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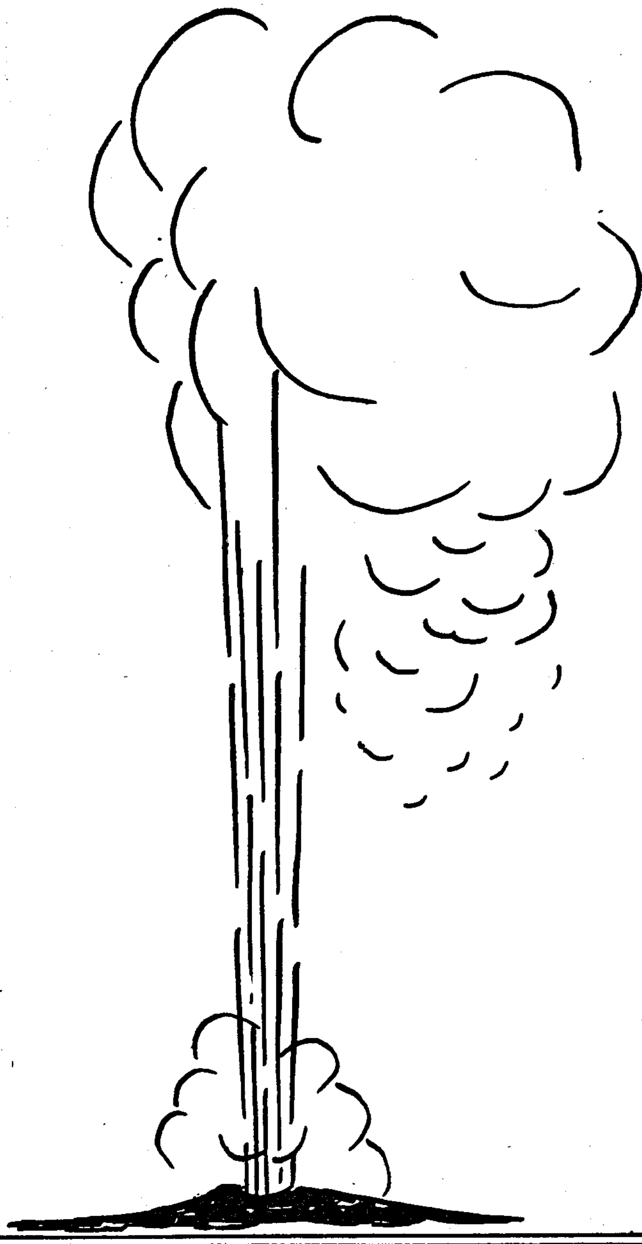

EVALUATION AND TARGETING OF GEOTHERMAL ENERGY RESOURCES IN THE SOUTHEASTERN UNITED STATES

Progress Report, July 1—September 30, 1977

By
John K. Costain
Lynn Glover, III
A. Krishna Sinha

Work Performed Under Contract No. EY-76-S-05-5103

Virginia Polytechnic Institute and State University
Blackburg, Virginia

U. S. DEPARTMENT OF ENERGY

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

Progress Report

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July 1, 1977 - Sept. 30, 1977

PREPARED FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION UNDER
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ABSTRACT

The objective of this program 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 near-term resource assessment for Region V places primary programmatic emphasis on the confirmation of radiogenic resources in the Atlantic Coastal Plain. This emphasis is based on the partial confirmation of the radiogenic model as described in this and previous reports from VPI&SU. Geothermal gradients known to date in the Atlantic Coastal Plain are consistent with those expected from a concealed radiogenic source. Our current work in the Piedmont appears to be confirming the linear relationship between heat flow and heat generation. This is important because it permits theoretical calculations of temperatures to be expected within the sediments of the Atlantic Coastal Plain, in the granitic rocks beneath the Coastal Plain, and in those exposed in the Piedmont. Sixteen holes suitable for excellent heat flow determinations have been drilled by VPI&SU and will be reported on as the holes reach thermal equilibrium and chemical analyses and heat determination of core samples are completed. Reconnaissance surface sampling of igneous rocks has been carried out to define the variation in surface heat generation that might be expected. Collation of existing gravity and magnetic data available for the Atlantic Coastal Plain has been completed and modeling of selected negative gravity anomalies has begun. Insight into restrictions on the vertical distribution of heat-producing elements is being obtained by consideration of restraints imposed by analyses of metamorphic mineral assemblages.

INTRODUCTION AND OVERVIEW

Region Five (the States east of the Rocky Mountains, excluding Texas and Louisiana) encompasses a diversity of geologic environments and a corresponding diversity of geothermal resource potential. Although the relatively stable tectonic setting of the eastern United States seems to rule out the possible occurrence of conventional, high-temperature hydrothermal resources, the region does contain geothermal resources which are being developed now, or which may be exploited in the future. The geothermal resources anticipated will be low- to moderate-temperature fluids that are best suited for direct heat applications.

The geothermal resources in Region Five may be grouped for discussion into six types:

I) radiogenic granitic rocks beneath the Atlantic Coastal Plain,

II) hot oil field brines produced with oil and gas from sedimentary basins,

III) hot, relatively fresh groundwater produced from aquifers of regional extent,

IV) hot water emanating from fault zones as a result of apparent leakage from greater depths,

V) hot dry rock in regions of abnormal gradient resulting from radiogenic heat, and

VI) normal geothermal gradient resources.

Knowledge of these individual resource types varies considerably. Region Five contains a number of sedimentary basins which have been thoroughly explored for oil and gas; a number of areas which produce hot fluids with the oil and gas have been identified. Increasingly deeper drilling for ground water has also identified intermediate depth aquifers which produce hot water, such as the Madison Formation of South Dakota. In much of Region Five, therefore, the resource assessment is different from the high risk geothermal exploration in the western States. In the eastern United States geothermal resource assessment is often more a question of whether or not a known hot or warm water occurrence can be developed economically.

The near-term resource assessment for Region Five places primary programmatic emphasis on the confirmation of radiogenic resources in the Atlantic Coastal Plain. This emphasis is based on the partial confirmation of the radiogenic model as described in ERDA Report VPI&SU-5103-4 and in the present report. Concurrent studies at VPI&SU, because of their geographic proximity to the Atlantic Coastal Plain, also bear directly on the assessment of geothermal resource types IV, V, and VI, above. The utilization of certain types of geothermal resources in Region V, specifically the hot dry rock and normal gradient resources, are dependent on technological advances before they can be economically developed. An assessment of the geothermal potential of these resources cannot be made without a reliable data base.

Relatively few oil and gas tests have been drilled on the Atlantic Coastal Plain, and the exploration of the Continental Shelf is just beginning. Relatively little is known about the temperature distribution in intermediate-depth aquifers. The voluminous data base available for the oil and gas fields of the Appalachian region, the Gulf Coast, and the Mid-Continent region is not available for the Atlantic Coastal

Plain. The urban centers of the east coast provide the most obvious target for supplement and local replacement of conventional energy sources with geothermal resources. The scarcity of subsurface data and the current low level of interest by the energy industry in exploring and developing low-temperature resources created a climate appropriate for Federal and State participation in stimulating their exploration and development. Encouraging results are already evident in the growing interest in this resource on the part of a number of potential users in the east. The current rate of inquiries now suggests that energy industry participation could be realized within a few years if not sooner.

Resource Assessment

The assessment of the TYPE I geothermal resource is based on the assumption that optimum sites in the Atlantic Coastal Plain will be associated with granitic rocks relatively high in heat-producing elements concealed beneath thermally insulating sediments of the Atlantic Coastal Plain. At these sites, isotherms will be warped upward, resulting in relatively high temperatures at shallow depths. An essential parallel study for the targeting of optimum sites in the Coastal Plain is the continued development of a geologic model for the exposed Piedmont province and extension of that model to include the basement under the Coastal Plain. Granitic rocks crop out over a large area of the central and southern Appalachian Piedmont and Blue Ridge and presumably extend eastward beneath the sediments of the Atlantic Coastal Plain. The crystalline basement beneath the sedimentary cover of the Atlantic Coastal Plain has been sampled in few locations and the nature and distribution of rock types is poorly known on a regional basis. This data base can be vastly improved by a systematic effort to acquire more geophysical and core data in the near future. Our current work in the Piedmont appears to be confirming the linear relationship between heat flow and heat generation (VPI&SU-5103-4 and this report) and this is important because:

1) it permits theoretical calculations of subsurface temperatures to be expected within the sediments of the Atlantic Coastal Plain, in the granitic rocks of the Piedmont, and in the granitic rocks presumed to exist beneath the sediments of the Coastal Plain,

2) it contributes to confidence in the selection of drill sites for the assessment of the Type V geothermal resource in the eastern United States without the expense of penetrating the sedimentary cover to measure directly (as we have done in the Piedmont) the concentrations of radiogenic elements in concealed sources.

3) it will define the existence and extent of one or more "heat flow provinces" (see VPI&SU-5103-4 for further discussion) in the eastern United States. Abrupt transitions are to be expected between heat flow provinces or sub-provinces and the linear relationship is the only known means of defining boundaries between heat flow provinces,

4) structural implications of the linear relationship are significant, but not well-enough confirmed at this time. Suffice it to say that at any one drill site, the heat flow value is the cumulative results of heat flowing from the mantle, lower crust, and upper crust. The heat generation value, however, is from "near-surface" rocks, i.e., core from the drill hole. Hence, any non-linearity between heat flow and heat generation suggests the presence of a subsurface structural or lithologic discontinuity which interrupts an otherwise controlled distribution of uranium and thorium in igneous rocks. Thus, the linear relationship might detect crystalline overthrust sheets in the Piedmont or basement beneath the Coastal Plain and play an

important role in the assessment of the Type IV geothermal resource in the Piedmont where both hot springs and suspected allocthonous igneous overthrusts are known to occur. Identical environments may be present in the basement beneath the Coastal Plain.

We emphasize the importance of understanding the geologic framework since it is this framework that controls the occurrence and distribution of geothermal resources in Region V and elsewhere. Choice of a drill site in the Atlantic Coastal Plain with a high geothermal resource potential depends on favorable:

1) concentration of radiogenic elements in granitic rocks beneath a sedimentary insulator,
2) thermal conductivity of the sedimentary insulator,
3) thickness of the sedimentary insulator, and
4) reservoir conditions in the permeable sedimentary rocks overlying the radiogenic heat source.

Because it is not economically feasible to select drilling sites on the Atlantic Coastal Plain without geophysical and geological models, it is advisable to base the development of these models on a substantial and accurate data base which can be partially derived from the exposed rocks of the Piedmont and enhanced by basement studies beneath the Atlantic Coastal Plain.

Our plan for targeting favorable sites on the Atlantic Coastal Plain involves five overlapping phases culminating in deep drilling to confirm the radiogenic model and the geothermal resource. Phase I is concentrating on the examination of exposed granites in the Piedmont to evaluate the range of uranium and thorium concentrations and geologic framework to be expected beneath the Coastal Plain. For the most part, the program to date has examined relatively young granitic plutons emplaced in a belt broadly parallel to the structural grain of the Appalachian Mountain System. It now becomes important to examine trends transverse to the structural grain and extending beneath the Coastal Plain. Phase II is a collation of existing basement geologic data, gravity and magnetic field data, and thermal gradient data from existing wells in the Coastal Plain. Phase III will involve an intermediate-depth drilling program during FY 1978 at sites identified during Phase II. Sixty holes approximately 1,000 feet in depth will be drilled on the Atlantic Coastal Plain by a subcontractor. The program will be managed by a firm obtained through an RFP. The contracting process has been initiated by the Resources Engineering Branch of ERDA, and intermediate drilling will begin in early calendar year 1978. All phases have involved cooperation with State and Federal agencies. Phase III will involve increased State participation and U.S.G.S. cooperation in site selection for intermediate drilling and more detailed exploration. Phase IV will involve site selection for deep exploratory holes. This activity will be initiated as data is obtained and interpreted from the intermediate-drilling gradient program. Site-specific surveys will be initiated during Phases III and IV and will include:

1) detailed gravity surveys and modeling of potential field data to define the shape and geologic framework of concealed radiogenic sources,

2) bottom-hole core sampling of basement in selected areas to furnish a data base for the interpretation of the potential field data, and

3) limited seismic surveys across target areas to define depth to basement, depth and thickness of thermal insulating units, depth and thickness of aquifers, and to identify faults in the basement and/or overlying sediments which could affect the performance of a production well, the estimated depth to basement, the nature of heat sources in the basement or otherwise add unexpected complexity to the choice of a drill site.

Phase IV will result in the selection of three or more sites for deep exploratory drill holes which apparently possess the prerequisite combination of depth to a production aquifer and abnormally high gradient.

Phase V of the program in the Atlantic Coastal Plain is the drilling of deep exploratory test wells. The drilling will be managed by the firm obtained for supervision of the intermediate-depth drilling program. Based on the results of the first well and the response of industry to the results of the first deep test, additional wells will be drilled. It is anticipated that at least five separate resource areas with a high geothermal resource potential will be identified. Choice of the sites will involve a broader consideration of economic and institutional factors. Phase V could evolve into an "industry-coupled" program involving cost-sharing by industry, or, given sufficient interest by industry, the cost of deep exploratory test wells could be completely borne by industry.

RESEARCH OBJECTIVES

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

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

Initial studies are developing a methodology for the location of radiogenic heat sources buried beneath the insulating sedimentary rocks of the Atlantic Coastal Plain.

PERSONNEL OF PROGRAM

(July 1, 1977 - September 30, 1977)

GEOLOGY AND PETROLOGY, Lynn Glover III, Principal Investigator

- J.A. Speer, Research Associate
- S.S. Farrar, Research Associate
- S.W. Becker, Research Associate
- A. Baldasari, Laboratory Aide

GEOCHEMISTRY, A. Krishna Sinha, Principal Investigator

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- S. Higgins, Part-time Laboratory Aide
- M. Lipford, Part-time Laboratory Aide
- R. Yarborough, Part-time Laboratory Aide

GEOPHYSICS, J. K. Costain, Principal Investigator

- L. D. Perry, Research Associate
- J.A. Dunbar, Research Specialist
- S. Whitlow, Graduate Research Assistant
- J. Hoban, Part-time Laboratory Aide

Administrative Assistant, Patricia C. Sullivan

Secretary, Margie Strickler, Geraldine Barber (part-time)

Drillers

- W. G. Coulson, Core Driller
- R. G. Gravley, Driller Helper
- J. W. Childress, Second Shift Core Driller
- G. D. Childress, Second Shift Driller Helper
- R. B. Stilwell, Second Shift Driller Helper

A. GEOLOGY

Lynn Glover III, Principal Investigator

J. A. Speer, Research Associate

S. S. Farrar, Research Associate

S. W. Becker, Research Associate

A. Baldasari, Laboratory Aid

Operations

During the last three months, from 7-1-77 to 9-30-77, six man-weeks were spent continuing detailed mapping of the country rocks surrounding the Rolesville batholith. Half a week was spent in reconnaissance examination of several gabbroic plutons and their contact aureoles, and, during a two-day period, samples were collected from the Marshall granite in northern Virginia. Drill hole sites were located in the Petersburg batholith, the Edgefield granite, and the gravity low near Salley, S.C., and a fifth site was located in the Rolesville batholith.

Drilling continued in the Rolesville batholith; RL-2, RL3, RL-4, and RL-5 were completed. A hole drilled in the Petersburg granite penetrated 300 feet of coastal plain sediment before reaching granite; final bottom depth was 832 ft.

Following is a list of all samples collected during the past year.

		Chemistry and heat production samples	Total Samples
Liberty Hill, S.C.	surface	26	143
	Kr 1	1	20
	Kr 2	5	18
	Kr 3	13	29
Winnsboro, S.C	surface	40	119
	Wn 1	16	17
Roxboro, N.C.	surface	6	6
	Rx 1	5	5
	Rx 2	6	6
	Rx 3	6	6
Slate Belt, N.C.	SB 1	--	2
Rolesville, N.C.	surface-granite	26	70
	-country rock	--	121
	RL1	16	16
	RL2	13	13
	RL4	21	21
	RL5	9	9

		Samples for Chemistry and Heat Production	Total Samples
Petersburg, VA	surface	33	58
	Pt 1	--	--
Reconnaissance-Virginia			
Berea		2	2
Fine Creek Mills		1	1
Marshall		3	3
Robinson River		2	2
Reconnaissance-North Carolina			
Churchland		2	2
Concord		2	2
Elm City		1	1
Gastonia		2	2
Lemon Springs		--	2
Lilesville		3	21
Mt. Mourne		1	1
Pee Dee		4	5
Rocky Mount		2	2
Sims		2	4
Wilton		1	2
Woodleaf		1	1
Reconnaissance-South Carolina			
Abbeville		--	12
Bald Knob		1	1
Buffalo		--	24
Calhoun Falls		--	12
Catawba		1	2
Clouds Creek		3	3
Clover		1	1
Columbia		2	6
Coronaca		1	1
Dutchman's Creek		--	36
Edgefield		4	8
Great Falls		1	1
Greenwood		--	4
Harbison		1	1
Mount Carmel		1	1
Newberry		3	3
Pageland		3	--
Rock Hill		--	3
York		2	2

	Samples for Chemistry and heat production	Total Samples
Reconnaissance-Georgia	3	3
Appling	2	2
Ben Hill	2	2
Danbury	2	2
Delhi	1	1
Elberton	5	5
Gladesville	--	24
Palmetto	4	4
Presley's Mill	--	11
Siloam	3	3
Sparta	1	1
Stone Mt.	3	3
Tyrone	3	3
Georgia U3	1	1

Gabbroic Plutons of the Southeastern U. S.

S. W. Becker

Closely associated with the belt of granitic plutons that crops out in the Piedmont of North and South Carolina and Georgia is a string of approximately 30 gabbroic plutons. The exact age relations between the gabbros and the granites is not known; few of the mafic bodies have been dated. Most of the gabbros, however, are thought to be "postmetamorphic"--approximately contemporaneous with the majority of the granites--because the mafic plutons show little evidence of deformation or recrystallization. More definite age relations have been determined for a few plutons. The Pee Dee Gabbro intrudes and must be younger than the Lilesville Granite which has been dated at 332 ± 14 m.y. (RbSr, Fullagar, reported by Bell et al., 1974). Three biotite samples from a diorite of the Mount Carmel complex have been dated by K-Ar methods at 387, 386, and 380 m.y. (Medlin, 1969). Ages of other plutons have yet to be determined.

The unmetamorphosed granitic and gabbroic plutons are probably closely related in time as well as in space, and can be considered a bimodal suite. Simultaneous basic and acidic igneous activity has been reported in many areas. Examples of extrusive bimodal activity include Tertiary composite lava flows in eastern Iceland (Gibson and Walker, 1964; Blake et al., 1965), banded pumice from Mt. Lassen, California (Macdonald and Katsura, 1965), and mixed lavas along the Gardiner River on the Yellowstone Plateau (Fenner, 1938, 1944; Hawkes, 1944; Wilcox, 1944). Intrusive bimodal suites, less commonly reported, include the Tertiary granites and gabbros of Skye (Moorbath and Bell, 1965). In addition, interlayered quartz-plagioclase gneisses and amphibolites thought to represent bimodal suites, have been described in Precambrian rocks from Colorado, Minnesota, Ontario, Rhodesia, and Swaziland (Barker and Perterman, 1974).

The origin of bimodal igneous activity is not well understood. Several mechanisms have been proposed for the simultaneous generation of acid and basic magmas. In some areas, such as Swaziland, where the silicic and basic rocks have similar initial strontium isotope ratios, the two magmas are thought to be derived from the same source (Manton, 1968). Possibile explanations for the generation of two magmas of different compositions are liquid immiscibility, crystal fractionation, and fractional melting. Liquid immiscibility, however, is unlikely in complex, hydrous systems (Yoder, 1968). Crystal fractionation is not an attractive alternative, either. Rocks of intermediate composition should form from fractional crystallization of a basalt, and are absent from most bimodal suites. Fractional melting is the most probable cause of bimodal magmas derived from similar sources (Yoder, 1968).

Rocks comprising some bimodal suites are formed from magmas clearly different in origin. Granitic plutons on the Isle of Skye, for example, have an average $Sr_0^{87/86}$ of 0.7124 $\pm$ .0015, whereas the associated basic rocks have $Sr_0^{87/86}$ equal to 0.7058 $\pm$ .0010. These ratios suggest that the granite magma formed as the basic magma, of lower crustal or upper mantle origin, passed through and melted upper crustal rocks.

Little work has been done on the comparative origins of the gabbros and granites. $Sr_0^{87/86}$ determinations that have been made on five of the gabbroic bodies are all less than 0.7045; those for the granites are less than 0.7050, with the exception of Stone Mountain, Georgia, Stone Mountain, North Carolina, and Mt. Airy, North Carolina (Fullagar, 1971; Kish, 1976; Whitney et al., 1976). The ratios suggest that the gabbros and most of the granites were derived from lower crustal or upper mantle sources.

Whatever the origin of the magmas, it is clear that processes responsible for the generation of the mafic melts must be directly related to the causes of felsic igneous activity. In order to describe fully the plutonic event that created the granites, it is necessary to understand the causes and conditions of emplacement of the gabbroic plutons. Examination of the contact aureoles of several of the plutons should allow determination of the temperatures and depths of emplacement. Comparison of the values obtained with similar data from the granitic plutons should reveal regional trends in depth of emplacement.

Structural, geologic, and petrologic features bearing on the low temperature energy potential of the granites of the Piedmont. (1) Depth of emplacement of granite plutons

J. Alexander Speer

The linear relationship between heat flow and heat production for plutonic bodies, first advanced by Birch et al. (1968) and Lachenbruch (1968) is consistent with a variety of heat-generation-depth relations. The three limiting cases discussed by Lachenbruch (1968, 1970, 1971) are (1) a constant source model, (2) a linear model, and (3) an exponential model. In order to test which model is most applicable to nature, two studies were undertaken, one in the Sierra Nevada Batholith (Lachenbruch, 1968) and the other in the Idaho Batholith (Swanberg, 1972; Swanberg and Blackwell, 1973). The technique used to obtain the heat-generation-depth relation is simple: Swanberg (1972) plotted heat generation values of the plutons against their estimated depths of emplacement whereas Lachenbruch (1968) inferred depths of emplacement from heat generation values of the plutons from an exponential depth-heat-generation relation and tested how well the results compared with inferred depth relations from other studies. This section is a review of these two approaches to the problem and the results of these two studies, as well as a presentation of results of our work on the granites of the southeastern U.S.

Lachenbruch (1968) felt that removal by erosion of nearly equal amounts of overburden at the sites of four boreholes was unlikely in view of the 80-145 m.y. ages of the plutons in which they were located, and that therefore, a uniform distribution of heat-producing elements to some depth, D, was unlikely. Assuming differential erosion, assuming A_o = 15 HGU, and observing that D = 10 km in the equation for the exponential model

$$A(z) = A_o e^{z/D}$$

where z is depth, he obtained a graph of heat production as a function of depth (figure A1a). Estimates of the depths of emplacement for the plutons in which the four boreholes in the Sierra Nevada were located were obtained by examining their respective heat production values. Implications of this model and these depths of emplacement were examined in light of what is known about the Sierra Nevada Batholith. A geologic argument presented was the observation that the average depth of emplacement, 17.3 km (10.7 mi), is "consistent with the estimate by Bateman and Wahrhaftig (1966), [that]. . . the volume of sediment attributed to erosion of the Sierra Nevada is sufficient to bury the range to a depth of more than 10 miles."

Kerrick (1970) reviewed the contact metamorphic aureoles in the Sierra Nevada and concluded that the total pressure in any of the aureoles did not exceed about 2 kb during emplacement of the plutons of the Sierra Nevada. The low pressure bracket was estimated at 1 kb. In view of the contact metamorphic mineral assemblages in the areas of Lachenbruch's (1968) boreholes, Lachenbruch's pressure estimates were considered excessive by Kerrick.

Swanberg (1972) and Swanberg and Blackwell (1973) measured the heat production[1] of surface samples of the Idaho Batholith and plotted the values against estimates of depth of emplacement obtained from geologic and petrologic evidence. The area is believed to have been undergoing

[1]They removed the contribution of K because they found no evidence of an exponential decrease of K with depth of emplacement of a granite. It has been added in figure A-1a to make their values comparable to the other data.

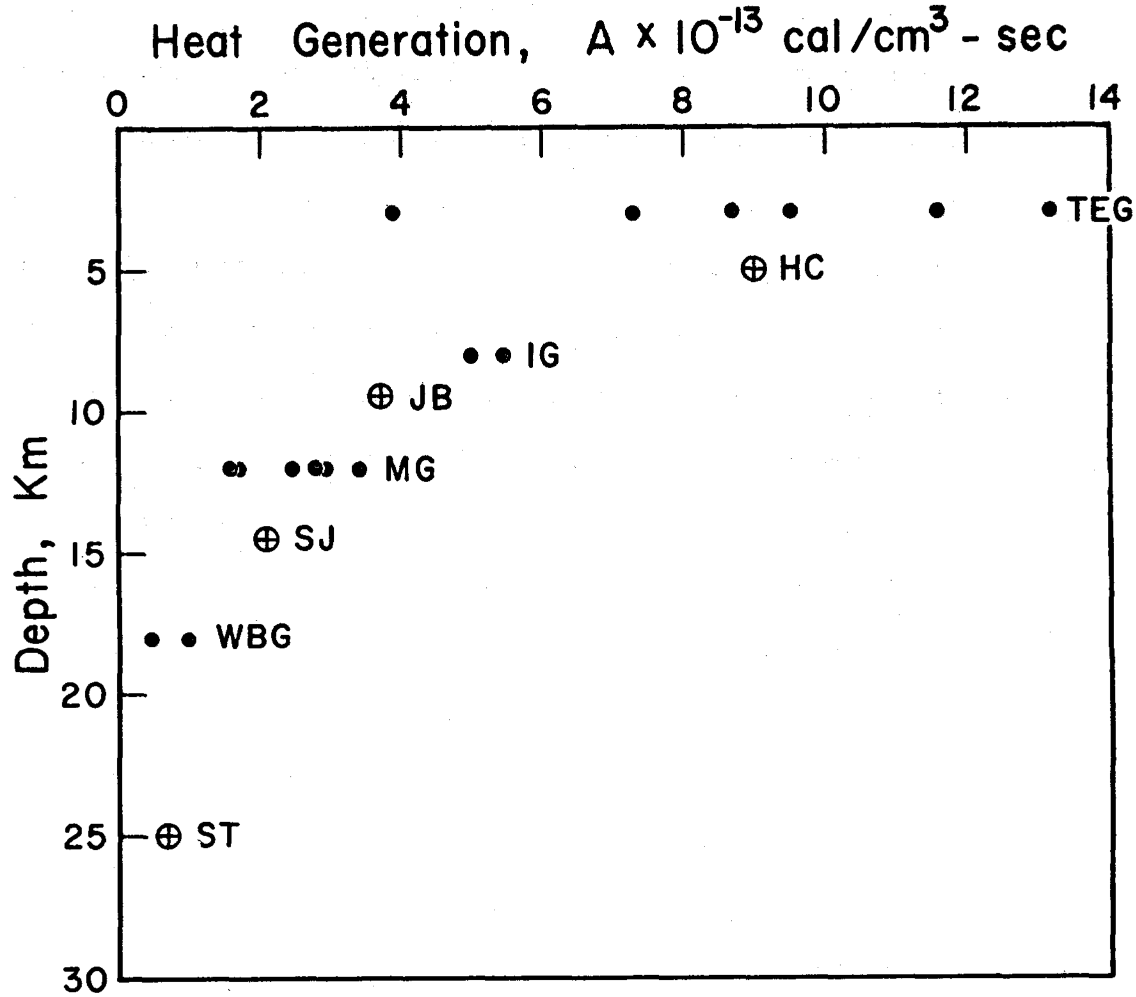

Figure A-1a. Heat generation-depth relations determined by Lachenbruch (1968) for the Sierra Nevada Batholith - ST, SJ, JB, HC, and by Swanberg and Blackwell (197?) for the Idaho Batholith - WBG, west border group; MG, main group; IG, intermediate group; and TEG, Tertiary epizonal group.

continuous uplift, with the plutons of each intrusive group emplaced at about the same depth, and successively younger groups emplaced at shallower depths. The resulting plot, included in Figure A-1a, is remarkably similar to that obtained by Lachenbruch (1968). It was concluded that these data show an exponential decrease of heat-generation with depth.

How reliable are the emplacement depths of these intrusive groups of the Idaho Batholith? The groups of plutons are ordered by depth largely by quantifying Buddington's (1959) epizone-mesozone-catazone classification of plutons. While there is some qualitative value in this classification, it is inappropriate for the demonstration of absolute depths of emplacement. There is some evidence regarding the depth of emplacement of these plutons from contact mineral assemblages. The classic relationships of Al_2SiO_5 polymorphs in the Idaho Batholith were described by Hietanen (1956, 1961, 1963, 1968, 1969). It is believed that a contact-metamorphic distribution of andalusite and sillimanite was superimposed on a regional metamorphic distribution of kyanite and sillimanite. The estimate of the pressure for the triple point is between 3.8 and 5.1 kb. Occurrence of what is described as primary muscovite in many of the main group intrusives indicates a pressure minimum of 3.5 kb. One of the Tertiary epizonal group plutons has a minimum depth of emplacement of 3-5 km based on estimated stratigraphic cover.

The depths of emplacement of the plutons in the Idaho Batholith are only generally known to lie near the Al_2SiO_5 triple point. No metamorphic assemblages have been described to document the increasingly shallow levels of intrusion suggested by Swanberg (1972) and Swanberg and Blackwell (1973).

In addition, the trend of increasing heat production in the Idaho Batholith parallels the chemical evolution, of the plutons from intermediate to acidic and the process responsible for magmatic differentiation has been neglected as a possible cause of differing heat production.

Work on depth of emplacement of the plutons in the southeastern U.S. has centered on the Winnsboro, Liberty Hill, Pageland, and Lilesville plutons. Compositions of garnet-cordierite pairs in the contact rocks give pressure estimates between 4.8 and 5.8 kb. These estimates are consistent with the occurrence of andalusite-sillimanite in the Winnsboro and Liberty Hill aureoles (P less than 5.3 kb), almandine garnet in all four aureoles (P greater than 2-3 kb), and primary muscovite in the finegrained Liberty Hill and Winnsboro granites (P greater than 3.5 kb). Depth of emplacement estimates and average heat generation of the plutons are:

	HGVU	Pressure at Depth of Emplacement
Lilesville	5.33	5.8kb
Pageland	5.96	----
Liberty Hill		
coarse	4.86	4.8
fine	8.74	4.8
Winnsboro		
coarse	5.29	5.3
fine	10.53	5.3

These values are plotted on a depth-heat generation graph in figures A1-b with Kerrick (1970) depth estimates for the Sierra Nevada plutons. Points from the Idaho Batholith are omitted because of the uncertainty of the

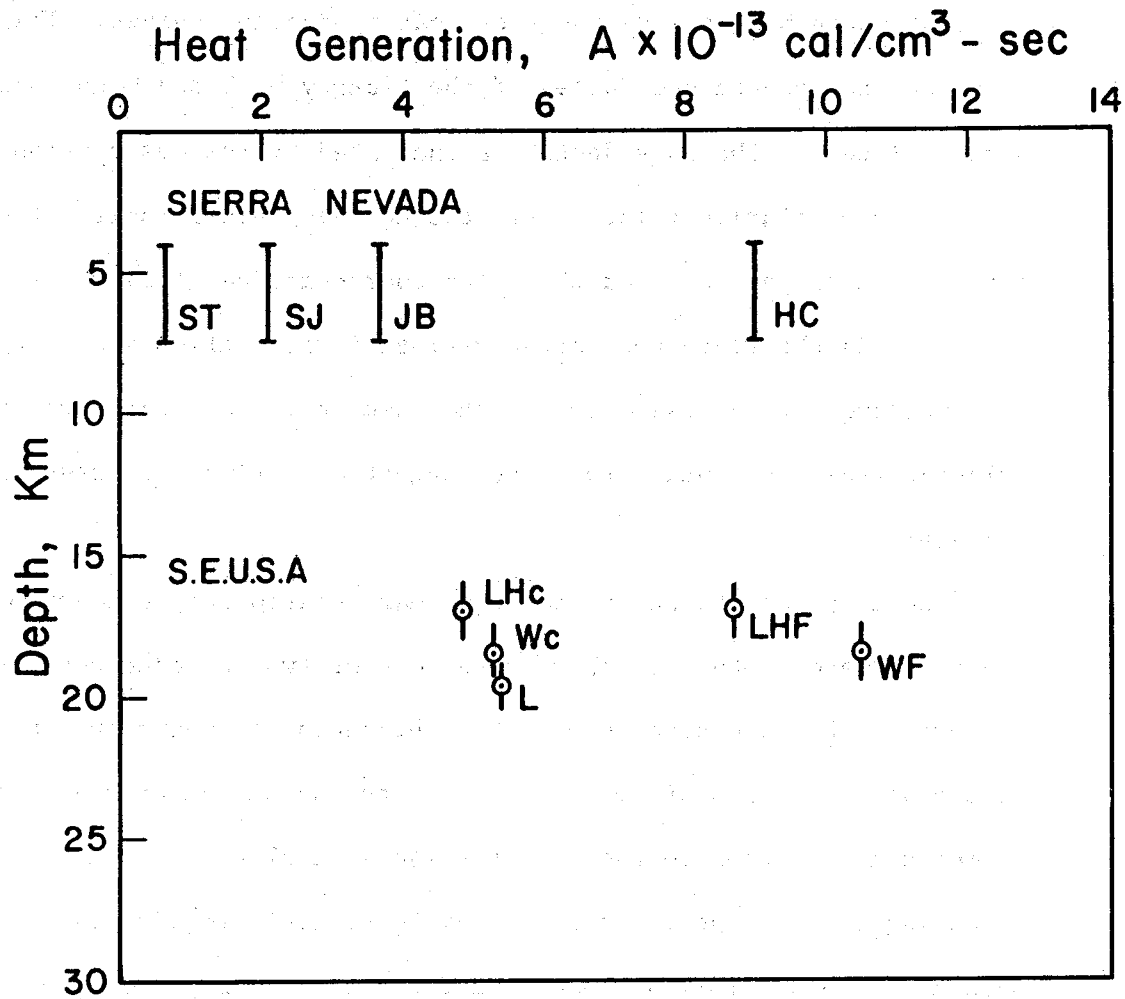

Figure A-1b. Heat generation-depth relations for the Sierra Nevada based on the pressure estimates of Kerrick (1970) and the southeastern U.S.A. plutons - L, Lilesville; LHc, Liberty Hill coarse; LHf, Liberty Hill fine; Wc, Winnsboro, coarse; Wf, Winnsboro fine.

depth of emplacement. It is important to note that the plutons emplaced at the same depth have a wide range of heat production values. That the fine- and coarse-grained facies of the Liberty Hill and Winnsboro plutons were emplaced at the same depths is indicated by the observations that (1) although relatively later than the coarse-grained facies, the fine-grained facies was emplaced while the coarse-grained facies was still plastic; (2) the fine- and coarse-grained facies define a single Rb-Sr isochron suggesting that they are the same age; and (3) there is no evidence from the contact rocks to suggest differing pressures of emplacement.

There appears to be no simple linear relationship between heat generation and depth. If there were, one of two consequences must follow: either the abundance of heat producing elements in a magma determines its depth of emplacement, or the abundance of heat-producing elements is adjusted to the proper value in a pluton and in host rock depending on its depth. While it may be possible to arrive at plausible mechanisms to accomplish these results, there is no petrologic evidence that either process is occurring.

ii Petrologic and geologic indicators of the crustal distribution of Th and U

S. W. Becker

The earth's upper crust is generally regarded as highly enriched in Th and U, but the concentrations of these elements as a function of depth are not well understood. Estimates of the crustal distribution of heat producing elements can be obtained either from geophysical means as discussed in the previous section, or from petrologic and geologic considerations. Petrologically-oriented studies of U and Th abundances suggest that the elements are distributed as a step function, with either one step or a series of steps.

Advocates of the one-step model include Heier and Adams (1965) and Lambert and Heier (1967, 1968). They measured U and Th in varying grades of metamorphic rocks in the Australian Shield which were thought to be similar in composition and mineralogy to crustal rocks of varying depths. High-pressure granulites, analogous to lower crustal rocks, were found to be markedly depleted in Th and U, whereas low-pressure granulites of similar major element composition and rocks representative of the upper crust, such as shales, granites, greywackes, and basalts, showed no similar depletion. The conclusion drawn was that U and Th are distributed as a step function, with high concentrations near the surface in a layer approximately 4.5 km thick, and low concentrations in the lower crust. Depletion occurs over a narrow zone, about 5 km. thick.

In view of our work on the plutons of the southeastern U.S., these estimates of depths to granulite facies rocks appear to be low. Mineral assemblages in the contact aureoles of the Liberty Hill, Winnsboro, and Lilesville plutons indicates depths of emplacement of 15-20 km, and the country rock surrounding these plutons is only at greenschist to amphibolite grade. The thickness of the zone above granulite facies rocks that is enriched in Th and U is probably greater in many areas than the 4.5 km suggested by Lambert and Heier (1968).

