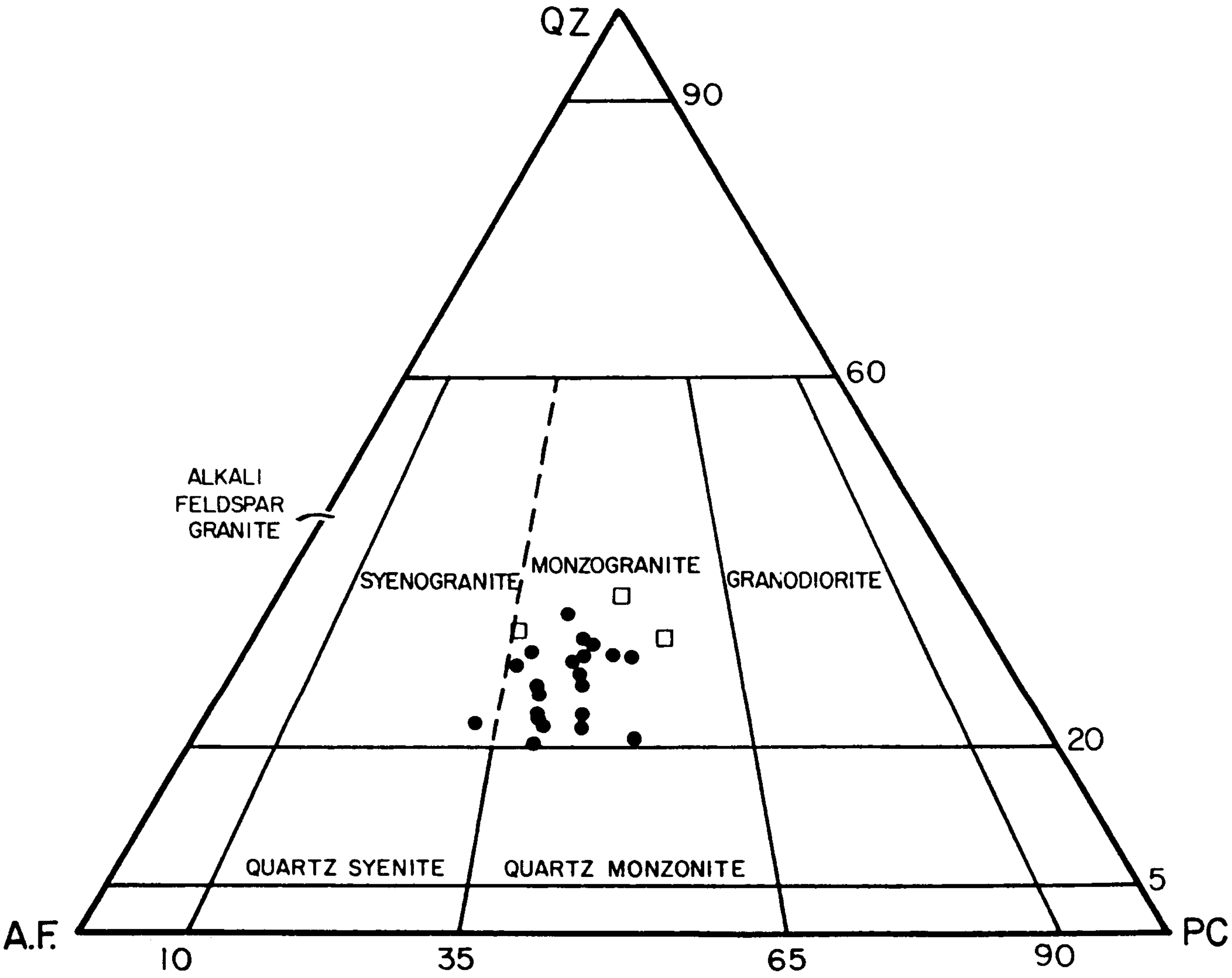


Figure A16. Rion pluton. Modal variation diagram for quartz (QZ)-alkali feldspar (A.F.)-plagioclase (PC). Symbols: closed circle (●), granite; square (□), aplite.

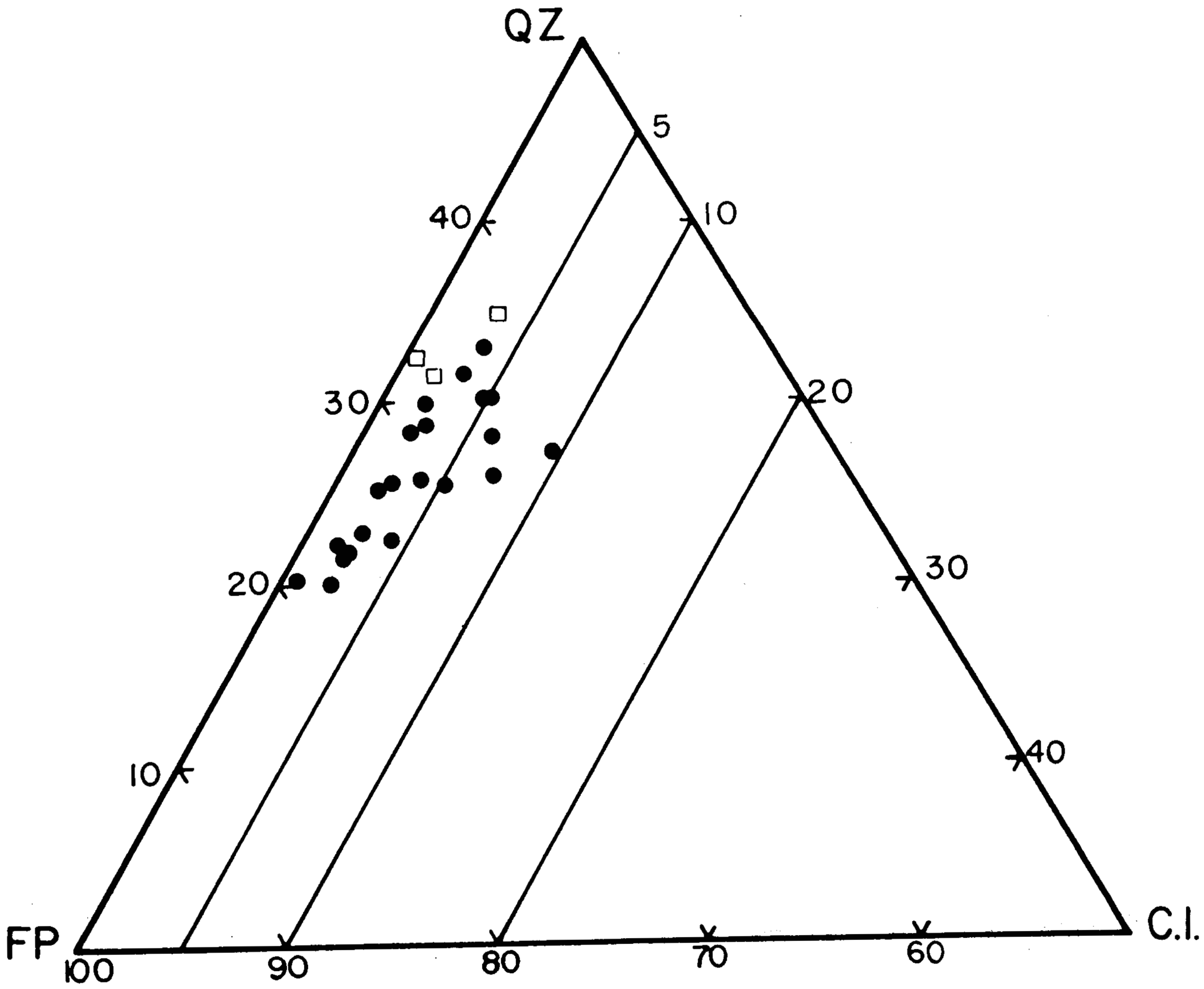


Figure A17. Rion pluton. Modal variation diagram for quartz (QZ)-feldspar (F)-color index (C.I.). Symbols: closed circle (●), granite; square (□), aplite.

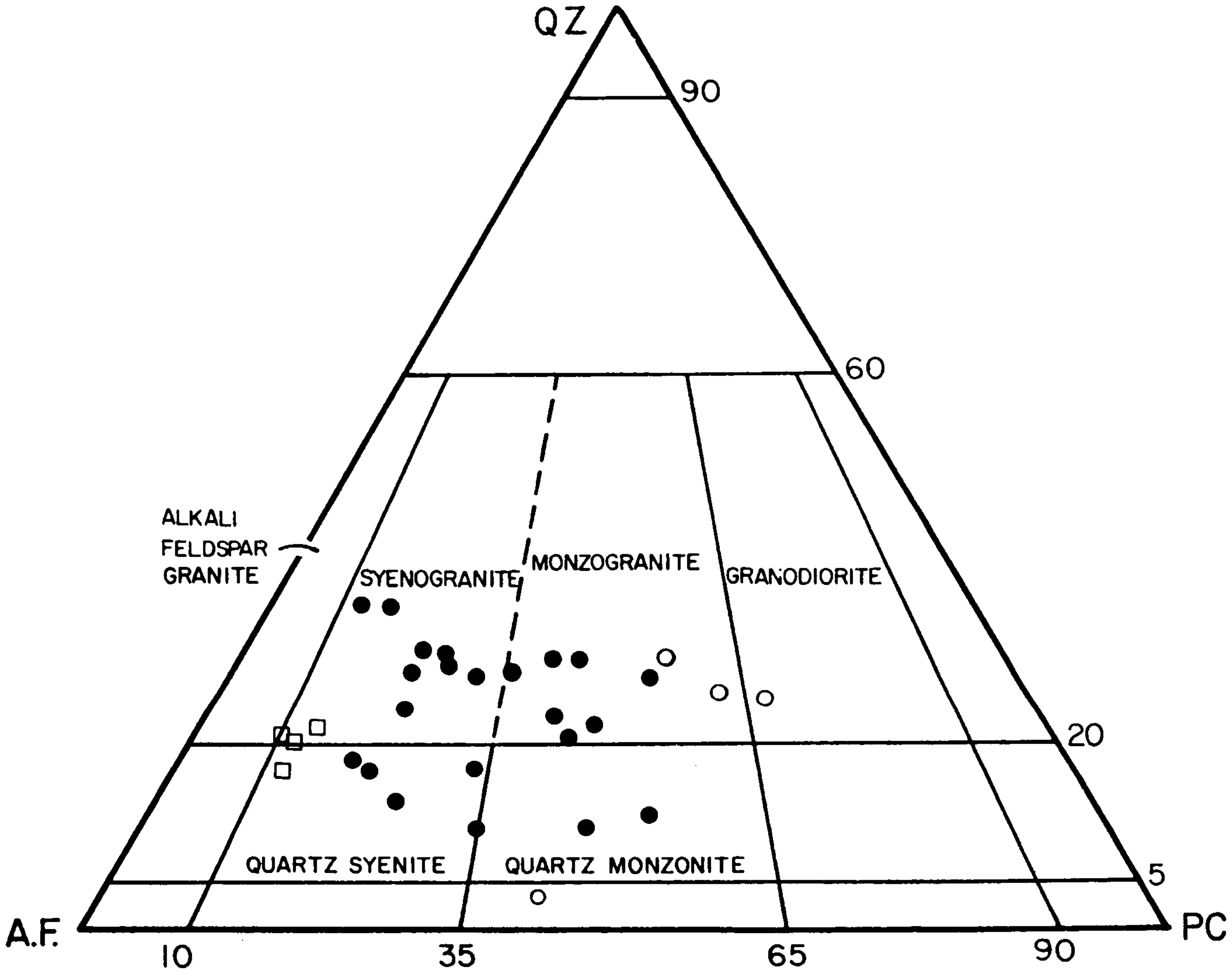


Figure A18. Winnsboro pluton. Modal variation diagram for quartz (QZ)-alkali feldspar (A.F.)-plagioclase (PC). Symbols: closed circle (●), color index less than 10; open circle (○), color index greater than 10; square (□), color index less than 10, and high alkali feldspar.

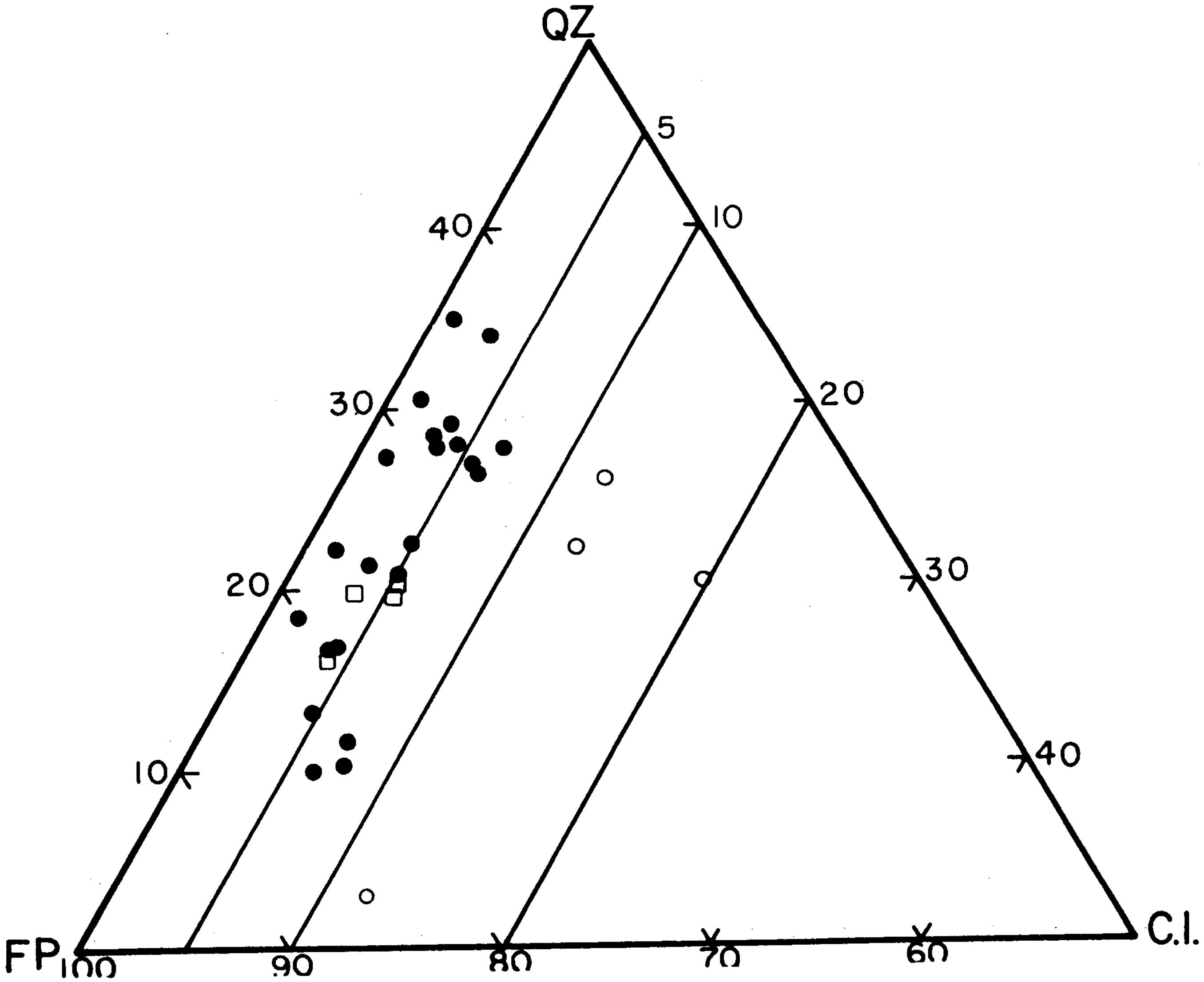


Figure A19. Winnsboro pluton. Modal variation diagram for quartz (QZ)-feldspar (F)-color index (C.I.). Symbols: closed circle (●), color index less than 10; open circle (○), color index greater than 10; square (□), color index less than 10, and high alkali feldspar. The symbols are to facilitate comparison with Figure A8.

than the Rion rocks, varying from the alkalic edge of the granite field to granodiorite, and from 35 to 3% quartz. These variations in the proportions of quartz, feldspar, and color index are discussed below.

Aplitic dikes, usually a few centimeters to tens of centimeters thick, have intruded the Rion and Winnsboro plutons. To date, only three have been point counted (Table A6, Figs. A16 and A17). They are quartz-rich leuco-monzogranites, with an average grain size of 1-2 mm. They bear rounded quartz grains equal in size to, or larger than, the microcline and plagioclase. Microcline is film microperthite. Plagioclase is highly saussuritized, and has normal oscillatory zoning, with cores of sodic oligoclase, and rims of albite.

Mafic dikes have been noted only in quarries, because of poor exposure. A complex lamprophyre dike at the Anderson (Winnsboro Blue) quarry (S6-34, Fig. A15) has been described by Witkus (1973), and Vogel and Wilband (1976). Several diabasic appearing dikes in the Rion quarry (S6-10) have not been examined for this report.

