[American Journal of Science, Vol. 281, March, 1981, P. 282-298]

GEOTHERMAL MEASUREMENTS IN THE SOUTHERN APPALACHIAN MOUNTAINS AND SOUTHEASTERN COASTAL PLAINS

DOUGLAS L. SMITH, ROBERT G. GREGORY*, AND JOHN W. EMHOF**

Department of Geology, University of Florida, Gainesville, Florida 32611

ABSTRACT. Twenty-three new values of heat flow for the southeastern United States suggest anomalously low thermal fluxes of ~0.3 to 0.4 heat flow units (1 HFU = μ cal/cm^{2}sec = 41.8 mW/m^2) in the Charlotte belt and in the Paleozoic sedimentary terrains of northeastern Alabama and northwestern Georgia. The highest heat flow values (~1.6 HFU) are for the Atlantic Coastal Plains province, where thermal gradients as high as 35°C/km were measured. Analyses by gamma ray spectrometry of uranium, thorium, and potassium abundances in surficial igneous and metamorphic rocks from the Blue Ridge and Piedmont provinces suggest subtle differences in radioactive heat generation among the various geologic belts and significantly higher heat production in intrusive granitic plutons. The data do not adhere to a linear relationship between heat flow and radiogenic heat production, and separate areas with distinct thermal conditions may eventually be identified in the southeastern United States. With additional measurements, various tectonic interpretations of the southern Appalachians may be corroborated or refuted according to a predicted thermal character of their final configurations.

INTRODUCTION

Recent representations of heat flow in the United States (Sass and others, 1976; Lachenbruch and Sass, 1977) have emphasized a relative paucity of geothermal data in the southeastern United States despite the diverse geological and structural terrains of the southern Appalachian Mountains and the Coastal Plains. The accumulation of sufficient heat flow and heat production information to depict adequately the thermal nature of the southeastern United States may provide significant clues to the challenging task of portraying the tectonic history of that area. This report summarizes previously published thermal data, new determinations of radioactive heat generation in crystalline rock areas, and twenty-three new heat flow values and estimates for Virginia, North Carolina, South Carolina, Tennessee, Georgia, Alabama, and Florida.

PREVIOUS WORK

Sass and others (1976) depicted the distribution of heat flow values in the southeastern United States with tentative heat flow contours limiting the southern Blue Ridge and Valley and Ridge provinces, western Georgia, and much of Alabama and Florida to less than 1.0 heat flow unit (1 HFU = 1 microcalorie/cm^{2}sec = 41.8 mW/m^2). Most of the Piedmont province and Atlantic Coastal Plain north of Florida were assigned a heat flow range of 1.0 to 1.5 HFU. This model was based on previous measurements (fig. 1) in Alabama of 1.0 HFU (Roy and others, 1968), Georgia of 1.0 HFU (Birch and Spicer, reported by Diment and Robertson, 1963), Tennessee of 0.8 HFU (Diment and Robertson, 1963), South Carolina of 1.1 HFU and 1.3 HFU (Diment and others, 1965a; Ziagos,

* Present Address: Environmental Science and Engineering, Inc., Jacksonville, Florida 32211
** Present Address: Amoco Production Company, New Orleans, Louisiana 70160

Sass and Munroe, 1976), Virginia of 1.0-1.7 HFU (Diment and Werre, 1964; Diment and others, 1965b; Reiter and Costain, 1973), and Florida of 0.9 HFU (King and Simmons, 1972).

Subsequent heat flow values reported by Smith (1976) for the Blue Ridge province and Costain (Costain, Glover, and Sinha, 1977; Costain and Sinha, 1978; Costain, 1978) for the Piedmont province are consistent with the earlier data. Smith and Fuller (1977) and Griffin, Reel, and Pratt (1977) presented measurements and estimates of heat flow in Florida that are largely less than 1.0 HFU but may be significantly influenced by circulating groundwater.

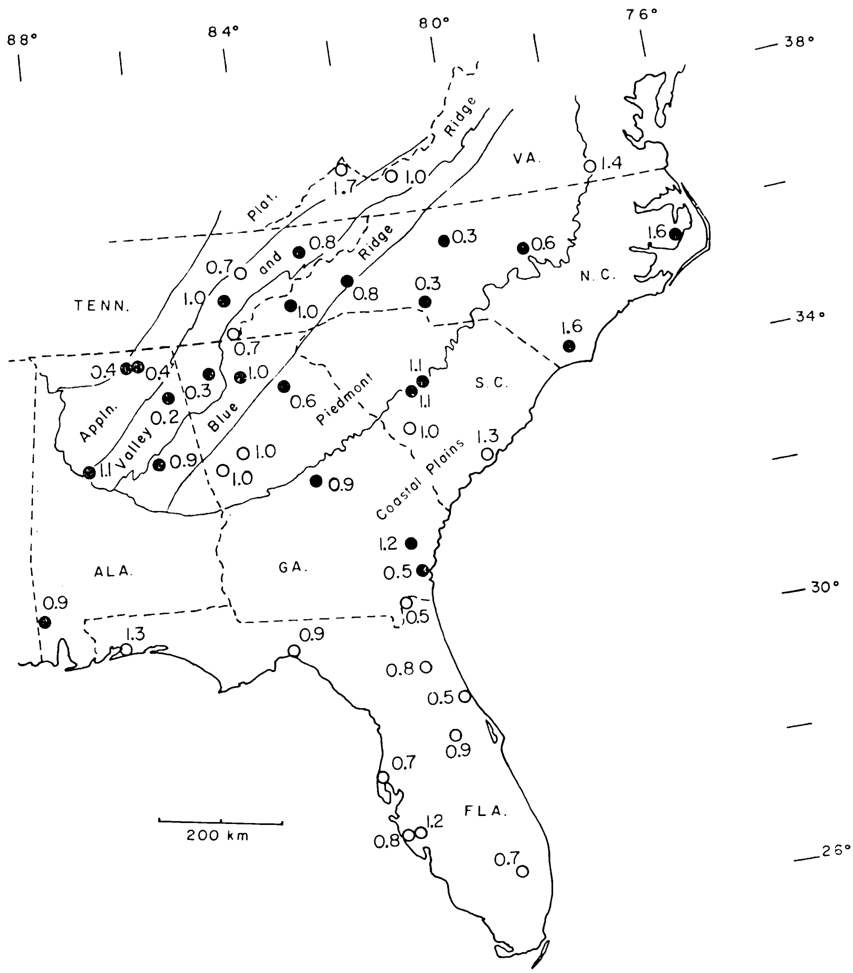

Fig. 1. Distribution of previously published (open circles) and new (closed circles) heat flow values (in heat flow units) in the southeastern United States. Sources for previously published values are cited in the text. Province boundaries are from Hatcher (1972).

