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REVIEW OF POTENTIAL HOST ROCKS FOR RADIOACTIVE WASTE DISPOSAL IN THE PIEDMONT PROVINCE OF GEORGIA

David B. Wenner
Kenneth A. Gillon
Department of Geology
University of Georgia

E. I. du Pont de Nemours Co.
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PREFACE

The disposal of radioactive waste in the proper geologic environment offers a high potential for isolating the waste from man's environment for the period of time required for the waste to decay to innocuous levels. As part of the National Waste Terminal Storage Program, the Savannah River Laboratory has responsibility for studies related to the storage of waste in the geologic environment in the Southeast. For the purposes of this study, the Southeast consists of the igneous and metamorphic rocks of the Piedmont, the sands and clays of the Coastal Plain, and the mudstone and shales of the Triassic basins from Maryland to Georgia. To implement these studies, a literature review of each of these three geologic provinces was performed by subcontract. The purpose was to designate areas that, from a geotechnical point of view, offer a potential for field exploration to investigate their characteristics and suitability for disposal of solidified high-level radioactive waste. Because of the geologic complexity of the Piedmont and its generally high potential for waste storage, the general study was complemented by four detailed studies of literature and existing knowledge by experts in the local geology. From all of these supporting studies, the Savannah River Laboratory prepared a summary report which designates the areas favorable for field exploration.

This report is a detailed study of the state of Georgia by David B. Wenner and Kenneth A. Gillon of the University of Georgia. This study is being published by the Savannah River Laboratory to make it generally available. However, the conclusions reached are those of Dr. Wenner and Mr. Gillon, and they alone are responsible for its content.

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1.0 ABSTRACT

A literature study was conducted on the Piedmont province of Georgia to designate areas that may be favorable for field exploration for consideration of a repository for storage of radioactive waste. The criteria utilized in such a designation was based upon consideration of the rock unit having favorable geological, geotechnical, and geohydrological features. The most important are that the rock unit have: (1) satisfactory unit dimensions (>100 km^2 outcrop area and at least 1500 meters (~5000 feet) depth of a continuous rock type) and (2) acceptable geohydrological conditions. Among all rock types, it is concluded that the granites of the large post-metamorphic plutons and large, homogeneous orthogneissic units offer the most favorable geologic settings for exploration for siting a radioactive waste repository. Virtually all other rock types, including most metavolcanic and metasedimentary lithologies have unacceptable unit dimensions, generally unfavorable geohydrologic settings, and deleterious mechanical and physical geotechnical properties. After consideration of all major lithologies that comprise the Georgia Piedmont, the following units were deemed favorable: (1) the Elberton Pluton; (2) the Siloam Pluton; (3) the Sparta Pluton; (4) two unnamed plutons adjacent to the Snelson body of S. W. Georgia; (5) the Lithonia Gneiss; (6) basement orthogneisses and charnockites of the Pine Mountain Belt.

2.0 INTRODUCTION AND BACKGROUND

This report presents the results of a geotechnical investigation to identify favorable geologic units among the crystalline rocks within the Piedmont province of Georgia for field exploration for possible storage of radioactive waste. This work represents an outgrowth of a study completed in June 1978 by Acres American, Inc., titled "Review of Potential Host Rocks for Radioactive Waste Disposal in the Southeast United States - Southern Piedmont Subregion," which included coverage of the states of Maryland, Virginia, North Carolina, South Carolina, and Georgia.

In the reconnaissance study conducted by Acres American of the Southeastern Piedmont, each of the major rock types, taken from published state geologic maps, were classified as being "favorable," "potentially favorable," or "unfavorable" for their suitability as host rocks for radioactive waste disposal. In the present study, further consideration was given towards evaluating the conclusions of the Acres report with the aim of (1) obtaining only two classifications, either favorable or unfavorable, for all rock units of the Georgia Piedmont, and 2) for providing a justification for this classification for each geologic unit.

In this report, no consideration was given to any socio-economic and nontechnical factors. The methods employed primarily involve a literature survey of published and unpublished material, along with discussions with numerous individuals from federal, state, and private organizations knowledgeable about particular regions within the state. No field work was undertaken in conjunction with this study.

3.0 OBJECTIVE

The objective of the present study is twofold: (1) to review the criteria used to assign rock characteristics to the acceptable, marginally acceptable, and unacceptable categories and to review the impact of the evaluation on the assignment of favorable, potentially favorable, and unfavorable categories; and (2) on the basis of a detailed knowledge of local rock units, to reassign the rock types currently in the potentially favorable category to either the favorable or the unfavorable categories.

4.0 GENERAL GEOLOGY OF THE GEORGIA PIEDMONT

4.1 Introduction

The Piedmont Province was originally designated by Fenneman (1938) on the basis of its physiography to include a broad upland region of the Southern Appalachians. The Piedmont is characterized by deep weathering of crystalline rocks with a surface topography of gently rolling hills. The region lies between the higher and steeper topography of the Valley and Ridge sedimentary rocks and Blue Ridge crystalline rocks to the northwest, and the flat lying sediments of the Coastal Plain to the southeast. However, in recent years, the Piedmont has been redefined to include only the region lying southeast of a major regional lineament, the Brevard Zone (Reed and Bryant, 1964; Hatcher, 1971). In accordance with this revision, this report covers the more restricted region as shown in Figure 1.

4.2 Geological Subdivisions of the Piedmont

The Piedmont Province is subdivided into a number of northeast trending tectonic provinces or belts that follow regional structural features. These belts (shown in Figure 1) have been defined on the basis of their similarities in topography, structure, rock type, and metamorphic grades.

The information and description of these belts, as described below, were taken from numerous sources that include King (1955); Hatcher (1971, 1972, 1978); Whitney, et al. (1978); Snoke, et al. (1979); and Cook, et al. (1979).

Brevard Zone - represents a major zone of cataclasis of regional extent, characterized by one or more ductile and one or more brittle deformations. Recent COCORP (Consortium for Continental Reflection Profiling) seismic data indicate this zone may be a thrust fault rooted in the sole thrust of the Blue Ridge - Piedmont Plate (see Cross Section B-B' of Appendix B).

Chauga Belt - consists of low-grade metamorphosed graphic phyllites and impure marbles overlain by the 640 m.y. Henderson paragneiss. This belt lies adjacent to the Brevard Zone throughout Georgia.

Inner Piedmont - is characterized by abundant and extensively deformed and metamorphosed granitic gneisses, amphibolite-hornblende gneisses and schists; lithologies appear to be derived from protoliths of quartzofeldspathic and pelitic sediments. The northwestern boundary with the Chauga Belt is one of steep metamorphic grade involving an antiform (Inner Piedmont)-synform (Chauga Belt) pair. The south-eastern boundary is delineated by the Kings Mountain Belt in North and South Carolina and by the Middleton Cataclastic Zone in Georgia. The southeastern extension of this fault zone is thought to extend to the Towaliga Fault Zone, which defines the Inner Piedmont boundary in central and southwest Georgia (see Figure 1).

Charlotte Belt - represents a zone of amphibolite grade para-gneisses, schists, and amphibolites intruded by numerous pre- and post-metamorphic plutons; much of this belt in Georgia consists of granitoid gneisses. The contact with the Carolina Slate Belt is of a steep metamorphic gradient, with the Charlotte Belt probably serving as a basement to the Carolina Slate Belt.

Carolina Slate Belt - consists of greenschist grade felsic vol-canic and associated volcanoclastic flows and tuffs, over-lain by sedimentary sequences of banded argillites. These units are preserved in broad synclinal structures that were subsequently intruded by plutons of various ages.

Pine Mountain Belt - is composed of amphibolite grade gneisses, schists and quartzites lying unconformably upon a Grenville age basement of orthogneisses and charnockites. This belt outcrops as an antiformal structure that is bound by the Towaliga and Goat Rock Faults to the northwest and southeast, respectively.

Kiokee Belt - consists of amphibolite grade felsic gneisses, quartzites, and schists that appear to underlie portions of the Carolina Slate Belt; this belt is bound to the north by a major zone of cataclasis, the Modoc Fault.

Belair Belt - consists of interlayered felsic and intermediate pyroclastic rocks with subordinate epiclastic rocks, all metamorphosed to the greenschist facies. This belt lies juxtaposed to higher grade rocks of the Kiokee Belt along the Augusta and Belair Faults. Rocks of this belt may be correlative with Carolina Slate Belt lithologies.

Uchee Belt - composed of amphibolite-grade migmatitic gneisses, amphibolites, and lenses of schist. A major gneiss unit (Phenix City Gneiss) gives Rb/Sr ages of 570 m.y. These rocks are similar in composition to the Inner Piedmont lithologies north of the Pine Mountain Belt.

4.3 The Precambrian and Paleozoic Tectonic, Structural, and Metamorphic History of the Georgia Piedmont

The Piedmont of the Southern Appalachians represents a region formed through a long history of multiple deformational, plutonic, and metamorphic events that took place largely during the Late Precambrian and Paleozoic Eras. The complex outcrop patterns presented on the geologic map in Appendix A represent a summation of these processes and events. These major events are presented chronologically in schematic fashion in Figure 2. The data utilized in this illustration represent a compilation of recent thinking constructed by this author from a number of sources that include: Hatcher (1978); Dallmeyer (1978); Fullagar (1971); Fullagar and Butler (1979); Snoke, et al. (1979); Cook (1979); and Carpenter, et al. (1978).

Geologists now attribute plate tectonics as a primary mechanism for the evolution of the southern Piedmont. Although details of the specific plate tectonic models are controversial, they can provide a comprehensible and consistent explanation to the complex tectonic, deformational, and metamorphic events that have gone into making the Appalachian Piedmont.

The following scenario of plate tectonic events, adopted principally from Cook, et al. (1979) but incorporating data from Fullagar and Butler (1979) and Snoke, et al. (1979), is presented in order to provide an interpretation of the complex events portrayed in Figure 2. This model is illustrated pictorially in Figure 3.

a. During the Late Precambrian (800 - 700 m.y.), rifting of a supercontinent resulted in development of a proto-Atlantic ocean (Iapetus Ocean) and a continental fragment (Piedmont microcontinent) (Figure 3A). At this time, volcaniclastics, ashfalls, and turbidites were deposited nonconformably over the Grenville-age basement of the North American continent and Piedmont microcontinent.

b. At a later period of time (700 - 600 m.y.) (Figure 3B) during the Late Precambrian, subduction formed east of the Piedmont microcontinent, thus resulting in the beginning of the Charlotte - Slate Belt island arc. Subduction is presumed to be responsible for deformation and metamorphism of the Charlotte Belt during the Virgilina Orogeny.

c. During Middle to Late Cambrian (550 - 500 m.y.) (Figure 3C), an eastward dipping subduction zone is presumed to have existed along the west edge of the Piedmont microcontinent to set the stage for a later collisional event. Volcanism and associated plutonism continued during this time in the proto Charlotte-Slate Belt island arc system.

d. During the Ordovician (~450 m.y.), a major collisional event occurred (Figure 3D) between the Piedmont microcontinent and the North American continent, resulting in the Taconic Orogeny. This event was presumably responsible for the major metamorphism and deformation of the Inner Piedmont and for partial thrusting of the Inner Piedmont over the North American shelf.

e. A second major collisional event occurred in the Devonian (~380 m.y.) between the Charlotte-Slate Belt island arc system and the Inner Piedmont continental land mass, resulting in the Acadian Orogeny (Figure 3E). Plutonism coincident with subduction was common in the Charlotte-Slate-Kings Mountain Belts (confined dominantly during the interval from 415 to 385 m.y.) and in the Inner Piedmont (340 - 350 m.y.). Much of the ductile movement on the major faults shown in Figure 1 is presumed to have occurred during this period of time.

f. A third collisional event (not depicted in Figure 3) occurred betwen North America and Africa, producing the Hercynian Orogeny during the Late Carboniferous and Permian (325 - 250 m.y.), and resulting in closure of the Iapetus and concomittant plutonism and metamorphism of the eastern Piedmont; this orogeny is responsible for metamorphism and plutonism in the Kiokee Belt and pervasive thrusting throughout the Southern Appalachians. This major thrusting event may be largely responsible for producing the allochthonous Piedmont block depicted in Cross Section B-B' of Appendix B.

g. Major uplift of the Inner Piedmont occurred subsequent to the Acadian Orogeny (Figure 3F), with near exhumation of the present erosion level occurring by Late Triassic (~220 m.y.).

h. During the Early Mesozoic Era (~200 m.y.), rifting began between North America and Africa, producing the present-day Atlantic Ocean (not depicted in Figure 3). This extensional event resulted in formation of the Triassic basins, diabase intrusions, zeolitization along fracture zones, and brittle reactivation along some Paleozoic-age fault systems.

