SOUTHEASTERN GEOLOGY

PUBLISHED AT DUKE UNIVERSITY DURHAM, NORTH CAROLINA

VOL. 26, NO. 1 AUGUST, 1985

SOUTHEASTERN GEOLOGY

PUBLISHED QUARTERLY

AT

DUKE UNIVERSITY

Editor in Chief:
S. Duncan Heron, Jr.

Managing Editor:
James W. Clarke

This journal welcomes original papers on all phases of geology, geophysics, and geochemistry as related to the Southeast. Transmit manuscripts to S. DUNCAN HERON, JR., BOX 6729, COLLEGE STATION, DURHAM, NORTH CAROLINA 27708. Observe the following:

1) Type the manuscript with double space lines and submit in duplicate.
2) Cite references and prepare bibliographic lists in accordance with the method found within the pages of this journal.
3) Submit line drawings and complex tables as finished copy.
4) Make certain that all photographs are sharp, clear, and of good contrast.
5) Stratigraphic terminology should abide by the North American Stratigraphic Code (Am. Assoc. Petroleum Geologists Bulletin, v. 67, p. 841-875).

Proofs will be sent authors.

Reprints must be ordered prior to publication; prices available upon request. Subscriptions to Southeastern Geology are $9.00 per volume (US and Canada), $11.00 per volume (foreign). Inquiries should be sent to: SOUTHEASTERN GEOLOGY, BOX 6729, COLLEGE STATION, DURHAM, NORTH CAROLINA 27708. Make checks payable to: Southeastern Geology.

SOUTHEASTERN GEOLOGY

Table of Contents

Vol. 26, No. 1

August, 1985

EVALUATION OF THE BEECH GROVE LINEAMENT AND FACTORS CONTROLLING STREAM ALIGNMENTS IN CENTRAL TENNESSEE

ARTHUR L. REESMAN
RICHARD G. STEARNS

Department of Geology, Vanderbilt University, Nashville, Tennessee 37235

ABSTRACT

The Beech Grove Lineament (BGL) was detected from Landsat imagery. It comprises nine separate stream valleys that form a remarkably straight 96-mile-long feature trending N 21°E. Originally, the lineament was assumed to be tectonically controlled. However, no evidence for structural control has been found during subsequent studies of joints, drilling by mineral exploration groups, and mine development in the Middle Tennessee Zinc District. There may be more than one cause for this feature. The northern 21-mile reach may be tectonically controlled judging from its parallelism to gravity and magnetic anomalies, and proximity to mineralization. The central 38-mile reach, which is the most striking on imagery, is not tectonic. It is believed to result from superimposed straight streams originally controlled by the strike of cuestas, developed during the erosion of now removed Pennsylvanian age sandstones and shales. In this area, stream capture has probably cut an original pair of streams into four. The southern portion of the BGL also may have resulted from superimposed drainage but evidence for such control is poor. It might be only a fortuitous alignment.

The BGL does not appear to be as uniquie as a cursory interpretation of Landsat imagery might suggest. Other straight and/or aligned stream valleys are equally well defined on topographic maps but are less obvious on Landsat imagery. Twelve other lineaments with lengths over 20 miles were defined from topographic maps and some of these are interpreted as probably tectonic, some not. Evidence considered for these include: presence or absence of nearby parallel joints, geophysical anomalies, and mineral prospects. The most certain cases for tectonic lineaments are the Stones River and Hickman Creek Lineaments.

INTRODUCTION

The Beech Grove Lineament (BGL) is probably the most striking linear feature visible on satellite imagery in central Tennessee. It was noticed and first described by Hollyday, Moore, and Burchett (1973) from ERTS (renamed Landsat) imagery. They defined it from the alignment of nine separate stream valleys. The feature is enhanced on the imagery as a result of agricultural cultivation in an otherwise wooded area. This nearly linear feature extends for about 90 miles in a N 21°E orientation across the eastern portion of the Central Basin of Tennessee (Figures 1, 2, and 3). A disturbed zone in the Catheys, Chattanooga, and Fort Payne Formations was discovered by Hollyday, and others (1973) in a cut along Interstate 24 at Beech Grove.