TABLE 1

Locations, temperature gradients (Γ), thermal conductivity (K) on N samples, and heat flow value (Q) for each measurement site

LOCATION	N. Lat	W.Long	Depth (m)	Gradient Interval	Γ(°c/km)	N	K (mcal/cm sec°C)	Q $\mu cal/cm^2 sec$	Quality	predominant rock type
ALABAMA										
Cristown, Ala. (U.S. Pipe F-20)	33°18'	87°16'	360	60-360	16.93 ± 0.27*	6	6.54 ± 0.95	1.11 ± 0.16	1	micaceous siltstone
Citronelle, Ala. (Ala. Surv. C-29-G5)	31°00'	88°15'	220	60-220	25.33 ± 0.10	20**	3.74 ± 0.30	0.95 ± 0.08	1	sand, clay
Talladega, Ala. (Phelps Dodge R-10)	33°16'	86°01'	340	60-300	11.67 ± 0.16*	5	7.59 ± 0.55	0.89 ± 0.06	1	chlorite schist
Colvin Gap, Ala. (Allison Bros. #1)	33°56'	84°50'	180	100-180	7.70 ± 0.28*	12**	3.14 ± 0.08	0.24 ± 0.01	3	shale
Huntsville, Ala. (H. M. Hill #1)	34°44'	86°30'	280	40-260	10.70 ± 0.69	6**	3.82 ± 0.24	0.41 ± 0.04	2	shale
Huntsville, Ala. (Crowson #1)	34°44'	86°30'	650	100-650	9.73 ± 0.13	18**	4.57 ± 0.18	0.44 ± 0.02	2	shale
GEORGIA										
Crane Eater, Ga. (Roth #1)	34°32'	84°52'	200	40-200	10.05 ± 0.80*	14**	3.43 ± 0.26	0.34 ± 0.03	2	shale
Braselton, Ga. (Va. Well & Supply)	34°05'	83°46'	146	20-146	10.68 ± 0.61	14**	6.02 ± 0.50	0.64 ± 0.04	3	biotite gneiss
Brunswick, Ga. (U.S.G.S. #19)	31°08'	81°30	350	20-350	12.24 ± 3.94	11**	4.16 ± 0.89	0.51 ± 0.16	3	sandstone, limestone
Jeffersonville, Ga. (Whittaker #1)	32°43'	83°15'	350	140-300	15.53 ± 0.06	8**	5.90 ± 0.95	0.92 ± 0.05	1	sandstone
Marblehill, Ga. (Ga. Marble Co. #66-120)	34°25'	84°21'	370	20-370	15.94 ± 0.15*	12	6.29 ± 0.94	1.00 ± 0.04	1	mica schist
Townsend, Ga. (U.S.G.S. Monitorwell	31°36'	81°36'	263	20-260	33.41 ± 1.01	13**	3.71 ± 0.54	1.24 ± 0.06	2	limestone

SOUTH CAROLINA										
Columbia, S. C. (Dutch Village)	34°10'	81°02'	245	40-245	16.73 ± 0.23	8**	6.49 ± 0.19	1.09 ± 0.03	2	mica schist
Lexington, S. C. (Laurel Meadows)	33°55'	81°10'	170	30-170	13.53 ± 0.29	6	8.23 ± 0.52	1.11 ± 0.02	2	granite
NORTH CAROLINA										
Bryson City, N. C. (N. C. Surv. 0-97, W-2)	35°26'	83°27'	163	40-163	17.34 ± 0.41	5**	6.07 ± 0.48	1.05 ± 0.09	2	granite gneiss
Old Fort, N. C. (N. C Surv. M81, G1)	35°38'	82°10'	219	40-219	17.04 ± 0.03	2	4.92 ± 0.33	0.84 ± 0.06	2	mica gneiss
Charlotte, N. C. (McCall Bros. #4)	35°17'	80°53'	239	60-239	6.49 ± 0.22	10**	5.13 ± 0.18	0.33 ± 0.02	2	gabbro
Bermuda Run, N. C. (McCall Bros. #2)	36°01'	80°25'	150	20-140	7.02 ± 0.47	18**	4.45 ± 0.20	0.31 ± 0.03	2	biotite gneiss
New Hill, N. C. (U. S. G. S. Sears #1)	35°41'	78°56'	251	40-251	15.89 ± 0.52	11**	4.01 ± 0.59	0.64 ± 0.01	2	graywacke, volcanic fragments
Bear Pen, N. C. (N. C. Surv. EE-36, K5)	34°07'	78°20'	200	40-200	28.37 ± 1.04	9**	5.77 ± 0.19	1.64 ± 0.08	1	sand, clay
Stumpy Point, N. C. (Twiford #1)	35°40'	75°45'	650	280-600	35.68 ± 0.97	12**	4.59 ± 0.25	1.64 ± 0.35	1	limestone clay, sand
TENNESSEE										
Mascot, Tn (Ascarco 1F-14)	36°05'	83°39'	550	100-550	10.61 ± 0.06	9	7.86 ± 0.43	0.83 ± 0.05	1	Dolomite
Sweetwater, Tn (U.S. Borax & Chem. S-3A)	35°34'	84°29'	175	30-100	10.16 ± 0.27	3	9.86 ± 0.78	1.01 ± 0.08	2	Dolomite

Errors given are standard deviations. (*) indicates topographic correction included. (**) indicates drill cuttings used. Quality value assigned in accordance with guidelines of Sass and others (1971a).

HEAT FLOW VALUES

Temperature measurements were made in boreholes with a thermistor probe assembly and, where sufficient local relief existed, were corrected for topographic variations. Most of the boreholes used in this survey were drilled for mineral exploration or water-level monitoring purposes; five holes logged were drilled for petroleum or natural gas exploration. No drilling was conducted expressly for thermal research. Heat flow values were determined as the product of a least squares temperature gradient and a harmonic mean of thermal conductivity values.