Subdivision of Granitic Rocks

The Rion monzogranite consists of a large central pluton with a small subsidiary body to the west. The intervening area has no exposures, so the two bodies may be contiguous, but Wagener (1970, 1973) believed them to be separated by a screen of metamorphic rocks. The small western body is the finer grained, and more mafic portion of the Rion pluton. It averages 7% biotite, compared to 2-3% for the main body. Average grain size in the main body of the Rion pluton increases gradually from about 1 mm in the west to 3-4 mm in the east. Grain size is coarsest in the southeastern part of the pluton, including the Rion quarry (S6-10, F6-60, F6-13). Modal compositions within the main Rion body indicate that a minor decrease in mafic minerals is associated with the increase in grain size from west to east.

The Winnsboro pluton consists of a number of large and small lenses of granite with abundant enclaves of country rock. This intimate association of Winnsboro granite with adjacent country rock appears to account for a large part of its modal variation. The most mafic and plagioclase-rich area (Wgm, Fig. A15) is adjacent to a major amphibolite unit. This mafic phase of the Winnsboro pluton contains more than 1% titanite, and up to 20% total mafic minerals. This rock type appears to have been contaminated by the amphibolite; to a lesser extent, other samples from this northern part of the pluton (S6-27, S6-28) may also have been contaminated. Other modal variation, including that of quartz content, may be due, in large part, to interaction with adjacent country rocks.

A small area of the Winnsboro pluton near the Rion pluton (Wgk, Fig. A15) is enriched in K-feldspar (squares, Fig. A18). Preliminary microprobe analyses of biotite and hornblende from rocks in this area indicate that Fe/Fe+Mg is significantly higher in this phase than in the mafic-rich phase to the north. Further microprobe analyses will be necessary to compare these data to analyses of mafic minerals from other parts of the complex. This variation could be an indication of differentiation within the Winnsboro pluton.

A contact aureole has not been delineated for the Winnsboro complex. The amphibolite facies metamorphic country rocks do not readily show contact metamorphic effects. A more detailed examination of these metamorphic rocks is necessary in order to make an estimate of the temperature and pressure of emplacement of the plutons.

Table A6. Modal data for the Winnsboro Plutonic Complex.

Sample	quartz	plagioclase	K-feldspar	Color Index	biotite	amphibole	accessories	muscovite	epidote
Rion Pluton:									
S6-10	23.2	28.9	46.0	1.8					
S6-13	28.9	29.4	39.0	2.7					
S6-33	30.5	28.5	36.2	-	3.6	-	0.5	0.5	tr
S6-34	27.4	30.6	32.8	-	7.9	-	0.6	0.7	tr
S6-36	30.0	29.7	35.4	-	4.9	-	0.1	0.2	tr
S6-40	31.6	23.9	41.3	-	2.8	-	0.5	tr	
S6-41	25.6	28.0	43.6	-	2.5	-	0.4		
S6-42	33.3	26.5	37.0	-	3.0	-	0.3	tr	
F6-3	26.1	29.7	36.9	-	5.5	-	0.5	0.5	0.3
F6-4	28.2	29.0	36.7	-	6.2	-	tr	tr	tr
F6-10	21.6	34.3	42.0	2.1					
F6-13	30.1	24.9	42.9	-	1.3	-	0.1	0.7	tr
F6-19	22.5	32.9	40.4	4.2					
F6-21	25.6	30.9	38.4	-	4.2	-	0.6	0.2	0.2
F6-22	20.2	39.5	38.0	2.3					
F6-40	23.0	29.4	45.2	2.3					
F6-44	20.5	31.0	48.0	0.6					
F6-45	28.4	24.9	44.6	2.1					
F6-52	22.4	24.7	51.5	1.5					
F6-59	25.5	28.3	44.4	1.8					
F6-60	21.9	30.1	45.6	2.3					
Winnsboro Pluton:									
S6-1	22.0	31.9	44.5	1.6					
S6-2	34.4	8.5	55.9	1.2					
S6-5	20.9	35.2	40.3	3.6					
S6-8	28.8	18.3	49.4	3.5					
S6-14	26.5	24.4	43.3	5.8					
S6-17	22.2	17.3	55.6	4.9					
S6-24	30.2	15.9	52.3	1.6					
S6-25	33.5	11.3	51.7	3.5					
S6-26	26.1	21.2	46.6	6.2					
S6-27	19.1	33.0	42.3	5.6					
S6-28	28.3	30.8	37.9	3.0					
S6-29	27.8	27.8	40.0	4.4					
S6-31	9.9	38.2	44.3	7.6					
S6-32	11.3	43.0	38.6	7.1					
S6-43	27.5	19.0	50.0	3.5					
F6-20	2.9	35.6	49.6	12.0					
F6-23	27.3	35.2	30.6	-	4.9	1.8	2.7		

Table A6 (continued).

Sample	quartz	plagioclase	K-feldspar	Color Index	biotite	amphibole	accessories	muscovite	epidote
Winnsboro Pluton (continued):									
F6-30	16.3	17.7	62.1	3.9					
S6-38	16.5	26.6	52.4	4.5					
S6-62	9.7	29.4	54.7	6.1					
F6-65	13.0	21.4	61.0	4.6					
F6-66	27.0	16.6	55.0	1.5					
F6-68	18.1	15.7	64.8	1.4					
Winnsboro Pluton > 10 CI:									
S6-18	25.8	34.6	27.1	-	7.4	2.8	2.2		
S6-20	21.9	40.5	24.6	-	8.4	2.5	1.9		
S6-22	19.6	41.2	19.6	-	10.7	5.9	3.0		
Winnsboro Pluton, K-feldspar-rich:									
S6-23	20.4	10.4	64.1	5.0					
S6-23-2	19.7	7.7	67.1	5.5					
S6-23-3	16.2	9.8	70.2	3.8					
F6-39	19.4	9.2	67.7	3.7					
Aplites:									
S6-3	35.1	30.7	31.3	-	1.8	-	0.8	0.3	-
S6-11	31.9	36.7	29.9	-	0.4	-	1.1	-	-
S6-38	32.6	24.0	43.0	-	0.3	-	-	0.2	-

Table A7. Microprobe analyses of Winnsboro biotites.

	1		2		3		4	
SiO_2	35.42		36.23		34.92		35.79	
Al_2O_3	14.74		15.47		14.08		15.08	
FeO	26.59		24.36		31.20		27.35	
TiO_2	2.51		3.55		4.02		2.44	
MnO	0.76		0.67		0.47		0.83	
CaO	0.0		0.0		0.0		0.04	
MgO	8.66		9.78		5.25		9.26	
Na_2O	0.03		0.05		0.05		0.07	
K_2O	7.96		8.54		7.83		8.02	
H_2O	3.86		3.98		3.82		3.94	
Sum	100.53		102.63		101.64		102.82	
			number of cations based on 24 oxygens					
Si	5.504	8.000	5.453	8.000	5.482	8.000	5.448	8.000
Al	2.496		2.547		2.518		2.552	
Al	0.203		0.197		0.086		0.153	
Ti	0.293		0.402		0.475		0.279	
Fe	3.455	6.058	3.066	5.944	4.096	5.948	3.482	6.123
Mn	0.100		0.085		0.062		0.107	
Mg	2.006		2.194		1.228		2.101	
Ca	0.0		0.0		0.0		0.007	
Na	0.009	1.587	0.015	1.654	0.015	1.583	0.021	1.584
K	1.578		1.639		1.568		1.557	
H	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
F/FM		0.639		0.590		0.772		0.631

[1] F6-39, Winnsboro

[2] S6-18, Winnsboro

[3] S6-23, Winnsboro

[4] S6-27, Winnsboro

Table A8. Microprobe analyses of Winnsboro amphiboles.

	1	2	3	4
SiO_2	43.70	41.13	43.38	41.50
Al_2O_3	7.99	8.40	7.93	7.98
FeO	21.95	28.26	24.07	26.61
TiO_2	1.66	2.06	1.58	2.03
MnO	0.89	1.13	1.19	1.46
CaO	11.09	10.09	10.71	10.28
MgO	9.33	4.48	6.87	5.13
Na_2O	1.84	2.38	1.83	2.46
K_2O	0.0	0.0	0.0	0.0
H_2O	1.96	1.88	1.92	1.88
Sum	100.41	99.81	99.48	99.33

number of cations based on 24 oxygens

	1		2		3		4	
Si	6.669	8.000	6.542	8.000	6.751	8.000	6.596	8.000
Al	1.331		1.458		1.249		1.404	
Al	0.106		0.117		0.206		0.091	
Ti	0.191		0.246		0.185		0.243	
Fe	2.801	5.335	3.759	5.337	3.133	5.274	3.537	5.283
Mg	2.122		1.062		1.594		1.215	
Mn	0.115		0.152		0.157		0.197	
Na	0.544		0.734		0.552		0.758	
Ca	1.813	2.358	1.720	2.454	1.786	2.338	1.751	2.509
K	0.0		0.0		0.0		0.0	
H	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
F/FM		0.579		0.786		0.674		0.754

[1]S6-18, Winnsboro

[2]S6-23, Winnsboro

[3]S6-27, Winnsboro

[4]F6-39, Winnsboro

Opaque Mineralogy

J. Alexander Speer

Granites

Mineralogic and textural data concerning the oxide and sulfide phases in the Liberty Hill and Winnsboro plutons are summarized in Table A9. Sample locations are given in Figs. A2 and A15. The rocks contain less than 2 modal percent oxide minerals and less than 0.1 modal percent sulfide minerals. In order of frequency of observation, the opaque minerals are magnetite, ilmenite, pyrite, chalcopyrite, and pyrrhotite. Hematite is common, but only as a subsolidus or weathering product. Molybdenite, sphalerite, and uraninite were also observed.

In the coarse-grained phases of the Liberty Hill and Winnsboro plutons, magnetite predominates in abundance over ilmenite. The magnetite contains octahedrally oriented, fine ilmenite lamellae as well as larger external and internal granular ilmenite. These ilmenite intergrowths are thought to represent "oxyexsolution" of a primary titanomagnetite ($Usp\text{-}Mt_{ss}$). The ilmenite intergrowths are present in the magnetite in amounts less than 10% of the grain and constitute the only ilmenite in some coarse-grained rocks. Many ilmenite grains contain networks and blebs of white-grey hematite, which contrast with the reddish grey color of the ilmenite, and indicate exsolution of the ilmenite-hematite solid solution. Only in rare instances has magnetite been oxidized to hematite in petrographically fresh rock.

In several coarse-grained rocks of the Liberty Hill and Winnsboro plutons, granular titanite mantles ilmenite and magnetite. The opaque appears to have been resorbed, suggesting that titanite has replaced

Table A9. Opaque mineralogy of the Liberty Hill and Winnsboro plutons.

sample numbers	magnetite(mt)		ilmenite(il)				hematite(hm)				chalcopyrite(cp)			pyrrhotite(po)			pyrite(py)			marcasite alter. prod.
	plain	il intergrowths	plain	intergrowths			rims			plain	grndmass	inclusions		grndmass	inclusions		grndmass	inclusions		
				hm	mt	tit	py	po	mt			mt	silicate		mt	silicate		mt	silicate	
Winnsboro																				
F6-3	+	0	0	+	0	0	0	0	0	0	+	0	0	0	+	0	0	+	0	0
F6-3	0	+	0	0	+	0	0	0	0	0	+	0	0	0	0	0	+	0	0	+
F6-39	0	+	+	0	+	0	+	0	0	0	0	+	0	0	+	0	+	0	0	+
F6-40	+	0	+	0	0	0	+	0	+	0	+	0	0	0	0	0	+	0	0	0
F6-45	0	+	0	+	+	0	0	0	+	0	0	+	0	0	+	0	0	+	0	0
F6-52	+	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F6-59	+	0	0	+	0	0	0	0	0	0	0	+	0	0	+	0	0	+	0	0
F6-60	+	0	0	+	0	0	0	0	0	0	+	+	+	0	+	+	+	+	+	0
F6-66	0	+	0	+	+	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0
S6-18	0	+	+	0	+	0	0	0	0	0	+	+	0	0	+	0	+	+	0	0
S6-20	0	+	0	0	+	0	0	0	0	0	+	+	0	0	+	0	+	0	0	0
S6-23	0	+	0	0	+	0	0	0	0	0	+	0	0	0	0	0	+	0	0	0
S6-23-3	0	+	+	0	+	0	0	+	0	0	+(1)	+	+	0	+	0	+	+	0	0
S6-24	0	+	0	0	+	0	0	0	+	0	+	0	0	0	0	0	0	0	0	0
S6-26	+	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S6-27	+	0	+	0	0	0	0	0	0	0	+	+	0	0	0	0	+	0	0	0
S6-34	+	0	0	+	0	0	0	0	0	0	+	+	+	0	0	0	+	+	0	0
Win 1-739	0	0	0	+	0	0	0	0	0	0	0	0	0	+	0	0	0	0	0	0
Liberty Hill - coarse-grained granite																				
F6-24	0	+	0	0	+	0	0	0	0	0	+	+	0	0	+	+	+	+	0	0
F6-25	0	+	+	0	+	0	0	0	0	0	+	0	0	0	0	0	+	0	0	0
S6-54	+	0	+	0	0	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0
S6-69	0	+	0	0	+	0	0	0	0	0	+	+	+	0	0	0	+	0	0	0
S6-70	0	+	0	0	+	0	0	0	0	0	0	0	0	0	+	+	+	0	0	0
S6-87	0	+	0	+	+	0	0	0	+	+	+	+	0	0	+	0	0	+	0	0
S6-88	0	+	0	0	+	0	0	0	0	0	0	0	0	0	0	0	+	0	0	0
S6-98	0	+	0	+	+	+	+	0	+	+	+	0	0	0	+	0	+	+	0	0
S6-110(2)	0	+	0	0	+	0	0	0	0	0	+	+	+	0	0	0	+	0	0	0

(+) present (1) intergrown with sphalerite
(0) absent (2) also contains molybdenite

Table A9 (continued).

sample numbers	magnetite(mt) plain	magnetite(mt) il intergrowths	ilmenite(il) plain	ilmenite(il) intergrowths hm	ilmenite(il) intergrowths mt	ilmenite(il) intergrowths tit	hematite(hm) rims py	hematite(hm) rims po	hematite(hm) rims mt	hematite(hm) plain	chalcopyrite(cp) grndmass	chalcopyrite(cp) inclusions mt	chalcopyrite(cp) inclusions silicate	pyrrhotite(po) grndmass	pyrrhotite(po) inclusions mt	pyrrhotite(po) inclusions silicate	pyrite(py) grndmass	pyrite(py) inclusions mt	pyrite(py) inclusions silicate	marcasite alter. prod.
S6-126	+	0	+	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S6-132	0	+	0	0	+	0	0	0	0	+	0	0	0	0	0	0	+	0	0	0
S6-135(3)	0	+	+	+	+	0	+	0	0	0	+	+	+	0	+	0	+	+	0	0
K1-323	0	+	+	+	+	+	0	0	+	+	+	+	+	0	+	+	0	0	0	0
K2-5	0	+	0	0	+	0	0	0	0	0	0	0	0	0	+	0	+	0	0	0
K2-6	0	+	0	0	+	0	0	0	0	0	+	0	0	0	+	0	+	0	0	0
K2-598	0	+	+	+	0	0	0	0	0	0	+	0	0	0	+	0	+	0	0	0
K2-118	0	+	+	+	+	+	0	0	0	0	+	0	0	0	+	0	+	0	0	0
K2-204	0	+	0	0	+	0	0	0	0	0	+	0	0	0	0	0	+	0	0	+
K3-294	+	0	0	0	0	0	0	0	0	0	+	0	0	0	+	0	+	0	0	0
K3-540	0	+	0	0	+	0	0	0	0	0	+	0	0	0	+	0	+	0	0	+
K3-794	0	+	+	+	+	+	0	0	0	0	+	+	0	0	+	0	+	0	0	+
K3-1303	0	+	+	+	+	0	0	0	0	0	+	+	+	0	+	+	+	0	0	+
Liberty Hill - fine-grained granite																				
S6-57	+	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S6-67	+	0	+	0	0	0	0	0	+	0	+	+	+	0	+	0	0	0	0	0
S6-99	+	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S6-100	+	0	+	0	0	0	0	0	0	0	+	+	0	0	0	0	0	0	0	0
S6-108	0	+	+	0	+	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0
S6-111	+	0	+	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K3-55(2)	0	+	0	0	+	0	0	0	0	0	0	0	0	0	+	0	0	0	0	0
K3-103	+	0	+	0	0	0	0	0	0	0	0	0	0	0	+	0	0	0	0	0

(+) present
(0) absent

(2) also contains molybdenite
(3) also contains uraninite

Table A10. Opaque mineralogy of the Liberty Hill contact metamorphic rocks.

sample number	magnetite(mt)		ilmenite(il)		hematite(hm)	pyrite(py)	pyrrhotite(po)	chalcopyrite(cp)	other
	plain	il intergrowths	plain	hm intergrowths					
S6-52	0	0	0	0	+	0	+	0	marcasite after po.
S6-59	0	+	0	+	0	0	0	+	
S6-60	?	0	0	+	0	0	0	0	
S6-61	0	+	0	+	0	0	0	0	
S6-62	+	0	0	0	+	+	0	0	
S6-63	+	0	0	+	0	0	0	0	
S6-64	0	0	+	0	0	0	+	+	pentlandite in po.
S6-75	0	+	0	+	0	0	0	0	
S6-76	0	+	0	+	0	0	0	0	
S6-79	0	+	0	+	0	0	0	0	
S6-81	+	0	0	+	0	0	0	0	
S6-82	0	+	0	0	0	0	0	0	
S6-93	0	+	0	+	0	0	0	0	
S6-105b	0	0	+	0	0	0	+	0	
S6-127	0	0	0	+	0	0	0	0	
K3-240	+	0	0	0	0	+	+	+	
K3-472	0	0	+	0	0	+	+	+	pentlandite in po.
K3-1075	0	0	+	0	0	+	+	+	py rims po.
K3-1079	0	0	+	0	0	+	+	+	marcasite after po.