4.4 Post Paleozoic Tectonic and Structural History of the Georgia Piedmont

Although the major orogenic cycles that have affected the Piedmont occurred during the Late Precambrian and throughout the Paleozoic, a number of important events occurred subsequently that set the stage for today's tectonic style. These include the following events.

a. During the early Mesozoic, extensional tectonics produced normal faulting parallel to the regional Appalachian trend that extended from Georgia to Canada, resulting in graben development with clastic filling, producing the Triassic basins, and widespread basaltic volcanism forming flows and intrusions within these basins. The Triassic basins within Georgia occur under portions of the Coastal Plain (Marine and Siple, 1974).

b. Pervasive diabasic dikes that crosscut the Piedmont formed nearly perpendicular to the regional Appalachian NE-SW trend, with orientations radially converging on the Blake plateau (May, 1971). These dikes crosscut the Triassic basins and may be early Jurassic (~190 m.y.) in age (Dallmeyer, 1975). In Georgia, a small portion of the larger dikes are shown on the state geologic map (Georgia Geological Survey, 1976), but are not presented in Appendix A.

c. Siliceous ultramylonite zones, called flinty crushed rock zones, occur with a west or northwest orientation and steep dip throughout the Piedmont along joint surfaces. These zones, considered to be post-orogenic and post-diabase in age, also formed as the result of extensional tectonics during the Mesozoic (Birkhead, 1973). Such zones also occur along many major Paleozoic-age fault zones in Georgia and represent brittle reactivation of essentially ductile Paleozoic faults.

d. Zeolitization of fractures occurs sporadically throughout the Piedmont, but appears to be most concentrated in the vicinity of the Churchland Pluton in the Charlotte Belt of North Carolina (Butler, personal communication). In Georgia, zeolite-filled fractures have been described in scattered localities thoroughout the older metamorphic rocks and post-metamorphic granitic plutons of the Piedmont (Ramspott, 1967). K/Ar age dates of a fracture-filled zeolite vein at the Richard B. Russell Dam Site along the Savannah River are ~180 m.y. (Pope, 1979). This is similar to dates recorded in fracture-filled zeolites in North Carolina (Butler, personal communication).

e. Cenozoic age overthrust fault activity, documented along the Belair Fault in Georgia (Prowell and O'Conner, 1978), represents a return to compressional tectonics. Vertical offset on this fault has been documented to be at least 30 meters since the

Late Cretaceous and 10 meters since late Eocene; there is evidence that no movement has occurred along this fault in the last 2,000 years (U.S.G.S., 1977). Other Paleozoic-age faults where movement may have occurred during the Cenozoic can be found in the Pine Mountain Belt area (Prowell, personal communication). Studies of major and minor fault zones, including the Modoc, Towaliga and Belair, in the vicinity of the Richard B. Russell Dam Project exhibit no evidence of recent fault activity (U. S. Army Corps of Engineers, 1977); the lack of disturbance in horizontal podosol marker beds are thought to indicate an absence of movement during the last 1 m.y., the estimated age of saprolite formation (Douglas, 1974).

f. Since the Triassic and Jurassic, some 2 - 3 km of erosion has occurred, based on the estimated amount of erosion of the Triassic basins (Marine, personal communication) and on the existence of zeolite in fractures that post-date the diabase dikes.

g. At the present time, major uplift is occurring throughout the Georgia Piedmont (see Bollinger, 1973) with rates as great as 7 mm/yr centered around Atlanta (see Figure 4). Also at the present time, the southeastern Piedmont may be subjected to high horizontal stresses (Stephenson and Pratt, 1979), consistent with Cenozoic age thrust faulting observed on the Belair Fault.

4.5 Seismicity

Most of the Georgia Piedmont lies in Seismic Zone 2, indicating that an area may be subject to moderate surface damage. A plot of earthquake epicenters for the southeastern U. S., including Georgia, is presented in Figure 4. Earthquakes have not been assigned to specific fault zones.

Detailed analyses of the potential for earthquake damage at the Richard B. Russell Project (U. S. Army Corps of Engineers, 1977) suggest that the maximum earthquake to be expected in the Piedmont would have an intensity of VII and a corresponding magnitude of 5.5.

4.6 Hydrogeology

Within virtually all rock types comprising the Piedmont, subsurface water movement is largely confined to fractures, with the degree of movement dependent upon the density and openness of fractures. Well data in general substantiates the argument that less groundwater movement occurs with increasing depth (LeGrand and Mundorff, 1952), persumably due to increasing lithostatic pressure resulting in closure of fractures.

One of the major difficulties in assessing hydrogeologic factors in the Piedmont of Georgia in the context of this study is the general absence of information at depths 300 to 1500 meters (~1,000 to 5,000 feet) pertinent to potential radioactive waste burial areas. Much of the current thinking in assessing groundwater movement in various Piedmont rocks is based on a number of assumptions. These can be summarized as follows:

a. Less groundwater movement occurs with increasing depth in all lithologic rock types.

b. Older rock types can be expected to be more fractured and thus more susceptible to groundwater transmission than younger rocks of equivalent type (due presumably to the fact that older rocks contain a greater summation of deformational events).

c. Massive high-grade metamorphic rocks, such as gneisses, and younger intrusive rocks have the lowest permeabilities of all Piedmont crystalline rock types.

There are some studies and observations that have a direct bearing on these assumptions. These are summarized below:

1. Observations by LeGrand and Mundorff (1952) of shallow wells in a variety of Piedmont rock types in the Charlotte, N. C. area confirm that massive rocks such as granites have relatively low water yields. They observed from wells of <400 ft (120 meters) depth, in a variety of rock types, an average yield (gal/min)/ft of: schist (0.15) > diorite (0.10) > granite (0.09) > slate (0.08); these yields, however, are highly dependent on the specific well sites (hill, valley, slope, etc.) and vary with well depth.

2. Studies of groundwater movement were made in drill holes at depths up to 500 ft (150 meters) in gneisses and schists in the vicinity of Atlanta, Georgia, for assessing potential sites for gas storage (Stewart, 1962). It was concluded that appreciable groundwater movement occurs at depths down to 500 ft. Similar observations were recorded in wells in the Lithonia Gneiss (Atkins, 1979).

3. Observations in deep mines in a wide variety of rock types in the Precambrian terrane of the Lake Superior Region (Yardley, 1975) and in the Maritime Province of Canada (Martinez, 1975) indicate that under most circumstances, mines are dry at depths greater than about 3000 ft (900 meters), except in one instance in a major thrust fault zone. However, at depths less than 3000 ft, water seepages were observed in some mines, although other mines were dry at depths of 2000 ft (600 meters).

4. Swedish KBS Project Studies (1979) made in rocks similar to those found in the Georgia Piedmont have a particular importance for understanding the geohydrological conditions at the depths of interest for radioactive waste storage (in the Swedish studies, ~500 meters). In particular, it was noted that hydraulically continuous fracturing in granite gneisses and granites were mostly limited to 100 - 200 m of the surface. Below these depths, the bedrock consists of blocks of low permeability, with conductivities less than 10^{-9} m/s, in between zones of continuous fracturing. Such zones were observed to be water bearing to depths of 900 meters. It was concluded that such fractures represent planes of weakness in the bedrock, but should provide mechanical protection against fracturing in the intervening, less fractured blocks. Any future movement that would occur on such fractures therefore would not be expected to appreciably alter the hydraulic conductivity of the intervening massive rock surrounding a repository.

Additional conclusions of importance from the KBS study center around models made of groundwater flow patterns. Such models suggest that flow times from a repository site buried at a depth of 500 m to the surface would take a very long time, greater than 3000 years in the worst possible case. It was also observed that groundwaters in deep mines are invariably chemically reducing, indicating that such waters lack the ability to dispense uranium and its decay products.

From the above described studies, it can tentatively be concluded that absolutely dry, water-free conditions can be expected at depths greater than 1000 meters in virtually all rock types, but that some groundwater transmission along major fault zones in granites and granite gneisses can be anticipated at the depths being evaluated by the Swedish KBS project (500 meters). At depths of 100 - 200 meters, hydraulically continuous fracturing to the surface exists in granite gneisses and granites. There would appear to be little evidence to suggest that other rock types, such as schists, represent less favorable repository mediums than granites and granite gneisses from hydrogeologic factors alone, except near the surface. However, it is not known to what extent that extrapolation of near-surface well data to the depths of interest in this study can be made.

Of particular importance to the hydrogeologic properties of the metamorphic rocks of the Piedmont is the control by various structural features. In the Piedmont, most lithologic units, sheared and cataclastic zones, and rehealed fault contacts are steeply inclined. As Snow (1977) has noted, such boundaries largely control groundwater flow, so that in a strongly anisotropic region, maximum permeability should occur along contact planes, with a minimum flow normal to such contacts; groundwater flow is also concentrated in planer openings parallel to bedding, foliation (which is commonly coplaner to bedding), and axial-plane cleavages. Joints not parallel to foliation are, of course, common, but apparently are not as effective or as continuous as water-bearing conduits as those parallel to foliation.

The assumption that older rocks can be expected to be more fractured than younger rocks of equivalent type appears to be largely unsupported by any evidence. Although older rocks have been subjected to a greater number of orogenic events (say the Grenville-age basement of the Pine Mountain Belt versus the younger, post-metamorphic granites), any previously formed fractures would be expected to be rehealed due to ductile behavior in rocks during a subsequent orogenic event which may have occurred at great depths under high lithostatic loads and temperatures. Thus both younger, post-metamorphic granites and older basement rocks have probably been fractured largely since uplift to shallow depths where rock essentially behaves in a brittle manner. The major fault zones of the Piedmont would appear to represent the only exception to this statement, since they would appear to be the focus of late-stage, brittle movement. Perhaps the strongly anisotropic, cataclastic textured rocks found in these fault zones are themselves 'weaker' than more isotropic type lithologies.

5.0 APPLICABLE CRITERIA FOR SELECTING AREAS

5.1 Introduction

The criteria for selection of favorable areas as potential radioactive waste repository sites is based on the concept that the host rock repository must have suitable chemical and physical properties to ensure long-term storage and thus prevent dispersion to the biosphere. Such a rock unit should display a number of favorable hydrologic, geologic, and geotechnical features. In this report, each of these three major criteria are discussed separately.