Thermal conductivity measurements were accomplished with a divided-bar apparatus similar to that described by Sass and others (1971) on borehole core or cuttings samples. Because many of the boreholes logged were not cored, cuttings represented the only source of thermal conductivity data. The determination of thermal conductivity on drill cuttings was achieved following procedures outlined by Sass, Lachenbruch, and Munroe (1971). The borehole logging equipment and divided-bar assembly, as well as general procedures employed, were described by Smith (1976). A complete listing of individual temperature and conductivity values and topographic corrections is given by Emhof (ms) and Gregory (ms). Table 1 summarizes the temperature, conductivity, and heat flow data for individual sites shown in figure 1. The standard errors given in table 1 refer to the statistics of the calculations. Actual errors for the heat flow values may be ± 20 percent.

Valley and Ridge-Appalachian Plateau.—Seven new heat flow values from the Valley and Ridge and Appalachian Plateau provinces of Tennessee, Alabama, and Georgia are dissimilar and reveal an extensive area of anomalously low heat flow (fig. 1). Measurements in the Valley and Ridge province near Mascot (1.0 HFU) and Sweetwater (0.8 HFU), Tenn. are consistent with earlier Valley and Ridge province values of 0.7 HFU (Oak Ridge, Tenn.; Diment and Robertson, 1963) and 1.0 HFU (Cripple Creek, Va.; Reiter and Costain, 1973).

Two new values in the Valley and Ridge portions of Alabama (Colvin Gap, 0.2 HFU) and Georgia (Calhoun, 0.3 HFU) and two values (both 0.4 HFU) from the Cumberland Plateau near Huntsville, Ala. suggest a region of anomalously low heat flow (fig. 1). The dominant lithology (table 1) for each of the four sites is shale, and, because only cuttings were available for thermal conductivity determinations, a higher uncertainty should be assigned to the actual values. The temperature profile in the shallowest hole (180 m at Colvin Gap, Ala.) displayed some evidence of a hydrologic influence. A single measurement (1.1 HFU) in a coal mining district near Cristown, Ala. does not appear to be related to the low values in northeastern Alabama and northwestern Georgia.

Measurements of heat flow in sedimentary terrains are always more susceptible to disturbances from groundwater than those in crystalline rocks. Groundwater in the Huntsville, Ala. area occurs in permeable zones in regolith and limestone layers (generally less than 40 m thick) which overlie the Chattanooga shale (Christensen, Faust, and Harris, 1975). Relatively few wells penetrating the shale are waterbearing, and the hydrologic influence on the two cased wells logged near Huntsville is not considered significant. The measurement site at Colvin Gap, Ala. is in a 600 m thick section of relatively impermeable Mississippian Floyd shale, but isolated fracturing or limestone stringers can sustain thermally disturbing water movement.

Blue Ridge.—Measurements near Bryson City (1.0 HFU), N.C. and Old Fort (0.8 HFU), N.C. yielded new determinations of heat flux in the southern Blue Ridge province to accompany the previously reported value at Ducktown (0.7 HFU), Tenn. Thermal conductivity analyses of drill cuttings from unknown depths in the Bryson City hole and cores machined from surface samples near the Old Fort hole were necessary; thus, some caution is essential for an interpretation of those heat flow values.

A uniform temperature gradient and consistent thermal conductivity values characterized an excellent heat flow determination (1.0 HFU) near Marblehill, Ga. in the Murphy belt. Although this area is considered by some workers (Crawford and Medlin, 1973) to be part of the Piedmont, Hatcher (1972, 1978) includes the Murphy belt in his definition of the Blue Ridge. A single heat flow measurement in schistose rocks of the Talladega group near Talladega, Ala. is also included here, following Hatcher's definition of the Blue Ridge. Tull (1978), however, has described a "Northern Alabama Piedmont" as including the Talladega group. Roy and others (1968) presented a heat flow value (0.95 ± 0.03 HFU) from the Hillabee chlorite schist near Talladega, Ala. Subsequent discussions (R. F. Roy, personal commun., 1977) revealed that our measurements (0.89 ± 0.06 HFU) were made in the same borehole although a separate suite of core samples was chosen for conductivity measurements.

Piedmont.—The heterogeneous nature of the Piedmont province and complex tectonic histories proposed for it (that is, Hatcher, 1978; Rankin, 1975; Whitney and others, 1978) imply a geothermal environment distinguished by variable heat flow values. Early determinations of 1.4 HFU in Virginia (Diment and others, 1965) and 1.0 HFU in Georgia (Diment and Robertson, 1963) have been augmented by initial values of 1.1 to 1.5 HFU (Costain, Glover, and Sinha, 1977) in South Carolina from a continuing investigation by Costain and others. This paper presents one heat flow estimate from the Inner Piedmont, two values each from the Charlotte belt and Carolina slate belt, and one from the Deep River Basin.

Two measurements of 0.3 HFU at Charlotte, N.C. and near Winston-Salem, N.C. suggest an abnormally low heat flow within the Charlotte belt. The low values are a direct result of low temperature gradients (6.49 and 7.02°C/km, respectively), but no evidence of hydrologic disturbance is apparent in the temperature profiles. A third temperature gradient, however, obtained over a 200 m depth just south of Charlotte, N.C. near Tega Cay, S.C. was 14.24°C/km. No representative rock samples from Tega Cay were available for conductivity measurements, and a heat flow value is not estimated. Another relatively low heat flow value (0.6 HFU) was determined for a site at the east edge of the Deep River Triassic basin near Raleigh, N.C. The proximity of the Carolina slate belt-Charlotte belt boundary to this feature suggests a relationship between the anomalous value near Raleigh and the two values of 0.3 HFU to the west (fig. 1).

Groundwater migration and aquifer conditions are not prominent within the crystalline rocks of the Charlotte belt, and the exceptionally low heat fluxes at Charlotte and Winston-Salem are not attributed to hydrologic conditions. Each of these boreholes, however, was originally drilled as a water well and was cased. The temperature gradient recorded near Raleigh has a higher probability of groundwater influence because the borehole (cased) penetrated a more heterogenetic rock column.

Boreholes in a granitic pluton and in a mica schist exposure approx 20 km apart near Columbia, S.C. yielded heat flow values of 1.1 HFU each, although machined core samples from a nearby quarry were used for conductivity determinations for one of the sites. Poor conditions (no casing in the hole, core cuttings for conductivity measurements, probable groundwater disturbance) at a borehole in biotite gneiss on the Inner Piedmont near Braselton, Ga. cause us to limit the calculated heat flow value of 0.6 HFU for that site to an estimated minimum value.

