GENERAL GEOLOGY OF THE EAST COAST WITH EMPHASIS ON POTENTIAL GEOTHERMAL ENERGY REGIONS: A DETAILED SUMMARY

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Introduction and Background

The relative stability of the East with respect to earthquakes and volcanic activity does not immediately suggest the vast reserve of low to moderate temperature (40° - 125°C?, or 104° - 260° F?) geothermal energy that probably exists here. It is understandably difficult to seriously consider geothermal prospects in the East as long as the word "geothermal" brings forth an image of Old Faithful erupting at Yellowstone! Nevertheless, for the low temperatures needed to economically heat large housing (3000 units) and industrial complexes, for example, some of the eastern hydrothermal reservoirs may be both large and favorably located with respect to potential utilization. The importance of developing this resource is easily understood from the observation that currently about 40% of our fuel consumption is devoted to space heating.

Below the effects of the diurnal and annual temperature variation at the surface, (several hundred feet), the temperature in the earth tends to show a regular rise with increasing depth. In the future, it may become economic in this country to develop geothermal sources in deep aquifers from regions of essentially "normal" geothermal gradient, as is currently being done with a gradient of 33°C/Km or 1.8°F/100 ft in the Paris Basin (Rybach, this program). Secondly, mining heat by circulating water through man-made hydraulic fractures in hot crystalline rocks of the basement below insulating sedimentary basins is an existing technology developed at Los Alamos that may have a future in the East. If so, the temperatures available by this method may even be sufficient to generate electric power. Thirdly, natural fracture zones and fold structures that allow convection of heat by the rise of deeply circulating ground water in regions of essentially normal heat flow, e.g. Hot Springs, Virginia, seem to have immediate but more modest(?) application because of apparent limitations in temperature, volume of water, and location.

Of primary interest at present, however, are elements of eastern geologic frameworks which are conducive to generating abnormal (greater than 30° C/Km, or 1.6°F/100 ft.) thermal gradients. These elements include: 1) sedimentary basin fillings of very low thermal conductivity (i.e. heat damming) sediments, e.g. water saturated clay-rich deposits, and 2) radiogenic heat sources in the crystalline continental crust, especially the younger granites of Late Paleozoic (300 - 260 m.y.) and younger ages. Optimal geologic frameworks occur where: 1) granites of high heat generating capacity (radiogenic heat supplied by spontaneous fission of naturally occurring U, Th, and ^{40}K in the granite), are 2) overlain by large confined or semiconfined aquifers, which 3) are in turn blanketed by thick (water saturated and clay-rich) strata of low thermal conductivity. Such frameworks appear to be most abundant east of the Fall Line, under the Atlantic Coastal Plain. Environmentally clean heat could be extracted by circulating water from an aquifer up one well, through a heat exchanger, and then reinjecting the water down a second well. The optimal geologic framework described above is often referred to as "the buried pluton concept" and is the principal targeting procedure being used by VPI&SU to explore the Atlantic Coastal Plain geologic province. It could be applied as well to many other suitable regions in the U.S. and elsewhere.

From the foregoing it is clear that the aspects of east coast geology of highest priority in a search for geothermal resources include: 1) the thickness, structure, stratigraphy, hydrology, and thermal conductivity of sediments beneath the Atlantic Coastal Plain, and 2) the structure, composition, age and intensity of metamorphism and of granite emplacement, and the heat production of rocks in the basement under the Atlantic Coastal Plain. Because the character of the Atlantic Coastal Plain sediments is discussed by other speakers on this program, the following is concerned with the evolution of 2) above, the heat sources in the basement.

Regional metamorphism and deformation play a key role in the evolution and location of basement radiogenic heat sources. Uranium and thorium in particular are mobilized in fluids and granitic melts during regional metamorphism. Moving under the influence of gravity, thermal gradients, and deformation, much of the uranium and thorium is permanently lost from or homogenized in a metamorphic terrain. A notable exception is the relative concentration of these elements (U, Th, and K) in granitic melts that may crystallize and remain within the zone of metamorphism. Thus the "plums" are radiogenic granites scattered through a "pudding" of metamorphic gneisses and schists that may be somewhat depleted in these heat producing elements. By "concentrated" we mean about 10 parts per million (ppm) of U in the granite vs. 1 - 2 ppm in the gneisses and schists of the metamorphic terrain. Hardly ore grade or very radioactive in the usual sense!

