THIRD TECHNICAL REPORT

GEOLOGICAL STUDIES IN AN AREA OF INDUCED SEISMICITY AT MONTICELLO RESERVOIR, SOUTH CAROLINA

BY

Donald T. Secor, Jr., Principal Investigator
David M. Pitcher
William A. Smith

Department of Geology
University of South Carolina

December 26, 1981

Sponsored by the U. S. Geological Survey, Contract No. 14-08-0001-19833

ABSTRACT

This is the third technical report of a continuing geological investigation of an area of induced seismic activity at Monticello Reservoir, South Carolina, and it summarizes the data and conclusions resulting from the first eighteen months of the investigation (3/1/80-9/1/81). This study was undertaken in order to provide geological background information necessary for an evaluation of the earthquake hazard at Monticello Reservoir. This region contains a thick stratified sequence of late Precambrian and Cambrian metasedimentary and metavolcanic rocks. In the early to middle Paleozoic this sequence was recrystallized and deformed under metamorphic conditions which varied from greenschist to amphibolite facies and experienced at least two episodes of folding. The region has been intruded by late to post kinematic granitoid plutons of Silurian and Carboniferous ages, and by numerous northwest trending diabase dikes of late Triassic and early Jurassic age. The region south of Monticello Reservoir in the Carolina slate belt experienced two episodes of faulting in the late Paleozoic and/or early to middle Mesozoic. The oldest group of faults trend approximately east-west, have only small displacement, and are characterized by intense silicification of the fault zones. The younger group of faults trend approximately north-south, have experienced dip-slip displacements up to 1700 m, and are characterized by carbonate mineralization in the fault zones. Both sets are cut by an undeformed diabase dike of late

Triassic or early Jurassic age. The induced seismic activity around Monticello Reservoir is occurring in a heterogeneous quartz monzonite pluton of Carboniferous age. Although through-going faults have not been found in the vicinity of the reservoir, the pluton contains large enclaves of country rock and is cut by numerous, diversely oriented small faults and joints. These local inhomogeneities in the pluton, in concert with a heterogeneous stress field, are interpreted to control the diffuse seismic activity around the reservoir. In view of the apparent absence of through-going faults, it is unlikely that a damaging local earthquake will occur in response to the small stress and pore pressure changes related to the impoundment of Monticello Reservoir.

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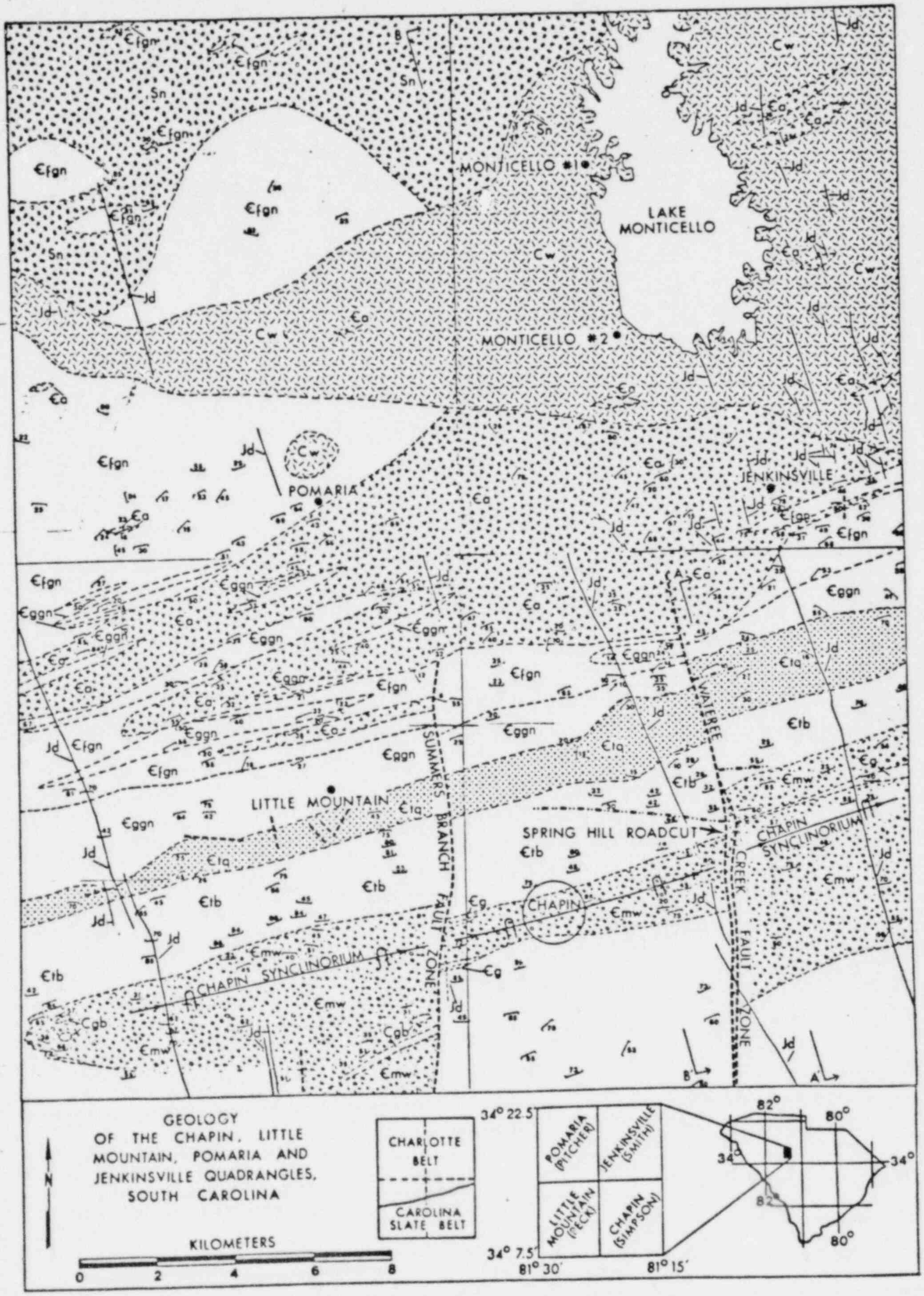
INTRODUCTION