Coastal Plains.—The highest values of temperature gradients and heat flow in this survey were found in the Coastal Plains province. A gradient of 35.68°C/km between 280 and 600 m depth was recorded at Stumpy Point, N.C. Two heat flow values of 1.6 HFU were calculated for the Coastal Plains of North Carolina. Temperature measurements in four additional boreholes in the Coastal Plains of North Carolina and South Carolina all exceeded 20°C/km (including a value of 28°C/km for a deep USGS hole at Summerville, S.C.) but are unaccompanied by representative samples for thermal conductivity.

Thermal conductivity values for four sites in the Coastal Plains of Georgia and Alabama (fig. 1) were calculated with cuttings from nearby drill holes rather than the holes in which the temperature gradients were measured. It is believed that the sedimentary rock sequences and properties at the measured drill holes and the adjacent areas in which the other holes were drilled were sufficiently similar to justify this action.

Although situated on the Coastal Plain, the Jeffersonville, Ga. hole is very near the overlap of the Coastal Plain sedimentary rocks onto the Piedmont province. The measured heat flow, 0.92 HFU, is more characteristic of the Piedmont province than the Coastal Plains. The heat flow value (0.5 HFU) calculated for Brunswick, Ga. may represent a minimum value. The temperature-depth profile suggests subsurface water flow that may be causing temperature inversions in the lower levels of the borehole. Wait and Gregg (1973) recorded temperature gradients of 27.56 and 25.59°C/km in the Brunswick area. The product of either of these gradients and the thermal conductivity measured in this study would yield heat flow values of approx 1.1 HFU which appear to be typical for the Coastal Plains. Smith and Fuller (1977) have demonstrated the thermal effects of the Floridan aquifer at a heat flow site in Florida immediately south of the Brunswick area.

RADIOACTIVE HEAT GENERATION

Representative igneous and crystalline metamorphic rocks were collected throughout the Piedmont and Blue Ridge provinces for determinations of uranium, thorium, and potassium abundances by gamma ray spectrometry. More than three hundred samples (each usually consisting of a mixture of several specimens) were taken from quarries, drill cores, road cuts, and other surface exposures. Rock exposures displaying obvious weathering were avoided to exclude samples in which leaching of the radioelements was probable; nevertheless, only a limited number of samples could be classed as completely unaltered.

Analyses of the samples were accomplished with a gamma ray spectrometer with a 6″ diam by 4″ thick NaI(Tl) crystal and standard procedures described by Smith, Gregory, and Garvey (1978). A total maximum error of less than 10 percent (or 0.5 ppm) is estimated for the radioelement abundances. Estimates of radioactive heat generation (in heat generation units = 10^{-13} cal cm^{-3} sec^{-1}) were computed on the basis of uranium, thorium, and potassium contents and the heat production coefficients from Birch (1954). Average heat generation values are summarized in table 2; individual radioelement abundances and sample locations are presented in detail by Garvey (ms), Emhof (ms), and Gregory (ms).

Overall average radioactive heat generation within the country rocks is highest in the Inner Piedmont province, followed by the Carolina slate and Charlotte belts and the Blue Ridge province, respectively. Subtle differences among average values are not emphasized because individual sample values were variable. Radioelement abundances in intrusive granitic rocks usually exceeded those in mafic and intermediate rocks more than two-fold, and the relative percentages of country rock and granitic exposures samples was not controlled.

TABLE 2

Average radioactive heat generation (in heat generation units of 10^{-3} cal cm^{-3} sec^{-1}) for representative surface samples of crystalline rocks. Numbers of samples given in parentheses.

Tectonic/Geologic unit	Alabama	Georgia	S. Car.	N. Car.-Va.	Average
Blue Ridge	4.17 (18)	4.12 (30)		3.71 (48)	3.92 (96)
Chauga belt	3.62 (8)		7.64 (3)		4.72 (11)
Inner Piedmont (all)	3.96 (8)	7.44 (62)	5.78 (10)	4.48 (25)	6.32 (105)
Inner Piedmont (granitic plutons only)		10.40 (24)		5.78 (17)	8.48 (41)
Kings Mtn-Pine Mtn belt	1.90 (4)		4.35 (3)		2.95 (7)
Charlotte belt		5.51 (21)	3.41 (10)	4.21 (26)	4.55 (57)
Carolina slate belt			7.06 (20)	3.03 (20)	5.05 (40)

The predominate rock types collected in the Blue Ridge province were granitic gneisses, mica gneisses, and mica schists. Quartzites averaging less than 1 HGU from the Blue Ridge of Alabama and other minor rock types are not included in table 2. Within the Inner Piedmont, most exposures were of biotite gneisses and granitic gneisses or of granitic plutons. In all areas, plutonic rocks display higher radioactivity, but the Elberton and Siloam intrusives in Georgia, with heat generation values of 11-14 HGU (Smith, Gregory, and Garvey, 1978), appear to have the greatest concentrations of radioelements.

APPLICABILITY OF DATA TO THERMAL MODELS

A linear relationship between radioactive heat generation, A, in surficial plutonic rocks and heat flow, Q, has been demonstrated (Birch, Roy, and Decker, 1968; Roy, Blackwell, and Birch, 1968b; Lachenbruch, 1968) to be

$$Q = q^* + bA \tag{1}$$

where q^* is considered to be a reduced heat flow exclusive of upper crustal radioactivity emanating from the lower crust and upper mantle. Within a thermal province, q^* and b are fixed, definitive parameters.

Roy, Blackwell, and Decker (1972) described a Central Plains–Eastern United States thermal province with $q^* = 0.8$ HFU and $b = 7.5$ km, but the parameters were based primarily on data from New England. Subsequent heat flow measurements in the Interior Lowlands and Great Plains provinces (Combs and Simmons, 1973) suggest that several separate thermal provinces within the central and eastern United States might be justified. Costain and Sinha (1978) identified thermal parameters of $q^* = 0.69$ HFU and $b = 6.5$ km based on measurements in the Piedmont province. Regional values of heat flow that are less than the postulated reduced heat flow values, as indicated by Smith (1976) for values in eastern Tennessee, are incompatible with the linear heat flow-heat generation relationship. The linear relationship of eq (1) apparently cannot be confirmed for the Basin and Range province where hydrothermal and magmatic convection exert a greater influence on surface heat flow than does crustal radioactivity (Lachenbruch and Sass, 1977).

The concept of an upper crustal zone enriched in radioelements contributing heat additively to a uniform flux generated below is subject to certain potentially restrictive considerations, if it is to be applicable to the southeastern United States. The contrast of radiogenic heat production between young granitic plutons and country rock in the Piedmont and Blue Ridge provinces implies a corresponding variation of heat flow values. Furthermore, the moderately higher heat flow values from the Atlantic Coastal Plains province seemingly require (for steady state conditions) an upper crustal heat component that exceeds that of the Piedmont and Blue Ridge. This situation can be attributed to thicker zones of radioelement enrichment in the subsurface rocks or to greater concentrations of radioelements, but an insufficiency of data precludes a test of these qualifications. Erosion of the Piedmont and Blue Ridge provinces may have left those areas with a lesser radioactive heat generation than a hypothetical buried extension of the Piedmont beneath the Coastal Plains province.

Costain (1978) described a mechanism whereby radioelements located along mineral grain boundaries would migrate downward through a series of microcracks within a surface zone of approx 7 km. The zone is continually renewed by downward percolation of radioelements to maintain a constant thickness upon erosion. Thus, the linear heat generation relationship survives differential erosion.

Measurements of heat flow at nine sites in this study were accompanied by determinations of radiogenic heat production (table 3). A plot of the data (fig. 2) fails to demonstrate a complete adherance to the linear relationship parameters of Roy, Blackwell, and Decker (1972) or Costain and Sinha (1978). Although possible errors resulting from uncorrected hydrologic influences on temperature gradients or leaching of surficial samples taken for radioactivity measurements might account for certain of the discrepancies, the three points (BR, CH, and NH in fig. 2) for the Charlotte belt appear to be sufficiently removed from the expected lines to require alternative explanations. If the Charlotte belt is indeed characterized by anomalously low heat flow (two or three measurements are not confirmation), and the irregularity cannot simply be attributed to decreased radiogenic heat production in the upper crust, either a wholesale heat diversion or refraction from lower crustal-upper mantle sources is necessary, or a separate thermal province with a significantly lower mantle heat flow is present. In the same fashion, the low thermal flux identified in the southern Valley and Ridge-Appalachian Plateau area of Alabama and Georgia (fig. 1) demands a special thermal model.

Assuming the linear relationships illustrated by lines A and B in figure 2 are generally valid, a reduced or mantle heat flow of approx 0.7

TABLE 3

Heat flow values and associated heat generation values for the southeastern United States. The proximity of the Columbia and Lexington, S.C. locations justifies the use of the same average heat generation value for that area.

Location	Heat Flow (HFU)	Heat Generation (HGU)	Rock Type
Blue Ridge			
Bryson City, N. C.	1.05	2.44	granite gneiss
Old Fort, N. C.	0.84	3.80	mica gneiss
Marblehill, Ga.	1.00	2.80	mica schist
Talladega, Ala.	0.89	3.00	chlorite schist
Charlotte belt			
Winston-Salem, N. C.	0.31	0.12	biotite gneiss
Charlotte, N. C.	0.33	1.10	gabbro
New Hill, N. C.	0.64	1.90	metavolanic
Carolina slate belt			
Columbia, S. C.	1.09	7.07	mica schist
Lexington, S. C.	1.11	7.07	granite

HFU is representative for most of the Piedmont and Blue Ridge provinces. The Charlotte belt and southern Valley and Ridge-Appalachian Plateau area, however, may have a reduced heat flow as low as 0.3 HFU. Thermal conditions in the mantle below the Coastal Plains are difficult to estimate because knowledge of the basement rocks in that province is limited.

IMPLICATIONS FOR TECTONIC MODELS

Recent descriptions of the geologic history of the southern Appalachians (Rankin, 1975; Hatcher, 1978) have attempted to incorporate the basic tenets of plate tectonics with observations from geologic mapping. No single hypothesis has been completely adopted, but most theories invoke the subduction of a proto-Atlantic or Iapetos Ocean between converging North American and African plates during the early Paleozoic. Hatcher (1978) proposed a collage of microcontinents in the southern Appalachians with at least three major sutures between continental fragments. Sutures within the Blue Ridge and along the Kings Mountain-Pine Mountain belt developed from the closures of a continental fragment and island arc (Carolina slate belt) with the North American craton. The present-day suture with remnants of the African continent is

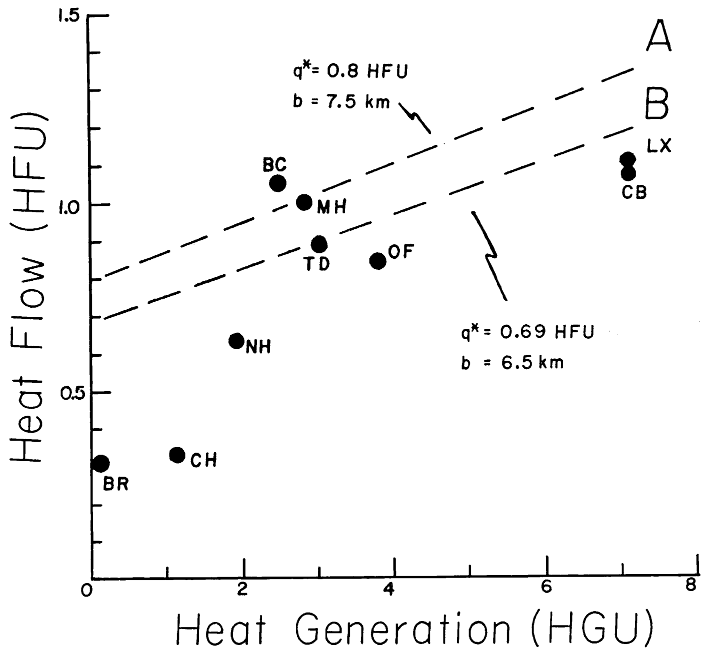

Fig. 2. Heat flow values (in heat flow units) from the Blue Ridge and Piedmont provinces plotted against respective heat generation (in heat generation units) of surficial rocks. Line A is from Roy, Blackwell, and Decker (1972), and line B is from Costain and Sinha (1978). Individual points, as listed in table 3, are BC: Bryson City; OF: Old Fort; MH: Marblehill; TD: Talladega; BR: Winston-Salem (Bermuda Run); CH: Charlotte; NH: New Hill; CB: Columbia; LX: Lexington.

beneath the Coastal Plains. Rankin (1975) also proposes an island arc origin for the slate belt but considers the Inner Piedmont as an allochthonous sheet and the Brevard Zone as an early plate suture.

Other interpretations exist, each with geological evidence, but as basic thermal data are accumulated and a distinct thermal pattern emerges, any theoretical assemblage of dissimilar blocks for the southeastern United States should conform to the observed thermal evidence. For example, proposals of large-scale thrusts causing excessive crustal thicknesses or of continental blocks derived from the metamorphism of island arc material should include a consideration of the relative radiogenic heat contribution expected of those assemblages to the regional heat flow. Absolute thermal requirements, however, cannot be a condition governing acceptance of tectonic models because predicted thermal conditions may be modifed by: (1) deviations from a steady-state conductive heat transfer system such as by convective overturn or large-scale hydrologic disruption, (2) refractive heat conduction resulting from assymetric conductivity patterns, and (3) our uncertainty concerning the distribution of radioactive heat generating elements with depth and the consequent effects of deep erosion or leaching.

To illustrate the simplistic method of estimating thermal conditions for hypothetical tectonic assemblages, consider the cross-sectional examples shown in figure 3. The relative thicknesses of individual blocks with characteristic heat generation refer to radioelement zones within the upper crust and do not imply a Moho depth; nor do the schematic arrangements depict any specific tectonic model. Profile A extends northwest-southeast in a representative manner across the southeastern United States and is based on a continuous North American craton extending to the northwestern edge of the Charlotte-Carolina slate belt region. The craton has an average heat generation similar to that observed in the core of the Blue Ridge province but thins and is covered with an allochthonous layer in the Inner Piedmont and eastern Blue Ridge. A separate craton (the African plate) furnishes upper crustal heat for the Charlotte belt, Carolina slate belt, and Coastal Plains. Sedimentary sequences of the Coastal Plains, Valley and Ridge, and Appalachian Plateau provinces contribute no significant radiogenic heat. A reduced flux of 0.4 HFU is uniform across the profile, but the configuration of upper crustal blocks yields a pattern of contrasting heat flow values.

In profile B, a crustal block representing the Blue Ridge, Pine Mountain-Kings Mountain, and a "stacked" Inner Piedmont is separated from the North American craton to the northwest by a thick sequence of Valley and Ridge sediments effectively devoid of radiogenic heat. An African craton underlies the Coastal Plains province, but the Carolina slate belt and Charlotte belt blocks represent former island arc and metasedimentary sequences. In this case, a different reduced heat flow (0.8 HFU) is assigned to the African block to produce heat flow values consistent with those observed in the Atlantic Coastal Plains province.

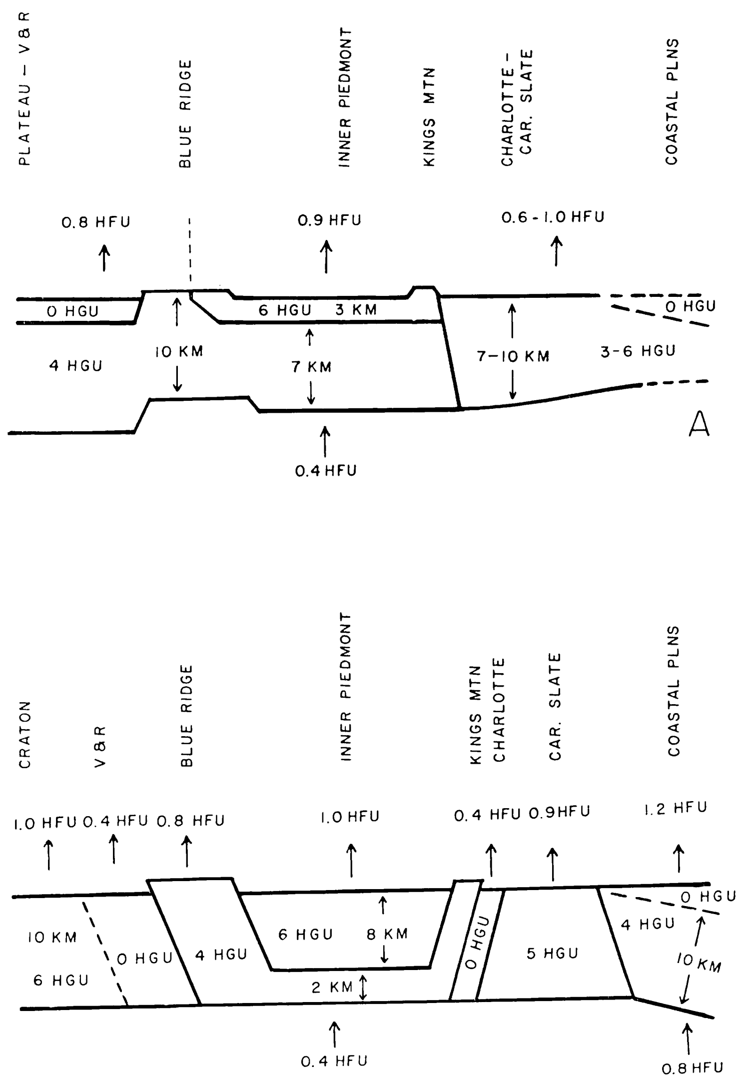

Fig. 3. Representative cross sections (from northwest to southeast) of the southern Appalachian Mountains and Atlantic Coastal Plains illustrating possible combinations of tectonic blocks and thermal properties. Not to scale.

A. A uniform heat flux of 0.4 HFU exists at the base of the upper 10 km of the crust which has varying heat production values and, therefore, varying surficial heat flow. Two major continental crustal blocks, the North American craton on the northwest and the African craton on the southeast, are represented.

B. A more complex schematic depicting a Blue Ridge-Kings Mountain belt with an allochthonous Piedmont is separated by an island arc Carolina slate belt from the African craton under the Coastal Plains.

The above examples merely illustrate how tectonic models for the southern Appalachians can accommodate simple tests of thermal properties, and how observed thermal conditions such as average heat generation and average heat flow can be used to corroborate hypothetical assemblages of upper crustal fragments. We have not intended to present our own models or to represent any specific model previously proposed.

CONCLUSIONS

Twenty-three new heat flow values for the southeastern United States range from 0.2 HFU in northeastern Alabama to 1.6 HFU along the coastline in North Carolina. The new data augment previous heat flow values to suggest general regions of characteristic heat flow values (fig. 4) in the southern Appalachians and Coastal Plains. Anomalously low values in the Charlotte belt and in an area of the Valley and Ridge and Appalachian Plateau of northeastern Alabama and northwestern Georgia suggest distinct thermal conditions in those regions. Heat flow values in the Blue Ridge and the remainder of the Piedmont are near the 0.8 to 1.0 HFU range, while those in the Atlantic Coastal Plains are apparently above 1.0 HFU. Measurements in Florida (Smith and Fuller, 1977) and elsewhere in the Coastal Plains suggest lower values of average heat flow. This contrast may reflect a stronger factor of hydrological influence, or it may be indicative of a lesser mantle heat flow.

Analyses by gamma ray spectrometry of over three hundred igneous and metamorphic surface rock samples for heat producing radioelement abundances have permitted estimates of heat generation that are variable among the separate geologic belts. Surface rocks in the Inner Piedmont exhibit the highest radioactive heat production, whereas those in the Blue Ridge produce the least amount of heat. Heat flow and heat generation values from the Blue Ridge and Piedmont provinces fail to demonstrate a linear relationship, particularly when data from the Charlotte belt are included.

That general characterizations of thermal conditions in the southeastern United States can contribute, at least as testing constraints, to tectonic models can be demonstrated. As additional thermal data are acquired, more reliable descriptions of thermal conditions will evolve, and a new and independent tool will be available to interpret the geological features of the southern Appalachians and the southeastern Coastal Plains.

ACKNOWLEDGMENTS

The arrangements for many of the boreholes logged and cores sampled in this survey were facilitated through the generous cooperation of numerous individuals in the Georgia Department of Natural Resources, Geologic and Water Resources Division, The Geological Survey of Alabama, the South Carolina Division of Geology, the North Carolina Department of Natural and Economic Resources, and the United States Geological Survey offices in Columbia, S.C. and Atlanta, Ga. We are particularly indebted to J. Sampair, E. P. Allen, G. Bain, P. Johnson, D. E.

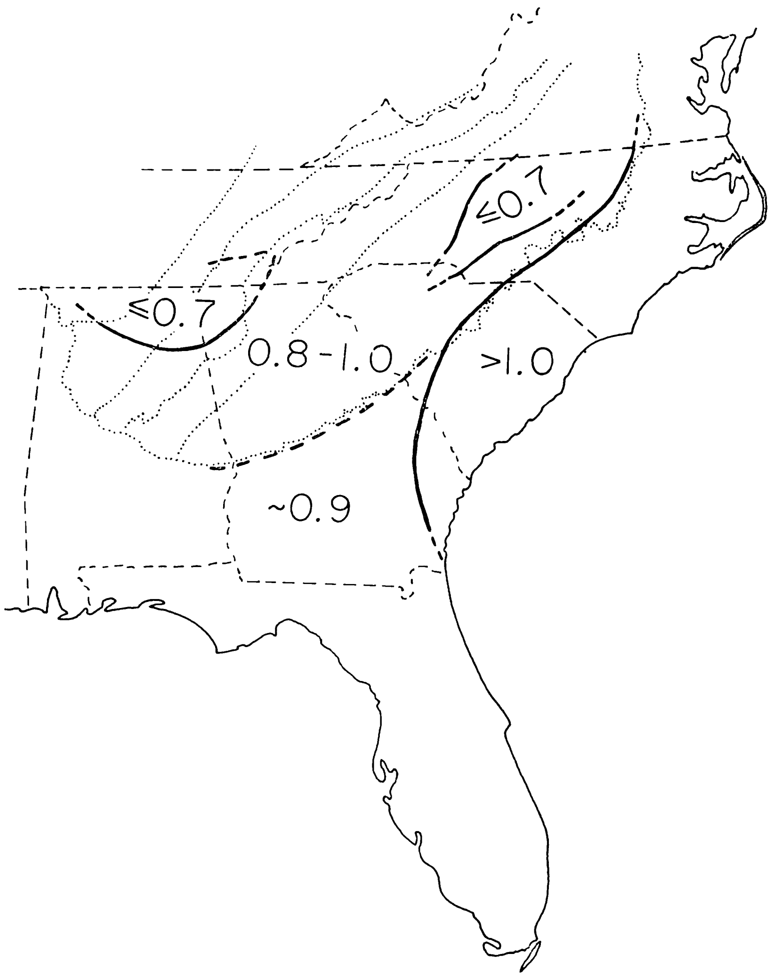

Fig. 4. Generalized regions of characteristic heat flow (in heat flow units) in the southeastern United States. Areas of heat flow equal to or less than 0.7 HFU include Valley and Ridge and Appalachian Plateau regions of northwestern Georgia and northeastern Alabama and the Charlotte belt in North Carolina. Heat flow throughout most of the southern Blue Ridge and Piedmont provinces appears uniform and generally within 0.8 to 1.0 HFU. The Atlantic Coastal Plains has a greater flux (>1.0 HFU) than most of the Florida peninsula and Gulf Coastal Plains.

Howell, H. Gill, S. M. Pickering, T. L. Neathery, and J. Ellerd. Officials from the U. S. Pipe Co., Southeastern Exploration Co., Georgia Marble Co., ASARCO, U. S. Borax and Chemical Co., and McCall Brothers Drilling Co. were also very instrumental in field investigations. We appreciate enlightening discussions with J. K. Costain, G. C. McCall, S. M. Pickering, and P. A. Mueller. J. H. Sass, R. W. Pierce, and P. A. Mueller critically reviewed the manuscript and provided numerous helpful suggestions for its improvement. This research was sponsored by the U. S. Geological Survey, Department of the Interior, under U. S. Geological Survey grant 14-08-0001-G-199.

References

Birch, F., 1954, Heat from radioactivity, *in* Faul, H., ed., Nuclear Geology: New York, John Wiley & Sons, p. 148-174.

Birch, F., Roy, R. F., and Decker, E. R., 1968, Heat flow and thermal history in New England and New York, *in* Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., eds., Studies of Appalachian Geology: Northern and Maritime: New York, John Wiley & Sons, p. 437-451.

Christensen, R. C., Faust, R. J., and Harris, W. F., 1975, Environmental geology and hydrology, Huntsville and Madison County, Alabama: Alabama Geol. Survey, Atlas Ser. 8, 118 p.

Combs, J., and Simmons, G., 1973, Terrestrial heat flow determinations in the north central United States: Jour. Geophys. Research, v. 78, p. 441-461.

Costain, J. K., 1978, A new model for the linear relationship between heat flow and heat generation [abs.]: Am. Geophys. Union Trans., v. 59, p. 392.

Costain, J. K., Glover, L., and Sinha, A. K., 1977, Low-temperature geothermal resources in the eastern United States [abs.]: Geol. Soc. America Abs. with Programs, v. 9, p. 937.

Costain, J. K., and Sinha, A. K., 1978, Relationship between heat flow and heat generation in the southeastern United States [abs.]: Geol. Soc. America Abs. with Programs, v. 10, p. 166.

Crawford, T. J., and Medlin, J. H., 1973, The western Georgia Piedmont between the Cartersville and Brevard fault zones: Am. Jour. Sci., v. 273, p. 712-722.

Diment, W. H., Marine, I. W., Neiheisal, J., and Siple, G. E., 1965a, Subsurface temperature, thermal conductivity and heat flow near Aiken, South Carolina: Jour. Geophys. Research, v. 70, p. 5635-5644.

Diment, W. H., Raspet, R., Mayhew, M. A., and Werre, R. W., 1965b, Terrestrial heat flow near Alberta, Virginia: Jour. Geophys. Research, v. 70, p. 923-929.

Diment, W. H., and Robertson, E. C., 1963, Temperature, thermal conductivity, and heat flow in a drilled hole near Oak Ridge, Tennessee: Jour. Geophys. Research, v. 68, p. 5035-5048.

Diment, W. H., and Werre, R. W., 1964, Terrestrial heat flow near Washington, D. C.: Jour. Geophys. Research, v. 69, p. 2143-2149.

Emhof, J. W., ms, 1977, A geothermal study of southern Virginia, North Carolina, and eastern Tennessee: M.S. thesis, Univ. Florida, 82 p.

Garvey, M. J., ms, 1975, Uranium, thorium, and potassium abundances in rocks of the Piedmont of Georgia: M.S. thesis, Univ. Florida, 95 p.

Gregory, R. G., ms, 1978, A geothermal study of Alabama, Georgia, and South Carolina: M.S. thesis, Univ. Florida, 108 p.

Griffin, G. M., Reel, D. A., and Pratt, R. W., 1977, Heat flows in Florida oil test holes and indications of oceanic crust beneath the Southern Florida-Bahamas Platform, *in* Smith, D. L., and Griffin, G. M., eds., The geothermal nature of the Floridan Plateau: Florida Bur. Geology. Spec. Pub. 21, p. 43-64.

Hatcher, R. D., 1972, Developmental model for the southern Appalachians: Geol. Soc. America Bull., v. 83, p. 2735-2760.

——— 1978, Tectonics of the western Piedmont and Blue Ridge, southern Appalachians: Review and Speculations: Am. Jour. Sci., v. 278, p. 276-304.

King, W., and Simmons, G., 1972, Heat flow near Orlando, Florida, and Uvalde, Texas, determined from well cuttings: Geothermics, v. 1, p. 133-139.

Lachenbruch, A. H., 1968, Preliminary geothermal model of the Sierra Nevada.: Jour. Geophys. Research, v. 73, p. 6977-6989.

Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States and the thermal regime of the crust, *in* Heacock, J. G., ed., The earth's crust: Am. Geophys. Union Mon. 20, p. 626-675.

Rankin, D. W., 1975, The continental margin of eastern North America in the southern Appalachians: the opening and closing of the Proto-Atlantic Ocean: Am. Jour. Sci., v. 275-A (Tectonics and Mountain Ranges), p. 298-336.

Reiter, M. A., and Costain, J. K., 1973, Heat flow in southwestern Virginia: Jour. Geophys. Research, v. 78, p. 1323-1333.

Roy, R. F., Blackwell, D. D., and Birch, F., 1968, Heat generation of plutonic rocks and continental heat flow provinces: Earth Planetary Sci. Letters, v. 5, p. 1-12.

Roy, R. F., Blackwell, D. D., and Decker, E. R., 1972, Continental heat flow, *in* Robertson, E. C., ed., The nature of the solid earth: Englewood Cliffs, N.J., McGraw-Hill, p. 506-543.

Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, F., 1968, Heat flow in the United States: Jour. Geophys. Research, v. 73, p. 5207-5221.

Sass, J. H., Diment, W. H., Lachenbruch, A. H., Marshall, B. V., Munro, R. J., Moses, T. H., and Urban, T. C., 1976, A new heat-flow contour map of the conterminous United States: U.S. Geol. Survey Open-File Rept. 76-756, 24 p.

Sass, J. H., Lachenbruch, A. H., and Munroe, R. J., 1971, Thermal conductivity of rocks from measurements on fragments and its application to heat flow determinations: Jour. Geophys. Research, v. 76, p. 3391-3401.

Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W., and Moses, T. H., 1971, Heat flow in the western United States: Jour. Geophys. Research, v. 76, p. 6376-6413.

Smith, D. L., 1976, Heat flow at Ducktown, Tennessee: Southeastern Geology, v. 18, p. 99-106.

Smith, D. L., and Fuller, W. R., 1977, Terrestrial heat flow values in Florida and the thermal effects of the aquifer system, *in* Smith, D. L., and Griffin, G. M., eds., The geothermal nature of the Floridan Plateau: Florida Bur. Geology Spec. Pub. 21, p. 19-130.

Smith, D. L., Gregory, R. G., and Garvey, M. J., 1978, A thermal reconnaissance of Georgia: heat flow and radioactive heat generation: Georgia Dept. Natural Resources, Bull. 93, p. 93-104.

Tull, J. F., 1978, Structural development of the Alabama Piedmont northwest of the Brevard Zone: Am. Jour. Sci., v. 278, p. 442-460.

Wait, R. L., and Gregg, D. O., 1973, Hydrology and chloride contamination of the principal artesian aquifer in Glynn County, Georgia: Georgia Dept. Natural Resources Hydrologic Rept., 93 p.

Whitney, J. A., Paris, T. A., Carpenter, R. H., and Hartley, M. E., 1978, Volcanic evolution of the southern slate belt of Georgia and South Carolina: a primitive oceanic island arc: Jour. Geology, v. 86, p. 173-192.

Ziagos, J. P., Sass, J. H., and Munroe, R. J., 1976, Heat flow near Charleston, South Carolina: U.S. Geol. Survey Open-File Rept. 76-148, 21 p.