In the case of the Appalachian Piedmont and its extension, the basement under the Atlantic Coastal Plain, patterns of metamorphism and igneous activity have wandered through space and time in a complex manner. Thus the U and Th concentrated in granites of one generation may be strongly depleted or homogenized during the metamorphism of another. Only granites that consolidate after the thermal peak of the last metamorphism in an area are likely to have relatively high radiogenic heat production. It is important, therefore, to try to understand these patterns of metamorphism and igneous activity in order to target productive granites beneath the Atlantic Coastal Plain. Targeting of such granites under the Coastal Plain can be assisted by using magnetic, gravity, and seismic surveys, but these are indirect methods that must be controlled by selective core drilling into the crystalline basement. Some cores should come from metamorphic basement rocks (the "pudding") so that we can determine composition, structure, density, seismic velocity, magnetic properties, heat production and the type and age of metamorphism. Other cores must come from young syn- to post-metamorphic granites (the "plums") so that besides their other properties, we can also measure their heat generation directly in order to verify the exploration model and to serve as a double check on certain heat flow related measurements made in the shallower wells of the Atlantic Coastal Plain.

The nature and timing of igneous and metamorphic activity in the crystalline Appalachians (i.e. Blue Ridge, Piedmont, and basement under the Atlantic Coastal Plain) are topics central to plate tectonic hypotheses for the origin of the Appalachians Because of previous research stimulated by this interest we have a moderate amount of background data to build upon. That is, the data base is sufficient to generate interesting ideas about the nature of possible radiogenic heat sources, but insufficient to verify them. Plate tectonic models provide us with rational hypotheses that explain some of the data and may give us some predictive capability about the nature of certain basement regions. Further discussion of such models, however, is beyond the scope of this paper.

Some Aspects of the Geologic History of the Piedmont as a Guide to the Nature of Heat Sources in the Atlantic Coastal Plain Basement

(The following account greatly oversimplifies a complex geologic terrain. The trends discussed here are not well documented and much work remains to be done.)

Widespread volcanism and plutonism (emplacement of granitic and gabbroic rocks) during the Eocambrian and Cambrian Periods, about 800 to 500 m.y. ago, extended over much of the Piedmont and Blue Ridge. The scanty data suggest that these plutons range from large to small in size, from shallow to deep levels of emplacement, and were associated with periods of extensive volcanism. All known rocks of this age in the Central and Southern Appalachians have been metamorphosed at least once and appear to be generally characterized by low heat production.

A more distinct pattern appears to have emerged in the igneous and metamorphic history beginning in Ordovician time, about 480 - 425 m.y. ago. In the eastern foothills of the Carolina Blue Ridge and in the western Piedmont of the Carolinas and Virginia, granitic and gabbroic plutons were emplaced during a regional metamorphism that probably ended abruptly as a result of cooling by deformation, uplift, and erosion during the Taconic Orogeny. If the eastern Piedmont was affected by this metamorphism, large regions (the Carolina Slate Belts) were never raised above low (greenschist grade) temperatures and pressures. Additionally, there are probably no Taconic age plutons in the eastern Piedmont south of about Fredricksburg, Virginia.

By latest Ordovician and Silurian time, approximately 400 m.y. ago, a few gabbroic and granitic plutons were injected along the central axis of the Piedmont in the Carolinas. Ductile deformation affected some of these plutons, which suggests that regional metamorphism may have continued from the Taconic event or may have migrated eastward with the plutonic activity. The intensity of igneous and metamorphic activity thus far recognized seems diminished by comparison with the Taconic evidence for relative crustal stability at this time recorded in Silurian rocks of the Valley and Ridge.

Late Devonian to Pennsylvanian time saw the central axis of metamorphism and plutonic intrusion migrate into, or at least reach an intensity maximum, in the eastern Piedmont. Dating of this metamorphism suggests a thermal maximum at about 350 m.y. ago (Acadian Orogeny). The metamorphism diminishes westward into the Blue Ridge where it partially overprints the earlier Taconic metamorphism. It was accompanied, mostly during its waning stage, by widespread plutonism over a span of about 330 to 260 m.y. ago. This produced a very large (ca. 60) group of syn- to post-metamorphic granitic plutons. These Late Paleozoic granites are most abundant along the Fall Line south of Richmond, Virginia, and in Georgia they trend westward into the region south of Atlanta. This westward trend in Georgia appears to be somewhat concordant with Late Paleozoic regional structural features that may link the Appalachians with the Ouachitas.

Because the 350 m.y. Acadian regional metamorphism was the last major metamorphic event to affect the eastern Piedmont, granites of this age or younger have generally retained much of their U and Th. Thus they are the best known sizable group of heat generating plutons south of New England. They commonly produce two or three times as much heat as their older metamorphosed counterparts and the enclosing country rocks.

From the above, the basic pattern in Middle and Late Paleozoic time was eastward migration of the axis of igneous and metamorphic activity. Thus it is natural to ask whether the trend continues in the basement below the Atlantic Coastal Plain. The answer is - possibly - yes. Within the past year several researchers have discovered ductile deformation overprinting young plutons in the easternmost parts of the Piedmont. If this foreshadows discovery of another still younger generation of plutonic and metamorphic activity under the Coastal Plain, we must determine this and also whether these rocks will have a comparable range of heat generation.

A second pattern is emerging from Piedmont studies that may help in exploring the Coastal Plain basement for heat sources. The Late Paleozoic metamorphic-plutonic age province in the eastern Piedmont is subdivided into several NE-trending belts that have been recognized for many years. Some of these belts are: Charlotte, Carolina Slate, Raleigh, Kiokee, Eastern Slate, etc. The basic rationale for recognizing such belts has involved considerations of the relative intensities of metamorphism, plutonism, and deformation. It now appears that low-metamorphic-grade belts are generally synformal (downwarped) and are only marginally injected by plutons in the age range of latest metamorphism. Much of the downwarping occurred during the protracted period of metamorphism-plutonism, and the low grade terrains, being more rigid than adjacent high grade (and higher temperature) terrains, resisted injection by granite. Those granites that did manage to inject the margins of these low grade (Carolina Slate) belts tend to be circular in surface outcrop and to have inverted teardrop or spike-like shapes. Thus their gravity and magnetic signatures also tend to be somewhat distinct.

Belts of high metamorphic grade, and therefore of greater ductility at the time of metamorphism, have antiformal (upwarped) shapes and contain large concentrations of granite generated during the time of metamorphism and upwarping. Structural studies strongly suggest wholesale migration of ductile country rock (the "pudding") and granitic magma (the "plums") into the crests of high grade belts and away from the bottoms of downwarping lowgrade belts. If this hypothesis proves true, high grade belts (unless very deeply eroded) should have higher heat generation than low grade belts because of the greater concentration of granitic magma emplaced during the last metamorphic-plutonic event. Additionally, granites coeval with the last metamorphism in these higher grade belts tend to be larger and more nearly concordant than plutons that penetrated more rigid crust. Thus these large bodies of magma, such as the Rolesville and Petersburg, may be 50 - 60 miles long and 20 - 30 miles wide, and locally surrounded by haloes of mixed rocks (migmatites) of granite and country rock. Such bodies tend to produce large elliptical regional gravity lows and may also be outlined by magnetic surveys.

Extrapolation from these Piedmont trends suggest that we might expect to find: 1) a continuation of this pattern of alternating high- and low-grade belts in the basement under the Atlantic Coastal Plain; 2) a concentration of the granites having highest heat production in and marginal to the high grade belts; 3) a possibility of even younger metamorphism and plutonism with heat production ranges different from those measured in the Piedmont. By combining indirect (magnetic, gravity, seismic) and direct (heat flow measurements from shallow and deep Coastal Plain wells, geologic and geophysical studies of selected basement cores) methods we can develop a knowledge of the basement that will eventually allow more routine selection of geothermal sites over buried granites of high heat production. Although a beginning has been made by the U.S.G.S. (high and low grade belts do exist under the Coastal Plain in North Carolina), VPI&SU, Princeton, and several state surveys, much work remains to be done, particularly in obtaining basement core samples to control geophysical-geological extrapolations on a regional basis.

Before leaving this discussion of the Paleozoic development of the Atlantic Coastal Plain basement, the anomalous crust beneath southern South Carolina, and much of Georgia and Florida merits some attention. In this region the familar schistosity of the northern basement and Piedmont is missing. Poorly dated, very low grade volcanics near the Georgia coast are probably Early Paleozoic or Eocambrian in age, and near the Georgia-Florida border, unmetamorphosed, nearly horizontal Early and Middle Paleozoic sedimentary rocks are found in the basement. Much of this is overlain by Early Mesozoic nonmarine sediments and basaltic lavas. Seemingly these differences are best explained by suturing another continental fragment onto the North American Plate during the late Paleozoic. Whatever the cause, the obviously different geologic history of this segment of the present continent suggests the possibility of different heat production-heat flow characteristics.

Finally Mesozoic and younger lineaments transverse (W to NW trending) to the regional Appalachian trend might in some areas exert a strong influence on heat flow and heat production. Probably there are diffuse but deep fracture zones that extend to the lower crust or mantle. In New England, they are characterized by offshore subsea volcanoes, anomalous seismicity, and Late Paleozoic-Mesozoic emplacement of alkalic granite and gabbro(?) plutons. The Conway Granite, belonging to this trend, has the highest heat flow recorded from a granite of comparable size in the Appalachians. In Virginia, numerous westerly aligned features suggest a similar lineament. Examples are the WNW trending offshore Norfolk scarp, the west trending central Virginia seismic zone, and the Mesozoic to Early Tertiary alkalic shallow intrusives in the Valley and Ridge of Highland County, central western Virginia. In South Carolina a similar feature passing NW through Charleston has been described by Columbia University and U.S.G.S. researchers.