(+) present
(0) absent

the oxides. The reaction probably occurred during the stage of deuteric alteration, with calcium and silica reacting with the titanium oxide component of the opaques:

$$\text{anorthite} + \text{alkali feldspar} + TiO_2 + H_2O \rightleftharpoons \text{muscovite} + \text{titanite} + \text{quartz}$$

The coarse-grained granites may therefore contain two generations titanite: magmatic titanite which is generally euhedral, and deuteric titanite which occurs as granular rims on opaque oxides. Hunt and Kerrick (1977) have calculated that at 4 kb, the above reaction occurs for pure rutile at a temperature of 550°C.

Two sulfide assemblages have been observed in the granitic rocks. The assemblage pyrrhotite + chalcopyrite + pyrite occurs only as inclusions, usually in magnetite and less commonly in silicates such as titanite and zircon. No sulfide inclusions have been observed in ilmenite. The intergranular assemblage, pyrite + chalcopyrite, coexists with both magnetite and ilmenite. From the contrasting occurrence of these two assemblages, it appears that pyrrhotite + chalcopyrite + pyrite is the initial sulfide assemblage that crystallized with magnetite and the early silicate minerals. Pyrite + chalcopyrite is a later sulfide assemblage that crystallized in equilibrium with both magnetite and ilmenite. Thus the activities of oxygen and sulfur appear to have increased during crystallization of the granite magma (Fig. A20).

The sulfide inclusion assemblage, pyrrhotite + chalcopyrite + pyrite, which is found in magnetite and the silicates, indicates that reequilibration occurred at low temperatures. Yund and Kullerud (1966) found that above 334° ± 10°C, pyrrhotite and chalcopyrite react to form pyrite + a cubic copper-iron solid solution + vapor. The high temperature inclusion assemblage,

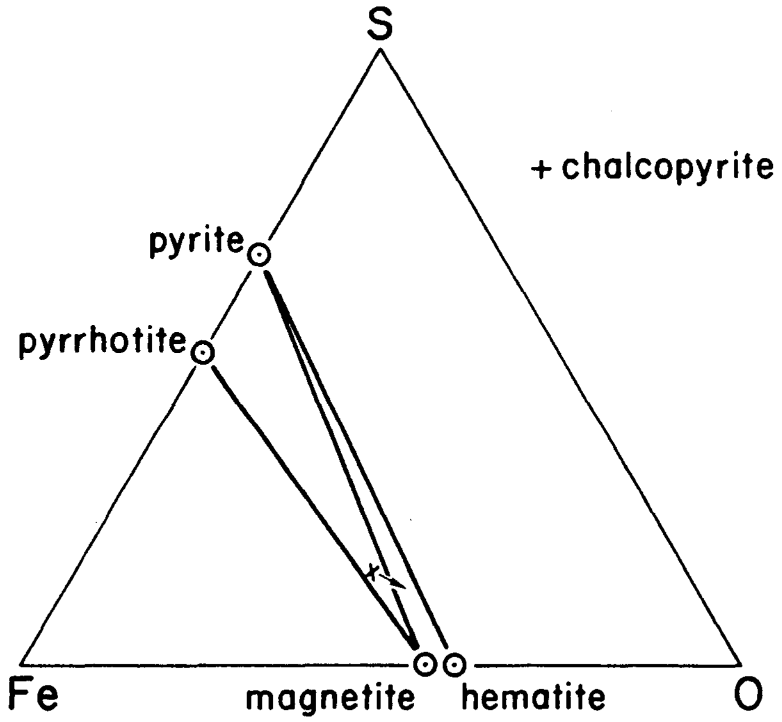


Fig. A20. Fe-O-S diagram showing the inclusion assemblage pyrite + pyrrhotite + magnetite (x), which occurs in early crystallizing phases in the granite, and the later crystallizing groundmass assemblage, magnetite + pyrite + ilmenite (represented by hematite). The transition indicates an increase in oxygen and sulfur fugacity with cooling of the magma.

therefore, was pyrrhotite + pyrite + an intermediate copper-iron solid solution + magnetite, which has a thermal stability above the granite solidus.

In the weathered granite samples, supergene alteration of the sulfides is common. Pyrite and chalcopyrite have rims of hematite and hydrous iron oxides.

Metamorphic Rocks

Mineralogic and textural data concerning the opaque mineralogy of the country rocks and hornfelses of the Liberty Hill contact aureole and xenoliths is summarized in Table A10. Locations are given in Fig. A2. As suggested by the wide variety of protoliths and metamorphic conditions represented by the metamorphic rocks, the opaque mineralogy of the country rocks is highly variable in the texture, abundance and number of phases present. Pyrrhotite and pyrite are the most common sulfides. Chalcopyrite is rare, except in calcareous rocks, where regular intergrowths with pyrrhotite make up to 5 volume percent of the rock. Such intergrowths probably represent an unmixed Cu-Fe intermediate solid solution which was the high temperature phase. Possible exsolved pentlandite from pyrrhotite was noted in two samples (S6-64, Ker 3 - 472). Sphalerite with exsolved chalcopyrite was observed in one specimen (Ker 3 - 999.3). Marcasite is a common alteration product of the pyrrhotite.

Magnetite and ilmenite are the common oxide minerals. In most metamorphic rocks they have well developed exsolution features: ilmenite from magnetite and hematite from ilmenite.

Uraninite

Uraninite, UO_{2+x}, has been identified in a coarse-grained granite of the Liberty Hill pluton (S6-135) by ore microscopy and qualitative electron microprobe analysis. The tabular grain , 0.04x0.01mm, is included in biotite at a high angle to the biotite cleavage. It is bounded by a large radiation damage halo composed of an inner ring of yellow crypto-crystalline material and an outer ring of black isotropic biotite. This large pleochroic halo, which is several times the volume of the uraninite grain, is the most important feature that indicated the special nature of the mineral. The radiation damage halos around zircons and xenotimes are only a fraction of the size of the grains that they surround. In reflected light the uraninite is a leaden grey, in contrast to the yellow grey of magnetite and red grey of ilmenite.

A qualitative analysis by electron microprobe showed the presence of uranium, thorium, and iron. Counts were collected for no other elements. As a comparison, counts for U, Th, and Fe were also made on uraninite from a pegmatite at Spruce Pine, N.C. The Liberty Hill uraninite contains less uranium and more thorium and iron. Magmatic and pegmatitic uraninites often contain larger amounts of Th and R.E.E. than hydrothermal uraninites (Frondel, 1958). What little compositional data is available on the Liberty Hill uraninite suggests a magmatic origin for this mineral.

Molybdenum Mineralization

in the Liberty Hill and Winnsboro Plutons

J. Alexander Speer

Molybdenite occurs as widely disseminated flakes in the fine-grained phases of both the Liberty Hill and Winnsboro plutons. In the fine-grained phase of the Winnsboro, the Rion pluton, concentrations of molybdenite are also found in quartz veins with pyrite and chalcopyrite. In only one sample (S6-110) was molybdenite observed in a coarse-grained rock of the Liberty Hill pluton. The disseminated molybdenite probably represents magmatic crystallization, whereas the molybdenite-chalcopyrite-pyrite-quartz veins are similar to conventional hydrothermal veins.

Deuteric alteration is more extensive in the fine-grained granites, in which molybdenum mineralization is common, than in the coarse-grained granites. Biotite is altered to chlorite, and plagioclase is altered to albite + epidote + white mica $\pm$ calcite $\pm$ quartz. Alkali feldspar is locally, but not invariably, altered to a red-brown, fine-grained material, but the reaction is probably caused by weathering rather than by deuteric alteration. The present alkali feldspar is apparently in equilibrium with the products of deuteric alteration. The deuteric mineral assemblage is the same as that found in the molybdenite-chalcopyrite-pyrite-quartz veins, suggesting that the reaction of the late magmatic fluids with the previously consolidated granite occurred under the same conditions and perhaps simultaneously with the molybdenite vein mineralization.

Recent experimental work in the $CaO-K_2O-Al_2O_3-SiO_2-CO_2-H_2O$ system (Johannes and Orville, 1974) allows an understanding of the reactions and conditions of the deuteric alteration associated with the molybdenum mineralization. Fig. A21 illustrates several reactions in T-X_{CO_2} space. The proposed path of T-X_{CO_2} conditions in Fig. A21 is suggested by the presence of the deuteric assemblages epidote and epidote + calcite and the absence of calcite alone in the Liberty Hill and Winnsboro plutons. The residual fluid of a granite magma would approach the invariant point from the water-rich side. Conditions remain those of the invariant point until either the fluid or one of the feldspars is consumed, and the rock is completely solidified. Because both feldspars remain in the rocks, the fluid must have been the first reactant to disappear.

The deuteric alteration, and probably the molybdenum mineralization, occurred at conditions along these reaction curves and at the invariant point. The intensity of alteration depends on the initial ratio of fluid to rock. Low fluid contents produce minimal alteration, as in the coarse-grained Liberty Hill and Winnsboro rocks, whereas higher fluid contents cause more extensive alteration as in the fine-grained Rion and Liberty Hill.

Fig. A21 is drawn for a total pressure of 4 kb, which is an estimate of the Liberty Hill emplacement pressure based on the mineralogy of the contact aureole. At 4 kb, the invariant point is at 475°C and X_{CO_2} = 0.03. This is an estimate of the maximum temperature and carbon dioxide content. The reduction of fluid pressure below total pressure or the addition of sodium to the system would lower the temperature and the X_{CO_2} of the invariant point along the line shown in Fig. A21, inset. The effect of sodium is evident in both the Liberty Hill and Winnsboro plutons in the restriction of

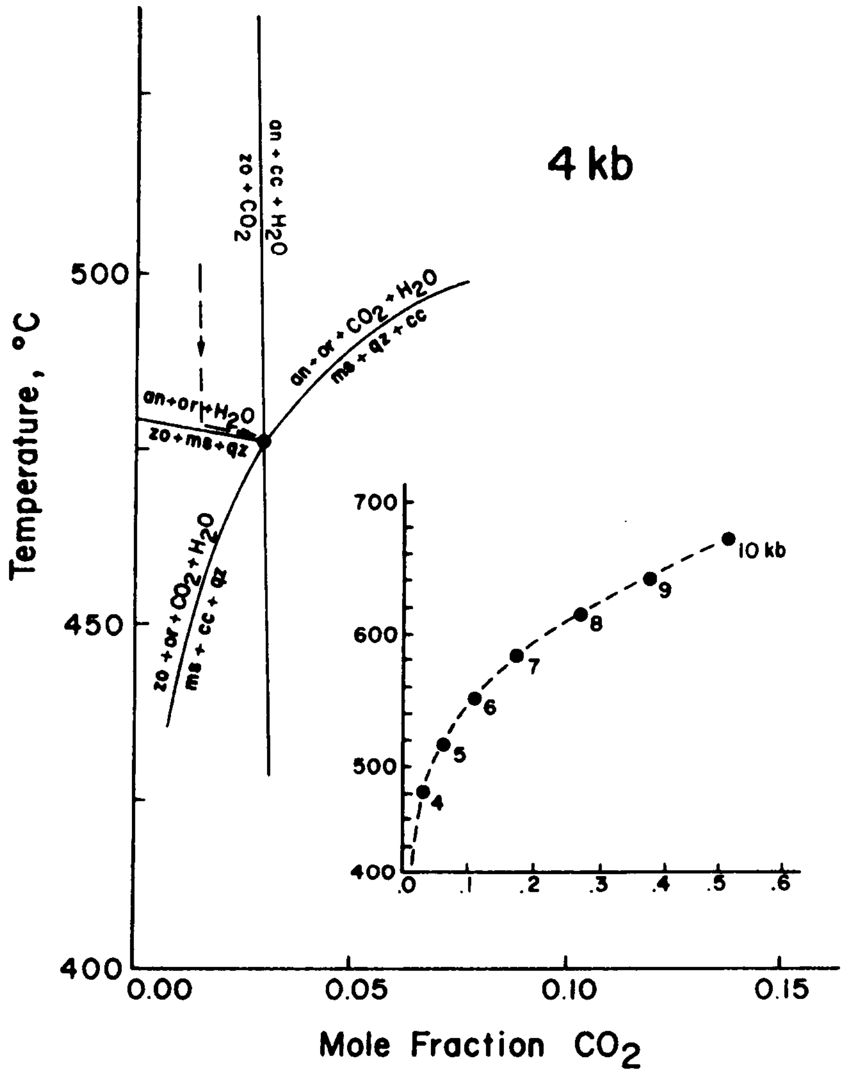


Fig. A21. Phase relations in the water-rich portion of the system $K_2O-CaO-Al_2O_3-SiO_2-H_2O$ from Johannes and Orville (1974). Dashed line shows probable path of descent of deuteric conditions in the Liberty Hill and Winnsboro plutons. Inset shows variation of the invariant point with pressure.

saussuritization of plagioclase to the cores of zoned crystals with an anorthite content greater than 25 mole percent. The reaction

$$An + Or + H_2O \rightleftarrows Zo + Ms + Qz$$

would thus be changed to

$$An_{25} + Or + H_2O \rightleftarrows Ab + Zo + Ms + Qz,$$

which accounts for the reverse zoning observed in altered plagioclase.

Molybdenum mineralization in the Southeast

The molybdenum mineralization of the Liberty Hill and Winnsboro plutons falls within the criteria used by Lowell and Guilbert (1970) and Clark (1972) to define porphyry copper-molybdenum and molybdenum deposits. Compared to ore grade deposits, the southeastern molybdenum occurrences differ only in scale and intensity rather than in nature. Any differences, especially in the alteration, can be accounted for by the high pressure of emplacement of the South Carolina plutons, as opposed to the lower pressures of the shallow Mesozoic deposits of the western United States.

Molybdenum occurrences in the southeastern United States are summarized in Table A11 and located in Fig. A22. All appear to be vein or disseminated copper-molybdenum mineralizations associated with granitic intrusive rocks with varying types of alteration. The plutons are post-metamorphic, 300 m.y. in age, except for the Newell prospect, which is probably older. Mineralization is a late magmatic feature in both the Liberty Hill and Winnsboro plutons as discussed above. Andersen and Fullagar (1977) dated altered material at the Boy Scout-Jones

Table A11. Molybdenite occurrences in the southeastern United States.

pluton or prospect	location	mineralization[1]	alteration	age	references
Boy Scout - Jones Moss - Richardson unnamed granite stock	Halifax Co., NC	mo-cp-py	prophylitic + argillic	307 ± 6 m.y. Rb-Sr	Robertson et al., 1947 Harvey, 1974 Andersen & Fullagar[2], 1977 Schrader et al., 1977
Sims (Connor) biotite granite	Wilson & Nash,Co., NC	mo-cp-py-sph-ga	yes	post-metamorphic	Councill, 1954 Cook, 1972
Newell or Dixie Queen mine Boger's Chapel quartz monzonite	Cabarrus Co., NC	mo-cp-py vein-disseminated	prophylitic	syn-metamorphic 388 ± 12 m.y. K-Ar 417 ± 15 m.y. K-Ar	Bates & Bell, 1965 Worthington & Lutz[2], 1975
Woodleaf granite	Rowan Co., NC	mo-cp-py vein	prophylitic w/ zeolites & fluorite	post-metamorphic	Privett, 1973
Catawaba granite	York Co., SC	mo-cp-py-bn vein-disseminated	potassic	325 ± 50 m.y. Rb-Sr	Fullagar[2], 1971 Beg and Larson, 1975
Liberty Hill pluton	Kershaw, Lancaster & Fairfield Co., SC	mo-cp-py disseminated	potassic/ prophylitic	299 ± 8 m.y. Rb-Sr	Fullagar[2], 1971 this report
Winnsboro pluton	Fairfield Co., SC	mo-cp-py vein-disseminated	potassic/ prophylitic	301 ± 4 m.y. Rb-Sr	Fullagar[2], 1971 this report
Wilton pluton	Granville Co., NC	mo	unknown	(∼300 m.y.) Rb-Sr	Anderson & Fullagar[2], 1977 Carpenter, 1970

[1]sulfide abbreviations: mo, molybdenite; cp, chalcopyrite; py, pyrite; sph, sphalerite; ga, galena; bn, bornite.