5.2 Hydrological Factors

The quantities of groundwater and their flow patterns are crucial to selection of a favorable geologic medium, since subsurface water penetration into potential repositories represents the major vehicle for migration of radioactive waste to the surface. This migration, of course, is largely dictated by the permeability of the host rock and the hydraulic gradient at the repository site.

Since in most of the Piedmont crystalline rocks, groundwater flow and permeability are restricted to interconnecting joints and shear zones, it is important to identify rock bodies that are massive and homogeneous with a minimal number of joints and fractures at the depths of interest between 300 to 1500 meters ($\sim$1000 to 5000 feet).

Generally, however, conclusive data on the geohydrologic nature of various metamorphic and igneous rocks in the Georgia Piedmont is lacking, particularly at the depths of interest. If extrapolation from shallower depths, where water well data is available ($<$120 meters) has any significance, it can be assumed that granites represent a relatively favorable geological medium from a geohydrologic point of view. However, there would appear to be little direct evidence to support this assumption.

In a previous study (Acres American, Inc., 1978), the position was held that the only hydrologically favorable rock types are massive, poorly foliated granite gneisses and younger granites; in contrast, schists, phyllites, slates, and metavolcanic rocks are considered to be unfavorable. It would appear, however, that there is little direct evidence to justify the overall favorability and unfavorability classifications for these rock types except on questionable extrapolation of shallow well data. Another assumption is that younger intrusive rocks are less jointed and fractured than older rocks of equivalent type. This assumption seems to have little basis for support as was discussed in Section 4.6.

One important geohydrologic factor that has a direct bearing in this study is the suggestion made by Snow (1977) that groundwater influx is greatest along bedding surfaces and cleavage planes (commonly parallel in the Piedmont). Much of the Georgia Piedmont is composed of steeply dipping lithologic contacts and fault zones (see Figure 1). One can anticipate that, strictly from a hydrologic point of view, rock units that consist of steeply dipping intermixed lithologies, such as many metasedimentary and metavolcanic rocks, would be expected to provide preferred avenues for relatively deep subsurface water percolation.

Another deleterious hydrologic factor that clearly has to be considered is the abundance and occurrence of major fault zones in the vicinity of a repository site. Such zones clearly could provide conduits for deep groundwater penetration, as was observed in deep mines at depths even greater than 900 meters (~3000 feet) (see Section 4.6). Although most of the major fault zones in the Georgia Piedmont that are shown in Figure 1 exhibit largely ductile fabrics, many show overprints of brittle textures, indicating post-orogenic removement. Such brittle fabrics would be expected to serve as preferred sites of deep groundwater influx to considerable depths.

5.3 Geotechnical Factors

The geotechnical factors which are of importance in determining the overall suitability of a host rock for storage of radioactive waste encompass a number of physical and mechanical properties such as compressive strength, modulus of elasticity, rock density, rock quality, rock material strength, and joint spacing. These factors determine whether the host rock will (1) support mined chambers stably for a long term, (2) be resistant to thermal alteration that would adversely affect the repository's stability, and (3) provide adequate physical properties to ensure no change in rock permeabilities.

A previous study (Acres American, Inc., 1978) concluded that many metamorphic rocks such as phyllites, slates, and metavolcanic rocks are anisotropic in their physical and mechanical properties to a sufficient degree so as to produce extreme variations in geotechnical properties. Furthermore, this study noted that these rock types in general exhibit low compressive strengths, poor rock quality, and a relatively high moisture content that would result in deterioration in strength upon exposure to air.

This study adopts these previous conclusions, which suggest that the most favorable rock types in terms of their physical and mechanical properties are younger plutonic rocks and massive, poorly foliated gneisses. These rock types are nearly isotropic, and have excellent properties both for excavational purposes and for sustaining large underground openings.

5.4 Geological Factors

5.4.1 Unit Dimensions

A host rock must have sufficient lateral and vertical dimensions to not only contain the repository, but provide a "buffer zone" that would ensure no migration to the surface. In this report, a potentially favorable site serving as a repository has to have a minimum surface area of 100 km^2 of a continuous rock type, and a vertical depth of at least 1500 meters (~5000 feet). In the context of this requirement, sites containing mixed lithologies on a smaller scale are considered unfavorable.

5.4.2 Structural Features

There are a number of factors that fall into this category and each is discussed below.

(1) The proximity to location of major faults has to be considered both from the standpoint of a potential for future movement on the fault, which could result in damage to a repository excavation site, and for being a conduit for groundwater access to the repository. As was noted previously, however, although the likelihood for anv movement on a fault in the Georgia Piedmont during the next one million years seems unlikely, such a fault zone that intersects a repository or even lies within the required unit dimension of the site has to be considered unfavorable, since such a fault could act as an avenue for groundwater flow to great depths. Thus a repository should lie at least 5 km away from a major fault zone to have an acceptable unit dimension.

However, the location of a repository within a rock unit of sufficient unit dimensional size that is located a satisfactory distance away from a major fault zone may be a favorable setting, since anv release of stress resulting in movement in a given region would be expected to occur within the fault zone rather than in the relatively stable rock unit. Thus the juxtaposition of a contiguous rock body to a fault zone might actually serve to 'protect' the body from future fracturing.

(2) The degree of joint spacing in a rock is an important factor that has to be seriously evaluated, especially if such fractures and joints extend to any substantial depth. A possible method for assessing the degree of joint spacing in a given rock type in the Piedmont can be gained from observations of flat rock outcrops. It can be expected that rock units that outcrop extensively should have a relatively low density of joints and fractures, since most rocks with a large number of vertically dipping fractures and joints would be expected to be preferentially weathered to substantial depths. This belief is adopted in this report, and a map of the flat rock outcrops in Georgia, shown in Figure 5, is used as an important criterion for site selection of favorable units.

(3) Seismic considerations would appear to be of little importance as a criterion for designating a favorable unit in the Georgia Piedmont. Most of the area covered in this report has only a relatively low to moderate potential for seismic hazards. This is especially true for any underground repository, since earthquakes are known to produce significantly less damage in subsurface structures (Pratt, et al., 1978).

(4) Regional stress factors are important in repository designation, but they cannot be utilized for selecting one site over another with the present state of knowledge. Effects of stress are of importance in the design of underground excavations.

5.4.3 Considerations of Plutonic Environments

Although plutonic bodies of sufficient lateral and vertical dimensions offer a number of positive features that would appear to make them favorable as repository mediums, there are a number of factors related to the pluton's mechanism of emplacement and subsequent history that may have a direct bearing on its favorability rating. In particular, there are many examples (see Taylor, 1972, and references therein) of shallow level (<4 km depth) epizonal plutons that have interacted with meteoric waters during their intrusion and crystallization histories, resulting in extensive fracturing and vein formation in both the pluton and the adjacent country rock. Such plutons could be affected adversely in their hydrologic and structural properties, which could make them unsuitable as repository mediums.

There are many instances where epizonal plutons have produced extensive fracturing of the country rock during their later stages of crystallization, resulting in influx of surface waters into the immediate environment of the pluton which subsequently generated hydrothermal systems around the plutonic heat source. Such plutons, in fact, are generally considered to be responsible for forming most present-day geothermal areas and have been attributed to the formation of many major ore deposits, such as most of the world's porphry copper deposits.

It is important to note that plutons affected in such a manner can usually be readily identified by the following types of geochemical, petrologic, and geologic analyses.

(1) Stable isotopic (D/H and $^{18}O/^{16}O$) analyses provide the best and most definitive method for assessing the extent to which meteoric waters may have gained access to a pluton during its crystallization or cooling history.

(2) Most plutons affected in this manner display classic petrologic evidence of their epizonal nature by the presence of miarolytic cavities, alteration of plagioclase and mafic minerals, and occurrences of low temperature vein minerals.

(3) Many such plutons are intruded into volcanic country rock.

(4) Many plutons affected in this manner are composite in nature, having formed by multiple intrusions closely spaced in time.

In the past year, stable isotopic studies of a number of post-metamorphic plutons in Georgia and South Carolina have been undertaken (see Wenner, et al., 1977). To date, none give definitive evidence of having interacted with meteoric waters, except for portions of the Sparta Pluton in Georgia. Because most post-metamorphic plutons in the Southern Appalachians are generally regarded as mesozonal (intruded at depths from 6-12 km), one would a priori expect that meteoric water interactions would be minimal. However, recent studies of granites adjacent to or buried under the Coastal Plain suggest that some post metamorphic plutons may have been intruded at epizonal levels. Thus the possibility exists that other plutons, particularly those that lie adjacent or beneath the Coastal Plain, may have also interacted with meteoric waters.

5.5 Mineral Resource Potential

The mineral resource potential of a rock unit that is designated favorable based strictly upon geologic, geohydrologic, and structural factors is an important feature that must be taken into consideration. However, it is felt that this is an economic facor that must be weighed against the particular importance of utilizing a given rock unit as a radioactive waste repository. In this report, the economic potential of each rock unit that is designated favorably is discussed in Section 7, but this factor is not employed in classifying a rock unit as either favorable or unfavorable.

5.6 Summary

The most favorable geologic units for storage of radioactive waste would appear to be the younger plutonic bodies and the massive, poorly foliated orthogneisses. These two rock types have a number of satisfactory geotechnical features, and potentially offer a hydrologic setting that can most easily be evaluated. It is important to point out, however, that each area that contains such a rock type with sufficient dimension has to be individually examined in order to assess the proximity to major fault zones, the extent of jointing and fracturing as observed from maps of flat rock outcrops, and the potential for resource utilization.

Most other Piedmont rock types that include virtually all metasedimentary and metavolcanic lithologies have one or more deleterious features that result in their unfavorable designation. Most such rock types lack sufficient unit dimensional continuity to be acceptable. Furthermore, many have a number of adverse mechanical and physical properties. Within the Piedmont, most units of this type are both steeply dipping and contain numerous lithologic variations that could provide potential zones for preferential deep groundwater influx into the subsurface, thus making them hydrologically unsuitable.

6.0 WEIGHTING FACTORS

Among all of the applicable criteria for ascertaining the favorability of a geologic unit, two factors clearly stand out as having the greatest overall impact in selection of a potential repository site, namely the requirement that the rock unit be continuous over an adequate dimension (>100 km^2 surface area and a minimum of 1500 meters depth) and that this unit have favorable hydrologic properties. The latter is, of course, extremely difficult to evaluate adequately for a given site, except by utilizing geologic maps showing the location of major fault zones and maps of flat rock outcrops that may reflect the extent of vertical jointing in a rock unit.

A factor deemed of secondary importance is the geotechnical, or mechanical and physical properties of the rock unit. Although these properties obviously can have a deleterious effect upon selection of a site, it is felt that many of these adverse features can be rectified by proper construction techniques. It should be noted that many rock types, such as most metasedimentary rocks, that have unfavorable geotechnical properties, also commonly have adverse hydrogeologic features and lack adequate unit dimensions. In this report, seismic effects are considered to have little or no importance as a site selection criterion.

Although the resource potential of a rock is an important factor in selecting a favorable unit, this factor is not used as a criterion for considering a unit either favorable or unfavorable. Obviously there has to be some evaluation of the relative economic worth of a rock unit serving either as a radioactive waste repository or for other economic purposes. However, this type of evaluation lies beyond the scope of this report.

7.0 POTENTIAL FIELD STUDY AREAS

7.1 Introduction

The geologic units discussed below have been designated in this study as favorable areas for field investigation for assessing the suitability for a radioactive waste repository on the basis of the applicable criteria discussed in Section 5. It should be emphasized, however, this designation is based entirely on geologic factors alone, and does not take into consideration any socio-economic constraints.

The various favorable units designated in this study are summarized in Figure 6. These were selected from among all of the geologic units shown on the geologic map given in Appendix A.

