VPI-SU-5103-2
Distribution Category UC-66

EVALUATION AND TARGETING OF GEOTHERMAL ENERGY RESOURCES IN THE SOUTHEASTERN UNITED STATES

Progress Report

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May 1, 1976 - October 31, 1976

PREPARED FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT NO. E-(40-1)-5103

DISCLAIMER

ABSTRACT

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. An optimum site for geothermal development in the tectonically stable eastern United States will probably be associated with crustal igneous rocks containing relatively high concentrations of radiogenic heat-producing elements buried beneath an insulating blanket of sediments of low thermal conductivity. Evaluation of plutonic rocks exposed in the Piedmont will aid in the interpretation of gravity and magnetic data for the Atlantic Coastal Plain.

Initial results of determination of heat generation from surface samples in South Carolina are encouraging, especially if granitic igneous rocks of similar heat generation can be found beneath sedimentary insulation. With the limited number of analyses available to date, the later fine-grained phases of the Liberty Hill and Winnsboro plutons clearly have a higher overall concentration of radiogenic elements. All of the samples with high heat generation are from fine-grained samples except for one xenocrystic rock with a fine-grained matrix.

Continued logging of existing wells in Coastal Plain sediments supports our earlier conclusion that these sediments do behave as efficient sedimentary insulators. Higher temperatures appear to be reached at shallower depths for wells drilled in Coastal Plain sediments in the vicinity of the Georgetown, South Carolina gravity law.

The wells are not cemented and are therefore not ideal for the determination of reliable geothermal gradients, but higher gradients could be caused by buried radiogenic granitic plutonic rocks which might also be responsible, in part, for the gravity law.

Detailed structural mapping in the vicinity of the warm springs in northwestern Virginia has confirmed structural control of the warm springs, and has revealed the existence of kink bands. The kink bands could be related to the development of zones of vertical permeability which serve as conduits in sedimentary rocks for ascending hot water.

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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 sedimentary 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 will be calibrated by detailed studies at eight sites.

Initial studies will develop a methodology for locating 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

Since this program consists 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 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 initial funding period for E-(40-1)-5103 was from May 1 - October 31, 1976. The present report summarizes accomplishments during this period. The primary source of funds for the drilling program during this period was ERDA Contract No. E-(40-1)-5104 with the South Carolina State Development Board which resulted in a drilling subcontract to VPI & SU. Contract E-(40-1)-5104 was granted a one-month extension of time without additional funds to November 30, 1976. This report thus reflects the interaction between two prime contracts which are interdependent. For the period December 1, 1976 - October 31, 1977 drilling funds will be provided from a renewal of Contract No. E-(40-1)-5103 as exploratory drilling begins in North Carolina and Virginia.

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 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 - October 31, 1976, drilling funds were provided by a subcontract with our cooperative agency in South Carolina, the South Carolina State Development Board.

No problems have arisen to date with the drilling operation. It is anticipated that one 48-hour shift per week will enable us to continue to meet our contractural obligations and production schedules during the coming year.

As of November 30, 1976, a total of over 2700 feet has been drilled in the Liberty Hill-Kershaw and Winnsboro plutons in South Carolina. This exceeds our anticipated footage during the initial subcontract period (May 1 - November 30, 1976) with South Carolina.

Results of analyses of the drill core will be included in subsequent reports after a study of the chemical and thermal properties of the core has been completed. The present report includes modal and chemical analyses of surface samples and some preliminary values of heat production from surface samples.

The first hole 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.

Three holes have now been completed in the Liberty Hill-Kershaw pluton, the deepest being approximately 1,300 feet. Temperature profiles in the two shallow holes are discussed in a subsequent section. The deepest hole has been logged for gamma radiation and for temperature, but has not yet recovered from the thermal effects of drilling. A complete report on the analysis of the core and on the heat flow and heat production from these holes will be included in a later report.

PROGRESS

A. Geology (South Carolina)

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

Operations

Nine 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. In addition, 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).

The following is a summary of the work completed on the surface samples.

Pluton	total samples collected	work completed: petrographic description	modal analyses	probe analyses	samples suitable for possible chemistry and heat production
Liberty Hill	97	71	31	9	23
Winnsboro	79	48	57	8	36

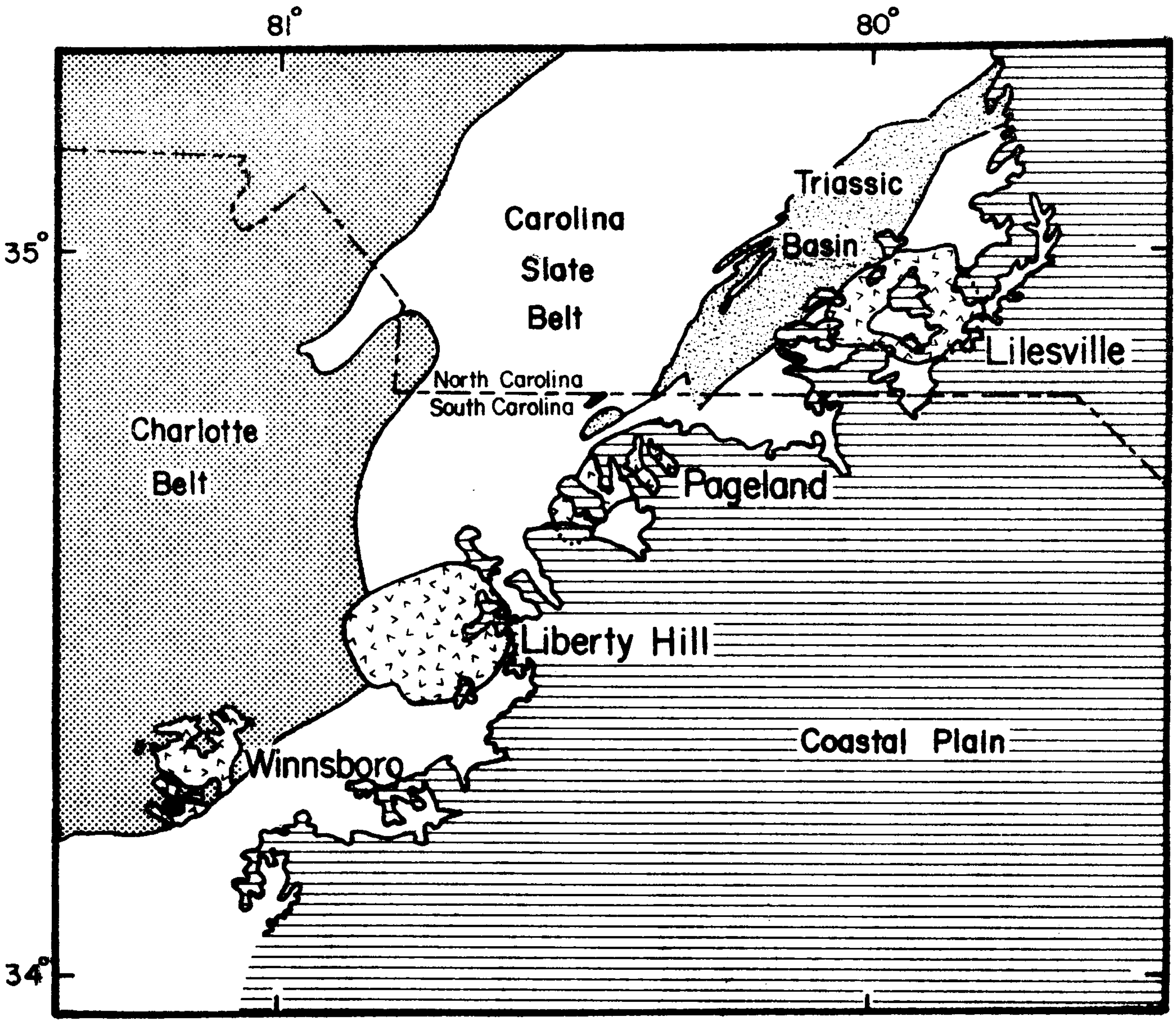

Figure A1. Index map showing locations of the ca. 300 m.y. postmetamorphic granitic plutons in North and South Carolina.

Two holes have been drilled in the Liberty Hill pluton to a depth of approximately 400 feet. Drilling is continuing in a third hole, presently (10/28/76) at 1000 feet. The core is logged when it is brought to Blacksburg. Sample intervals are chosen for petrography, chemical analysis, and heat production and thermal conductivity measurements. Summary of drill core work to date (10/28/76):

hole	length of core received	samples collected for chemistry, petrography, and heat production	other samples	modal analyses
Ker 1	425 ft.	1	3	1
Ker 2	420 ft.	5	6	1
Ker 3	910 ft.	5	2	-

The following reports are descriptions of the general geology and petrography of the Liberty Hill pluton by Speer and Becker and of the Winnsboro plutonic complex by Farrar and Becker.

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 ± 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 ± 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.
Ћd	*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 volcani-clastic 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

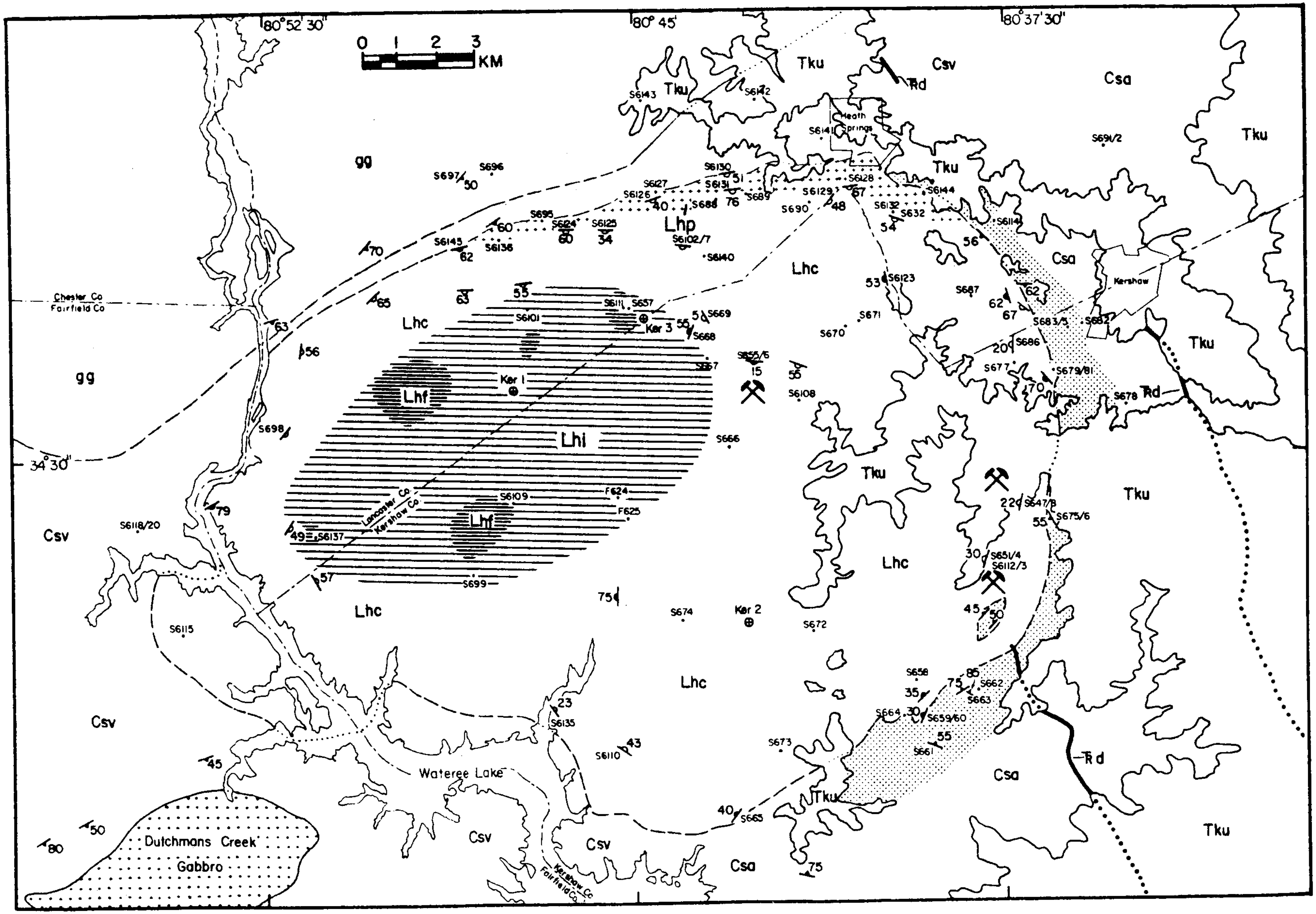

Figure A2. Geologic map of the Liberty Hill pluton, South Carolina.

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

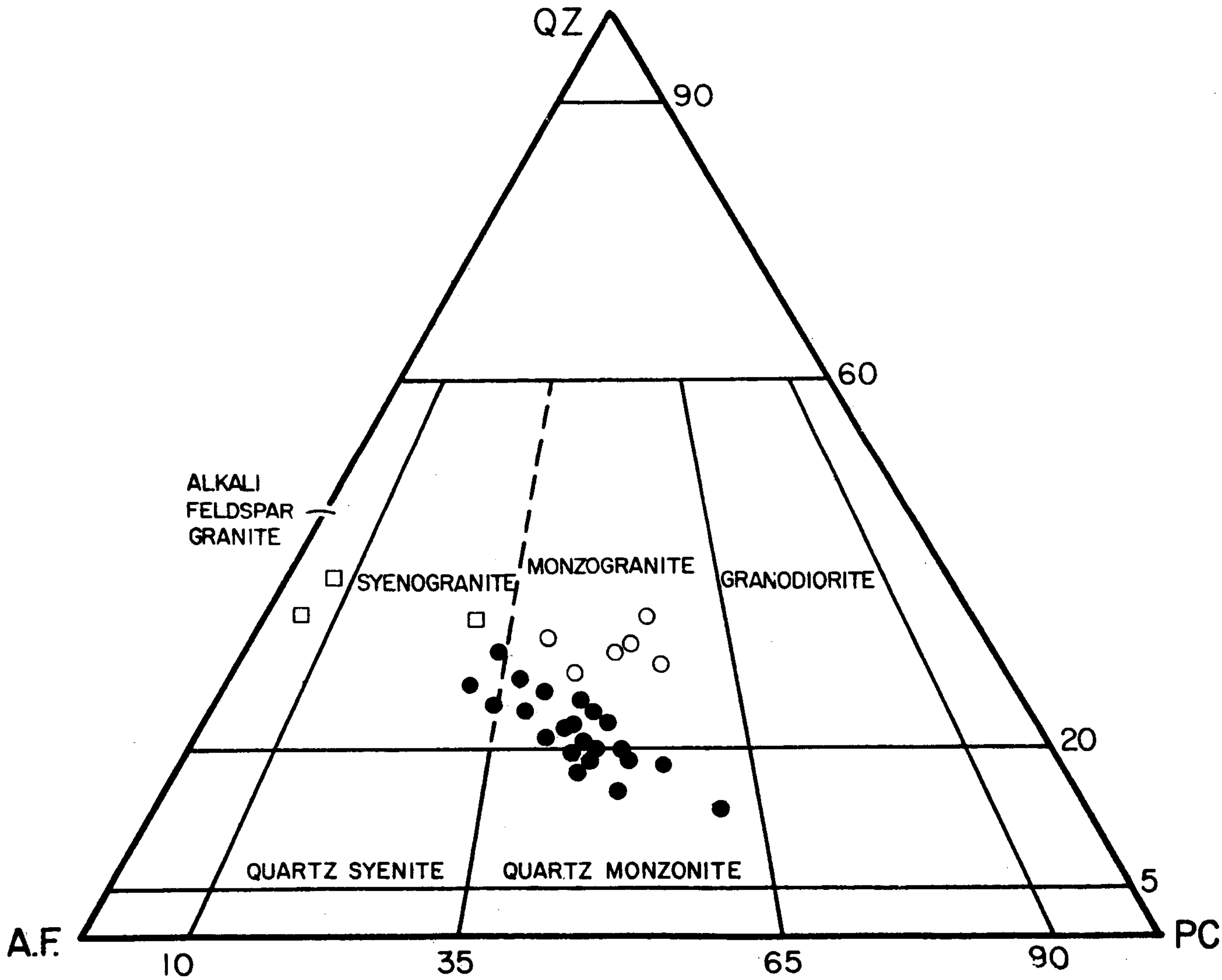

Figure A3. Triangular diagram of modal volume percent of alkali feldspar (A.F.), plagioclase (PC), and quartz (QZ) in rocks of the Liberty Hill pluton, South Carolina. Solid circles (●) are the very coarse phase; open circles (○), the fine- to medium-grained phase; and open squares (□), aplite dike rocks.

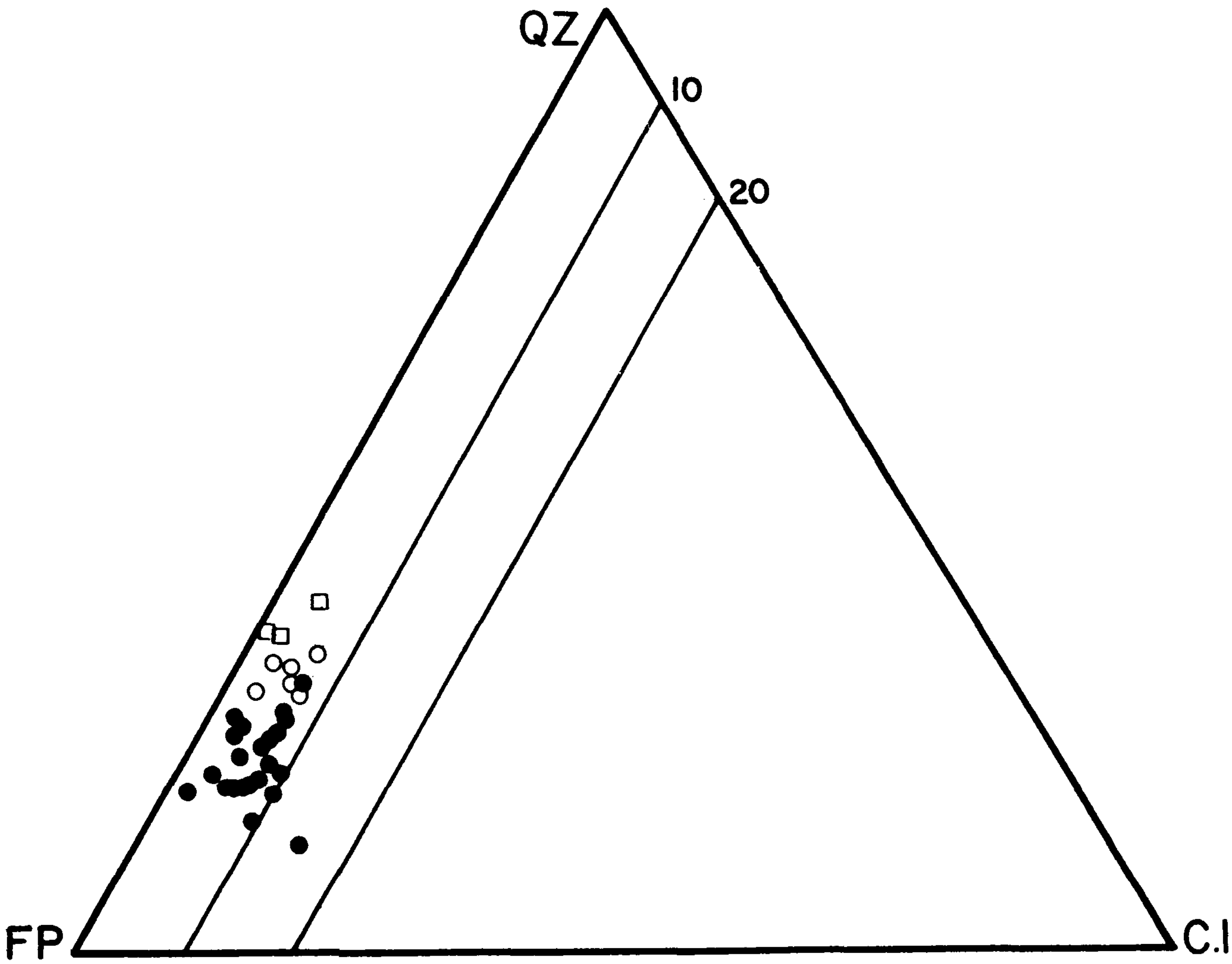

Figure A4. Triangular diagram of modal volume percent of total feldspar (FP), color index (C.I.), and quartz (QZ) in rocks of the Liberty Hill pluton, South Carolina. Solid circles (●) are the very coarse phase; open circles (○), the fine- to medium-grained phase; and open square (□), aplite dike rocks.

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, and molybdenite. 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. A2,A3, 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

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 5.5 kb, but more than 2.5 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

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 A5, 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.

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. A6). 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-

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
- F625 — Sample locality

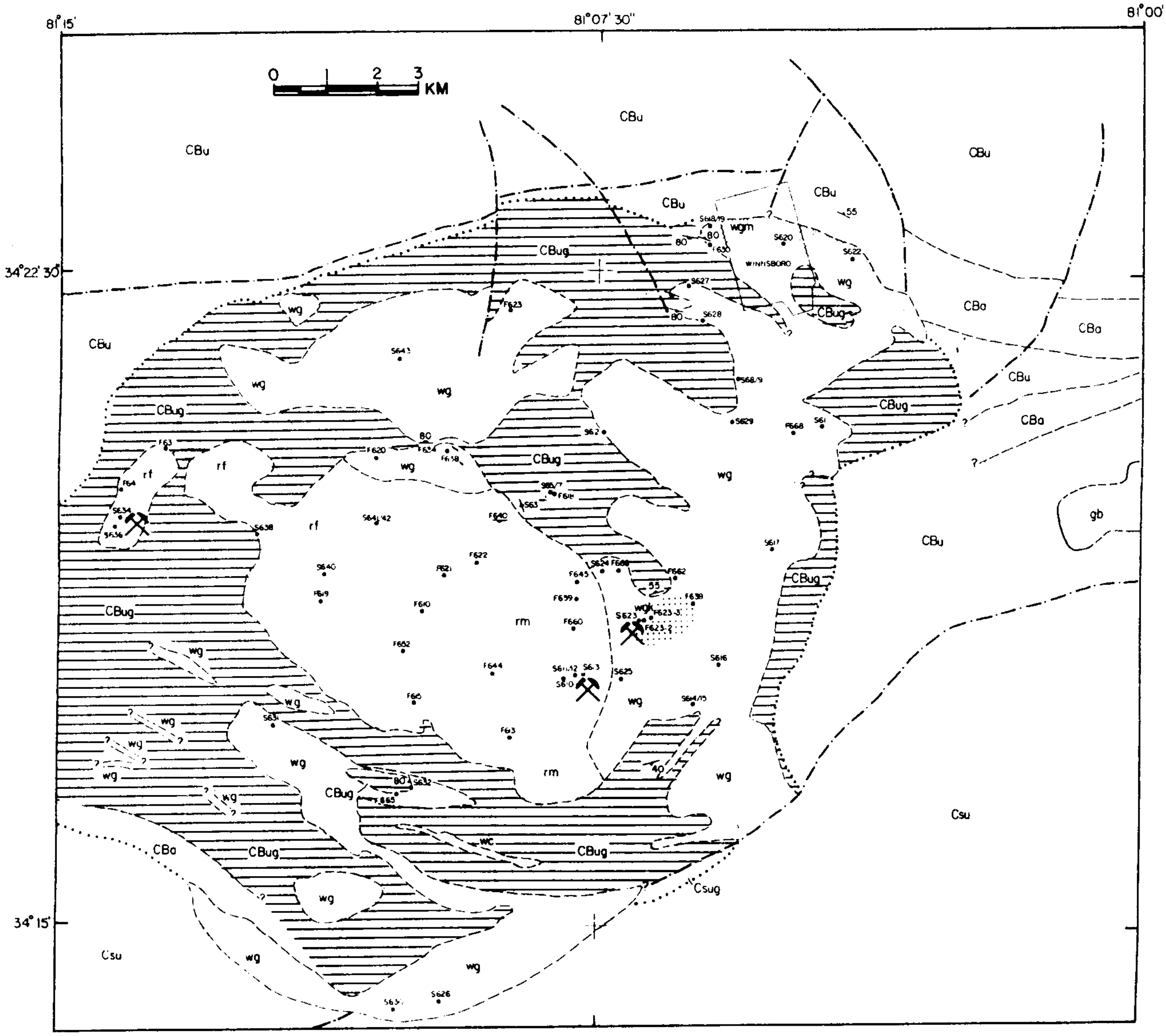

Figure A5. Geologic map of the Winnsboro complex, South Carolina.

crystallizing magmatic grains. Saussuritization has caused reverse zoning in some plagioclase cores.

Modal analyses of the Rion pluton, presented as Table A4, are represented in Figures A6 and A7. Rion rocks plot as a relatively tight cluster in the monzogranite field (Fig. A6) and are generally leucocratic (Fig. A7).

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 'a 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 A5 and A6).

Modal analyses of Winnsboro rocks are given in Table A4 and illustrated in Figures A8 and A9. The Winnsboro rocks have a much wider modal variation

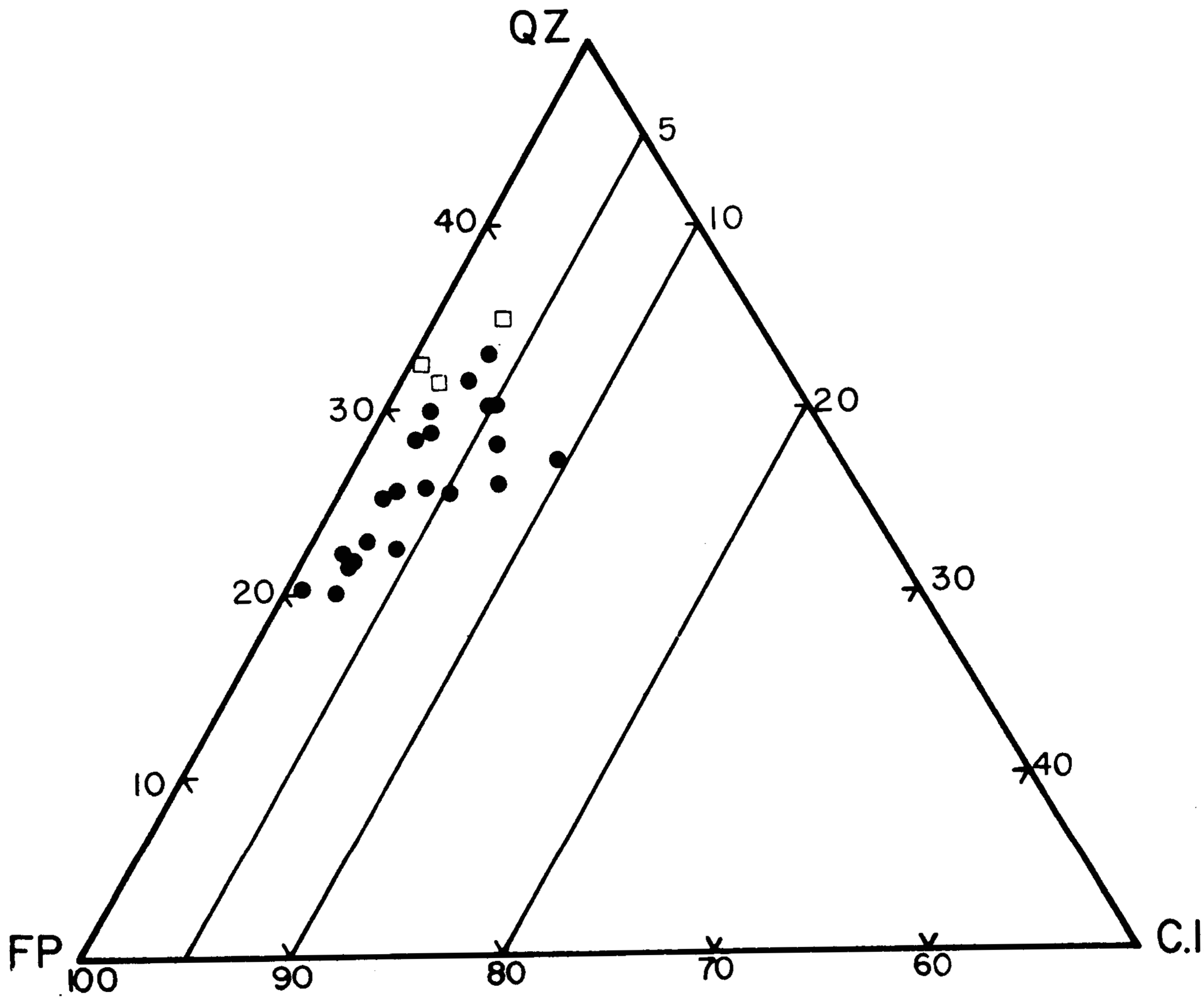

Figure A6. Rion pluton. Modal variation diagram for quartz (QZ)-feldspar (F)-color index (C.I.). Symbols: closed circle (●), granite; square (□), aplite.

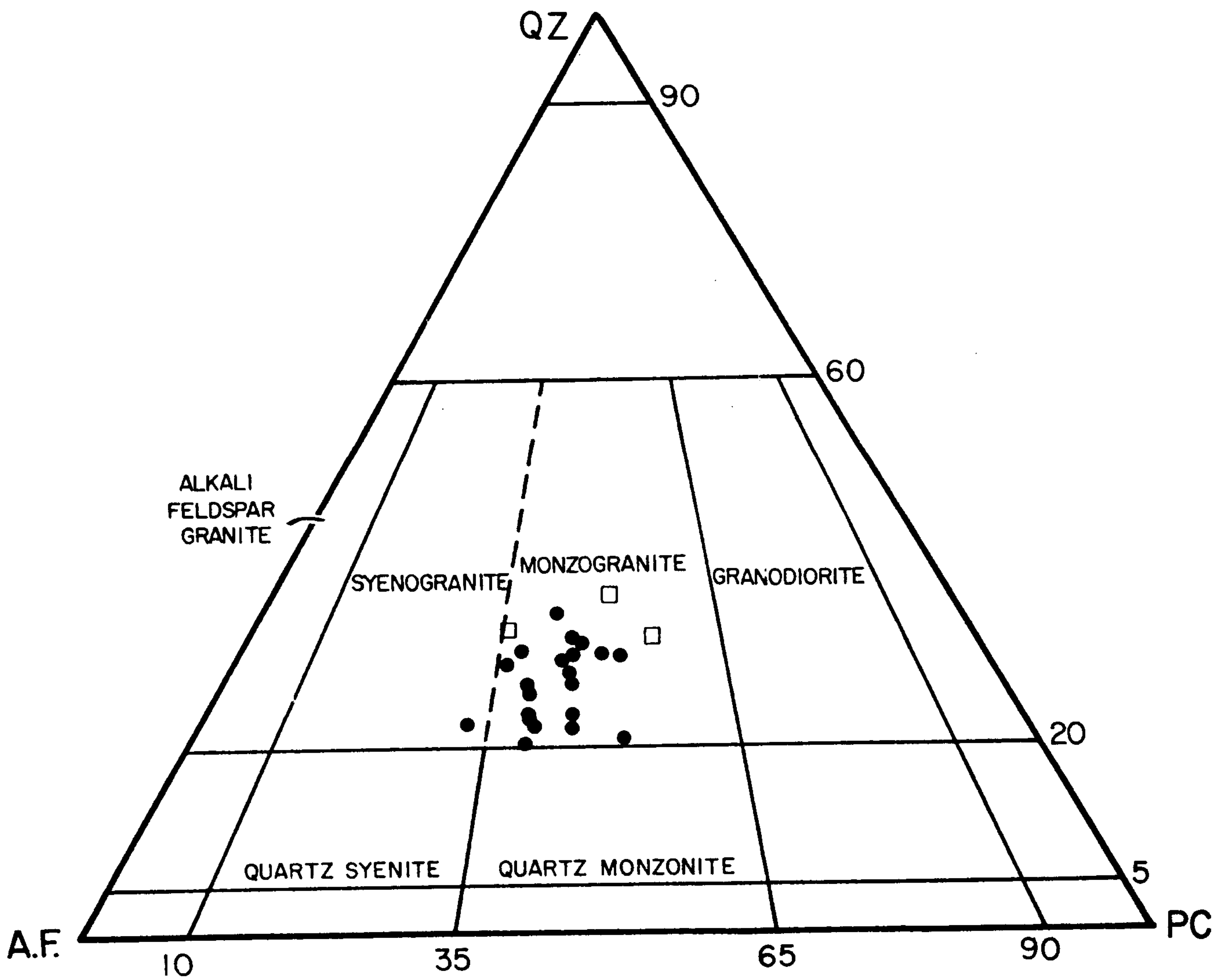

Figure A7. Rion pluton. Modal variation diagram for quartz (QZ)-alkali feldspar (A.F.)-plagioclase (PC). Symbols: closed circle (●), granite; square (□), aplite.