Monticello Reservoir, a pump storage facility built in conjunction with the V. C. Summer nuclear station in Fairfield County, South Carolina, is the most thoroughly documented case of induced seismic activity in the eastern United States (Talwani, 1979; Talwani and others, 1980). The reservoir has a volume of approximately 0.5 km^3, a surface area of 27 km^2 and a maximum depth of 48 m. Prior to impoundment this region had a very low level of local seismic activity. Filling of the reservoir commenced on December 3, 1977, and was completed on February 8, 1978. About three weeks after filling was initiated the frequency of local earthquakes abruptly increased by a factor of approximately 100. The largest events ($M_L \approx$ 2.6-2.9) occurred during the first two years following impoundment. Although the general level of seismic activity has gradually decreased with time, it is still substantially greater than the pre-impoundment level.

Monticello Reservoir has been the focus of an intense research effort aimed at evaluating the hazard and developing a capability for predicting earthquakes (Talwani and others, 1978, 1980; Talwani, 1979; Zoback, 1979; Zoback and Hickman, 1982; Secor, 1980; Secor and others, 1981). The reservoir is located in a geologically complex area of the Charlotte belt in the Piedmont province of central South Carolina (Fig. 1). Although a number of geological studies had been completed in the vicinity of the reservoir (Kesler, 1936, 1972; McCauley, 1961; Overstreet and Bell, 1965; McKenzie and McCauley, 1968; Secor and



MONTICELLO #1
LAKE MONTICELLO
MONTICELLO #2
POMARIA
JENKINSVILLE
LITTLE MOUNTAIN
SPRING HILL ROADCUT
CHAPIN
CHAPIN SYNCLINORIUM
SUMMERS BRANCH FAULT ZONE
WATEREE CREEK FAULT ZONE
GEOLOGY
OF THE CHAPIN, LITTLE
MOUNTAIN, POMARIA AND
JENKINSVILLE QUADRANGLES,
SOUTH CAROLINA
KILOMETERS
0
2
4
6
8
N
CHARLOTTE BELT
CAROLINA SLATE BELT
POMARIA (PITCHER)
JENKINSVILLE (SMITH)
LITTLE MOUNTAIN (PECK)
CHAPIN (SIMPSON)
34° 22.5'
34° 7.5'
81° 30'
81° 15'
82°
80°
34°

Figure 1.

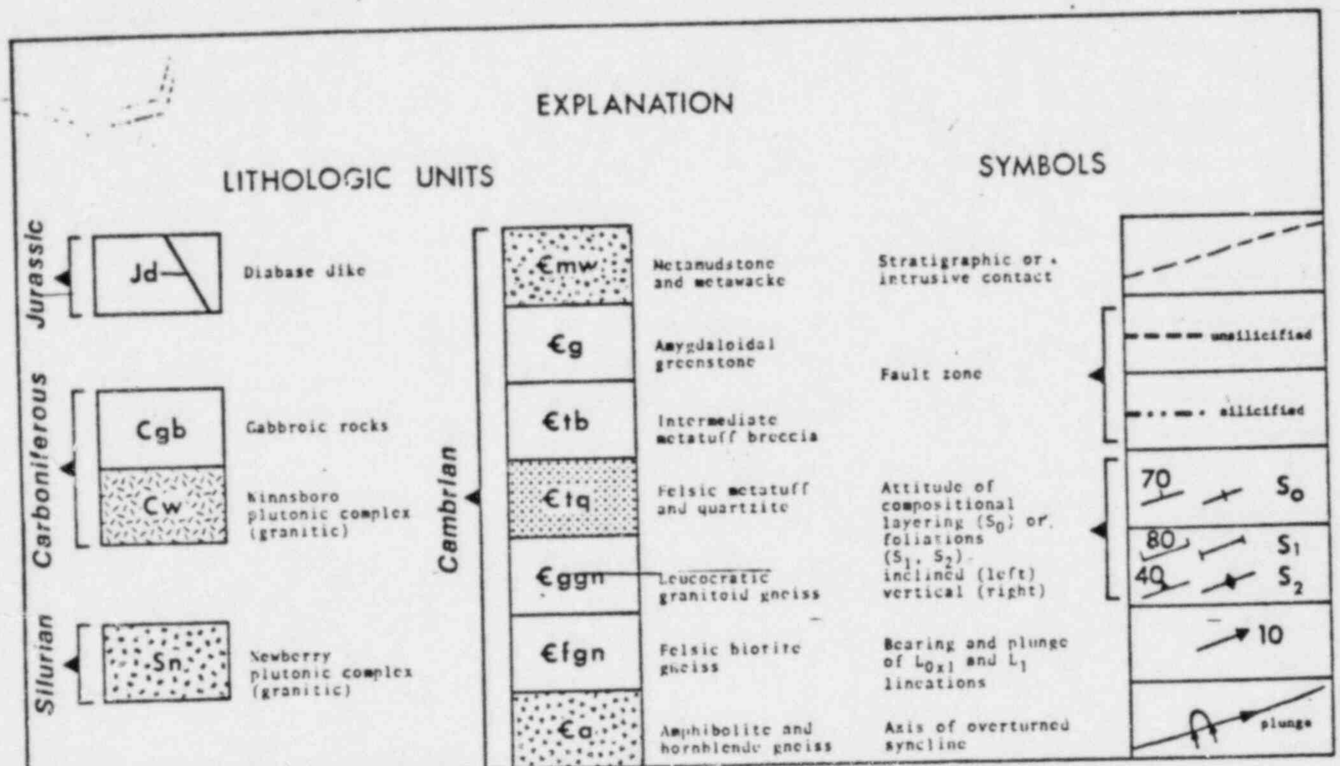


Figure 1. A geological map of the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles (U. S. Geological Survey 7 1/2' topographic series).

Wagener, 1968; Wagener, 1970, 1973, 1977a; Costain and others, 1976, 1977; Scuth Carolina Electric and Gas Company, 1977; Glover and others, 1977; Bourland and Farrar, 1980), the structure and distribution of rock units was poorly known at the time of impoundment. The present study was initiated in order to provide a geological framework necessary for the interpretation of the seismic activity. In particular, our studies were directed toward determining: 1) if there are through-going faults in the region that might eventually slip, thus producing a large earthquake; 2) if there are lithological boundaries in the vicinity of the reservoir controlling the distribution of seismic activity and 3) if there are foliations or systematic jointing directions along which slip might be initiated by the stress and pore pressure changes related to reservoir impoundment. In order to make the above evaluations, we undertook the preparation of detailed geological maps of the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles (U.S.G.S. 7 1/2' topographic series) surrounding the reservoir (Fig. 1). This geological mapping constitutes the main data base for the following geological synopsis.

ROCK UNITS

A sequence of metavolcanic and metasedimentary rocks and associated metaplutonic rocks underlies most of the central and southern parts of the study area. The stratified rocks constitute a sequence several kilometers thick, and the metaplutonic rocks form lenticular masses in this sequence. This lithostratigraphic assemblage is considered by many geologists (e.g. Butler and Ragland, 1969; Seiders and Wright, 1977; Black, 1978, 1980; Whitney and others, 1978) to have accumulated during the evolution of a late Precambrian to Cambrian magmatic arc. The oldest parts of this sequence are units of felsic gneiss (Єfgn) and amphibolite (Єa). Relict compositional layering and volcanic textures in these rocks suggest that they have resulted from the metamorphism of quartzo-feldspathic sedimentary and volcanic rocks interlayered with mafic tuffs and/or flows. The felsic gneiss and amphibolite units have been intimately injected by numerous partially concordant sheets of granitoid intrusive rocks related to overlying extrusive felsic metavolcanic tuffs (Єtq). Both the intrusive orthogneiss and the felsic metavolcanic rocks are characteristically sodic-rich, although the metaplutonic rocks also include a wider compositional spec~~trum from ton~~alite to granite. The thickness of orthogneiss sheets varies from a few centimeters to a kilometer. Only a few of the thickest and most continuous sheets are separately distinguished on Figure 1. In many places the felsic metavolcanic tuff unit (Єtq) has been silicified and accessory pyrite has been introduced. Locally, (as on Little Mountain, Fig. 1), the silicification is nearly complete and the rock is quartzitic. These highly altered rocks in the felsic metavolcanic tuff unit are interpreted to mark a volcanic exhalative horizon which occurs widely in the Carolina slate belt in South Carolina and Georgia (Espenshade and Potter, 1960; Kesler, 1972; Hartley, 1976). Immediately above the exhalative horizon is a 1-2 km thick sequence of intermediate to felsic metavolcanic lithic tuff breccia (Ꞓtb). This volcaniclastic deposit is in part probably a product of episodic subaqueous debris flows as evidenced by its coarse and poorly sorted character and by the local occurrence of water rounded pebbles of volcanic rock and quartzite in poorly sorted tuff breccia. The metavolcanic lithic tuff breccia unit grades into an overlying sequence of metamudstone, metasiltstone and metawacke (Ꞓmw) through an interval of a few hundred meters in which the two units are interbedded. Elsewhere in the Carolina slate belt, well preserved sedimentary structures in the Ꞓmw unit suggest that it is a turbidite sequence deposited below wave base (Brown, 1971; Kearns and others, 1981). The Ꞓmw unit contains a sequence of amygdaloidal greenstone (Ꞓg), 0-100 m thick, near its base, which is interpreted to have originally been a series of intermediate to mafic flows or flow breccias.

Most of the northern part of the study area is underlain by late to post-kinematic granitoid plutonic rocks. Two distinctive groups of plutonic associations can be recognized: the Newberry and Winnsboro plutonic complexes.

The Newberry complex (Sn), which occurs in the northwestern corner of the study area, is an extremely homogeneous, medium grained biotite quartz monzonite. This unit also outcrops extensively in regions north and west of the study area (McCauley, 1961; Wagener, 1977a). The Newberry pluton appears to be composite, consisting of a group of thick, irregular, partially concordant sheet intrusions enclosing numerous large enclaves of felsic gneiss. The Newberry pluton extends for more than 35 kilometers from the region west of Newberry, S.C., eastward to Blair, S.C., on the Broad River. In some places the Newberry quartz monzonite exhibits a faint compositional layering caused by subtle variations in the biotite content. A weak subhorizontal cleavage is evident in weathered outcrops. This cleavage may be of tectonic origin, or it may be the result of weathering and exfoliation. The initial $^{87}Sr/^{86}Sr$ ratio for the Newberry quartz monzonite is 0.7024 ± 0.0003, and the Rb-Sr whole rock age is 415 ± 9 m.y. (Fullagar, 1981).

The northeastern and north-central parts of the study area are underlain by a sparsely porphyritic medium to coarse grained biotite-hornblende quartz monzonite (Cw), which is here interpreted to be a part of the Winnsboro plutonic complex (Wagener, 1970, 1977a). The relative proportions of phenocrysts and of biotite and hornblende in the quartz monzonite are variable, and thin sheets of granite, aplite and pegmatite also occur. Numerous xenoliths and large enclaves of gneiss and amphibolite are present. The results of drilling and detailed geological mapping at the V. C. Summer nuclear station indicate that in this area approximately 30%-70% of the volume of the pluton is occupied by enclaves or large xenoliths of gneiss and amphibolite (South Carolina Electric and Gas Company, 1977). Two 1.1-1.2 km deep boreholes were drilled into the area of induced seismicity along the west side of Lake Monticello by the U. S. Geological Survey (Monticello #1 and #2, Fig. 1) in order to measure stresses and to determine the character of the rock in the region of seismic activity. Visual inspection of core and cuttings from

Monticello #2 indicates that enclaves and xenoliths of gneiss and amphibolite are mostly concentrated in the top 830 m of the hole and comprise approximately 15% of the total volume of the pluton (Fig. 2). Cores and cuttings from Monticello #1 indicate that here the pluton is relatively free of inclusions. Several extensive outcrop areas of amphibolite occur in the eastern part of the Jenkinsville quadrangle (Fig. 1). These are interpreted to be enclaves surrounded by quartz monzonite. There almost certainly are additional large enclaves of country rock within the margins of the Winnsboro plutonic complex that were not detected during our field studies because of the thick mantle of residual soil and sparse exposures. The irregular character of the magnetic field over the Winnsboro complex (Fig. 3) may be partly a result of the compositional inhomogeneity of the quartz monzonite, but it probably also indicates irregularity in the subsurface distribution of enclaves and xenoliths. Leucocratic dikes of aplite and pegmatite are extremely abundant in the amphibolite unit (Ꞓa) where it is in contact with the Winnsboro plutonic complex in the southern part of the Jenkinsville quadrangle, locally comprising more than 50% of the total volume. The initial $^{87}Sr/^{86}Sr$ ratio of the Winnsboro plutonic complex is 0.7047 ± 0.0004 and its Rb-Sr whole-rock age is 295 ± 4 m.y. (Fullagar, 1971; Fullagar and Butler, 1979). Several Rb-Sr and K-Ar mineral ages in the range 309-286 m.y. were determined for the quartz monzonite in the foundation rock of the V. C. Summer nuclear station at the south end of Lake Monticello (South Carolina Electric and Gas Company, 1977; Fullagar and Kish,

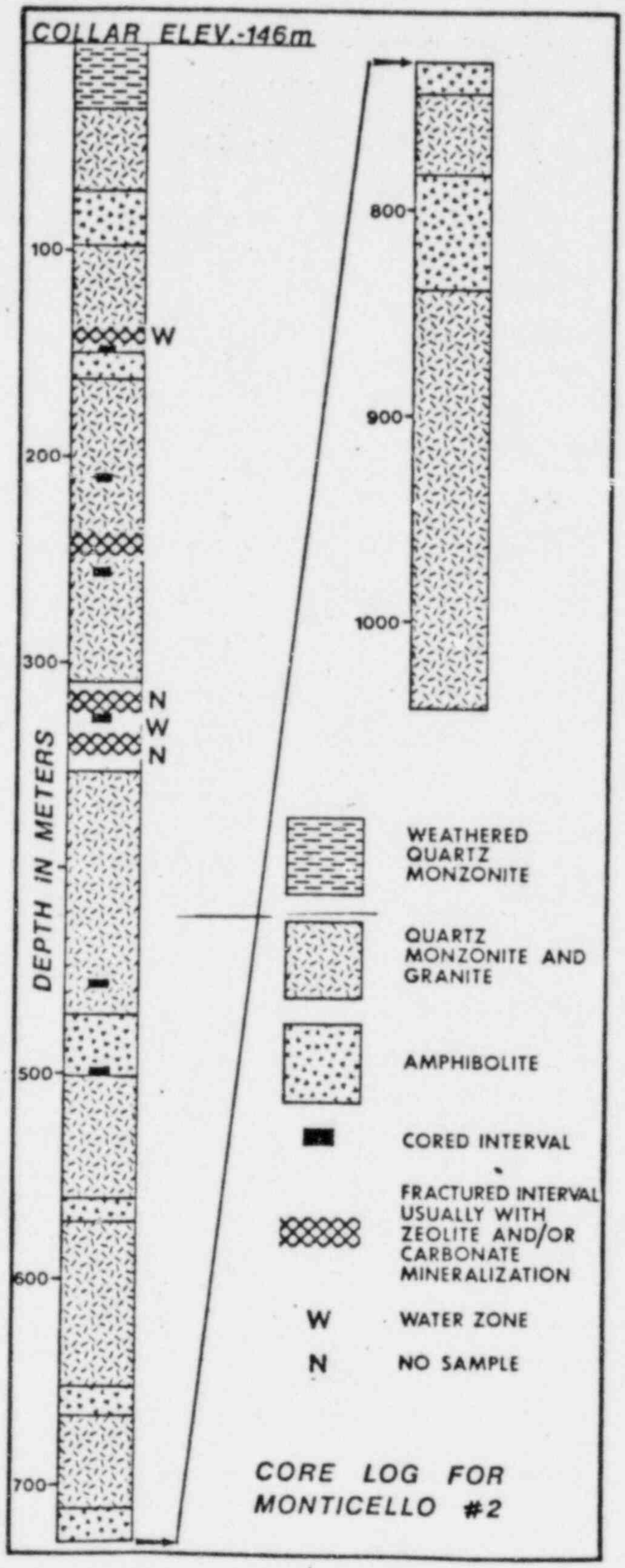


Figure 2. Lithologic log for Monticello #2, compiled from core and cutting samples. Modified from information supplied by D. E. Prowell.

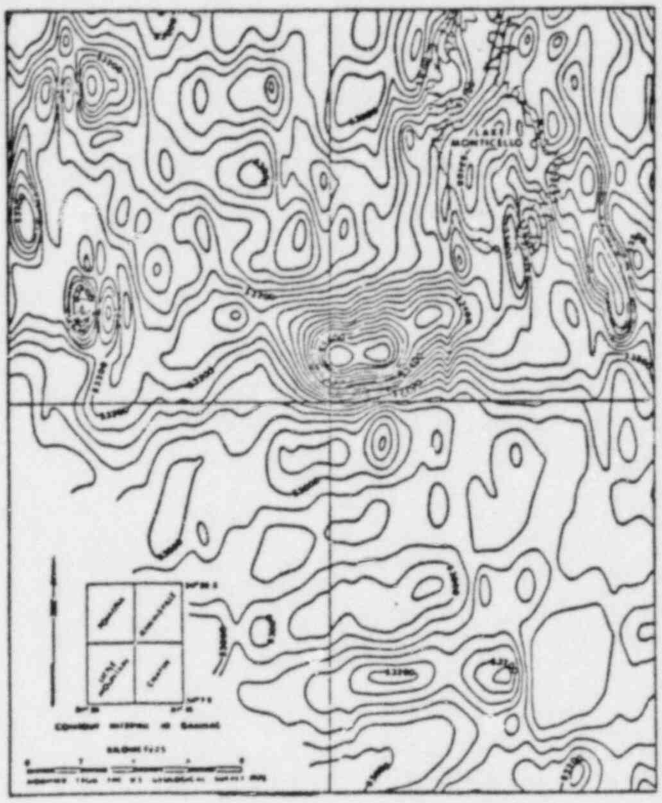


Figure 3. Aeromagnetic map of the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles (modified from U. S. Geological Survey, 1978). Contour interval 40 gammas.

1981).

Several small plugs and sheets of gabbroic rock (Cgb, Fig. 1) intrude the rocks of the Carolina slate belt in the southern part of the Little Mountain quadrangle. These clearly are post-metamorphic because the associated contact metamorphism overprints the regional greenschist facies metamorphism. They are tentatively interpreted to be of Carboniferous age because mafic plutonic rocks are associated with Carboniferous granitic rocks elsewhere in the Piedmont (Waskom and Butler, 1971).

The youngest rocks in the study area are a series of steeply dipping olivine diabase dikes 0-10 m thick and up to several kilometers long, trending N15W-N30W. Paleomagnetic studies have been conducted on 24 different dikes from the South Carolina Piedmont (Dooley and Smith, 1981). The average pole position (83.9°E, 66.1°N) is similar to that reported for other North American diabases of Mesozoic age (deBoer, 1967; Smith and Noltimier, 1979; Sutter and Smith, 1979). Although previous studies have indicated that many of the diabase dikes in the Piedmont have anomalously old K-Ar whole-rock ages because of excess argon contamination (Dooley and Wampler, 1977), eleven dikes in the present study have K-Ar whole-rock ages in the range 207-180 m.y., in excellent agreement with the paleomagnetic results.[1] An anomalous age of 288 m.y. was determined for one dike from the Salem Crossroads area north of Monticello Reservoir. The paleomagnetic pole positions and most of the K-Ar whole rock ages, therefore, indicate a

[1]The K-Ar whole rock ages were determined by R. E. Dooley using facilities at the Georgia Institute of Technology.

late Triassic or early Jurassic age for the diabase dikes in the study area.

DEFORMATIONAL HISTORY

The rocks in the study area have been affected by two strong episodes of folding (D_1, D_2), and are cut by a variety of later faults and joints.

The earliest deformation (D_1) was an episode of tight to isoclinal passive folding. The associated regional metamorphism (M_1) varies from greenschist facies in the Carolina slate belt to amphibolite facies in the Charlotte belt. The Chapin synclinorium is a major upright F_1 fold crossing the southern part of the study area. The initial compositional layering in the stratified rocks (S_0) has been strongly transposed by S_1 slaty cleavage. S_1 contains a strong elongation lineation (L_1) which parallels the L_{0x1} intersection lineation. The average orientations of L_1 and L_{0x1} in the study area (Figs. 4a, 4b) indicate that the Chapin synclinorium plunges 11° to the N75E. The 415 m.y. old Newberry plutonic complex contains rotated xenoliths which carry the S_1 foliation and so the time of D_1 must be Silurian or older. Whole-rock K-Ar studies of slates from the Carolina slate belt in North Carolina (Kish and others, 1979) indicate that the most probable time for D_1 is early Ordovician.

In the region north of the Chapin synclinorium the S_1 foliation has been extensively reoriented by mesoscopic to macroscopic F_2 flexural flow folds (Fig. 4c). In most places F_2 folds are coaxial

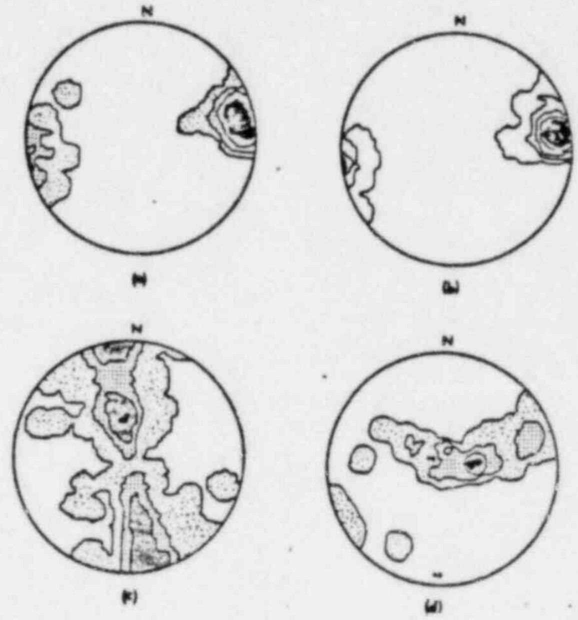


Figure 4. Lower hemisphere, equal area projections of structural data from the region south of Monticello Reservoir. (a) 63 L_1 elongation lineations from the slate belt portion of the Chapin and Little Mountain quadrangles. Contours: 1, 5, 15 and 25%. (b) 41 L_{0x1} intersection lineations from the slate belt portion of the Chapin and Little Mountain quadrangles. Contours: 1, 5, 15, 25 and 35%. (c) Poles to 713 S_1 foliation planes from the Chapin and Little Mountain quadrangles. Contours: 0.5, 2, 5 and 10%. (d) 106 L_{0x1} and L_1 lineations from the Wateree Creek fault zone in the vicinity of Spring Hill in the Chapin quadrangle. Contours: 1, 5, 12 and 20%. "A" is axis of drag folding, "B" is the net-slip vector for the Wateree Creek fault zone.

with L_1 and L_{0x1}. The time of D_2 is thought to be middle to late Paleozoic (pre 295 m.y.) because the 295 m.y. old granitic rocks of the Winnsboro plutonic complex are undeformed, and because F_2 style folds have been observed in rotated xenoliths in the plutonic complex.

The post-D_2 faults in the study area are divided into several groups based on orientation and on the character of the mineralization that has occurred in the fault zones.

The oldest group of faults, trending approximately east-west, dip steeply, and are characterized by repeated episodes of brecciation and silicification. The adjacent wall rocks are cut by numerous irregular extensional veins partly infilled with comb quartz. The displacement along faults of this group has apparently been small for generally the same rock unit is present on both sides of the fault surface. Faults containing silicified breccia are of widespread occurrence in the Appalachian Piedmont (Conley and Drummond, 1964; Odom and Hatcher, 1980). Those in the eastern Piedmont of South Carolina are thought to be of late Paleozoic or early Mesozoic age because they cut Carboniferous metagranitic rocks near the Fall Line and are themselves cut by late Triassic or early Jurassic diabase dikes.

The east-west trending silicified fault zones are displaced by a later set of steeply dipping faults trending N-S to N15°W. The Wateree Creek fault zone in the central and southern parts of the Chapin quadrangle (Fig. 1) is the most thoroughly documented example of this north-south trending fault set. The Wateree Creek fault zone displaces stratigraphic units on the flanks of the Chapin synclinorium in a manner suggesting down-to-the-east, predominately dip-slip displacement (Fig. 1). The apparent offset of the axis of the Chapin synclinorium in cross section also indicates predominately dip-slip displacement of approximately 1700 meters (compare A-A' and B-B', Figs. 1 and 5). In the vicinity of the Wateree Creek fault zone the L_1 and L_{0x1} lineations have been dispersed along a portion of a small circle on the stereonet (Fig. 4d) by fault-related drag. The axis of the drag fold derived from the data in Figure 4d (4°S 3°W) is subhorizontal, indicating predominately dip-slip displacement in the fault zone.

A portion of the Wateree Creek fault zone is exposed in a large roadcut near Spring Hill in the east-central part of the Chapin quadrangle (Fig. 1). The average dip of fault surfaces in this outcrop is 78° to the west, ~~indicating~~ that at this level of exposure the faults in the Wateree Creek zone are high-angle reverse. Thoroughly brecciated rock is exposed in several places along the fault zone. Samples recovered from several core holes drilled into the fault zone below the level of weathering indicate that veins and open spaces in the breccia have been infilled predominately with carbonate minerals and accessory quartz. The apparent brittle character of the breccia and the mineralogy of the associated vein fillings suggests that the faulting occurred at low temperatures and pressures within a few kilometers of the earth's surface. Detailed field investigations, including backhoe trenching, in the southern part of the Chapin quadrangle indicate that a diabase dike, petrologically similar

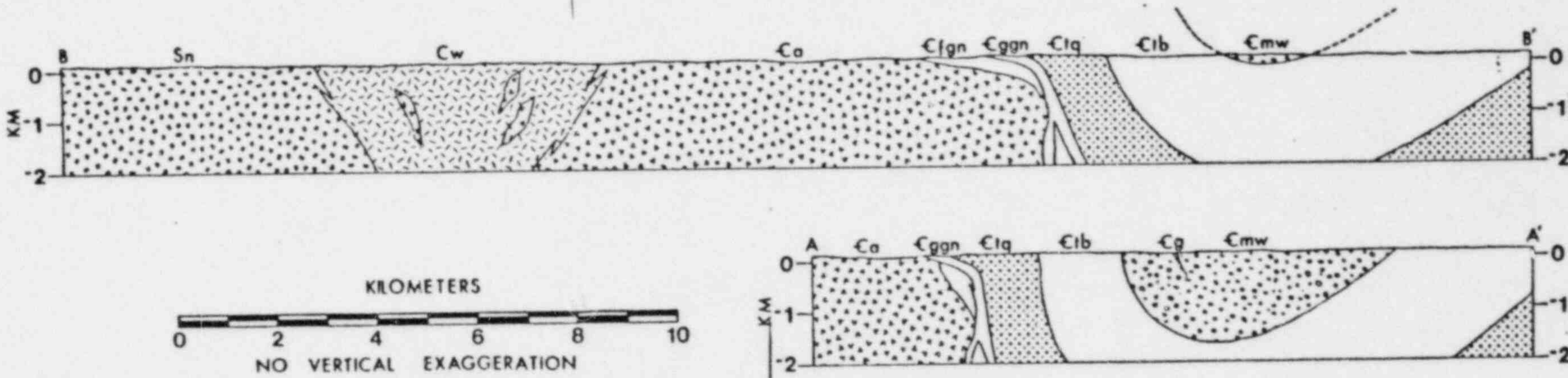


Figure 5. Geological cross sections across the Pomaria, Jenkinsville and Chapin quadrangles, on either side of Wateree Creek fault zone. See Fig. 1 for location of section lines.

to the late Triassic and early Jurassic diabase dikes, intrudes across the Wateree Creek fault zone (Fig. 1). Therefore, the faulting is thought to have occurred prior to the early Jurassic.

The north-south trending Summers Branch fault zone in the Little Mountain quadrangle offsets stratigraphic units on the flanks of the Chapin synclinorium in a manner suggesting down-to-the-west, dip-slip displacement. The Summers Branch fault zone is interpreted to be similar to the Wateree Creek fault zone, although actual outcrops of rock from within the fault zone have not been found.

During excavation for the foundations of the V. C. Summer nuclear station, a distinctive group of fractures containing druzes and vein fillings of laumontite were encountered. Although there is considerable variability to the attitudes of the mineralized fractures, two steeply dipping sets oriented N60°E and N28°W can be recognized (South Carolina Electric and Gas Company, 1977). Fractures of the northeast trending set have undergone oblique slip displacements up to 2 m. Fractures of the northwest trending set displace those of the northeast set and have undergone oblique slip displacements up to several cm. Undeformed laumontite crystals fill openings along both sets. A potassium-argon age of 45 ± 5 m.y. has been determined on laumontite crystals from the N60E trending fracture set. Because of the open crystal structure of laumontite this age is regarded as a conservative minimum estimate of the time of most recent fault movement (South Carolina Electric and Gas Company, 1977). Fractures and alteration zones containing zeolite and carbonate minerals were encountered at several levels in Monticello #2, and in some cases were associated with a substantial influx of groundwater (Fig. 2). Zeolite mineralization has also been observed nearby along northwest trending fractures in the spillway to the Parr Shoals dam, and in a borehole in the Winnsboro plutonic complex east of the study area (Costain and others, 1977). The above local occurrences of fractures associated with zeolite mineralization are thought to be a manifestation of a Mesozoic thermal event, perhaps associated with the emplacement of diabase dikes, that has affected a large area in the central Piedmont of North and South Carolina (Privett, 1973a, 1973b, 1974a, 1974b, 1977; Brown and Gilbert, 1977; Butler, 1977; Wagener, 1977b).

In most outcrops in the study area the rocks are cut by one or more joint sets in which the individual fractures have little or no lateral displacement. The fractures are usually 10-200 cm in length, although in most places a few longer fractures are present which extend beyond the limits of exposure. Short joints often are arranged in echelon patterns located near the termination of a nearby long joint. Approximately 100 joint measurements have been made at each of 50 localities in the study area. In general, the orientations of the sets and the joint frequencies are variable from one locality to another, although in most places there are one or more sets oriented at a high angle to S_1 and L_{0x1} or L_1. The controls on orientation and frequency are not well understood, although the orientations of other fabric elements and the degree of lithological heterogeneity probably are important. In general, joint frequency is lowest in the

Winnsboro plutonic complex, and highest in the low grade metamorphic rocks of the Carolina slate belt. However, even in otherwise homogeneous structural and lithological domains, joint orientation and frequency are variable.

SUMMARY DISCUSSION

In order to make judgments about the possible earthquake hazard at Monticello Reservoir, it is necessary to evaluate the above geological information in light of the ambient stress field in the region of seismic activity. Information about the stresses is available from the following three sources: 1) composite fault plane solutions derived from seismic data (Talwani and others, 1980; South Carolina Electric and Gas Company, 1980), 2) stress measurements made in the U.S.G.S. boreholes, Monticello #1 and #2, by the hydraulic fracturing technique (Zoback, 1979; Zoback and Hickman, 1982), and 3) stress measurements made in the foundation excavation of the V. C. Summer nuclear station by the overcoring technique (South Carolina Electric and Gas Company, 1977).

The seismic studies at Monticello Reservoir indicate that the epicenters of induced earthquakes are occurring in three groups (see Fig. 21 in Talwani and others, 1980, and Fig. 3 in Zoback and Hickman, 1982) located in areas underlain by rocks of the Winnsboro plutonic complex. One large group is located at the southwest corner of Lake Monticello, near both the V. C. Summer nuclear station and the site of Monticello #2. Another large group is located in the west-central part of the lake around the site of Monticello #1. A third smaller group is located at the north end of the lake. Almost all of the foci are located at depths of less than two kilometers, and composite fault plane solutions indicate that the mechanism of faulting is predominately thrusting with the P axes approximately horizontal and with directions varying from N34E through due east to S76°E (Talwani and others, 1980). Analysis of the source characteristics of some of the earthquakes suggests that the seismicity is occurring along pre-existing fractures (Duc, 1980; Talwani and others, 1980). The apparent scatter in the locations of the earthquake foci suggest that the foci are not located along a single major fault but instead are located along numerous small fractures pervading the rock mass. Variability in the orientation of nodal planes for various sub-groups of earthquakes (Talwani ~~and others, 1~~980) suggests variability in the orientation of pre-existing fractures and also perhaps temporal and/or spatial variability in the orientation of the causative principal stresses.

The above observations are further reinforced by stress measurements and fracture orientation studies made in the U. S. Geological Survey boreholes Monticello #1 and #2 which are located in the two clusters of most intense seismic activity (Zoback, 1979; Zoback and Hickman, 1982). Hydrofrac stress measurements made in these holes indicate that within a few hundred meters of the surface the rock is in a state of incipient failure by thrust faulting. At greater depths the rock is not critically stressed, although the magnitudes of the horizontal principal stresses vary erratically with depth (Zoback and Hickman, 1982). Fracture studies made with a borehole televiewer (Zoback and Hickman, 1982) indicate that the rock at Monticello #2 is much more intensely fractured than the rock at Monticello #1. Although a degree of preferred orientation is evident in some restricted intervals of the boreholes, in general the fracture orientations are variable and erratic. Comparison of fracture orientations with the orientations of nodal planes derived from composite fault plane solutions indicates that there are fractures having an orientation favorable for reactivation in the regions of seismicity (Talwani, 1981; Zoback and Hickman, 1982).

Several determinations of the magnitudes and directions of the horizontal principal stresses were made by the strain-relief, overcoring technique in the foundation excavation for the V. C. Summer nuclear station (South Carolina Electric and Gas Company, 1977). The magnitude of the greatest horizontal principal compressive stress varied from +31 to +97 bars, and its direction varied from N35°W through due north to N15°E. These directions are approximately perpendicular to the direction of greatest horizontal compressive principal stress inferred from composite fault plane solutions (Talwani and others, 1980; South Carolina Electric and Gas Company, 1980).

One of the primary objectives of this study was to determine if there are through-going faults or other major lithological boundaries in the vicinity of Monticello Reservoir having orientations favorable for reactivation in connection with the induced seismic activity.

Because the directions of the principal stresses are variable, it is difficult to precisely predict the planar orientations that would be most susceptible to reactivation. However, the average direction for the greatest horizontal compressive principal stress derived from composite fault plane solutions is N71°E. The most favorable orientations for thrust faults resulting from a greatest compressive principal stress having this orientation would be N19W 30°SW or N19W 30°NE. In the Chapin and Little Mountain quadrangles two sets of major faults having orientations E-W 65°S and N15°W 78°SW are present. These are not orientations favorable for reactivation, and furthermore, there is no evidence that major through-going faults are present in the region of seismic activity. The northernmost control point on the Wateree Creek fault zone (Fig. 1) is located in the Chapin quadrangle approximately eight kilometers south of Monticello Reservoir. The only major lithological boundaries near the region of seismic activity are the contacts between the Winnsboro plutonic complex and surrounding rocks. These strike almost perpendicular to the preferred faulting directions and are interpreted to be irregular intrusive contacts with numerous apophyses extending outward into surrounding rocks. Because of their orientation, irregularity, and intrusive character, these contacts probably retain substantial cohesion and would be unlikely to function as guides for new through-going fractures.

Another objective of this study was to determine if there are foliation directions along which slip might be initiated by the stress and pore pressure changes related to reservoir impoundment. Almost all of the seismic activity is located in the Winnsboro plutonic complex which underlies Monticello Reservoir. The Winnsboro complex is post-kinematic and is generally unfoliated, although in some places an emplacement related irregular gneissic layering is present. In addition, the Winnsboro complex contains numerous foliated xenoliths and enclaves of felsic gneiss and amphibolite having a maximum length on the order of 1-2 kilometers. Because the larger enclaves are sparsely distributed, and because the foliation in them is folded and diversely oriented, it is unlikely that the enclaves could function as guides for the development of new through-going fractures.

The above geological and geophysical studies indicate that the Winnsboro plutonic complex contains numerous diversely oriented small fractures and lithological inhomogeneities having a maximum length on the order of 1-2 kilometers. These local inhomogeneities, in concert with an inhomogeneous stress field, are interpreted to control the diffuse seismic activity that is occurring around Monticello Reservoir. In view of the apparent absence of through-going faults in the vicinity of the reservoir, it is concluded that there is little likelihood that damaging local earthquakes will occur in response to the small stress and pore pressure changes related to reservoir impoundment.

ACKNOWLEDGMENTS

We wish to thank R. E. Dooley, P. D. Fullagar, D. E. Prowell, A. W. Snoke, P. Talwani and M. D. Zoback for providing us with research results prior to publication. Four 50'-80' core holes were drilled into the Wateree Creek fault zone in connection with a research program being conducted by D. E. Prowell of the U. S. Geological Survey. The following University of South Carolina students assisted with geological and geophysical field studies: Mel Blackwell, Ken Bramlett, Bruce Crawford, Steve Durgin, J. C. Hare, Jack Horkowitz, Chris Jones, Phil Kimbrell, Sarah Logan, Mark Snyder, and John Willis. The illustrations were drafted by Tania Garcia.

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