[2]reference for age of pluton.

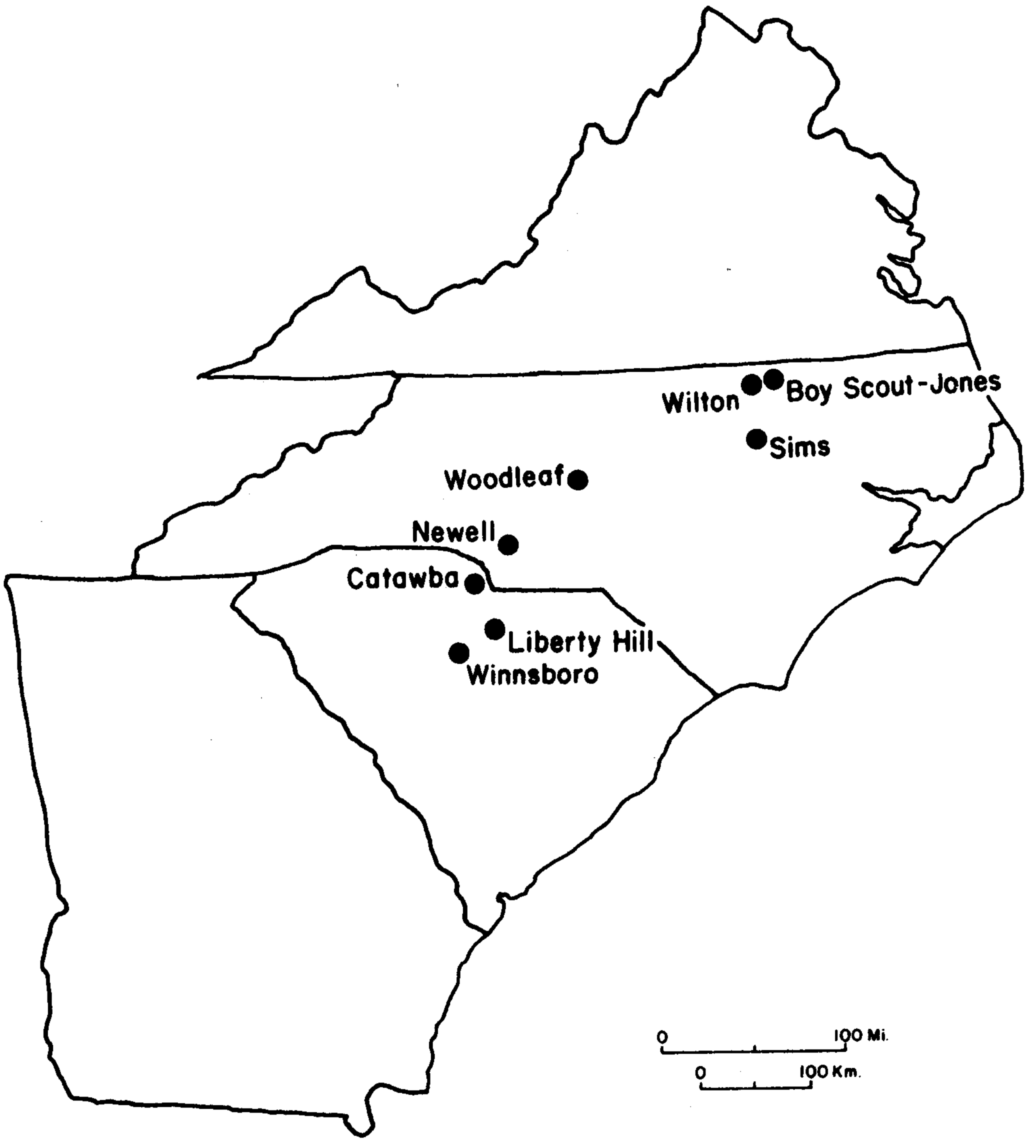


Fig. A22. Index map showing known localities of molybdenum mineralization associated with the ca. 300 m.y. plutons.

prospect at 288 ± 7 m.y. and determined an age of 279 ± 6 m.y. from a sericite mineral isochron. With an age of 307 ± 6 m.y. on the fresh granite, they concluded that the mineralization was a late consolidation feature of the granite. The sparse molybdenum-copper mineralization may be a general feature of the 300 m.y. old plutons, as suggested by Andersen and Fullagar (1977). As of this time, no deposit appears to be of economic value.

Uranium-molybdenum relations

Lowell and Guilbert (1970) suggest that the differentiation index of an intrusive rock may dictate whether copper or molybdenum predominates in a deposit, molybdenum tending to be associated with more silicic rocks. Uzkut (1974) demonstrates that molybdenum increases with increasing silica and alkali contents, with alkaline rocks exhibiting the highest molybdenum contents. If, as is commonly suggested, uranium is also enriched in more silicic and alkali-rich rocks, a sympathetic relation may exist between molybdenum and uranium. For the Liberty Hill and Winnsboro plutons, the fine-grained granites, which are more closely associated with the molybdenum mineralization, have the highest uranium contents. Uraninite-molybdenite deposits constitute one of the several types of uranium deposits that have been recognized (Dybek, 1962). Associated with granitic rocks, they have been found as veins (Stevenson, 1951) and as massive deposits near country rock contacts (Harshman and Bell, 1970).

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B. GEOCHEMISTRY (South Carolina)

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Introduction

Geochemical characteristics of igneous rocks have been used extensively by numerous workers to identify the nature of the magma, depth of crystallization and distribution of elements during crystallization. As an integral part of the targeting procedures for locating areas of high heat production (and high subsurface temperatures), 60 chemical analyses of whole rock samples have been completed. The generic names of the rocks are at variance with those determined by modal analysis because normative classifications do not provide for hydrous mineral paragenesis.

Winnsboro Peraluminous Plutonic Complex

Twenty-nine samples from the plutonic complex have been analyzed for major elements to determine the magmatic affinities of the complex. The two major igneous phases that can be recognized in the field--coarse-grained Winnsboro and medium- to fine-grained Rion granites (see Section A)--can also be distinguished on chemical criteria (Table B1).

Using normative quartz, i.e., greater or less than 17%, Streckeisen (1976) has proposed a classification scheme for use with chemical analyses. All the Winnsboro pluton samples (labelled Wgn in all figures) have less than 17% normative Qz (see Table B2) and can be classified as alkali-feldspar granites to (syeno-) granites. The samples from the Rion pluton have greater than 17% normative Qz and can be classified as monzogranites or (syeno-)granites.

Like the Liberty Hill complex, the variations in Na_2O, K_2O, CaO, SiO_2 are not large enough to justify the use of Peackocks' index for assignment of a specific magma series. However, comparisons with other known magmatic trends, especially the Southern California batholith, on an AFM diagram suggest a calc-alkaline affinity. Thornton and Tuttle's (1960) differentian indices versus oxide weight percent values also indicate a calc-alkaline trend.

The differences in the chemical trends of the two plutons are best shown in a Harker-type variation diagram (Fig. B1). Although the MgO content for both units is rather similar, there is a marked variation in the total iron content. The Rion granites are lower in iron by nearly 30% and as such have low Fe/Mg ratios, suggesting a source region that was either low in iron, or derivation from a magma that had already

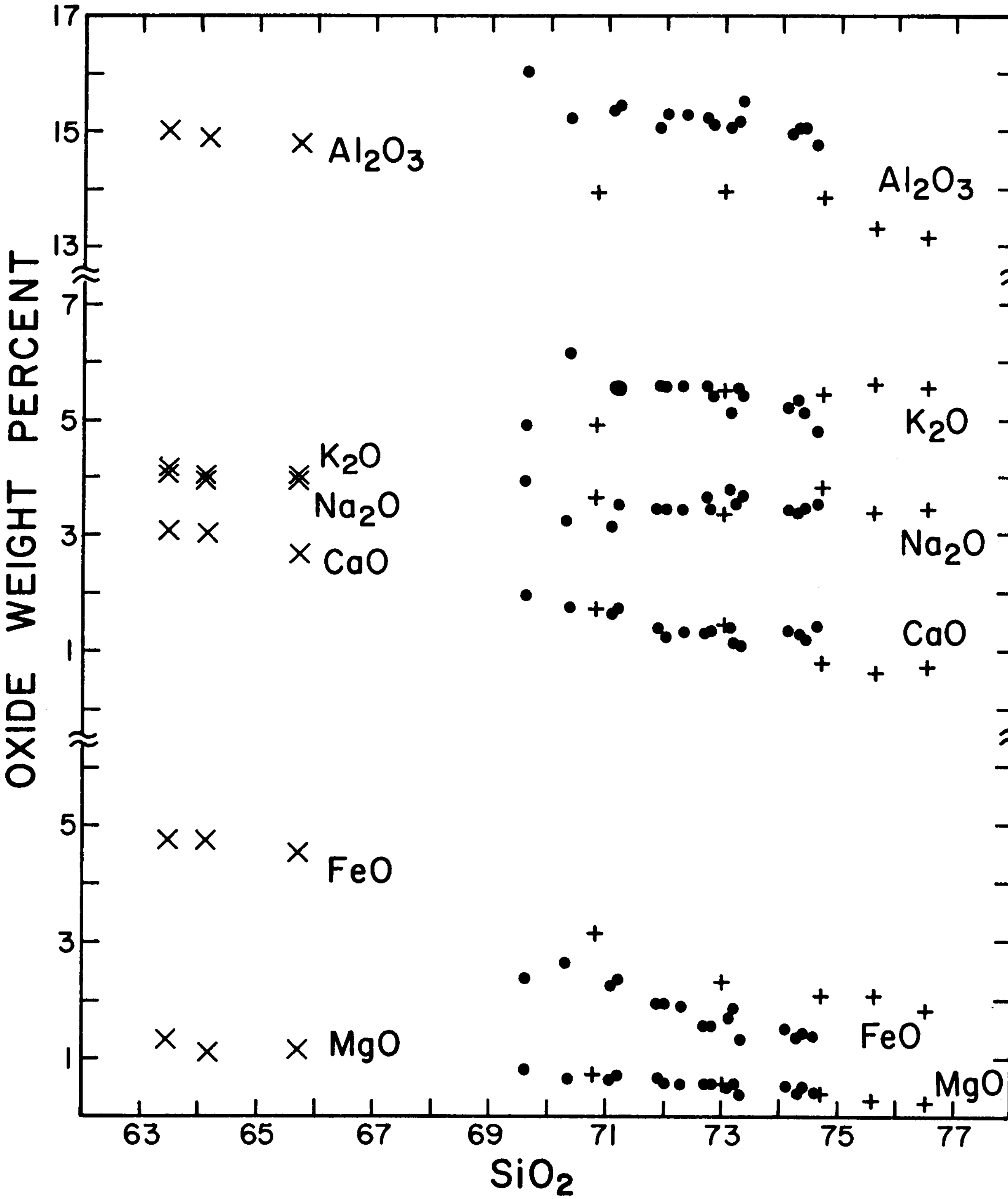

Figure B1. Variation diagram showing chemical differences in the Winnsboro Complex. Solid circles = Rion granite; + = Winnsboro granite; x = marginal facies.

undergone fractionation. Al_2O_3 values from the Rion granites are consistently higher than those of the Winnsboro granites and may reflect the higher anorthite content of the plagioclase feldspars or the aluminous nature of the source rock. Na_2O/CaO ratios which reflect the sodic/calcic nature of the plagioclase feldspars are consistently between 2.5 to 3.1 in the core facies of the Rion. The Winnsboro granite shows a generally increasing Na_2O/CaO from NE to SW (further implications are considered later). K_2O contents of the two bodies appear to show different trends: The Winnsboro granite shows a slight increase with increasing SiO_2, while Rion granite samples show a slight decrease.

Three samples from unit Wgm (NE part of the complex) show very consistent differences from the two granite bodies. Characteristically they are low in SiO_2, with high MgO, FeO, and CaO contents. K_2O/Na_2O ratios are generally around one, with Al_2O_3 content intermediate between the Rion and Winnsboro granites.

Earlier work on the Winnsboro complex and surrounding country rock by Wagener (1973) has shown this area (Wgm) to be in contact with high grade (upper amphibolite facies) amphibolites and quartz feldspar meta-arenites. Although the silica content is nearly 74%, the K_2O content is below 2.6%. Therefore, the possibility of K metasomatism accompanied by lowering of K_2O content in the margin facies of the granite is a strong possibility (see also Section A).

Two samples of high perthite content (Wgk) show the highest K_2O and Na_2O contents and the lowest MgO and CaO values. With the patchy occurrence of this body in the Winnsboro granite, it is difficult to evaluate its genetic relationship at the present time.

Figures B2 and B3 are preliminary contours for Differentiation Index (DI) and FeO + MgO. Even with the limited data on the Winnsboro

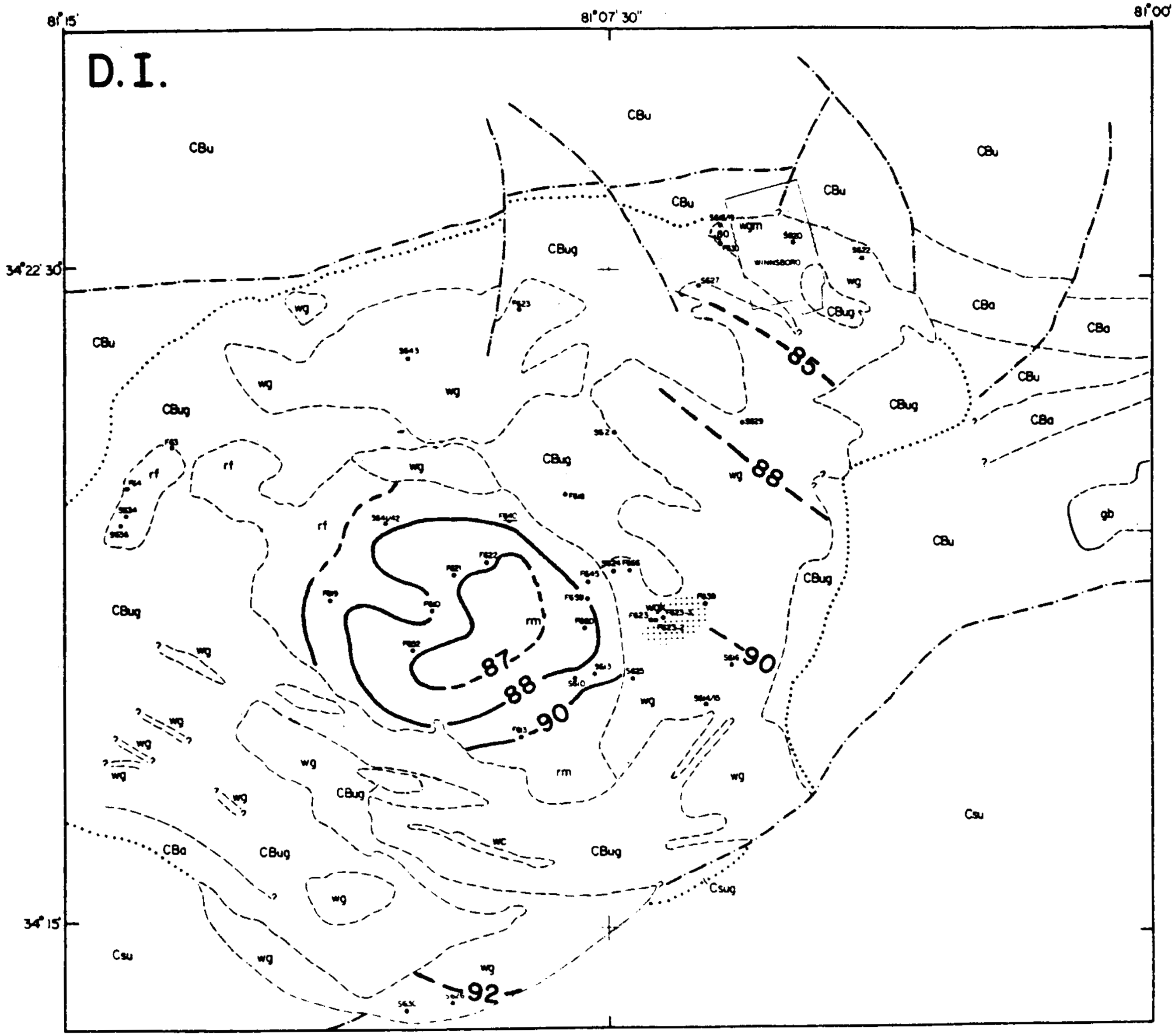

Figure B2. Contour diagram, Differentiation Index (DI) to rock type. Note the systematic increase in DI for unit Wg from NE to SW.

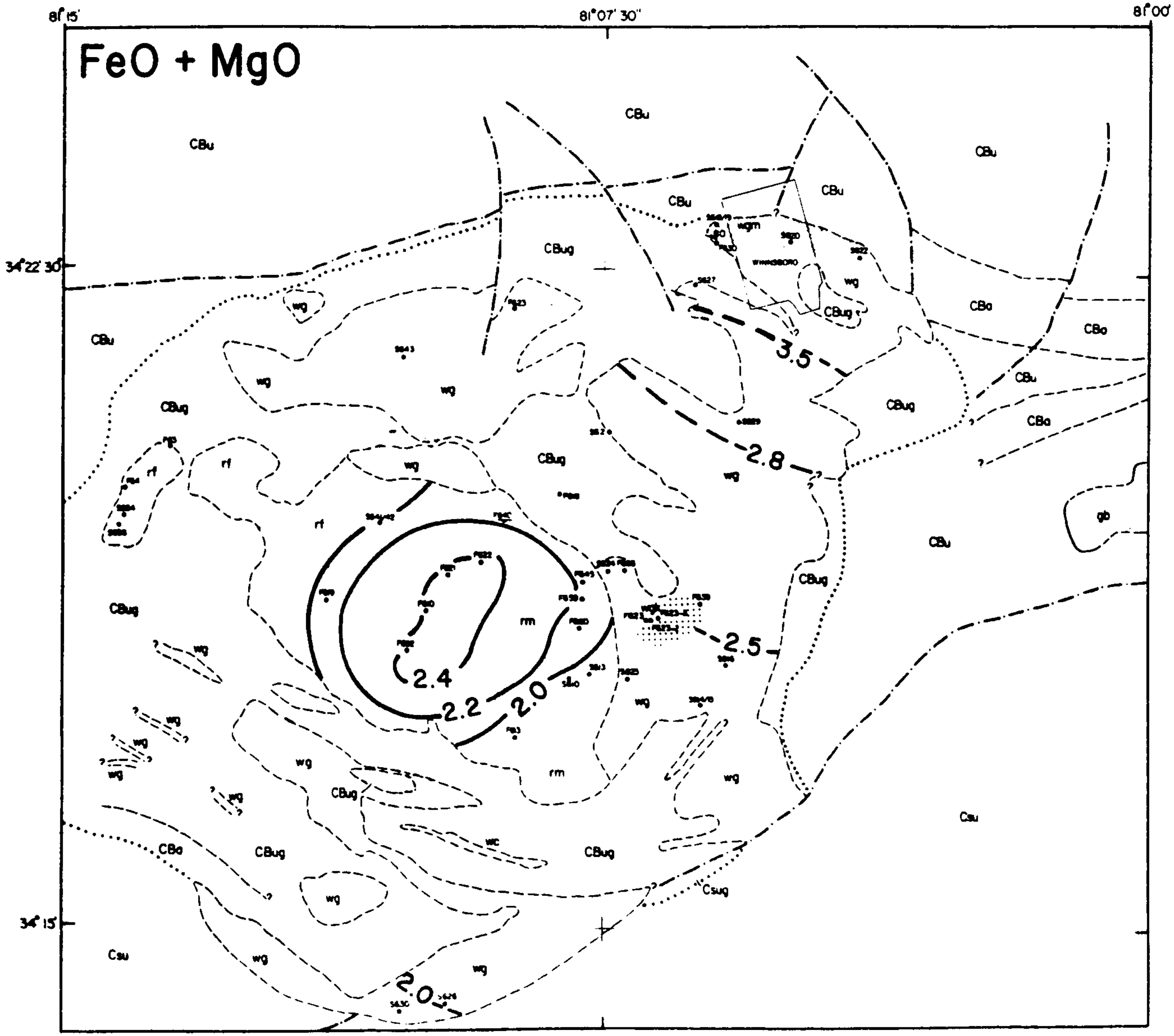

Figure B3. Contour of sum of FeO and MgO for the Winnsboro complex. Note higher values in the core facies of the Rion granite (rm, rf).

granite, there appears to be an increase in DI going south in the body, while FeO + MgO decrease. The Rion granite shows a more symmetrical pattern of contours, with the core facies being high in FeO + MgO and the margins being more differentiated (from 87 to 90 in DI). The smaller body of Rion in the far west is considered too small to permit any contouring.

Because of the variations in the ratios of elements and DI, it is suggested that the Rion is intrusive into the Winnsboro granite (see Section A). The data suggest that after the Winnsboro was emplaced, there must have been some rotation of the body (about a horizontal axis) prior to the emplacement of the Rion. The present pattern of distribution of elements reflects a variable erosion surface. This concept is also borne out by the exposure of different metamorphic grades (greenschist in south to amphibolite in the north).

The depth of emplacement is difficult to evaluate at the moment because of lack of samples which can be considered as final residual fluids during crystallization. However, Wagener (1973) has presented an analysis of an aplitic dike in the Winnsboro granite, which suggests emplacement at nearly 2 Kb and 650-750°C. Because it is difficult to associate this dike to the rest of the plutonic complex, data from the most differentiated Winnsboro and Rion granites (assuming a wet system) indicate depths of emplacement of approximately 12-14 Km at 700-800°C. However, since no muscovite occurs within these rocks, it is unlikely that P_{H_2O} can be considered as P_{Total}.

Because our efforts involve the use of bulk and trace element chemistry as targeting techniques, it is important to attempt to understand the mode of origin of these rocks. If anatectic melting of Slate Belt volcanic rocks result in the formation of the Winnsboro and Rion magma, it is likely that U, Th and alkali enrichment of the liquid will result. It is important to recognize that anatectic melts of granulite facies rocks (depleted in U, Th, K and other low-temperature melting fractions) will not result in substantial enrichment of heat-producing elements.

The available Sr^{87}/Sr^{86} ratios of the Winnsboro complex give initial values of 0.7030 $\pm$ .0014 (Fullagar, 1969) and suggest derivation from the lower crust. However, initial strontium isotopic ratios of meta-rhyolites from the Carolina slate belt are very similar--0.704 $\pm$ .001. As such, strontium data cannot distinguish between derivation of these magmas at lower crustal levels or much shallower melting of volcanic rocks.

Generally, if a plutonic mass has formed by fractional crystallization from a parent magma, normative quartz shows a positive correlation with normative orthoclase, i.e., with increasing differentiation, alkali components also increase (for example, Skaergaard studies of Wager and Brown, 1967). But samples of the Rion granite show a very strong negative correlation, i.e., with increasing normative Qtz, the values of normative Or decrease. This suggests a process of partial melting or anatexis. Wagener's (1973) trace element data for K/Rb, Rb/Sr, and Zr also show evidences for anatexis.

Attempts to further confirm this can be attempted by using Platens' (1965) approach of using normative Ab/An ratios of host rock and its melted equivalents on Q-Ab-Or diagrams. Because the samples do not plot near an eutectic point as defined by Bowen and Tuttle (1958) for varying P_{H_2O} conditions, the data can be better interpreted by using Platens' approach. The normative Ab/An ratio for the country rock is variable (3.5-26), and those of Rion and Winnsboro range from 3-10 with an approximate average of 5. Therefore, the partial equilibrium melting of various bulk compositions in initial stages would enrich the liquid in orthoclase and quartz components, and the degree of enrichment will be greater if the Ab/An ratio is lower in the country rock. The final stage of melting is reached when the melts do not have a cotectic compo-ition. Some of the aplitic dikes of Wagener may represent this condition.

Based on the earlier discussions it appears that the Winnsboro complex is derived by anatexis of source rocks with variable Ab/An (normative) ratios.

Table B1. Chemical analyses for Winnsboro Pluton.

	S7618	S7620	S7622	F23	F4	S7623	S7634
SiO_2	63.45	64.14	65.72	66.80	69.61	69.91	70.35
Al_2O_3	15.03	14.90	14.79	15.99	16.01	15.65	15.30
CaO	3.12	2.99	2.68	1.75	1.96	1.02	1.77
MgO	1.31	1.18	1.15	0.71	0.80	0.36	0.66
K_2O	4.14	4.06	4.13	5.77	4.91	6.60	5.65
FeO	4.76	4.77	4.51	3.70	2.35	2.48	2.26
Na_2O	4.05	3.91	3.99	4.05	3.91	3.96	3.26
MnO	0.10	0.10	0.11	0.10	0.05	0.07	0.04
TiO_2	0.87	0.90	0.86	0 56	0.41	0.33	0.39
P_2O_5	0.53	0.49	0.47	0.21	0.17	0.08	0.16
TOTAL	97.37	97.45	98.42	99.63	100.21	100.47	99.83

Table B1 (continued).

	S7627	F18	S7636	F3	F22	S7623(2)	F21
SiO_2	70.84	71.01	71.07	71.17	71.88	71.92	72.01
Al_2O_3	13.94	15.76	15.36	15.46	15.06	15.09	15.29
CaO	1.70	1.41	1.65	1.71	1.38	0.86	1.25
MgO	0.72	0.63	0.63	0.70	0.58	0.34	0.54
K_2O	4.91	5.81	5.54	5.53	5.57	6.56	5.57
FeO	3.12	2.09	2.22	2.33	1.91	2.32	1.95
Na_2O	3.65	3.24	3.16	3.46	3.44	3.73	3.47
MnO	0.08	0.04	0.04	0.07	0.04	0.06	0.05
TiO_2	0.49	0.39	0.37	0.43	0.28	0.31	0.29
P_2O_5	0.20	0.19	0.14	0.18	0.11	0.06	0.12
TOTAL	99.67	100.57	100.18	101.04	100.25	101.26	100.55

Table B1 (continued).

	F52	F19	S7642	S7629	F40	F10	F13
SiO_2	72.34	72.67	72.82	73.03	73.11	73.25	73.29
Al_2O_3	15.25	15.22	15.11	19.94	15.02	15.18	15.49
CaO	1.43	1.29	1.33	1.44	1.43	1.12	1.08
MgO	0.51	0.56	0.55	0.57	0.48	0.55	0.36
K_2O	5.58	5.55	5.43	5.55	5.13	5.49	5.45
FeO	1.87	1.56	1.58	2.27	1.71	1.89	1.28
Na_2O	3.44	3.65	3.45	3.32	3.77	3.50	3.65
MnO	0.04	0.05	0.05	0.09	0.06	0.05	0.05
TiO_2	0.28	0.22	0.21	0.36	0.26	0.28	0.14
P_2O_5	0.10	0.10	0.08	0.14	0.10	0.10	0.06
TOTAL	100.84	100.87	100.62	100.69	101.07	101.43	100.66

Table B1(continued).

	S7633	F45	S7610	S7641	S7613	S7614	S7616	S7626
SiO_2	73.41	74.15	74.27	74.39	76.62	74.69	75.64	76.52
Al_2O_3	14.88	14.95	15.04	15.02	14.74	13.83	13.29	13.13
CaO	1.26	1.36	1.28	1.17	1.38	0.78	0.61	0.59
MgO	0.52	0.51	0.38	0.51	0.39	0.39	0.29	0.20
K_2O	5.29	5.22	5.31	5.14	4.79	5.40	5.65	5.56
FeO	1.84	1.49	1.34	1.44	1.42	2.03	2.04	1.84
Na_2O	3.51	3.40	3.44	3.47	3.52	3.91	3.37	3.43
MnO	0.05	0.51	0.05	0.05	0.05	0.06	0.07	0.83
TiO_2	0.26	0.18	0.16	0.19	0.17	0.21	0.23	0.16
P_2O_5	0.11	0.07	0.06	0.08	0.07	0.08	0.04	0.02
TOTAL	101.14	101.39	101.33	101.47	101.16	101.38	101.24	101.54

Table B2. C.I.P.W. Norms and indices for Winnsboro Pluton.

	S7618		S7620		S7622		F23	
Q	14.17		16.21		17.64		14.24	
C					0.01		0.40	
Or	25.13		24.62		24.80		34.22	
Ab	35.20		33.95		34.31		34.39	
An	10.89		11.41		10.39		7.34	
Hy	10.42		10.44		10.09		7.85	
Hyen		3.16		2.95		2.91		1.77
Hyfs		7.26		7.49		7.18		6.08
Di	1.23		0.45					
Diwo		0.60		0.22				
Dien		0.19		0.06				
Difs		0.44		0.17				
Il	1.70		1.75		1.66		1.07	
Ap	1.29		1.19		1.13		0.50	
TOTAL	100.03		100.03		100.03		100.01	
Salic	85.39		86.19		87.14		90.59	
Femic	14.64		13.84		12.88		9.42	
Al_2O_3/SiO_2	0.24		0.23		0.22		0.24	
D.I.	74.50		74.78		76.74		82.85	

Table B2 (continued).

	F4		S7623		S7634		S7627	
Q	21.43		17.14		23.85		24.44	
C	1.10		0.30		0.99		0.01	
Or	28.96		38.83		33.44		29.12	
Ab	33.03		33.36		27.63		30.99	
An	8.60		4.58		7.75		7.15	
Hy	5.71		4.99		5.23		6.89	
Hyen		1.99		0.89		1.64		1.80
Hyfs		3.72		4.10		3.59		5.09
Il	0.78		0.62		0.74		0.93	
Ap	0.40		0.16		0.38		0.47	
TOTAL	100.01		100.00		100.01		100.01	
Salic	93.12		94.22		93.66		91.72	
Femic	6.89		5.78		6.35		8.29	
Al_2O_3/SiO_2	0.23		0.22		0.22		0.20	
D.I.	83.41		89.33		84.92		84.55	

Table B2 (continued).

	F18	S7636	F3	F22
Q	24.87	25.75	23.79	25.56
C	2.02	1.50	1.10	1.12
Or	34.14	32.68	32.29	32.83
Ab	27.26	26.69	28.98	29.04
An	5.72	7.26	7.23	6.11
Hy	4.81	5.10	5.39	4.55
Hyen	1.56	1.57	1.73	1.44
Hyfs	3.25	3.53	3.66	3.11
Il	0.74	0.70	0.81	0.53
Ap	0.45	0.33	0.42	0.26
TOTAL	100.01	100.01	100.01	100.01
Salic	94.02	93.87	93.39	94.66
Femic	5.99	6.13	6.62	5.34
Al_2O_3/SiO_2	0.22	0.22	0.21	0.21
D.I.	86.27	85.12	85.06	87.43

Table B2 (continued).

	S7623(2)		F21		F52		F19	
Q	20.92		25.77		25.83		25.48	
C	0.43		1.56		1.18		1.09	
Or	38.29		32.74		32.70		32.51	
Ab	31.17		29.20		28.87		30.62	
An	3.83		5.39		6.39		5.70	
Hy	4.65		4.51		4.28		3.96	
Hyen		0.84		1.34		1.26		1.38
Hyfs		3.81		3.18		3.02		2.57
Il	0.58		0.55		0.53		0.41	
Ap	0.14		0.28		0.24		0.24	
TOTAL	100.00		100.01		100.01		100.01	
Salic	94.63		94.66		94.96		95.40	
Femic	5.37		5.35		5.04		4.60	
Al_2O_3/SiO_2	0.21		0.21		0.21		0.21	
D.I.	90.38		87.71		87.40		88.61	

Table B2 (continued).

	S7642		S7629		F40		F10	
Q	27.16		27.04		26.48		27.15	
C	1.32		0.19		0.90		1.66	
Or	31.89		32.57		29.99		31.99	
Ab	29.02		27.90		31.56		29.20	
An	6.04		6.19		6.37		4.84	
Hy	3.99		5.13		3.98		4.41	
Hyen		1.36		1.41		1.18		1.35
Hyfs		2.63		3.72		2.79		3.06
Il	0.40		0.68		0.49		0.52	
Ap	0.19		0.33		0.23		0.23	
TOTAL	100.01		100.01		100.01		100.01	
Salic	95.43		93.88		95.31		94.84	
Femic	4.58		6.13		4.70		5.17	
Al_2O_3/SiO_2	0.21		0.19		0.21		0.21	
D.I.	88.07		87.50		88.04		88.34	

Table B2 (continued).

	F13		S7633		F45	
Q	27.28		27.88		29.36	
C	1.75		1.34		1.38	
Or	31.93		30.91		30.43	
Ab	30.63		29.37		28.38	
An	4.92		5.47		6.20	
Hy	3.08		4.29		3.75	
Hyen		0.89		1.28		1.25
Hyfs		2.19		3.01		2.50
Il	0.26		0.49		0.34	
Ap	0.14		0.26		0.16	
TOTAL	100.00		100.01		100.00	
Salic	96.52		94.97		95.75	
Femic	3.49		5.04		4.25	
Al_2O_3/SiO_2	0.21		0.20		0.20	
D.I.	89.84		88.16		88.17	

Table B2 (continued).