Hollyday and others (1973) and later Moore and Hollyday (1976) were primarily interested in the relationship of the lineament to the occurrence of ground water in its vicinity. In the earlier paper they concluded: 1) that there was a concentration of karst features (sink holes and caves) near the lineament, 2) that low-flow investigations revealed anomalous flows of streams in the vicinity of the lineament that could possibly be explained by movement of ground water from one stream basin to another along or near the lineament, and 3) that the occurrence of sphalerite veins near the central portion of the lineament, and at the Jersey Miniere's Elmwood Mine (30 miles to the north but very near the lineament), may have resulted from precipitation of mineralizing solutions conducted along fractures related to the lineament.

Because the BGL is such a striking feature on Landsat imagery and because its

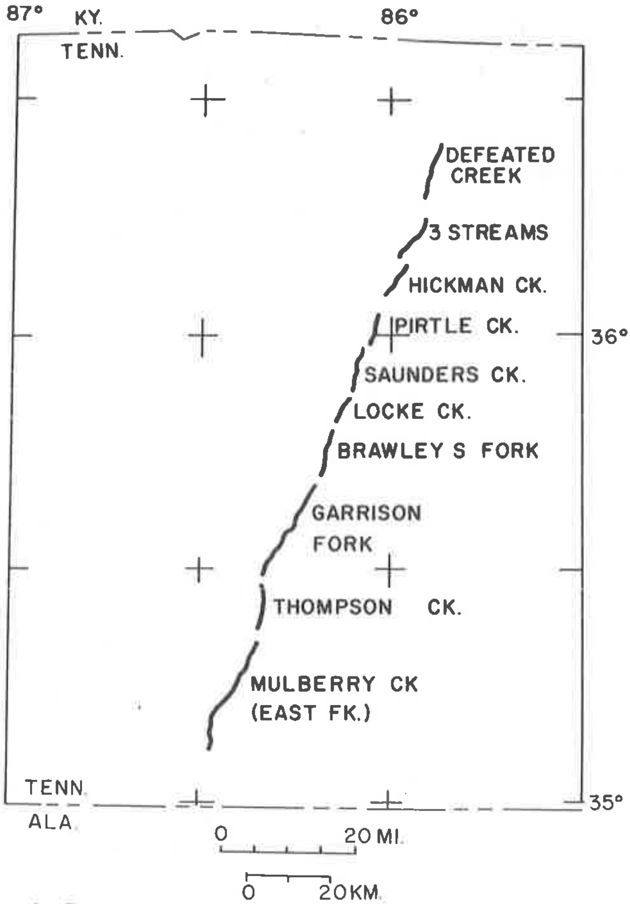

Figure 1. The Beech Grove Lineament coomprises nine stream valleys as defined by its discoverers, Hollyday, Moore, and Burchett (1973). The most striking portions on the Landsat image are northern Garrison, Brawleys, Locke, and Saunders Creeks (see Figure 2).

trace occurs about 11 miles east of the then-proposed site of a nuclear power plant near Hartsville, Tennessee, the Nuclear Regulatory Commission directed the Tennessee Valley Authority (TVA) to determine the significance of the lineament (the site actually has been deferred and may be abandoned). With the exception of the disturbance near Beech Grove and a small mapped fault on Locke Creek (one of the nine creeks on the lineament), there was no previously known structure related to the linement.

After an intensive study utilizing Landsat and other imagery, gravity, aeromagnetic, and structure contour maps, seismic information and field investigations, which included mapping, joint studies, and trenching, the TVA (1975) concluded that the BGL was not a fault or fault zone and that there was doubt that it represented any type of geologic feature. They believed that only 18 to 20 miles of the feature should be considered to have much validity and that to extend the feature 80 or so miles farther, would require that the lineament pass through valleys which were not parallel to its supposedly straight course. They also pointed out that there were very few joints parallel to the lineament. This report is unpublished in readily accessible literature, so it is mentioned here in some detail.