Other workers have proposed that the closest approximation to the crustal distribution of Th and U is a series of steps, with Th and U concentrations generally decreasing at successively greater depths (Roy et al., 1968; Blackwell, 1971, Swanberg, 1972). This model is probably more accurate than the one step approximation, because the crust is composed of numerous layers of widely varying lithologies. In some localities, as where a pluton has not reached the surface, or where sediments overlie crystalline rocks of low metamorphic grade, heat production may actually increase with depth (cf. Lambert and Heier, 1968, Fig. 3). Generally, however, heat production will decrease at greater depths. With a large number of steps or layers, the distribution of heat producing elements in the crust as a whole could approximate an exponential distribution, but this exponential relation between abundance of Th and U and depth cannot be expected in any single body of rock.

iii Location of U and Th in igneous rocks (summary of the Literature)

J. Alexander Speer

Heat generation in rocks is given by the equation:

$$H = 0.718U = 0.193Th + 0.262\ K^{1}$$

As most rocks contain less than 10% K, high heat production values will be largely the result of high uranium or high thorium contents. Any understanding of the behavior of U and Th during generation and crystallation of a magma and deuteric alteration and weathering of a granite would be helped immeasurably if the distribution of U and Th in the melt and rock were known. This particular section is a review of the literature dealing with the location of U and Th in igneous rocks. References dealing with meteorites or mantletype xenoliths have not been considered. The studies are all similar in that the U-Th balance of the rocks is based on the modes, whole rock U and Th contents, and U and Th contents of the individual minerals.

The results of the literature studies are summarized in Table A1. In wholly crystalline rocks, U(Th) can be largely in the major minerals, or in the accessories, or in both. Closer examination reveals that in studies concluding that a large percentage of the U is in the major rock-forming minerals, the U content has been determined on mineral separates. This method probably yields systematically higher values of U owing to the difficulty in obtaining pure mineral separates.

[1] Heat production (H) is in mass units, μ cal/gm yr, U and Th are in ppm, and K is in wt %. Revised heat generation constants are from Ryback (1976).

Table A1

Rock Types (Number of Samples Studied)	% of Uranium in Rock-forming Minerals	U-bearing Accessory Minerals	Grain Boundaries and Fissures	Groundmass (glass)	Reference
granodiorite (1)	∿2	"most"	"appreciable"	-	Dostal & Capedri (1975)
rhyolite (4)	<1	10-33	-	90-67	[FTTS]
basalt (2)	<3	-	-	>97	
basalt (2)	<1	-	-	>99	Dostal <u>et al</u>. (1976)
andesite (3)	<1	-	-	>99	[FT TS]
dacite (1)	<1	-	-	>99	
S. Ca. Bath.					
norite-gabbro (5)	91-96			-	
tonalite (4)	70-90			-	
ggd (4)	63-93			-	
S. N. Bath.					
monzonite (5)	35-90			-	Larsen & Gottfried (1961)
granodiorite (1)	85			-	[FM MS]
I. Bath.					
monzonite (2)	78-99			-	
granodiorite (1)	72			-	
tonalite (1)	76			-	
granites (6)	40-50	50-60		-	Leonova & Tauson (1958) [FM MS]
syenite (3)	70	30		-	
qz syenite (3)	60-80	40-20		-	Leonova & Pogiblova (1961)
alaskite (1)	50	50		-	[FM MS]
granite	80			-	L'vov (1963) in Komarov <u>et al</u>. (1967) [FM TS]
granite (3)		"very considerable part"		-	Komarov <u>et al</u>. (1967) [FT TS]
granite:					
coarse (3)	16	84		-	Baranov & DuLieh-Tlien
medium (8)	32	68		-	[FM(?) MS]
fine (8)	43	57			

granite (a)	41	45.2	6.0	-	Barthel & Mehnert (1970) [FT TS]
granite (b)	37.5	56.7	5.5	-	
granite (2)		abundant accessories "minor" rare accessories "considerable amounts"		-	Willgallis (1970) [EM TS]

[FM MS] - Fluorometric methods on mineral separates.
[FT TS] - Fission track on polished thin sections.
[EM TS] - Electron microprobe analysis on polished thin sections.

Accessory U(Th) minerals could coat grain boundaries and fissures, and U(Th) minerals commonly occur as microscopic and submicroscopic inclusions in the major rock-forming minerals. For these reasons, particle track analysis on polished thin sections is probably a better method of U determination, and provides an easily interpreted map of U(Th) distribution. Interestingly enough, the few particle track studies indicate smaller amounts of U(Th) in the major minerals.

The particle track work most applicable to the southeastern U.S. plutons is Barthel and Mehnert's (1970) study of the U-Th distribution in Malsburger granite. Table A2 reproduces their Table 4, and gives a breakdown by mineral of the relative amounts of uranium (thorium). Considering that the accessories make up less than 0.5% by volume of the rocks, a small proportion of the rock is contributing a large amount of the total heat production. They also find the primary location (Hauptgitterplätze) of U and Th is in U-Th minerals such as uraninite, thorianite, thorite, uranothorite, brannerite, coffinite, whereas the primary location for trace elements other than U and Th(Y, Ce, Zr, etc.) is in the more abundant accessories zircon, apatite, monazite, xenotime, titanite, and allanite. The U (Th) content of the grain boundaries of the rocks they studied are small and are the result of secondary mineralization. The contribution from this source is probably highly variable depending on the geologic history of the deuteric alteration, hydrothermal fluids, and ground water.

Table A2

Zahl der α-Spuren pro Mineral (in %), Barthel and Mehnert (1970)
Number of α-tracks per mineral (in %)

Gesteintyp (rock type)	zircon	apatite	biotite	plagioclase	K-feldspar	quartz	Submikr. Einschlüsse (Inclusions)	Korngrenzen (grain boundaries)
ÄuBerer Kerngranit[1]	28.8	4.9	17.7	13.9	9.4	7.7	11.5	6.0
Ganggranit[2]	41.8	6.4	15.5	9.0	7.5	5.5	8.5	5.5

[1] 4.2 ppm U; 20 ppm Th
outer granualr granite

[2] 4.7 ppm U; 40 ppm Th
aplite

A few conclusions that can be drawn from these admittedly few studies are:

1. in most wholly crystalline rocks, a large percentage of the U (Th) is in the accessory minerals; in some rocks it may be equally divided between the major and accessory minerals.

2. The abundant accessory minerals (zircon, apatite, titanite, allanite, monazite, etc.) contribute only a small portion of the U (Th) balance whereas the rare but highly radioactive accessory minerals (uraninite, thorianite, thorite, uranothorite, coffinite, etc.) contribute a major portion.

3. the U(Th) contents of the major felsic minerals are small and nearly constant, and as granites do not vary greatly in model abundances of felsic minerals, the vast differences in whole rock U(Th) contents are the result of the mafic and accessory minerals in a rock.

4. U and Th contents differ from mineral to mineral, and partition coefficients for U(Th) vary from rock to rock depending on the mineral assemblage.

5. U and Th contents of a mineral can vary from grain to grain in a rock and can be compositionally zoned within a single grain.

6. only a small portion of the U(Th) is located along grain boundaries and fissures in secondary U(Th) minerals resulting from hydrothermal, deuteric, and weathering processes.

7. in glassy rocks, U(Th) is almost entirely enriched in the quenched melt except in cases where a U(Th) bearing accessory has begun to crystallize.

Willgallis (1970) also studied the Malsburger granite and reached the same conclusions as Barthel and Mehnert (1970). Using the electron microprobe limited his accuracy because of the lower limit of U (Th) detectibility and prevented his quantifying the U-Th balance of the rocks. Nevertheless, his results indicate that the U and Th contents of different grains of the same mineral (especially zircon) can be highly variable. It also shows that U and Th can be inhomogenously distributed within a single grain.

Structural, geologic, and petrologic features bearing on the low-temperature energy potential of the granites of the Piedmont

(iv) Grain Size

J. Alexander Speer

In each of the two post-metamorphic plutons studied thus far, two major facies can be distinguished on a textural and mineralogical basis. The most readily apparent difference is grain size--a coarse- and a fine-grained facies (see previous reports for descriptions). Average heat production values vary by nearly a factor of two between these two facies:

	coarse	fine
Liberty Hill	4.86 HGVU	8.74 HGVU
Winnsboro	5.29 HGVU	10.53 HGVU

Is the high heat production (high U(Th) content) in the fine-grained facies a result of grain size or are both high heat production and fine-grain size a result of some other condition? This question is important, for it is noted that the fine-grained rocks resist weathering more successfully than do the coarse-grained rocks. The difference in heat production could then be a result of differential weathering rather than of a petrogenetic origin.

Grain size is important in determining the location of U(Th) in a rock because grain boundaries may be important sites for U(Th). A fine-grained rock has more grain boundary area. Section iii suggests that U(Th) along grain boundaries contributes only a minor portion to the U-Th balance of a rock, but because the few studies of this point are not definitive, grain surface area may play an important role.

The role of weathering is even more difficult to evaluate. U(Th) values of drill core samples are sometimes higher than surface samples. Isotopic disequilibrium studies indicate 0-55% of the U and 50-80% of the Th has been lost (see Merz and Sinha, 2nd Progress Report of this contract). The isotopic disequilibrium studies have not as yet centered on a comparison of the fine- and coarse-grained granites in terms of the possibility of differential U loss, and whether weathering was important in causing the difference in heat production values.

The relatively tight clusters of heat production values around the averages is noteworthy. Major element chemistry shows that, while on the whole the fine-grained granites are more differentiated than the coarse-grained granites, the range of fine-grained granite compositions coincides with the compositions of the more differentiated coarse-grained granites. If higher heat production was the result of differentiation, a trend should be evident showing the increase of heat production with differentiation rather than a bimodal distribution of heat production values.

The relation of U(Th) content and grain size has been noted before in a study of rock types in a granite massif (Baranov and Du Lien-T'ien 1961). Successively younger facies of the massif have generally increasing U contents and decreasing Th contents as well as decreasing grain size (except pegmatites):

Rock	Samples	U	Th	% U in essential minerals	% U in accessory minerals
		$n.10^{-4}\%$			
Coarse	3	7.2	4.2	16.5	83.5
Medium	8	8.1	3.2	31.8	68.2
Fine-granites		5.9	3.1		
aplites	8	17.1	2.7	43.4	56.6
pegmatites		54.0	2.9		

From the ratio of the uranium content of the accessory minerals to that the major minerals, they concluded that the uranium content of a rock is related to the rate of crystallization as exemplified by the grain size of a rock. In finer-grained rocks which crystallized rapidly, the major minerals would include more of the uranium in the melt than did the same minerals of the slowly crystallizing magma.

In light of section iii, Baranov and Du Lien-T'ien (1961) found the average U contents of the felsic minerals to be nearly identical for the coarse- ($1.4 \times 10^{-4}\%$) and medium-grained ($1.5 \times 10^{-4}\%$) granites, implying that the rate of crystallization of the mafic and accessory minerals is responsible for the variations in whole rock U content.

This explanation is attractive for the Liberty Hill and Winnsboro plutons in view of the volatile-rich conditions indicated for the fine-grained granites by their mineralogies. A volatile-rich granite magma lies close to the solidus. A drop in pressure resulting from intrusion into a higher level in the crust (the fine-grained granites are intruded into the coarse-grained granites, presumably from below), would pressure quench a volatile-rich granite. In comparison, volatile-poor granites can crystallize only by a drop in temperature, which occurs much more slowly, especially at the depth of emplacement of the Liberty Hill and Winnsboro plutons.

Rolesville Batholith Drill Cores

Stewart Farrar

Five drill cores were taken of the Rolesville batholith (Fig. A2-A5). RL 1 is in the Castalia pluton. RL 2, 4, and 5 are in the main phase of the batholith. RL 3, in the coarsely porphyritic Archers Lodge border phase, was abandoned when it was found to lie wholly within a fracture zone from which no fresh sample could be obtained.

RL 1 lies approximately in the center of the main lobe of the Castalia pluton. The core consists of medium grained (2-5 mm) biotite granite. It contains no xenoliths, and only minor pegmatite dikes (Fig. A2). The granite is massive, unlayered, and quite uniform in composition and grain size. It has a very weak local biotite foliation. An approximate mode gives equal amounts of quartz, plagioclase (An_{20-25}) and K-feldspar, with 5% biotite. It has accessory titanite, zircon, allanite, and opaque.

The pegmatite dikes in RL 1 contain biotite, quartz, and two feldspars. In outcrop they also contain minor garnet, although it was not observed in core samples.

The uniformity of the RL 1 granite is also indicated by the linearity of the gamma log for this hole (Fig. A2).

RL 2, 4, and 5 all lie in the main phase of the Rolesville batholith. The petrographic logs of these cores (Figures A3, A4, A5) indicate the diversity of the main phase. The dominant rock type in each core is a medium- to coarse-grained (0.4-2.5 cm) biotite granite. An approximate mode is 5% biotite, 25% quartz, 35% plagioclase, 35% K-feldspar (see report VPI&SU-5103-3 for modes of surface samples).

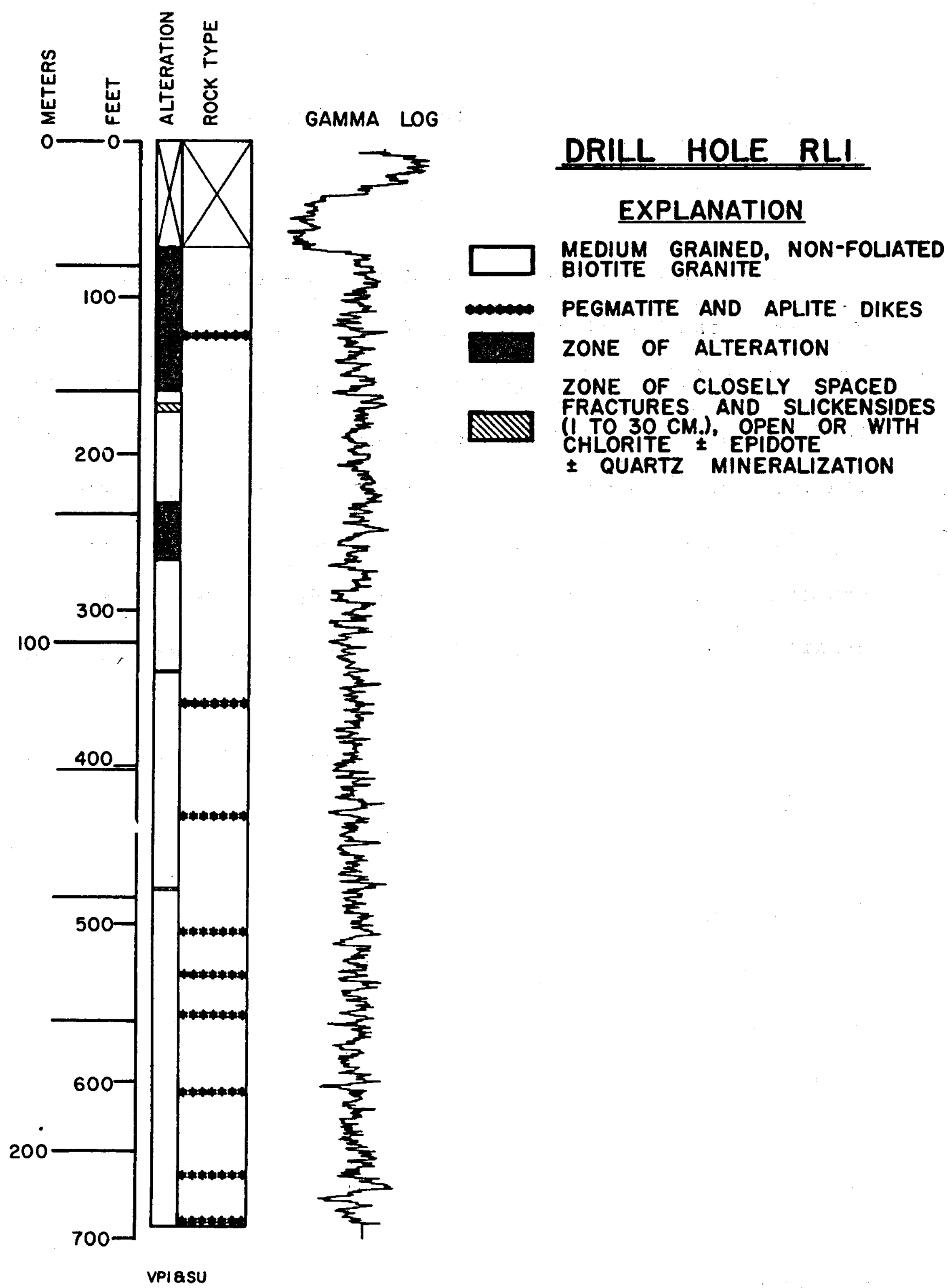

Figure A2. Lithologic and gamma log of the R1 1 drill hole, Castalia pluton of the Rolesville batholith.

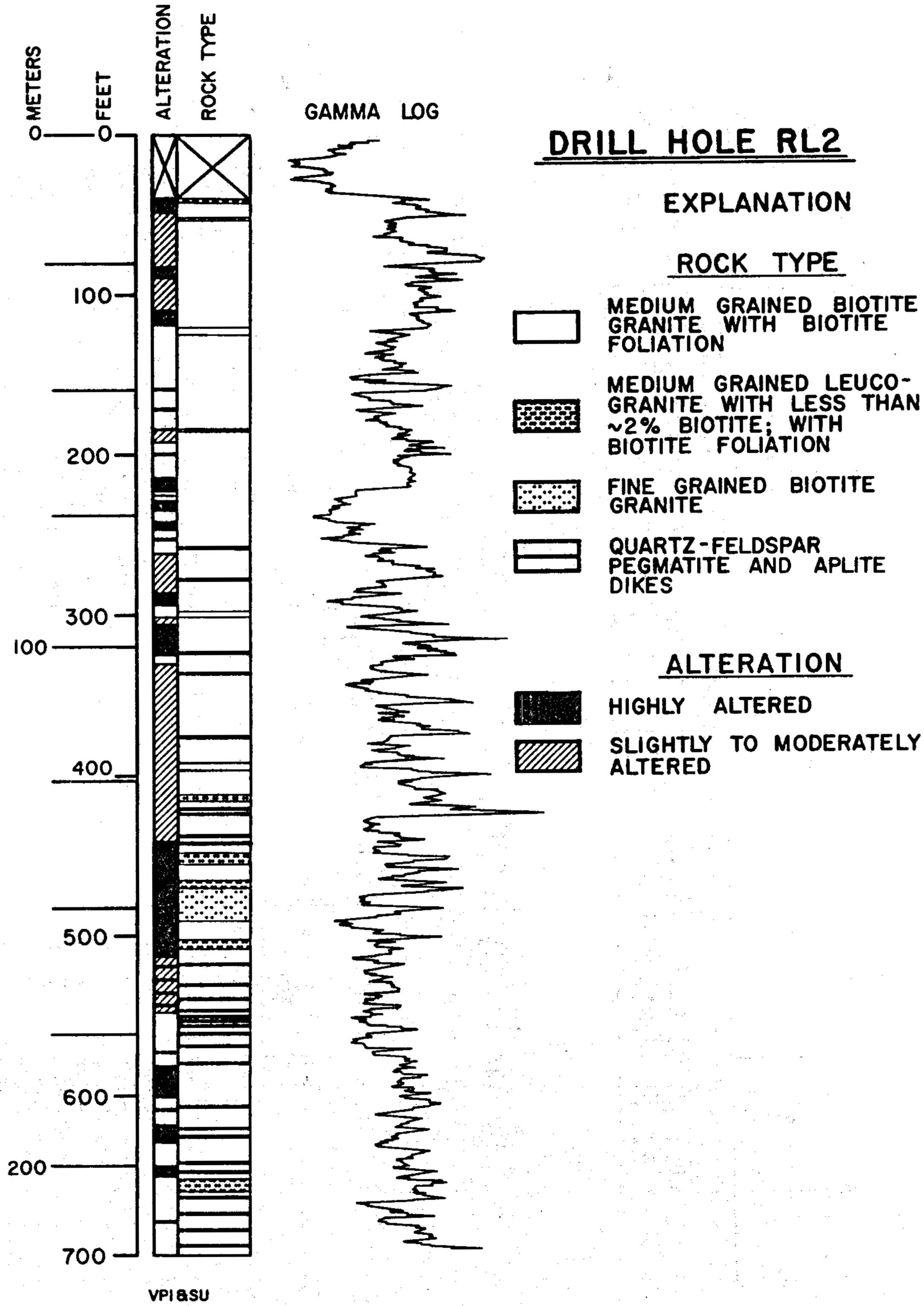

Figure A3. Lithologic and gamma log of the Rl 2 drill hole, Rolesville batholit

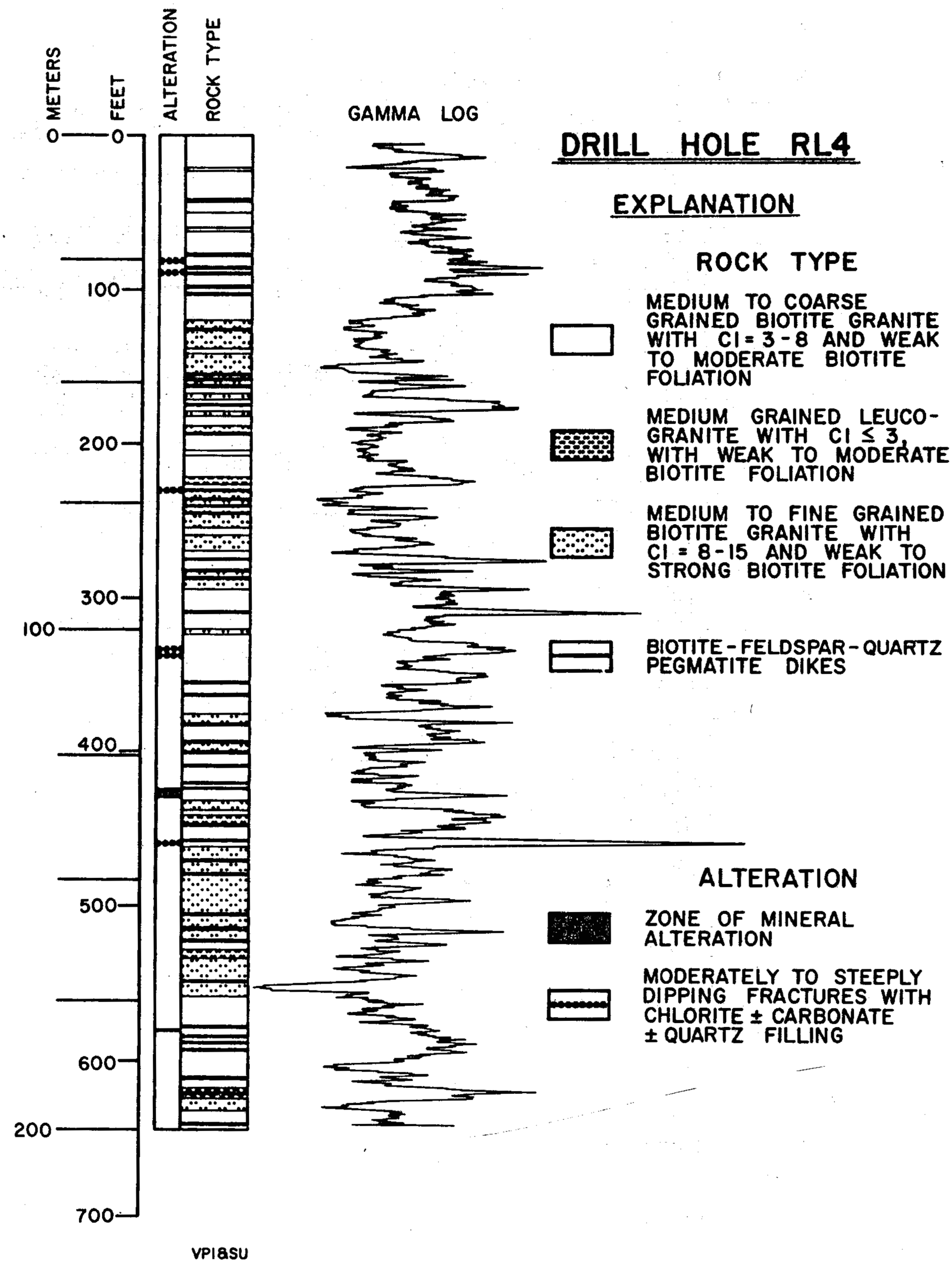

Figure A4. Lithologic and gamma log of the Rl 4 drill hole, Rolesville batholith

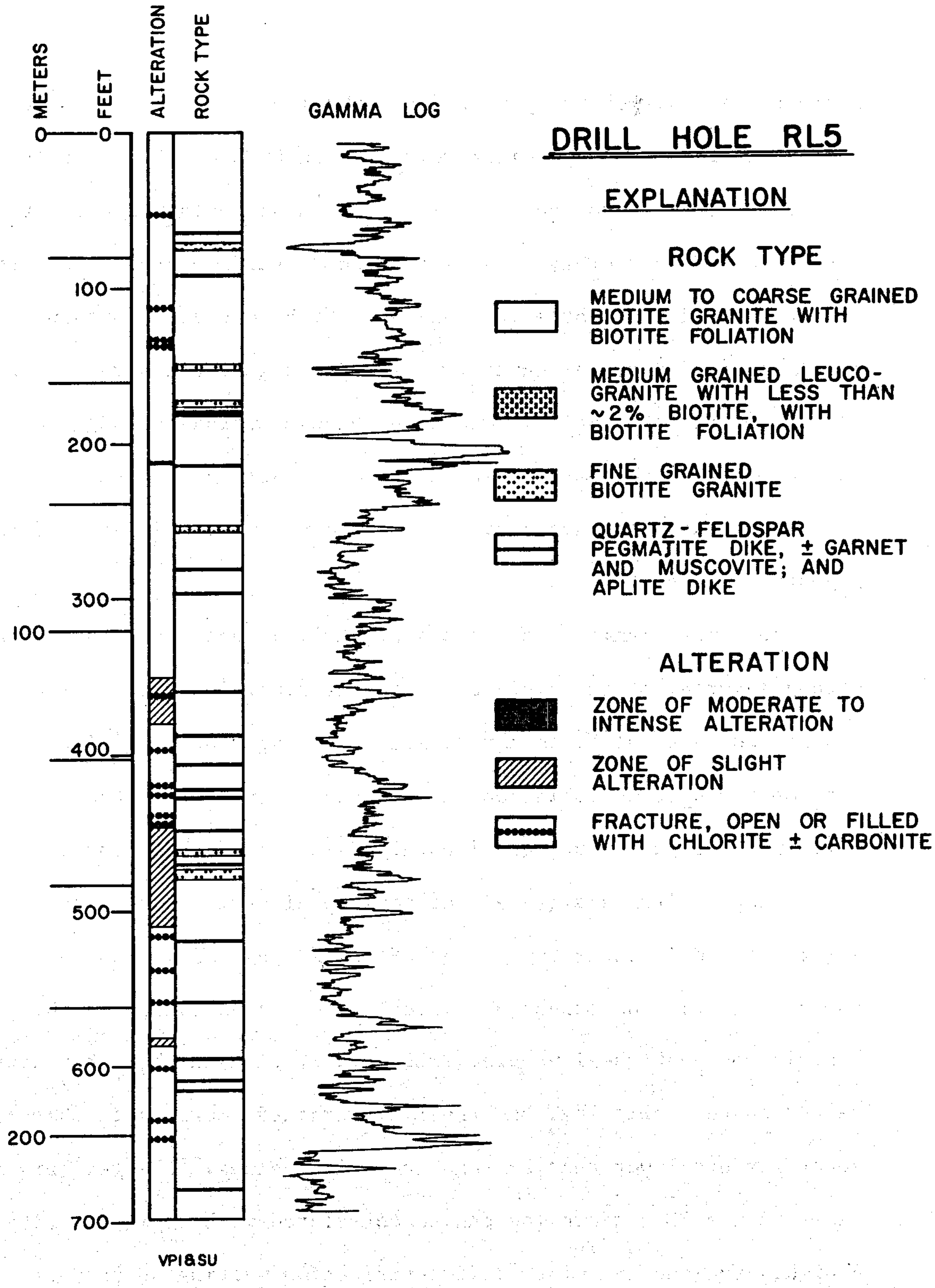

Figure A5. Lithologic and gamma log of the Rl 5 drill hole, Rolesville batholith.

A finer grained, generally more mafic granite (C.I. ≡ 10) is an important component of RL 4, but a minor rock type in RL 2 and 5. A medium-grained biotite leucogranite (C.I.≡ 2) is also a minor component of each core. This rock type is also found in surface exposures--apparently as dikes cutting the other two phases. Each core also contains a combination of biotite-quartz-two feldspar pegmatitic dikes and biotite-quartz-two feldspar aplitic dikes which have intruded along fractures in the other three phases. In RL 5, and in surface exposures north of RL 5, garnet and muscovite are accessory minerals in some of the pegmatite dikes.

The three granitic rock types of RL 2, 4, and 5 all have weak to strong layering of the biotite. This layering, in the core samples, appears to be parallel to a moderate to strong biotite foliation. In outcrop the biotite foliation can be seen to cut across the compositional layering. No xenoliths were identified in any of these cores.

The plentiful small scale compositional variations in these cores are reflected in their gamma logs (Figs. A3, A4, A5). Most of the gamma log variation cannot be directly tied to variation in the petrographic log, but the leucogranite generally gives higher than average values on the gamma log, and the finer grained, more mafic phase generally has lower than average gamma log values. The two largest peaks in the RL 4 gamma log can be correlated with pegmatite dikes. A highly radioactive mineral (identification waiting on preparation of polished sample) was found in a sample from the pegmatite causing the greatest deflection.

Alteration is plentiful in RL 2, but less important in the other cores. Alteration includes saussuritization of the plagioclase, and alteration of biotite to chlorite. There has been some introduction of sulfides and muscovite along fractures, and local earbonate-zeolite assemblages along the latest fractures.

Review

After one year's study of the post-metamorphic plutons of the southeastern Piedmont, several facts are beginning to emerge. The plutons are multiple-intrusive granitic complexes with weakly concentric distribution of rock units, suggesting that they are centered complexes. The younger units are characterized by, among other features, their finer grain size and higher heat productions. These fine-grained granites compose 40% or less of the exposed outcrop. They cannot be separated from the coarse-grained granites in terms of major element chemistry, but their mineralogies indicate higher volatile contents during crystallization.

The only detectable regional difference among the plutons is the more sodic nature of the southernmost plutons as indicated by their more sodic plagioclases. Mineral assemblages and compositions of coexisting phases in contact aureoles and xenoliths indicate that some of the plutons were emplaced under pressure and temperature conditions of 4.5-5.5 kb and 750-800°C. The high temperatures are consistent with the interpretation, based on Sr isotopes, that the granites were derived from the lower crust or upper mantle. Associated gabbros are tentatively believed to be of the same age, suggesting that the late Paleozoic plutonic event was a granite-gabbro bimodal suite.

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B. GEOCHEMISTRY

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Post-Metamorphic Plutons

Three post-and syn-metamorphic plutons, Liberty Hill and Winnsboro, South Carolina and Rolesville, North Carolina, have been studied in detail and reported in previous progress reports (VPI&SU-2,3,4). Data on them will be discussed further here.

Each of the three plutons has been divided on the basis of field and chemical evidence into two or more units. Liberty Hill is divided into coarse and fine grained units, Winnsboro into Winnsboro and Rion granites and Rolesville into Rolesville, Castalia and Louisberg plutons. Mean chemical compositions of surface samples from these units are given in Table B1. In addition, samples from three cores in Liberty Hill (Ker 1, 2 & 3, VPI&SU-3) and one in Rion (Win 1, report VPI&SU-4) have been analyzed, and their mean compositions are given in Table B2.

Comparison of the surface and core data reveals that between the Win 1 core and Rion surface samples there are no differences in oxide weight percentages which exceed the standard deviation on either core or surface means. The same is true for the Th values though the U values differ by an amount greater than the standard deviation of the surface samples. Both U and Th means are higher in the core than on the surface but the difference is small, about 2 ppm for both U and Th. There is little difference between the major element compositions of the Liberty Hill fine surface samples and the fine grained portions of Ker 3, although the latter has higher Na_2O, the difference being greater than the standard deviation on either mean. The U contents of the fine grained core samples vary greatly, as shown by the large standard deviation, and in fact there is only one Ker 3 sample which

Table B1

Mean Compositions of Surface Samples

No. of Samples	Winnsboro granite (6)	Rion (16)	Liberty Hill coarse (15)	Liberty Hill fine (4)	Rolesville (18)	Castalia (3)	Louisbei (1)
U ppm	2.68	5.23	2.87	4.55	3.99	4.34	3.07
(st. dev.)	(0.43)	(1.58)	(0.71)	(0.67)	(1.56)	(1.74)	
Th ppm	14.64	31.55	14.57	28.7	17.83	13.76	30.81
(st. dev.)	(2.48)	(3.62)	(4.05)	(3.88)	(4.51)	(3.57)	
SiO_2	72.91	72.73	67.25	71.72	71.18	75.26	72.53
(st. dev.)	(3.30)	(1.71)	(3.18)	(1.29)	(2.91)	(3.43)	
Al_2O_3	15.02	15.20	15.99	15.59	15.59	14.12	15.22
(st. dev.)	(2.39)	(0.29)	(1.00)	(0.22)	(0.94)	(0.44)	
CaO	1.14	1.41	2.14	1.48	1.82	1.59	1.58
(st. dev.)	(0.50)	(0.24)	(0.42)	(0.12)	(0.44)	(0.64)	
MgO	0.48	0.54	0.95	0.55	0.70	0.54	0.52
(st. dev.)	(0.20)	(0.11)	(0.16)	(0.12)	(0.27)	(0.47)	
K_2O	5.47	5.36	5.66	5.53	4.52	4.22	5.11
(st. dev.)	(0.27)	(0.25)	(0.48)	(0.18)	(0.46)	(0.53)	
FeO	2.50	1.80	3.00	1.85	1.77	1.26	1.45
(st. dev.)	(0.68)	(0.35)	(0.77)	(0.42)	(0.55)	(0.79)	
Na_2O	3.62	3.50	3.55	3.46	3.73	3.70	3.63
(st. dev.)	(0.28)	(0.17)	(0.22)	(0.19)	(0.30)	(0.34)	
MnO	0.08	0.05	0.06	0.04	0.04	0.05	0.04
(st. dev.)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	
TiO_2	0.33	0.27	0.52	0.29	0.30	0.17	0.25
(st. dev.)	(0.15)	(0.09)	(0.14)	(0.12)	(0.11)	(0.11)	
P_2O_5	0.11	0.11	0.19	0.12	0.11	0.06	0.10
(st. dev.)	(0.07)	(0.04)	(0.05)	(0.05)	(0.04)	(0.03)	

Table B2

Mean Compositions of Core Samples

No. of Samples	WIN1 Rion (17)	KER1 LH fine (1)	KER2 LH coarse (5)	KER3 LH coarse (9)	KER3 LH fine (3)
Uppm	7.32	5.65	3.11	2.32	6.59
(st. dev.)	(1.90)		(0.02)	(0.08)	(4.40)
Th ppm	33.58	21.33	14.18	11.64	29.25
(st. dev.)	(4.40)		(0.90)	(2.02)	(8.36)
SiO_2	72.65	73.82	66.31	67.22	72.12
(st. dev.)	(1.08)		(0.41)	(2.43)	(2.32)
Al_2O_3	15.46	14.37	16.06	15.81	15.34
(st. dev.)	(0.28)		(0.09)	(0.47)	(0.21)
CaO	1.41	1.38	2.53	2.34	1.44
(st. dev.)	(0.11)		(0.10)	(0.40)	(0.28)
MgO	0.46	0.49	0.96	0.88	0.42
(st. dev.)	(0.09)		(0.04)	(0.16)	(0.15)
K_2O	5.50	5.27	5.02	5.17	5.41
(st. dev.)	(0.31)		(0.18)	(0.25)	(0.14)
FeO	1.82	1.91	3.28	3.23	1.93
(st. dev.)	(0.26)		(0.13)	(0.61)	(0.75)
Na_2O	3.53	3.72	4.06	3.95	3.92
(st. dev.)	(0.07)		(0.07)	(0.17)	(0.19)
MnO	0.05	0.05	0.06	0.06	0.04
(st. dev.)	(0.01)		(0.01)	(0.01)	(0.01)
TiO_2	0.23	0.29	0.60	0.57	0.27
(st. dev.)	(0.04)		(0.03)	(0.11)	(0.15)
P_2O_5	0.10	0.08	0.21	0.20	0.11
(st. dev.)	(0.02)		(0.01)	(0.04)	(0.07)

has U greater than the surface mean. The difference between the Th values is insignificant. The differences between the Liberty Hill coarse and fine surface samples are reflected in the core specimens. The fine grained samples appear more highly differentiated having higher SiO and lower CaO, MgO, FeO, TiO_2 and P_2O_5. The coarse core has virtually the same U and Th as the surface samples although the scattered Th values of Ker 3 have a lower mean than the surface values. Any increases in U and Th from surface to core samples appear to be slight.

Strekeisen's (1976) classification scheme based on normative Or-An-Ab proprotions was used to classify the samples. Samples with <17% normative Qz are classified separately from those with >17%. The only samples to have <17% normative Qz are six Liberty Hill coarse grained surface samples, the whole of the Liberty Hill coarse grained core, Ker 2, and four coarse grained samples from Ker 3. These fall in the calc-alkaline syenite field of the appropriate Or-Ab-An diagram. For the higher normative Qz samples no distinction is made, on Strekeisen's diagram, between alkaline and calc-alkaline fields. All the high Qz Liberty Hill samples are defined as syenogranites as are the Rion and most of the Winnsboro samples. Three Winnsboro granite samples fall in the alkali feldspar granite field. The samples from the entire Rolesville complex fall in one group on the margins of the syenogranite and monzogranite fields.

In terms of alumina saturation, all the Rolesville and Winnsboro-Rion samples are peraluminous, containing normative corundum. One of the Liberty Hill coarse surface samples, the coarse grained Ker 2 core and five coarse grained Ker 3 samples, including the four low normative

Qz ones mentioned above, have no normative corundum. Using the classification given in Carmichael et al. (1974) these samples would be metaluminous, i.e., having a molecular proportion of Al_2O_3 less than molecular $CaO + Na_2O + K_2O$ but greater than $Na_2O + K_2O$. The rest of the Liberty Hill coarse samples and all the Liberty Hill fine samples are peraluminous.

It is difficult to assign definitions such as alkaline or calc-alkaline to the plutons because the narrow range of compositions precludes the use of Peacock's (1931) alkali-lime index. However, when our data are plotted on a K-Na-Ca triangular diagram and compared with data from well-known alkaline and calc-alkaline rock series, they compare most closely with the calc-alkaline series.

Figure B1 shows plots of normative Qz-Ab-Or for all three plutons with the water saturated phase diagrams for various pressures. The Winnsboro and Rion data all fall in one field while the Liberty Hill fine samples plot towards the edge of the Liberty Hill coarse field. The three Castalia points fall just outside of the Rolesville field. On all three diagrams the inner solid line encloses 90% of the data points so the position of the smaller fields is the most important feature of the diagrams. For the Liberty Hill and Winnsboro plutons, petrologic evidence (see petrology section report) suggests depth of emplacement of about 14-16 km or 4-1/2 to 5 kb. The Liberty Hill plot is consistent with such a depth of emplacement as the most differentiated samples lie near the 5 kb cotectic. The petrologists believe that feldspar was an early crystallizing phase. For the Winnsboro-Rion the situation is less clear. Again, it is likely that

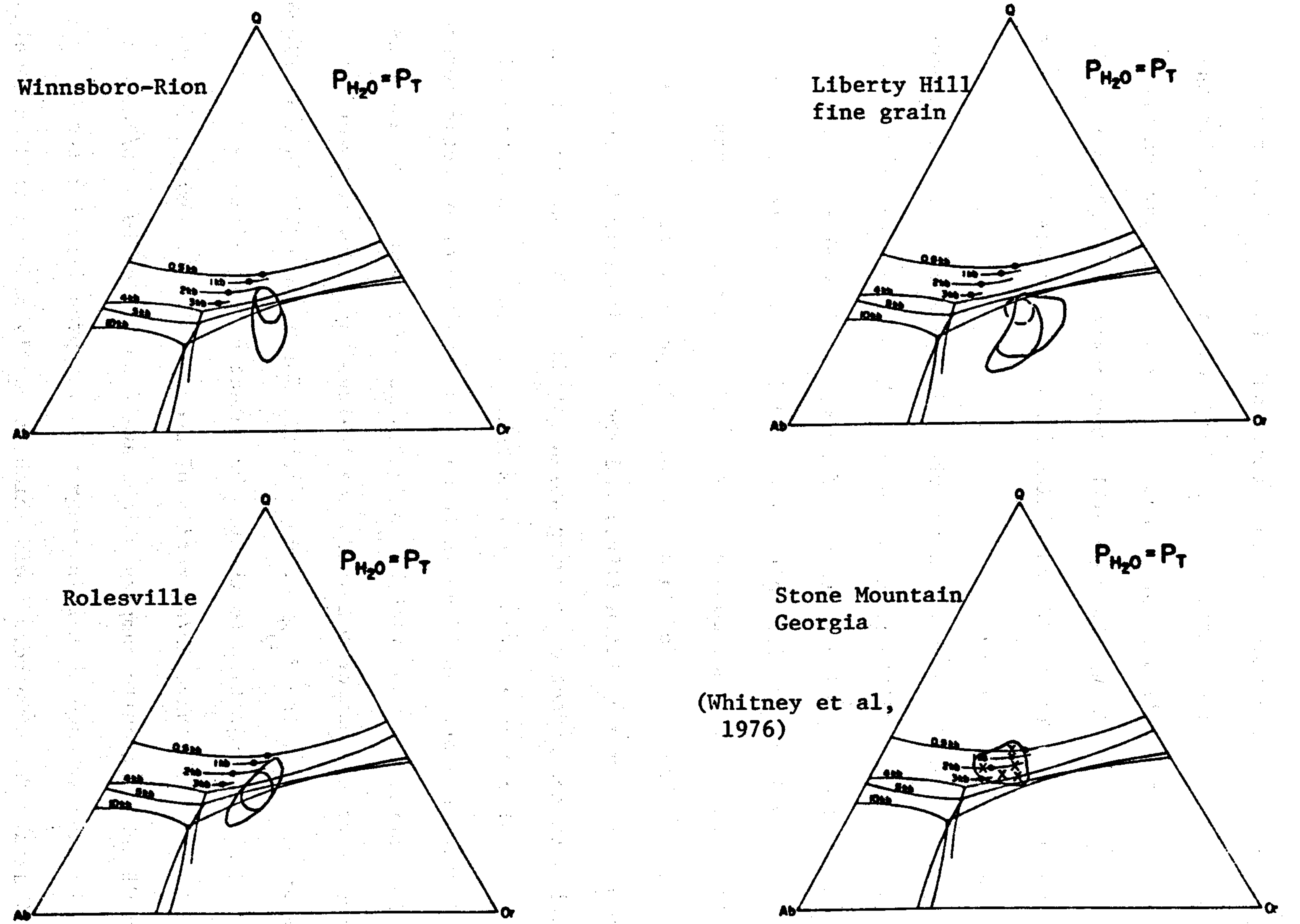

Fig. B1. Normative Q-Ab-Or diagram. Outer field encloses all data points, inner field 90% of them. Stone Mountain data is shown for comparison.

feldspar was an early crystallizing phase, but the normative data lie completely in the primary feldspar field only for P_{H_2O} less than 2 kb. However, on a diagram for $P_{H_2O} = 0$, the data fall within the primary feldspar field at pressures of 4-5 kb. In comparison with the Liberty Hill data, the Rolesville data suggest a shallower depth of emplacement. The field containing 90% of the points lies close to the $P_{H_2O} = 2$ kb minimum.

As well as differences in the phase diagrams arising from amount of water present, differences arise from the presence of other components. The very highest totals of normative Qz + Ab + Or are 89% for Liberty Hill, 92% for Rolesville, and 93% for Winnsboro. Significant amounts of other components are present and one of these is anorthite. The effect of An on the Q-Ab-Or phase diagram has been demonstrated by von Platen (1965) and the base diagrams in Figure B2, which show the effect of varying Ab/An ratios on the position of the $P_{H_2O} = 2$ kb cotectic, are taken from this reference. The effect of increasing proportions of An is to make the minimum or eutectic composition increasingly Or rich and slightly more Qz rich. The result is movement of the eutectic towards the An-free eutectics of lower pressures, e.g., the $P_{H_2O} = 2$ kb eutectic for Ab/An = 5.2 is very close on a Q-Ab-Or projection to the 0.5 kb eutectic for Ab/An = ∞.

Our samples have Ab/An ratios of about 2.5 to 6.5 except for the six Winnsboro granite samples which have from 4.5 to 10.6 Ab/An. It can be seen at once that this diagram is inappropriate for the Liberty Hill data. The Winnsboro field which is mostly made up of Rion samples with Ab/An less than six, lies well below the $P_{H_2O} = 2$ kb eutectic for

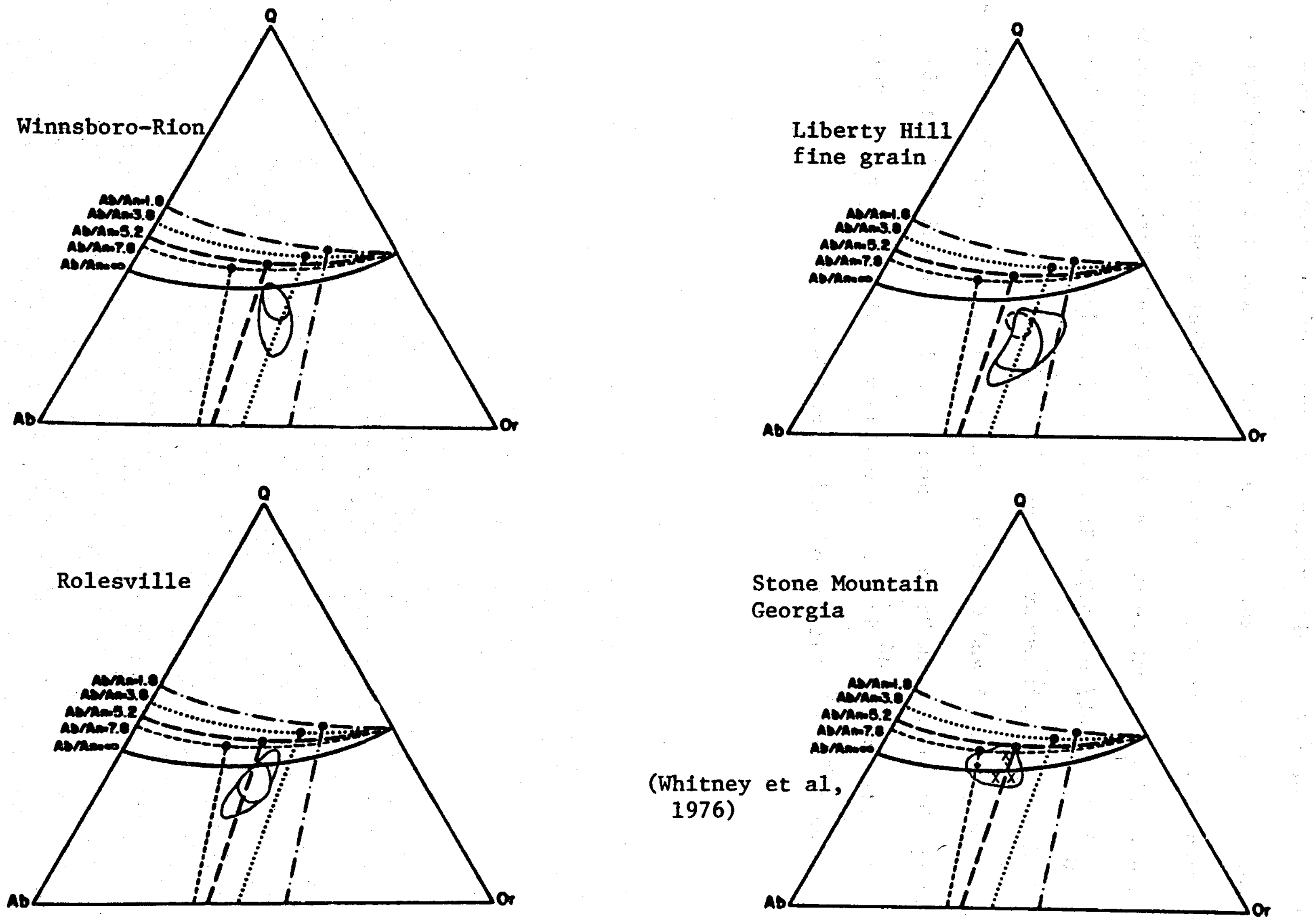

Fig. B2. Normative Q-Ab-Or diagram, as in Fig. B1, showing the effect of an An component.

Ab/An of 7.8 or less. This implies a pressure of equilibration considerably greater than 2 kb. The same could be said of the Rolesville data except for one point, shown in the outer field, which has Ab/An = 5.3, a total or normative Qz + Ab + Or of 92% and plots very close to the P_{H_2O} 2 kb for Ab/An = 5.2. This is good evidence for a relatively shallow depth of emplacement of the Rolesville pluton.

The Liberty Hill and Winnsboro granites have been dated by Fullagar (1971) by the whole-rock Rb-Sr isochron method. Liberty Hill is 299 ± 15 m.y. with Sr^{87}/Sr^{86} initial of 0.7046 ± .0010 and Winnsboro 301 ± 4 m.y. with Sr^{87}/Sr^{86} initial of 0.7047 ± .0004.

Analytical Procedure

The Philips PW1450 automatic sequential X-ray spectrometer has been calibrated for the ten major element oxides: SiO_2, Al_2O_3, CaO, MgO, K_2O, FeO, Na_2O, MnO, TiO_2, P_2O_5. The most recent recalibration for the major elements was performed in September 1977 and the measuring parameters selected at that time are given in Table B3.

For all elements, except silicon and aluminum, other than slight adjustments in two theta angles the measuring parameters have remained unchanged since the machine came into operation. However, in September, the analysing crystal for Si and Al which had been PET was replaced by EDDT due to thermal instability of the former crystal.

In September, the method of analysis was changed slightly to allow use of a monitor. When analyses are performed by the XRF, up to four samples can be loaded at one time and now the monitor, a Corning glass disc, is run with batches of three samples. Sample intensities are automatically divided by the intensities obtained on the monitor and these intensity ratios are used by the XRF computer in calculating element concentrations. This method has the advantage of eliminating the effect of any fluctuations in measured intensities with time.

The Philips minicomputer, P952M, programmed with Philips softwear package XR55-P2, calculates concentrations from intensities using the results of a regression analysis on standards data. We used sixteen standards, including five U.S. Geological Survey ones (Flanagan, 1976), which ranged from 58% to 73.4% SiO_2 and thus the regression was applicable to intermediate-felsic rock compositions. The Philips regression analysis module allows alpha correction factors to be calculated, to correct for the

Table B3

Measurement Parameters for Major Element Analyses

Element	Crystal	2 Theta Angle Degrees	KV	mA	Counting Time Seconds
Si	EDDT	108.20	60	45	10
Al	EDDT	142.79	60	45	20
Ca	LIF200	100.35	60	45	20
Mg	TLAP	45.30	40	70	40
Mg background	TLAP	44.29	40	70	20
Mg background	TLAP	45.74	40	70	20
K	LIF200	136.82	60	20	10
Fe	LIF200	57.65	60	30	10
Na	TLAP	55.22	40	70	40
Mn	LIF200	63.10	60	45	40
Mn background	LIF200	62.20	60	45	20
Mn background	LIF200	63.74	60	45	20
Ti	LIF200	86.28	60	45	10
Ti background	LIF200	85.50	60	45	4
Ti background	LIF200	87.00	60	45	4
P	PET	89.51	60	45	40

interference of another element, or elements, on an element intensity. Table B4 gives the results of the September 1977 regression analysis, alpha correction factors, intercept and inverse of slope of the regression line and statistical parameters showing the fit of the line to the data after alpha corrections have been applied. The concentrations are calculated, by the computer, using the equation:

$$C_i = (d_i + E_i R_i)(1 + \Sigma \alpha_{ij} C_j)$$

where:

C_i = concentration of element i,

D_i = intercept of element i regression line,

E_i = inverse slope of element i regression line,

R_i = intensity ratio of element i,

α_{ij}= alpha correction factor for element j on element i

C_j = concentration of element j

One USGS standard was excluded from the regression for use as a measure of the accuracy of our analyses. Data obtained by us on this sample together with the published analysis are given in Table B5 with the differences between the two expressed as a percentage error. We believe that our analyses are sufficiently accurate, for samples with up to about 75% SiO_2, to enable detailed element distributions and correlation to be studied. Due to lack of standards with SiO_2 > 75%, we have some difficulty in analyzing high SiO_2 samples. Analyses with apparent SiO_2 contents of over 75% SiO_2 often have apparent total oxide concentrations of well over 100%. Corrections to be applied to high SiO_2 data are at present being designed for us by Philips.

Table B4

Regression Data

Element (oxide)	Intercept	1/Slope	Sigma Error	Interfering Oxide	Alpha
SiO_2	40.510	3.561	0.325	FeO	-1.043
				K_2O	.298
				Al_2O_3	-.736
				SiO_2	.333
Al_2O_3	.377	5.711	0.249	SiO_2	-.331
CaO	.0121	40.084	.0527	K_2O	1.458
MgO	.0194	8.764	.117	FeO	1.718
				SiO_2	-.821
K_2O	-.0115	.833	.0492	SiO_2	.448
FeO	-.238	1.341	.107	CaO	3.079
Na_2O	-.226	.751	.152		
MnO	.0195	.0235	.0062	SiO_2	-.643
TiO_2	-.0208	.0030	.0223		
P_2O_5	.0023	.0755	.0162		

Table B5

Accuracy of Analytical Data

	Published (chemical method)	Published range	Our Data	% Error
SiO_2	65.93	64.50 - 65.98	65.00	±1.4%
Al_2O_3	16.34	15.82 - 16.67	16.53	±1.3%
CaO	3.20	3.16 - 3.26	3.15	±2%
MgO	1.02	0.83 - 1.11	0.81	±20%
K_2O	3.60	3.43 - 3.70	3.60	0%
FeO	3.87	3.87 - 4.19	3.99	±3%
Na_2O	4.25	3.93 - 4.28	4.35	±3%
MnO	0.10	0.09 - 0.10	0.09	±10%
TiO_2	0.61	0.60 - 0.68	0.65	±7%
P_2O_5	0.25	0.20 - 0.27	0.24	±4%

NOTE: % error is the difference between our data and the published chemical method data expressed as a percentage of the latter. Since QLO-1 is a new USGS standard with relatively few analyses, the range of values on this standard including XRF and AA determinations published in Flanagan (1976), is included.

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C. GEOPHYSICS

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Geothermal Gradients and Heat Flow

by

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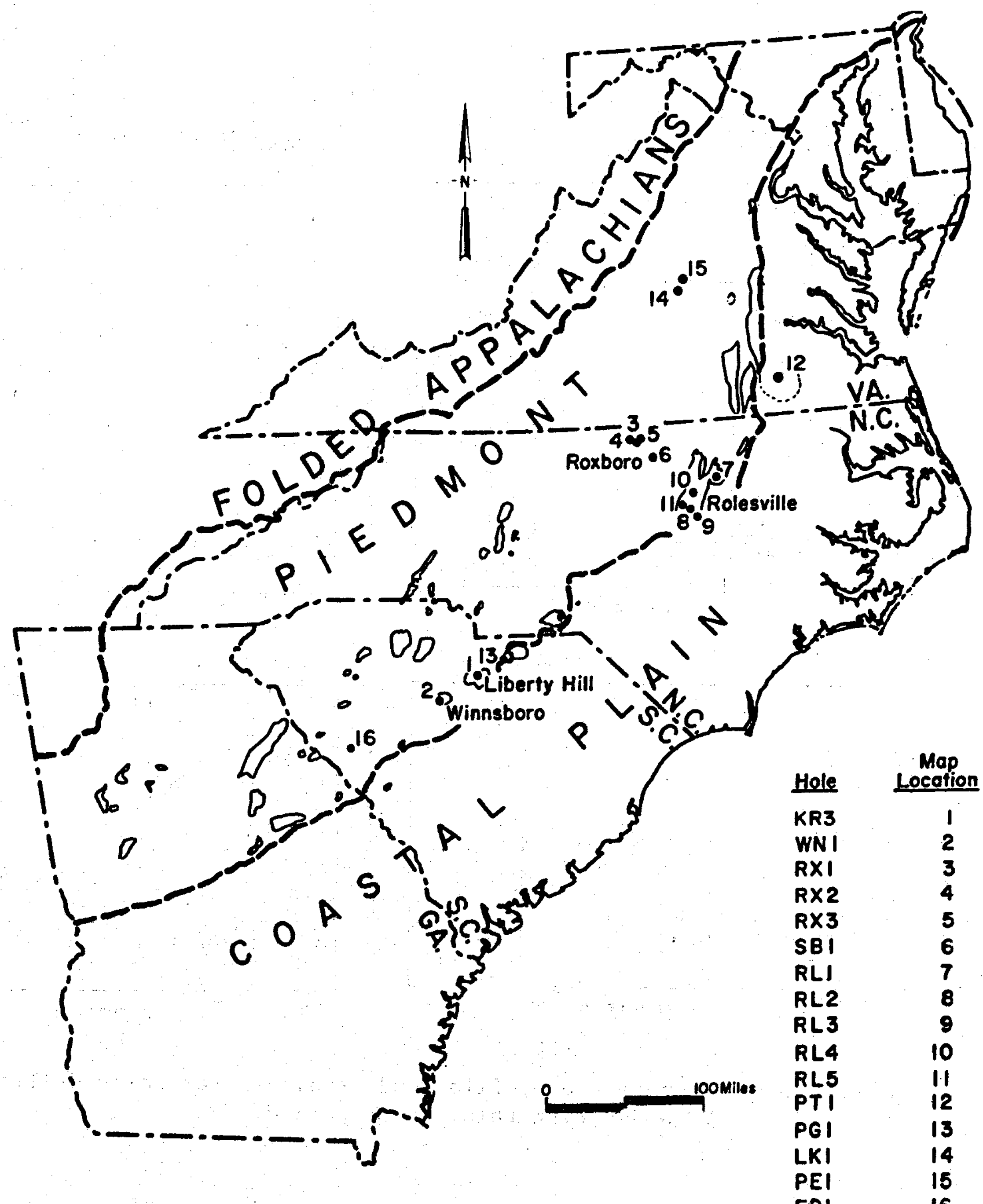
Figure C-1 shows locations of holes drilled to date by VPI&SU in the southeastern United States. Temperature profiles and gradients at locations not reported in previous reports are shown in Figure C-2.

Table C-1 summarizes geothermal gradients, thermal conductivity, and heat flow determinations available to date for this contract. This table appears in each report, beginning with VPI&SU-5103-4, and is periodically updated as thermal conductivity values and heat flow determinations become available. Slight changes in geothermal gradients appearing in Table C-1 are the result of relogging these holes as they reach thermal equilibrium and recover from the effects of drilling. Changes in gradients are not expected to be more than a few percent.

The method by which thermal conductivity and gradients are determined are described in previous reports (VPI&SU-5103-1,2,3,4). Thermal conductivity determinations are reported herein for RX2, RX3, RL1, and SB1 (Roxboro, Rolesville, and Slate Belt). Values are given in Tables C-2, C-3, C-4, and C-5.

Heat flow values are determined in two ways: 1) Multiplication of the average thermal conductivity over the gradient for that interval, and 2) The Bullard approximation (Bullard, 1939). The results are the same within experimental error.

Heat flow values completed to date under this contract are shown in Figure C-3.



Hole	Map Location
KR3	1
WN1	2
RX1	3
RX2	4
RX3	5
SB1	6
RL1	7
RL2	8
RL3	9
RL4	10
RL5	11
PT1	12
PG1	13
LK1	14
PE1	15
ED1	16

Figure C-1. Locations of holes drilled to date by VPI&SU in SE United States.

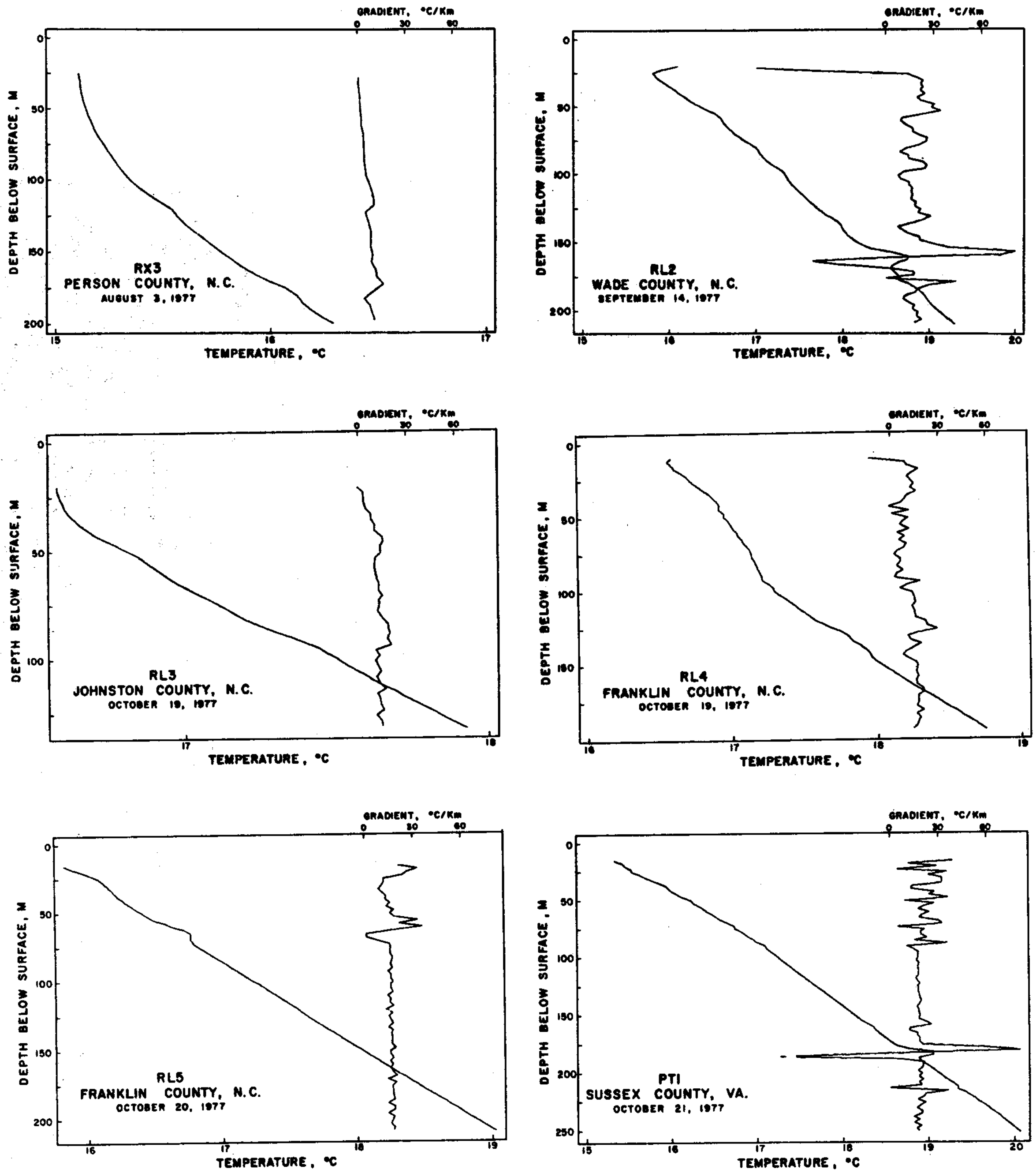


Figure C-2. Temperature profiles and gradients for holes drilled by VPI&SU during this report period.

TABLE C-1 SUMMARY OF HEATFLOW DATA NOVEMBER 19, 1977

LOCATION	LATITUDE	LONGITUDE	DATE LOGGED	HOLE DEPTH (METERS)	DEPTH INTERVAL (METERS)	GRADIENT[3] (°C/KM)	CONDUCTIVITY[3] (MCAL/CM-SEC-°C)	HEAT FLOW (CAL/CM^2-SEC)
LIBERTY HILL - KERSHAW PLUTON, LANCASTER CO., SOUTH CAROLINA								
KR3	34°32'20"	80°44'51"	11/18/76	277	316.8-404.3	14.91 ±0.02 (36)	7.14 ±0.57 (24)[4]	1.07 ±0.09[1]
					334.3-341.8	14.68 ±0.07 (4)	6.94 ±0.47 (3)[4]	1.02 ±0.07[1]
								1.02 ±0.03[2]
					344.3-356.8	15.06 ±0.07 (6)	7.09 ±0.54 (5)[4]	1.07 ±0.09[1]
								1.05 ±0.02[2]
					359.3-369.3	14.88 ±0.07 (5)	7.33 ±0.20 (4)[4]	1.09 ±0.04[1]
								1.09 ±0.01[2]
					371.8-384.3	14.85 ±0.06 (6)	7.07 ±0.28 (5)[4]	1.05 ±0.05[1]
								1.05 ±0.01[2]
					386.8-401.8	15.00 ±0.13 (7)	6.94 ±0.69 (6)[4]	1.04 ±0.11[1]
								1.04 ±0.01[2]
RION PLUTON, FAIRFIELD CO., S. C.								
WN1	34°18'48"	81°08'42"	7/5/77	574.3	24.24-571.74	18.18 ±0.04 (220)	8.06 ±0.24 (26)	1.47 ±0.05[1]
ROXBORO METAGRANITE, PERSON CO., N.C.								
RX1	36°23'12"	78°58'00"	5/19/77	240	146.8-249.3	10.83 ±0.03 (42)	8.97 ±0.41 (32)	0.97 ±0.05[1]
					146.8-184.3	11.03 ±0.06 (16)	9.08 ±0.11 (15)	1.00 ±0.02[1]
								1.00 ±0.01[2]
					219.3-231.8	10.94 ±0.12 (16)	9.76 ±0.59 (5)	0.96 ±0.08[1]
								0.95 ±0.01[2]
RX2	36°25'31"	79°01'53"	5/19/77	214	149.3-209.3	11.20 ±0.04 (25)	8.77 ±0.45 (23)	0.98 ±0.05[1]
					149.3-189.3	11.30 ±0.07 (17)	8.87 ±0.21 (16)	1.00 ±0.03[1]
								1.00 ±0.03[2]
					191.8-209.3	11.05 ±0.04 (8)	8.54 ±0.73 (7)	0.94 ±0.08[1]
								0.95 ±0.01[2]
RX3	36°25'39"	78°53'42"	8/7/77	211.5	134.9-199.9	10.36 ±0.22 (14)	8.33 ±0.58 (14)	0.86 ±0.08[1]
					144.3-169.9	10.43 ±0.37 (6)	8.40 ±0.67 (10)	0.88 ±0.10[1]
					181.9-194.9	9.00 ±0.46 (3)	8.14 ±0.25 (4)	0.73 ±0.06[1]
SLATE BELT PERSON CO., N.C.								
SB1	36°19'40"	78°50'00"	6/5/77	211.5	81.7-181.7	11.70 ±0.09 (28)	8.21 ±0.86 (10)	0.96 ±0.11[1]
					121.7-136.7	13.60 ±0.28 (7)	8.32 ±0.74 (6)	1.13 ±0.13[1]
								1.14 ±0.03[2]
					139.2-149.2	14.04 ±0.71 (5)	8.04 ±1.11 (4)	1.13 ±0.22[1]
								1.11 ±0.05[2]

ROLESVILLE BATHOLITH, FRANKLIN CO., N.C.								
RL1	36°04'15"	78°07'43"	8/16/77	210.6	142.5-210.0	19.05 ±0.11 (28)	7.61 ±0.42 (10)	1.45 ±0.09[1]
					182.5-207.3	19.05 ±0.10 (11)	7.61 ±0.42 (10)	1.45 ±0.09[1]
								1.45 ±0.01[2]
RL2	36°47'17"	78°25'04"	9/14/77	212.8	24.3-209.8	18.80 ±0.19 (75)		
					102.5-127.5	15.71 ±0.13 (11)		
					197.5-210.0	17.14 ±0.36 (6)		
RL3	35°57'05"	78°20'00"	10/19/77	121.9	42.5-132.5	13.79 ±0.11 (37)		
					42.5- 52.5	14.80 ±0.40 (5)		
					55.0- 65.0	10.80 ±0.40 (5)		
					67.5- 82.5	13.14 ±0.26 (7)		
					85.0- 95.0	18.80 ±0.40 (5)		
					97.5-132.5	13.17 ±0.14 (15)		
RL4	35°43'36"	78°19'45"	10/19/77	196.3	102.4-194.9	15.34 ±0.12 (38)		
					102.4-124.9	15.01 ±0.44 (10)		
					152.4-194.9	16.63 ±0.08 (18)		
RL5	35°51'17"	78°28'54"	10/20/77	211.5	72.5-210.0	16.23 ±0.03 (56)		
PETERSBURG GRANITE, SUSSEX CO., VA.								
PT1	36°49'45"	77°19'15"	10/21/77	253.0	14.9- 87.4	23.09 ±0.23 (30)[5]		
					92.4-154.9	17.73 ±0.04 (26)[6]		
					192.4-252.4	18.88 ±0.14 (25)[illegible]		
PAGELAND PLUTON, LANCASTER CO., S.C.								
PG1	34°34'25"	80°50'52"		213.4				
LAKESIDE CUMBERLAND CO., VA.								
LK1	37°41'25"	78°08'52"	9/16/77	205.0	59.3-204.3	13.46 ±0.07 (58)		
					59.3- 81.8	11.49 ±0.07 (10)		
					121.3-144.3	14.30 ±0.17 (10)		
					164.3-204.3	13.31 ±0.05 (17)		
PEGMATITE BELT, GOOCHLAND CO., VA.								
PE1	37°45'56"	78°05'37"	9/16/77	200.0	119.8-199.8	15.17 ±0.10 (33)		

TABLE C-1 SUMMARY OF HEATFLOW DATA NOVEMBER 19, 1977

EDGEFIELD PLUTON,
EDGEFIELD CO., S.C.

ED1	33°55'11" 82°07'10"	ON SITE

1 - INDICATES HEAT FLOW VALUE IS THE PRODUCT OF A MEAN GRADIENT AND A MEAN THERMAL CONDUCTIVITY
2 - INDICATES HEAT FLOW VALUE IS FROM THE BULLARD APPROXIMATION
3 - VALUE IN PARENTHESES IS THE NUMBER OF TEMPERATURE POINTS OR THE NUMBER OF THERMAL CONDUCTIVITY VALUES
4 - THERMAL CONDUCTIVITY VALUES FROM 1.270 CM THICK SAMPLES
5 - GRADIENT FROM THE SEDIMENTARY COVER OF THE PLUTON
6 - GRADIENT FROM WITHIN THE PLUTON

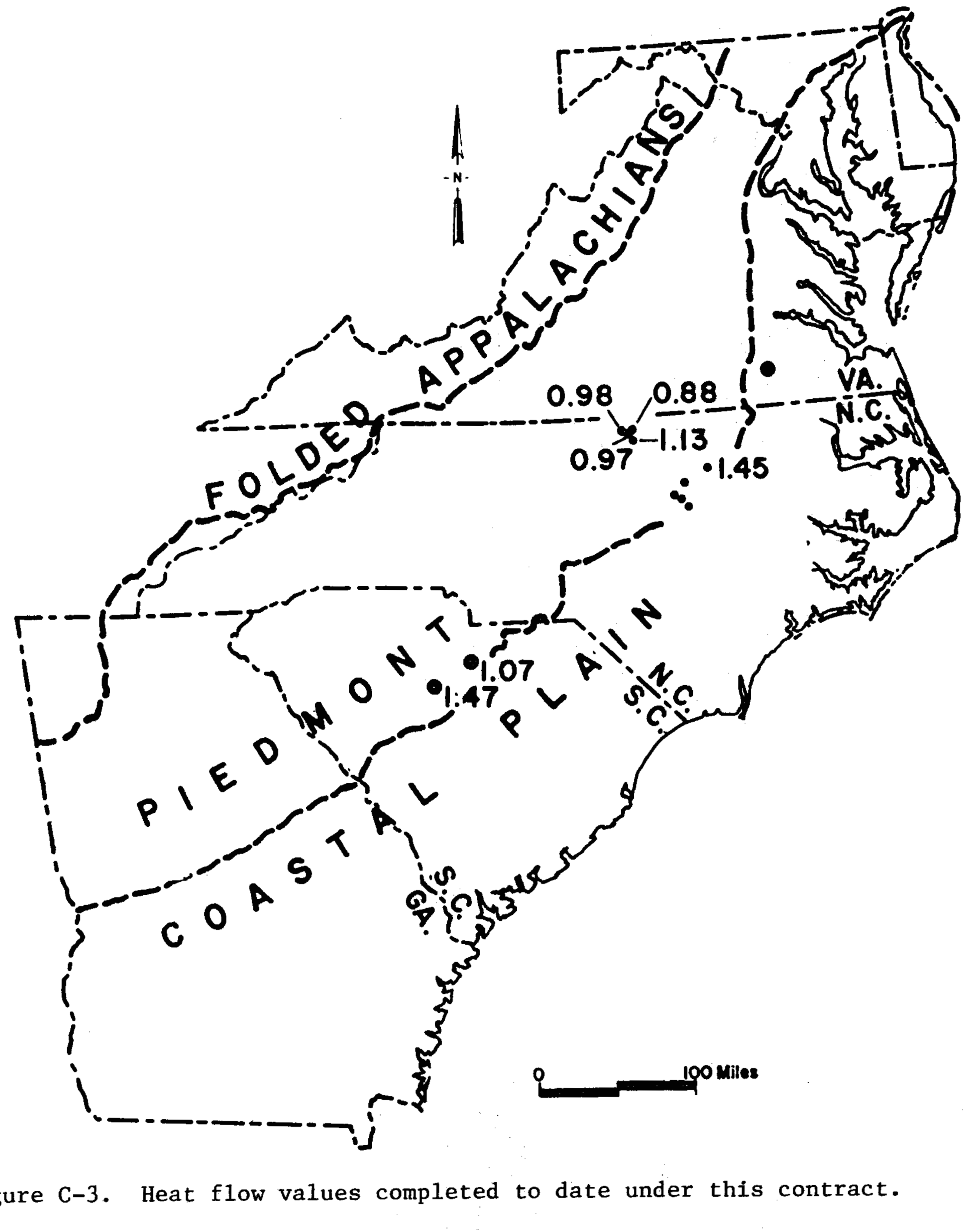


Figure C-3. Heat flow values completed to date under this contract.

THERMAL CONDUCTIVITY VALUES FROM CORE OF DRILL HOLE RX2
(SAMPLES ARE 2.680 CM IN DIAMETER BY 1.270 CM THICK)

SAMPLE IDENTIFICATION	DEPTH (METERS)	THERMAL CONDUCTIVITY MCAL/CM-SEC-°C
RX2-437	133.2	8.83
RX2-494	150.6	8.73
RX2-503	153.3	8.73
RX2-511	155.8	8.70
RX2-527	160.3	8.76
RX2-535	163.1	9.50
RX2-543	165.5	8.99
RX2-552	168.3	8.96
RX2-560	170.7	8.52
RX2-568	173.1	8.86
RX2-577	175.9	8.88
RX2-585	178.3	8.85
RX2-593	180.7	8.93
RX2-601	183.2	8.77
RX2-609	185.6	8.98
RX2-617	188.1	8.91
RX2-634	193.2	6.89
RX2-642	195.7	8.82
RX2-650	198.1	8.68
RX2-658	200.6	8.86
RX2-667	203.3	8.88

Table C-2. Thermal conductivity values for drill hole RX2 (Roxboro metagranite, lower amphibolite facies)

THERMAL CONDUCTIVITY VALUES FROM CORE OF DRILL HOLE RX2
(SAMPLES ARE 2.680 CM IN DIAMETER BY 1.270 CM THICK)

SAMPLE IDENTIFICATION	DEPTH (METERS)	THERMAL CONDUCTIVITY MCAL/CM-SEC-°C
RX2-675	205.7	8.76
RX2-683	208.2	8.86
AVERAGE		8.74
STANDARD DEVIATION		0.46

Table C-2 (continued). Thermal conductivity values for drill hole RX2 (Roxboro metagranite, lower amphibolite facies).

THERMAL CONDUCTIVITY VALUES FROM CORE OF DRILL HOLE RX3
(SAMPLES ARE 2.680 CM IN DIAMETER BY 1.270 CM THICK)

SAMPLE IDENTIFICATION	DEPTH (METERS)	THERMAL CONDUCTIVITY MCAL/CM-SEC-°C
RX3-478	145.7	8.29
RX3-485	147.8	9.44
RX3-494	150.6	7.65
RX3-502	153.0	7.93
RX3-510	155.4	9.29
RX3-519	158.2	9.02
RX3-527	160.6	7.56
RX3-535	163.1	8.57
RX3-543	165.5	7.97
RX3-551	167.9	8.27
RX3-608	185.3	7.80
RX3-617	188.1	8.33
RX3-625	190.5	8.34
RX3-633	192.9	8.09
AVERAGE		8.33
STANDARD DEVIATION		0.58

Table C-3. Thermal conductivity values for core from drill hole RX3 (Roxboro metagranite, greenschist facies).

THERMAL CONDUCTIVITY VALUES FROM CORE OF DRILL HOLE RL1
(SAMPLES ARE 2.680 CM IN DIAMETER BY 1.270 CM THICK)

SAMPLE IDENTIFICATION	DEPTH (METERS)	THERMAL CONDUCTIVITY MCAL/CM-SEC-°C
RL1-163	49.7	7.70
RL1-607	185.0	7.86
RL1-615	187.5	7.02
RL1-623	189.9	7.87
RL1-631	192.3	8.22
RL1-639	194.8	7.36
RL1-647	197.2	7.93
RL1-656	199.9	7.54
RL1-664	202.4	6.90
RL1-672	204.8	7.53
RL1-680	207.3	7.88
AVERAGE		7.62
STANDARD DEVIATION		0.40

Table C-4. Thermal conductivity values for core from drill hole RL1 (Castalia pluton, Rolesville batholith).

THERMAL CONDUCTIVITY VALUES FROM CORE OF DRILL HOLE SB1
(SAMPLES ARE 2.680 CM IN DIAMETER BY 1.270 CM THICK)

SAMPLE IDENTIFICATION	DEPTH (METERS)	THERMAL CONDUCTIVITY MCAL/CM-SEC-°C
SB1-407	124.0	6.83
SB1-415	126.5	8.62
SB1-424	129.2	8.56
SB1-432	131.7	8.84
SB1-440	134.1	8.45
SB1-448	136.6	8.65
SB1-457	139.3	7.70
SB1-465	141.7	9.18
SB1-473	144.2	6.65
SB1-481	146.6	8.62
AVERAGE		8.21
STANDARD DEVIATION		0.86

Table C-5. Thermal conductivity values for core from drill hole SB1 (Slate Belt).

Heat Generation

by

L. D. Perry and J. K. Costain

Results of heat generation determined for core samples from holes RX2, RX3 (Roxboro metagranite), and RL1 (Castalia pluton, Rolesville batholith) and for surface samples from the Petersburg granite in Virginia are given in Tables C-6, C-7, C-8, and C-9. The conversion factors used for heat generation are those given by Rybach (1976, pg. 311).

The highest value of heat generation found to date by us in the southeast is for surface samples of the Petersburg granite, Va. (approximately 17 HGU). Values of heat generation from core from the Petersburg granite (PT1) are not yet available since this hole was just recently completed. The value of 17 HGU is for sample AB710B and was inadvertently omitted from Table C-9.

Table C-10 lists results of heat generation determinations from a reconnaissance survey in the southeastern United States.

Table C-11 lists heat generation determinations for the Marshall granite in Virginia. Structural complications and low values of heat generation led us to reconsider this site as one of high priority, as discussed elsewhere in this report under "Fulfillment of Contractual Requirements".

TABLE C-6 HEAT GENERATION DATA FROM CORE OF DRILL HOLE RL1 C-6-1

DEPTH INTERVAL (FEET)	(METERS)	SAMPLE NO.	DENSITY, GM/CM³	URANIUM (U), PPM	THORIUM (TH), PPM	POTASSIUM (K), %	K20, %	HEAT GENERATION, A X 10^{-13} CAL/CM³-SEC
90-96	27.4-29.3	RL1-090	2.63	5.8	12.2	2.9	3.4	5.1
180-186	54.9-56.7	RL1-180	2.66	5.2	11.4	2.9	3.5	5.6
203-210	61.9-64.0	RL1-203	2.66	4.6	11.9	2.9	3.5	5.4
220-226	67.1-68.9	RL1-220	2.66	4.8	11.8	2.7	3.2	5.4
253-259	77.1-78.9	RL1-253	2.65	4.7	11.6	3.0	3.5	5.4
273-279	83.2-85.0	RL1-273	2.65	5.0	11.7	2.8	3.3	5.5
294-300	89.6-91.4	RL1-294	2.63	4.9	11.8	2.8	3.3	5.4
312-318	95.1-96.9	RL1-312	2.66	4.9	11.6	2.8	3.4	5.5
408-414	124.4-126.2	RL1-408	2.65	4.6	11.0	2.8	3.4	5.2
584-590	178.0-179.8	RL1-584	2.64	5.5	12.0	2.8	3.3	5.8
AVERAGE			2.65	5.0	11.7	2.8	3.4	5.5
STANDARD DEVIATION			0.01	0.4	0.3	0.1	0.1	0.3

TABLE C-7 HEAT GENERATION DATA FROM CORE OF DRILL HOLE RX2 C-7-1

DEPTH INTERVAL (FEET)	(METERS)	SAMPLE NO.	DENSITY, GM/CM³	URANIUM (U), PPM	THORIUM (TH), PPM	POTASSIUM (K), %	K20,%	HEAT GENERATION, A X 10^{-13} CAL/CM³-SEC
74-84	22.6-25.6	RX2-23	(2.67)	2.4	11.0	2.7	3.2	3.9
99-104	30.2-31.7	RX2-30	(2.67)	3.0	10.0	2.9	3.5	4.1
240.3-245.3	73.2-74.8	RX2-73	(2.67)	2.8	10.5	2.8	3.4	4.0
299.6-304	91.3-92.7	RX2-91	(2.67)	2.4	9.6	2.8	3.3	3.6
333-338	101.5-103.0	RX2-102	(2.67)	2.4	9.8	2.8	3.3	3.7
544-549	165.8-167.3	RX2-166	(2.67)	3.3	11.6	2.7	3.3	4.5
AVERAGE				2.7	10.4	2.8	3.3	4.0
STANDARD DEVIATION				0.4	0.8	0.1	0.1	0.3

(2.67)...ASSUMED DENSITY

TABLE C-8 HEAT GENERATION DATA FROM CORE OF DRILL HOLE RX3 C-8-1

DEPTH INTERVAL (FEET)	(METERS)	SAMPLE NO.	DENSITY, GM/CM³	URANIUM (U),PPM	THORIUM (TH),PPM	POTASSIUM (K),%	K20,%	HEAT GENERATION, A X 10⁻¹³ CAL/CM³-SEC
34-38	10.4-11.6	RX3-10	(2.67)	2.0	9.5	2.7	3.3	3.4
77-81	23.5-24.7	RX3-24	(2.67)	2.4	7.4	1.9	2.3	3.1
305-309	93.0-94.2	RX3-93	(2.67)	1.5	5.0	2.3	2.7	2.2
459-464	139.9-141.4	RX3-140	(2.67)	1.8	5.4	1.7	2.0	2.3
554-559	168.9-170.4	RX3-169	(2.67)	1.4	3.8	1.4	1.7	1.8
635-640	193.5-195.1	RX3-194	(2.67)	1.9	6.5	2.4	2.9	2.8
AVERAGE				1.8	6.3	2.1	2.5	2.6
STANDARD DEVIATION				0.4	2.0	0.5	0.6	0.6

(2.67)...ASSUMED DENSITY

TABLE C-9 HEAT GENERATION DATA FROM SURFACE SAMPLES OF THE PETERSBURG GRANITE

LOCATION	SAMPLE NO.	DENSITY, GM/CM³	URANIUM (U),PPM	THORIUM (TH),PPM	POTASSIUM (K),%	K20,%	HEAT GENERATION, A X 10⁻¹³ CAL/CM³-SEC
PETERSBURG	AB7-11C	(2.67)	14.2	4.9	5.1	6.2	10.8
PETERSBURG	AB7-17	2.62	8.1	20.1	3.4	4.1	8.8
PETERSBURG	AB7-21	2.61	6.5	16.3	3.7	4.4	7.3
PETERSBURG	AB7-23	2.64	7.0	21.8	3.5	4.2	8.5
PETERSBURG	AB7-26A	2.71	8.7	21.1	3.4	4.1	9.6
PETERSBURG	AB7-26B	2.64	5.0	19.9	3.9	4.7	7.1
PETERSBURG	AB7-3A	(2.67)	2.8	11.4	3.4	4.1	4.4
PETERSBURG	AB7-3B	2.74	2.6	13.9	3.2	3.9	4.7
PETERSBURG	AB7-41	2.69	2.5	7.5	2.5	3.0	3.3
PETERSBURG	AB7-53	2.64	4.2	15.5	3.4	4.1	5.8
PETERSBURG	AB7-6A	(2.67)	0.8	2.0	0.7	0.8	1.0
PETERSBURG	AB7-6B	(2.67)	2.9	0.5	5.5	6.6	3.2
PETERSBURG	AB7-61A	2.60	10.7	17.9	4.4	5.3	10.1
PETERSBURG	AB7-61B	(2.67)	6.1	17.4	2.8	3.3	7.2
PETERSBURG	AB7-73	2.61	7.3	28.8	3.7	4.4	9.7
PETERSBURG	AB7-75	2.63	11.1	13.6	3.4	4.0	9.6
PETERSBURG	AB7-76A	(2.67)	0.9	2.3	0.6	0.7	1.1
PETERSBURG	AB7-76B	(2.67)	3.3	0.7	5.5	6.6	3.4

TABLE C-9 HEAT GENERATION DATA FROM SURFACE SAMPLES OF THE PETERSBURG GRANITE

LOCATION	SAMPLE NO.	DENSITY, GM/CM^3	URANIUM (U),PPM	THORIUM (TH),PPM	POTASSIUM (K),%	K20,%	HEAT GENERATION, A X 10^{-13} CAL/CM^3-SEC
PETERSBURG	AB7-3	(2.67)	8.5	9.6	3.7	4.5	7.6
PETERSBURG	AB7-9A	(2.67)	2.2	14.1	4.2	5.0	4.6
PETERSBURG	AB7-9B	(2.67)	11.9	34.4	3.6	4.3	13.7
PETERSBURG	AB7-96B	2.60	11.1	18.6	4.2	5.1	10.4
PETERSBURG	F7-3	(2.67)	8.4	13.0	3.6	4.4	8.2
PETERSBURG	F7-7	(2.67)	5.4	20.3	3.5	4.2	7.6
PETERSBURG	F7-8	(2.67)	6.9	20.2	4.3	5.1	8.6
AVERAGE		2.66	7.6	14.3	3.7	4.4	7.8
STANDARD DEVIATION		0.03	5.7	8.3	1.2	1.4	4.0

(2.67)...ASSUMED DENSITY

TABLE C-10 HEAT GENERATION DATA FROM RECONNAISANCE SURVEY IN S.E. UNITED STATES C-10-1

LOCATION		SAMPLE NO.	DENSITY, GM/CM³	URANIUM (U),PPM	THORIUM (TH),PPM	POTASSIUM (K),%	K20,%	HEAT GENERATION, A X 10⁻¹³ CAL/CM³-SEC
APPLING	GA	F7-33	(2.67)	2.7	18.7	3.4	4.0	5.6
APPLING	GA	F7-34	(2.67)	3.9	18.7	3.7	4.4	6.4
APPLING	GA	F7-35	(2.67)	2.8	23.3	4.0	4.8	6.6
DANBERG	GA	CB7-10	(2.67)	3.8	39.0	4.2	5.0	9.9
DANBERG	GA	CB7-12	(2.67)	1.9	6.5	2.1	2.6	2.8
DELHI	GA	F7-36	(2.67)	2.2	3.8	4.9	5.9	3.1
ELBERTON	GA	F7-37	(2.67)	3.7	45.9	4.3	5.1	11.0
ELBERTON	GA	F7-38	2.63	3.4	43.2	4.3	5.1	10.3
NORTH PALMETTO	GA	CB7-6B	2.66	4.9	26.1	3.2	3.8	8.1
SILOAM	GA	CB7-7	(2.67)	7.7	37.3	4.1	4.9	12.0
SILOAM	GA	CB7-7B	(2.67)	7.2	20.9	3.4	4.1	8.8
SILOAM	GA	CB7-8	(2.67)	5.7	35.4	3.1	3.7	10.2
SOUTH PALMETTO	GA	CB7-4A	2.62	2.2	4.1	3.1	3.8	2.7
SOUTH PALMETTO	GA	CB7-4B	(2.67)	2.1	6.7	1.9	2.2	2.9
SOUTH PALMETTO	GA	CB7-5	(2.67)	9.6	41.2	3.8	4.5	13.7
SPARTA	GA	CB7-9	(2.67)	4.7	20.2	4.0	4.8	7.3
STONE MTN	GA	CB7-1	2.64	3.9	4.2	3.8	4.6	4.0
STONE MTN	GA	CB7-2	2.64	4.0	4.4	3.9	4.6	4.1

TABLE C-10 HEAT GENERATION DATA FROM RECONNAISANCE SURVEY IN S.E. UNITED STATES

LOCATION		SAMPLE NO.	DENSITY, GM/CM^3	URANIUM (U),PPM	THORIUM (TH),PPM	POTASSIUM (K),%	K20,%	HEAT GENERATION, A X 10^{-13} CAL/CM^3-SEC
STONE MTN	GA	CB7-3	2.63	3.8	20.6	4.2	5.1	6.7
CLOVER	NC	F7-28	(2.67)	2.1	12.5	3.4	4.1	4.2
CONCORD	NC	F7-20	(2.67)	0.2	0.9	4.1	4.9	1.2
CONCORD	NC	F7-21	(2.67)	0.6	2.9	3.7	4.5	1.8
ELBERTON	NC	CB7-38	(2.67)	1.2	5.2	1.6	1.9	2.0
ELM CITY	NC	F7-12	(2.67)	4.1	10.8	4.4	5.3	5.3
GASTONIA	NC	F7-26	(2.67)	2.2	14.7	3.8	4.6	4.6
LANDIS	NC	F7-19	(2.67)	11.0	11.1	3.6	4.3	9.5
LANDIS	NC	F7-23	(2.67)	3.1	20.3	3.7	4.4	6.2
LILESVILLE	NC	CB7-29	2.69	2.5	17.2	3.6	4.3	5.3
MT MOURNE	NC	F7-25	(2.67)	3.9	26.7	4.1	4.9	7.9
PEEDEE	NC	S7-43	3.09	0.3	1.0	0.8	1.0	0.6
ROCKY MOUNT	NC	F7-14	(2.67)	5.4	19.9	3.3	4.0	7.5
SAPROLITE,CONCORD	NC	CONC01	(2.67)	0.4	1.1	2.5	3.1	1.0
STONE MT	NC	CB7-30	2.58	1.3	5.9	2.8	3.4	2.4
STONE MT	NC	CB7-30	2.58	1.3	5.9	2.8	3.4	2.4
STONE MT	NC	CB7-32	2.63	2.1	12.2	3.3	4.0	4.1
STONE MT	NC	CB731B	2.63	1.1	4.1	2.8	3.3	2.0

TABLE C-10 HEAT GENERATION DATA FROM RECONNAISANCE SURVEY IN S.E. UNITED STATES

LOCATION		SAMPLE NO.	DENSITY, GM/CM^3	URANIUM (U), PPM	THORIUM (TH), PPM	POTASSIUM (K), %	K2O, %	HEAT GENERATION, A X 10^{-13} CAL/CM^3-SEC
WOODLEAF	NC	F7-31	(2.67)	7.6	15.9	3.6	4.4	8.2
YORK	NC	F7-29	(2.67)	6.8	25.1	3.8	4.6	9.3
YORK	NC	F7-30	(2.67)	5.2	20.9	3.9	4.7	7.6
CAROLINA SLATE BELT	SC	CB7-67	(2.67)	1.3	7.9	2.6	3.1	2.7
CAROLINA SLATE BELT	SC	CB7-69	(2.67)	2.0	9.1	3.1	3.8	3.5
CATAWBA	SC	CB7-25	2.63	2.7	10.1	3.3	3.9	4.1
CLOUD'S CREEK	SC	CB7-17	(2.67)	2.4	10.9	3.4	4.1	4.1
CLOUD'S CREEK	SC	CB7-18	(2.67)	4.3	11.4	3.4	4.1	5.4
CLOUD'S CREEK	SC	CB7-19	2.69	3.3	10.1	3.4	4.1	4.6
COLUMBIA	SC	CB7-20	(2.67)	5.7	13.2	3.1	3.8	7.3
COLUMBIA	SC	CB7-21	2.64	4.4	10.3	3.6	4.3	5.2
CORANACA	SC	CB7-13	(2.67)	1.1	3.5	3.3	4.0	2.1
CORONACA	SC	CB7-14	2.65	1.7	21.5	5.7	6.8	5.9
EDGEFIELD	SC	CB7-15	2.65	9.1	32.2	3.7	4.4	11.8
EDGEFIELD	SC	CB7-16	2.58	4.4	18.2	5.3	6.3	6.8
GREAT FALLS	SC	Z7-3	2.63	3.0	10.1	3.2	3.9	4.2
HARBISON	SC	CB7-68	(2.67)	3.4	9.1	3.3	3.9	4.4
MT CARMEL	SC	S7-42	2.64	0.6	0.9	4.9	5.9	1.6

TABLE C-10 HEAT GENERATION DATA FROM RECONNAISANCE SURVEY IN S.E. UNITED STATES C-10-4

LOCATION		SAMPLE NO.	DENSITY, GM/CM³	URANIUM (U),PPM	THORIUM (TH),PPM	POTASSIUM (K),%	K20,%	HEAT GENERATION, A X 10^{-13} CAL/CM³-SEC
NEWBERRY	SC	CB7-23	2.58	7.4	28.6	4.1	4.9	10.0
NEWBERRY	SC	CB7-24	2.76	4.5	20.6	3.5	4.2	7.3
NEWBERRY	SC	CB724B	2.64	3.9	10.6	2.8	3.3	4.8
PAGELAND	SC	CB7-26	(2.67)	3.1	15.8	3.3	4.0	5.3
PAGELAND	SC	CB7-27	2.68	4.5	15.2	3.6	4.3	6.2
PAGELAND	SC	CB7-28	2.65	3.9	18.3	3.9	4.7	6.4
BEREA	VA	P7-1	(2.67)	3.1	2.6	3.8	4.6	3.2
BEREA	VA	P7-2	(2.67)	5.1	7.0	4.3	5.1	5.3
EDGERTON	VA	P7-10	(2.67)	5.9	28.5	4.0	4.8	9.4
PETERSBURG	VA	P7-11	(2.67)	3.0	15.2	3.2	3.9	5.2
SKIPPERS	VA	P7-15	(2.67)	6.5	18.3	4.0	4.8	8.0

(2.67)...ASSUMED DENSITY

TABLE C-11 HEAT GENERATION DATA FROM SURFACE SAMPLES OF THE MARSHALL GRANITE

LOCATION	SAMPLE NO.	DENSITY, GM/CM³	URANIUM (U), PPM	THORIUM (TH), PPM	POTASSIUM (K), %	K20, %	HEAT GENERATION, A X 10^{-13} CAL/CM³-SEC
MARSHALL	S7-81	(2.67)	2.8	25.4	2.8	3.4	6.6
ROBINSON RIVER	S7-82	(2.67)	2.7	10.9	3.9	4.6	4.4
MARSHALL	S7-83	(2.67)	2.3	12.3	3.8	4.6	4.4
MARSHALL	S7-84	(2.67)	3.1	12.6	2.9	3.5	4.7
ROBINSON RIVER	S7-85	(2.67)	3.2	13.4	3.8	4.6	5.1
AVERAGE			2.8	14.9	3.4	4.1	5.0
STANDARD DEVIATION			0.4	5.9	0.5	0.6	0.9

(2.67)...ASSUMED DENSITY

Relationship Between Surface Heat Generation and Surface Heat Flow

by

J. K. Costain and L. D. Perry

Figure C-4 shows the correlation between near-surface heat generation and heat flow for drill holes KR3, WN1, RX1, RX2, and RX3. These are the first five sites for which heat flow and heat generation values have been completed. The linear relationship continues to exist (see VPI&SU-5103-4 for further discussion) and we anticipate that this relationship will become an essential component of our targeting procedure for reasons discussed earlier in this report. The additional values of heat flow and heat generation in this report have revised slightly the equation relating heat flow, q, to heat generation, A, and we now have

$$q = 0.69 + 6.9 \times 10^{5} A \qquad (1)$$

The values of heat flow and heat generation used are from Tables C-1, C-7, and C-8 in this report and Tables C-1, C-5, C-6, and C-8 in VPI&SU-5103-4. These five points are plotted in Figure C-4.

With the addition of RX2 and RX1 to Figure C-4, we now observe that the linear relationship is preserved in the Roxboro metagranite in rocks which range from lower amphibolite facies to greenschist facies (see VPI&SU-5103-3, p. A-78, for a discussion of the Roxboro metagranite by Lynn Glover). As far as we know, this is the first observation that the linear relationship is preserved in postmetamorphic as well as in premetamorphic granites.

It is interesting to note that Diment et al. (1965) obtained a heat flow value at Alberta, Virginia of 1.4 HFU. Reiter and Costain (1973) obtained a value of heat generation of 11.2 HGU from a quarry at Dolphin,

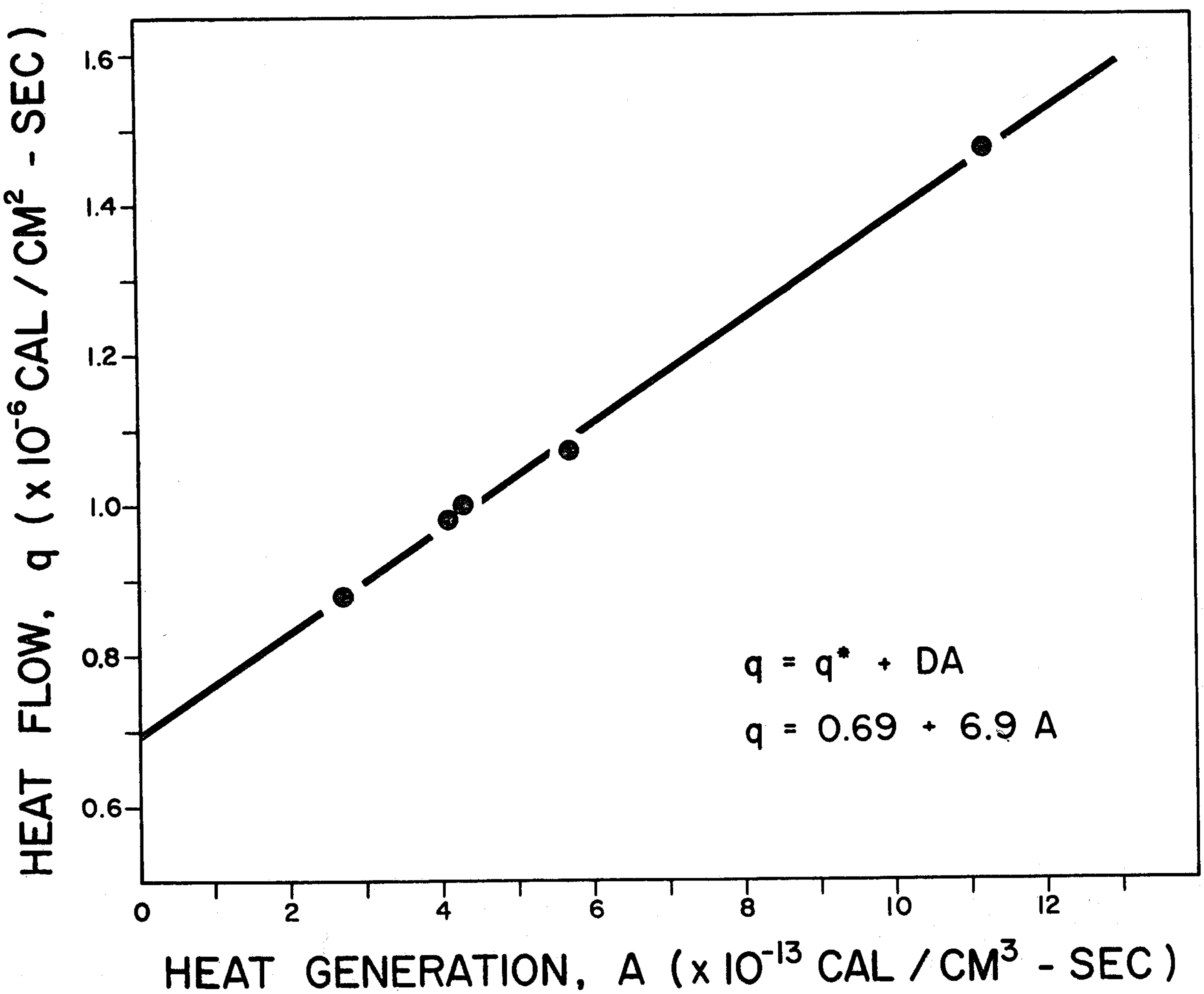


Figure C-4. Linear relationship between heat generation and heat flow in SE United States

Virginia about 9 km from Alberta. The value of the 11.2 HGU predicts a heat flow of 1.46 HFU based on equation (1) above. This heat flow value is within about 4% of that found by Diment et al., although the heat generation value is not from core from the heat flow hole.

Additional determinations of thermal conductivity and heat generation are in progress and will be reported as they become available.

Determinations of thermal conductivity and heat generation are not yet complete for RL1 (Castalia pluton of the Rolesville batholith; see VPI&SU-5103-3, p. A53, for a discussion of the Rolesville Batholith by Susan Becker and Stewart Farrar). Preliminary values of heat flow and heat generation indicate that these values will not plot on the linear relationship defined to date in the southeastern United States. The implications of this will be discussed in a subsequent report. It is noteworthy that the heat flow is considerably higher than would be predicted from the values of heat generation determined from core from the hole.

Further Partial Confirmation of Radiogenic Model

by

John K. Costain

Figure C-2 shows the temperature profile and geothermal gradient obtained by VPI&SU in a hole drilled in the center of a gravity minimum in Virginia. The location of the drill hole is shown in Figure C-5. The site was chosen to fulfill two objectives of our contract:

1) to determine heat generation and heat flow in the Petersburg granite in Virginia, and
2) to evaluate the association of negative Bouguer gravity anomalies with granitic intrusions beneath Coastal Plain sediments.

The Petersburg granite was encountered at a depth of approximately 300 ft beneath the sediments of the Atlantic Coastal Plain. This is additional partial confirmation of the radiogenic model. See also VPI&SU-5103-4, p. C-23.

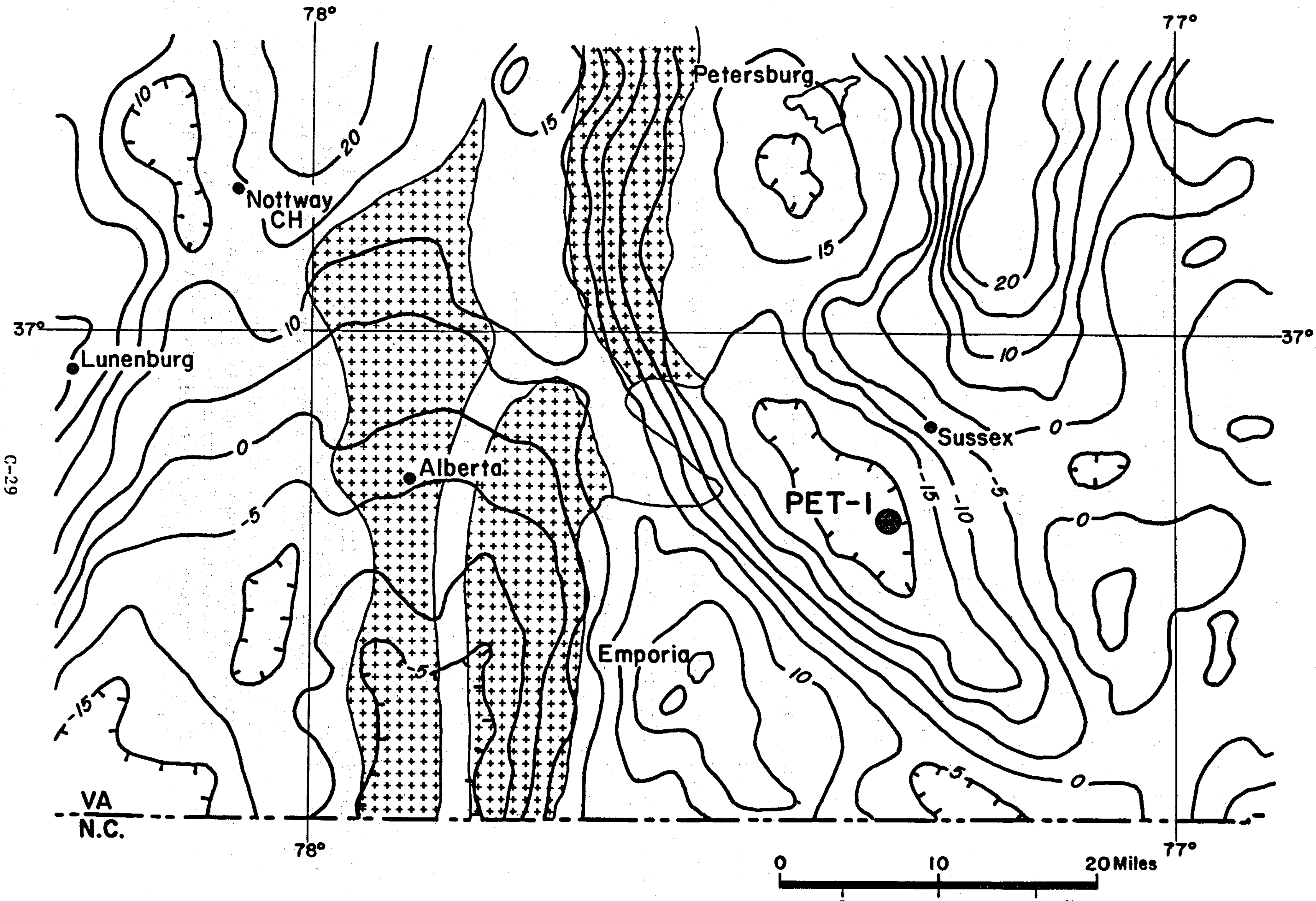


Figure C-5. Location of hole PT1 drilled into Coastal Plain sediments to Petersburg granite. Stippled pattern is exposed Petersburg granite, concealed by Coastal Plain sediments to the east.

Warm Springs Project

by

P. A. Geiser and J. K. Costain

Evaluation of the Type IV resource (hot water emanating from fault zones as a result of apparent leakage from greater depths) is continuing in the Warm Springs anticline, Va. Additional structural and hydrologic data were collected this summer to provide a data base for the development of a mathematical model of ground-water flow in the vicinity of the postulated transverse fracture zones (Costain, 1975; Geiser, 1976). The amount and diversity of structural data and the desired method of cross-correlation of the structural data have necessitated the development of computer software to plot digitized geologic contacts and to selectively plot structural data (bedding, cleavage, joints, and linears). The program is now operational and a manuscript describing software and its proposed utility is in preparation for publication by Costain and Geiser.

The Type IV geothermal resource remains an attractive possibility in the Appalachian Mountain System, especially if fracture zones of regional extent can be predicted and confirmed beneath thick sequences of impermeable shale in the Valley and Ridge province.

References: Costain, J. K., (1975), Geological and geophysical study of the origin of the warm springs in Bath County, Virginia; Final Report prepared for ERDA, Contract No. E-(40-1)-4920.

Geiser, P. A., (1976), Structural mapping in the Warm Springs anticline, northwestern Virninia; in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, Progress Report prepared for ERDA, VPI&SU-5103-2, Contract No. E-(40-1)-5103, p. 116-164.

SUMMARY

During FY 1978 major emphasis will be placed on the evaluation of the geothermal resource potential of the Atlantic Coastal Plain. Collation of existing gravity and magnetic potential field data for the eastern United States has been completed, the modeling of selected gravity anomalies has begun. Sampling of basement beneath the Atlantic Coastal Plain in as many locations as possible will validate and refine the gravity and magnetic models. Continuing effort to examine the geologic framework of the Piedmont is important since, presumably, this is the framework that extends beneath the Atlantic Coastal Plain.

The present report includes additional discussion about the implications of the observed linear relationship between heat flow and heat generation. The nature of the gross vertical distribution of the heat-producing elements is still unknown, but an understanding of this is important for the evaluation of the Type I geothermal resource. The discussions by Speer in this report emphasize the contributions of metamorphic petrology to interpretations of proposed distributions.

COMPLIANCE WITH CONTRACTUAL REQUIREMENTS

FULFILLMENT OF CONTRACTUAL OBLIGATIONS

The following contract items were initiated or continued, as set forth in the Scope of Work, Attachment A to the contract, during the second phase of the program:

1. Coastal Plain Investigations: Determine geothermal gradient and heat flow in suitable existing wells in the Coastal Plain of Virginia, North Carolina, and South Carolina. Collation of existing geologic, magnetic, gravity and other appropriate geophysical data to assist in targeting buried potential geothermal sources.

4. Hot Springs Project: Geologic structure mapping to define hydrologic framework of the warm springs in the vicinity of recently discovered electrical resistivity anomalies. Reconnaissance study of nearby Highland County dikes and stocks.

5. Rolesville batholith, North Carolina: Field investigations of geologic framework, petrography, chemistry, heat production, heat flow and thermal gradient. Drilling approximately 3400 feet to sample below weathering and to obtain heat flow and heat production.

6. Felsic volcanic rocks, SE Roxboro Quadrangle, North Carolina: Field investigations of geologic framework, petrography, chemistry, heat production, heat flow and thermal gradient. Drilling approximately 2200 feet to sample below weathering and obtain heat flow and heat production.

7. Roxboro Granite, North Carolina: Field investigations of geologic framework, petrography, chemistry, heat production, heat flow and thermal gradient. Drilling approximately 1500 feet to sample below weathering and to obtain heat flow and heat production.

8. Marshall Granite, Virginia: Field investigations of geologic framework, petrography, chemistry, heat production, heat flow and thermal gradient. Drilling approximately 1600 feet to sample below weathering and to obtain heat flow and heat production.

9. Petersburg Granite, Virginia: Preliminary field studies and shallow drilling 300 feet to evaluate heat production and bulk chemistry.

Fulfillment

Contract item 1 - Completed, updating will continue.

Contract item 4 - completed except that some structure mapping is continuing.

Contract item 5 - Analysis of the chemistry, heat production, heat flow and geologic framework is continuing on the Rolesville plutonic complex because this complex should be typical (and therefore serve as a model for targeting) of potentially productive basement geologic frameworks under the Coastal Plain. All of the original contract objectives for the Rolesville have been met and analysis of the data (geologic and potential field) is continuing as a separate item under the third contract phase.

Contract item 6 - Field investigations of geologic framework and heat flow studies are complete. Heat production and petrography of the core are continuing.

Contract item 7 - Complete except that some petrographic analysis and chemistry are continuing.

Contract item 8 - Field investigations and some chemistry done. Preliminary analysis indicated unfavorable structural complexities (mostly faulting) and very low heat production values. Because of this it was thought more productive to deepen an existing hole in the pegmatite region near Columbia, Va. in the central Piedmont. Approximately 700 feet of core (Pg1) was taken after study of the geologic framework. Petrography, chemistry, and heat flow studies are in progress. Another hole (Lk1) in the central Piedmont was also deepened to get additional heat flow data on background Piedmont rocks.

Contract item 9 - Contract objectives have been completed.

Reconnaissance sampling of plutons in the southeast was conducted to provide background information on heat generation to guide future selection of drill sites. See Table C-10.

Compliance with Contractual Requirements

Principal investigators John K. Costain, Lynn Glover III, and A. K. Sinha, in accordance with Article A-I of Appendix A to the hereinmentioned contract, have devoted 10 weeks, four weeks, and 10 weeks, respectively, of their efforts to performance under the contract. They plan to devote 4.3 weeks, 2.9 weeks, and 2.9 weeks, respectively to the contract during the next three-month report period.

All contract requirements have been complied with.

John K Costain

John K. Costain

A K. Sinha

A. K. Sinha

Lynn Glover III

Lynn Glover III

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