	S7610		S7641		S7613	
Q	29.37		29.95		31.02	
C	1.43		1.80		1.41	
Or	30.97		29.93		27.98	
Ab	28.73		28.94		29.45	
An	5.88		5.21		6.32	
Hy	3.19		3.64		3.35	
Hyen		0.93		1.25		0.96
Hyfs		2.26		2.39		2.39
Il	0.30		0.36		0.32	
Ap	0.14		0.19		0.16	
TOTAL	100.00		100.01		100.00	
Salic	96.37		95.82		96.17	
Femic	3.63		4.18		3.84	
Al_2O_3/SiO_2	0.20		0.20		0.20	
D.I.	89.06		88.82		88.45	

Table B2 (continued).

	S7614		S7616		S7626	
Q	27.29		30.82		31.81	
C	0.32		0.61		0.44	
Or	31.48		32.98		32.36	
Ab	32.64		28.17		28.59	
An	3.30		2.73		2.75	
Hy	4.40		4.17		3.71	
Hyen		0.96		0.71		0.49
Hyfs		3.45		3.45		3.21
Il	0.39		0.43		0.30	
Ap	0.19		0.09		0.05	
TOTAL	100.01		100.00		100.00	
Salic	95.02		95.31		95.95	
Femic	4.98		4.69		4.05	
Al_2O_3/SiO_2	0.19		0.18		0.17	
D.I.	91.40		91.97		92.76	

Liberty Hill Pluton

In an attempt to determine the crystallization history and classification of the magma series, 22 surface samples have been analyzed for the ten major elements (Table B3). All the samples analyzed can be classified as peraluminous felsic rocks, with syenitic and (syeno-granite affinities (Streckeisen, 1976).

The classification of the magma series (alkaline, calc-alkaline or peralkaline) is generally provided by using Peackock's Index (1931). Because of the limited variations in the data, unreasonable extrapolations would be necessary, and Peackock's indices were not used. Other commonly used indices of Thornton and Tuttle (1960) suggest a calc-alkaline association, although in comparison with Nockold's (1954) averages of igneous rock compositions, the Liberty Hill samples lie in between calc-alkaline and alkaline trends.

To further clarify the magma series, the Liberty Hill trend was compared with well-known alkaline and calc-alkaline suites for different regions. The two alkaline provinces chosen for comparisons were Monzol-Tuva (Pavlenko, 1974) and the Scottish tertiary volcanics (Nockolds and Allen, 1954). The data from Southern California batholith (Larsen, 1948) was used to provide the calc-alkaline trend. On a triangular diagram (Na_2O-CaO-K_2O) the Liberty Hill data define a trend very similar to the calc-alkaline Southern California batholith, although slight enrichment in K displaces the trend towards the K-Ca line. Similar comparisons in AFM diagrams suggest a calc-alkaline trend although a slight enrichment in alkali components over the Southern California Batholith data is seen.

Major element variations as shown in a Harker diagram (Fig. B4) show a major discontinuity in SiO_2 between 67-69%. The coarse-grained syenitic (normative) rocks are restricted in SiO_2 content between 64 and 67%, while all other samples (coarse- to fine-grained granites) range from 69 to 73%, although the fine-grained samples are generally higher in silica. Because of the abrupt variations in SiO_2 content, it is likely that crystallization histories of the two rock types are not related in any simple manner. The granites are generally higher in total alkali content, although some of the coarse-grained xenocrystic rocks (with fine-grained matrix) show similar enrichment (samples S671, S674, S100).

The distribution of selected elements (FeO+MgO; K_2O and Differentiation Index) has been contoured in Figures B5, B6 and B7. Although the number of analyses are limited and restricted to the eastern half of the pluton, generalized contours suggest a reverse zonation of the coarse-grained peraluminous magma. The central part of the pluton, syenitic in composition, is the least differentiated. Because field data (see Section A) indicates emplacement as a high temperature predominantly crystallized material, mechanical mixing could severely contort the relict zoning. The apparent zoning suggests that the magma cooled from the center outwards. However, another consideration that could yield similar results would involve country rock contamination. At the present time, no analyses of the country rocks are available to fully evaluate this model.

The central area of the pluton is made up of patches of fine-grained rocks. Samples from these areas show a relatively higher alkali content, lower Al_2O_3/SiO_2 ratios and lower normative apatite. Consideration of the data from the variation diagrams and the intrusive

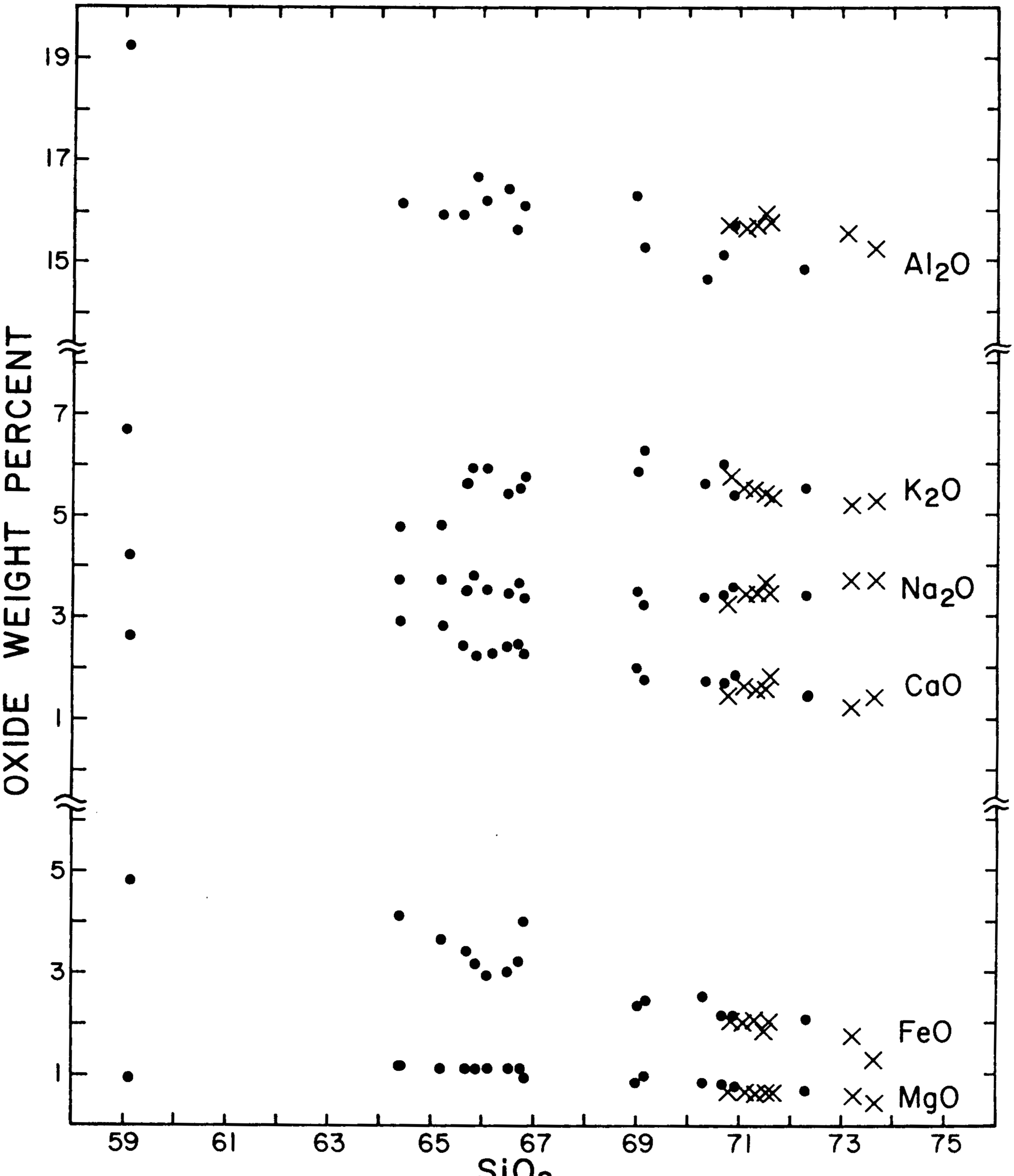

Figure B4. Variation diagram showing chemical differences in the Liberty Hill complex. Note the discontinuity in SiO_2 at 67%. Solid circles = coarse grained (LHc); x = fine grained (Lhf).

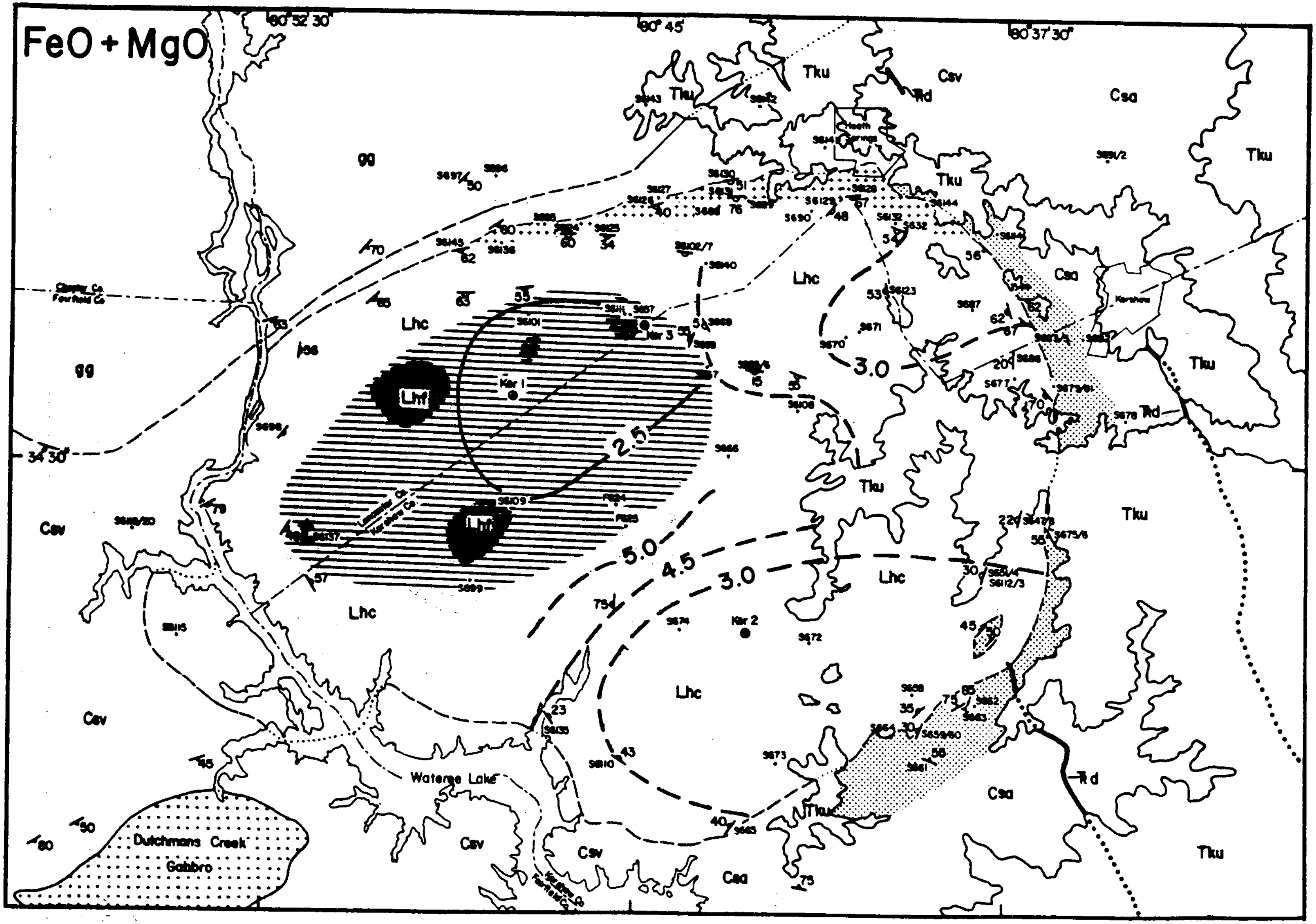

Figure B5. Contour diagram showing zonation of complex. The margins of the coarse-grained facies (Lhc) appear to be relatively depleted in mafic constituents.

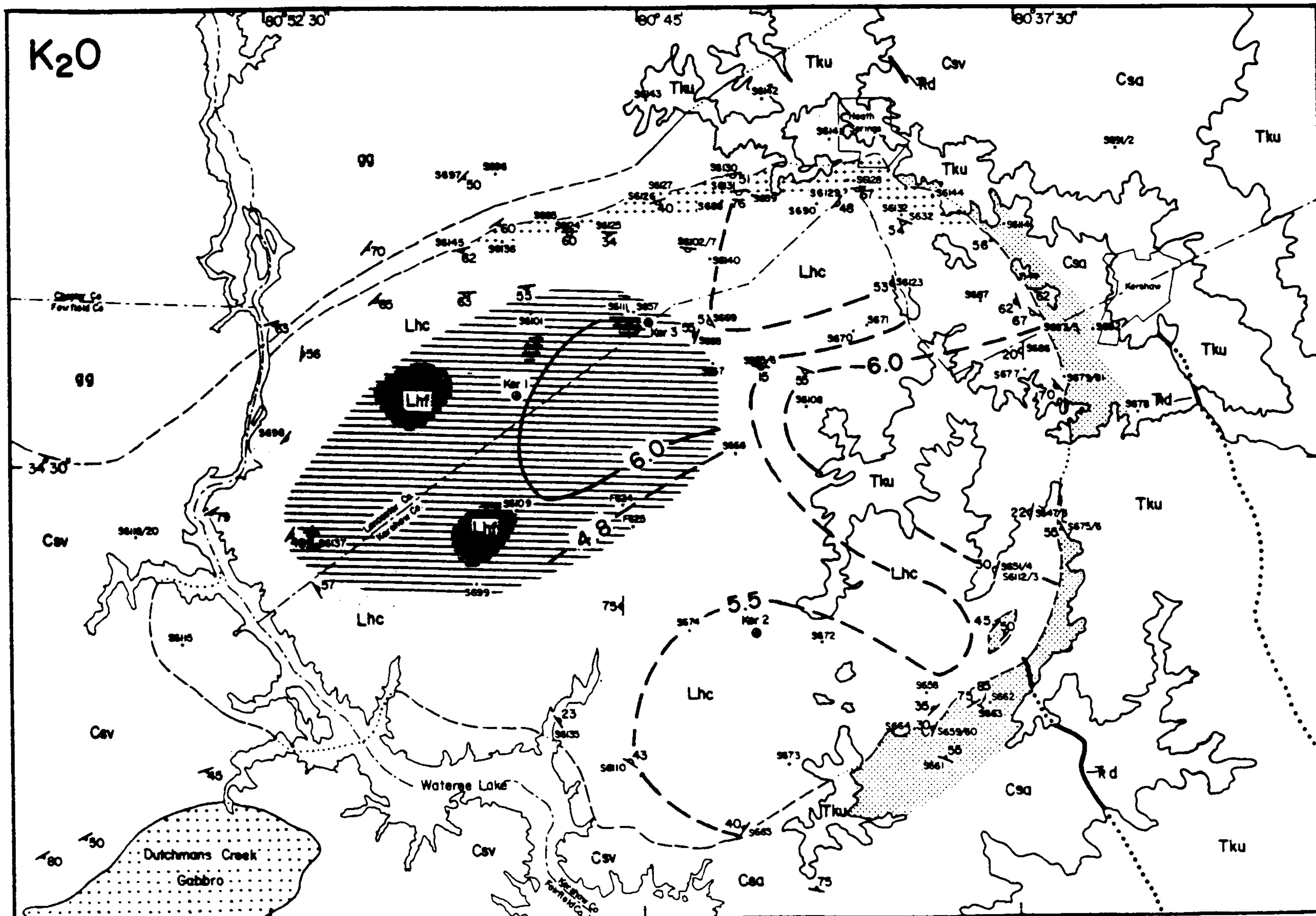

Figure B6. Contour diagram showing variations in K_2O content of both coarse-grained (Lhc) and fine-grained (Lhf) facies of the complex.

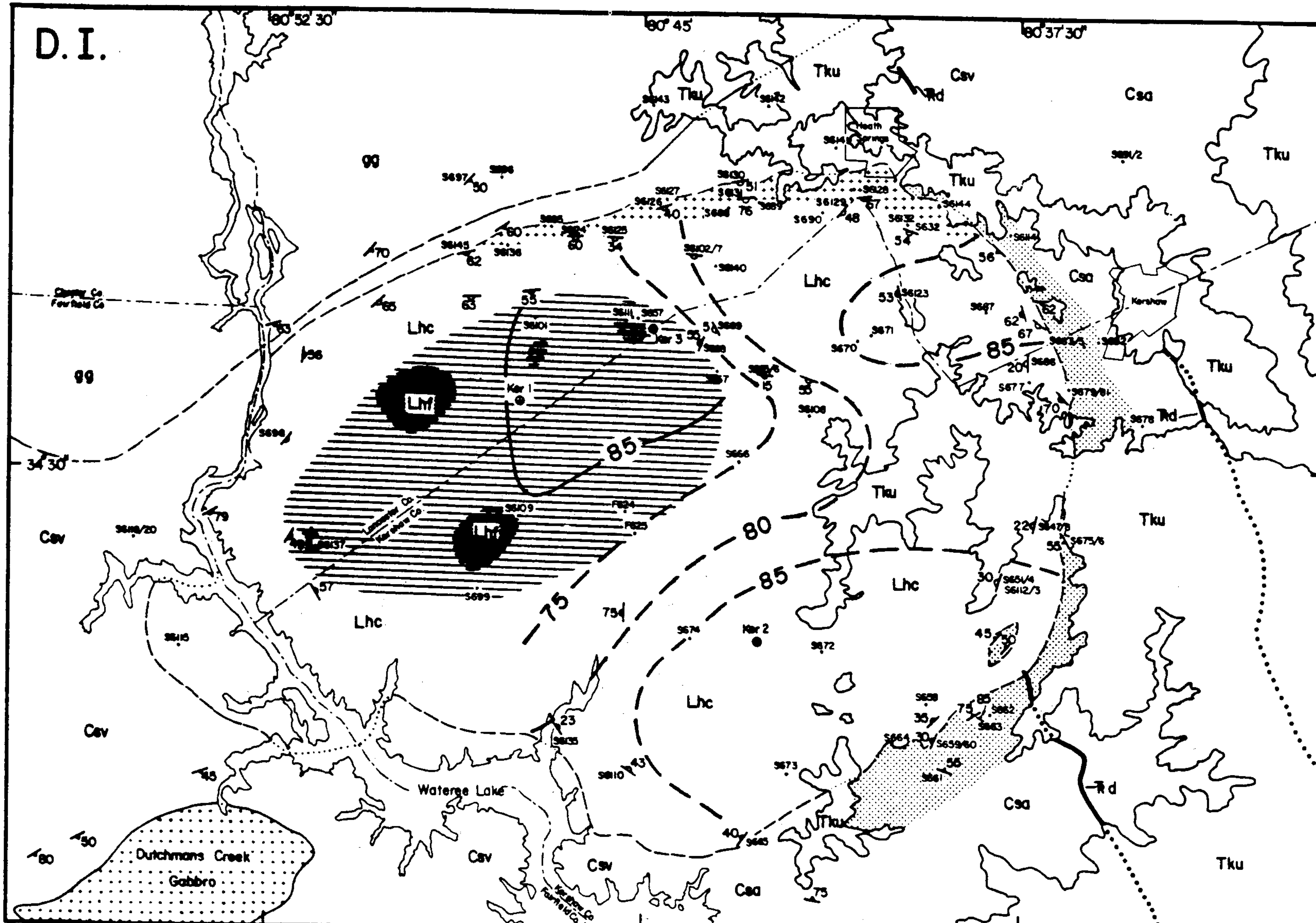

Figure B7. Contour diagram showing trends of differentiation. The margine of the coarse-grained rocks (Lhc) show higher DI values.

nature of this phase, it appears to have been perhaps derived from a source region other than the coarse-grained phase exposed around it.

Normal fractional crystallization of a magma results in a positive correlation between normative Or and Q. The coarse-grained syenitic mass in the central zone of the body shows such a trend, but the coarse- and fine-grained granites show a negative correlation (similar to Winnsboro). As such, fractional melting (anatexis) of bulk rocks of varied compositions appears likely.

Normative plots (Q-Ab-Or-An) to determine temperatures and pressures of crystallization are difficult from the present data. The samples analyzed do not appear to be the lowest temperature residual fluids (aplites, pegmatites). Also, the two phases studied do not appear to be water saturated (less than 4% biotite in the fine-grained phase and 4% biotite and amphibole in the coarse-grained phase--see Section A). Therefore, it is difficult to use experimental data which are projected for either wet or dry systems. Assuming that the most differentiated sample of the fine-grained phase (S6101) with normative Q + Or + Ab + An = 95.53 most closely approximates the final liquid, and using experimental data of $P_{H_2O} = 0$, the depth of crystallization would be approximately 7 kb at nearly 750°C. However, better crystallization conditions can be determined from contact aureole mineralogy.

Table B3. Chemical analyses for Liberty Hill Pluton.

	S6108	F25	F24	S669	S6135	S689
SiO_2	59.14	64.39	65.23	65.66	65.87	66.13
Al_2O_3	19.23	16.07	15.88	15.87	16.69	16.21
CaO	2.59	2.93	2.82	2.37	2.23	2.31
MgO	.92	1.16	1.14	1.08	1.08	1.10
K_2O	6.71	4.75	4.81	5.58	5.91	5.91
FeO	4.89	4.07	3.61	3.43	3.31	2.95
Na_2O	4.18	3.71	3.72	3.52	3.74	3.48
MnO	0.08	0.08	0.07	0.07	0.07	0.05
TiO_2	0.82	0.74	0.68	0.59	0.61	0.51
P_2O_5	0.27	0.26	0.24	0.23	0.22	0.19
TOTAL	98.85	98.55	98.19	98.40	99.71	98.84

Table B3(continued).

	S688	S656	S690	S647	S686	S665	S654	S667
SiO_2	66.48	66.66	66.80	69.00	69.14	70.34	70.68	70.84
Al_2O_3	16.42	15.60	16.06	16.28	15.27	14.66	15.13	15.72
CaO	2.42	2.41	2.28	1.95	1.76	1.75	1.65	1.44
MgO	1.10	1.06	0.99	0.82	0.90	0.82	0.74	0.60
K_2O	5.43	5.49	5.68	5.86	6.26	5.62	5.97	5.76
FeO	3.02	3.17	2.99	2.45	2.42	2.48	2.09	2.10
Na_2O	3.45	3.61	3.35	3.47	3.24	3.36	3.42	3.24
MnO	0.06	0.06	0.05	0.05	0.04	0.06	0.04	0.04
TiO_2	0.53	0.57	0.53	0.42	0.41	0.40	0.34	0.40
P_2O_5	0.17	0.23	0.17	0.14	0.14	0.14	0.12	0.18
TOTAL	99.09	98.84	99.90	100.42	99.58	99.61	100.16	100.32

Table B3 (continued).

	S6110	S657	S6111	S674	S6100	S658	S671	S6101
SiO_2	70.90	71.13	71.28	71.51	71.57	72.30	73.18	73.64
Al_2O_3	15.68	15.66	15.71	15.91	15.81	14.82	15.52	15.26
CaO	1.81	1.61	1.54	1.58	1.80	1.41	1.20	1.34
MgO	0.73	0.60	0.61	0.62	0.59	0.66	0.57	0.37
K_2O	5.39	5.54	5.52	5.41	5.33	5.49	5.18	5.31
FeO	2.15	2.00	2.08	1.83	2.03	2.03	1.72	1.22
Na_2O	3.54	3.44	3.45	3.65	3.45	3.40	3.68	3.71
MnO	0.05	0.03	0.04	0.04	0.04	0.04	0.04	0.04
TiO_2	0.37	0.30	0.32	0.27	0.34	0.34	0.23	0.12
P_2O_5	0.15	0.13	0.12	0.09	0.16	0.12	0.09	0.06
TOTAL	100.77	100.43	100.66	100.03	101.11	100.61	101.41	101.05

Table B4. C.I.P.W. norms and indices for Liberty Hill Pluton.

	S6108		F25		F24		S669	
Q			14.71		15.84		15.56	
C	1.05		0.12		0.00		0.29	
Or	40.12		28.59		28.94		33.51	
Ab	35.78		31.98		32.05		30.27	
An	11.21		13.08		12.65		10.42	
Hy	7.89		9.46		8.63		8.28	
Hyen		1.79		2.94		2.89		2.74
Hyfs		6.10		6.52		5.74		5.54
Ol	1.73							
Olfo		0.36						
Olfa		1.37						
Il	1.58		1.43		1.31		1.14	
Ap	0.65		0.63		0.58		0.55	
TOTAL	100.01		100.01		100.00		100.01	
Salic	88.17		88.49		89.49		90.04	
Femic	11.85		11.52		10.51		9.97	
Al_2O_3/SiO_2	0.32		0.25		0.24		0.24	
D.I.	79.90		75.29		76.84		79.34	

Table B4 (continued).

	S6135		S689		S688		S656	
Q	13.40		15.27		17.27		16.54	
C	0.61		0.35		0.88			
Or	35.02		35.33		32.38		32.82	
Ab	31.73		29.79		29.46		30.90	
An	9.65		10.34		11.00		10.26	
Hy	7.91		7.49		7.59		7.59	
Hyen		2.70		2.77		2.76		2.63
Hyfs		5.21		4.72		4.83		4.96
Di							0.26	
Diwo								0.13
Dien								0.05
Difs								0.08
Il	1.16		0.98		1.02		1.09	
Ap	0.52		0.45		0.41		0.55	
TOTAL	100.01		100.01		100.01		100.01	
Salic	90.42		91.08		91.00		90.52	
Femic	9.59		8.93		9.01		9.49	
Al_2O_3/SiO_2	0.25		0.24		0.25		0.23	
D.I.	80.15		80.39		79.12		80.25	

Table B4 (continued).

	S690		S647		S686		S665	
Q	17.75		19.52		19.94		22.97	
C	0.67		1.01		0.30		0.20	
Or	33.94		34.48		37.14		33.33	
Ab	28.66		29.23		27.53		28.54	
An	10.31		8.72		7.85		7.80	
Hy	7.25		5.91		6.13		6.07	
Hyen		2.49		2.03		2.27		2.05
Hyfs		4.76		3.88		3.86		4.02
Il	1.02		0.79		0.78		0.76	
Ap	0.41		0.33		0.33		0.33	
TOTAL	100.01		100.01		100.01		100.01	
Salic	91.33		92.97		92.76		92.84	
Femic	8.68		7.04		7.25		7.17	
Al_2O_3/SiO_2	0.24		0.24		0.22		0.21	
D.I.	80.35		83.23		84.61		84.84	

Table B4 (continued).

	S654		S667		S6110		S657A	
Q	22.07		24.91		23.40		24.36	
C	0.33		1.96		1.08		1.38	
Or	35.21		33.93		31.61		32.59	
Ab	28.89		27.33		29.73		28.98	
An	7.39		5.95		7.94		7.11	
Hy	5.18		4.75		5.21		4.71	
Hyen		1.84		1.49		1.80		1.49
Hyfs		3.34		3.26		3.40		3.22
Il	0.64		0.76		0.70		0.57	
Ap	0.28		0.42		0.35		0.31	
TOTAL	100.01		100.01		100.01		100.01	
Salic	93.89		94.08		93.75		94.43	
Femic	6.12		5.93		6.26		5.58	
Al_2O_3/SiO_2	0.21		0.22		0.22		0.22	
D.I.	86.18		86.17		84.73		85.94	

Table B4 (continued).

	S6111		S674		S6100		S658	
Q	24.52		23.94		25.06		26.21	
C	1.54		1.38		1.46		1.00	
Or	32.40		31.68		31.15		32.59	
Ab	29.00		30.61		28.87		28.60	
An	6.81		7.18		7.80		6.17	
Hy	4.85		4.49		4.66		4.85	
Hyen		1.51		1.53		1.45		1.63
Hyfs		3.34		2.96		3.20		3.22
Il	0.60		0.51		0.64		0.64	
Ap	0.28		0.21		0.37		0.28	
TOTAL	100.01		100.00		100.01		100.01	
Salic	94.27		94.79		94.34		94.23	
Femic	5.74		5.21		5.67		5.78	
Al_2O_3/SiO_2	0.22		0.22		0.22		0.20	
D.I.	85.92		86.23		85.08		87.05	

Table B4 (continued).

	S671		S6101	
Q	27.12		27.23	
C	1.87		1.10	
Or	30.19		31.05	
Ab	30.71		31.06	
An	5.29		6.19	
Hy	4.19		3.01	
Hyen		1.38		0.91
Hyfs		2.81		2.10
Il	0.43		0.22	
Ap	0.21		0.14	
TOTAL	100.00		100.00	
Salic	95.17		96.63	
Femic	4.83		3.37	
Al_2O_3/SiO_2	0.21		0.21	
D.I.	88.02		89.34	

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C. GEOPHYSICS

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Heat Production and Heat Flow

As part of a planned intercalibration between several gamma-ray spectroscopy laboratories in the United States, 20 samples from the Liberty Hill-Kershaw and Winnsboro plutons, SC were sent to laboratories of the U. S. Geological Survey and the University of Wyoming. Their results of uranium, thorium, and potassium determinations for these samples are given in Tables C-1 and C-2 along with computed values of heat generation.

Maximum values of heat generation given in Tables C-1 and C-2 for surface samples are about 12-13 HGU (1 HGU = 10^{-13} cal/cm^{3}-sec). Values of 13 HGU predict a heat flow of 1.8 HFU based on an assumed linear relationship between heat flow and heat production (see Report VPI&SU-5103-1, Table 2, p. 9). These values of heat flow and heat production are close to those already reported for post-metamorphic plutonic rocks in Virginia (Reiter and Costain, 1973). For plutonic rocks buried beneath sedimentary insulators, this heat flow would result in relatively high geothermal gradients of about 40°C/Km (Table 2, Progress Report VPI&SU-5103-1) in rocks of relatively low thermal conductivity of 4.5 TCU (1 TCU = 10^{-3} cal/cm-sec-°C). Average thermal conductivity values of about 4.5 TCU are already known to be appropriate for Coastal Plain sediments in South Carolina.

The heat generation determinations available to date are thus somewhat optimistic since (1) they predict relatively high temperatures at relatively shallow depths in Coastal Plain sediments where they overlie buried plutonic rocks, and (2) the determinations of heat generation

Table C-1. Heat generation values for surface samples from the Liberty Hill pluton, SC.

Location	Sample No.	Density, gm/cm^3	Uranium (U), ppm	Thorium (Th), ppm	Potassium (K), %	K_2O, %	Heat generation, A x 10^{-13} cal/cm^3-sec
<u>Coarse-grained rocks</u>							
Liberty Hill pluton, S. C.	S6-47	2.63	3.3	18.04	4.39	5.27	6.0
	S6-54**	2.64	3.0	14.5	4.5	5.40	5.2
	S6-56**	2.66	1.8	10.8	4.3	5.16	3.9
	S6-58	2.58	3.43	17.82	4.31	5.17	5.91
	S6-65**	2.65	2.4	18.9	4.8	5.76	5.74
	S6-69**	2.66	1.5	14.6	4.4	5.28	4.4
	S6-71**	2.61	6.2	29.2	4.3	5.16	9.6
	S6-74	2.63	4.88	27.17	4.41	5.29	8.49
	S6-86**	2.65	1.6	24.4	4.5	5.40	6.1
	S6-88	2.67	2.02	20.62	4.33	5.20	5.73
	S6-89*	2.65	1.7	15.0	4.2	5.04	4.6
	S6-90	2.64	2.26	20.17	4.16	4.99	5.7
	S6-108	2.66	1.72	8.89	5.45	6.54	3.8
	S6-110**	2.64	2.4	16.3	4.5	5.40	5.2
	S6-135	2.66	4.06	12.32	4.03	4.84	5.49
	F6-24	2.69	2.83	9.54	3.63	4.36	4.22
	F6-25	2.68 (2.65)***	3.17	11.99	4.0	4.80	4.92
<u>Fine-grained rocks</u>							
Liberty Hill pluton, S. C.	S6-57	2.63	5.13	31.89	4.25	5.10	9.40
	S6-99**	2.61	2.6	23.0	4.6	5.52	6.5
	S6-100	2.64	5.70	28.02	4.19	5.03	9.12

Table C-1 (continued).

Location	Sample No.	Density, gm/cm^3	Uranium (U), ppm	Thorium (Th), ppm	Potassium (K), %	K_2O, %	Heat generation, A x 10^{-13} cal/cm -sec
<u>Fine-grained rocks</u> (cont.)							
	S6-101*	2.61	8.0	26.5	3.9	4.68	10.1
	S6-111*	2.64 (2.63)***	4.7	34.0	4.2	5.04	9.5
<u>Aplite</u>							
Liberty Hill pluton, S. C.	S6-51	2.59	6.45	33.81	4.90	5.88	10.5

*Denotes analysis by U. S. Geological Survey, Denver, Colorado.

**Denotes analysis by University of Wyoming, Laramie, Wyoming.

***Average value for group.

Table C-2. Heat generation values for surface samples from the Winnsboro, SC pluton.

Location	Sample No.	Density, gm/cm^3	Uranium (U), ppm	Thorium (Th), ppm	Potassium (K), %	K_2O, %	Heat generation, A x 10^{-13} cal/cm^3-sec
Winnsboro pluton, S. C.	S6-2	2.61	2.79	12.67	4.16	4.99	4.71
	S6-16	2.60	2.65	16.64	4.68	5.62	5.38
	S6-24	2.61	4.90	17.99	4.16	4.99	6.86
	S6-25	2.58	1.51	12.12	4.36	5.23	3.85
	S6-26	2.62	2.32	18.71	4.44	5.33	5.50
	S6-27	2.67	2.24	13.01	3.93	4.72	4.48
	S6-29	2.65	3.56	14.44	4.33	5.17	5.59
	S6-43**	2.57	2.0	17.2	4.3	5.16	4.91
	F6-23	2.63	2.76	10.94	4.25	5.10	4.45
	F6-30	2.62	2.04	21.25	4.62	5.54	5.80
	F6-66	2.62	2.20	7.92	4.01	4.81	3.54
	S6-14**	2.61 (2.62)***	1.7	16.7	4.1	4.92	4.7
>10 CI							
Winnsboro pluton, S. C.	S6-18**	2.71	4.0	15.5	3.0	3.60	5.9
	S6-20	2.69	4.88	13.90	3.21	3.85	6.1
	S6-22	2.70 (2.70)***	4.42	16.27	3.3	3.96	6.31
K-feldspar rich							
Winnsboro pluton, S. C.	S6-23**	2.63	2.0	17.2	4.3	5.16	5.0
	S6-23-2	2.63	1.12	20.55	4.77	5.72	5.18
	F6-39	2.62 (2.63)***	3.64	21.22	4.87	5.84	6.87

Table C-2 (continued).

Location	Sample No.	Density, gm/cm^3	Uranium (U), ppm	Thorium (Th), ppm	Potassium (K), %	K_2O, %	Heat generation, A x 10^{-13} cal/cm^3-sec
<u>Rion pluton</u>							
Winnsboro, S. C.	S6-10**	2.62	6.6	34.6	4.3	5.16	10.7
	S6-13	2.62	8.7	30.5	3.75	4.50	11.18
	S6-33	2.61	7.97	35.5	4.35	5.22	11.65
	S6-34*	2.64	3.8	41.0	4.4	5.28	10.2
	S6-36	2.64	4.71	32.13	4.35	5.22	9.24
	S6-42	2.63	8.21	33.47	4.29	5.15	11.53
	F6-3	2.65	4.89	31.62	4.40	5.28	9.31
	F6-4	2.65	2.97	22.67	3.91	4.69	6.51
	F6-10**	2.60	3.8	36.4	4.7	5.64	9.4
	F6-13	2.61	3.87	28.35	4.11	4.93	7.94
	F6-19**	2.62	4.0	39.2	4.5	5.40	9.91
	F6-21	2.60	3.28	31.66	4.35	5.22	8.15
	F6-22*	2.60	4.4	35.0	4.2	5.04	9.4
	F6-40	2.62	6.38	32.56	4.30	5.16	10.24
	F6-45	2.62	6.01	32.07	4.09	4.91	9.88
	F6-52	2.64	6.38	31.93	4.37	5.24	10.22
	F6-59	2.62	6.09	33.08	4.27	5.12	10.15
	F6-60	2.62	7.77	32.84	4.20	5.04	11.11
	F5-18	2.64	6.14	45.85	4.43	5.32	12.42
		(2.62)***					

that are available to date are all from surface samples, and the concentration of radioelements may be affected by weathering.

Table C-3 lists values of least-squares gradients for holes Ker 1 and Ker 2 in the Liberty Hill-Kershaw pluton and a preliminary value for Ker 3. Figure C-1 shows temperature profiles and gradients for Ker 1 and Ker 2.

The important conclusion to be reached from the gradients determined from Ker 1 and Ker 2 is that shallow holes (<125 m) in this pluton do not give reliable thermal gradients. The considerably higher preliminary gradient in Ker 3 is closer to a reliable equilibrium value. Ker 2 was drilled into a pavement surface and the effects of the resulting local difference in the boundary condition at the surface are clearly propagated downward to depths of at least 125 m. We will attempt to correct for perturbations of gradients in shallow holes.

An equilibrium temperature log was obtained from DDH Ker 3 drilled into the Liberty Hill-Kershaw pluton in Lancaster County, SC. Drilling was completed on November 1, 1976. In order to evaluate the transient thermal effects of drilling on the geothermal gradient, temperature logs were obtained over a period of several months. Temperature profiles and gradients are shown in Figure C-2. Geothermal gradients are tabulated in Table C-4. Transient thermal effects of drilling are evident several months after the cessation of drilling; however, the gradient of 14.6°C/Km obtained on March 3, 1977 (Fig. C-3) is essentially an equilibrium gradient, and a reliable heat flow determination will be obtained from this hole after thermal conductivity determinations have been completed.

Table C-3. Least-squares gradients in holes drilled by VPI&SU in the Liberty Hill-Kershaw pluton, S. C.

Well	Interval, m	Number of points	Least-squares Gradient, °C/km	Zero-depth Temperature, °C
Ker 1	81.69-124.19	18	9.15	17.31
Ker 2	99.22-121.72	10	9.38	17.60
Ker 3	94.50-112.0	8	15.49	16.14
Ker 3	289.50-317.0	12	14.49	16.32
Ker 3	329.50-374.5	19	15.35	16.08

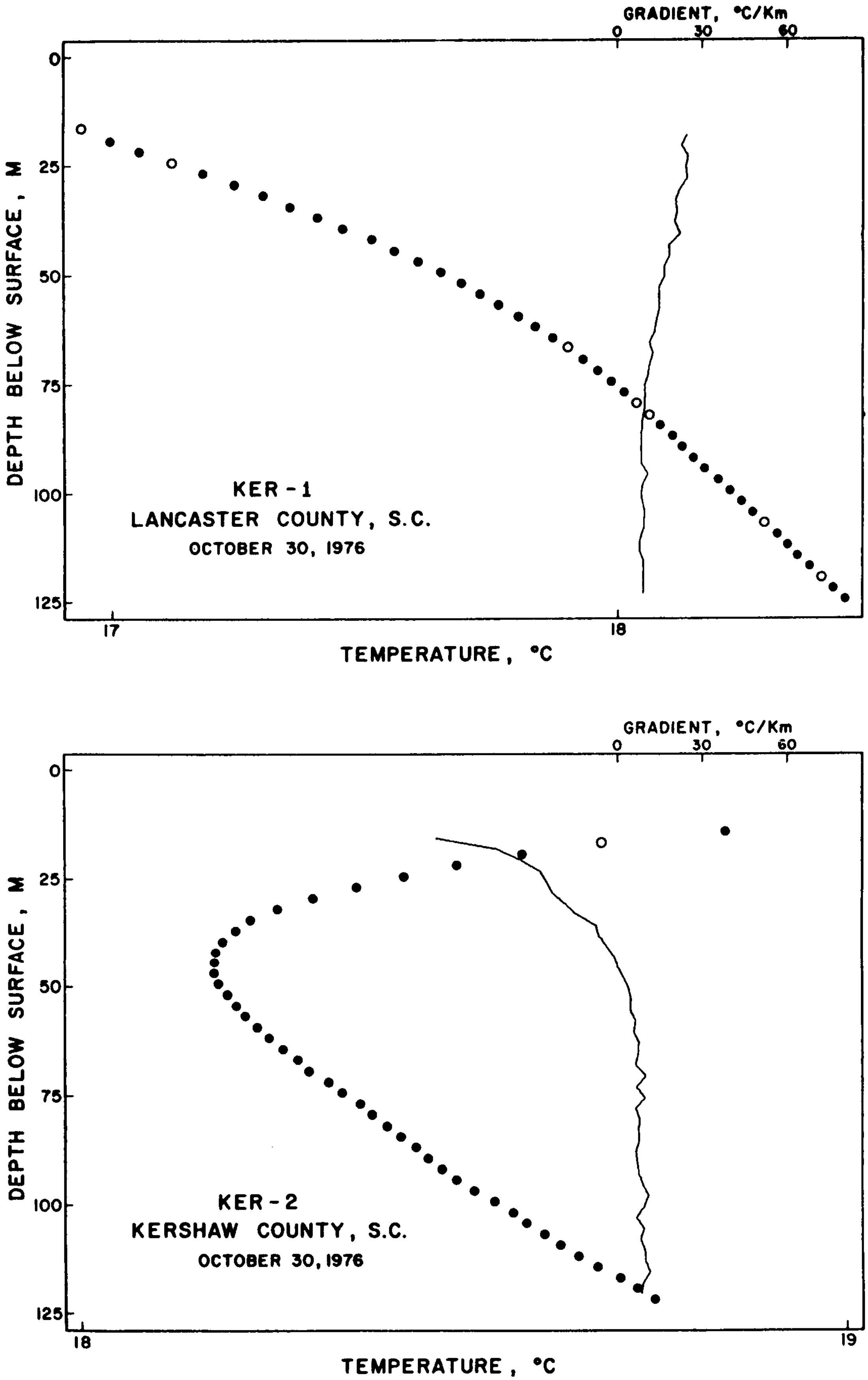

Figure C-1. Temperature and gradient profiles in the Liberty Hill-Kershaw pluton, S.C.

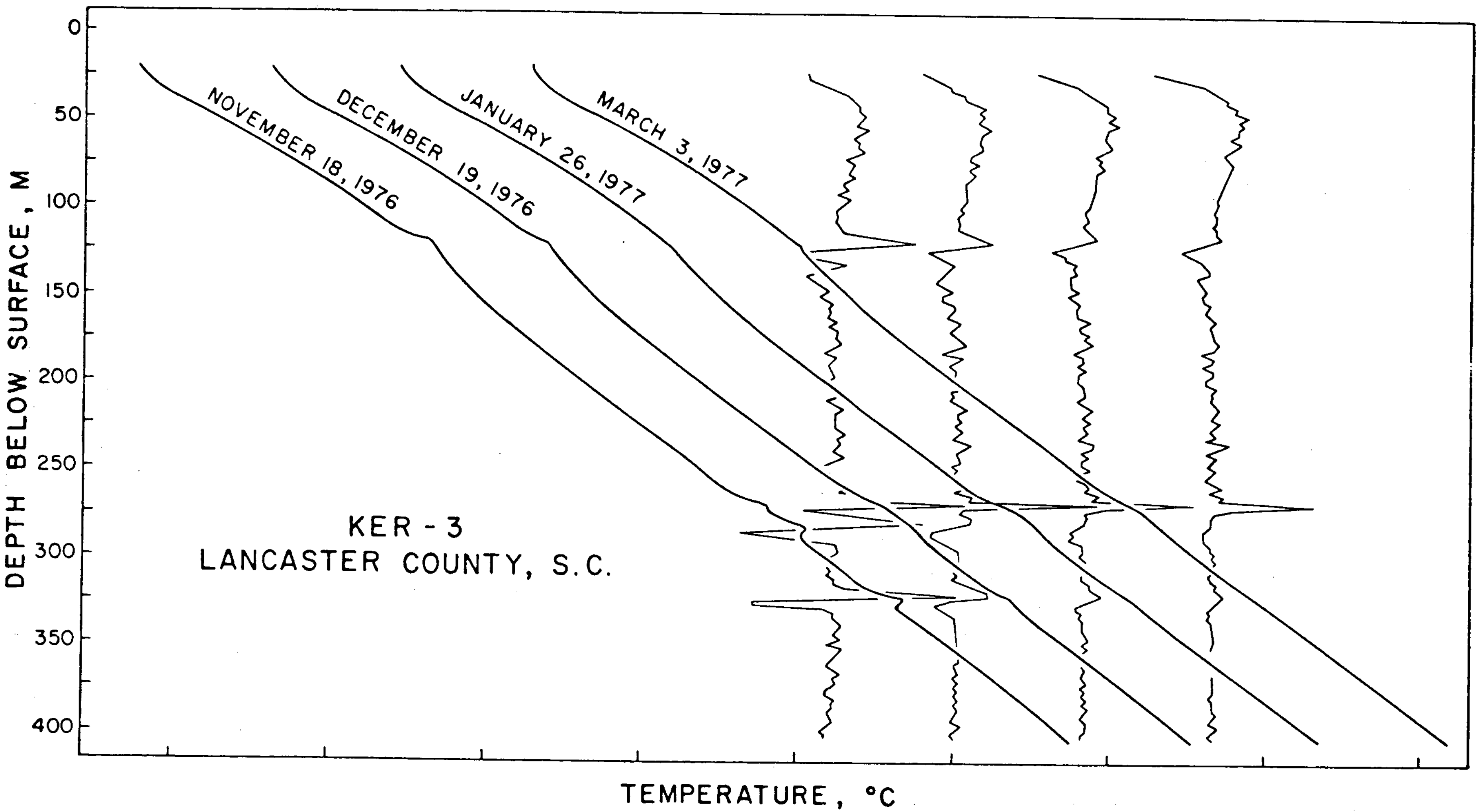

Fig. C-2. Comparison of temperature and gradient logs over a four-month period for Ker 3.

Table C-4. Geothermal gradients in Ker 3 and Win 1.

	Nov. 19, 1976	Dec. 19, 1976	Jan. 26, 1977	% change from Nov. 19
Ker 3	14.6°C/Km	14.8°C/Km	14.9°C/Km	+2.05
Win 1	--	--	18.4°C/Km	

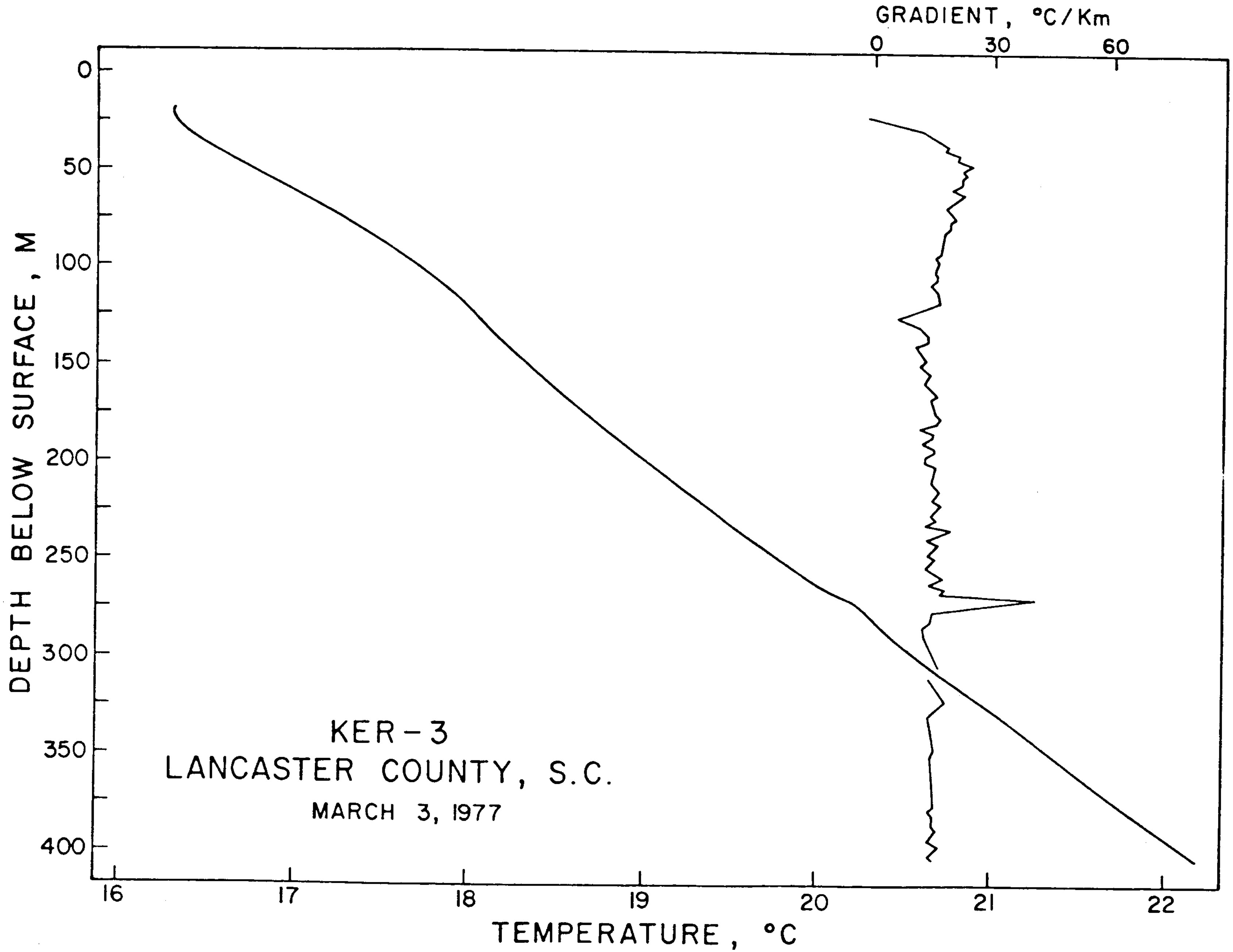

Fig. C-3. Temperature and gradient logs for Ker 3, March 3, 1977.

Preliminary temperature logs have been obtained from DDH Win 1 in the Winnsboro pluton in Fairfield County, SC. This hole has not yet reached thermal equilibrium, and a reliable gradient for heat flow determination is not yet available.