The evidence presented by the TVA refuted some of the findings by Hollyday, and others (1973). The karst and cave distribution does not seem to be related to the lineament, and an improved map contoured on the top of the Knox Formation by Manning and Statler (1975) did not show any offset or irregularities suggestive of

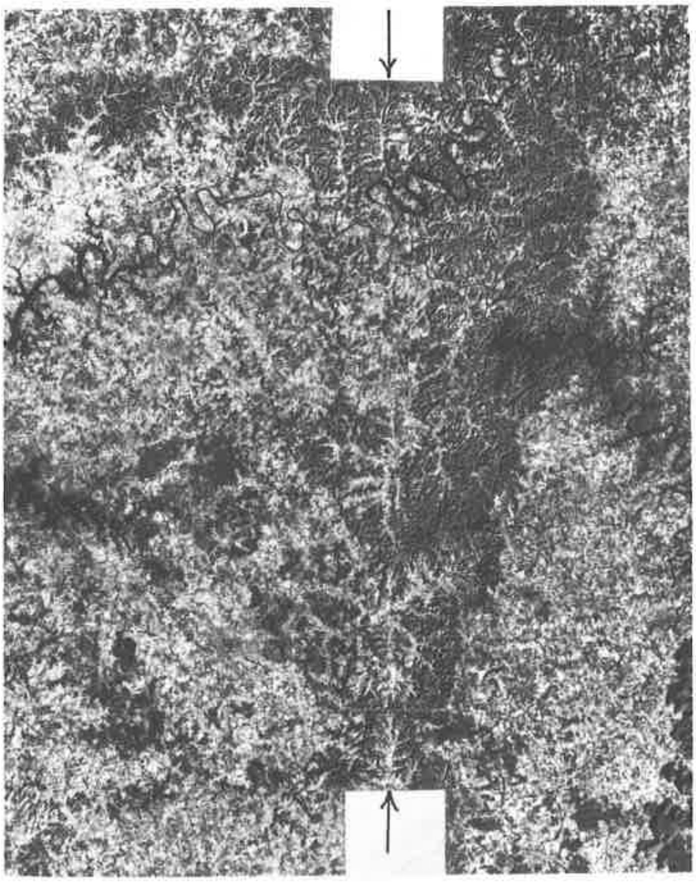

Figure 2. Part of a Landsat image (E-1086-15544, Nashville, TN, Nov. 16, 1975) showing the Beech Grove Lineament from the vicinity of Beech Grove to its northern end. The most striking part occupies the bottom half of this figure. Figure 3 shows geographic features and scale.

faulting. An alternative explanation for the disturbed zone in the cut at Beech Grove, offered by C. W. Wilson, Jr., who mapped the quadrangle, was included in the TVA report. He suggested that the disturbance resulted from solution-induced collapse which occurred in an area where there was intense weathering through the Fort Payne, Chattanooga, and Catheys Formations as well as solutional widening of joints in limestone of the underlying Bigby Formation. As a result, he postulated that parts of the three overlying formations might have slumped or collapsed into the widened joints. This disturbed area is near the drainage divide between the Duck River (as represented by Garrison Fork) and Stones River Basins, where the maximum effects of vertical leaching would be expected. Deep and intense weathering may well be a feature of a fracture zone. Thus, Wilson's explanation is compatible with a lengthy fracture zone potentially extending beyond the smaller area of observed fracturing. A lack of a satisfactory alternative explanation has kept open the possibility of a tectonic origin.

Since 1975, additional information has emerged including more detailed gravity, magnetic and structure maps. Despite the conclusions of the earlier TVA studies, our assessment was that the lineament merits further study. This paper reconsiders the lineament in order to clarify its nature and origin. The lineament is drawn in as much detail as possible and re-evaluated in terms of its relationship to geological and geophysical features, and other possible lineations. We then attempt to re-interpret its origin.

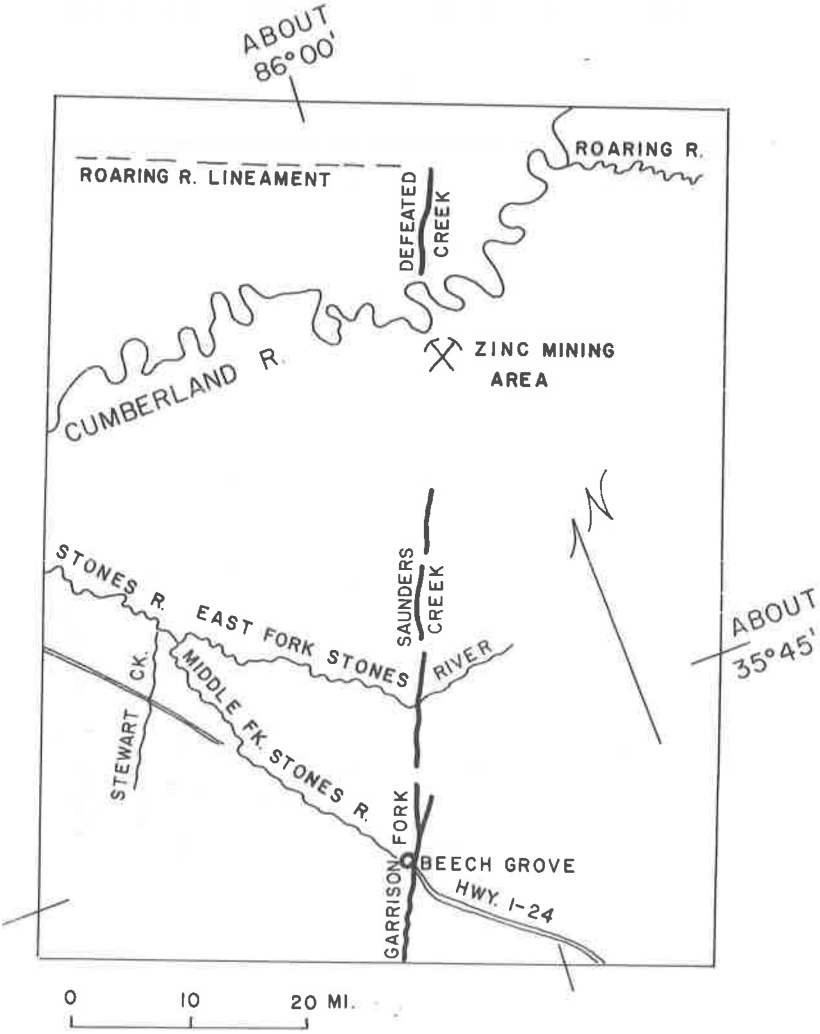

Figure 3. Lineaments and geographic references for the image shown on Figure 2.

RE-EVALUATION OF THE BEECH GROVE LINEAMENT

General

When viewed on Landsat imagery (Figure 2), the Beech Grove Lineament is obvious for over half of its length. Thus, we rule out the hypothesis that it is fictitious. We present four possibilities to explain its occurrence. First, it may result from a fortuitous alignment of streams. Second, it could be a lengthy structural feature (trace of a fracture system). Third, it might consist of remnants of a major stream that originally followed a rectilinear course, subsequently disarranged by stream piracy. Lastly, combinations of the above, including the possibility that imagination may fill in some of the less obvious portions of the linear; thus it may have both "real" and "imaginary" components.

Continuous Trace

To begin re-examination, the lineament was drawn in as much detail as possible

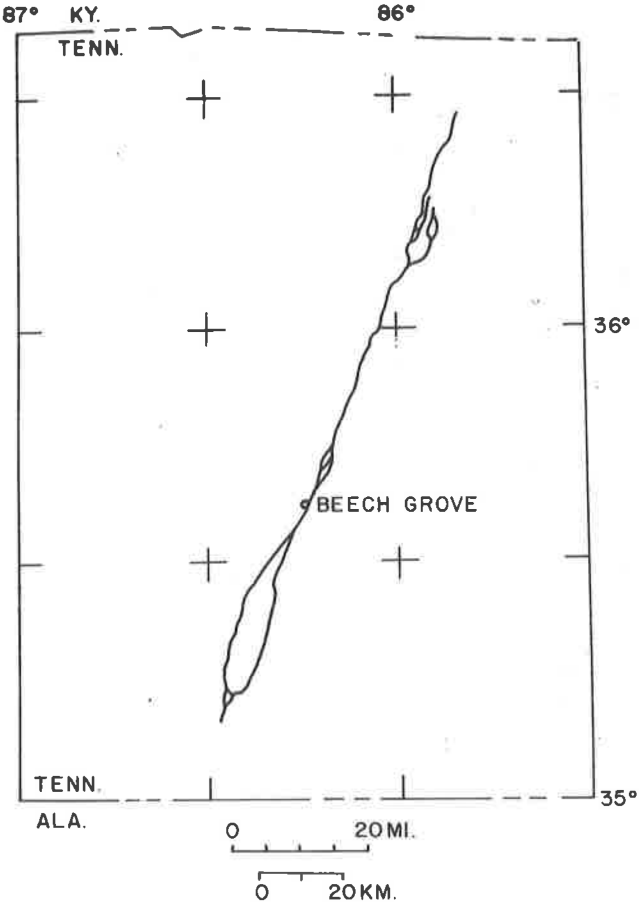

Figure 4. The Beech Grove Lineament drawn as a continuous trace using the streams on Figure 1 plus gaps in drainage divides between them. Some alternate locations are equally likely. The "snarl" of stream courses near 36°15' is referred to as the "Gordonsville Knot".

following the trend suggested by Hollyday, and others (1973) (Figure 1). In this approach, it was assumed to be a continuous, though not necessarily straight, feature. If the lineament passed along stream valleys because erosion is favored along straight zones, it should also pass through gaps, or low places in divides, between stream basins close to the same line because erosion should also be favored there. As drawn in Figure 4, the resulting feature is a continuous trace defined by topographic lows including the nine stream segments plus the interconnecting gaps in drainage divides. To aid in drawing the lineament both Landsat imagery and hyperaltitude photographs were used together with 1/24,000-scale topographic maps. This version has no specific geologic significance, but it results in a clearly defined lineament. We believe that the trace we have described, along and between the nine valleys, is objective and reproducible. Other versions have been drawn using other working hypotheses.

This continuous-trace version is slightly sinuous where it crosses divides between the nine stream valleys. In extending the most probable course across divides, alternate paths or gaps were observed where more than one valley heads on opposite sides of the divide. An example is shown on Figure 4 between the Duck and Stones basins at about 35° 40' N (north of Beech Grove at the head of Garrison Fork). Here, there are three possible courses. The most complex area is the tangle of alternate paths at about 36° 15' N near Gordonsville. This area is referred to hereafter as the "Gordonsville Knot."

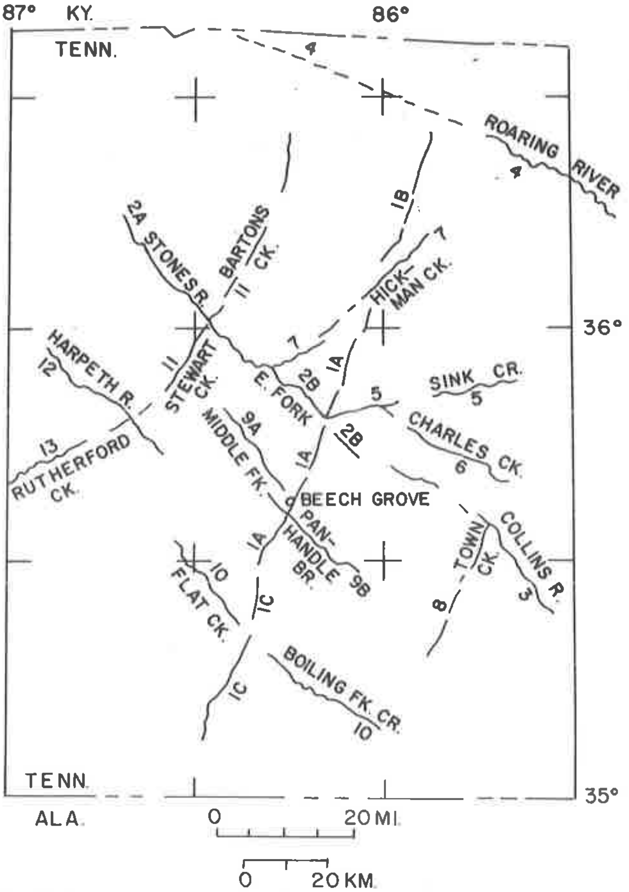

Figure 5. Straight stream segments in the vicinity of the Beech Grove Lineament. These are at least 20 miles long and are derived from streams on 1:250,000-scale topographic maps. It appears that the Beech Grove is not unique.

To measure the straightness of the lineament, a straight line was drawn from its north to its south end. This line is 96 miles long and trends N 21°E. The trace of the continuous lineament departs an average of 2400 ($\pm$ 2470 feet) from the straight line. A slightly better fit could be obtained by shifting the entire line eastward and rotating it counter-clockwise a fraction of a degree. A least-squares, best-fit line was not run, but we believe it would probably exhibit an average departure of about 2000 feet over the 96-mile length. The reason to consider the deviation of the lineament from a straight line is to gain a preliminary estimate of a potential width of a causative zone of fracture concentration, assuming that the BGL is structurally-controlled. Meaningful outcrops, wells, geophysical gradients, and parallel fractures or other structures logically might be sought not only on the lineament as drawn but within a band roughly as wide as the deviation.

The Beech Grove Lineament and Other Linear Features

Hollyday, Burchett, Moore and others (personal communications) prepared lineament overlays from ERTS false color image, frame E-1086-15544 (Nashville, TN). Using the same image, different observers plotted different linear features. Generally when two or more (even all) agreed on a feature, its length would be different. Some plotted only straight linears, whereas others included curvilinear and more or less circular features. The results were a mixture of objective and subjective interpretations.

Moore (1976) plotted several lineaments from Skylab photographs to compare with lineaments drawn from Landsat imagery. Only a few of the lineaments were found by this experienced observer to be present on both, and the lengths and/or continuity of the matching lineaments differed. The four main reasons advanced by Moore for the differences in lineament expression are: differences in resolution, spectral response, time of the year, and sun angle. The images and the observer's perception of them both are different.

Recognizing the biases inherent in the use of imagery, we were reluctant to use image interpretation as a sole basis for the development of a regional system of potentially related features. In the spirit of the descriptive definition of Hollyday, and others (1973) of the BGL as straight and aligned stream courses, we looked for streams in a more complete source: topographic maps. Although made from photographs, much ground checking minimizes bias in the mapping, and hopefully will minimize bias in the selection of straight and aligned streams. Maybe alignments based on streams alone merit comparison with the BGL, and perhaps collectively they related to the origin of the BGL.

In central Tennessee, straight stream segments with a length of 20 miles or greater were compiled from 1:250,000-scale (or two degree) topographic maps. For this compilation, first all streams were drawn; then the 20-mile straight segments were abstracted. Figure 5 shows the resulting map. There are 12 such segments including the BGL. Notice that the lineament is discontinous when drawn this way. It breaks up just north of 36 degrees latitude at the "Gordonsville Knot" which is described in detail later.

After finding these trends they were located on the ERTS false color image on which the Beech Grove is so well displayed (some are marked on Figure 3). Indeed, the linears were visible on the ERTS image as linear trends; but the longest one (Stones River Lineament, 55 miles long) is not very apparent on either ERTS or Skylab pictures (perhaps a sun angle effect). Another, the Roaring River Lineament (4), which was scarcely 25 miles long on the stream map, was extended 40 more miles from the blue-filtered photograph, RL 52 Feb 74, taken from Skylab 4 (dashed line). This lineament cuts across topographic features, except along Roaring River, and it passes close to the north tip of BGL.

Clearly the Beech Grove Lineament is not unique. It is not even the longest trend. The longest is the Stones River to Collins River trend, though it has gaps in the continuity of its trend. Some of the sinuous parts of the BGL could be viewed as gaps. It would be easy to segment the BGL into three parts: a northern segment about 20 miles in length (Defeated Creek portion), a central 35-mile segment (Garrison Fork

Table 1. Summary of information on the Origin of Straight Stream Lineaments in Middle Tennessee. (Locations on Figure 5).

Number and Name	Approx. Length in Miles	Approx. Trend	Geophysical Anomalies Mag.	Grav.	Are Abundant Parallel Joints Known?	(Are they close?)	Are Mineral Prospects Nearby?	(No.) if Yes	Tectonic of Not?	Notes
1A Beech Grove Central Garrison-to Saunders Creek	38	N21E	No		No	(nearby)	Yes	(4)	NOT TECTONIC	SUPERIMPOSED STREAMS
1B Beech Grove Northern Defeated Creek	21	N21E	Yes	Yes	No	(nearby)	Yes and a Mine!	(3)	POSSIBLY TECTONIC	(Mineral Prospects & Gravity could be attributed to Hickman)
1C Beech Grove South E.F.k. Mulberry Ck	25	curved	No	N.A.	No	(far away)	No		PROBABLY NOT TECTONIC	(Could be non-straight continuation of superimposed stream)
2A Stones River	29	N43W	Yes	Yes	Yes	(nearby)	Yes	(3)	TECTONIC	
2B E. