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SHEARON HARRIS NUCLEAR POWER PLANT

FAULT INVESTIGATION

Responses to Mr. W. R. Butler's
letter of 16 May, 1975

TABLE OF CONTENTS

	PAGE
Question 1.	1
Question 2.	4
Question 3.	5
Question 4.	10
Question 5.	21
Question 6.	24
Question 7.	26
Question 8.	28
Question 9.	29
Question 10.	33
References	35

FIGURES

Figure 1.	Following Page 9
Figure 2.	Following Page 14
Figure 3.	Following Page 27

MAP

In Pocket

QUESTION 1:

Provide a discussion of problems associated with zeolite mineral dating and parent relationship considerations (ie Sr^{87}/Sr^{86} ratios).

RESPONSE:

K-Ar DATING OF ZEOLITES

Theoretical and Experimental Basis

The potassium within zeolites occupies large cavities and channels within the framework alumino-silicate (Deer & Others, 1963). These voids are cation exchange sites where potassium is held largely by ionic, electrostatic, forces. Zeolites function as cation exchangers because when a zeolite containing a particular cation is in contact with a solution containing another cation, an equilibrium distribution of each cation between the zeolite and the aqueous phase will be set up. The equilibrium distribution is achieved rapidly since the porous structure makes possible rapid passage of ions in and out (Cotton & Wilkinson, 1966). Because in general one ion will have a greater "preference" for a particular zeolite (due to size restrictions, bond strength, effects of ligands in the solution, etc. (Day & Selbin, 1968), it will tend to concentrate there. Exchange by zeolites is naturally prevented only when they are physically separated from the aqueous phase. Because of the lack of any bond energy, except that due to weak Van der Waals forces (Day & Selbin, 1968), argon has no "preference" for the zeolite structure. Therefore any cation which might displace potassium, would more easily displace argon.

The chance that a significant amount of radiogenic argon would diffuse into these zeolites is considered extremely remote. The host rocks of the zeolites are diabase dikes which themselves contain very small volumes of radiogenic argon, the largest being 7.9×10^{-7} scc/gm and only slightly greater than that found in the zeolites (up to 3.4×10^{-7} scc/gm). Therefore the host rocks of the zeolites could not be a source of radiogenic argon for the zeolites. If it is possible for zeolites to capture radiogenic argon thereby yielding old ages, one must, in this case, make an extremely ad hoc assumption of an ambient partial pressure of ^{40}Ar from an unknown source.

Even under this rather unlikely circumstance one is faced with two alternatives: (1) either this occurred in pre-Cenozoic time (which would itself require an old age for the zeolites), or (2) that there was a recent thermal event sufficient to expel argon from the crustal rocks thereby building up the required ambient pressure of radiogenic argon. All available evidence in the region (as indicated by the lack of Cenozoic K-Ar ages) shows that this has not happened. Furthermore the diabase dikes, because of their low Ar concentration, should be readily affected by such conditions,

and the agreement between their K-Ar ages and geologic age demonstrates that they have not. Finally the best evidence that there has not been a thermal episode after zeolite formation sufficient to release radiogenic argon from local crustal rocks, is the existence of heulandite.

The experimental evidence available indicates that K-Ar dates of zeolites are less than their true age. MacIntyre's (1966) work showed that due to their low retention of argon, K-Ar dates on zeolites can be more than an order of magnitude less than their geologic age. G. H. Curtis has made a study of the relation of zeolite K-Ar age to grain size. From analyses of contemporaneous zeolites, Curtis found that the smaller grain sizes yielded the youngest ages and the largest grain sizes gave older ages (personal communication by G. H. Curtis). As Curtis pointed out, this investigation indicates that argon loss and not argon addition was the prevailing process.

In light of both theoretical considerations and the available experimental background, there seems to be no doubt that the K-Ar zeolite ages reported are less than the true age of the zeolites.

Sr^{87}/Sr^{86} RATIOS: GENETIC IMPLICATIONS

The zeolites could potentially contain strontium of two general types (sources). The first potential type is that common to the diabases which have initial Sr^{87}/Sr^{86} ratios of 0.7051 ± 0.0001 as determined in this study. Other diabases in the Carolina Piedmont which have been examined have initial Sr^{87}/Sr^{86} of 0.705 (Ragland & Fullager, 1973). The present day Sr^{87}/Sr^{86} ratios of the zeolites are only slightly greater than those of the diabases, being 0.7053.

The second potential type (source) is a secondary one, that which could have been acquired by cation exchange processes with groundwater.

The 87/86 ratio of continental crustal rocks (Faure & Powell, 1972) and hence ground waters are greater than that of mantle derived rocks such as the diabase dikes. The crustal average being calculated from the average Rb/Sr ratio of continental rocks is 0.719, a value in good agreement with observed $Sr^{87/86}$ ratios in continental surface waters (Faure and Powell). The lowest values observed are in marine waters where Sr^{87}/Sr^{86} ratios have been shown to be remarkably constant in the oceans at any one time in

geologic history. The present day value being 0.709 (Peterman & Others, 1970). The crustal Sr^{87}/Sr^{86} value of 0.719 is just that, an average for continental rocks and an average Rb/Sr ratio of 0.24 (Taylor, 1965). For surface and ground waters in terrains with rocks of low Rb/Sr ratios, the Sr^{87}/Sr^{86} values of the water will be less than 0.719. For example limestone with little clay materials have such low Rb/Sr ratios that the Sr^{87}/Sr^{86} ratio increases insignificantly with time, and consequently might be as low as the sea water value when they formed.

A strong case can be made however that the ground water in the region of this study must be greater than at least 0.709, the present oceanic value, (it is probably closer to 0.715). The rocks in the area through which the water moves are not limestones, but are rocks which much more closely approach the average continental crust, they are in fact more silicic than the average continental crust.

Thus it is possible to distinguish between the two potential sources of strontium in the zeolites, i.e. that strontium common to the diabase, and that which might have been introduced later by ion exchange processes with ground water. The data for the zeolites, suggest that both types of strontium might be present. Furthermore the data indicates the strontium of one of the zeolites which presently has a Sr^{87}/Sr^{86} ratio of 0.7060, contains little strontium other than that which genetically relates it to the diabase. The other samples are interpreted as indicating exchange of the primary (diabase type) strontium with secondary (ground water type) strontium.

Since the Sr^{87}/Sr^{86} ratio of the diabase is presently only slightly higher than the initial ratio and less than 0.706, the zeolites could have formed at any time after the initial crystallization of the diabase, so long as the temperature-pressure conditions were sufficient for their formation.

QUESTION 2:

Provide a discussion of the relationship of the site fault to the Jonesboro Fault and include a reevaluation of the carefully defined term "complementary" which is defined in Glossary of Geologic Terms - "as faults thought to be conjugate but origin unknown."

RESPONSE:

Delete that portion of the definition of the word "complementary" following the word "episode".

Movement took place along the Jonesboro Fault during an extremely long span of time including the initiation of deposition of Triassic sediments and ending subsequent to the intrusion of Jurassic diabase dikes. Movement along the site fault took place after deposition and lithification of several thousand feet of Triassic Basin sediments and ended shortly after the intrusion of the youngest of the Jurassic diabase dikes. Assessment of the small vertical and horizontal components of movement on the plant site fault indicates that this fault is probably short and shallow rooted as opposed to the Jonesboro Fault along which movement started much earlier. Both the Jonesboro Fault and the plant site fault are considered to be rooted in the crust. Upper mantle material intruded into the Triassic Basin and the Piedmont in the form of diabase dikes does not follow either of the faults. The site fault and the Jonesboro Fault belong to a conjugate set of normal faults. Stresses responsible for these faults caused rotational deformation, emphasized by major motion along the Jonesboro Fault, which is the main fault of the set. The site fault is an antithetic normal fault belonging to this conjugate set. The normal tendency is for the main and antithetic fault planes to have parallel strikes. In regions of differential vertical motion however, the strike of the antithetic set may angle in on to that of the main fault. The geometry of the fault set precludes that the two faults intersect. East of the site stresses were most probably released by faults parallel to the site fault in an "en echelon" arrangement.

QUESTION 3:

Discuss evidence for an episode of regional metamorphism other than paleomagnetism and a general discussion of burial metamorphism, as well as the need for such an episode in determining the capability of the site fault. This discussion should include considerations of the temperature - pressure - phase relationships of the zeolite minerals examined.

RESPONSE:

There has been general confusion concerning what to call the low grade metamorphic process that influenced the sediments and igneous rocks of the Newark Formation. In general the term "burial" metamorphism has been used to explain the occurrence of zeolites and other minerals typical for this metamorphic facies. The evidence (geochemical and paleomagnetic) indicates that the Newark Formation in all grabens of the eastern U. S. were metamorphosed and that this process also influenced dike rock in the metamorphics outside of the Triassic Basins. We are primarily referring to an episode during which the geothermal gradient was high, resulting in sustained periods when rock temperatures exceeded about 100° C. but were probably not generally much higher than about 300° C.

The partial reset of biotites and hornblende in intrusive rocks near the Deep River Basin, which causes yield of younger than true geologic ages on K-Ar dating, as discussed herein in the response to Question 9, is typical of the occurrence of low-grade metamorphism in such rocks in the region. It is generally agreed that the temperature range in which this partial resetting is initiated is about 200° to 300° C.

In an ongoing analyses of over 150 Triassic - Jurassic dikes along the Eastern Seaboard by deBoer, it was found that these dikes have paleomagnetic directions comparable to those of the late Triassic lavaflows after demagnetization of 150 Oe. If this process is continued, however, these directions invariably change, and most start clustering again at 350 Oe. Clearly then, the dikes contain a paleomagnetic spectrum consisting of at least three magnetic vectors: a low coercivity induced magnetization parallel to the present field; a magnetization (TRM) parallel to that of contemporaneous Triassic - early Jurassic lavaflows; and a high coercivity (CRM) magnetization which was obtained in a field similar to that which magnetized the Belknap and Gore intrusive complexes of the White Mountains (Rb/Sr ages 149 ± 3,

157 ± 3, and 158 ± 3 mil. years).

Ongoing studies of the thermal behavior of the same samples yield a bimodal distribution suggesting different Curie temperatures for the different magnetic components. The high stability fraction (CRM) has a relatively low Curie temperature of about 250° C, the intermediate stability fraction (TRM) has Curie temperatures varying from about 400° C to 550° C. Paleomagnetic evidence suggests that the CRM event occurred after 180 but before 150 m. y. ago. It is probably related to the crustal thinning and fracturing of the entire Appalachian Belt in the early phase of continental break up.

With regard to the evidence for regional burial metamorphism, Ragland stated on page 30 of his report, dated December 26, that"The two processes' (mesogenetic diagenesis and "burial" metamorphism) are obviously completely gradational into one another and the boundary is man-made". On page 33 he stated "in many instances it is impossible to distinguish between mineral assemblages formed by these two processes" (hydrothermal activity and "burial" metamorphism.

In recent years the once popular idea that simple lithostatic pressure caused by overburden can cause metamorphism (so-called "burial" metamorphism) without an accompanying heat source or directed stress has fallen into considerable disfavor. The occurrence of thousands of feet of unmetamorphosed ancient sedimentary rocks, plus the recognition that there is no such thing as an entirely stress-free environment in the earth's crust, has led to this changing of ideas.

Although there is no evidence for stress playing a major part in the "burial" metamorphism of rocks in Triassic basins of eastern North America, it is quite reasonable to assume that this was an area of extremely high heat flow at that time, probably approaching geothermal gradients found along modern oceanic or continental rift zones. The huge magma reservoirs ("mantle plumes"?) that fed the basaltic dikes, sills, and flows were locally ponded in the crust (Weigand & Ragland, (1970), and would have provided enormous sources of heat. This heat would have been the driving force behind mesogenesis - "burial" metamorphism - hydrothermal activity, long before and after the intrusion/extrusion and solidification of any single igneous body. Thus for the sake of this discussion, "burial" metamorphism, hydrothermal activity, and mesogenesis are considered effects of the same cause, primarily heat, and differ from one another mainly due to differences in temperature, fluid pressure and total pressure and chemical environment.

In the context of the present Fault Investigation Report, it is intended to be understood that "burial" metamorphism requires only that depth of cover which is necessary to form sufficient thermal insulation to sustain temperatures of 100^{o} C plus for geological periods of time on an areal basis. The recent suggestion by Dallmeyer (1975) that some rock units earlier considered to be Triassic may in fact be Jurassic is consistent with the interpretation that the low - grade metamorphic event described in the Fault Investigation Report is of Jurassic age. A schematic chart of possible episode - temperature correlations is enclosed as Figure 1.

Zeolites or related mineral assemblages that characterize these processes can be summarized as follows:

1) Mesogenetic Diagenesis

a - clinoptilolite
b - heulandite
c - stilbite
d - analcite

2) Intermediate

a - analcite
b - mordenite
c - clinoptilolite
d - heulandite
e - albite

3) Burial Metamorphism (zeolite facies)

a - laumontite
b - albite
c - wairakite

4) Burial Metamorphism (prehnite-pumpellyite facies)

a - pumpellyite
b - prehnite
c - albite

Hydrothermal processes can result in any of these assemblages. In general, T and P_t increase from 1 to 4, although variations in P_f relative to P_t can cause many exceptions to this generalization.

There is an overwhelming amount of evidence to indicate that both igneous and sedimentary rocks of Mesozoic basins

in eastern North America have been affected by these processes. In the Connecticut Valley the presence of pumpellyite, albite, laumontite, actinolite, epidote, and chlorite in Mesozoic igneous and sedimentary rocks suggest the prehnite - pumpellyite facies and hydrothermal activity (Heald, 1956; Coombs, in Armstrong and Besancon, 1970). In the New Jersey Triassic basin the presence of prehnite, laumontite, and heulandite, as well as the conversion of analcite to albite and kaolinite plus montmorillonite to illite plus chlorite with increasing depths all indicate the presence of "burial" metamorphism and mesogenesis (Van Houten, 1961, 1962, 1965). In the Dan River basin of Virginia, Thayer (1970) also found kaolinite plus montmorillonite coverting to illite plus chlorite with increasing depth. Similar results were obtained by Lewis (1974) in the subsurface Dunbarton basin of South Carolina, where he found montmorillonite - chlorite) or to a mixed layer montmorillonite - illite with increasing depth. Because dips of sedimentary strata in the Deep River basins are generally less than those in other basins, Hooks and Ingram (1955) found it difficult to determine clay mineral changes with depth. They found that the low P-T assemblage, kaolinite plus montmorillonite, predominates in the Deep River basin. Thayer (personal communication, 1975), however reported the presence of both illite and mesogenetic chlorite in some samples from the Deep River basin.

The presence of coal in the Deep River basin provides another means of determining the importance of these processes in this area. The percentage of volatiles in coals from the Deep River basin that are unaffected by igneous intrusion varies from 35 to 40 percent (Reinemund, 1955). These percentages approximately correspond with the boundary of the laumontite and heulandite zones of burial metamorphism - mesogenesis (Kisch 1969). There is additional evidence from the literature to support the fact that the presence of heulandite is compatible with the volatile content of coal found in the Deep River basin. Heulandite occurs with coal containing about 39 percent volatiles in the Lena Coal basin, Poland (Zaporozhtsevr, 1963) and with coal containing about 36 percent volotiles in the Werrie basin, New South Wales, Australia (Kisch, 1966).

The presence of vesicles in the dikes provides a means of estimating the maximum depth of emplacement of the dikes. Moore (1965) and Jones (1969) found no vesicles in modern pillow lavas on the sea floor below 5 kilometer water depths. The dikes solidified rapidly enough that the vesicles were preserved as spheres, thus the state of stress in the solid

rocks had no effect on the existence of vesicles. Although pillow lavas and these diabase magmas were both supersaturated with respect to a fluid phase (otherwise no vesicles) at the time of extrusion/intrusion, small differences in viscosities between the two types probably did exist and thus did affect the relative size of vesicles, the existence of vesicles at a particular lithostatic pressure probably was not appreciably affected. An overburden of 5 kilometers of water would be equivalent to an "overburden" of about 6000 feet of basaltic magma. Thus it seems that 6000 feet (1.7 km) is a reasonable lower limit for the emplacement of the dikes. This would be equivalent to a maximum P_t of about 0.6 KB. Given a reasonable geothermal gradient in a high heat flow area of 60 ± 10° C. per kilometer, the maximum ambient temperature in the surrounding sedimentary rocks would be 102 ± 17° C.

As referenced on page 36 of Ragland's report, Senderov (1973) reported that the reaction involving laumontite to heulandite occurred between 100 and 160° C at low to moderate pressures; 0.6 kb would certainly be considered a low pressure. Castono and Sparks, (1974) found laumontite apparently in equilibrium in core holes in the San Joaquin Valley at a minimum teperature of 96° C. Thus presumably the theoretical heulandite stability field is close to the maximum ambient temperatures and pressures at the level of dike emplacement. A further discussion of limitation and constraints on these P-T considerations can be found on page 36 of Ragland's report.

Conclusion. From the Fault Investigation Report and the response to Question 1., it is seen that the diabase dike rocks are the source of argon found in the fragile, undisturbed zeolite minerals in the fault gouge. There is no evidence for the occurrence of a thermal episode adequate for crystallization of these zeolites in post-Jurassic time. Conversely, there is evidence from several lines of investigation that such a thermal regime did exist during the Jurassic. The depth of burial of the rocks exposed presently at the land surface at the time of intrusion of the diabase dikes could have been a maximum of 6000 feet, if a continuous column of molten magma of that maximum height is taken as intruding the entire rock column. The lower limit of the depth of such burial is not established but would have been sufficient to provide thermal insulation for the long term sustenance of temperatures needed for crystallization of the mineral suite associated with zeolite phase metamorphism.

The available evidence converges to the interpretation that the site fault last moved during Jurassic time and is therefore incapable.

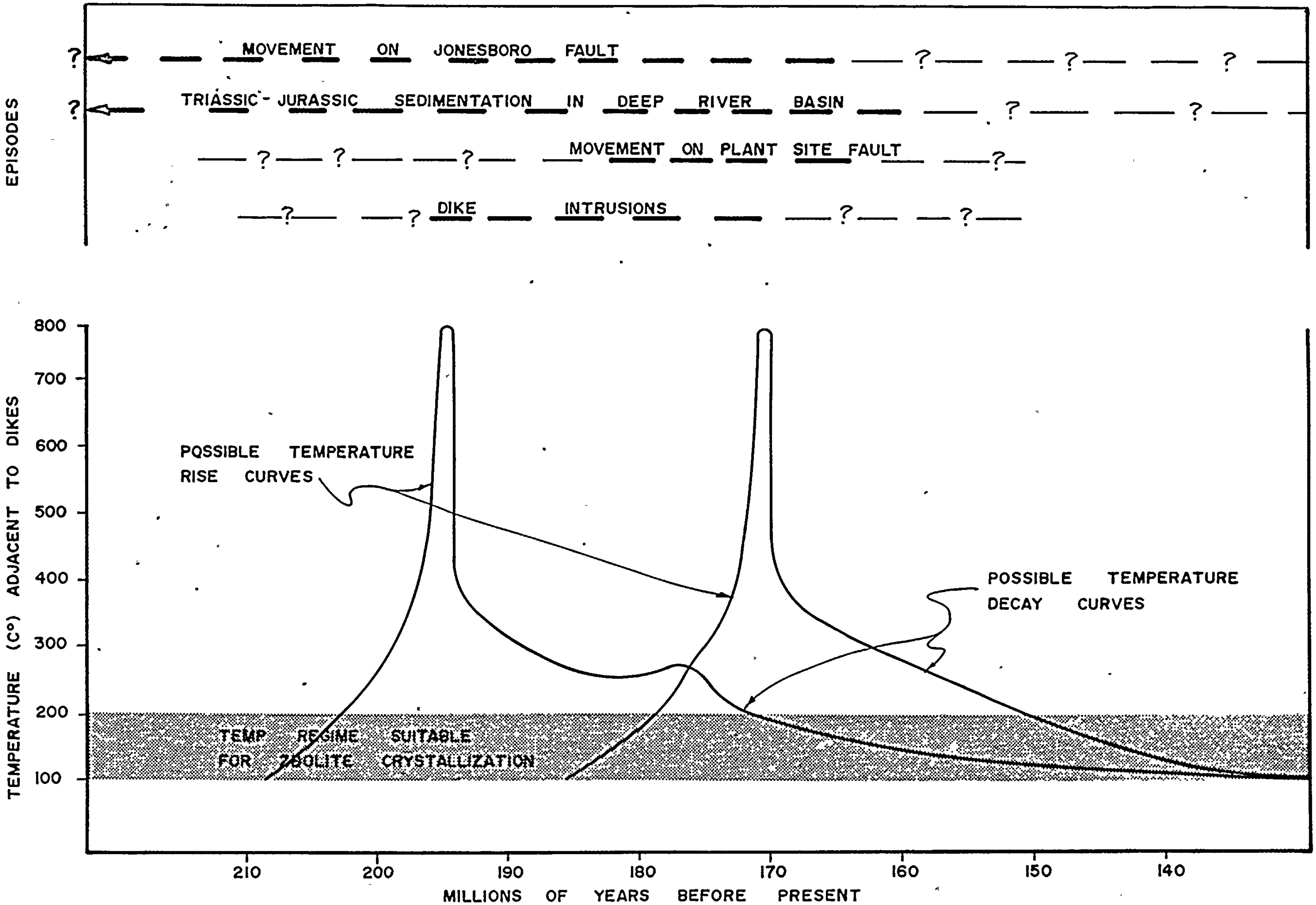


FIGURE I SCHEMATIC EPISODE - TEMPERATURE HISTORY CHART

QUESTION 4:

Provide further documentation of the lack of offset of Cretaceous (?) rock by the Jonesboro Fault. Include items such as maps, photos, etc.

RESPONSE:

The following is a report of a field examination conducted in January, 1975, which provides evidence of the lack of offset of the sedimentary deposits by the Jonesboro Fault.

FIELD WORK

Four areas where the Jonesboro Fault trace was mapped by Conley (1962) were examined in addition to several areas where good exposures of the Cretaceous deposits were found. The areas examined are indicated on the accompanying map, taken from Conley (1962). The field work was carried out January 22 through 24, 1975.

CONCLUSIONS

The Cretaceous beds are judged not to have been displaced by movement on the Jonesboro Fault on the basis of the following facts:

1) Horizontal bedding was observed in the Cretaceous beds where they are well exposed, and good correlations of these beds can be carried across the projected location of the fault with no apparent offset.

2) No jointing or any other evidence of deformational strain is present in the observed exposures of the Cretaceous deposits. Particularly significant is the lack of strain in the exposure overlying the projected location of the fault (Position 3).

3) No apparent fault controlled drainage is exhibited in the development of the dendritic stream pattern throughout the area underlain by Cretaceous deposits.

4) The residual sandy soil, derived from the Cretaceous deposits, is the same and supports the same vegetation on either side of the projected location of the fault.

DISCUSSION

Field Observations

Bedrock observation is excluded to deep road cuts, excavations and isolated outcrops of very resistant rocks (e.g., diabase dikes and felsic metamorphic rocks) because of the soil and vegetation cover. A field check indicated that mapping of the rock types underlying the soil cover could be done by examining the residual soil for pieces of the parent rock (float). The mapped location of the Jonesboro Fault was verified; although it is not directly observable because of the cover.

Drainage

The drainage pattern in the Coastal Plain part of Moore County is dendritic. (See map.) The Jonesboro Fault, which is crossed by Crane Creek, Dunhams Creek, Little River and Nicks Creek (from east to west) did not influence the development of the streams' patterns. Contrasting with this, in the northern part of the county the stream pattern of Deep River is obviously controlled by faulting. (See map.)

Cretaceous Deposits

Age and Correlation. Regarding the age of the deposits which he referred to as Tuscaloosa formation, Conley (1962, p. 13 and 14), in a review of the previous literature, stated the following:

> "Upper Cretaceous Tuscaloosa Formation: The Tuscaloosa formation is the basal Coastal Plain unit in Moore County. In this report it is divided into a lower and an upper member. The Tuscaloosa formation was named by Smith and Johnson in 1887 after the city of Tuscaloosa, Alabama. L. W. Stephenson (1907) subdivided the Cretaceous of North Carolina into three formations. He called the basal unit the Cape Fear formation. He considered it Lower Cretaceous in age and correlated it with the Patuxent formation of Virginia. He named the overlying unit the Bladen formation, (Black Creek formation in present terminology) and correlated it with the Tuscaloosa formation of Alabama. In 1912 he renamed the Cape Fear formation the Patuxent formation and correlated it, on lithology, with the Patuxent of Virginia and Maryland.
>
> Sloan (1904) named the sands and clays of supposedly Lower-Cretaceous age in South Carolina, the Middendorf Formation. However, Berry (1914) studied plant fossils from this formation and found that they were actually of Upper Cretaceous age. Cooke (1936) correlated the Middendorf formations of South Carolina with the Tuscaloosa formation of Alabama and

extended the Tuscaloosa into North Carolina. Horace G. Richards (1950) described the Tuscaloosa formation in North Carolina and stated that it occurred in southern Moore County.

W. B. Spangler (1950) from a study of cuttings obtained from oil-test wells drilled on the North Carolina Coast, found that the subsurface contained both lower and upper Cretaceous beds. He applied the name Tuscaloosa formation only to beds of Eagle Ford-Woodbine age. P. M. Brown (1958) also found rocks of Woodbine and Eagle Ford age in the subsurface stratigraphy of the North Carolina Coastal Plain. These he assigned to the Tuscaloosa (?) formation.

S. D. Heron (1958) mapped the basal Cretaceous outcrops between the Cape Fear River in North Carolina and the Lynches River in South Carolina. He returned to the Classifications of Stephenson and Sloan, dividing the Tuscaloosa formation into the Lower Cretaceous (?) Cape Fear formation and the Upper Cretaceous Middendorf Formation. He named the lower part of the Black Creek formation, below the Snow Hill member, the Bladen member. Heron (1960) stated, "The Middendorf is considered the updip facies of the Bladen member of the Black Creek formation and both of these formations have overlapped the Cape Fear formation."

Groot, Penny and Groot (1961) collected samples containing plant microfossils from the Tuscaloosa formation of the Atlantic Coastal Plain, including one sample from the basal part of the lower member of the Tuscaloosa formation in Moore County.

They found that the Tuscaloosa formation of the Atlantic Coastal Plain is Upper Cretaceous age, but slightly older than Senonian, although some Senonian species are present."

Conley's lower and upper members of the Tuscaloosa formation are designated Cape Fear Formation and Middendorf Formation, respectively, by Swift and Heron (1969). Quoting from the latter (p. 206-210 and 213):

"Heron (1958a, 1960) and Heron and Wheeler (1959, 1964) recognized that the Tuscaloosa Formation in North Carolina is actually two genetically unrelated sedimentary units. The upper unit, designated the Middendorf Formation, consists of a heterogeneous sequence of lenticular clays, muddy sands, clean sands, and pebbly sands. The clay minerals are mainly kaolinite (Figure 4). Beds are lenticular, with continuities of 100 meters or less (Heron, 1958a). A lower unit is easily distinguished in the Cape Fear Valley.......

....This lower unit is essentially the one designated "Cape Fear" by Stephenson (1907). It is here proposed that the name be reaccepted for these basal Cretaceous beds of the Cape Fear River Valley.......As defined, the Cape Fear Formation rests on the crystalline basement. It is overlain by the Black Creek Formation in the Cape Fear River Valley (Figure 7). Conley (1962) described upper and lower Tuscaloosa units in Moore County, North Carolina. The lower unit is the up-dip extension of the Cape Fear Formation; here it is overlain by the Middendorf......Brown (1962, 1963) has recognized an unnamed Lower Cretaceous unit in the adjacent subsurface of northeastern North Carolina with which we correlate the Cape Fear Formation......

.....The Cape Fear pinches out against the Fall Line in Harnett and Moore Counties. It is presumed to thicken down-dip toward the fossiliferous marine lower Cretaceous of the coastal oil wells. It is estimated to be 15-70 meters thick where exposed in the Cape Fear River Valley."

"The name "Middendorf Phase" was first used by Sloan (1904, 1907, 1908) in South Carolina for sands and kaolin clays lying between the Hamburg and overlying Black Creek Formation "phases" .....Berry (1914) relegated the Middendorf to member rank in the Black Creek Formation. Cooke (1926) raised it back to formational rank and included within it the Patuxent (Hamburg) of South Carolina. In 1936, Cooke discarded the term Middendorf in favor of the Tuscaloosa. Dorf (1952) advocated a return to Middendorf Member of the Black Creek Formation. Heron (1958a, 1960) and Heron and Wheeler (1959, 1964) favored a formational rank for the Middendorf. We propose that the Middendorf Formation, defined by criteria established in the previous section, be readopted for these strata......

...The outcrop of the Middendorf approximately coincides with the Sandhills of the Carolinas.....Near Columbia, South Carolina, the Middendorf is overlapped by Eocene sediments (Bartlett, *et al.*, 1968). The Middendorf is estimated to be less than 70 meters thick where exposed. It is presumed to thicken seaward into the fossiliferous marine Cretaceous of the coastal wells."

Regardless of the general lack of fossils in these sediments, and the disagreement as to the formation names, they have been assigned an age of at least as old as Upper Cretaceous by the principal authors. This is the important point to be derived from the above quotations as concerns the time of last movement on the Jonesboro Fault.

Field Examination. Nonmarine sandstones, kaolinite clays and pebbley clayey sandstones of Conley's Upper Tuscaloosa formation (or Swift and Heron's Middendorf Formation) are well exposed at several locations close to the mapped Jonesboro Fault. (Positions 1, 2, 3 and 4 on the map.) The bedding at Positions 1 and 2 was verified to be essentially horizontal, as the bedding features are well exposed. (See Photos 1, 2, 3 and 4.) Measured sections at Positions 1, 2, 3 and 4 are shown on Figure 2. An excellent correlation is made between Positions 1, 2 and 3 and a good correlation is made from Position 3 to Position 4 which are located on either side of the projected location of the Jonesboro Fault. The fact that the bedding is horizontal, and that correlations can be carried across the fault projection, are evidence that the last movement on the fault occurred prior to deposition of the Cretaceous sediments.

Structure. The Cretaceous beds exhibit no deformational structures in the areas examined for this report. No joints were seen in the four good exposures where sections were measured. Of particular significance are the lack of joints or any other deformational features such as folding or slumping at Position 3 which is located on the surface projection of the Jonesboro Fault line. If even slight movement had occurred after deposition of the Cretaceous sediments some form of strain would be evident in this exposure. (See Photo 5.)

Soil and Vegetation. A buff to white colored, medium grained, sandy soil covers all of the flat topped ridges underlain by Cretaceous deposits in the area of this field examination. The soil is the same on either side of the Jonesboro Fault projection. From the exposures it is evident that the soil developed in situ from leaching and bleaching of the red sandstone. (See Photos 1 through 5.) The vegetation supported by this soil is not noticeably different on either side of the projected fault line.

Cretaceous - Tertiary Contact. The contact between Cretaceous and Tertiary deposits can be seen to be essentially horizontal as mapped by Conley. (See map.) Displacement of this contact by movement along the Jonesboro Fault after the Tertiary deposits were laid down would probably have resulted in a map pattern that would reveal such displacement.

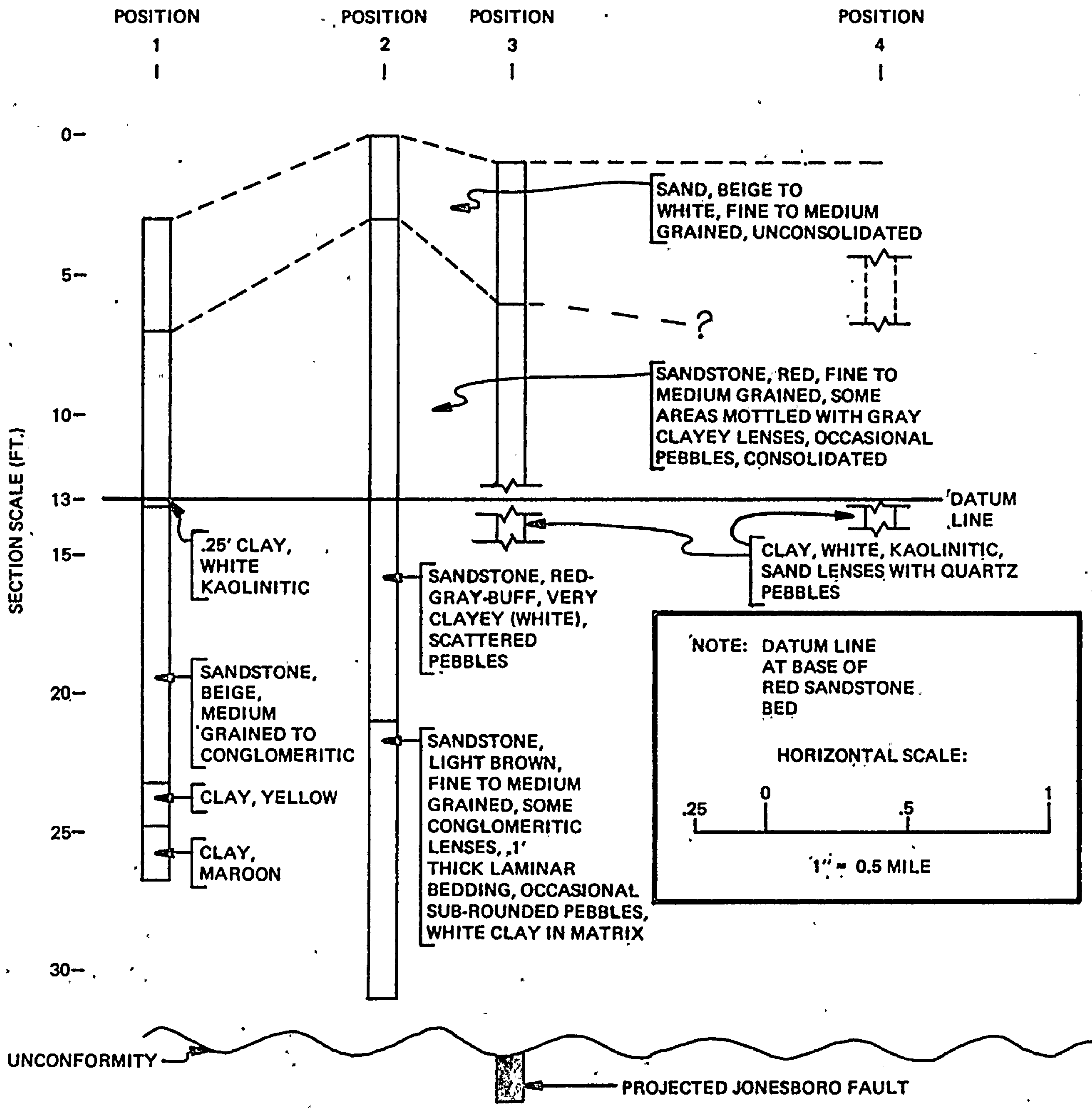


Figure 2
SECTION THROUGH POSITIONS 1–2–3–4

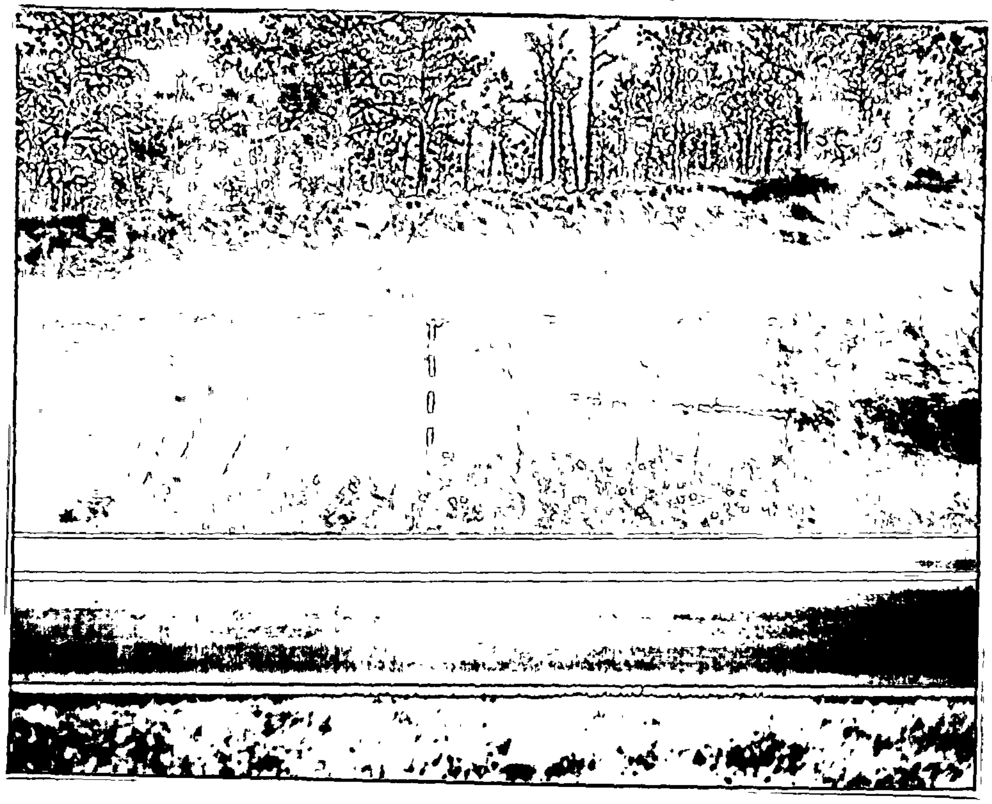


Photo 1

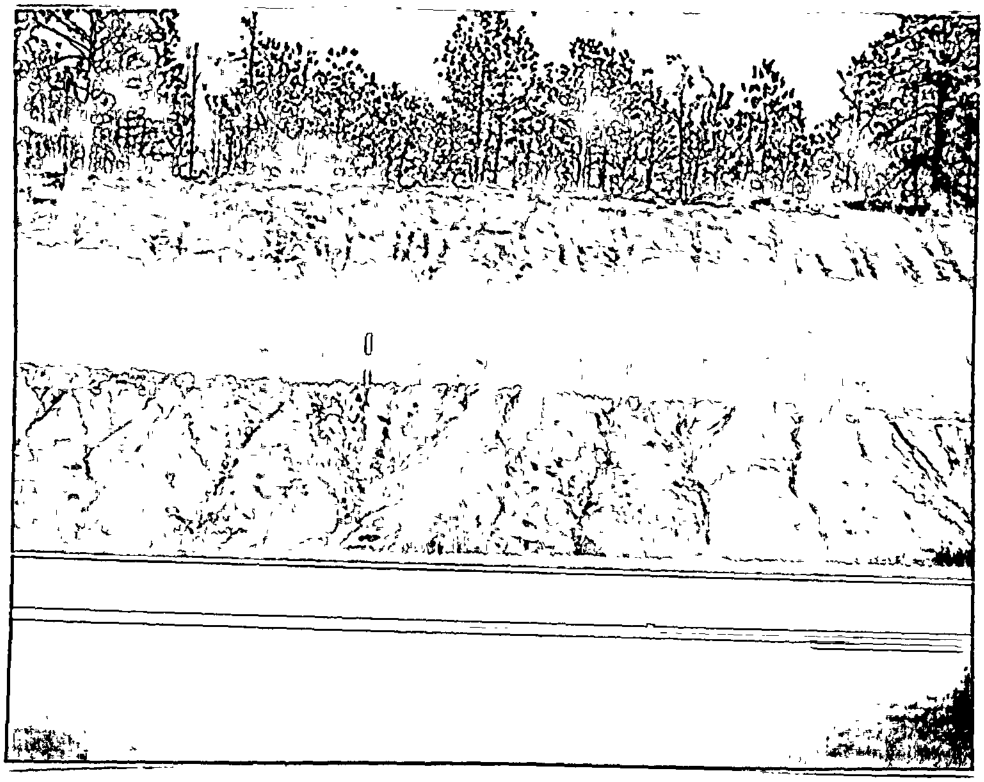
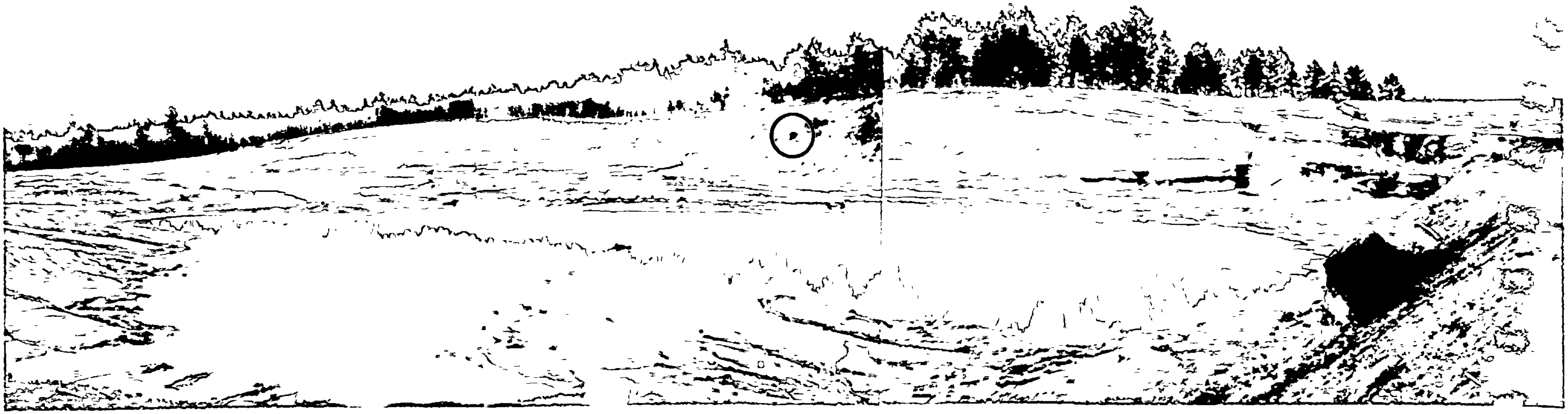


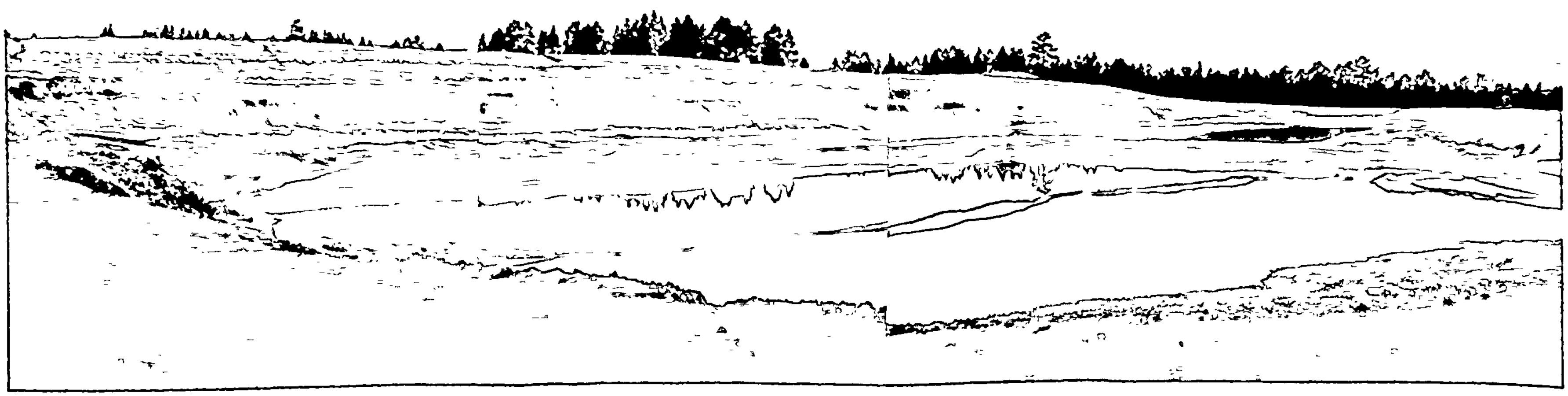
Photo 2

Photo 5 (C54-821, 1/75-Harris). Photograph at Position 3 showing the massive red sandstone unit of the Cretaceous deposit. Note the horizontal bedding and the lack of jointing. This exposure lies over the projection of the Jonesboro Fault.

Photos 3 and 4. Panoramic view looking towards the southwest of a fill excavation approximately 1/2 mile wide at this point. The section for Position 2 was measure at the area on which the man is seen on Photo 3. The photographs illustrate horizontal bedding of the Cretaceous deposits and the lack of deformational structures.



Photograph 3



Photograph 4

Photo 1 (C54-813, 1/75-Harris).Photograph at Position 1. Road cut on east side of Highway 15/501, south of Little River. Exposure shows horizontal bedding, buff colored residual sandy soil developed from the red sandstone and the clayey, pebbley sandstone underlying the massive red sandstone.

Photo 2 (C54-815, 1/75-Harris). Photograph at Position 1, approximately 100 feet south of Photo 1. Same description as Photo 1 except that this photo shows that the unit underlying the red sandstone contains more kaolinite clay and is therefore lighter in color.

Photo 5

QUESTION 5:

Provide numerical analyses to substantiate the statement, "it seems reasonable that a load of this magnitude could in no way present a threat to fault stability." As stated on p. VII-8.

RESPONSE:

Reservoir loading is one element which could effect the existing principal stresses in the plant area. The loading could increase, decrease or have no affect on the chances for reactivation of the fault depending on the factors of load magnitude, existing principal stresses, fault orientation, Poisson's ratio, pore pressures and the friction angle and cohesion of faulted material.

The existing state of stress, fault orientation and other factors are discussed in the fault investigation report. The report p. VII-8 points out that the previous loads of hundreds of feet of sediments did not reactivate the fault and therefore the small load of the Shearon - Harris reservoir would have nil affect. The following analysis illustrates what the reservoir loading would be at depth.

A conservative auxiliary reservoir pool depth of 30 feet was used to calculate load imposed on the auxiliary reservoir floor. Since the intensity of the vertical pressure on any horizontal section through the loaded soil decreases from a maximum at a point located directly beneath the load to zero at a very large distance from this point the pressure distribution can be represented by a bell - or dome - shaped space. See Terzaghi & Peck (1967).

Theory and experience has shown that the shape of the pressure bells is more or less independent of the physical properties of the loaded subgrade. Therefore, it is customary and justifiable to compute these stresses on the assumptions that the loaded material is elastic, homogeneous, and isotropic. It was therefore decided to use one of a set of equations known as Boussinesq's equations which determine the state of stress at point N. Most of the other components of stress at point N, in contrast to the vertical pressure Pv, depend to a large extent on the stress - deformation characteristics of the loaded material. Since the material found in the auxiliary reservoir area are not even approximately elastic and homogeneous, the other stress equations of Boussinesq are not so generally suitable. The equation used was as follows:

$$P_V = \frac{3Q}{2\pi z^2}\left[\frac{1}{1+(r/z)^2}\right]^{5/2}$$

Where: P_v = vertical component of stress
Q = concentrated vertical load
Z = vertical distance between N and surface of the mass
r = horizontal distance from N to the line of action of the load

The loaded area can be assumed horizontal and the load (reservoir water) to be shapeless and infinite. For calculation purposes a loaded area of 1 square foot was assumed with a column of water 30 feet in height resting on that area. Therefore Q was computed as shown:

Q = pwAh
pw = density of water
A = area
h = depth of water
Q = (62.4 lb/ft^3) (1 ft^2) (30 ft)
Q = 1872 lb

A series of depths and horizontal distances were picked arbitrarily to a depth of 10,000 feet. The following calculations illustrate the pressure distribution from one loaded area:

① $z = 10'$, $r = 0$

$$P_v = \frac{3(1872)}{2(3.14)(10)^2}\left[\frac{1}{1+(0/10)^2}\right]^{5/2} = 8.94 \text{ lb/ft}^2$$

$z = 10'$, $r = 10'$

$$P_v = \frac{3(1872)}{2(3.14)(10)^2}\left[\frac{1}{1+(10/10)^2}\right]^{5/2} = 3.16 \text{ lb/ft}^2$$

② $z = 500'$, $r = 0$

$$P_v = \frac{3(1872)}{2(3.14)(500)^2}\left[\frac{1}{1+(0/500)^2}\right]^{5/2} = 0.0036 \text{ lb/ft}^2$$

$z = 500'$, $r = 500'$

$$P_v = \frac{3(1872)}{2(3.14)(500)^2}\left[\frac{1}{1+(500/500)^2}\right]^{5/2} = 0.0013 \text{ lb/ft}^2$$

③ $z = 5000'$, $r = 0$

$$P_v = \frac{3(1872)}{2(3.14)(5000)^2}\left[\frac{1}{1+(0/5000)^2}\right]^{5/2} = 0.00036 \text{ lb/ft}^2$$

④ $z = 10{,}000'$, $r = 0$

$$P_v = \frac{3(1872)}{2(3.14)(10{,}000)^2}\left[\frac{1}{1+(0/10{,}000)^2}\right]^{5/2} = 0.0000089 \text{ lb/ft}^2$$

As indicated by the calculations the load imposed at the surface decreases rapidly when transferred downward. Since the reservoir is widespread there is an infinite number of point loads and thus the r = o case seems to be most applicable. Stress increments of less than 0.000036 lb/ft^2 can hardly be expected to alter existing conditions at a depth of one mile where the unit weight of overlying materials impose pressures of the order of 900,000 lb/ft^2 $p = (150\ lb/ft^3)\ (6000\ ft)$.

QUESTION 6:

Provide numerical analyses to substantiate the contention made regarding cohesion and pore pressure development along the fault plane as stated on p. VIII-4.

RESPONSE:

The fault plane is coated with clay, whereas sheared clay, soft brecciated siltstone and fractured sandstone are mixed throughout the broader fault zone. The value of cohesion is related to the maximum effective stress to which the soil has been subjected in the past, and will dominate over friction in the clay coating the fault plane. Pore water pressure is an important factor in the friction component, especially in brecciated materials in the fault gouge. The friction component can be altered with a change in pore water pressure.

Pore pressures as well as loadings have been much greater in the past than will be imposed by the new reservoir, of 30 feet maximum head. Section VI-15 of the Fault Investigation Report describes remnants of a sedimentary deposit which have overlain the fault to a presumed depth of some 400 feet. Groundwater levels in these sediments surely imposed greater pore pressures on the fault without reactivation than would be imposed by the planned reservoir. There will be in fact no added increment of the pore pressure in the fault plane over the area explored above present values consequential to impoundment of the reservoir. Groundwater elevations in much of the terrain traversed by the fault are presently higher than the proposed reservoir level, and the fault zone materials are saturated.

Despite the fact that the reservoir could not impose pore pressures greater than past or present levels a conservative assumption was made that an added water depth of 30 feet would be imposed on the existing groundwater level. This increment of water imposed instantaneously on the reservoir floor would be (30. feet) (62.4 lb/ft^3)/144 = 13 lb/in^2. This pressure could be induced at all points along the saturated fault zone. The hydrostatic pressure at an assumed minimum possible earthquake focal depth of 6000 feet would be (6000 ft) 62.4 lb/ft^3/144 =2600 lb/in^2. Therefore the increase of 13 lb/in^2 would increase the pressure one half of one percent at that depth.

Further evidence of the slight effect of this head increment is the result of the permeability tests performed at and adjacent to the fault. They indicate that at depths of 90 to 100 feet, pressures of 30 PSI were never capable of inducing absorption rates greater than 0.1 gallons per minute, and that pressures of even 70 to 90 PSI seldom produced an absorption above 0.5 gallons per minute. It may be inferred, therefore, that a pressure of 13 PSI would be insufficient to cause absorption of any consequence, even at depths of only 100 feet.

The relationships between reservoirs and seismic activity is a subject of continuing research. Lomnitz (1974) noted that "In the reports on fluid injection, hydrostatic pressures of the order of 100 bars were necessary to trigger earthquakes". He concluded that "tectonic environments likely to produce seismic effects due to reservoir impounding may share some of the following features: (a) They may be associated with steep gradients of the earth's relief; (b) they may be regions of residual heating in the lower crust of the earth, as expressed by hot springs and other post-volcanic manifestations."

The maximum hydrostatic pressure increase due to the site reservoir would be only 1 bar (as compared to 100 bars) and of course the Piedmont area of the proposed reservoir does not fit the description of a tectonic environment as described by Lomnitz.

QUESTION 7:

Provide all evidence available to support your statement that the site fault is overlain by undisturbed Pliocene strata.

RESPONSE:

The conclusion that the undisturbed sediments which overlie the fault should be included in the group mapped and described by Reinemund (1955) as "high-level surficial sand and gravel deposits of possible Pliocene age" is given on page VI-II of the Fault Investigation Report. The following describes augering completed to assess the distribution of these sediments where they overlie the fault.

A total of 21 continuous, 6 inch diameter, flight auger borings were drilled on December 18, 1974, to assist in the definition of extent of water laid sediments exposed in Trench FET-19W. The borings were located by pacing methods on an approximate 120 foot grid and ranged in depth between 4 and 15.5 feet. Disturbed cuttings samples spun off by the auger were visually inspected for evidence of stream sorting and deposition and logged in brief form according to Unified Soil Classification System Terminology.

Of the 21 borings, seven encountered an apparent basal layer containing rounded quartz pebbles immediately overlying bedrock and three encountered traces of clean uniform sand. This information, combined with the relatively deeper soil depths at these locations was judged to indicate continuations of the same High Level Surficial Deposit exposed in Trench FET-19W and limits were drawn accordingly (see accompanying location plan, Figure 3.)

Following are the brief logs of the borings:

FA-1

0'-4'	lean clay, yellowish/orng
4'-8'	silt to clay, grey/brown
8'-9'	lean clay, brown, containing few rounded quartz pebbles*
9'-13'	siltstone, red

FA-2

0'-3'	lean clay, yellow/orng
3'-6'	silt, tan to grey
6'-7'	lean clay, yellow/brn
7'-8'	lean clay, gritty, containing few rounded quartz pebbles*
8'-12'	siltstone, red

FA-3

0'-5'	silt to clay, yellow/orng
5'-6'	silt, trace of free, clean uniform sand**
6'-8'	siltstone, red

FA-4

0'-9'	lean clay, yellow/orng trace of free, clean, uniform sand at 7.5'**
9'-11'	siltstone, red

FA-5
0'-7' lean clay, yellowish/orng
7'-8' silt to clay, light grey trace rounded gravel.*
8'-8.5 siltstone, red

FA-6
0'-2' clayey sand, yellow/orng
2'-6' silt to clay, yellow/br
6'-9' silt to clay, trace of free clean sand at 7'**
9'-10' siltstone, red

FA-7
1'-3' clayey sand, yellow/or
3'-4' silt
4'-5' lean clay
5'-7' silt, gritty & trace of rounded gravel 6.5'-7.0'*
7'-8.5 siltstone, red

FA-8
0'-1.5 silty sand, yellow/br some angular gravel
1.5-3' lean clay, yellow/orng
3'-6' siltstone, red

FA-9
0'-2' silty sand, yellow/br some gravel
2'-5' lean clay, gritty with trace rounded gravel toward bottom*
5'-7' siltstone, red

FA-10
0'-3' silt, slightly clayey
3'-4' siltstone, red

FA-11
0'-2' silt to clay, yellow/orng
2'-3' lean clay, red/orng
3'-4' siltstone, red

FA-12
0'-2' lean clay, yellow/orng
2'-3' silt, yellow/or
3'-6' lean clay, mottled with grey
6'-7' silty sand, some rounded gravel*
7-7.5' siltstone, red

FA-13
0'-3' silt, yellow/orng
3'-6' siltstone, red

FA-14
0'-3' silt, yellow/orng
3'-4' siltstone, red

FA-15
0'-8' silt to clay
8'-9' clayey sand, grey, gravelly
9-9.5' clayey sand, yellow/br, gravely
9.5-12 silt, tan
12-15.5 siltstone, red

FA-16
0'-3' silt
3'-4' siltstone, red

FA-17
0'-3' silt to clay
3-7.5' siltstone, red

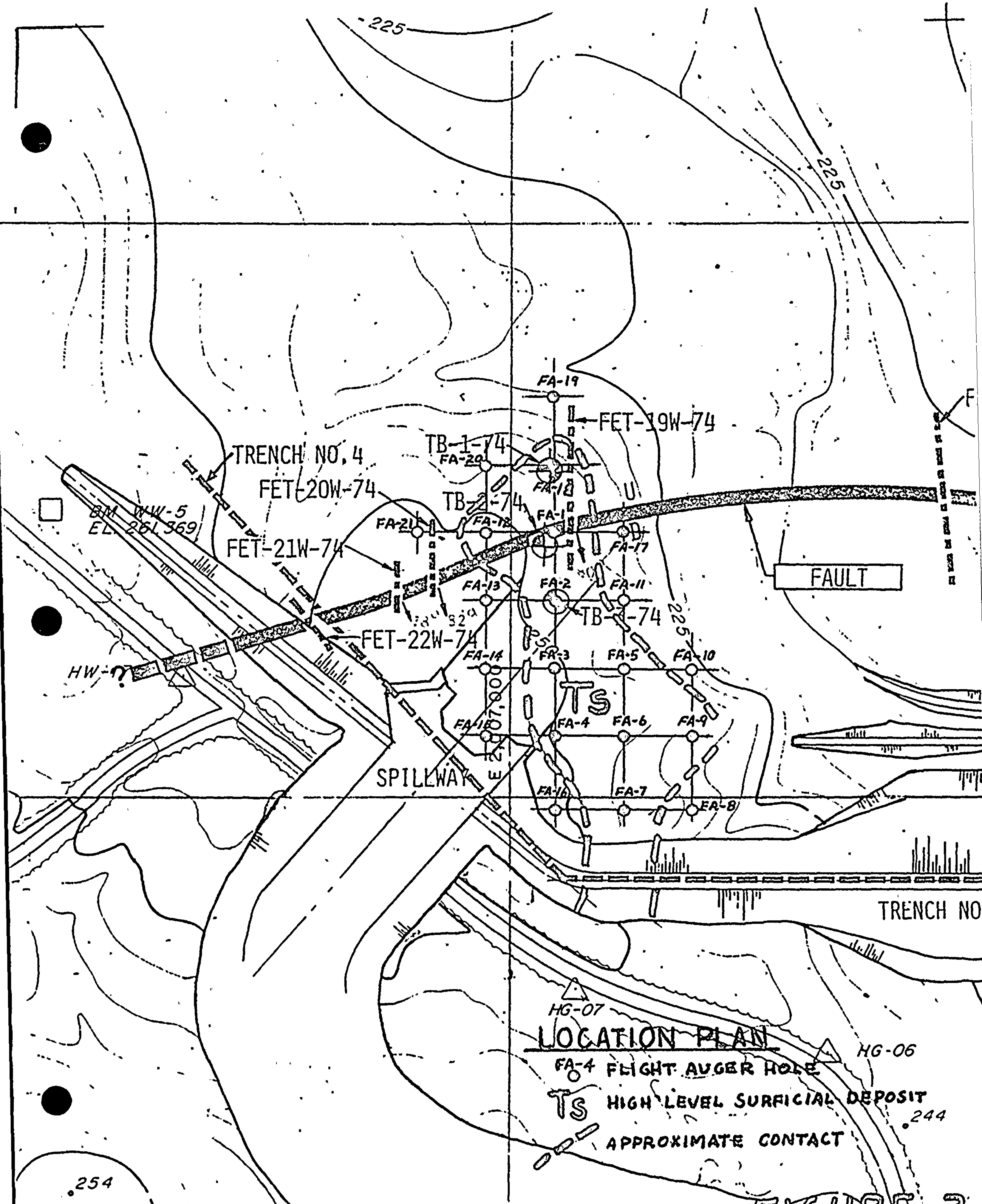
FA-18
0'-5' lean clay
5'-6' silt
6'-7' lean clay to clayey sand
7'-8' clayey sand, with rounded gravel*
8'-10' siltstone, red

FA-19
0'-1' silt
1'-3' lean clay, yellow/br
3'-5' lean clay, yellow/br with grey mottle
5'-8' silty sandstone, red

FA-20
0'-2' lean clay, yellow/orng
2'-4' lean clay, yellow/orng
4'-6' siltstone, red

FA-21
0'-2' clayey sand, yellow/orng
2'-4' silt, yellow/tan
4'-6' siltstone, red

* similar basal layer to that exposed in Trench FET-19W
** Free sand judged to be indicative of the small pockets and lenses of clean uniform sand exposed in Trench FET-19W



225
TRENCH NO. 4
BM WW-5
EL 261.369
FET-20W-74
FET-21W-74
FET-22W-74
FET-19W-74
TB-1-74
TB-2-74
FA-19
FA-20
FA-12
FA-21
FA-18
FA-1
FA-17
FA-13
FA-2
FA-11
FA-14
FA-3
FA-5
FA-10
FA-15
FA-4
FA-6
FA-9
FA-16
FA-7
FA-8
FAULT
Ts
SPILLWAY
HW-?
TRENCH NO
HG-07
HG-06
.244
.254
LOCATION PLAN
FA-4 FLIGHT AUGER HOLE
Ts HIGH LEVEL SURFICIAL DEPOSIT
APPROXIMATE CONTACT

FIGURE 3

QUESTION 8:

Discuss the significance to age-dating the site fault of your statement on page II - 7 that the saprolite developed in diabase overlying the fault is undisturbed by shearing movement. Document the evidence for your statement.

RESPONSE:

Page VI-8 of the Fault Investigation Report documents the evidence indicating the unsheared nature of saprolite, over 35 feet thick, which has formed at East Dike 2 during some period since last movement on the fault. An estimate of the time required for the saprolite to form is based on weathering rates at another location as discussed on page VI-9. See Photos I and J in the Report which document the unsheared nature of the saprolite.

QUESTION 9:

Does the granitic pluton cross-cut the Jonesboro Fault? What is the age of this intrusive and what is its relationship to the Jonesboro Fault?

RESPONSE:

Three samples of intrusive rocks near the Jonesboro Fault were obtained on 27 May, 1975. These samples were provided to Teledyne Isotopes for potassium - argon age determinations. The results of these age determinations are appended hereto in the form of a letter report dated 3 June, 1975, by Teledyne Isotopes.

The three samples were selected on the basis of location relative to the Jonesboro Fault and on the basis of apparent intensity of deformation and alteration of the intrusive rock bodies. Sample 1. was from a drilled core obtained during the investigation of the main dam foundation. In hand specimen this sample appeared to be the most highly altered of the three samples taken. Sample 2. was taken from a prominent outcrop along State Road 1119 southeast of the Shearon Harris Site and represents the intrusive body identified in gravity and airborne magnetics as that which could cross-cut the Jonesboro Fault and intrude into the Triassic - Jurassic Basin sediments. Sample 3. was taken from an abandoned rock quarry on the left bank of the Cape Fear River at Buckhorn Dam. Samples 2. and 3. do not appear to be altered in hand specimen. By virtue of appearance and degree of alteration it would have been expected that Sample 1. would have represented the oldest rock and Samples 2. and 3. some younger intrusive.

The actual ages obtained are as follows:

Sample 1., 238 m. y. ± 32 m. y.
Sample 2., 290 m. y. ± 23 m. y.
Sample 3., 256 m. y. ± 13 m. y.

The significance of these three age dates is the straightforward indication that the rock bodies are pre - Triassic in age and that reset of the biotite and hornblende constituents has occurred. These ages offer further substantiation for a protracted thermal event subsequent to the intrusion of the igneous rocks. It is commonly agreed that reset reducing biotite ages can occur in the 200° to 300° C. range. Sample 1., which geologically seems clearly to be

the older rock, yields the younger age.

The dating of these samples clearly indicates that one of two conditions prevail.

(1) The intrusive plutonic rock body southeast of the Shearon Harris Site forms a geometric key into the Triassic - Jurassic sediments but is older than these sediments. If this is correct, virtually all movement on the Jonesboro Fault is vertical and normal. The tight cluster of linear features shown on Plate C.10 and other Plates of the remote sensing section of the Fault Investigation Report may represent fracture patterns associated with relatively small right lateral displacement along the Jonesboro Fault which took place late in the history of movement and broke up the Triassic - Jurassic rocks adjacent to the keyed igneous intrusive body.

(2) The "key" does not really exist as indicated in the somewhat sparse gravity point data and lateral movement on the Jonesboro Fault may have occurred subsequent to the deposition of the exposed Triassic - Jurassic sediments unhindered by any keying effect.

It is concluded that the intrusive rocks predate Triassic - Jurassic sedimentation. If the igneous body keys into the Triassic sediments almost all movement on the Jonesboro Fault is vertical and normal with only minor late right lateral displacement. It may be that the key effect as it appears in some geophysical data is spurious.

TELEDYNE ISOTOPES
WESTWOOD LABORATORIES
50 VAN BUREN AVENUE
WESTWOOD, NEW JERSEY 07675
(201) 664-7070 TELEX 134474

3 June 1975

Mr. Norman Tilford
Ebasco Services, Inc.
P. O. Box 186
Liberty, North Carolina 27298

Dear Mr. Tilford: Re: W. O. #3-3806-212

The analytical data for the rocks you submitted to us for age determination are as follows:

T.I. No.	Ebasco No.	Age (m.y.)	Ar^{40}Rad(sccx10^{-5})	% Ar^{40}Rad	% K
KA75-267	#1 Heavy mineral separate	235 ± 32	2.46 2.03	70.2 80.0	2.22 2.21
KA75-268	#2 Biotite separate	290 ± 23	4.10 4.59	81.2 83.6	3.45 3.47
KA75-269	#3 Biotite separate	256 ± 13	5.19 4.97	82.2 52.9	4.63 4.61

The constants used for the calculations of the isotopic ages are: $\lambda_\beta = 4.72 \times 10^{-10}\ yr^{-1}$, $\lambda_\epsilon = 0.585 \times 10^{-10}\ yr^{-1}$, and K40 = 1.19×10^{-4} atom percent of potassium. The errors stated are the standard deviation for replicate determinations except for sample #3 for which a minimum system error of 5 percent is stated even though the precision of the analytical results was about 3 percent.

Sample #1 had very little biotite. The material analyzed was that obtained from a repeated heavy liquid separation. The material was probably a mixture of hornblende with some biotite present as indicated by the potassium content which is higher than would be expected for pure hornblende. For samples #2 and #3, biotite was visible in the rock and separation on a vibrating table combined with heavy liquids was possible although a completely pure biotite was not obtained as indicated by the potassium contents. In all three specimens feldspar should be absent as a result of heavy liquid separation, so the impurities present should be low in potassium and have little effect on the age determination. The alteration in Sample #1 may indicate some argon loss.

Although distinct ages may be represented by the three specimens, the data taken together are consistent with an age of 260 ± 27 m.y. One would be more comfortable with closer agreement between the samples, but the rock body dated does appear to be definitely older than the dike swarm in the area which was found to be about 220 ± 24 m.y. Certainly the pluton does not post date the fault which intersects the dikes. Perhaps with your better knowledge of the

geology of the area and the location of the samples you can come up with a more satisfactory interpretation of the data.

Yours truly,

Donald F. Schutz
Vice President
Manager Westwood Laboratories

DFS:mm

QUESTION 10:

Describe the fault zone that penetrates the right abutment of the auxiliary dam and assess the stability and leakage hazard it presents. Describe the treatment (such as grouting) planned for this zone.

RESPONSE:

The fault zone that penetrates the right abutment of the Auxilliary Dam is well exposed in Trench FET-22W, located at the upstream toe of the dam, and immediately to the east in Trenches FET-21W, 20W and 19W. (See Photographs L, M and N and Plate 5 of the Fault Investigation Report. The trench exposures at these locations invariably showed a blanket of several feet of residual clay soil overlying deeply weathered bedrock. Within this zone of deep weathering or saprolite, fault associated joints, fractures and shear planes were observed to be of restricted permeability as a result of secondary clay fillings which accumulated during the weathering process.

At depth beneath the dam the fault zone can be expected to be similar to that explored by boring FT-2-74, located adjacent to Trench FET-19W some 500 feet to the east of the dam. In this boring, water pressure testing within the fault zone produced maximum permeability values of 10^{-4} cm/sec., a typical value for the silty sand cores of many operating earth dams.

The topography and drainage developed in the terrain traversed by the fault is not influenced by the presence of the fault acting as a groundwater conduit. This furnishes evidence at the geological time-span scale that the fault has not transmitted any appreciable quantities of water during past or present regimes.

The low, 7 foot high, operating head resulting from a normal pool elevation of 252 feet and the long seepage path through the abutment along the fault zone further support our conclusion that there is no leakage hazard along the fault zone.

The low embankment height of ± 15 feet and the high angle of intersection with the plane of the fault suggests low, relatively uniform loading on both sides of the fault and supports our conclusion that there is no stability hazard within the foundation as a consequence of the fault.

A further factor of safety against such hazards will be provided during construction when geologic mapping of the core trench and dam foundation will be completed. Along with normal documentation mapping, specific attention will be directed to the fault zone area where the potential for leakage and instability will again be considered. Borings will be drilled and water tested on reduced spacings through the fault zone and grouting will be conducted during the specified curtain and consolidation grouting programs as required.

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