Each of the units designated as favorable meet the minimal unit dimensional requirements of >100 km^2 surface area and 1500 meters depth, consist of either the younger post-metamorphic plutons or of relatively homogeneous orthogneisses, have what would appear to be favorable hydrogeologic properties as evidenced by occurrences of flat rock outcrops presented on Figure 5, and be located an acceptable distance away from the major Paleozoic fault zones. In the ensuing discussion, each of these favorable units are described in detail, and a number of both advantageous and disadvantageous features are discussed. No attempt is made to rank these units in any sequentially preferred manner.

7.2 Elberton Pluton

This pluton is a medium grained, light grey to pinkish equigranular granite that is exceedingly homogeneous, both chemically and petrographically over its entire outcrop area (Hess, 1979). The surface outcrop exposure of this body, however, has recently been remapped (Whitney and Ellwood, 1979) to include an area that differs considerably from that shown on the state geologic map (Georgia Geological Survey, 1976); this modification is shown on the updated map given in Appendix A.

Much of the southern portion of the outcrop area described as the Elberton Pluton on the map of Appendix A (south of Lexington) consists of an older granite gneiss. The Elberton Pluton is clearly post metamorphic, having been dated by the Rb/Sr whole rock method at 350 m.y. (Whitney, et al., 1979). Detailed mapping

(Hess, 1979) and seismic COCORP data (Cook, et al., 1979) suggests that this pluton widens just below the surface and extends to considerable depth as depicted in Cross Section B-B' in Appendix B. Recent paleomagnetic anisotropy measurements indicate that the Elberton Pluton acted as a stable hinge block between two major fault zones, the Towaliga and Middleton, that has rotated about 30° (Whitney, et al., 1979).

There are a number of features about this pluton that warrant its favorable consideration as a repository site, namely:

(1) The extreme uniformity in both texture and modal and chemical composition.

(2) The relatively young age.

(3) The relatively large surface and probable subsurface dimension.

(4) The fact that this pluton lies between two major Paleozoic-age fault zones, the Towaliga and Middleton, which apparently has allowed the Elberton body to act as a stable hinge block during uplift.

(5) The juxtaposition of these two major fault zones may allow the Elberton body to act as a hydrogeologically insulated block of the type described in the Swedish KBS project studies (see discussion in Section 4.6).

(6) The probable lack of significant amounts of jointing and fracturing as evidenced by the occurrence of numerous flat rock outcrops (see Figure 5).

(7) The fact that this body has been extensively studied.

One major factor to be considered in any future repository utilization is the high economic potential of the Elberton Pluton. This unit serves as one of the major sources of dimension stone in the country. Most active quarries are located in the vicinity of Elberton near the northern end of the body.

7.3 Siloam Pluton

This body consists dominantly of a coarsely porphyritic granite characterized by large perthitic phenocrysts (Whitney and Stormer, 1977). Humphrey (1970) has made a regional study of the surrounding country rock in Greene and Hancock Counties. This body is one of the youngest post-metamorphic granites in the southern Piedmont, having been dated at 269 ± 3 m.y. by Rb/Sr methods (Jones and Walker, 1973).

The favorable features that warrant consideration of this body as a repository medium include:

(1) The young age.

(2) The fact that it lies between two major fault zones, the Middleton and Modoc.

(3) The limited resource potential (only one active crushed stone quarry exists near Siloam).

Adverse features of this body include:

(1) The marginally acceptable surface outcrop dimension and its unknown subsurface extent.

(2) The body may have a relatively high density of joints and fractures due to a general paucity of observed flat rock outcrops (this may also be due to the fact that porphyritic rocks weather differently than equigranular rocks) (see Figure 5).

7.4 Sparta Pluton

This is in all probability a composite pluton that consists of a variety of textural rock types that dominantly include both a porphyritic, coarse grained granite and an equigranular, medium- to fine-grained granite (Humphrey, 1970). The interrelationships between these differing textural types, however, are poorly understood at the present time. This pluton is dominantly post-metamorphic (~300 m.y., Fullagar and Butler, 1976), although some lithologies may be older.

Factors that make this pluton favorable for more detailed investigation include:

(1) The relatively large surface outcrop.

(2) The relatively young age.

(3) The low resource potential (no active quarrying currently exists within this pluton, although there are several inactive sites near Sparta).

(4) The proximity to a major Paleozoic fault zone to the north, the Modoc.

(5) The probable sparsely jointed and fractured nature as evidenced by an average density of flat rock outcrops (see Figure 5).

Adverse factors to be considered are:

(1) The probable existence of a complex mixture of differing textural assemblages reflecting its composite nature.

(2) The fact that the geologic setting along the southern contact is unknown due to cover by Coastal Plain sediments.

(3) The probable fact that the southern end of the body may have interacted with meteoric waters during its intrusive history and hence may be unduly fractured or affected in other adverse ways.

(4) The unknown subsurface extent.

7.5 Two Unnamed Plutons of S. W. Georgia (A, B in Appendix A)

Two plutons of relatively large surface outcrop are shown north of the Pine Mountain Belt on the geologic map of Appendix A; however, virtually no information exists on the nature of these two granite bodies. These two units, however, appear to be similar to an unacceptably small pluton, termed the Snelson granite body (see Appendix A), which lies midway in between. The Snelson granite would appear to be an older syn-or pre-metamorphic pluton based on descriptions of its foliated texture (Hewett and Crickmay; 1937) and its semi-conformable outcrop pattern with surrounding lithologies as shown on the geologic map of Appendix A.

There would appear to be several desirable features about these two granitic plutons, namely their relatively large surface dimensions, the existence of a major fault zone to the south (Towaliga), and the possible infrequency of jointing in the southwesternmost body as evidenced by an average density of flat rock outcrops (see Figure 5), However, it should be emphasized that these two granites have not been studied in detail, and thus may be more complex than shown on the geologic map of Appendix A.

7.6 Lithonia Gneiss

This unit represents a regionally homogeneous, medium grained, ~480 m.y. old (Grunenfelder and Silver, 1958) amphibolite-grade granitic orthogneiss consisting of alternating light and dark bands on a scale of 1/10 to 1/2 inches. It is largely composed of oligoclase, microline, quartz, biotite, and muscovite, with occasional stringers of garnet and tourmaline. Recent mapping by the U.S.G.S. for the Atlanta 2° Sheet indicates that this gneiss is exceedingly homogeneous both petrographically and chemically (Atkins, 1979). However, as shown on the geologic map of Appendix A, there exist several infolded younger schistose units along the western edge of this gneissic unit that are well displayed by the cross Sections X-X', Y-Y' and Z-Z' in Appendix B. It should be noted that the northeastern end of this unit has not been mapped in detail, and the possibility exists that the Lithonia Gneiss may be more complex in this area than shown on the geologic map of Appendix A.

There are a number of favorable features that would appear to make this particular unit attractive for further study, namely:

(1) The large surface outcrop exposure.

(2) The regionally homogeneous nature.

(3) The fact that this unit has the greatest density of flat rock outcrops of any geneissic or granitic unit in Georgia (see Figure 5), which would suggest a minimal density of joints and fractures.

(4) That much information will shortly exist for the western half of this unit when geologic mapping of the Atlanta area is complete.

There are, however, several deleterious factors to consider, namely:

(1) This unit has been subjected to a major regional folding, which, unlike the post-metamorphic plutons, may constrain its vertical extent to an unacceptably shallow depth.

(2) The relatively high resource potential due to active utilization of this unit for crushed rock along the western side, in the vicinity of Atlanta.

(3) The known existence of a deep, water-bearing fracture at a depth of 120-150 meters (400-500 feet) (Atkins, 1979) may indicate an unacceptable geohydrologic setting. However, this single occurrence may not be indicative of the body as a whole.

7.7 Orthogneisses and Charnockites of the Pine Mountain Belt

These rocks constitute a major exposure of Grenville-age (~1000 m.y.; Odom, et al., 1976) basement rock in the Pine Mountain Belt. One major unit, the Woodland Gneiss, consists of a moderately foliated, granulite grade biotite-garnet orthogneiss locally intruded by charnockite plutons (designated as the Cunningham Granite by Clarke, 1952) that range from hypersthene gabbros to hypersthene granites. Recent mapping by Schamel and Bauer (1979) indicates that this orthogneiss crops out more extensively than shown on the geologic map in Appendix A. This orthogneiss occurs as an antiform of Grenville-age basement terrane in the Pine Mountain Belt.

There would appear to be several features about the Grenville-age basement orthogneisses and charnockites of the Pine Mountain Belt that warrant their favorable evaluation, namely:

(1) The relatively extensive outcrop exposure.

(2) The likelihood that these rock types may provide a favorable hydrogeologic setting (charnockites and many gneisses in Grenville-age basement terranes are known to be exceedingly poor water reservoirs.

(3) The fact that the Pine Mountain basement terrane lies between two major faults, the Towaliga and Goat Rock.

(4) The basement terrane in all probability extends to considerable depths.

However, there are several deleterious factors that have to be evaluated before further consideration of this area can be made, such as:

(1) The possible existence of numerous surficial joints and fractures as suggested by the deep weathering of these rocks of the Pine Mountain Belt.

(2) Lithologically heterogeneous (however, in the context of the applicable criteria outlined in this study, one could logically consider both rock types to constitute a single unit of metaplutonic rock).

(3) A proper understanding of the northernmost bordering thrust fault (see Figure 1) should be developed where the Woodland Orthogneiss is exposed over its broadest extent. If this fault extends northeasterly into the orthogneiss, this would effectively produce two different areas whose unit dimensions would be unacceptable.

8.0 DISCUSSION OF AREAS EXCLUDED

In this report, all areas shown on the geologic map in Appendix A containing metavolcanic rocks, slates, phyllites, and schists are considered unfavorable because:

(1) Virtually all of these rock types have surface outcrop patterns considerably less than 100 km^2 surface area.

(2) These rock types have numerous deleterious geotechnical properties as outlined in Section 5.3.

(3) Most of these rocks have a number of negative geohydrological features that are principally related to their steeply dipping lithologic contacts, foliations, and fractures, which could potentially provide access for deep groundwater penetration.

(4) Most are highly jointed and fractured as generally observed by their deep weathering characteristics.

Many sections of the Piedmont, as shown on the geologic map in Appendix A, however, consist of gneissic type lithologies that have a number of desirable features that might make them appear potentially favorable as host rocks for a radioactive waste repository. Upon inspection of the geologic map, it is apparent that most gneisses have surface outcrop dimensions that are too small to be considered acceptable. However, several gneissic units shown on the geologic map in Appendix A appear at first hand to have sufficient surface outcrop dimensions. Upon inspection of more detailed geologic maps, it is apparent that most gneissic units consist of more cómplex lithologies than shown on the state geologic map. (Many of the lithologic units shown on the state geologic map were lumped together for simplicity - others simply represent a lack of detailed information).

There are several examples that serve to illustrate how some gneissic units shown on the state geologic map in Appendix A as consisting of a single lithologic type, actually are more complex both structurally and lithologically. Reference to county locations can be made from Figure 6.

(1) At the north end of Greene County, southwest of the Elberton Pluton and northwest of the Siloam Pluton, a seemingly simple and homogeneous gneissic unit (mapped as unit fgla in Appendix A), and shown in the legend to be a biotite gneiss and feldspathic biotite gneiss, actually consists of a complex mixture of isoclinally folded biotite schists, paragneisses, and amphibolites (Humphrey, 1970; Davis, 1980).

(2) In Putnam County, southwest of the Siloam Pluton, the state geologic map in Appendix A shows a gneissic unit consisting of granite gneiss (ggl) and miscellaneous gneisses (fgla). However, detailed geologic mapping displays a far more complex picture of steeply dipping interbedded gneisses and schists in an antiformal-synformal relationship (Libby, 1971).

(3) At the north end of Clarke County, the state geologic map in Appendix A shows a large homogeneous, seemingly favorable gneissic unit (Figure 3) immediately east of the Lithonia Gneiss. However, in all probability this unit consists of a complex mixture of paragneisses, schists, and amphibolites as revealed in the instance where this unit was mapped in detail along its southern edge in Clarke County (Woolsey, 1973).

The above described examples merely serve to illustrate how many geologic units, especially gneisses, are generally more complex, both lithologically and structurally, than shown on the state geologic map of Appendix A. This complexity is generally evident upon inspection of detailed geologic maps. However, most areas in the Georgia Piedmont have not been mapped in sufficient detail to reveal the probable complexity that exists. In such cases, it is assumed that most gneissic terranes, even though shown on the state geologic map in Appendix A as a single homogenous unit, actually are far more complex lithologically and thus unacceptable as a continuous unit.

The only gneissic units deemed favorable as repository sites are those which were revealed to be sufficiently homogeneous, either from inspection of detailed geologic maps or through conversations with various individuals. In this study, only two gneissic terranes appear to be acceptable, namely the Lithonia Gneiss and the Woodland Gneiss.

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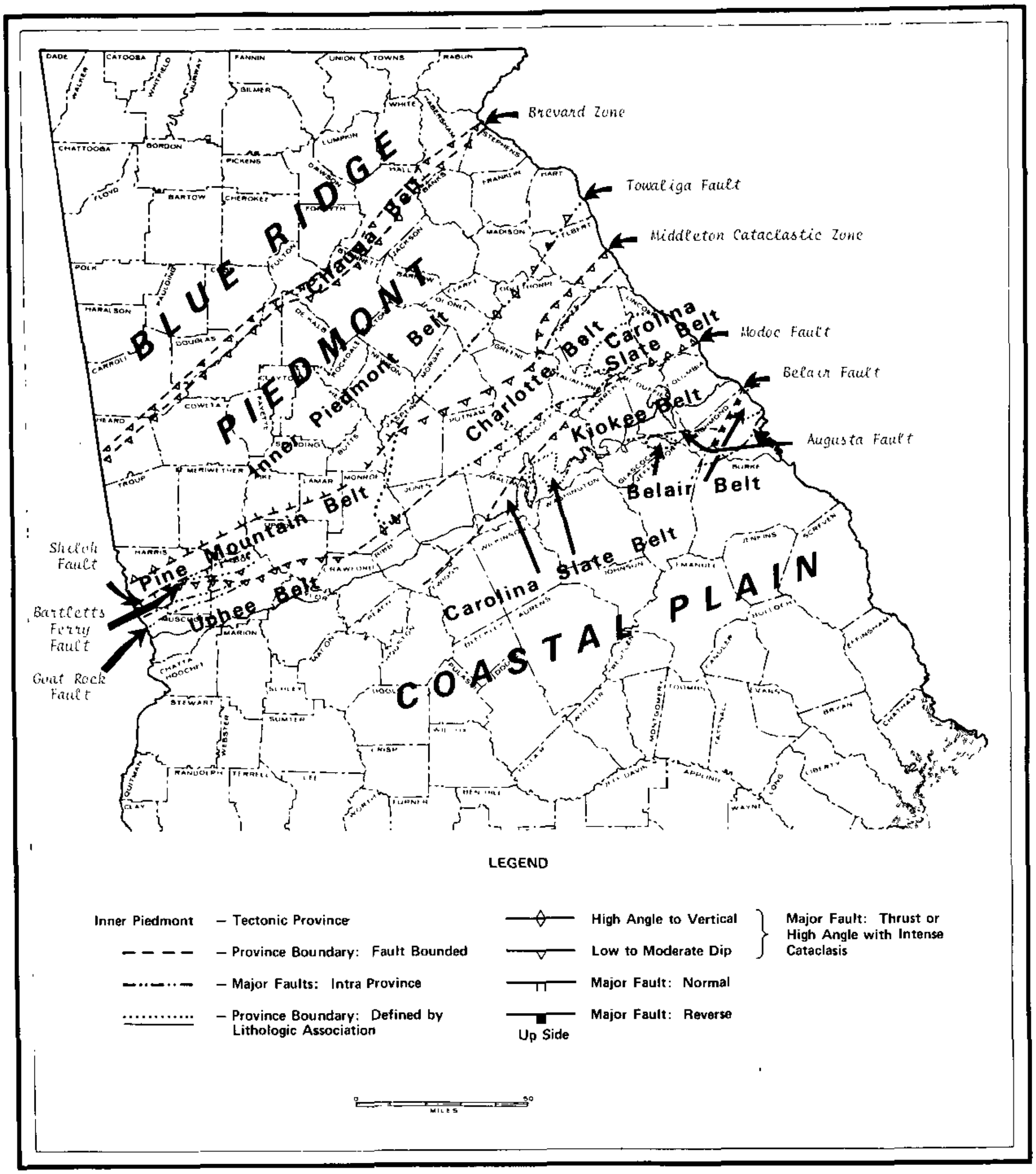


Adapted From: Hatcher (1978), Whitney et al (1978), Snoke et al (1979), Schamel and Bauer (personal communication), Georgia Geological Survey (1976).

FIGURE 1. Tectonic Map of Georgia Piedmont.

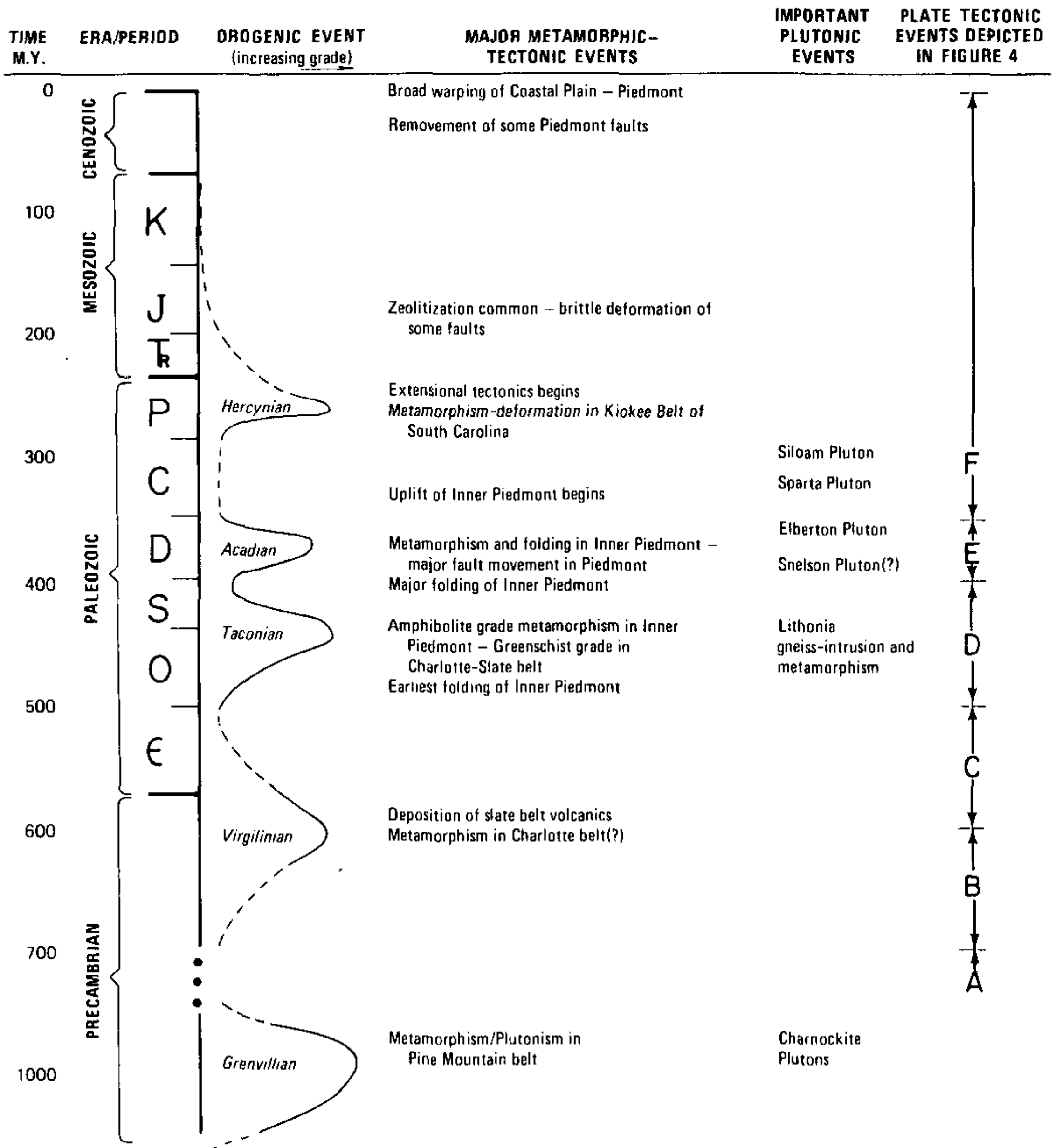
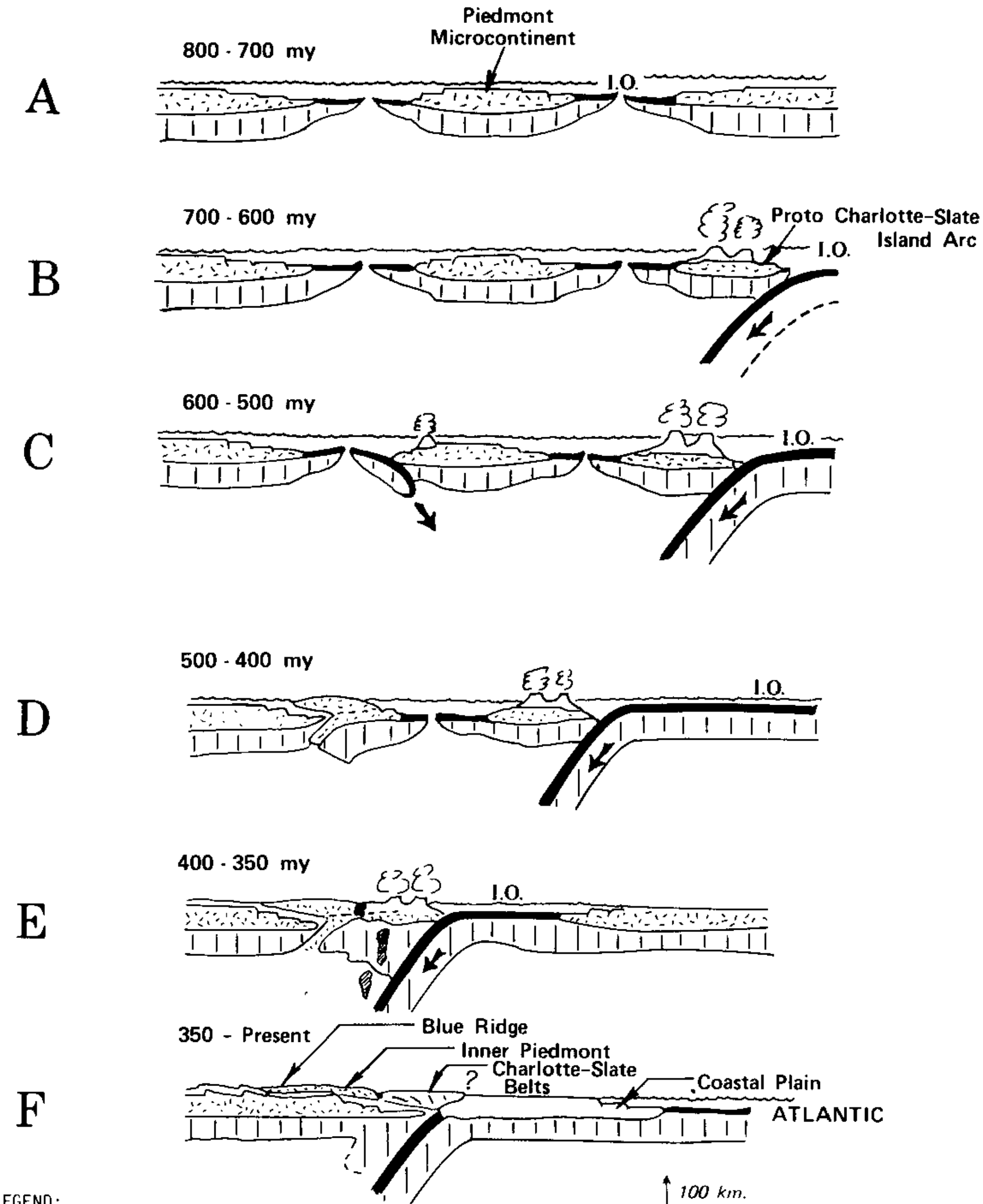


FIGURE 2. Major Orogenic Events of the Piedmont Province.



LEGEND:

Blackened Areas Represent Oceanic Crust

Lined Areas Represent Lower Lithosphere

I.O. = Iapetus Ocean

? = Proto-African-North American Suture (unknown location)

Modified After Cook et al (1979)

FIGURE 3. Schematic Plate Tectonic Model of the Southern Appalachians.

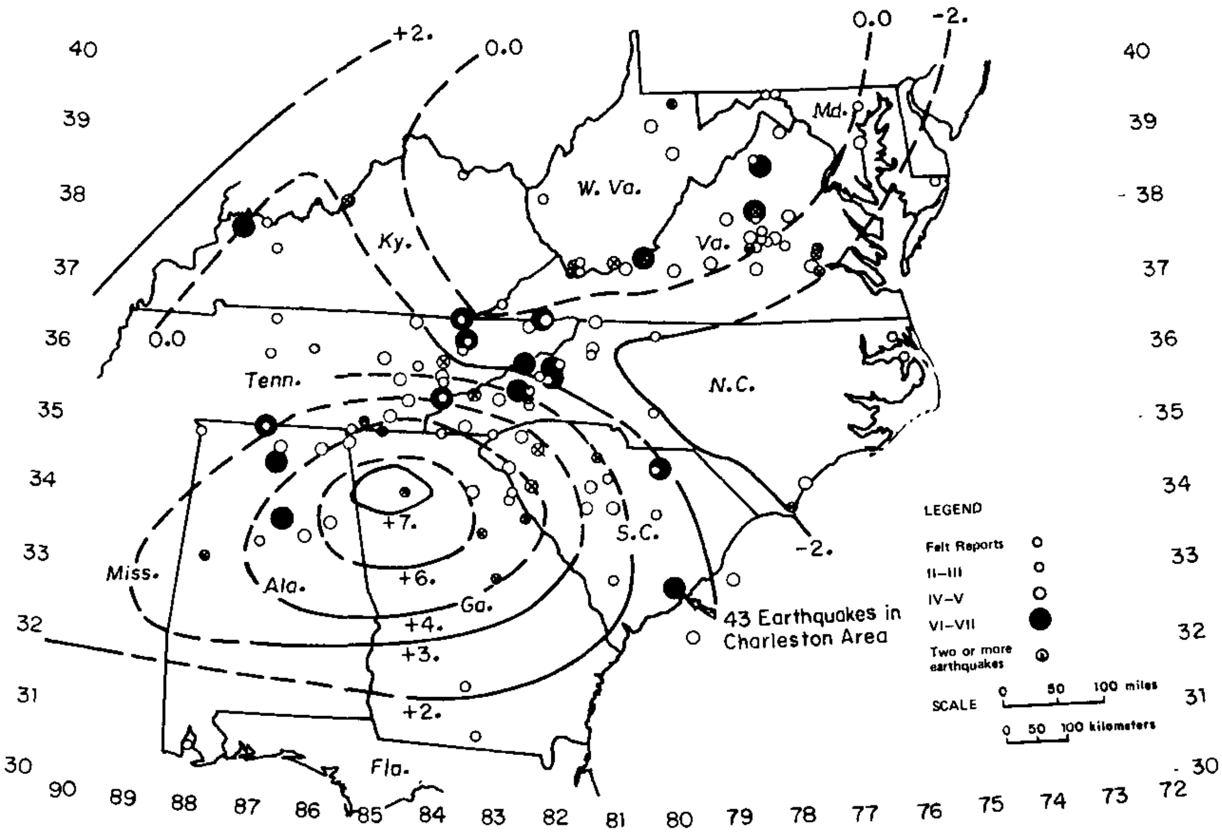


FIGURE 4. Seismicity (1920-1970) and Crustal Movement Rate for the Southeastern United States (Bollinger, 1973). Isobase Contours in mm/yr.

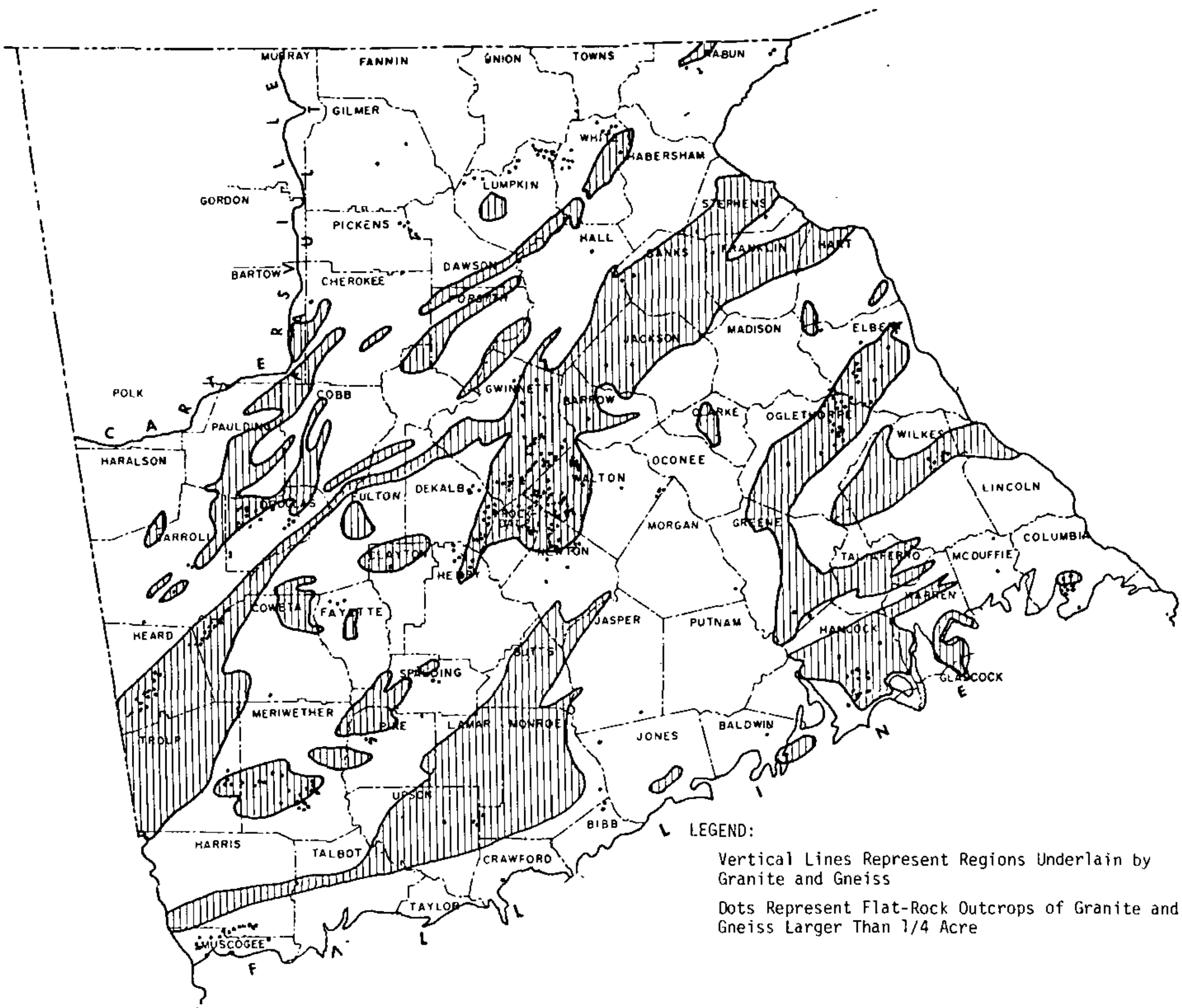


FIGURE 5. Areas of Flat-Rock Outcrop and Widespread Granite and Gneiss Districts of North Georgia (Georgia Geological Survey, 1969).

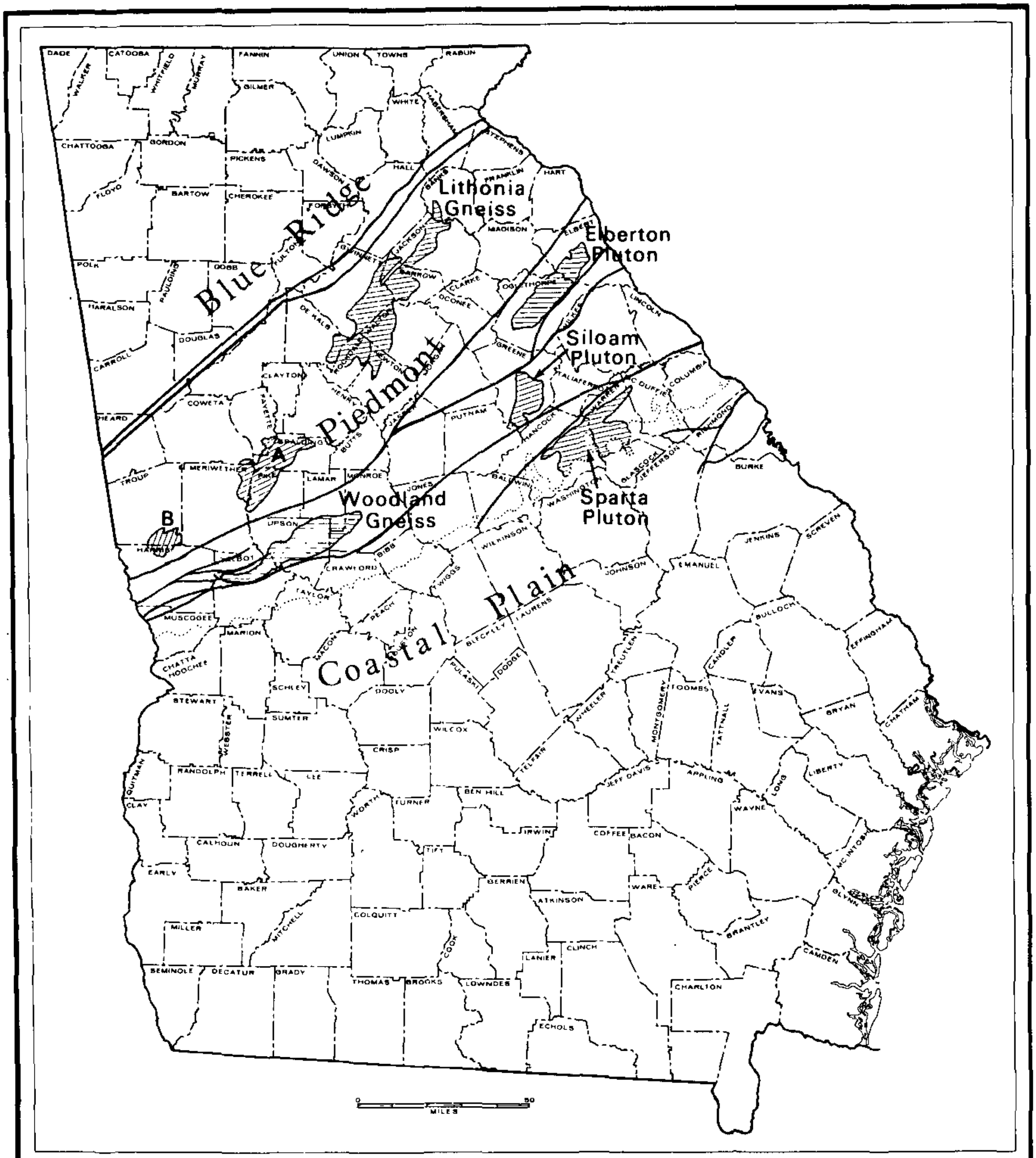


FIGURE 6. Favorable Field Study Areas in Georgia Piedmont.

APPENDIX A

Geologic Map of the Piedmont Province of Georgia showing major lithologic units and the location of cross sections shown in Appendix B. Information from this map was obtained from the Georgia State Geologic Map (Georgia Geological Survey, 1976). Modifications have been made in the vicinity of the Elberton Pluton based on data from Ellwood, et al. (1980), Davidson (1979), Hess (1979), and Rosen (1978).

BLUE RIDGE AND PIEDMONT CRYSTALLINE ROCKS

GRANITES

gr1	GRANITE UNDIFFERENTIATED
gr1a	NON-PORPHYRITIC GRANITE
gr1b	PORPHYRITIC GRANITE
gr2	GRANITE GRANITE GNEISS
gr2a	GRANITE GNEISSIC BIOTITE GRANITE
gr3	GRANITE BIOTITIC GNEISS AMPHIBOLITE
gr4	CHARNOCKITE
gr5	SYENITE

GRANITE GNEISS

gg1	GRANITIC GNEISS UNDIFFERENTIATED
gg2	GRANITE GNEISS GNEISSIC GRANITE (AUGEN OR PORPHYRITIC)
gg3	MUSCOVITE GRANITE GNEISS
gg4	GRANITE GNEISS AMPHIBOLITE
gg5	CALC-SILICATE GRANITE GNEISS
gg6	GRANITE GNEISS GRANITE

INTERMEDIATE GNEISS

fg1	BIOTITE GNEISS FELDSPATHIC BIOTITE GNEISS
fg1a	BIOTITE GRANITE GNEISS FELDSPATHIC BIOTITE GNEISS AMPHIBOLITE-HORNBLENDE GNEISS
fg2	BIOTITIC GNEISS UNDIFFERENTIATED
fg3	BIOTITIC GNEISS MICA SCHIST AMPHIBOLITE
fg4	BIOTITIC GNEISS AMPHIBOLITE

BIOTITE GNEISS

bg1	BIOTITE GNEISS
bg2	BIOTITE GNEISS AMPHIBOLITE
bg3	BIOTITE GNEISS HORNBLENDE GNEISS GRANITE GNEISS
bg4	BIOTITE GNEISS MICA SCHIST

METAMORPHOSED MAFIC ROCKS (MAY INCLUDE METASEDIMENTARY VARIETIES)

mm1	AMPHIBOLITE
mm2	HORNBLENDE GNEISS
mm3	HORNBLENDE GNEISS AMPHIBOLITE
mm4	HORNBLENDE GNEISS AMPHIBOLITE GRANITE GNEISS
mm5	HORNBLENDE-BIOTITE GNEISS AMPHIBOLITE
mm6	HORNBLENDE GNEISS GRANITE GNEISS BIOTITE GNEISS
mm7	AMPHIBOLITE EPIDOTE QUARTZITE GRANITE GNEISS
mm8	AMPHIBOLITE BIOTITIC GNEISS QUARTZ SERICITE SCHIST
mm9	AMPHIBOLITE MICA SCHIST BIOTITIC GNEISS
mm10	AMPHIBOLITE METAGRAYWACKE MICA SCHIST
mm11	MAFIC HORNFELS

MAFIC SCHISTS

ms1	AMPHIBOLITIC SCHIST
ms2	AMPHIBOLITIC SCHIST AMPHIBOLITE
ms3	AMPHIBOLITIC SCHIST AMPHIBOLITE-METAGRAYWACKE MICA SCHIST

METAGRAYWACKE

pm1	METAGRAYWACKE UNDIFFERENTIATED
pm2	METAGRAYWACKE MICA SCHIST
pm3	METAGRAYWACKE MICA SCHIST CALC-SILICATE GNEISS
pm3a	METAGRAYWACKE MICA SCHIST-QUARTZITE AMPHIBOLITE
pm4	MICA SCHIST METASILTSTONE
pm5	SLATE QUARTZITE CONGLOMERATE
pm6	CONGLOMERATE

MICA SCHIST

pms1	MICA SCHIST
pms2	MICA SCHIST AMPHIBOLITE
pms3	MICA SCHIST GNEISS
pms3a	MICA SCHIST GNEISS AMPHIBOLITE
pms4	MICA SCHIST QUARTZITE GNEISS AMPHIBOLITE
pms5	GRAPHITE SCHIST
pms6	SERICITE SCHIST
pms6a	SERICITE SCHIST AMPHIBOLITE
pms6b	SERICITE SCHIST AMPHIBOLITE GRANITE GNEISS
pms6c	SERICITE SCHIST MICACEOUS QUARTZITE SERICITE PHYLLITE
pms6d	QUARTZ SERICITE SCHIST BIOTITIC GNEISS
pms6e	QUARTZ MICA SCHIST HORNBLENDE SCHIST BIOTITIC GNEISS
pms7	BUTTON MICA SCHIST
pms8	CROSS-BIOTITE SCHIST

PELITIC AND CALCAREOUS ROCKS

mu	UNDIFFERENTIATED PELITIC ROCKS, includes mica schists, metasiltstones, metaconglomerates and metagraywackes
m1	MARBLE
m2	CALCAREOUS MICA SCHIST MICACEOUS MARBLE MICA SCHIST

PHYLLITIC ROCKS

pp1	PHYLLITE UNDIFFERENTIATED
pp1a	META-ARGILLITE PHYLLITE
pp2	GRAPHITIC PHYLLITE
pp3	PHYLLITE AND QUARTZITE
pp3a	PHYLLITE QUARTZITE CALC-SILICATE GNEISS

ALUMINOUS SCHIST

pg1	GARNET MICA SCHIST
pg2	GARNET MICA SCHIST GNEISS
pg3	GARNET MICA SCHIST AMPHIBOLITE
pa1	ALUMINOUS SCHIST
pa2	SILLIMANITE SCHIST
pa2a	SILLIMANITE SCHIST GNEISS
pa2b	SILLIMANITE SCHIST GNEISS AMPHIBOLITE
pa2c	SILLIMANITE SCHIST AMPHIBOLITE

QUARTZITE

q1	QUARTZITE
q1a	QUARTZITE MICA SCHIST
q1b	QUARTZITE MICA SCHIST AMPHIBOLITE
q1c	QUARTZITE METAGRAYWACKE
q1d	QUARTZITE PHYLLITE
q2	QUARTZITE BIOTITE GRANITE GNEISS
q3	EPIDOTE QUARTZITE AMPHIBOLITE SERICITE SCHIST BIOTITE GRANITE GNEISS

CATACLASTIC ROCKS

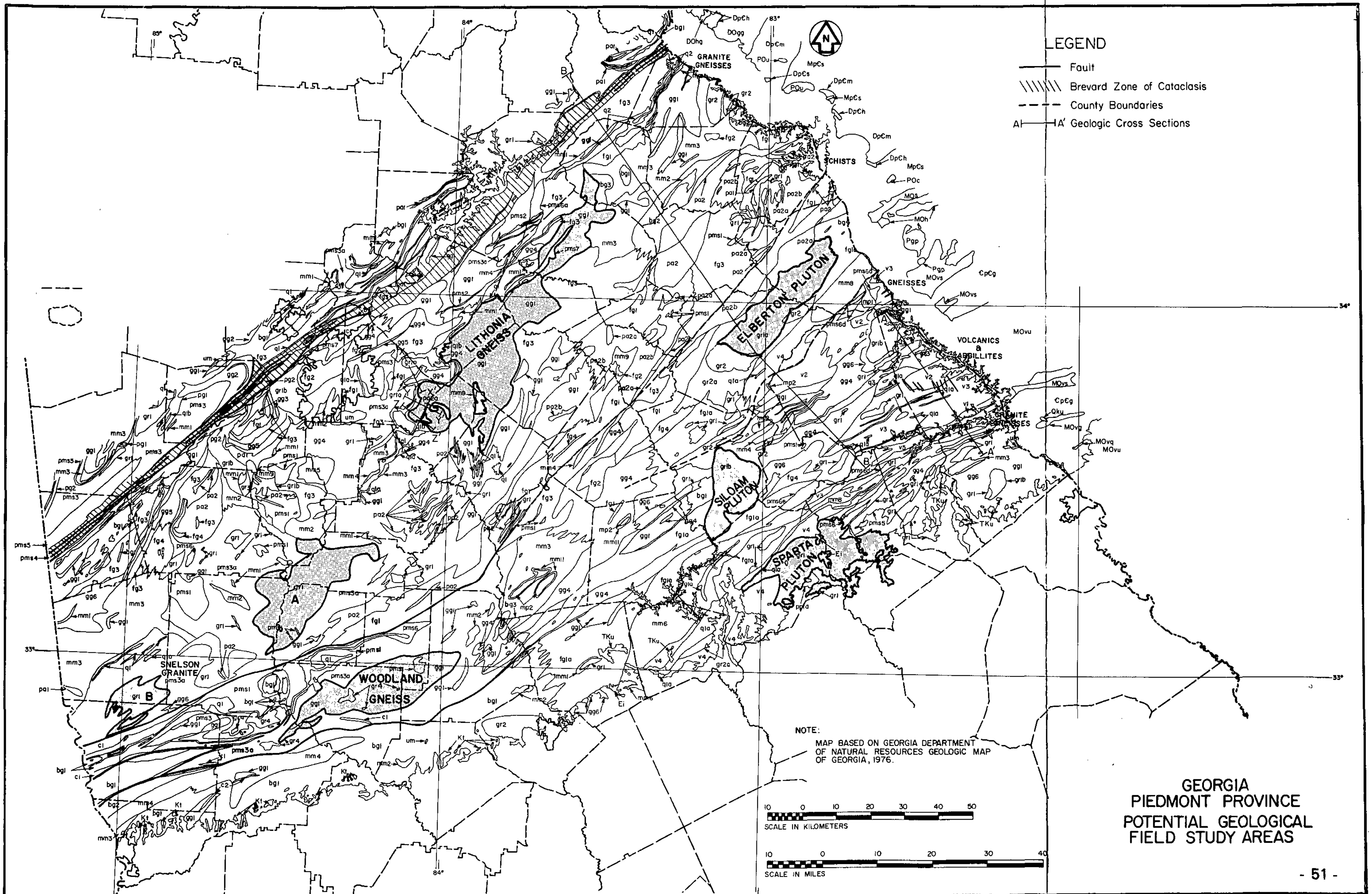
c1	MYLONITE & ULTRAMYLONITE
c2	FLINTY CRUSH ROCK

METAVOLCANIC ROCKS

v1	MAFIC TO INTERMEDIATE METAVOLCANIC ROCKS
v2	METADACITE
v3	FELSIC METAVOLCANICS
v4	UNDIFFERENTIATED METAVOLCANICS SERICITE PHYLLITE META-ARGILLITE QUARTZ MICA SCHIST
v5	META-ARGILLITE SERICITE PHYLLITE METAVOLCANICS

MAFIC AND ULTRAMAFIC ROCKS

um	ULTRAMAFIC ROCKS UNDIFFERENTIATED
mp1	AMPHIBOLITE GABBRO
mp2	GABBRO
mp3	AMPHIBOLITE ULTRAMAFIC
d	DIABASE



GEORGIA
PIEDMONT PROVINCE
POTENTIAL GEOLOGICAL
FIELD STUDY AREAS

APPENDIX B

Geologic cross sections of selected traverses shown on the geologic map of Appendix A. Traverses A-A' and B-B' represent generalized schematic cross sections based upon both surface and subsurface interpretations of geophysical data (A-A' from gravity and B-B' from seismic COCORP data). Cross Sections X-X', Y-Y', and Z-Z' represent extrapolated surface information obtained from geologic mapping.

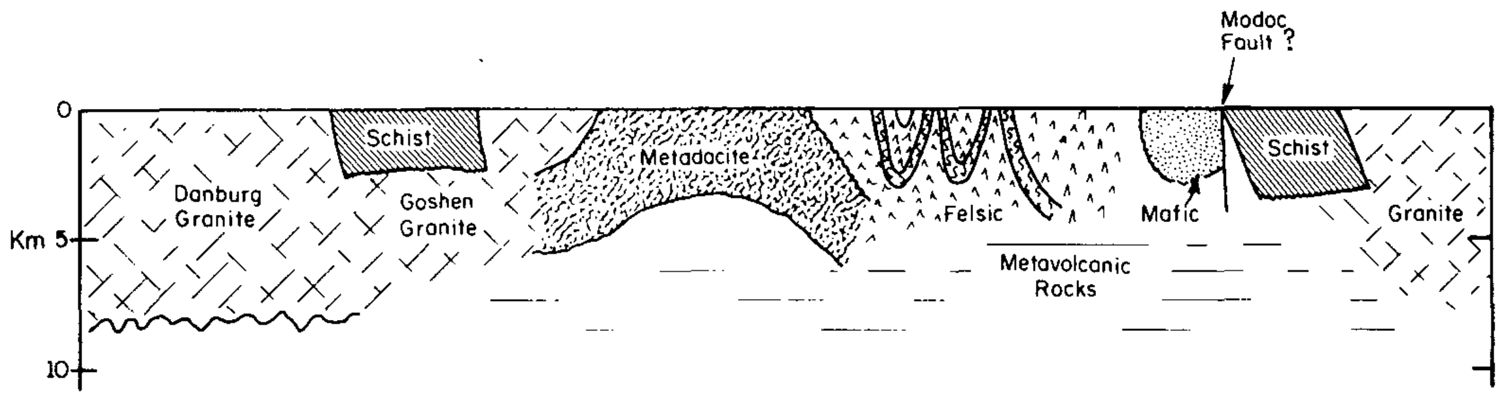


FIGURE B-1. Cross Section A - A' (from Long et al, 1976).

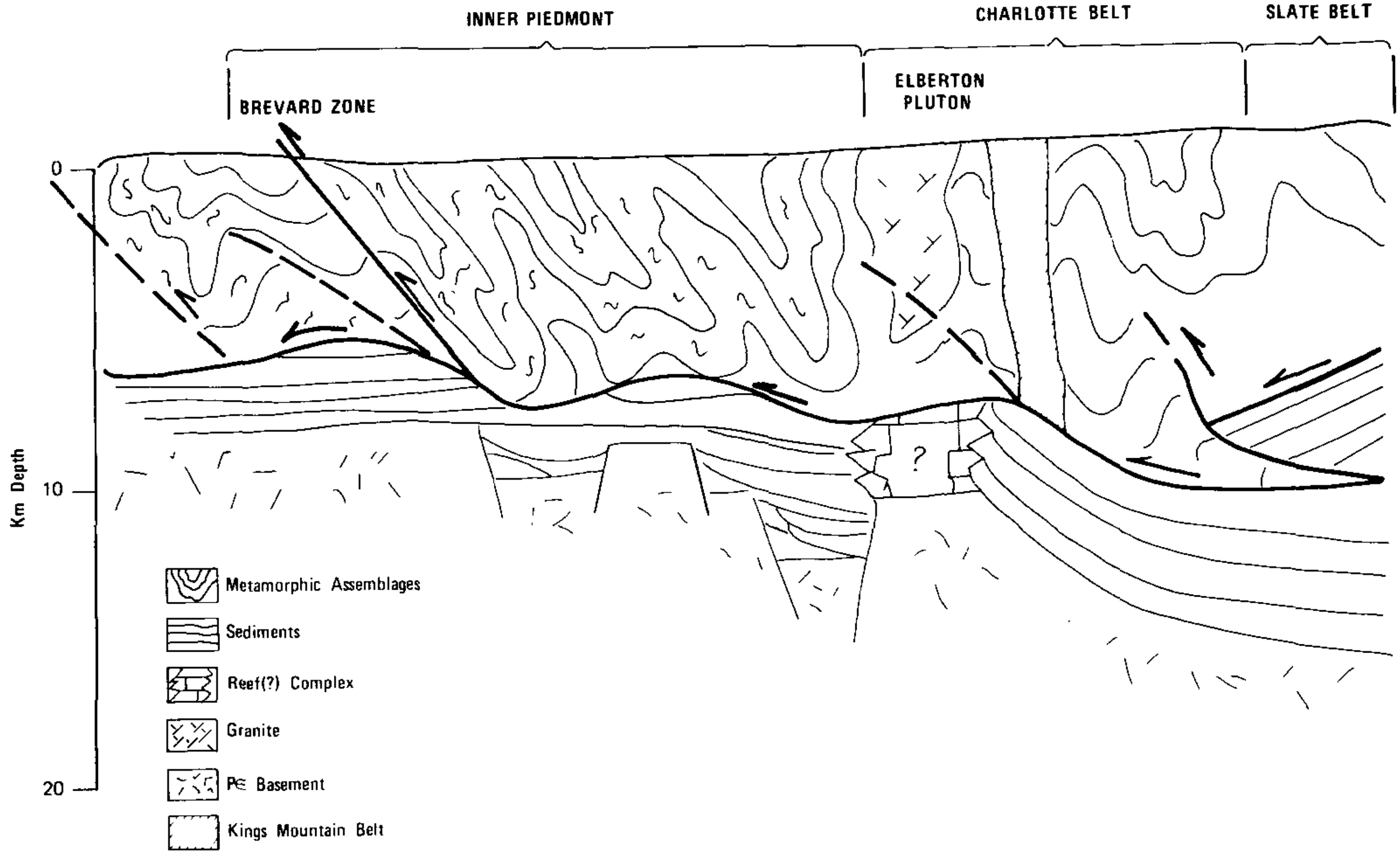


FIGURE B-2. Cross Section B - B' (from Cook et al, 1979).

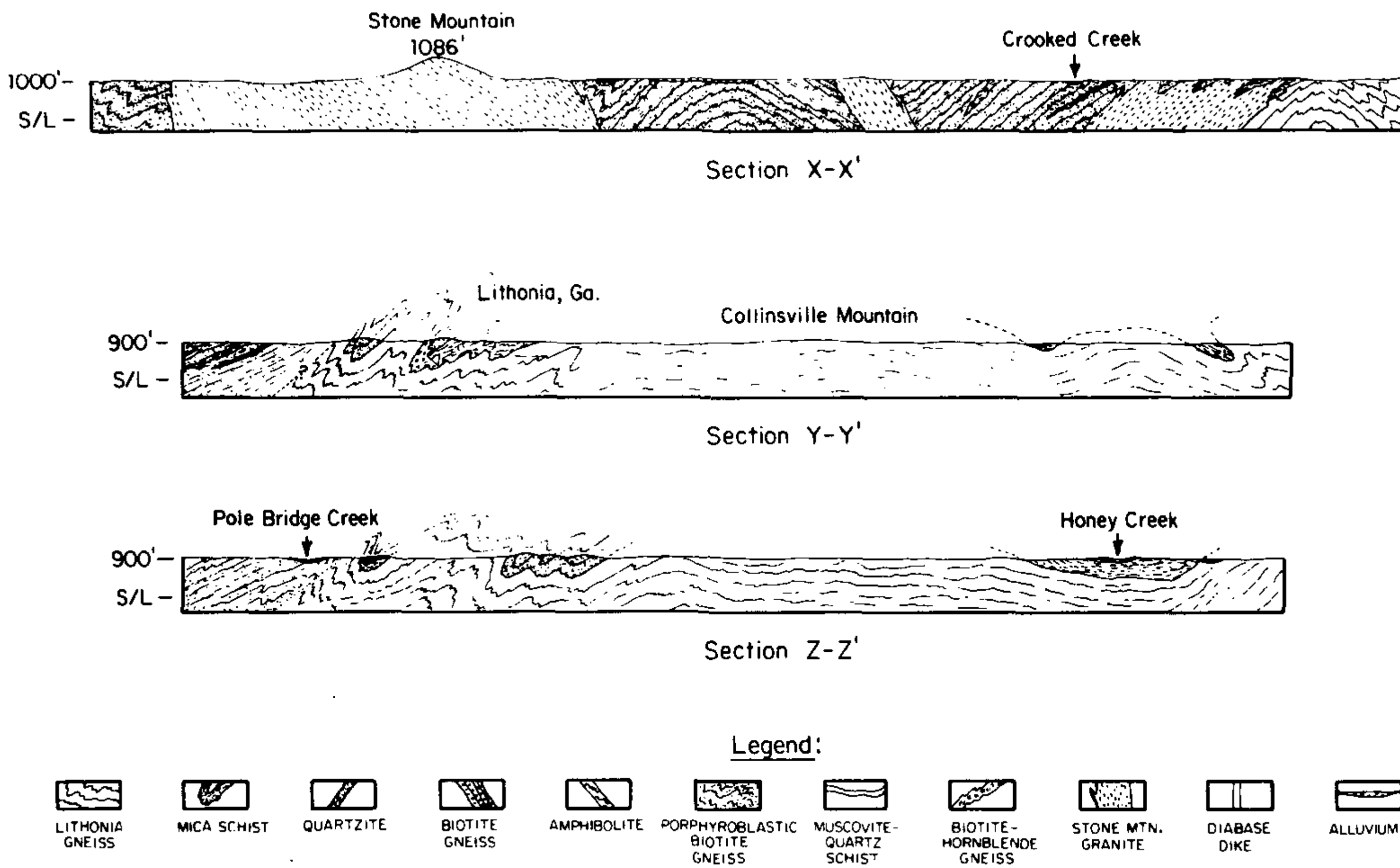


FIGURE B-3. Cross Sections X - X', Y - Y', and Z - Z'.