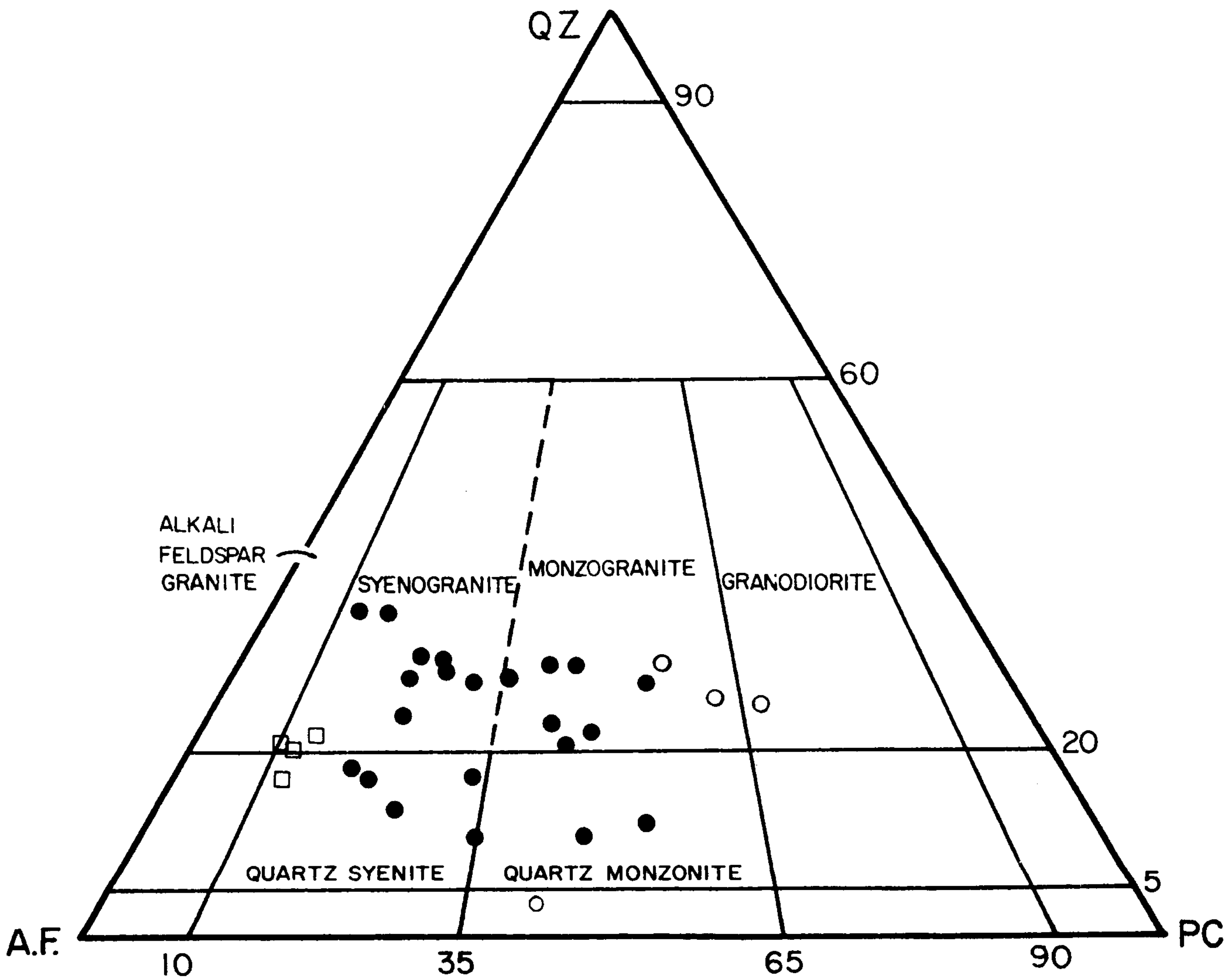

Figure A8. Winnsboro pluton. Modal variation diagram for quartz (QZ)-alkali feldspar (A.F.)-plagioclase (PC). Symbols: closed circle (●), color index less than 10; open circle (○), color index greater than 10; square (□), color index less than 10, and high alkali feldspar.

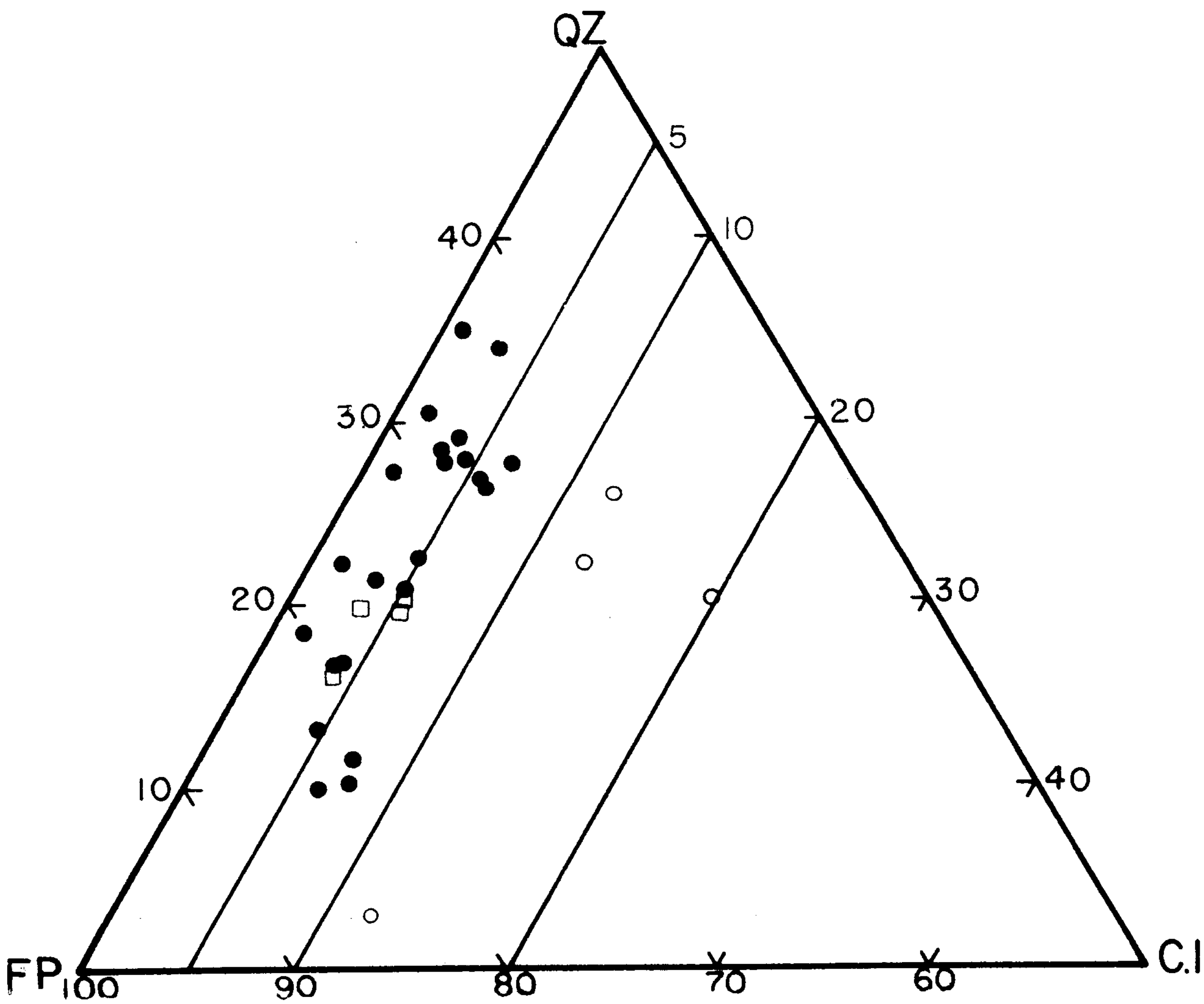

Figure A9. Winnsboro pluton. Modal variation diagram for quartz (QZ)-feldspar (F)-color index (C.I.). Symbols: closed circle (●), color index less than 10; open circle (○), color index greater than 10; square (□), color index less than 10, and high alkali feldspar. The symbols are to facilitate comparison 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 A4, Figs. A6 and A7). 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. A5) 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. A5) 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. A5) is enriched in K-feldspar (squares, Fig. A8). 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 A4. 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 A4 (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 A5. 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 A6. 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					
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

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B. Geochemistry (South Carolina)

A. K. Sinha and B. A. Merz

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

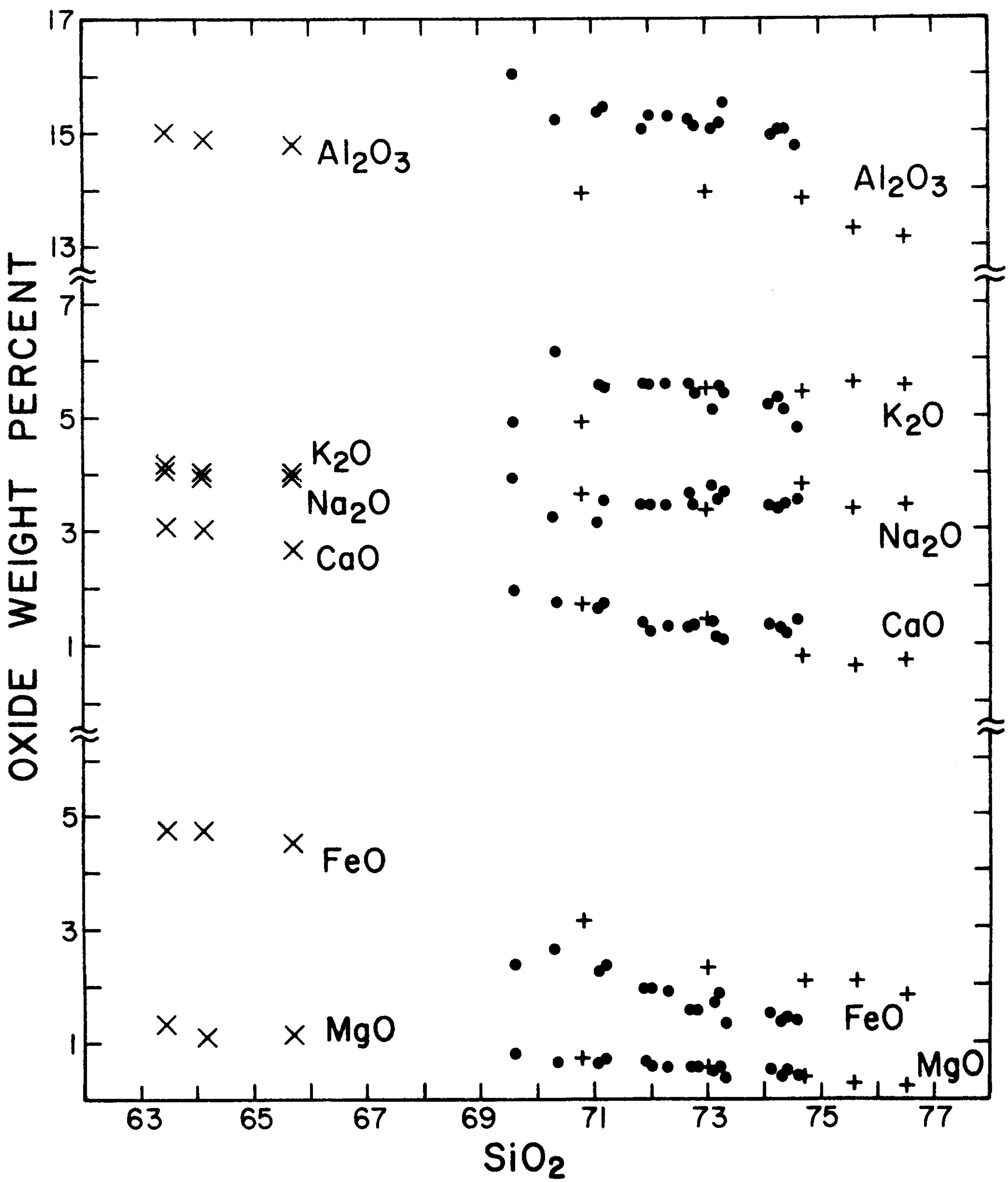

Figure B1. Variation diagram showing chemical differences in the Winnsboro Complex. Solid circles = Rion granite; + = Winnsboro granite; x = marginal facies.

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

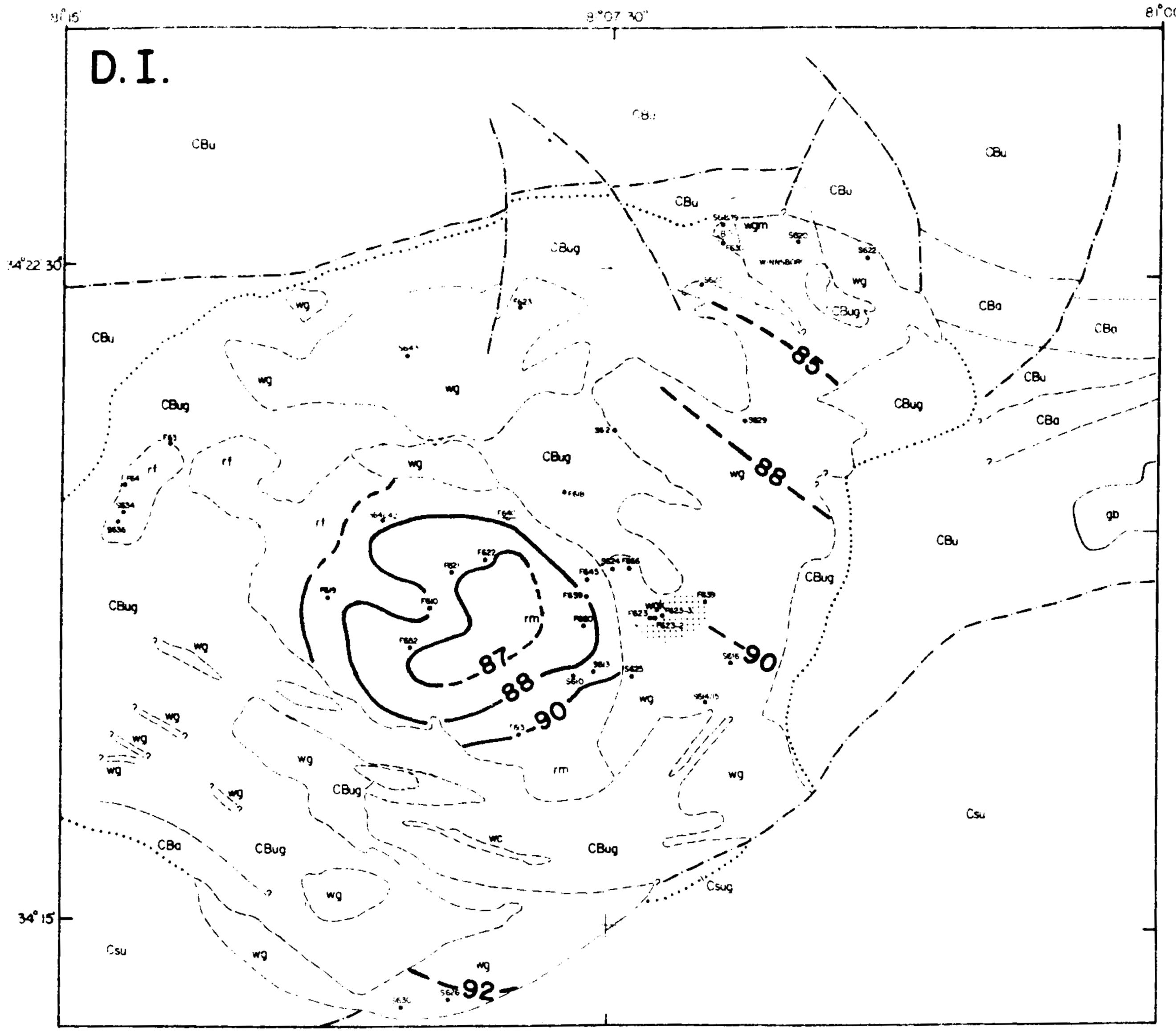

Figure B2. Contour diagram, Differentiation Index (DI) to rock type. Note the systematic increase in DI for unit Wg from NE to SW.

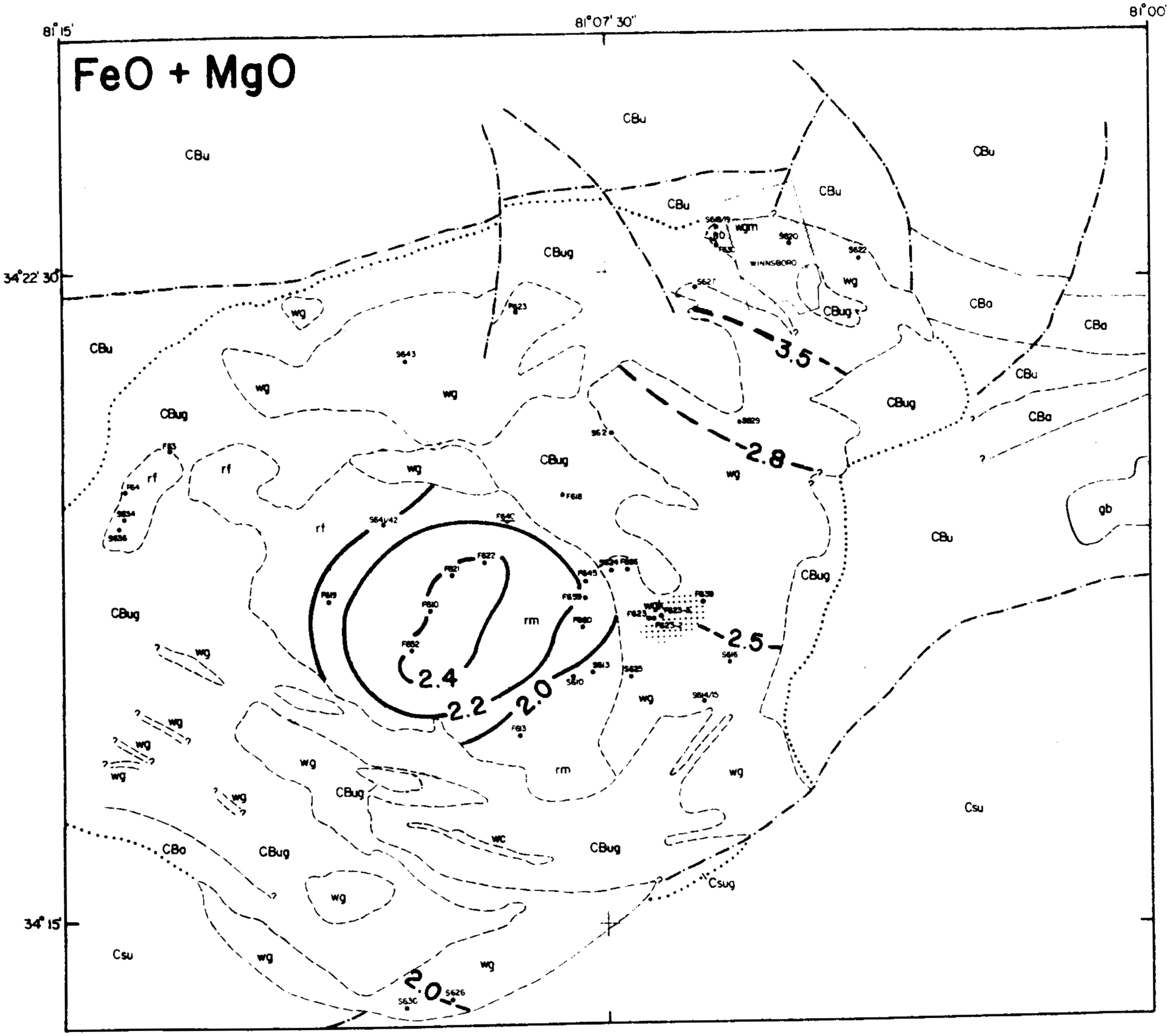

Figure B3. Contour of sum of FeO and MgO for the Winnsboro complex. Note higher values in the core facies of the Rion granite (rm, rf).

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 ± .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 ± .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

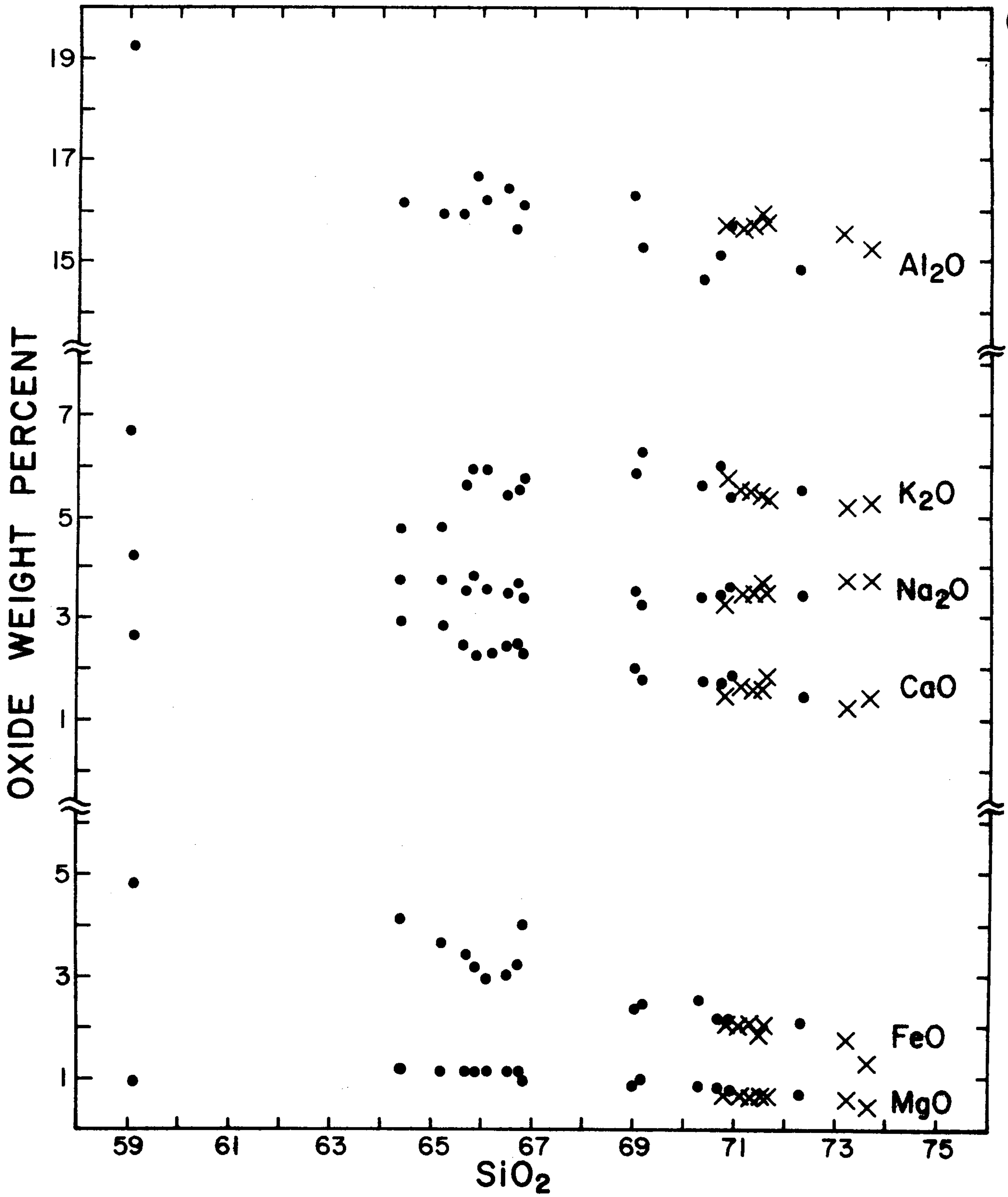

Figure B4. Variation diagram showing chemical differences in the Liberty Hill complex. Note the discontinuity in SiO_2 at 67%. Solid circles = coarse grained (LHc); x = fine grained (Lhf).

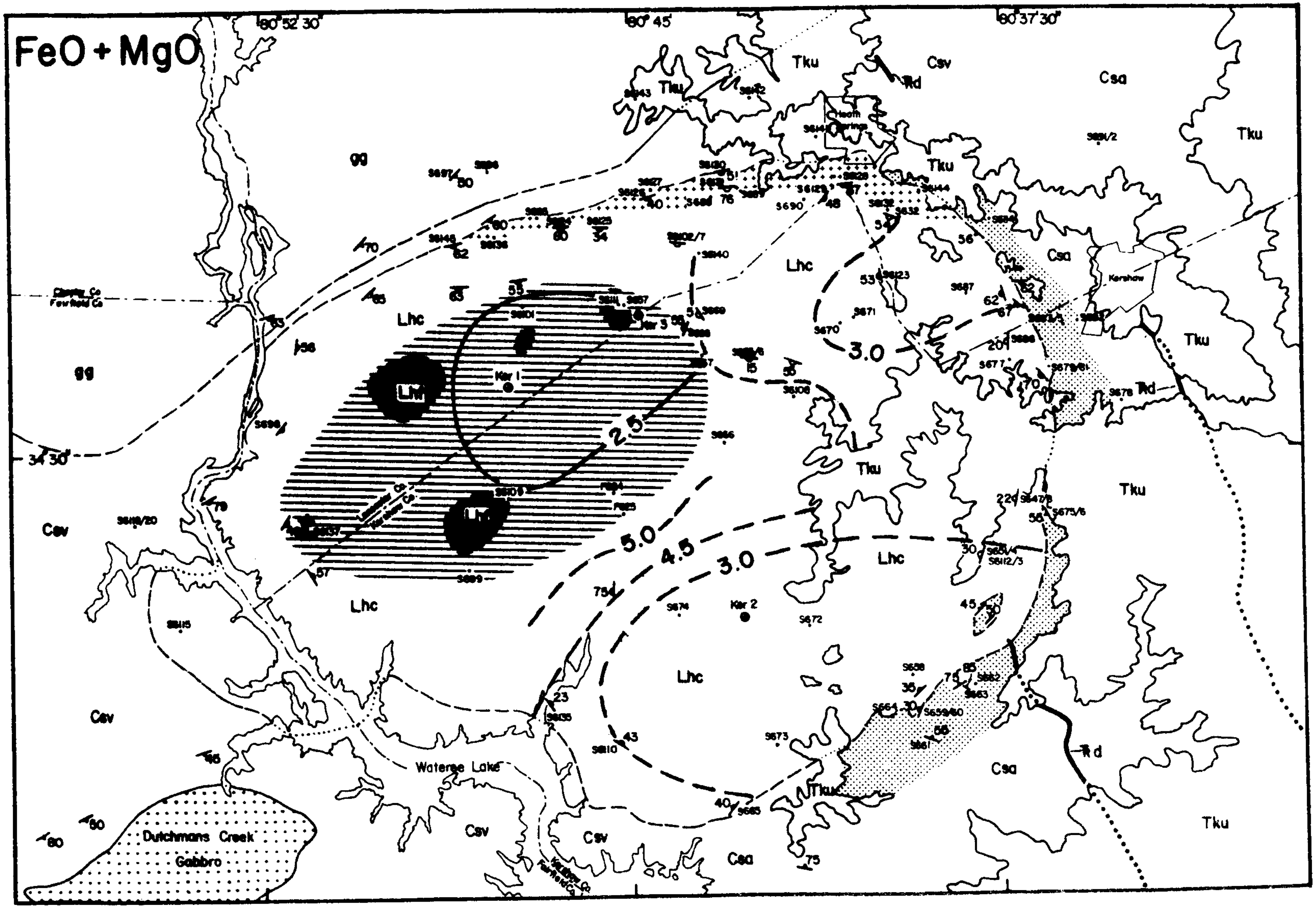

Figure B5. Contour diagram showing zonation of complex. The margins of the coarse-grained facies (Lhc) appear to be relatively depleted in mafic constituents.

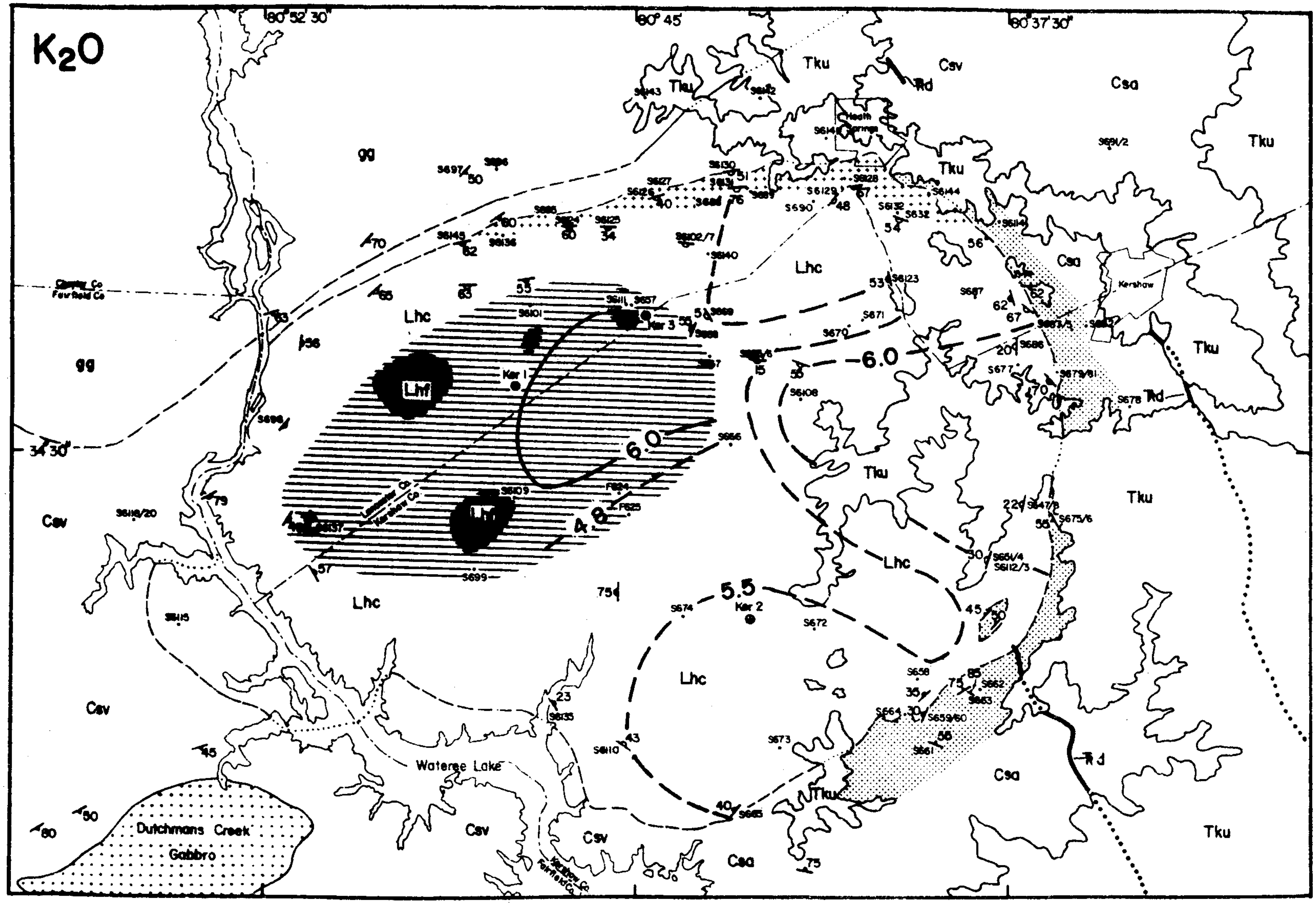

Figure B6. Contour diagram showing variations in K_2O content of both coarse-grained (Lhc) and fine-grained (Lhf) facies of the complex.

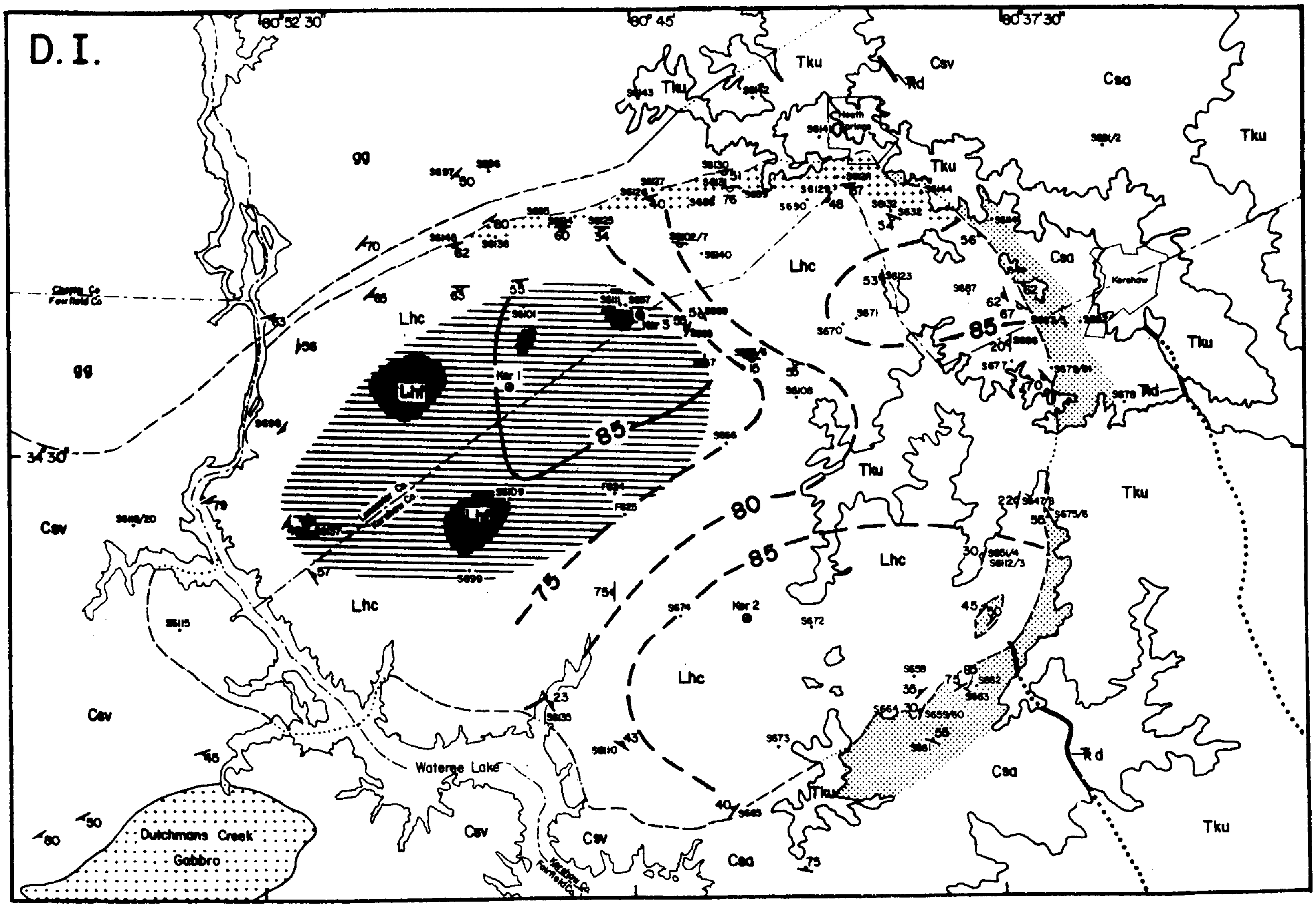

Figure B7. Contour diagram showing trends of differentiation. The margine of the coarse-grained rocks (Lhc) show higher DI values.

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 (South Carolina)

John K. Costain

The geophysical data base will be primarily comprised of temperatures and geothermal gradients in existing holes and in some holes which we drilled ourselves, heat generation in rocks, and heat flow. In addition, we have obtained existing partial aeromagnetic and gravity coverage of those areas of interest to us.

Geothermal gradients in existing holes in Coastal Plain sediments are described in a following section (Section D) in a discussion of the insulating properties of Coastal Plain sediments.

Pertinent magnetic data, gravity data, geothermal gradients in plutonic rocks, heat production in plutonic rocks, and other geophysical data for the Piedmont are discussed herein in Section C.

Magnetic data. Figure C-1 shows the available aeromagnetic coverage over the Liberty Hill-Kershaw pluton. The areal extent of the pluton is well defined by a circular positive magnetic anomaly (marked "H") associated with the contact aureole. Flanking the magnetic high on either side are belts of less-pronounced lows (marked "L"). The positive anomaly associated with the contact aureole is not located over the pluton or over the contact zone but is offset about 4000-5000 feet from the contact zone as mapped in the field.

Preliminary interpretations of the aeromagnetic data have been made by Dr. E. S. Robinson of our Department of Geological Sciences. Dr. Robinson has investigated several two-dimensional models and computed magnetic anomalies along the profiles shown in Figure C-1 . Field

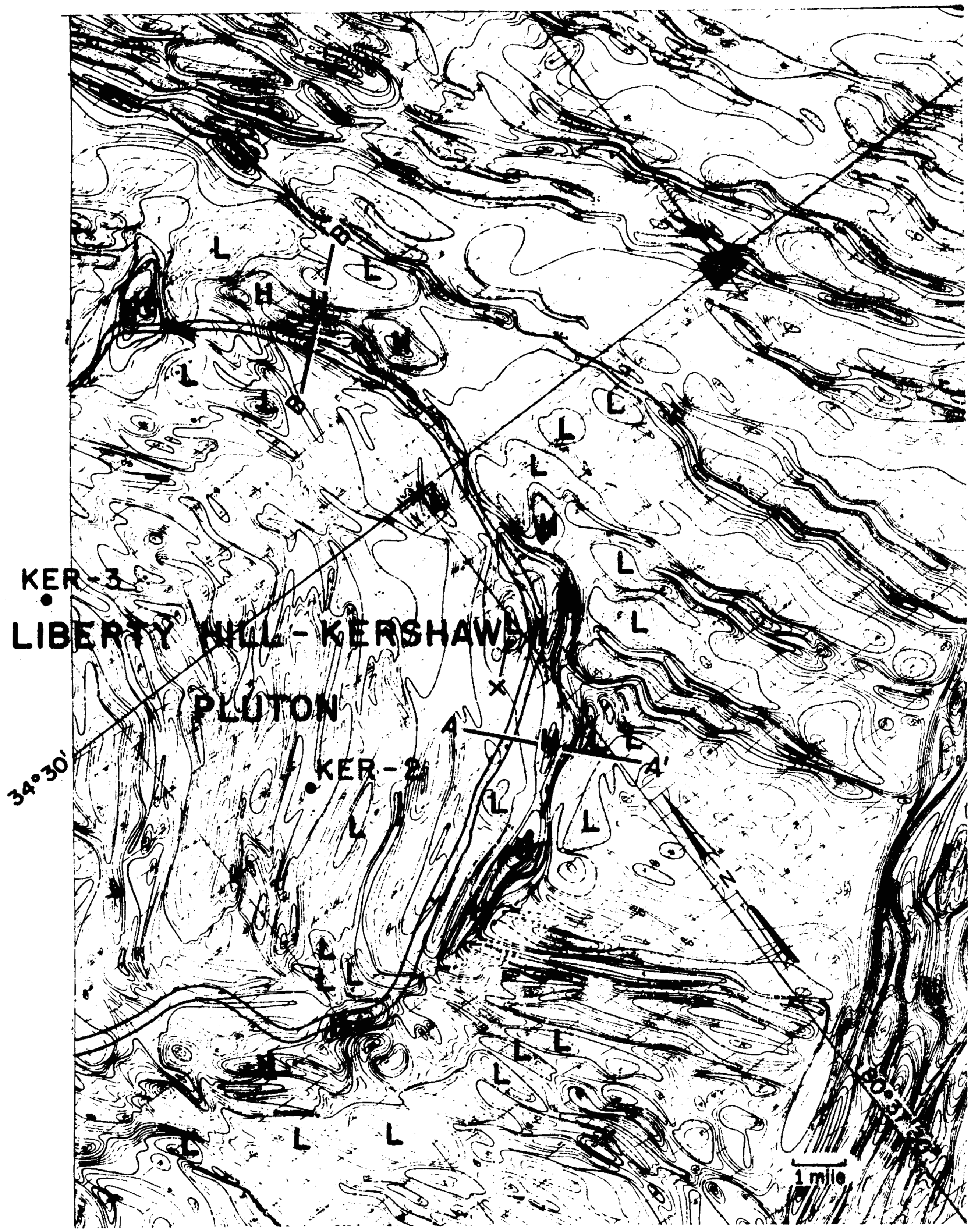

Figure C-1. Available aeromagnetic data over the Liberty Hill-Kershaw pluton, S. C.

observations by Dr. J. Alexander Speer over this pluton indicate that profile B-B' would probably be unsatisfactory for analysis since in this location the pluton is cut by northwest-trending diabase dikes of Triassic age. These dikes are strongly magnetic and account for much of the northwest grain in the magnetic field. The magnetic field along profile A-A' appears to be relatively undisturbed by magnetic effects other than those caused primarily by the geometry of the pluton.

The purpose of the preliminary model studies was to confirm the apparent attitude of the discordant contact of the pluton with the country rock. Gravity studies by Bell and Popenoe (written communication) and geologic mapping have concluded that the pluton has a steep-sided inward-dipping shape. An inward-dipping contact is consistent with the model fields obtained by Dr. Robinson along profile A-A'. His two-dimensional model assumes a magnetic aureole with an outcrop width of 2000 feet dipping inward toward the center of the pluton at an angle of 30 degrees. A non-magnetic zone in country rock parallel to the aureole and with an outcrop width of 3000 feet was assumed to lie between the magnetic aureole and the discordant contact of the country rock with the pluton. The non-magnetic zone was incorporated into the model in an attempt to reconcile the non-coincidence of the magnetic high associated with the contact aureole with the contact zone as mapped in the field.

According to J. A. Speer, the magnetic low at the location marked "X" on Figure C-1 coincides with a poorly-exposed but apparently large xenolith of non-magnetic country rock. Other xenoliths of smaller outcrop area have been observed in the interior of the pluton. Further observations of possible coincidence of magnetic lows with xenoliths will be attempted. The observed local magnetic lows inward from the large positive magnetic anomaly associated with the contact aureole may thus be due in part to the presence of large xenoliths of country rock which are non-magnetic.

Surface exposures are generally poor in the area, but the apparent correlation of a magnetic low with a xenolith is an interesting one. The magnetic data might provide an indication of future drill sites that should be avoided.

Preliminary negotiations with the U. S. Geological Survey are underway to complete the aeromagnetic coverage of the Liberty Hill-Kershaw pluton, with funds provided by ERDA and partial support by the U.S.G.S.

Gravity data. The Simple Bouguer gravity map of South Carolina by Long, Talwani, and Bridges (1975) is shown in Figure C- 2 . Several large gravity lows are associated with granitic-intrusive rocks in the Piedmont; other gravity lows to the east and southeast of the Piedmont may also be associated with granitic-intrusive rocks buried beneath Coastal Plain sediments.

We have logged three existing holes in Georgetown County, S. C. (Fig. D- 4), in the vicinity of the Georgetown gravity low. Comparing Figures D- 4 and D- 5, it is apparent that higher temperatures appear to be reached at shallower depths in the Georgetown wells, in comparison with the Clubhouse Crossroads Core Hole No. 1 (CCCH-1) northwest of Charleston, S. C. This might be a consequence of buried radiogenic granitic plutonic rocks beneath Coastal Plain sediments in the Georgetown area, or higher gradients due to lower thermal conductivity of Coastal Plain sediments in the Georgetown area.

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, S. C. 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. Final calibrations to the gamma-ray instrumentation in our own laboratory are still in progress.

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). We will eventually have a reliable heat flow-heat generation determination from our drill hole KER-3 in the Liberty Hill-Kershaw pluton. 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&S&-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 (see following Section D on the insulating properties of Coastal Plain sediments).

The heat generation determinations available to date are thus somewhat optimistic since (1) they predict relatively high temperatures

Table C-1 . Heat generation from surface samples of Kershaw-Liberty Hill pluton, S. C.

Sample	Uranium, ppm	Thorium, ppm	Th/U	Potassium, %	Heat generation, HGU
S669	1.5	14.6	9.7	4.4	5.2
S689	1.7	15.0	8.8	4.2	5.4
S656	1.8	10.8	6.0	4.3	4.6
S686	1.6	24.4	15.3	4.5	7.3
S665	2.4	18.9	7.9	4.8	6.8
S654	3.0	14.5	4.8	4.5	6.3
S6110	2.4	16.3	6.8	4.5	6.2
S6111	4.7	34.0	7.2	4.2	11.4
S671	6.2	29.2	4.7	4.3	11.5
S699	2.6	23.0	8.9	4.6	7.7
S6101	8.0	26.5	3.3	3.9	12.2

Table C-2 . Heat generation from surface samples of Winnsboro pluton, S. C.

Sample	Uranium, ppm	Thorium, ppm	Th/U	Potassium, %	Heat generation, HGU
S7618	4.0	15.5	3.9	3.0	6.8
S7623	2.0	17.2	8.6	4.3	6.1
S7634	3.8	41.0	10.8	4.4	12.2
F22	4.4	35.0	8.0	4.2	11.4
F19	4.0	39.2	9.8	4.5	12.0
F10	3.8	36.4	9.6	4.7	11.3
S7610	6.6	34.6	5.2	4.3	12.9
F7614	1.7	16.7	9.8	4.1	5.7
S7643	2.0	17.2	8.6	4.3	6.1

at relatively shallow depths in Coastal Plain sediments where they overlie buried plutonic rocks, and (2) the determinations of heat generation 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-3 shows temperature profiles and gradients for KER-1 and KER-2. The deeper hole KER-3 has not yet recovered from the thermal effects of drilling; this hole will be logged several more times, and an equilibrium temperature profile and gradient will be given in a subsequent report.

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.

Gravity and magnetic potential field data are often useful in the interpretation of the shape and depth extent of plutonic rocks. Similarly, reasonable assumed distributions of radiogenic elements in models of plutonic rocks should give values of temperature, geothermal gradients, heat flow, and heat generation which are in agreement with observed values. We have designed a thermal model based on arbitrary distributions of heat-producing radiogenic elements, and flexible enough to describe a complex three-dimensional geologic environment. The numerical model is based on the concept of a point source which continually radiates heat.

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

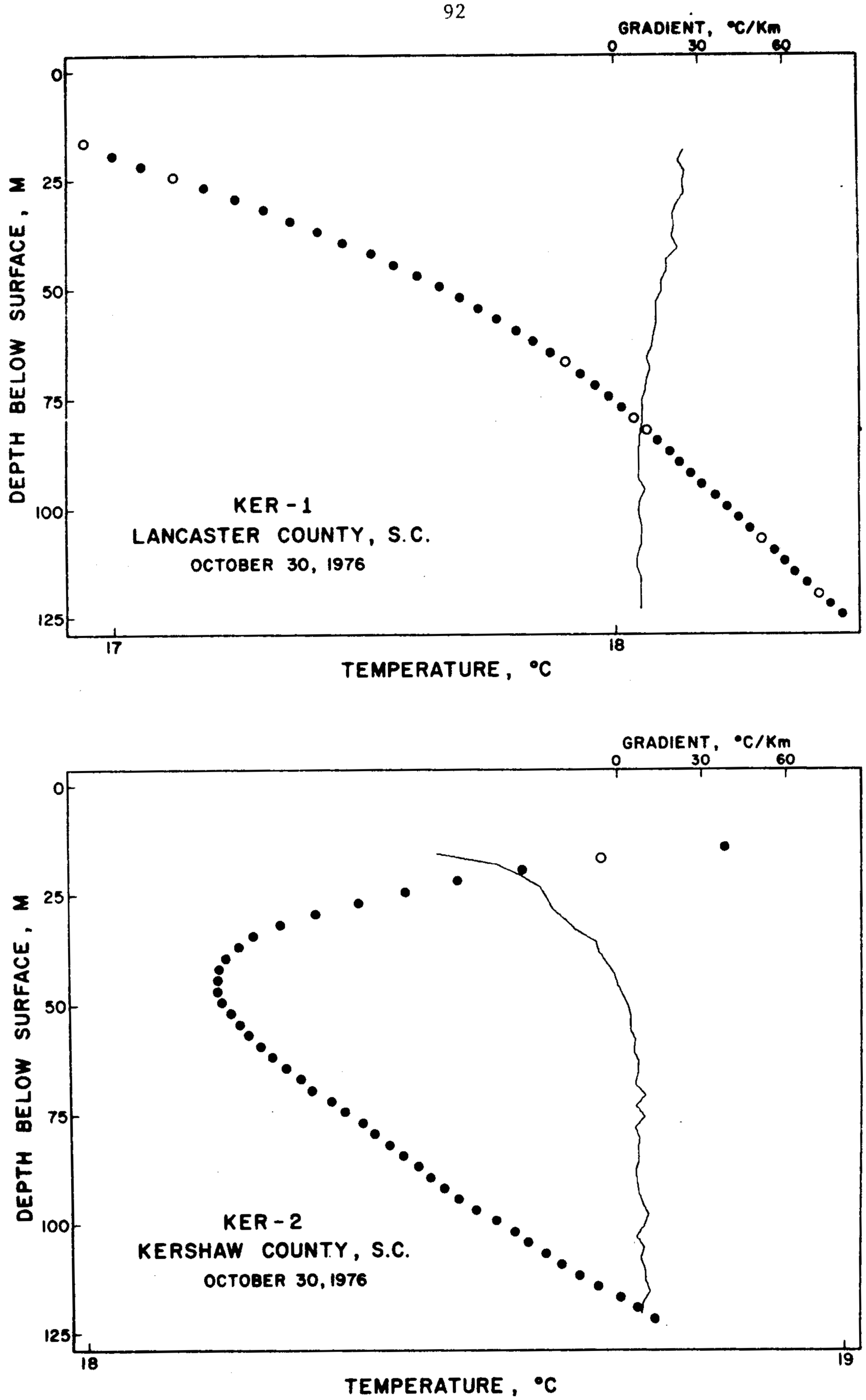

Figure C-3. Temperature and gradient profiles in the Liberty Hill-Kershaw pluton, S.C.

The temperature, v, at a distance r from a continuous point source of strength q is given by (Carslaw and Jaeger, 1959, p. 261):

$$v = \frac{q}{4\Pi kr} \operatorname{erfc} \frac{r}{\sqrt{4kt}}$$

where k is thermal diffusivity, and t is the time since introduction of the heat source. The complementary error function, erfc x, is defined as 1 - erf x where

$$\operatorname{erf} x = \frac{2}{\sqrt{\Pi}} \int_0^x e^{-z^2} dz .$$

As t goes to infinity, the temperature, v, at a distance r reduces to

$$v = \frac{q}{4\Pi kr}$$

The strength, q, is the temperature to which the amount of heat liberated would raise unit volume of the substance (Carslaw and Jaeger, 1959, p. 256). If the rate of heat generation, A', at the point source is known or assumed, then

$$A' = \rho cq$$

and

$$v = \frac{A'}{(4\Pi kr)(\rho c)} \operatorname{erfc} \frac{r}{\sqrt{4kt}}$$

or

$$v = \frac{A'}{(4\Pi kr)(\rho c)}$$

as t goes to infinity.

The heat generation, A', in calories/cm^3-sec, is given by measurements of heat generation in rocks (Table C-1, C-2, this report), ρ is density, and c is specific heat.

Any arbitrary three-dimensional distribution of heat-generating elements can thus be modeled by numerical integration of point-source distributions, and values of heat flow and generation can be computed.

A computer program has been written during this report period to model plutonic igneous rocks with arbitrary geometry and distributions of uranium, thorium, and potassium. The method of images (Carslaw and Jaeger, 1959, p. 273) has been used to maintain the boundary condition of 0°C at the (plane) surface of the earth.

The geometry of the distributions used to model heat flow and heat generation must be compatible with geometries used to model gravity and magnetic data. The computer program has been designed to accept input data much of which is identical to that used in our programs to model gravity and magnetic data. When sufficient analyses of heat generation in rocks and determinations of heat flow in plutons become available, the program will be used to aid in the selection of optimum drilling sites and in the interpretation of data.

D. Insulating Properties of Coastal Plain Sediments

(South Carolina and North Carolina)

J. K. Costain

An optimum site for geothermal development in the tectonically stable eastern United States will probably be associated with crustal igneous rocks containing relatively high concentrations of radiogenic heat-producing elements buried beneath an insulating blanket of sediments of low thermal conductivity. Preceeding sections have discussed the geology, geochemistry, and geophysics of exposed crystalline rocks in the Piedmont of South Carolina. Evaluation of these plutonic rocks will aid us in projections beneath Coastal Plain sediments and in the interpretation of gravity, magnetic, and seismic data for the Atlantic Coastal Plain. This section discusses the thermal properties of sedimentary insulators.

Locations of holes logged by us in sediments of the Coastal Plain during the present report period (May 1 - October 31, 1976) are shown in Figures D-1 and D-2. Table D-1 lists pertinent data pertaining to these holes as well as to those described in Progress Report VPI&SU-5103-1 for the report period May-June, 1976. Figures D-3 through D-8 show temperatures and gradients only for those holes logged in Coastal Plain sediments during the period July 1 - October 31, 1976. The method of temperature measurement is described in Progress Report VPI&SU-5103-1. The holes were logged by Mr. C. S. Rohrer, Research Specialist.

On Figures D-3 through D-8 , solid circles correspond to stable water temperatures and open circles indicate slightly unstable temperature

Well No.	Latitude	Longitude	State	Bottomhole temp., °C	Well depth, meters	Average surface temp., °C	Average gradient, °C/Km
CCCH-1	32°53'15"	80°21'25"	SC	38.7	752	18.2	27.3
JAS-103	32°22'05"	80°55'01"	SC	20.6	72	18.7	26.4
HAM-18	32°51'03"	81°04'51"	SC	24.3	204	18.2	29.9
HAM-50	32°40'40"	81°11'10"	SC	24.3	204	18.2	29.9
HAM-68	32°47'44"	80°57'11"	SC	24.5	229	18.3	27.0
HAM-69	32°44'38"	80°55'53"	SC	23.7	192	18.3	28.1
BFT-59	32°31'36"	80°40'29"	SC	25.5	228	18.7	29.8
BFT-450	32°40'21"	80°46'26"	SC	23.6	180	18.4	28.9
BFT-786	32°15'14"	80°42'15"	SC	23.0	157	19.0*	25.5
BFT-787	32°15'14"	80°42'15"	SC	21.1	69	19.0*	30.4
COL-52	33°00'02"	80°27'20"	SC	21.2	102	18.1	30.4
COL-53	32°59'40"	80°27'40"	SC	21.8	128	18.1	28.9
COL-63	32°28'45"	80°20'02"	SC	25.4	173	19.2*	35.8
COL-92	32°39'42"	80°39'24"	SC	23.4	173	18.4	28.9
COL-96	32°44'11"	80°27'09"	SC	24.2	166	18.4	34.9
COL-97	33°02'56"	80°35'45"	SC	21.4	116	18.0	29.3
CHN-136	32°49'35"	79°57'15"	SC	23.1	123	18.9	34.1
HO-1	33°50'55"	79°03'39"	SC	20.8	134	17.7	23.1
HO-35	33°41'57"	78°53'35"	SC	19.2	138	18.0	8.7
HO-290	33°39'55"	78°55'45"	SC	21.3	125	18.0	26.4
HO-308	33°45'05"	78°58'04"	SC	20.9	109	17.8	28.4
HO-319	33°42'45"	79°01'39"	SC	22.6	172	17.8	27.9
HO-337	33°52'33"	78°39'06"	SC	19.0	102	17.8	11.8
HO-346	33°50'55"	78°42'23"	SC	21.0	102	17.8	31.4
HO-321	33°44'32"	78°50'54"	SC	19.0	114	17.7	11.4
GEO-43(77)	33°23'25"	79°17'36"	SC	24.0	214	18.2	27.1
GEO-81	33°22'53"	79°13'30"	SC	23.7	153	18.3	35.3
GEO-89	33°21'50"	79°10'05"	SC	24.6	189	18.3	33.3
BRK-59	33°24'55"	79°55'50"	SC	22.2	179	17.8	24.6
SU-69	33°56'02"	80°20'48"	SC	20.0	64	17.7	36.0
RIC-310	34°05'35"	81°02'15"	SC	20.2	246	17.5	11.0
MLB-112	34°37'15"	79°41'15"	SC	18.2	82	17.0	14.6
KER-1	34°31'12"	80°47'31"	SC	18.5	125	16.3	17.6

*These are only approximations because there was no contour above 19.0° for interpolation.

Table D-1. Data pertaining to holes logged in South Carolina during May 1 - October 31, 1976.

Well No.	Latitude	Longitude	State	Bottomhole temp., °C	Well depth, meters	Average surface temp., °C	Average gradient, °C/Km
YK-147	35°01'50"	81°01'25"	SC	19.2	211	16.2	14.2
SP-297	34°59'30"	81°59'10"	SC	16.8	131	16.0	6.1
SP-297A			SC	16.8	109	16.0	7.3
P5R	33°08'50"	81°36'30"	SC	26.0	389	17.7	21.2
P6R	33°16'40"	81°44'12"	SC	23.5	314	17.7	18.6
P7R	33°17'00"	81°35'54"	SC	23.5	349	17.7	16.7
P8R	33°19'35"	81°44'36"	SC	23.5	309	17.7	21.2
P9R	33°19'10"	81°43'51"	SC	20.4	223	17.7	12.0
DRB-1p	33°17'50"	81°40'24"	SC	27.3	574	17.7	16.7
DRB-2	33°16'43"	81°39'27"	SC	27.3	584	17.7	16.5
DRB-6	33°17'15"	81°39'09"	SC	27.5	469	17.7	17.2
DRB-7	33°17'05"	81°39'00"	SC	27.7	589	17.7	17.0
DRB-8	33°16'51"	81°38'54"	SC	27.4	596	17.7	16.2
AA-39-V2	34°25'05"	78°36'05"	NC	21.3	150	17.5	25.3
EE-36-K5	34°07'27"	78°20'19"	NC	22.9	200	17.2	28.5
GG-34-S4	33°56'22"	78°11'53"	NC	21.6	100	17.7	39.0
HH-39-J3	33°53'35"	78°35'20"	NC	23.5	196	17.7	29.6
Y-42-F9	34°38'35"	78°54'50"	NC	21.1	140	16.6	32.1
Y-44-06	34°37'13"	79°04'42"	NC	20.0	140	16.6	24.3
Z-47-M1	34°32'08"	79°17'37"	NC	19.7	160	16.7	18.8
BB-45-M4	34°22'25"	79°07'38"	NC	22.0	165	16.9	30.9
J-11-V5	35°50'47"	76°16'09"	NC	27.0	395	16.3	27.1
O-10-W2	35°25'22"	76°12'26"	NC	23.1	260	16.6	25.0
P-21-K5	35°22'53"	77°05'19"	NC	22.3	260	16.5	22.3
S-18-U4	35°05'08"	76°50'08"	NC	23.5	235	17.2	26.8
C-12-R5	36°25'50"	76°22'25"	NC	25.6	400	15.8	24.5
C-15-S4	36°26'51"	76°36'07"	NC	22.3	270	15.7	24.4
C-26-Q7	36°26'44"	77°33'52"	NC	17.3	150	15.4	12.7
G-9-C4	36°09'04"	76°07'55"	NC	21.4	180	16.1	29.4
G-19-B4	36°09'54"	76°56'16"	NC	21.8	315	16.0	18.4
H-15-I2	36°03'48"	76°36'40"	NC	18.2	75	16.1	28.0

Table D-1. (Continued).

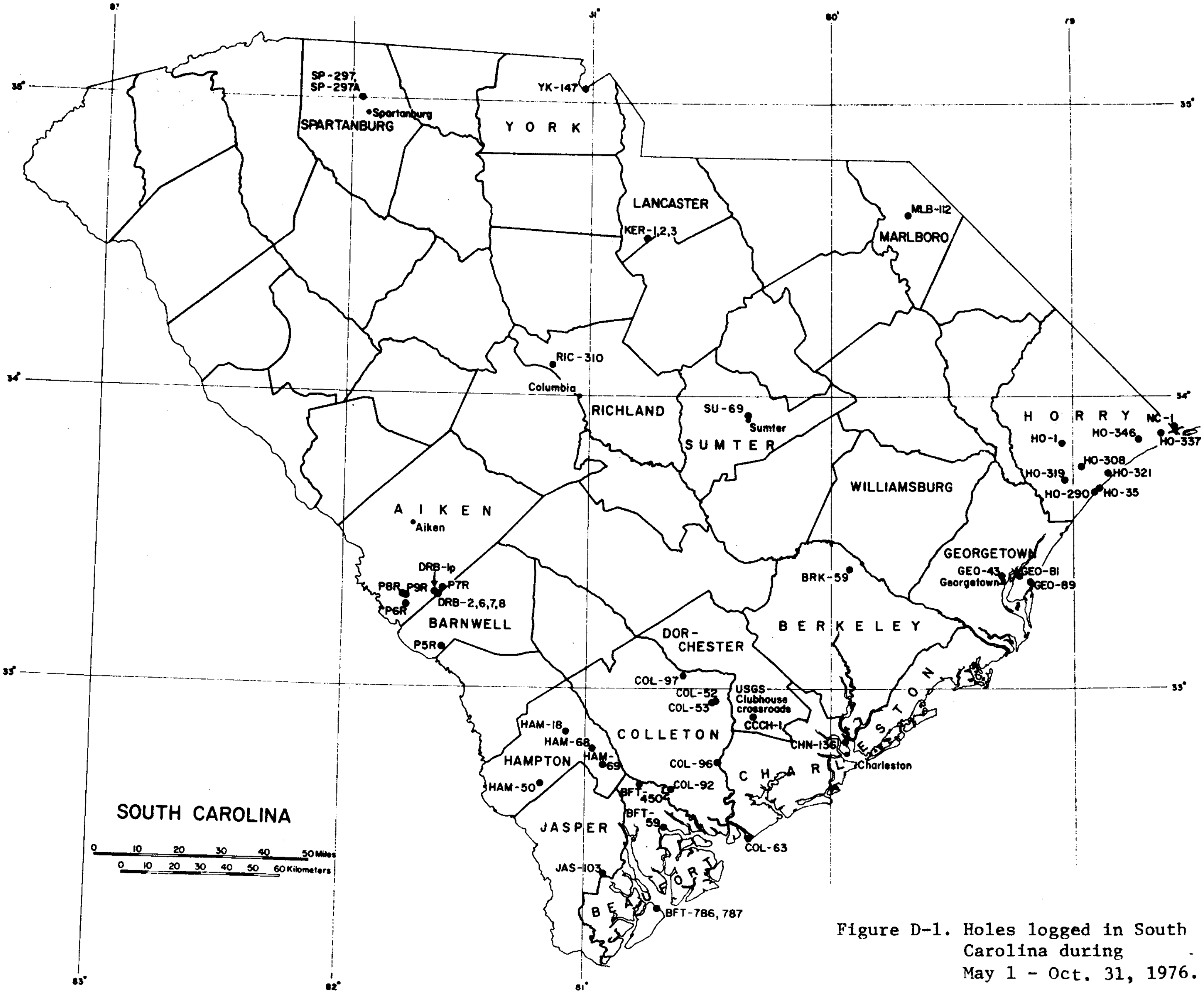

Figure D-1. Holes logged in South Carolina during May 1 - Oct. 31, 1976.

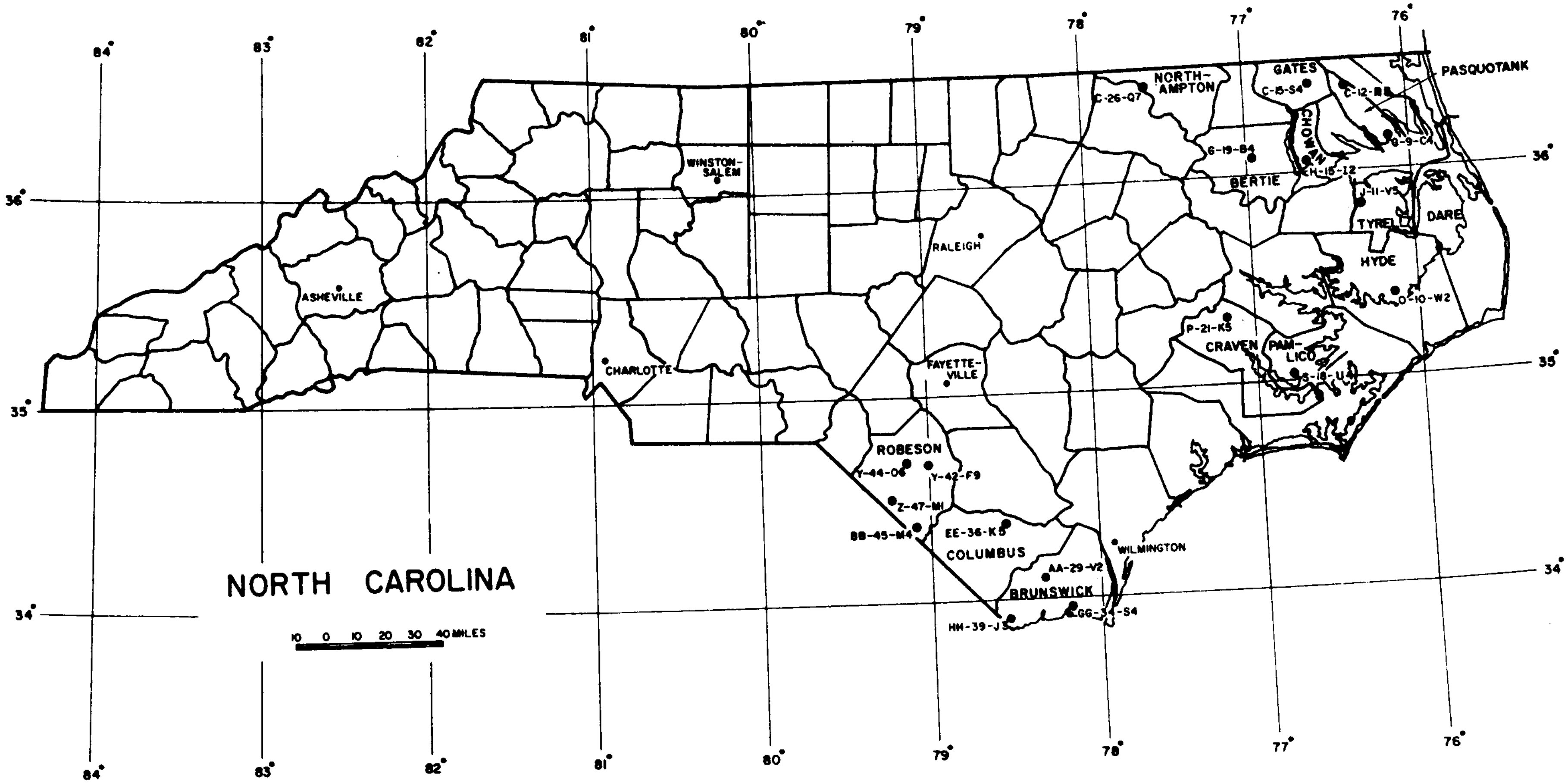

Figure D-2. Holes logged in North Carolina during May 1 - Oct. 31, 1976.

measurements, often as a result of normal convection cells in large-diameter wells.

We have found that reliable average geothermal gradients in Coastal Plain sediments can often be obtained by subtracting the mean annual surface air temperature from the bottom-hole temperature, and dividing by the depth of the hole. This appears to be a valid procedure for most holes, including those whose gradients have obviously been disturbed by ground-water circulation in the hole as a result of the establishment of communication between aquifers by the drill holes (VPI&SU-5103-1). For the present report we have attempted to obtain more accurate mean annual surface air temperatures, and have prepared Figures D- 9 and D-10 from data recently tabulated by the U. S. Department of Commerce for South Carolina and North Carolina (U. S. Dept. of Commerce, 1973). The results of average gradients determined using bottom-hole temperatures and mean annual air temperatures are given in Table D-1. The average gradient for wells in thicker accumulations of Coastal Plain sediments is about 28° C/Km.

One particularly useful group of holes made available to us was located at the Savannah River Plant on the Atlantic Coastal Plain about 30 km southeast of the Fall line (Fig. D-1). Temperatures and gradients in these holes are plotted to the same scale in Figure D-8. Many of the wells penetrate metamorphic basement rocks. For each of the DRB series of wells, the temperature data clearly define the top of crystalline basement rock at a depth of about 275 m where there is a well-defined inflection in the temperature profile. Where the wells penetrate the overlying sediments they are cemented to prevent circulation between confined aquifers. The gradients within the sediments are therefore considered to be reliable and representative of Coastal Plain sediments.

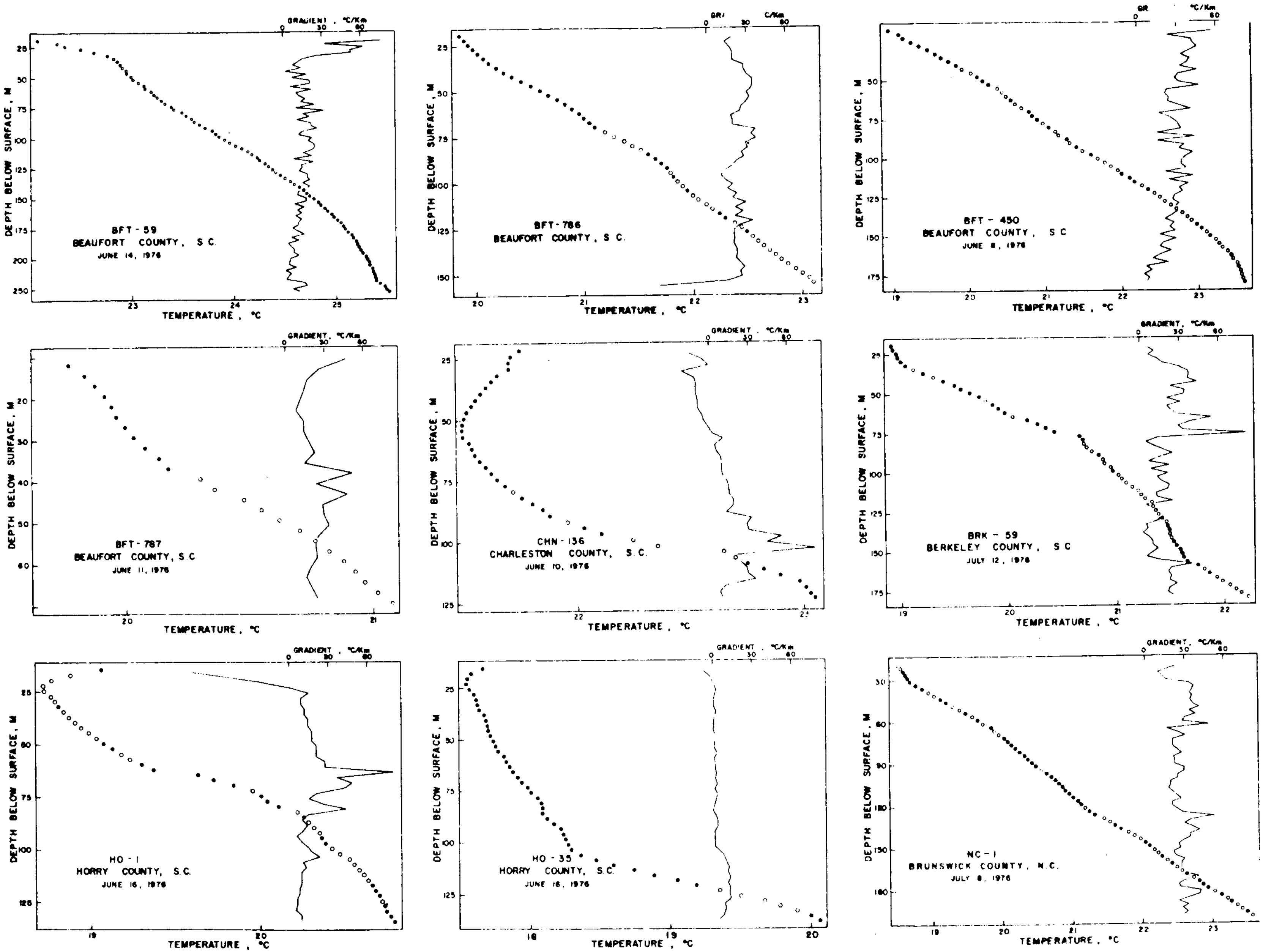

Figure D-3. Temperature and gradient profiles for holes in South Carolina.

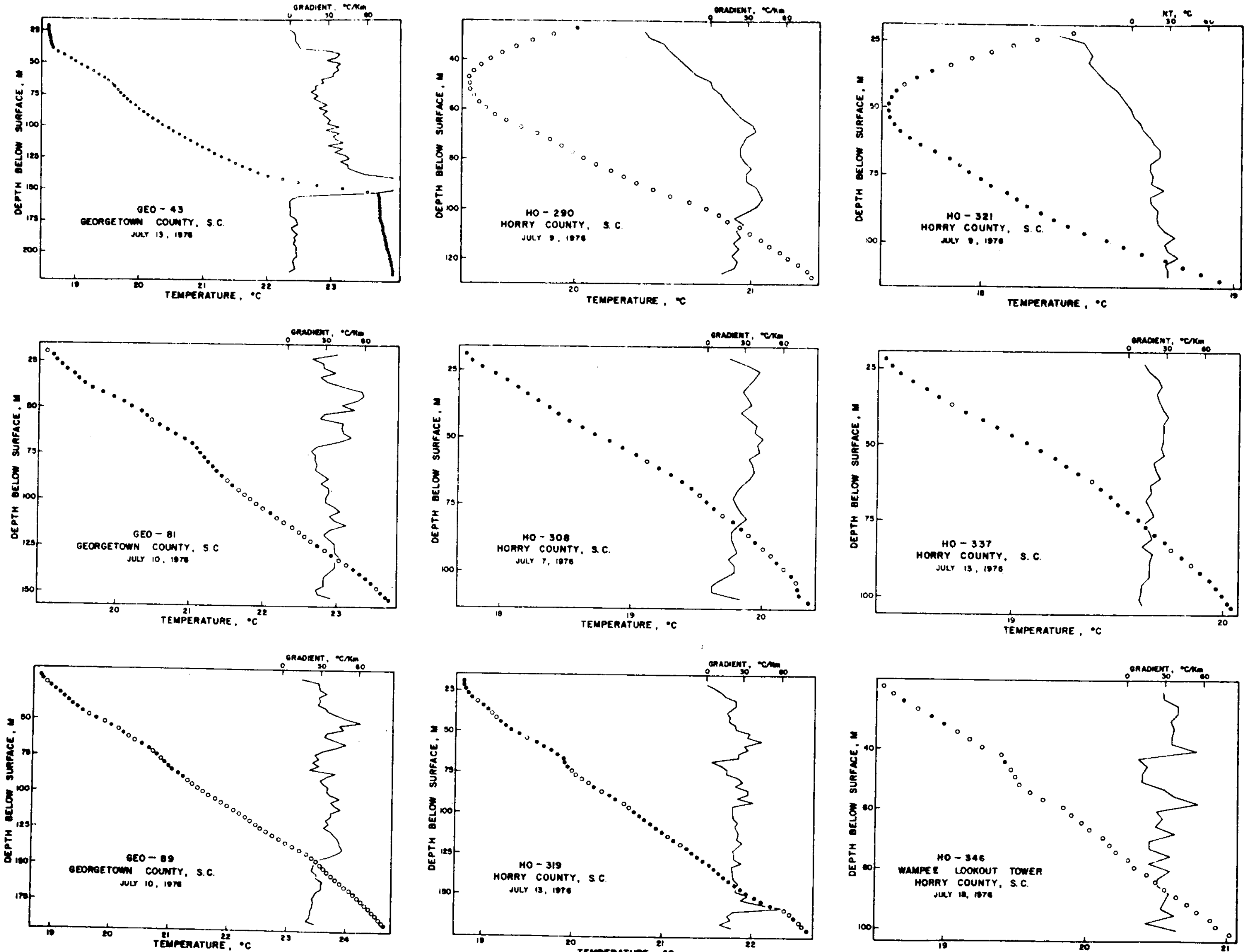

Figure D-4. Temperature and gradient profiles for holes in South Carolina.

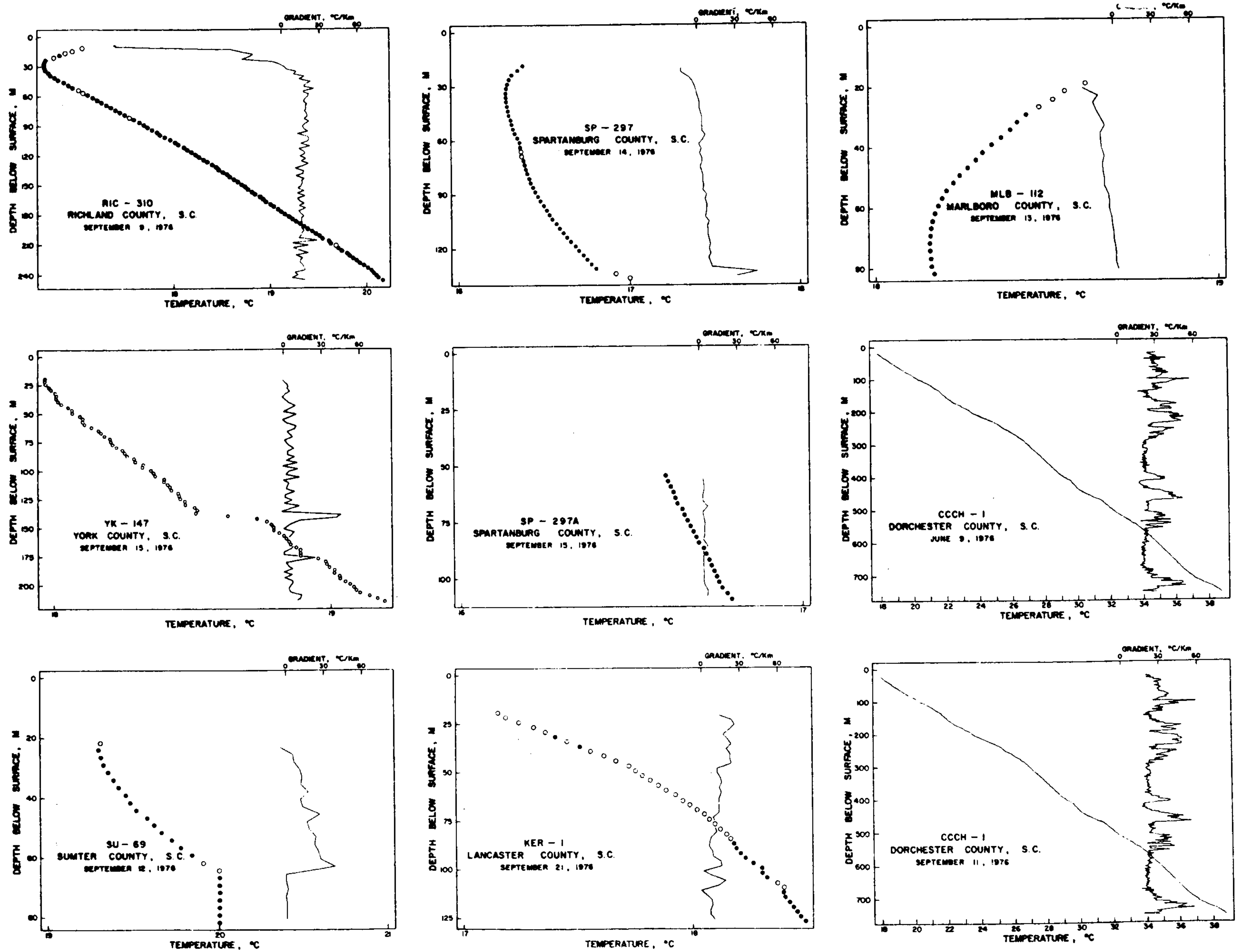

Figure D-5. Temperature and gradient profiles for holes in South Carolina.

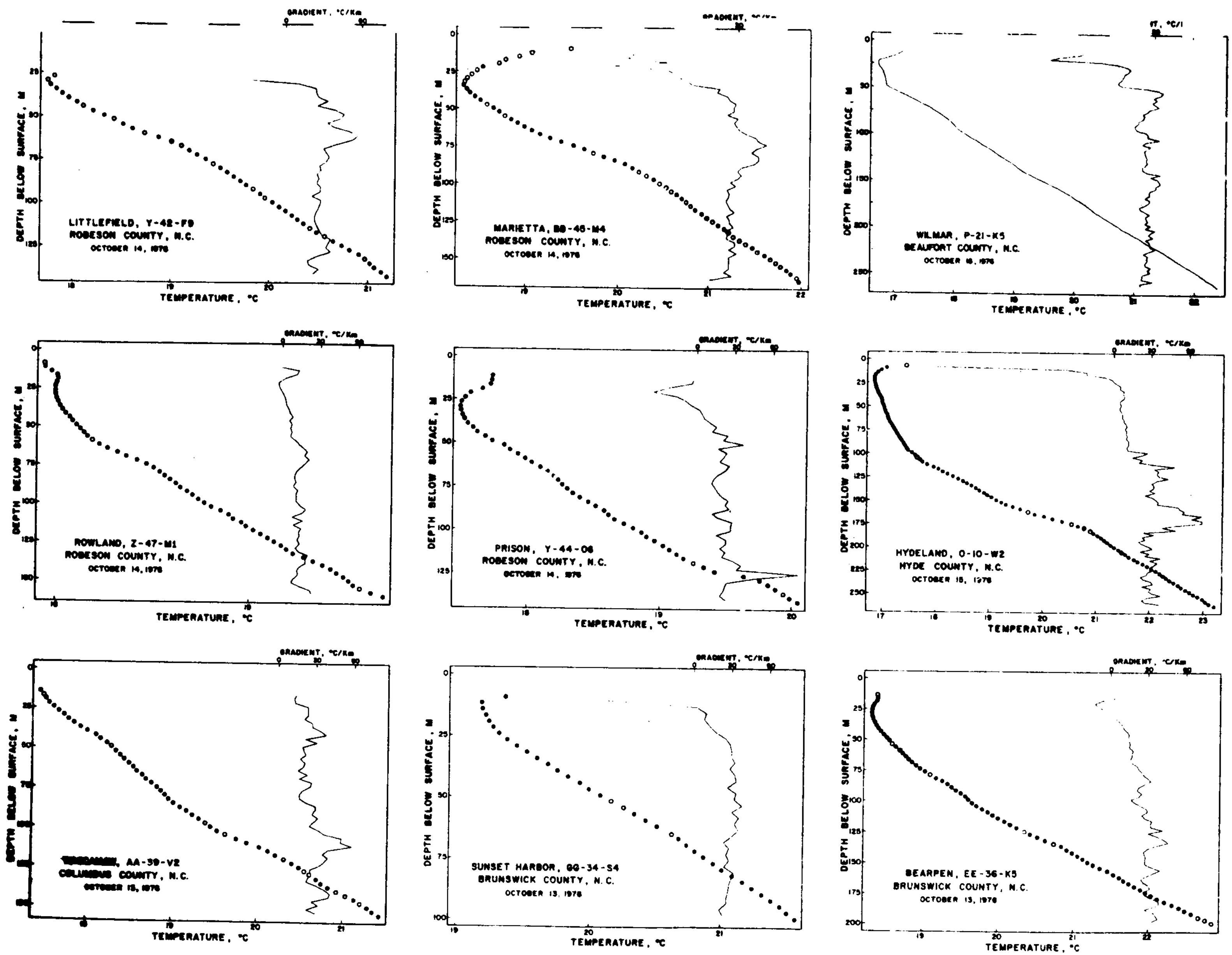

Figure D-6. Temperature and gradient profiles for holes in North Carolina.

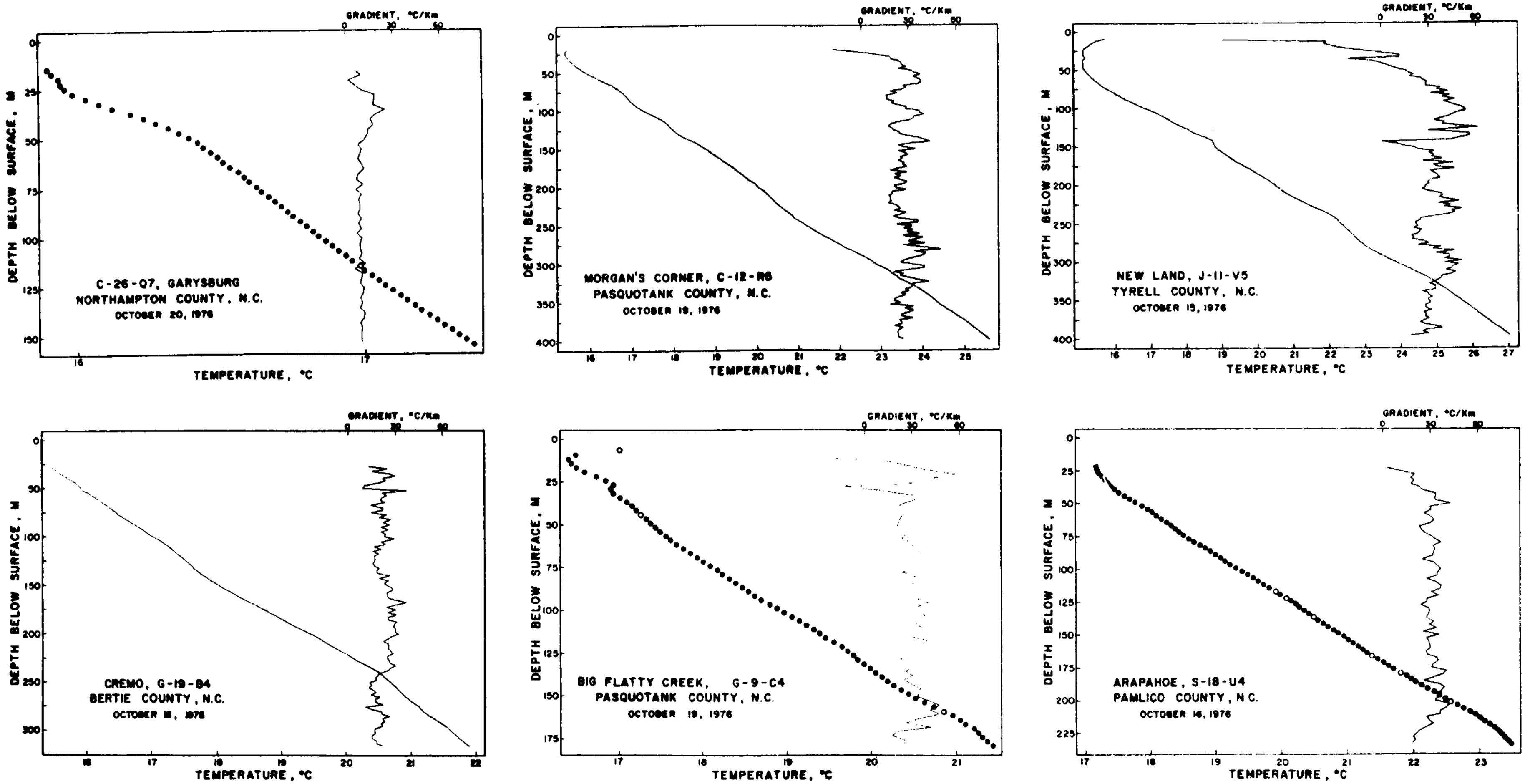

Figure D-7. Temperature and gradient profiles for holes in North Carolina.

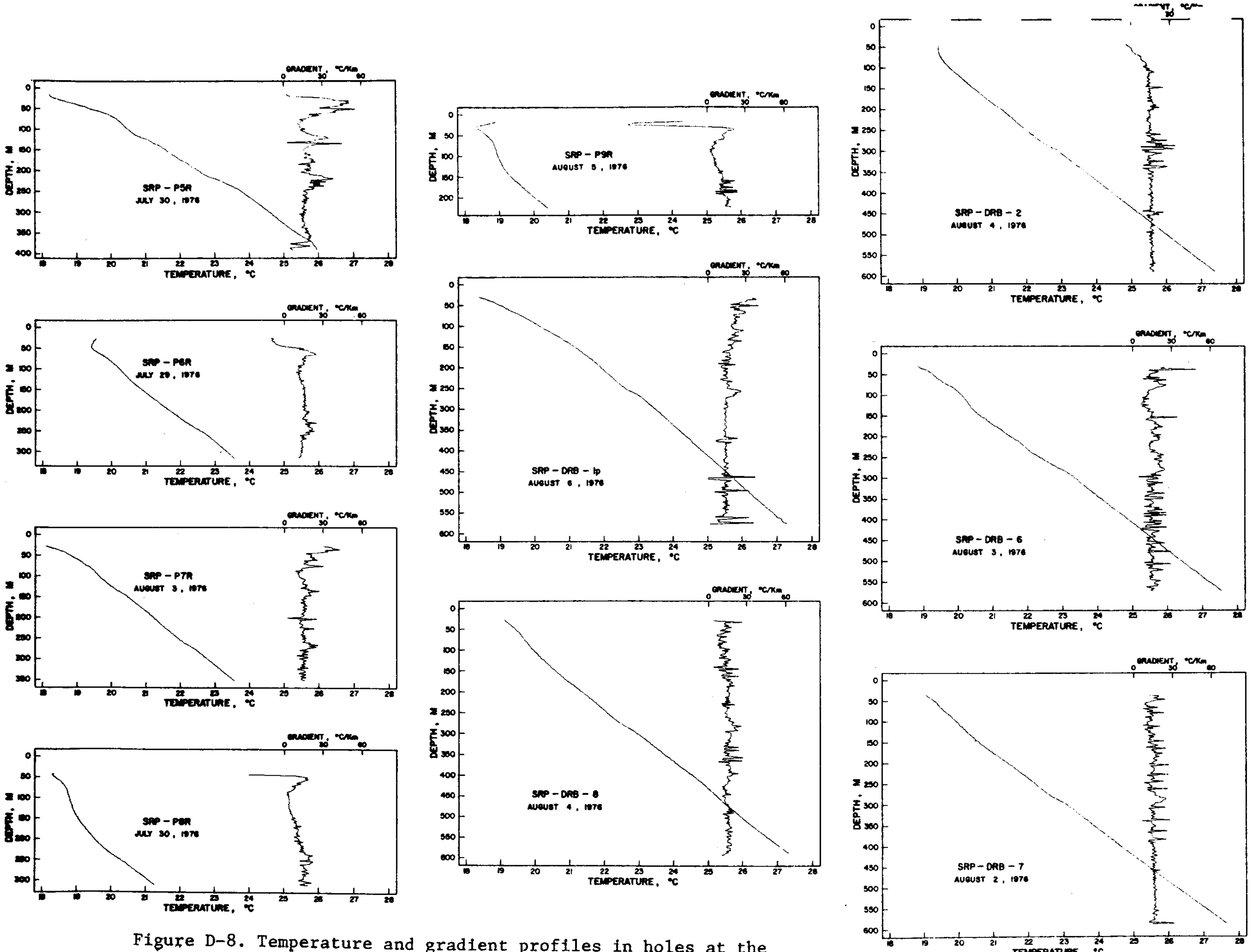

Figure D-8. Temperature and gradient profiles in holes at the Savannah River Plant near Aiken, S. C.

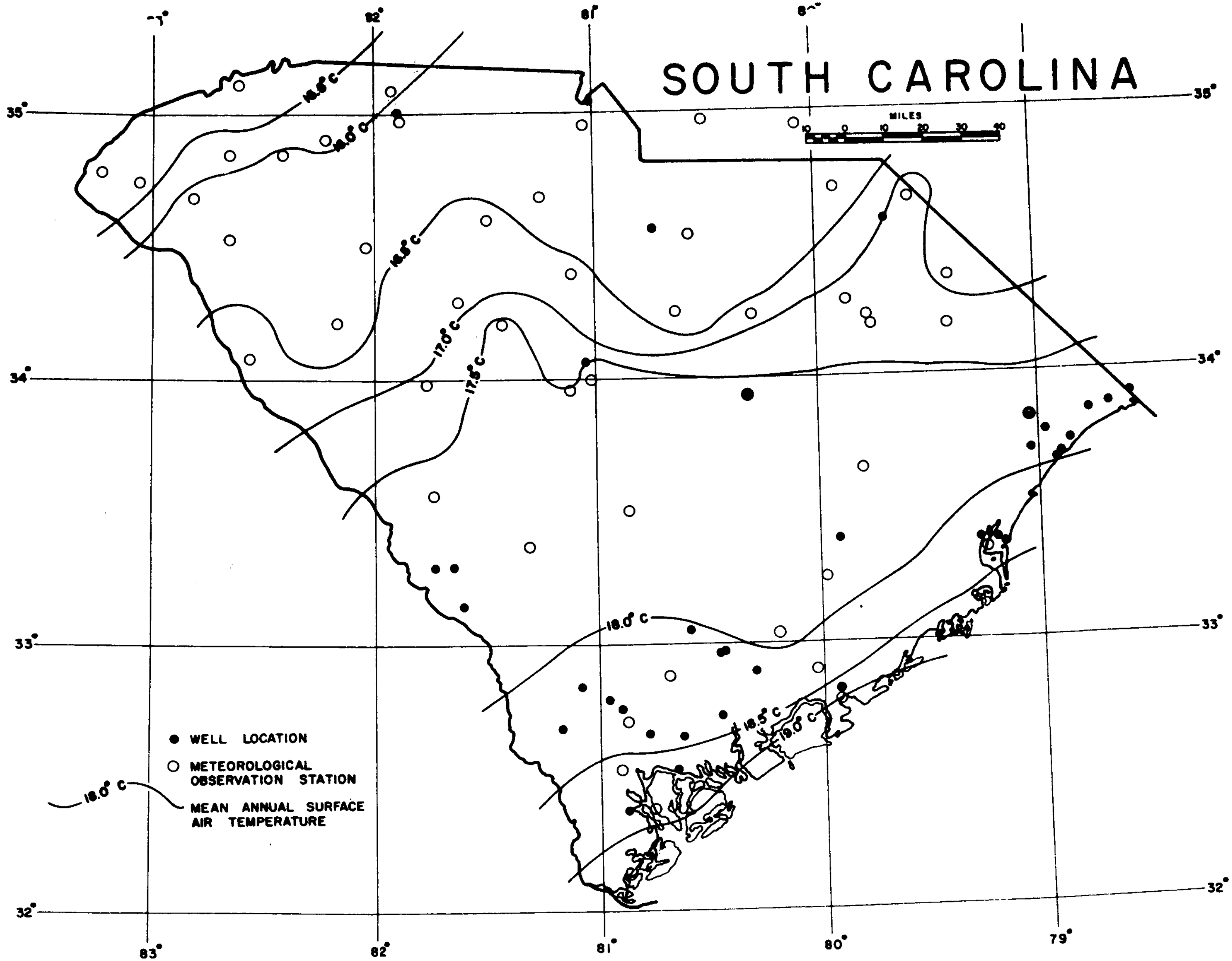

Figure D-9. Contour map of mean annual surface air temperature for South Carolina.

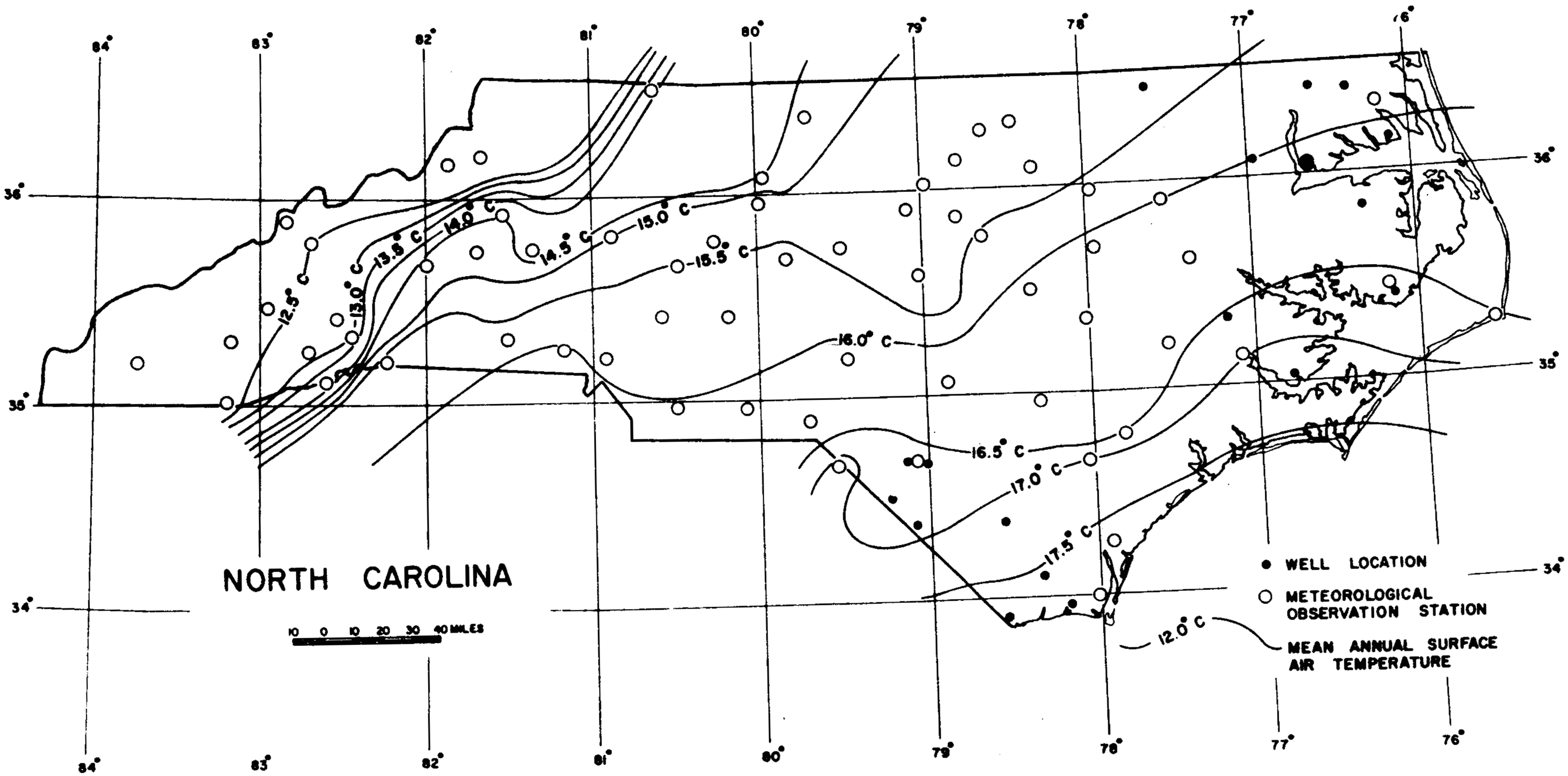

Figure D-10. Contour map of mean annual surface air temperature for North Carolina.

Previous heat flow determinations in several of these holes by Diment et al. (1965) gave heat flow values of about 1.0 HFU (1 HFU = 1 heat flow unit = 10^{-6} cal/cm^2-sec). Thermal conductivities of Coastal Plain sediments in this location are therefore about 6-7 TCU (1 TCU = 1 thermal conductivity unit = 10^{-3} cal/cm-sec-°C). These values are consistent with the predominantly quartzose sedimentary section. To the east and south, thicker accumulations of clay and silt cause a decrease in the average value of thermal conductivity and thereby an increase in the insulating potential of these sedimentary blankets.

Large and rapid changes in the geothermal gradients can be seen in Figure D- 8, particularly within the overlying sediments. These can be readily explained by large differences in the thermal conductivity between sand and clay. The prominent spikes in the gradient within the basement metamorphic rocks cannot be explained on the basis of lithologic changes. A more probable explanation for these gradient anomalies is that water is present in extensive fracture and microfracture zones penetrated by the wells. Because of the low thermal conductivity of water (1.4 TCU) the average thermal conductivity in a water-saturated fractured zone will be considerably less than that of the unfractured metamorphic rock itself which is about 6-7 TCU (Diment et al., 1965, p. 5639). For a heat flow of 1 HFU through water having a thermal conductivity of 1.4 TCU, the gradient would be 67°C/Km. The observed excursions of the gradient in basement rock are nowhere near this value, but are just under 30°C/Km for most of the holes, with the exception of DRB-1p where the gradient anomalies are about 40°C/Km (Fig. D-8). These values of the gradient correspond to thermal conductivity values between about 2.5 TCU and 3.5 TCU, and might be consistent with values for crystalline rock with well-developed fractures and microfractures. The implication is, therefore, that since the gradient anomalies are larger, DRB-1p penetrates a more extensive fracture zone than any of the other wells. Marine (1966, 1967a, 1967b, 1975) has inferred properties about these fracture zones from swabbing and pump tests and has described the water-transmitting properties of the fractured crystalline rock in these zones. Our temperature data for DRB-7 (Fig. D-8) are consistent with his conclusion that this well did not penetrate rocks which are extensively fractured (Marine, 1966, p. D225). Injection and swabbing tests in DRB-7 resulted in extremely low rates of flow (Marine, 1967a,Table 1). In well DRB-6 below a depth of 536 m relatively high rates of flow were obtained during injection and swabbing tests (Marine, 1967a,Table 1). Our temperature data suggest that DRB-6 is quite fractured both above and below this depth as evidenced by excursions in the gradient throughout the extent of the hole in the metamorphic basement rock. Evidence for Marine's "shallow fracture zone" (Marine, 1966, Fig. 4) can be found on our temperature log of DRB-2 (Fig. D-8). In this case the temperature data appear to confirm the presence of a (sub-horizontal) fracture zone that apparently is found by Marine in all other wells except DRB-2. Our data suggest that the zone is also present beneath DRB-2.

Our standard depth interval for temperature measurements is 2.5 m. A better evaluation of the degree of fracturing might be obtained by using a smaller depth increment. It might then be possible to correlate fracture zones from well to well. For example, even with a relatively large depth interval of 2.5 m there appears to be a similar deflection of the gradient curve at a depth of about 450 m in all wells that penetrate basement rock, implying a continuous, essentially horizontal fracture zone beneath these wells. At this depth in DRB-2, injection and swabbing tests (Marine, 1967a, p. B205, Table 1) indicate a rate of flow that is over 100 times greater than rates above and below this depth.

While details of fracture zones beneath the Savannah River Plant are not directly related to the objectives of our own program, any new method of detecting zones of fracture permeability in crystalline rock is of potential importance for geothermal applications. Precision temperature measurements may be of some value in evaluating fracture permeability.

One of the objectives of our overall program is to determine the thermal conductivity of sedimentary insulators. An unusual opportunity for accomplishing this objective has arisen in South Carolina, where the U. S. Geological Survey is now drilling through Coastal Plain sediments to basement near Charleston, S. C. The hole is located about one mile west of the U.S.G.S. Clubhouse Crossroads Core Hole No. 1 (CCCH-1) shown on Figure D-1, and is designated CCCH-2. At the present time, CCCH-2 has penetrated about 400 feet of basalt at a depth of about 3000 feet. Present interpretations consider the basalt to be a flow within Coastal Plain sediments; the U.S.G.S. hopes to penetrate the basalt and eventually drill into basement rocks. We should obtain an excellent heat flow determination in the basalt interval. Since the heat flow must be constant anywhere in the hole, and in particular within the overlying relatively unconsolidated sediments of the Coastal Plain, then we should recover accurate estimates of the thermal conductivity of the sediments once we have determined a gradient log within the sediments. In order to ensure an accurate conduction gradient log in the sediments, funds have been approved by ERDA to cement CCCH-2 to prevent circulation between the confined aquifers within the Coastal Plain sediments.

At a logging interval of 2.5 m, the noise level in our logging instrumentation is less than 3°C/Km (Report VPI&SU-5103-1). Hole CCCH-1 near Charleston, S. C. was logged on two separate occasions to check the repeatability of the system, and to verify the large variations in the geothermal gradient that are commonly observed in Coastal Plain sediments. Figure D-5 shows the close correspondence between the two logs.

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E. Warm Springs Project (Virginia)

John K. Costain

ERDA Contract No. E-(40-1)-4920 provided funds for a geological and geophysical study of the origin of warm springs occurring in the Warm Springs anticline in northwestern Virginia during the period June 1, 1975 - April 30, 1976 (Costain, 1976 ; Costain, Keller, and Sears, 1976). Further aspects of this work are being continued under ERDA Contract No. E-(40-1)-5103. Our earlier work suggested structural control of the occurrence of warm springs and water gaps in northwestern Virginia. Preliminary structural mapping by Dr. Peter A. Geiser of the University of Connecticut supports structural control of the springs and furthermore indicates the existence of kink bands in the folded sedimentary rocks in the Warm Springs anticline. Additional investigations by Dr. Geiser during the coming year will attempt to determine the relationship of the stress field that caused the kink bands to the fracture zones believed to control the occurrence of warm springs, and to the water gaps and observed offset of topographic ridges. His preliminary interpretation suggests faulting in crystalline basement rocks as the origin of strain in the overlying sediments.

We have observed what we believe is a significant correlation between the offset of topographic ridges and the occurrence of cold springs elsewhere in Virginia at considerable distances from the Warm Springs anticline. The observed relationship is similar to that found in northwestern Virginia. This implies that vertical zones of enhanced permeability might also exist elsewhere in the southeastern United States and that their locations might be predicted from surface studies. If the origin of the stress field that resulted in vertical fracture zones is due to faulting in basement crystalline rocks, then the absence of surface manifestations of hot springs elsewhere in Virginia, and possibly in folded sedimentary rocks in North and South Carolina as well, might be due to simple upward attenuation of strain, and hence vertical permeability, within an overlying thick sequence of sedimentary rocks. Further studies of a regional nature are planned in order to establish the degree of correlation between topographic offsets, springs, and kink bands.

The results of structural mapping by Dr. Geiser in the Warm Springs anticline during the period May 1 - October 31 are found on the following pages.

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Costain, J. K., G. V. Keller, and C. E. Sears, 1976, Preliminary geological and geophysical study of the origin of hot springs in northwestern Virginia, abstract, Transactions, Amer. Geophys. Union, v. 57, no. 4, 353-354.

Structural Mapping in the Warm Springs Anticline, Northwestern Virginia

Dr. Peter A. Geiser

University of Connecticut

Storrs, Conn.

Prepared for the Energy Research and Development Administration

Under Contract No. E-(40-1)-5103

STRUCTURAL SETTING

At the latitude of this study, the Warm Springs anticline comprises the first major uplift of the folded Appalachians, east of the Alleghaney front. The 030 trend of the structure parallels that of the central Appalachians of which it is considered a part (Rodgers 1970, p. 39). The Warm Springs anticline has an unusual structural position as it lies at the boundary of one of the major structural transitions in the folded Appalachians termed in this report, the Roanoke recess. This region is marked by an abrupt change in both the structural trend and style of the Appalachian fold belt.

Immediately to the south of the study area the dominant 030 trend of the central Appalachians is crossed by the 055 trend of the southern Appalachians in the form of the Rich Patch anticline (Butts, 1933). The surface expression of the structural style also undergoes a dramatic change, from that of the central Appalachians to the north, which is dominantly folding, to that of the southern Appalachians, which is dominantly thrusting.

Although Rodgers (1970, p. 43) suggests the folds of the southern arc may have formed before the central, the map pattern does not seem to agree with this, rather it suggests that the southern folds have been superposed on the central. The following observations from Butts (1933) map are believed pertainent to this conclusion.

1) The curvature of 2nd order fold traces in the Rich Patch anticline, into appressed crescentic shapes characteristic of type 2 interference patterns (see Ramsay 1967, p. 525-531) with the 030 trend as the first fold set.

Tectonic Directions

The tectonic directions (Whitten, 1966, p. 106) used herein are a purely geometric frame of reference based on the 1st order fold of bedding, (see Ramsay, 1967, p. 354-355), the Warm Springs anticline. The b tectonic direction coincides with the Pi pole to bedding (Figure 1a). The ac plane is normal to this axis and is the plane of best fit to the bedding girdle. The ab surface is the family of planes co-axial with b.

Frequency of Structure

The term frequency is defined by Price (1966, p. 112) as "the number of planes of one particular joint set encountered in a linear traverse at right angles to the joint planes." Its usage in this report is with reference to both cleavage and jointing. Measurements were made using a 1.5' ruler, held normal to the set of features being measured. The number of surfaces intersecting the ruler were counted and the result converted into surfaces/foot.

Cleavage Sense

The sense of cleavage is the apparent direction of rotation of the cleavage with respect to the normal to bedding. The method of determining sense is shown in figure 2. Poles to cleavage and bedding are plotted on an equal area net with a line drawn along the great circle connecting the cleavage and bedding poles. The arrow, indicating the direction from the cleavage to bedding pole, gives the sense, while the length of the line is the dihedral angle between the two surfaces.

Figure 1a. Bedding Orientation
Warm Springs Anticline
Area I

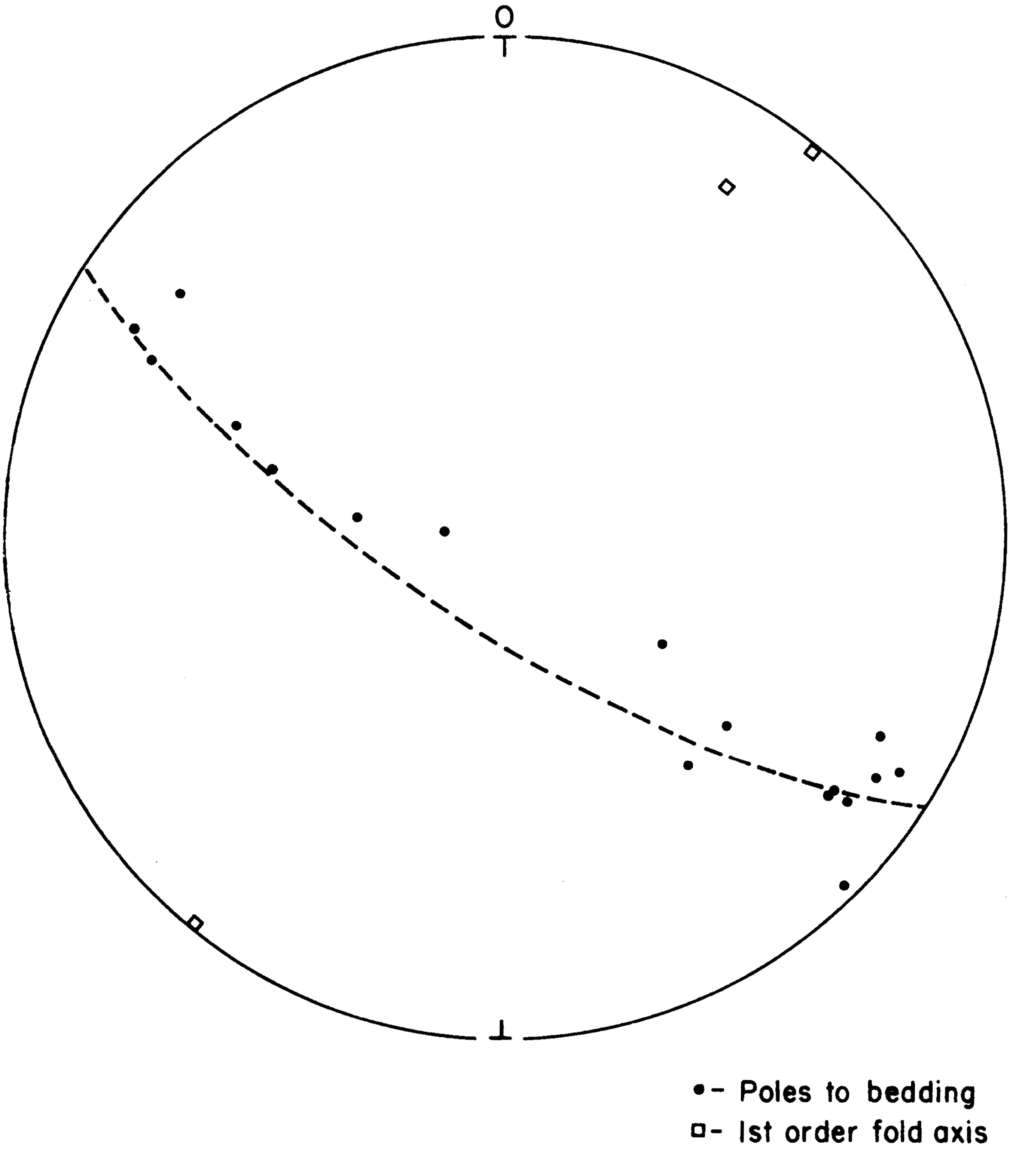


Figure 1b. Bedding Orientation Warm Springs Anticline Area III

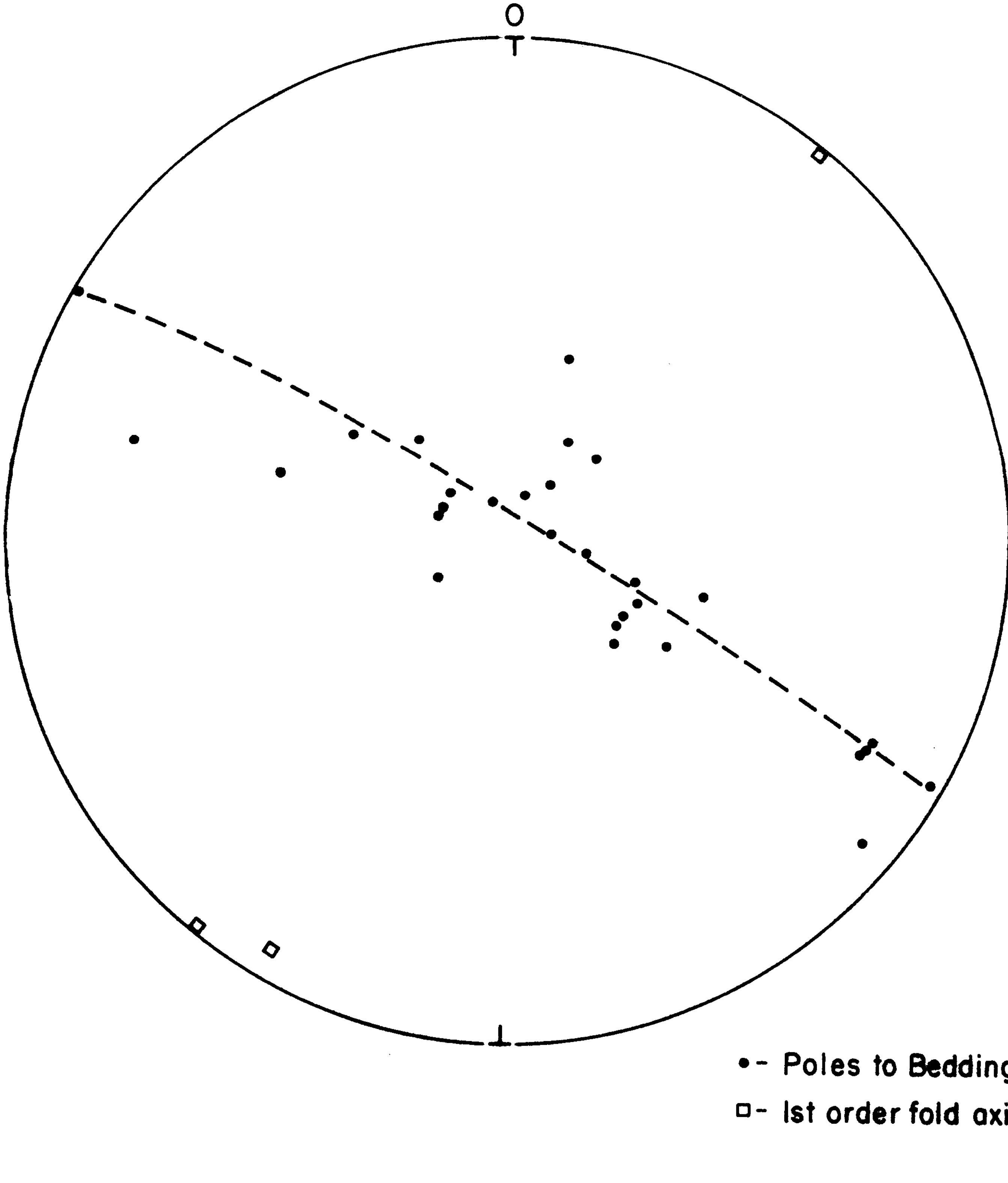
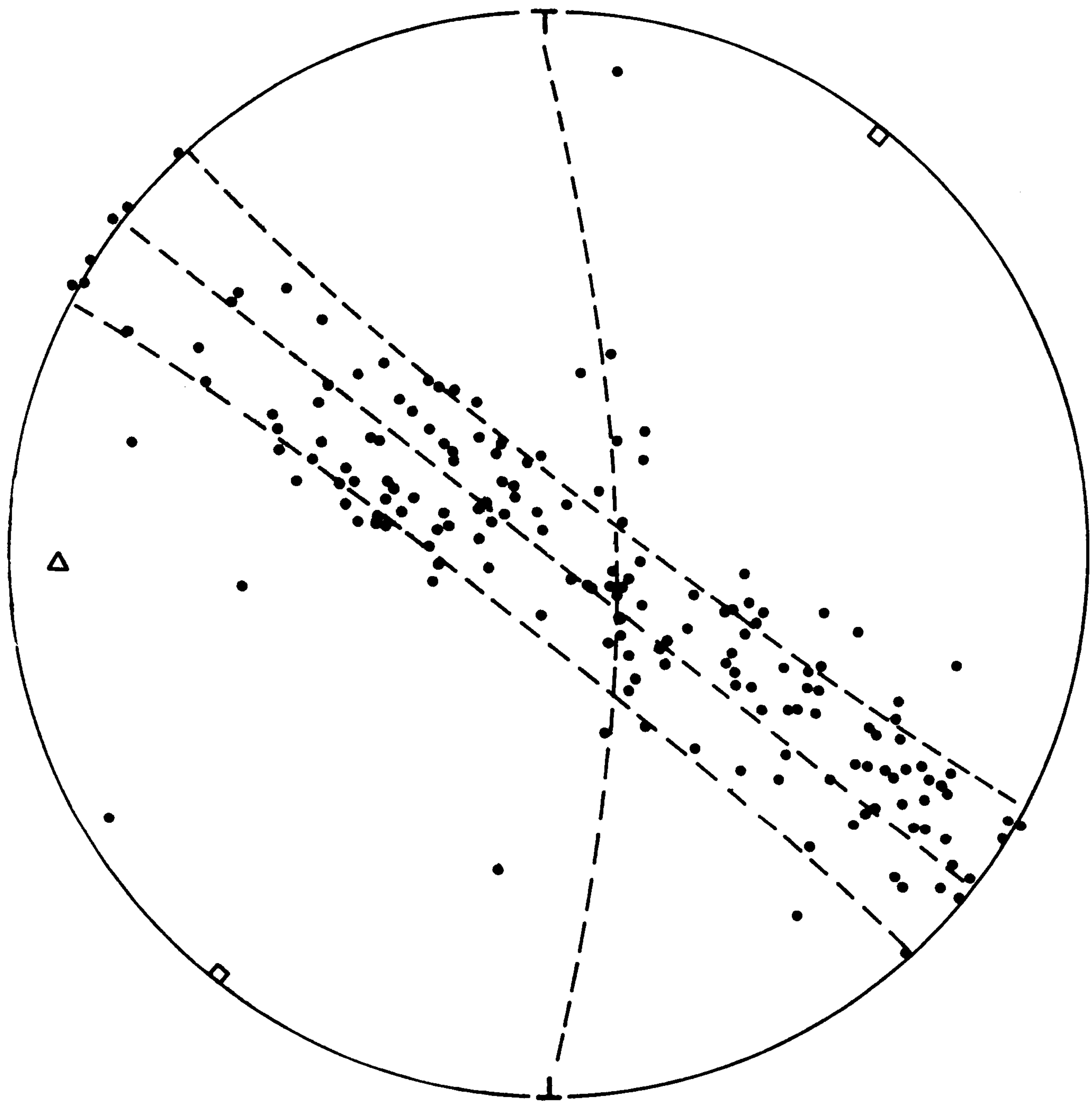
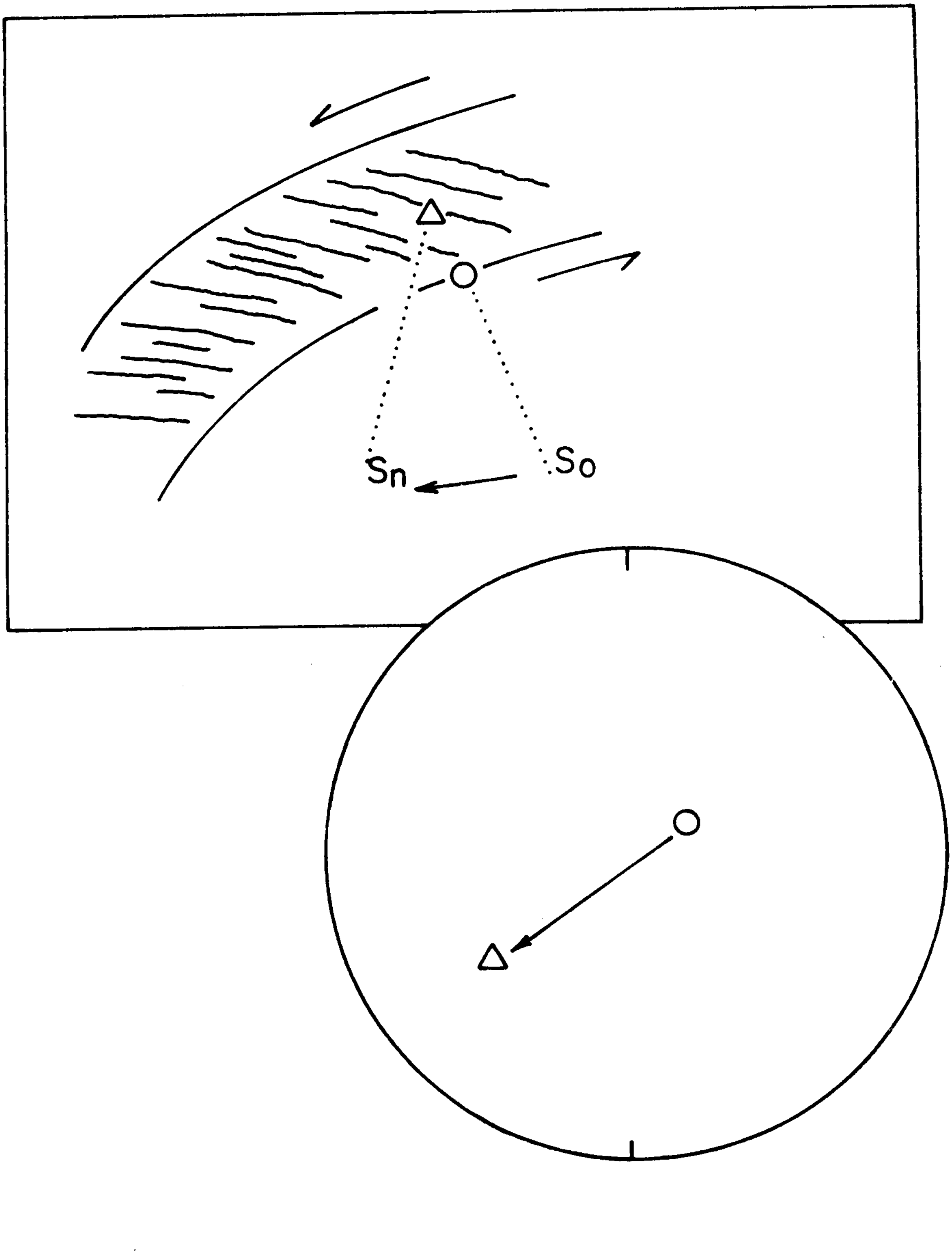


Figure 1c.

Summary Diagram
Bedding Orientation
Warm Springs Anticline
Areas I, II, III





METHOD OF SENSE DETERMINATION

Figure 2.

2) The abrupt termination and deflection of the 030 trending anticline, by the 050 anticline south of New Castle, Virginia.

On a larger scale, the Roanoke recess marks the intersection between the 38th Parallel structural lineament and the folded Appalachians. The nature of this lineament has been described by Dennison and Johnson (1971) among others, as a zone in which both igneous and tectonic activity occurred from the Precambrian through Eocene. The origin and significance of continental lineaments is poorly understood, but they are generally considered to reflect some sort of fundamental crustal structure (Hills, 1963, p. 457-464).

METHODS

Stratigraphic Boundaries

The stratigraphic boundaries of this report are largely those used by Sears (see Costain, 1975). The only contacts actually established during field work were those of the Tuscarora quartzite on Little Mountain and the extension of the Beekmantown Dolomite north to Healing Springs. One nomenclature change has been made, the unit mapped by Sears as the Lincolnshire formation is designated "undifferentiated Ordovician Limestones." This unit includes, in Kays (1956) terminology, the Lincolnshire formation, the Bolarian series and the Eggleston and Moccasin formations.

Since there is neither good exposure nor sharp lithologic contrast between the Eggleston and the Martinsburg formations, the contact between the two is approximate at best. The same comment applies to the Juniata-Martinsburg contact which is also gradational.

Structural Measurements

All structural measurements were made using a Brunton compass attached to a mechanical device, developed by Geiser, which enables the attitude of surfaces as small as $1cm^2$ to be measured. The device is essentially a two axis universal stage which permits as many as three directional parameters (strike and dip of a surface, and rake of a line contained in that surface) to be measured by leveling the compass.

FOLDS OF BEDDING

First Order Fold

It is difficult to establish a regular wavelength in this part of the Appalachians. Possibly this may be due to the structural transition which occurs in this region, which if nothing else, produces a highly complex map pattern. Measurements using the next structure to the west, gives the Warm Springs anticline a wavelength of about 6 miles.

In profile, the fold is asymmetric with a steep western limb whose average dip appears to be on the order of 50°. A more accurate figure cannot be given as the true dip of the units on the western limb can only be determined from enveloping surfaces constructed from accurately drawn cross sections. Dips measured in the field cannot be directly used to infer the attitude of the 1st order structure as the anticline contains many higher order folds, particularly along the western margin, which can result in deceptive readings. The reason for this can be readily seen in figure 3, showing the effect of kinking, whereby measurements obtained at the surface cannot be generalized to any depth.

The general geometry of the fold as deduced from cross sections and general outcrop pattern, indicates a broad open fold, without the large scale, abrupt limb dip changes which characterize 1st order folds in Pennsylvania and Maryland which have the geometry of large scale kinks.

The anticline has been divided into three regions. Poles to bedding from southern and central regions (Area I) have been plotted and the data presented in figure 1a. An estimate of the plane of best fit gives a vertical great circle whose pole (the fold axis) is 039. The second such diagram (Figure 1b) from the northern end of the structure defines a fold axis at 15/032. A third fold axis deduced from the southern end of the anticline (Figure 1c) is at 10/210. These three axes define an axial plane at 034/82.

An interesting feature is shown in figure 1a. This figure shows an apparently anomalous set of poles which suggest an axis of east-west folding. Admittedly the data supporting this suggestion is not strong, however, the data does aquire significance in the light of other structures which indicates similar kinematics.

2nd Order Folds

Second order folds can be found only by mapping and deduction from cross section. This fold set has wavelengths on the order of 1000' with amplitudes on the order of 80'. In profile they are similar to that of the 1st order structure, with broad open forms. No further analysis of these folds has been made.

Kink Bands

The western limb of the Warm Springs anticline contains a number of unusual folds which have a kink geometry. These structures achieve their most striking expression in the apparent periodic offset of ridges along Little Mountain. The offsets result from the interaction between topography and the sudden dip reversals due to kinking, not to faulting. No evidence of similar structures were found on the eastern limb of the anticline which forms Warm Springs Mountain.

The geometry of kink folds has been described by Faill (1973), the nomenclature used herein is from this paper, while the method used to deduce the attitude of the kink plane is also derived from this work. The reasoning and method used follows from the informatiom available which includes: 1) the change of attitude in bedding as a kink axis is crossed; 2) the trace of the kink band as seen in outcrop pattern. As it is known that both the kink axis and the trace of the kink band must lie in the kink plane, locating these two lines defines the plane. The kink axis is obtained from the intersection of the bedding attitudes on either side of the axis. In practice, this is relatively easy to spot as the bedding dip changes are significant and occur in a short distance. The trace of the kink band is obtained from the field map (plate I). The outcrop pattern of the Tuscarora quartzite was used exclusively to determine the trace, as the unit is easily traceable and its upper and lower contacts are readily found. The two lines deduced in this manner are plotted on an equal area net to solve the plane.

The six kink planes found in this manner are shown in figure 4. The planes have generally shallow dips ($\leq 10^{\circ}$). The relationship between the topography and the kink bands is shown in the reconstruction of the prominent offset of the Tuscarora formation on Little Mountain west of Valley View (Figure 3).

Two interpretations are possible in this reconstruction, both involve kinking about a sub-horizontal kink axis plus a clockwise rotation about a second axis approximately normal to the kink plane (Figure 3). Most,

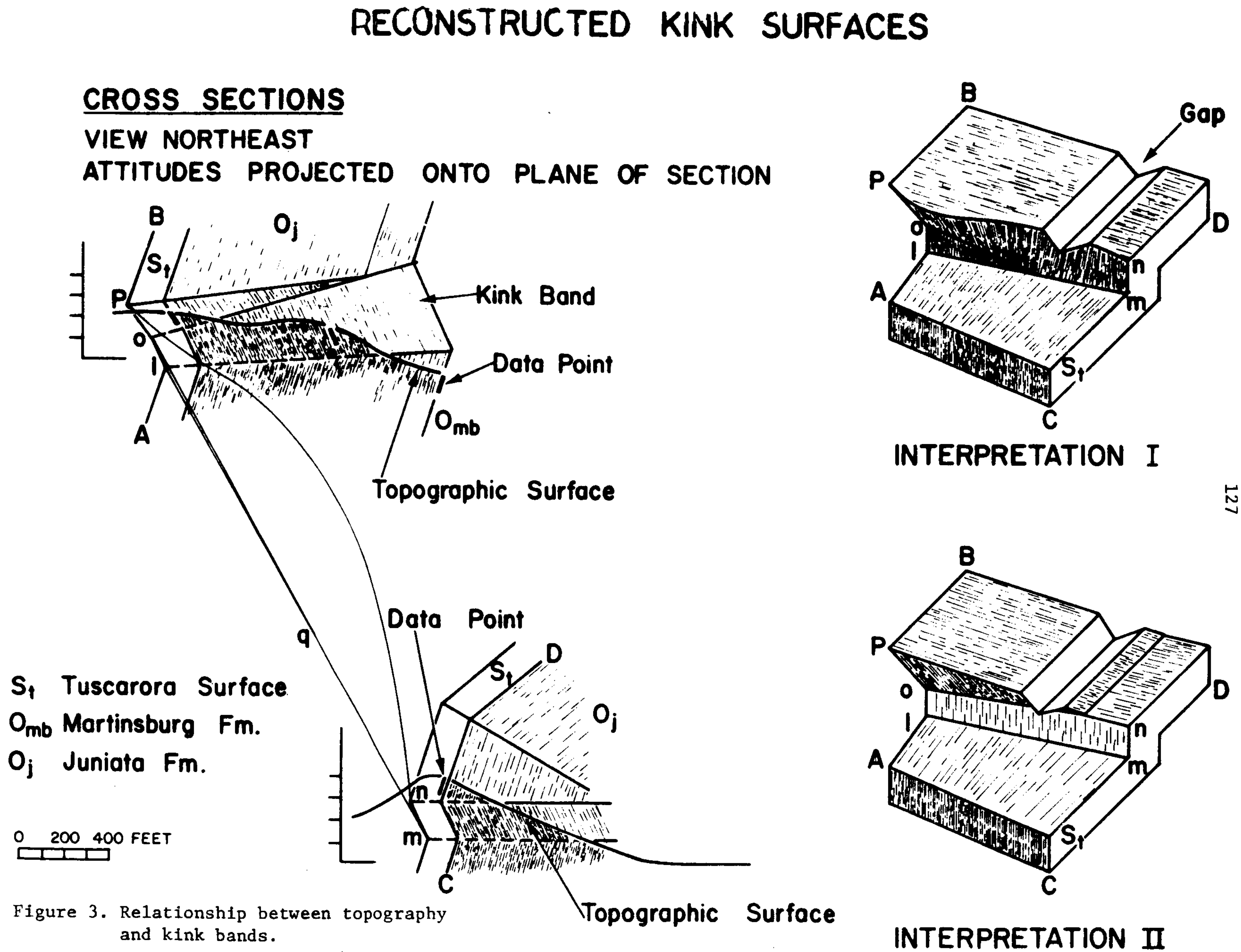
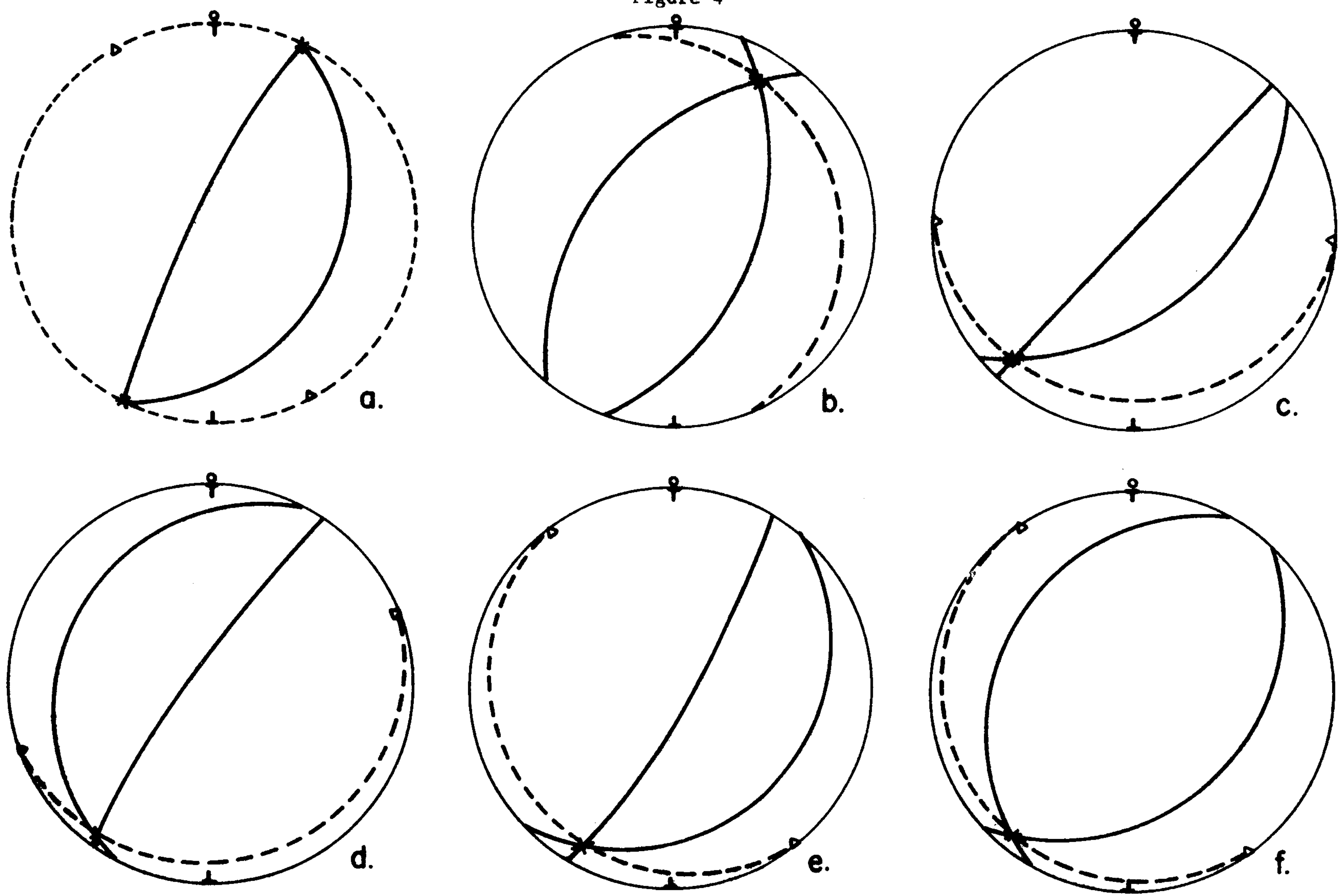


Figure 3. Relationship between topography and kink bands.

KINK BANDS

West Limb Warm Springs Anticline - Warm Springs, Va.

Figure 4



✱ — KINK AXIS   △ — KINK BAND TRACE   ---- KINK PLANE but not all the kinks are believed to have the geometry of interpretation II. An example of a kink which seems to closely follow interpretation I is found on the ridge north of Chimmney Run Gap (Plate I). In this case the bedding is seen to gradually become more overtuned as elevation is gained to the north out of the gap. Thus the panel of beds lying in the kink band (labeled lmno) appears to have been "twisted" about the steeply dipping axis normal to the kink plane. The second interpretation results from the same kinematics but in this case all surfaces have remained plane.

Figure 5 is a photograph of a kink band in the Brailler shale, west limb of the Warm Springs Anticline.

A final point of interest is the relationship between the kink bands and water gaps. It was empirically observed that, with the exception of Warm Springs Gap, each gap was located in an area which had been kinked. Thus, in ascending either to the north or south out of a gap, a kink plane is encountered. This relationship suggests that the gaps are structurally controlled and that the process involved in kinking produced an increased susceptibility to erosion. Some evidence for this is found in the presence of massive solution - collapse breccias along U.S. Route 220 at the mouths of both Healing Springs and Warm Springs gaps.

CLEAVAGE

Introduction

A prominent cleavage, expressed by concentrations of clay minerals and/or organic residues, is developed in a number of units in the Warm Spring anticline (see Table 1). The Lurich and the undifferentiated Ordovician Limestones have the best cleavage development. Cleavage was found at every exposure of the Martinsburg formation; however, the generally poor

Figure 5. Kink band in Brallier Shale, west limb of Warm Springs anticline, View, looking north from west bank of Jackson River.

TABLE 1

Geometric Data for Solution Cleavage
in the
Warm Springs Anticline, Virginia

Unit	Sp So	Spacing/ft.
Oj	+86	-
Omb	+55	-
Ola	+46	5/ft.
Olu	+83	16/ft.
Olu	+77	12
Olu	+58	24
Ou	-80	12
Ou	-73	12
Ou	+76	14
Ou	+74, +80, -70	14
Ou	+78	6
Ou	-80	4
u	+76	-
Ou	+74	14
Ou	-71	18
Ou	-87	22
Oj	+88	15
Ou	+68	6
Ou	+10	-
Omb	+90	-
Omb	-56	10
Ou	+45	9
Ou	+76	8
Srh	-75	-
Olu	+73	14
Ou	-78	12
Olu	+89	21/ft.
Olu	-76, -86	7/ft.
Olu	+68, +84	11, 9

Table 1, continued

Unit	Sp So	Spacing/ft.
Ou	-84	-
Ou	-70	10
Olu	+88, +70?, +82	25, 32, 41
Contact Ou-omb	-21, -9, -60	46
Omb	-16	-
Omb	-30	12
Olu	-87	8
Olu	+74, -80	12
Olu	-90	16
Omb	+74	18/ft.
Ou	-40	40
Ou	-52	18
Olu	-60	12
Ou	+82	10
Ou	-80	12
Ou	+48	6
Ou	-85, -51	-
Ou	-87	6
Olu	-56	7
Olu	-28, -78	8, 5
Olu	+78	32
Olu	-78	4
Ou	-49	20/ft.
Olu	-55	18
Ou	+64, +18	-
Ou	+84	-
Ou	-26	-
Ou	+81	-
Ou	-64	16
	+62	

Table 1, continued

Mean bedding (So) - Cleavage (Sp) angle = -87°

s = 31°

Mean Cleavage Frequency = 14.8/ft.

s = 9.7

Srh = Rose Hill Formation

Oj = Jiniata Formation

Omb = Martinsburg Formation

Ou = Undifferentiated Ordovician Limestones

Olu = Lurich Formation

exposure of this unit precludes any definitive statement on its cleavage development. Sporadic cleavage development in the more argillaceous lithologies of the Juniata and Rosehill formations was also found. The cleavage frequency as well as two geometric properties of the cleavage were determined. The geometric properties found are the dihedral angle between bedding and cleavage, and the cleavage "sense." These data are given in table 1. A histogram (Figure 6) of the bedding-cleavage angle and sense has been constructed from this data in the table. The mean angle between bedding and cleavage is -87° and the mean cleavage frequency is 15/foot. The standard deviation of the bedding cleavage angle is large, which is atypical of this parameter as determined in other areas (Geiser 1974a, 1976 ms). The significance of the large standard deviation is not understood. In addition to the angular parameters, the poles to cleavage in the mapped area were plotted on an equal area net (Figure 7). The poles form a partial girdle whose pole coincides with that of the 1st order anticline. The two maxima may simply be an artifact of several effects. These effects are: 1) the asymmetric shape of the Warm Springs anticline; 2) the lack of recognizable cleavage in the steeply dipping Tuscarora and Jiniata formations; 3) the possibility that some cleavage has been misidentified as jointing.

Cleavage of the type found in the Warm Springs anticline has been recognized at a number of other localities in the Appalachian foreland of Maryland, Pennsylvania and New York (Geiser, 1970; Faill and Nickelsen, 1973; Groshong, 1971; Geiser, 1974; Groshong, 1975) as well as in other mountain belts such as the Appenines (Alvarez, Engelder and Lowrie, 1976) and the Canadian Rockies (Geiser, 1976 ms).

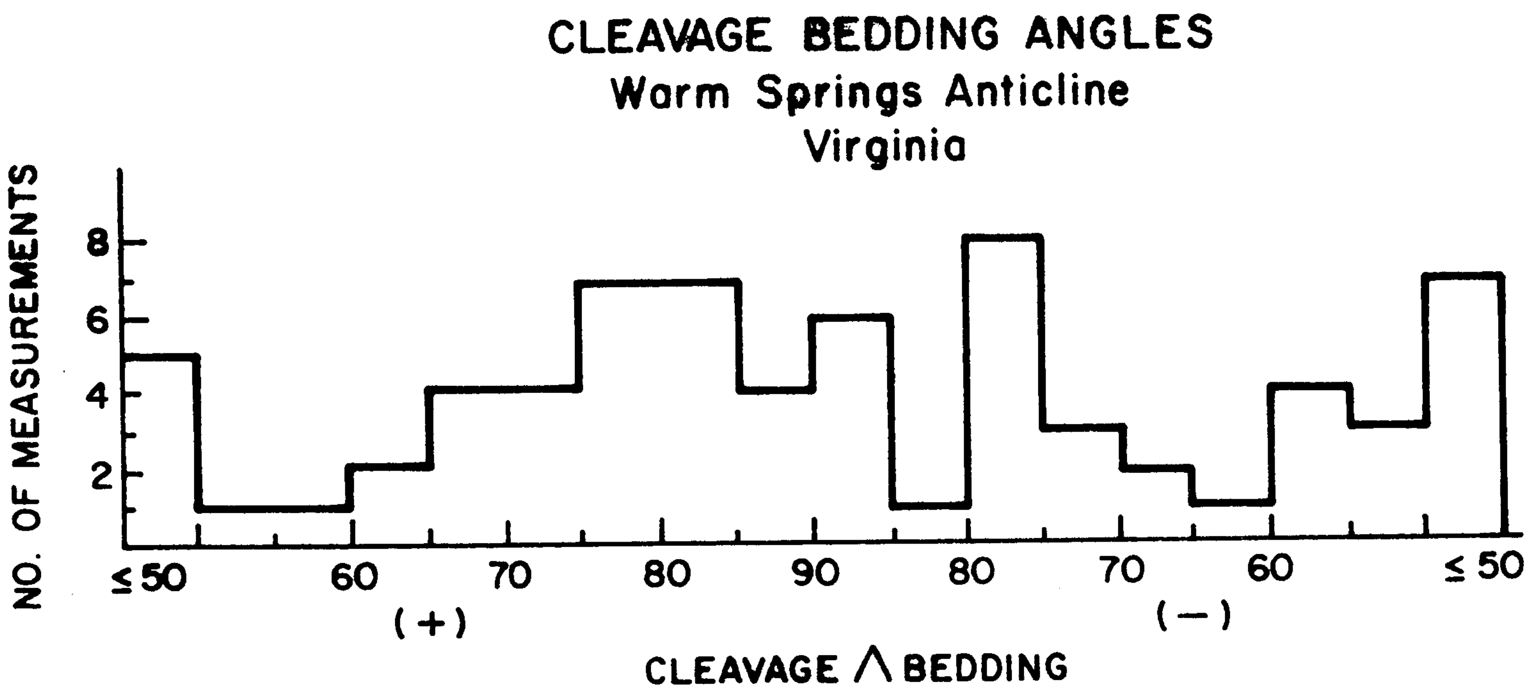


Figure 6. Histogram of bedding-cleavage angles, Warm Springs anticline (See table for data).

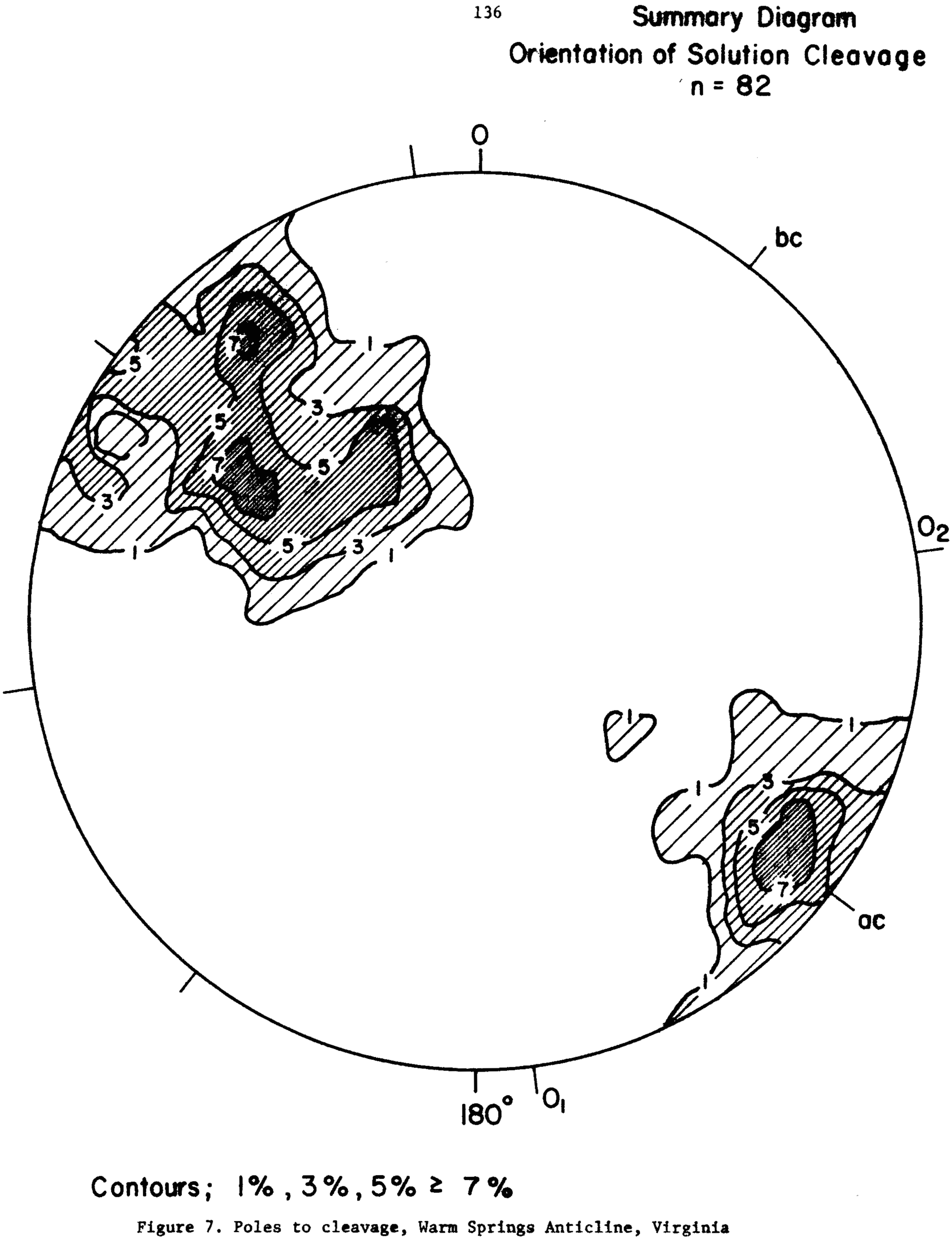


Figure 7. Poles to cleavage, Warm Springs Anticline, Virginia

Where it has been studied the cleavage is interpreted as a solutional phenomena of the early deformational history. Finite strain analysis by both Geiser (ibid.) and Groshong (ibid.) indicates that the cleavage initially forms parallel to the $\lambda_1 \lambda_2$ plane of finite strain under pure shear strain. Groshong (1975) finds evidence that the cleavage forms at low values of deviatoric stress (75-100 bars), while both Geiser (ibid.) and Groshong (ibid.) have independently shown that bulk strain outside the cleavage zones is less than 6%. Finally, preliminary investigations by Geiser of volume loss associated with the cleavage formation indicates values in excess of 10%, while Alverez, et. al. (1976), report evidence for layer parallel shortening of up to 25%.

The initial bedding-cleavage angle has been shown by the various workers, to be 90°. Departures from this value have been explained by two mechanisms: 1) angular shear strain accumulated during finite amplitude folding, rotating the cleavage from its initial relations (Geiser 1970, 1974b); 2) depth of formation of cleavage may control the initial attitude of σ_1 and thus the initial cleavage bedding angle such that it is less than 90° (Geiser, 1976 ms).

Lithologic Control of Cleavage

There is an apparent correlation between cleavage development and lithology. The most prominent cleavage development seems to occur in sedimentary rocks containing a high proportion of argillaceous and/or organic material (Faill and Nickelsen, 1973). However, it is not completely clear that cleavage does not develop in the more mature sedimentary rocks. Geiser (1970) has reported it from the Keefer sandstone, while Groshong (1976 personal comm.) claims evidence that structures interpreted as joints may in fact be cleavage. Evidence from the Warm Springs anticline (discussed in the section on jointing), seems to lend some support to this suggestion.

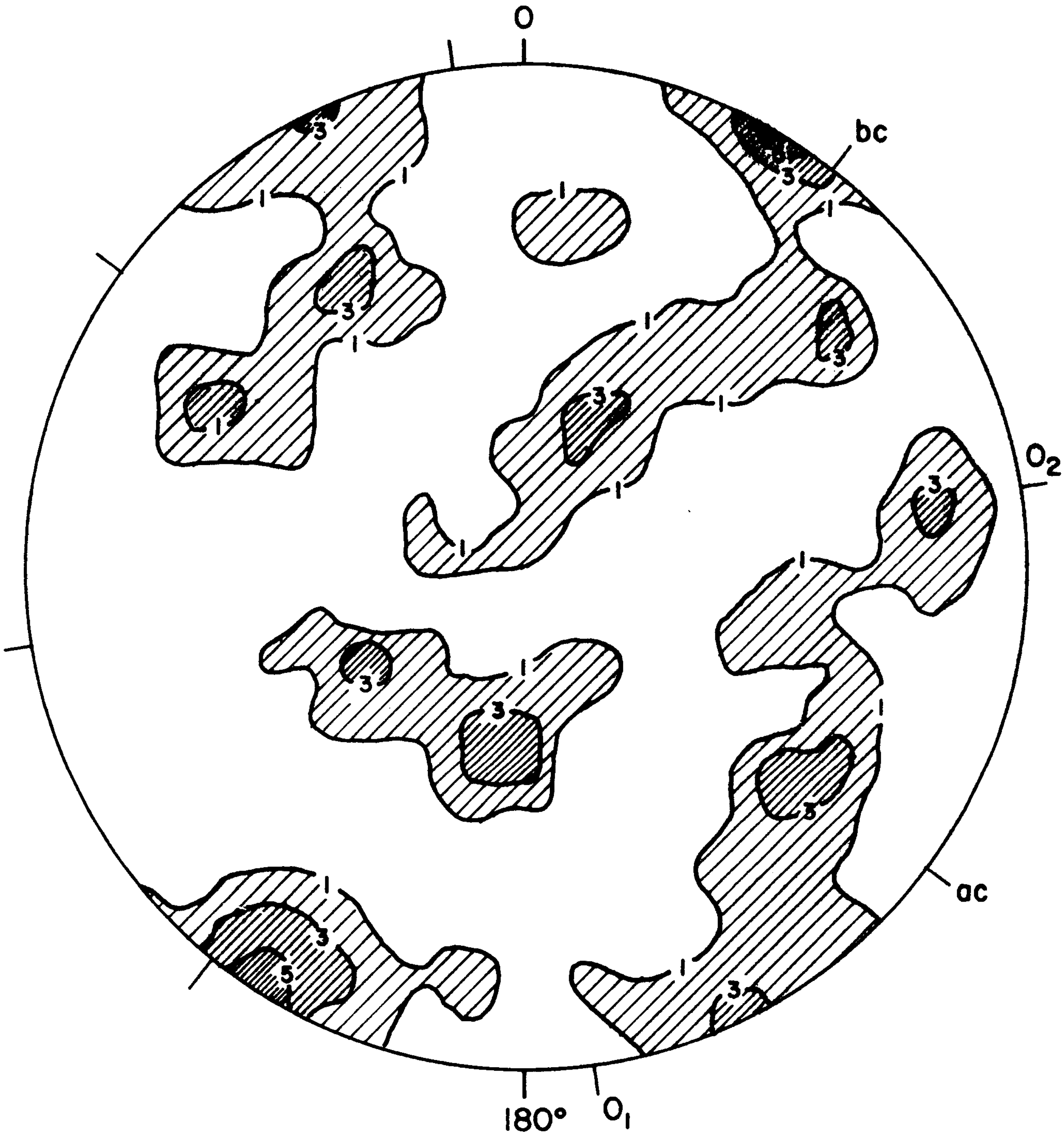
JOINTS

Systematic jointing (Price 1966, p. 111) is a pervasive structure throughout the Warm Springs anticline and was found in all units encountered except the Martinsburg where jointing is non-systematic. The joint data has been compiled into a series of contoured diagrams of poles to the joint surfaces (Figure 8). A summary of the data from these diagrams is given in table 2.

The joint data has been referenced to the tectonic directions obtained from the bedding poles of the 1st order structure (Figure 1a). This reference system was chosen as well defined relations have been empirically observed between the joint sets and the tectonic directions, (Price 1966, p. 113). Following this observation, joint sets are commonly referred to as ac joints (parallel to the ac direction), bc joints (parallel to the bc direction) and oblique joints which are at 45° to both the ac and bc directions. These tectonic directions have been indicated on each joint diagram as well as the bedding pole diagram.

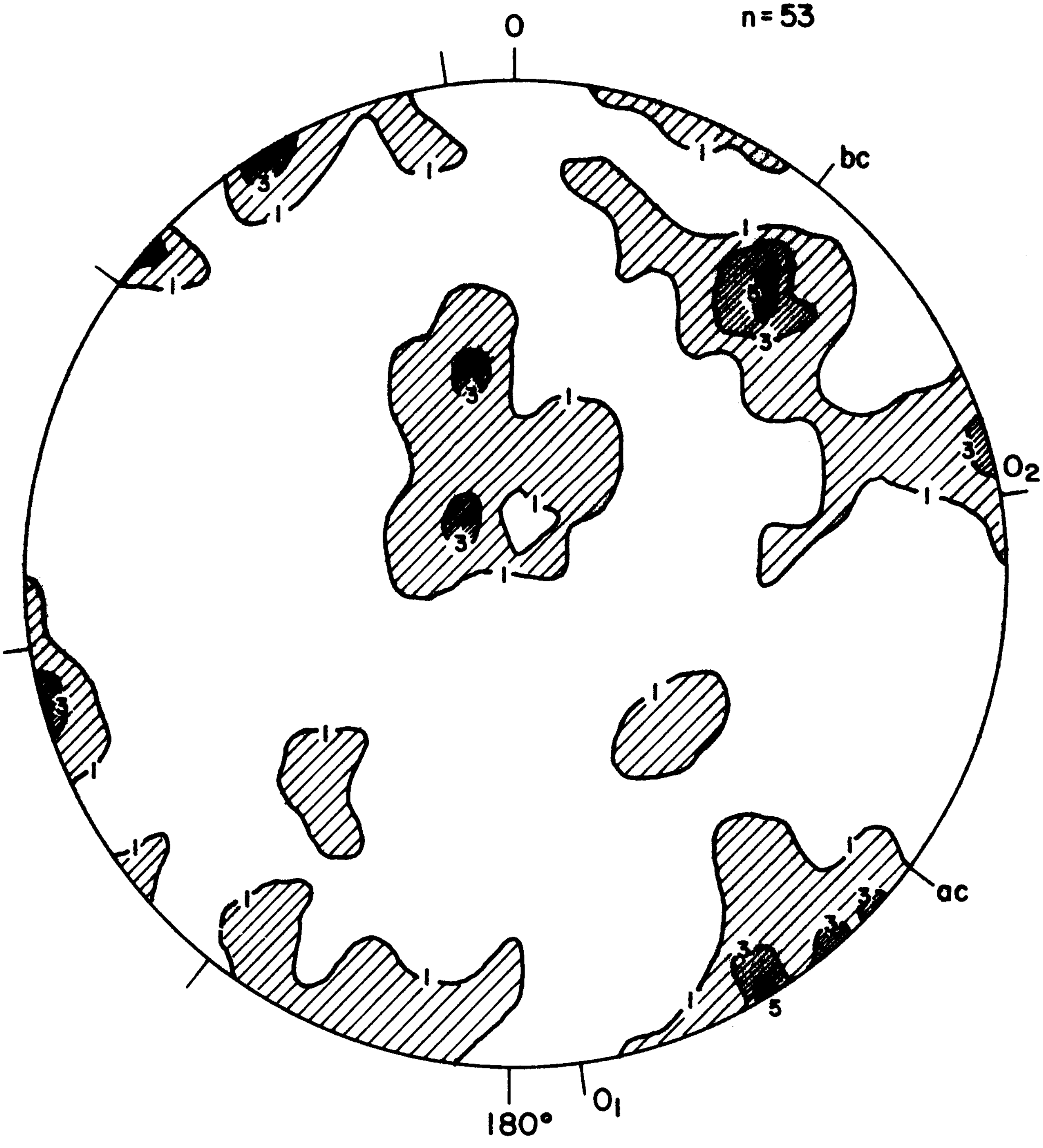
The data compiled from the diagrams in table 2, indicate that although there is some variability from unit to unit, the ac joints are the dominant set with bc joints the next most common. Both sets of oblique joints are also found but apparently do not occur together in the same unit. The only joint set which cannot be directly related to the tectonic directions is the 060-067 set.

Figure 8a. **Summary Diagram Orientation of Joints in Tuscarora Fm. n= 72**



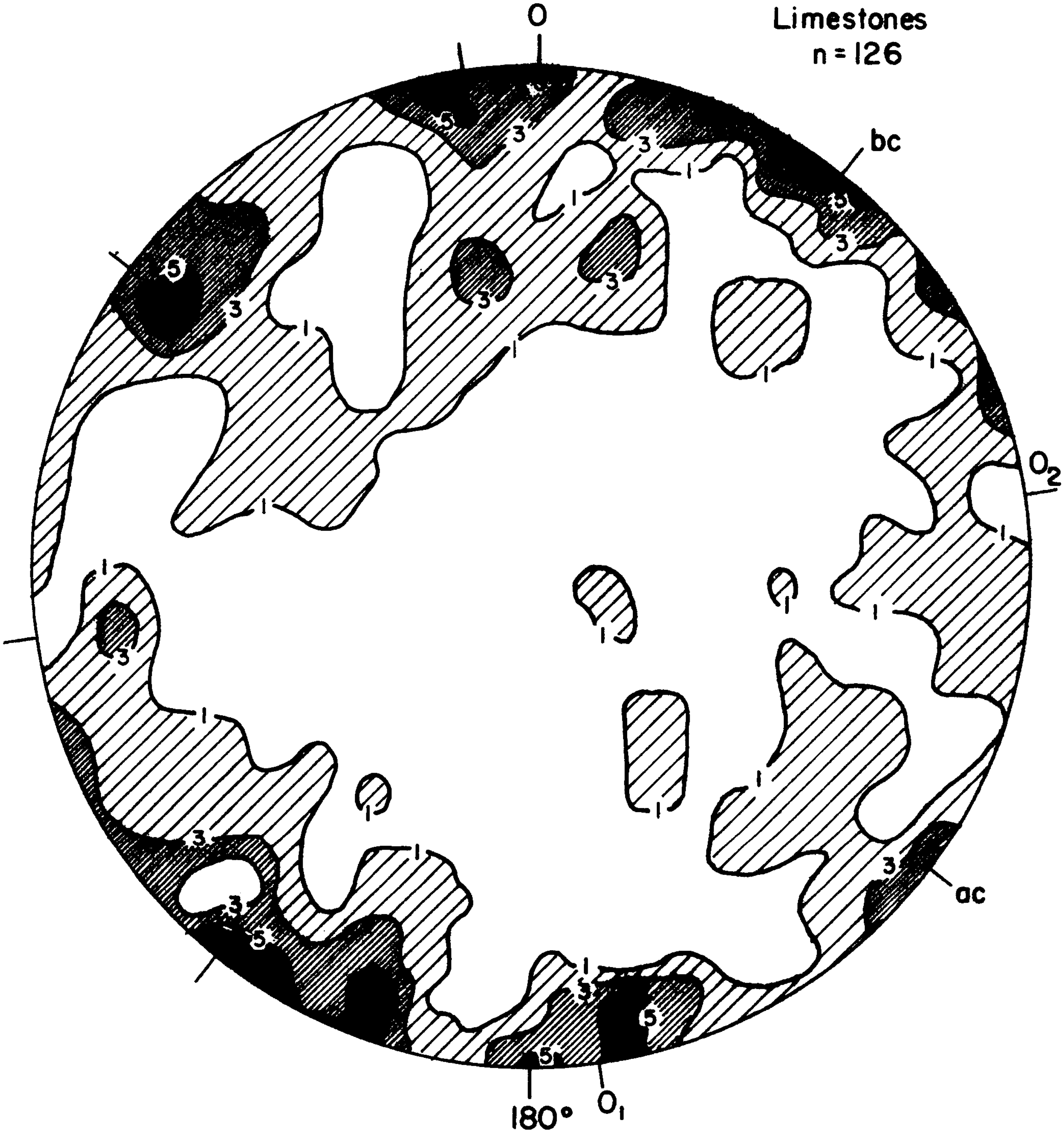
Contours; 1%, 3%, 5%

Figure 8b. **Summary Diagram Orientation of Joints in Juniata Fm. n=53**



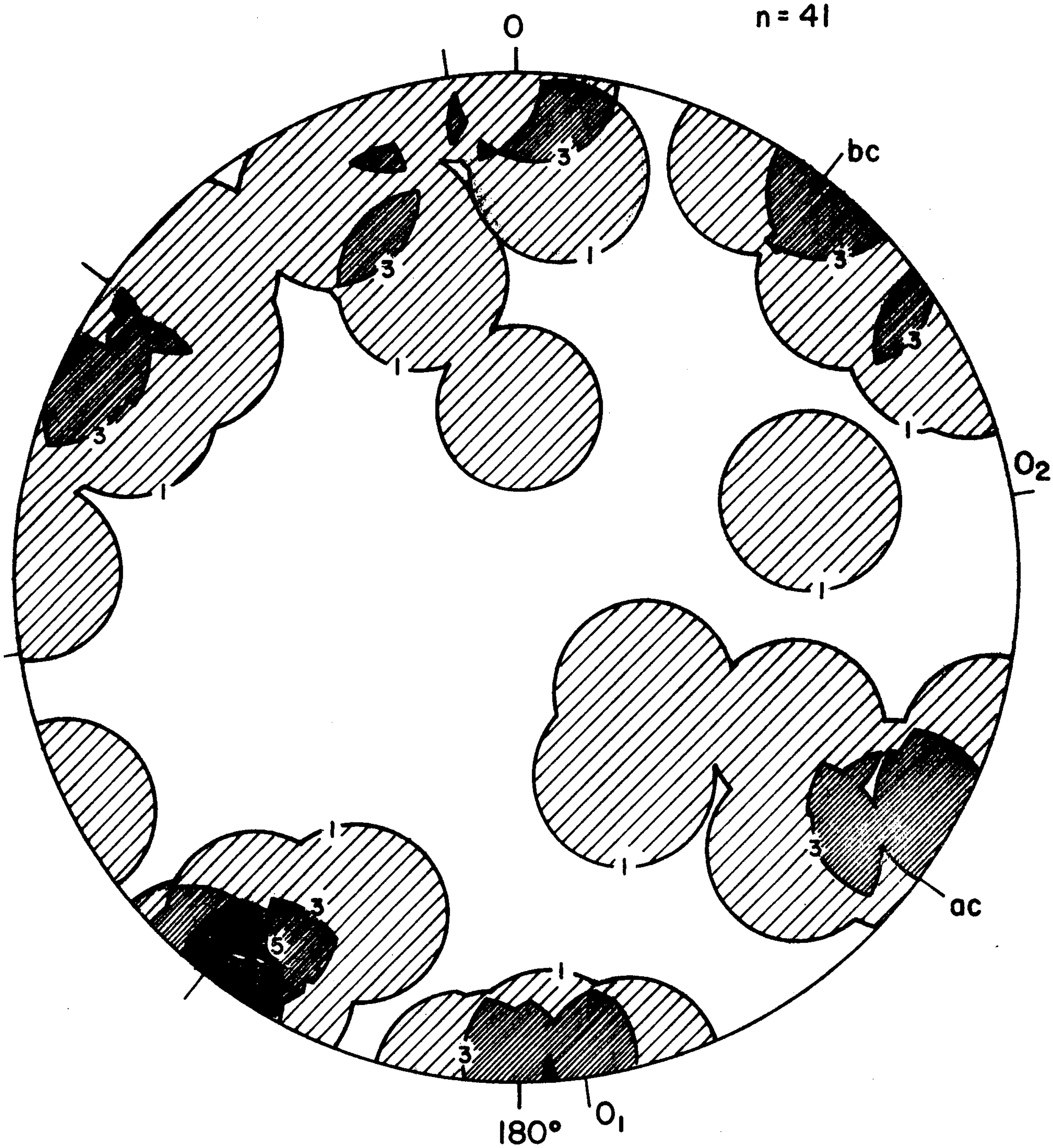
Contours; 1%, 3%, ≥ 5%

Figure 8c. Summary Diagram Orientation of Joints in Undifferentiated Ordovician Limestones n = 126



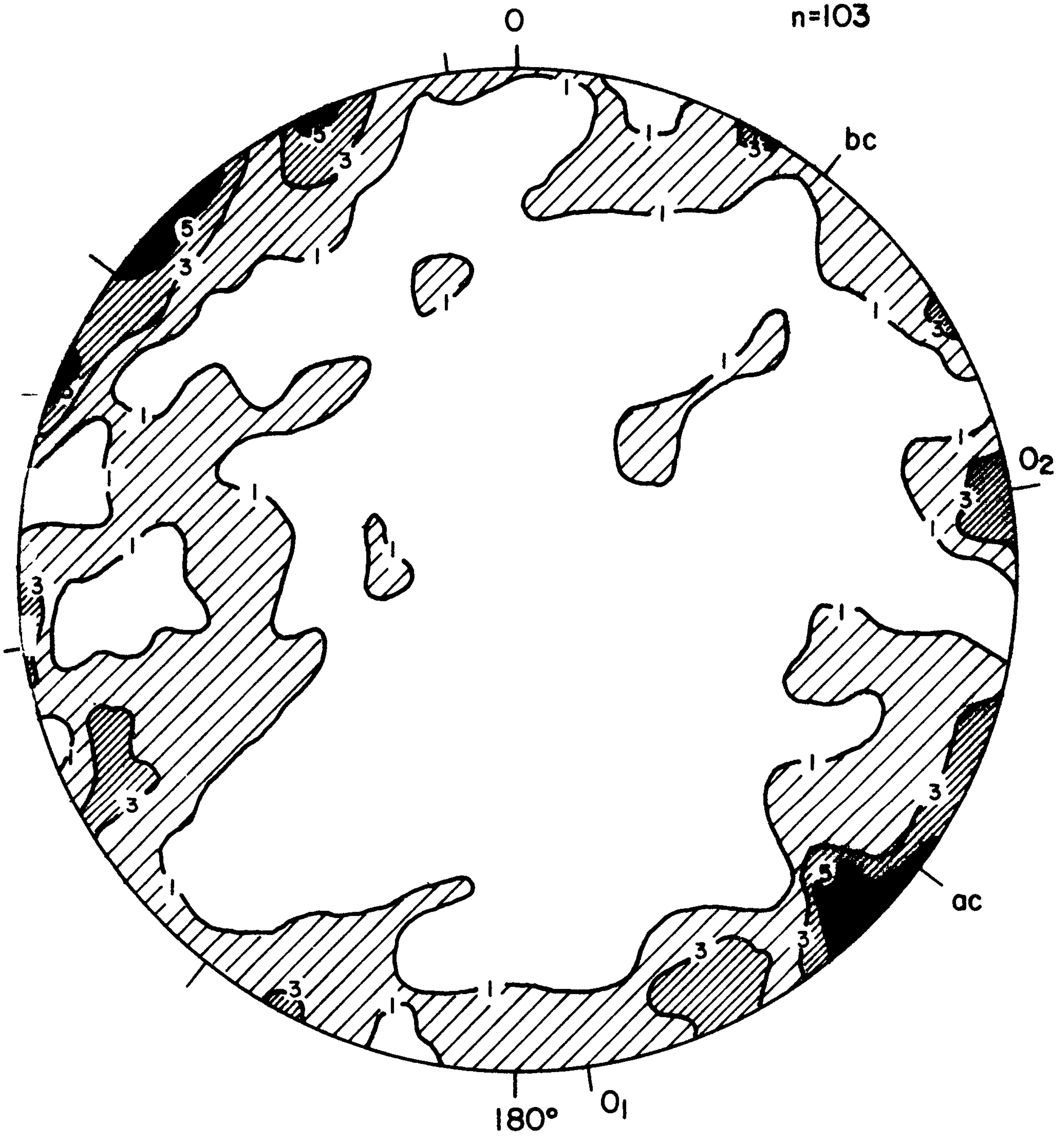
Contours; 1%, 3%, ≥ 5%

Figure 8d. Summary Diagram Orientation of Joints in Beekmantown Fm. n = 41



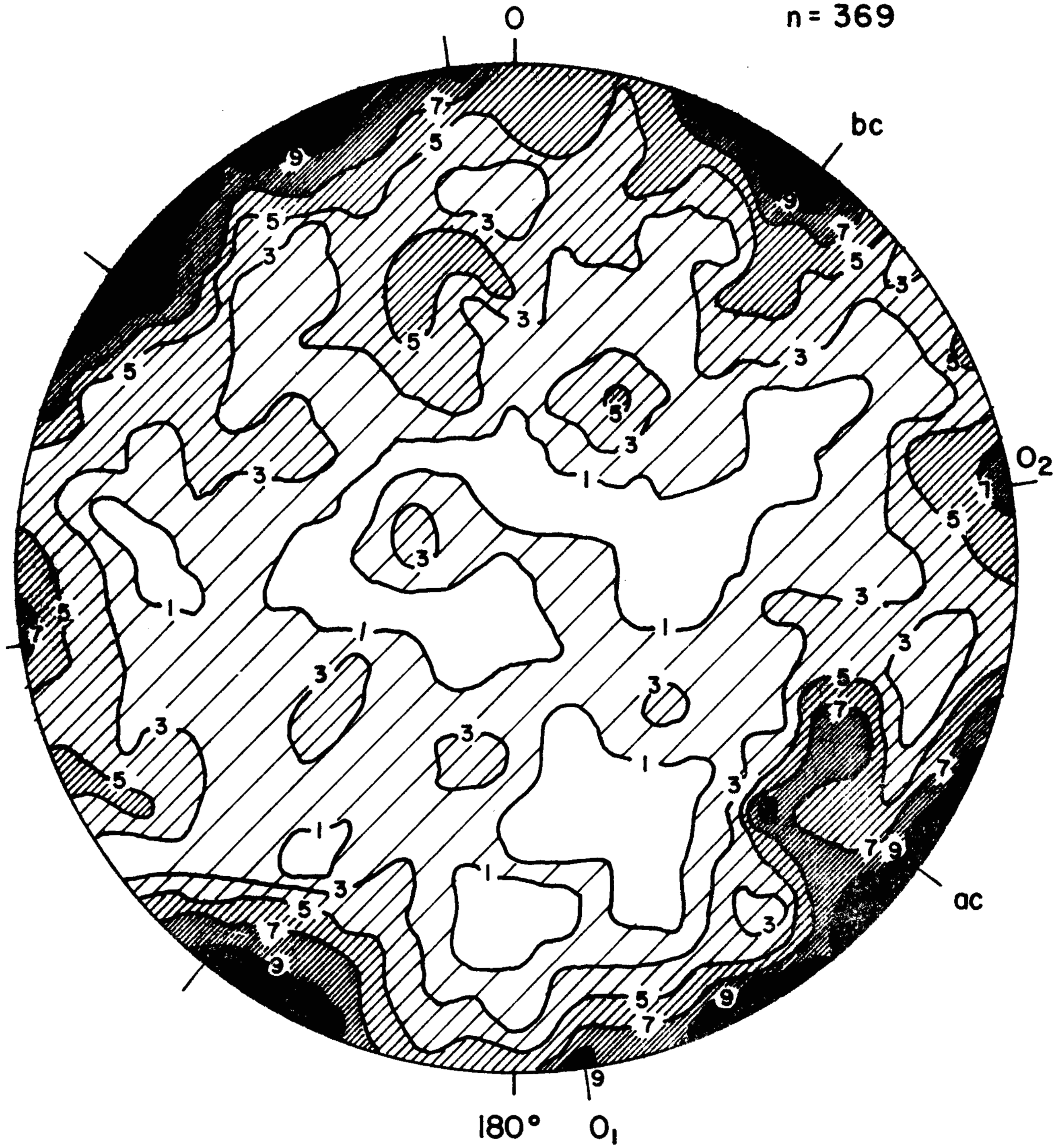
Contours; 1,3,5, Circle Overlap

Figure 8e. **Summary Diagram**
Orientation of Joints in
Lurich Fm.
n=103



Contours; 1%, 3%, 5%

Figure 8f. Summary Diagram
Orientation of all Joints Measured
Warm Springs Anticline
n = 369



Contours; 1%, 3%, 5%

TABLE 2

Summary of Joint Data

Diagram	Orientation of Surface Normal to Pole Maxima			n
	1st maxima	2nd maxima	3rd maxima	
Tuscarora Fm.	302	064		72
Juniata Fm.	68 322, 060			53
Undifferentiated Ordovician Limestones	304	085	039	126
Lurich Fm.	047	065	352	103
Beekmantown Dol.	309	029	086	91
Joints with Frequency of 1/ft.	322, 009, 067			235
Joints with Frequency of 1/ft.	322	348	028, 084	134
Extension Joints	69 037			44
All Joints	038, 323	063	350, 082	369
Tectonic Directions	b = 039, ac = 309, oblique Jts. 354, 084			

Joints with a Frequency of Greater than 1/foot

Joint sets with the best development in terms of frequency (Figure 9a) seem to be equally distributed between the ac set and the 060-067 set. However, when the joints are plotted on a diagram correlating joint frequency with orientation, then it is apparent that the joint set with the highest frequency, is the bc. Thus the most common joints do not have the greatest joint frequency.

Another noteworthy feature is that these joints tend to form a weak girdle which coincides with that formed by the cleavage (Figure 7). If these girdles are superposed (compare Figures 9a and 7) then the field observation that development of jointing and cleavage seem to be mutually exclusive is supported, as the cleavage maxima along the girdle almost exactly corresponds with the joint minima.

The contoured diagram (Figure 10) correlating frequency with orientation, indicates that the direction with the highest frequency of joints per foot is about   with a secondary maxima at   . Poles to joints with the highest frequency form a weak girdle whose pole is   .

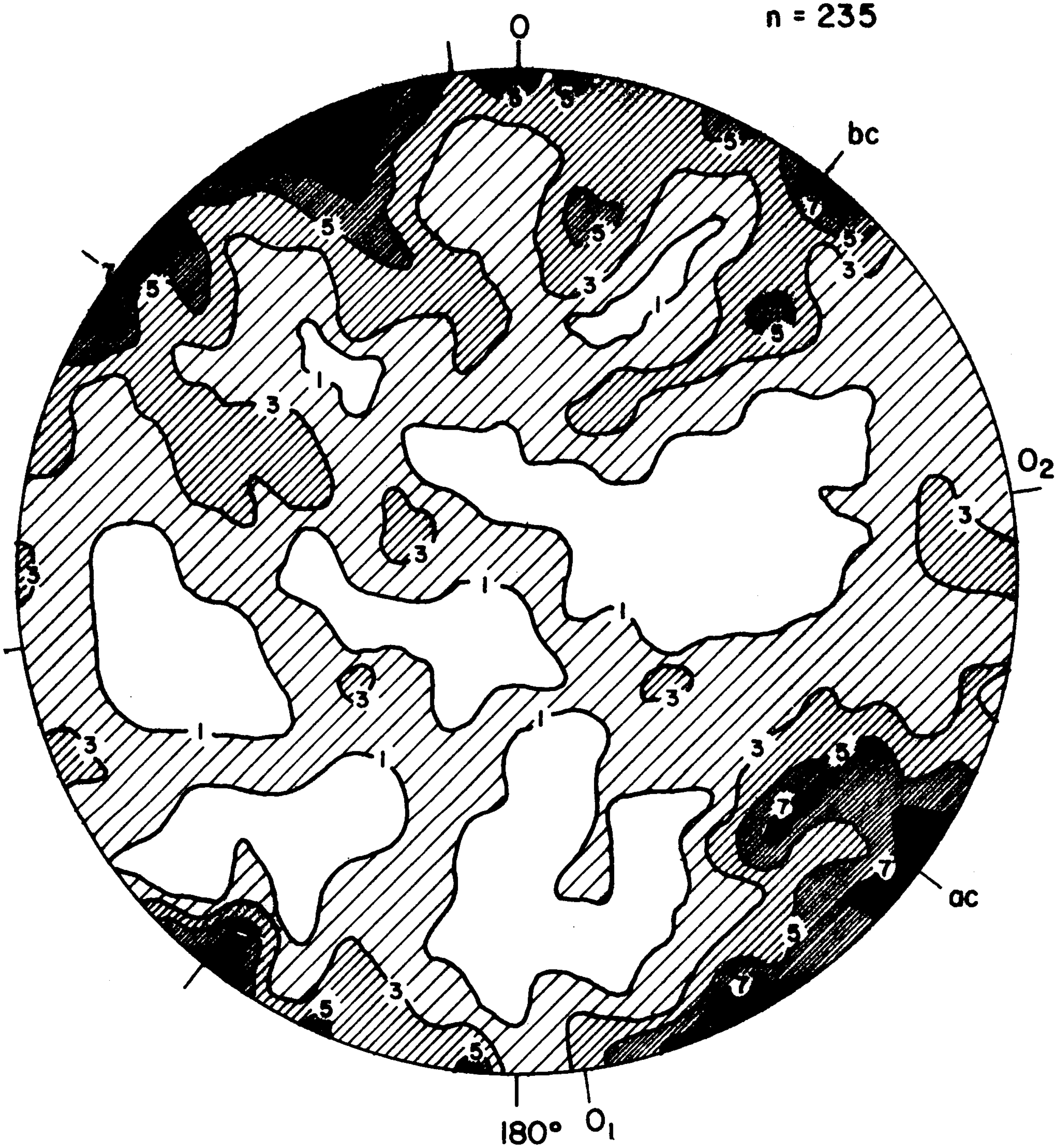
Joints with Spacing of Less than 1/foot

This joint set (Figure 9b) has a much more unequal distribution than that with the higher frequency as ac joints form a distinct maxima. The three other weakly developed maxima reflect the three remaining tectonic directions. The 060-067 joint set does not produce a significant maxima in this group of joints.

"Extension" Joints

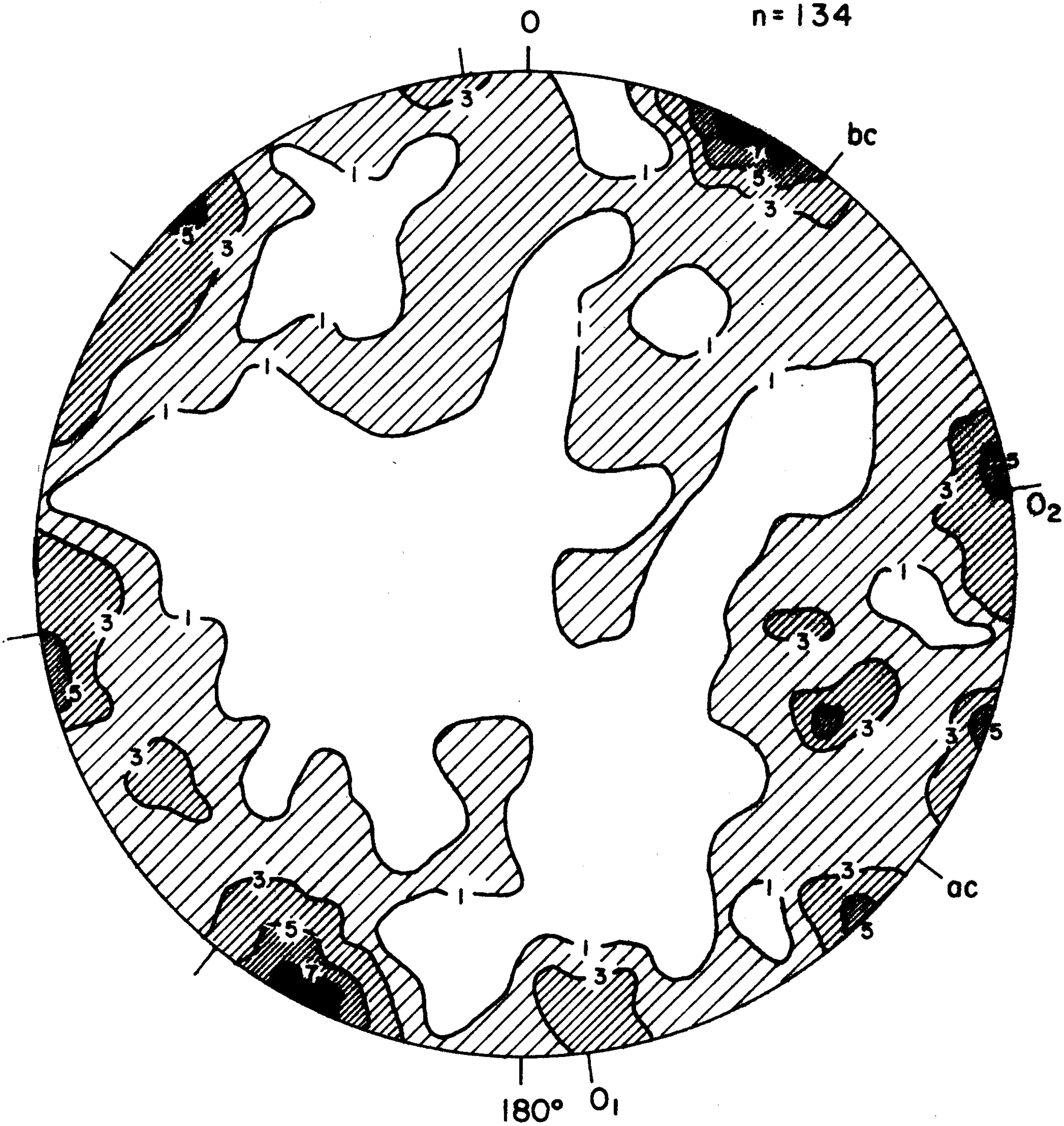
"Extension" joints were recognized by the presence of sparry or fibrous calcite as joint fill. This is not sufficient evidence to

Figure 9a. Summary Diagram
Orientation of Joints with
Spacing > 1/ft.
n = 235



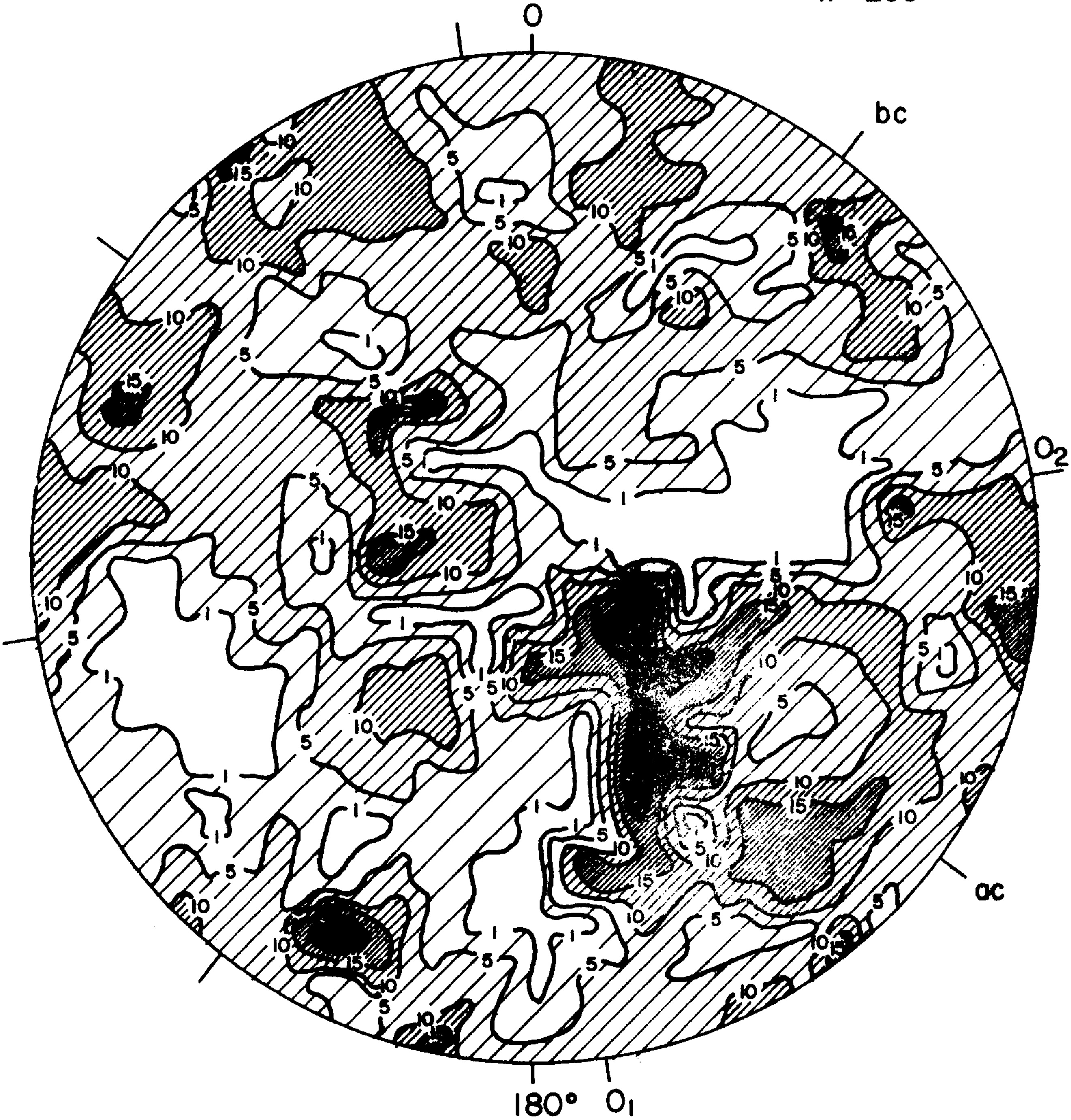
Contours ; 1%, 3%, 5% ≥ 7 %

Figure 9b. Summary Diagram Orientation of Joints with Spacing < 1/ft. n= 134



Contours; 1%, 3%, 5% ≥ 7%

Figure 10. Joints with Spacing > 1/ft.
Frequency
With Respect to Orientation
n = 235



Contours; 1/ft, 5/ft, 10/ft, 15ft, ≥ 20/ft categorically state that these joints are true extension joints; i.e. joints whose "total displacement is directed normal to the fracture surface" (Hobbs, Means and Williams, 1976, p. 296). The appearance of the calcite fill simply means that at some time in the history of the joint there was a significant displacement component normal to its surface.

Thr presence of two types of fill, fibrous and sparry, does suggest that some of the joints represent an instantaneous response to stress (sparry fill), while those with fibrous fill indicate response at the slower rates characteristic of diffusion flow laws (see Elliott, 1973; Durney and Ramsay, 1973). No attempt has been made to analyse these two types of joints separately. Poles to the "extension" joints, plotted and contoured by the Mellis method are shown in figure 11. This diagram shows a single maxima corresponding to a plane at . This plane includes the b tectonic direction and is one of the set defined by the cleavage girdle (Figure 7).

Joints - Discussion

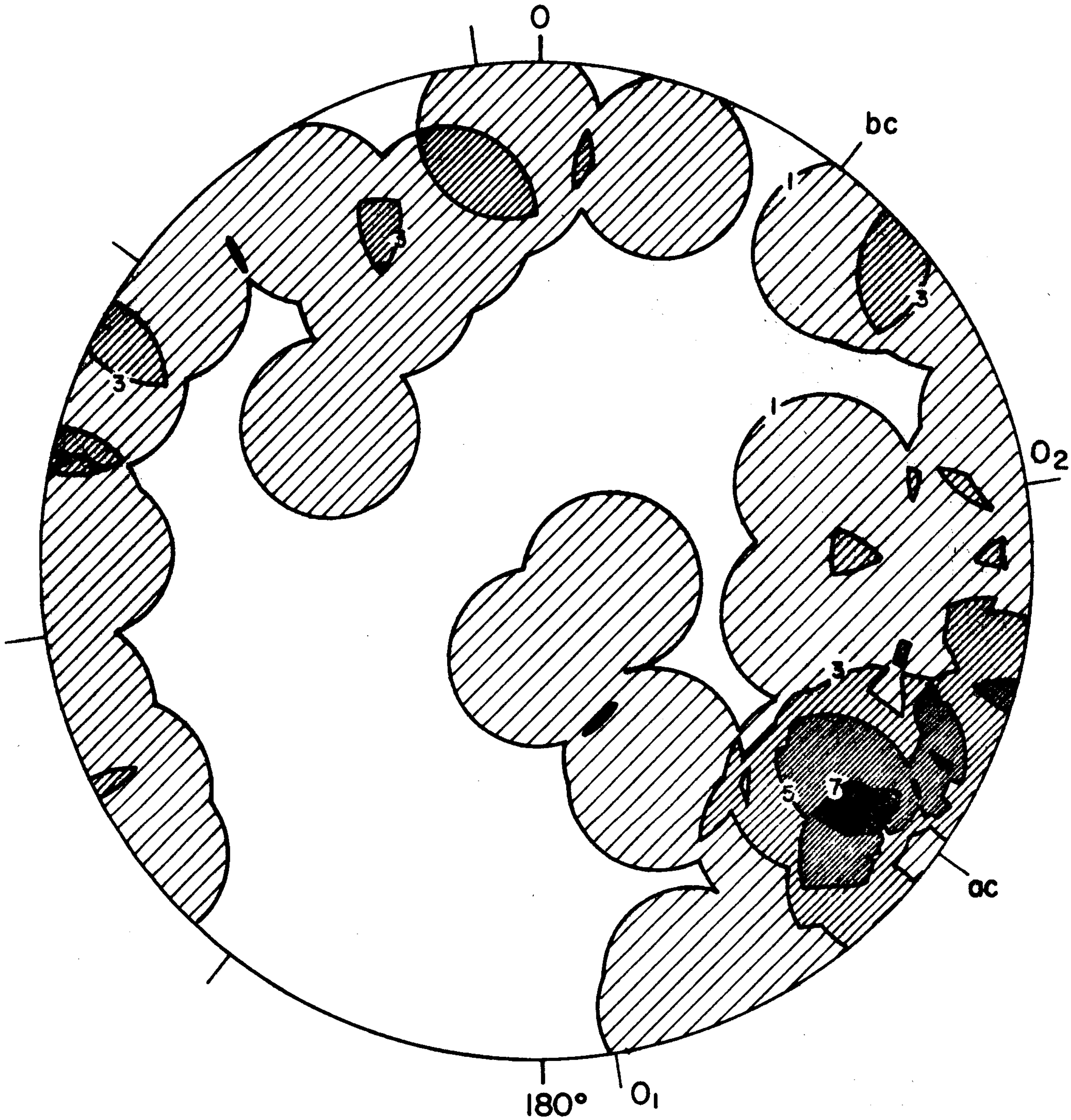
The following observations may be made of the data presented:

1) Ac joints are most common, but the set with the greatest joint frequency (joints/foot), form a girdle about the 052 direction.

2) There exists a joint set with strikes ranging from 060-067 which does not fit the tectonic directions defined by the first order structure. This set has been found in the Tuscarora quartzite, the Juniata formation and the undifferentiated Upper Ordovician Limestones.

3) Cleavage and systematic joint development appears to be almost mutually exclusive. Thus units with extensive cleavage, such as the Martinsburg shales, or even individual beds having cleavage within units

Figure 11. Summary Diagram
Orientation of Extension Joints
n = 44



Contours 1, 3, 5, ≥ 7 Circle Overlap

generally lacking cleavage, will lack systematic joints.

4) Two sets of extension joints are found with different strain histories. One set suggesting brittle failure (sparry fill) and a second set suggesting "creep" (fibrous fill). Pole diagrams for all joints have a single maxima in the "b" tectonic direction.

In general, the origin of joints is not well understood, other than that they represent some type of brittle failure and are empirically observed to have a symmetrical relationship to folds (e.g. Hobbs, Means and Williams, 1976, p. 294; Price, 1966, p. 114). Price (1966, p. 142-147) indicates that joint frequency is largely controlled by thickness and lithology. Price cites a number of studies to show that frequency is proportional to the thickness of the bed and will tend to be higher for rocks with relatively large Youngs moduli. Thus in order to accurately assess the factors controlling jointing, joint studies should be corrected for the effects of thickness and lithology. A detailed study of this type was considered to be beyond the scope of this report, although some effort was made in this direction by plotting the joints by formation.

With this proviso, some rather speculative conclusions are suggested by the joint data.

I. Jointing post-dates cleavage. This conclusion is suggested by the following:

a) Cleavage of the type found in the Warm Springs anticline is known to pre-date finite amplitude folding (Geiser, 1970, 1974; Groshong, 1971, 1975).

b) In the few places where cleavage and joints occur together, joints cut cleavage.

c) Due to the accumulation of insoluble residues along cleavage surfaces, the formation of the cleavage produces a layer anisotropy normal to bedding. The presence of such an anisotrophy would seem to provide a potential inhibition to the formation of structures transecting it.

II. Some of the structures identified as jointing may be cleavage. This is inferred from:

a) The coincidence between one of the principal joint sets and the cleavage girdle.

b) The joint set with the densest spacing coincides with the cleavage girdle.

c) The geometric problem of having significant bedding parallel shorteinin in a bed with cleavage, yet no evidence of shortening in immediately adjacent beds, supposedly lacking cleavage.

d) Groshong has reported (Groshong, R., 1976, personal comm.) evidence of insoluble residues on "joint" faces in the Tuscarora Formation.

III. The 060-067 joint set may be related to motion on faults with a left lateral component, transverse to the Warm Springs anticline. Motion on such a fault set would produce extensional effects in the sector in which the joint set lies. The 060-067 set, which cannot be correlated with any of the tectonic directions, would thus comprise a set of pinnate fractures associated with faulting (see Hobbs, Means and Williams, 1976, p. 294-296).

FAULTS

No positively identifiable faults were found. The only locality where bed displacement due to faulting appears as a strong probability is at Falling Springs Gap. Although no actual fault surface was observed here, the Tuscarora formation can be shown to have a left lateral displacement on the order of 35-50 feet over less than 100 yards.

STRUCTURE - DISCUSSION

The key to understanding the unique aspects of the Warm Springs structure are believed to be the kink bands developed in the western limb of the fold. Two separate histories for the kinking are considered possible; they may either represent early high mode folds, initiated as buckles and later modified to kinks (Johnson, 1970, p. 112-122; Geiser 1976 ms), or they are late superposed structures.

The possibility that they are early high mode folds has been tentatively rejected as, to date, the folds have only been found on the steep western limb. Beam theory (Johnson, 1970) indicates that the various fold modes should be evenly distributed along the buckling member and no restricted to a particular part.

With regard to the second hypothesis, that of superposition, the folds cannot be regarded as the simple result of a reactivated stress system coaxial with the first. Such a system would simply result in renewed growth of the first order structure. This condition would hold for any global layer parallel stress, except one which has a large deviatoric component directed subparallel to the fold axis. Such a system might superpose shorter wavelength folds on the first order structure. However, this solution does considerable violence to our existing knowledge of Appalachian deformation whose known history shows no evidence of such a stress system.

An alternative superposition solution which does not require such unwarranted assumptions, does exist. In this concept, the kinking is a response to deep seated movement on faults with a trend of about 090. The exact depth of the faults is not known, however, there seems a reasonable possibility that the faulting may be in the crystalline basement particularly if the deformation is related to activity along the 38th Parallel fracture zone. The features which suggest such a solution are:

1) The kinematics of this system could produce narrow zones of high stress with an orientation of close to that of the First order fold. This obviates the need to postulate a large scale system for which there is no other evidence.

2) The gaps in Little Mountain and zones of warm spring development form linears along 090. At least one of these linears, connecting Falling Springs (Spring No. 134, Reeves, 1932) Falling Springs Gap and Layton Springs (Spring No. 142, Reeves, 1932), extends beyond the Warm Springs anticline.

3) ERTS imagary (NASA ERTS E-1172-15312-501) shows a set of regionally developed linears parallel to the 090 trend.

Two different models of basement motion can be envisioned and are shown in figure 12. Both models would result in an external torsion being applied to the Warm Springs structure. It does not seem possible to determine, without additional study, whether the different kinematics of the models shown in figure 12 would result in different sets of structures. At the present, the left lateral strike slip motion is preferred, as such motion is suggested by the 060-067 joint set. This joint set, which does not fit any of the tectonic directions, can be interpreted as pinnate fractures arising from such a motion along an 090

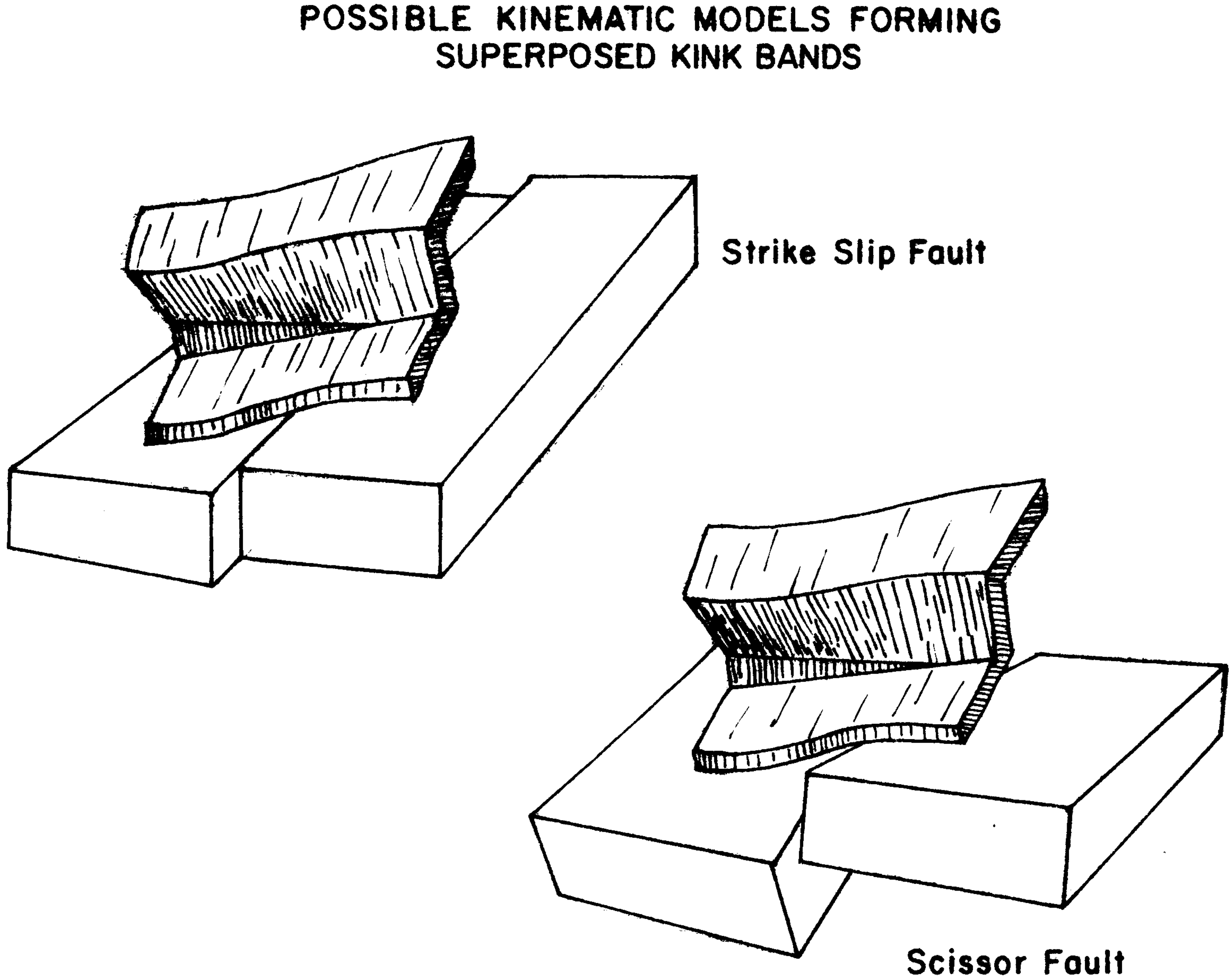


Figure 12. Models of basement motion producing transverse structures in Warm Springs Anticline.

trend. Left lateral motion also fits all the observed offsets of the Tuscarora Formation.

To summarize, the data presented herein, suggest the following general structural sequence.

I. Formation of spaced solution cleavage.

II. Finite amplitude folding, producing 1st and 2nd order folds and continuation of cleavage development.

III. Development of ac, bc and oblique joint sets.

IV. Left lateral basement motion, along an 090 trend producing kinking in the western limb of the 1st order fold and the 060-067 joint set.

The first three events are considered as part of the late Palezoic (Devonian - early Permian) deformation of the Appalachian foreland. At present, all that can be said with regard to the age of the last structural event is that it has a maximum possible age of middle Permian and a minimum age of Eocene or younger. In the later case the transverse strike slip faulting may be a part of the most recent activity along the 38th Parallel Fracture zone as reported by Dennison and Johnson (1971).

CONCLUSIONS - ORIGIN OF WARM SPRINGS, BATH CO., VIRGINIA

The purpose of this study was to aid in the evaluation of the proposed structural model (Costain, 1975) for the origin of the warm springs in the Warm Springs anticline. According to the model, water moves from topographically high regions downwards to a depth of about 3 km. The water is heated on the normal geothermal gradient and then moves westward along southeast dipping thrusts. The heated water is then postulated to rise rapidly along cross-faults in the northwest limb of the anticline.

Three structural features are required by the proposed model.

1) An extensive permeability in the cover rocks.

2) Southeastward dipping thrust faults.

3) Cross faults.

With regards to the existence of these features, the findings of this study are as follows:

I. Permeability: The presence of a pervasive system of jointing and cleavage indicates a potential permeability in the cover. The directional qualities of the structures suggest that any permeability of the rocks due to this system would be anisotropic.

II. Southeastward dipping thrusts: No direct evidence of thrusting was found, however, two lines of thought are suggested here:

a) The concentric geometry of the Warm Springs anticline, as well as the evidence given by Harris (1971), that first order anticlines are located by thrusting, indicate a high probability that thrusts will be encountered at depth. Based on tentative reconstruction from existing sections, such faults would be expected at depths of 3 km or less.

b) The presence of thrust faults may not be necessary for transverse flow of fluids, as the existing joint and cleavage network would seem to present a potential for flow both parallel (bc joints and cleavage) and transverse (ac joints) to the Warm Springs anticline.

III. Cross faults: The cross faults postulated by Costain (1975) were believed to have a surface expression in the ridge offsets of Little Mountain (Costain, personal comm. 1976). Investigation of these offsets has shown that they result from the interaction between topography and superposed kink bands in the northwest limb of the anticline and are not the direct result of faulting. Despite the lack of any significant direct surface expression of faulting, the kinematics suggested by the kink bands and the 060-067 joint set, suggests that the Warm Springs anticline is cut by deep seated transverse faults with a large left lateral component along 090. Such motion could readily generate narrow zones of enhanced permeability due to the formation of pinnate fractures as suggested by the 060-067 joint set. In addition, properly oriented pre-existing joint and cleavage sets might also open, providing additional permeability. Evidence for this behavior is suggested by the extension joint data (Figure 11).

The findings of this study then, is that with some slight modification, there does exist field evidence which meets the requirements of the structural model for the origin of the warm springs as proposed by Costain (1975). The revised model envisions downward percolation of water along joint and cleavage systems. The water, heated on the existing geothermal gradient, moves laterally either along joint or thrust systems. Rapid vertical movement occurs along narrow zones of jointing and fracturing produced by deep seated movement along the 090 trends.

RECOMMENDATIONS

Three areas for further study are suggested:

I. A detailed study of jointing including mapping, with particular emphasis of the zones of the 090 linears. The study should include, if possible, the effects of lithology and bedding thickness on the areal distribution of the joints. As this work requires utilizing the maximum amount of exposure, it should be done when vegetation is at a minimum.

II. On a regional scale further evidence should be sought for interference phenomena arising from intersecting deformation trends. Ridge offsets, similar to those in the Warm Springs anticline, are not uncommon in the Appalachians. If such offsets are the result of behavior similar to that proposed in this study, then transverse zones of enhanced permeability may be a relatively common and readily recognizable feature of the folded Appalachians.

III. Scale model studies to investigate the effects of transverse motion on pre-existing folds would seem to offer potential for insight. Such studies should help to reveal how strain is distributed in the cover and thus aid in the evaluation of the field data.

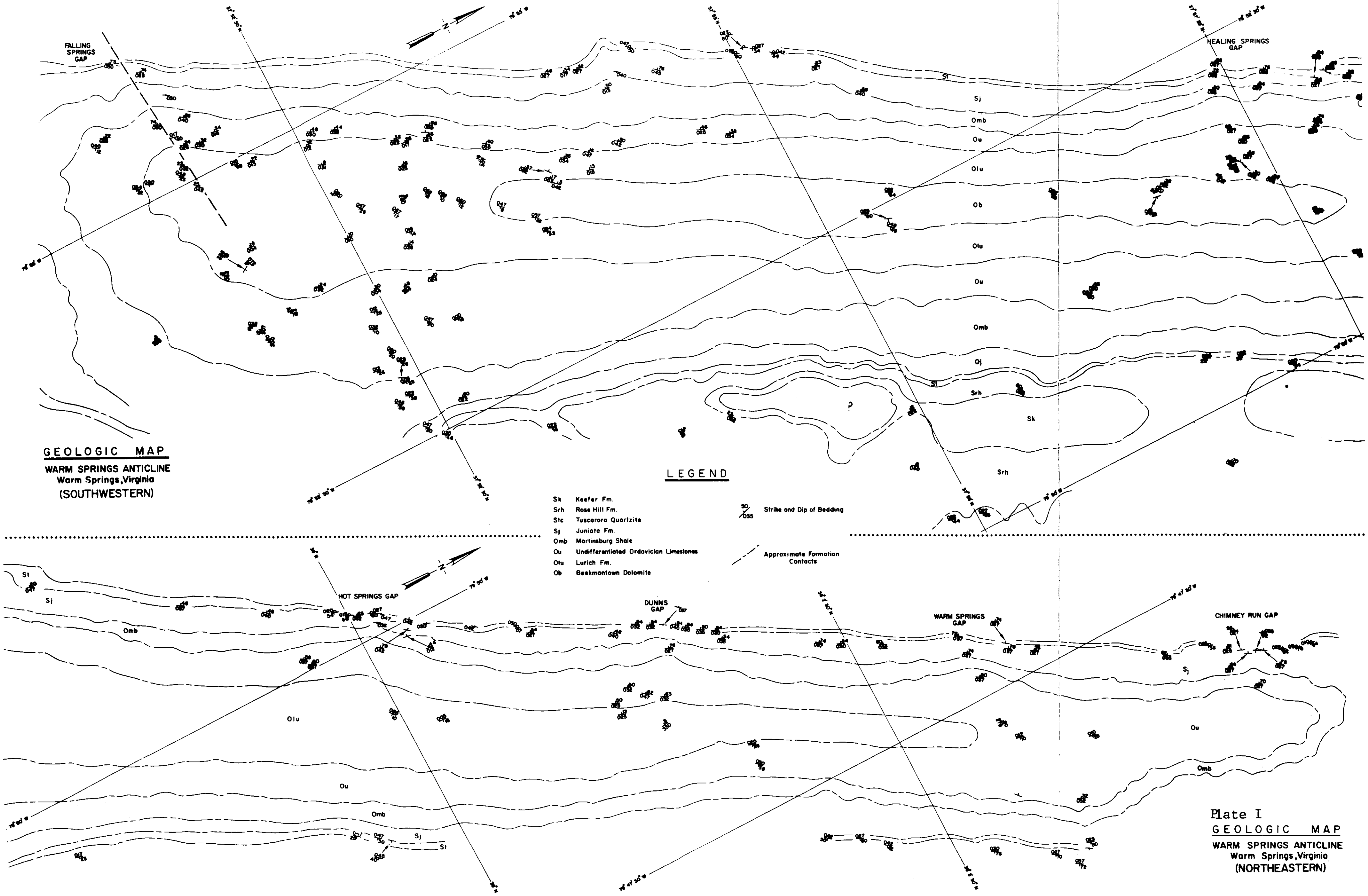


Plate I
GEOLOGIC MAP
WARM SPRINGS ANTICLINE
Warm Springs, Virginia
(NORTHEASTERN)

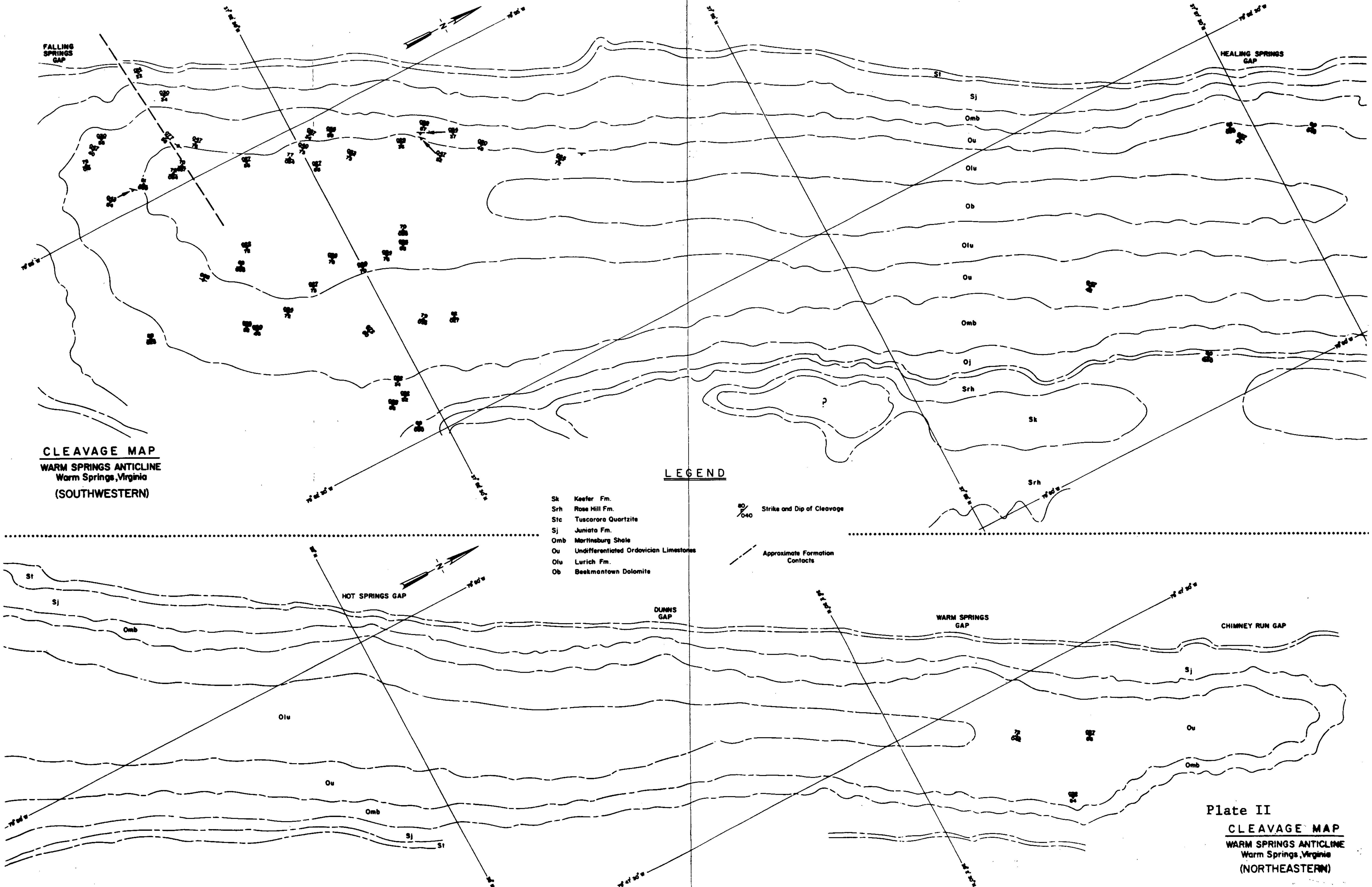


Plate II
CLEAVAGE MAP
WARM SPRINGS ANTICLINE
Warm Springs, Virginia
(NORTHEASTERN)

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(End of Report by Dr. Peter A. Geiser)

OVERVIEW AND SUMMARY

Initial results of determinations of heat generation from surface samples are encouraging, especially if granitic igneous rocks of similar heat generation can be found beneath sedimentary insulators. With the limited number of analyses available to date, the later fine-grained phases of the Winnsboro and Liberty Hill plutons, i.e., the Rion phase of the Winnsboro, clearly have a higher overall concentration of radiogenic elements, with maximum values of heat generation of approximately 13 HGU. All of the samples with high heat generation are from fine-grained samples except for one (S671) which is a xenocrystic rock with a fine-grained matrix.

Because the coarse-grained rocks are more susceptible to weathering, the measured heat productions may be lower than from those rocks (fine-grained) that are weathered less readily. We plan to conduct a series of leaching experiments to identify the portion of uranium and thorium tied up in grain boundaries versus intracrystalline sites.

Continued logging of existing wells in Coastal Plain sediments supports our earlier conclusion that these sediments do behave as efficient sedimentary insulators. Higher temperatures appear to be reached at shallower depths for wells drilled in Coastal Plain sediments in the vicinity of the Georgetown gravity low. The wells are not cemented, however, and the temperatures and apparently higher gradients may be influenced by convection. Higher gradients here could be the result of higher heat flow caused by buried radiogenic granitic plutonic rocks which might also be responsible, in part, for the gravity low.

Detailed structural mapping in the vicinity of the warm springs in northwestern Virginia has confirmed structural control of the warm springs, and has revealed the existence of kink bands. We are investigating the possible relationship of kink bands to the development of zones of vertical permeability which could serve as conduits in sedimentary rocks for ascending hot water.

PERSONNEL OF PROGRAM

(May 1 - October 31, 1976)

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S. S. Farrar, Research Associate
S. W. Becker, Research Associate

Geochemistry, A. Krishna Sinha, Principal Investigator

B. A. Merz, Research Associate
S. Hall (part-time)
S. Mackmull, Research Assistant

Geophysics, J. K. Costain, Principal Investigator

C. S. Rohrer, Research Specialist
R. T. Williams (part-time)
L. D. Perry (part-time)

Structural Geology, Warm Springs Project, northwestern Virginia

Peter A. Geiser, University of Connecticut, Storrs

Secretary

Margie Strickler

Drillers

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

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.

N. K. Olson, State Geologist, Division of Geology, South Carolina State Development Board, provided maps and unpublished material. His cooperation and assistance was essential for the coordination of our work in South Carolina and is gratefully acknowledged.

Phil Johnson, Water Resources Division, U. S. Geological Survey, Columbia, S. C., 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, N. C., 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. Wendell 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.

Brenda Higgins, U.S. Geological Survey, supplied a geologic description of the Clubhouse Crossroads Core Hole No. 1 (CCCH-1) near Charleston, South Carolina. Discussions with Ms. Higgins and with Hans Ackerman, U.S. Geological Survey, were very helpful in the interpretation of our temperature log of CCCH-1. The cooperation of the U.S. Geological Survey in allowing us access to CCCH-1 is gratefully acknowledged.

I. Zietz of the U.S. Geological Survey provided umpublished 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, were helpful in the interpretation of the petrology and chemistry of the rock samples.

The Molecular Structures Laboratory in the Department of Geological Sciences 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.

Principal investigators John Costain, Lynn Glover III and Krishna Sinha, in accordance with Article A-I of Appendix A to the hereinmentioned contract, have devoted 66%, 16% and 15% respectively of their efforts to performance under the contract.

All subcontract requirements have been complied with.

John K Costain
A. K. Sinha
Lynn Glover III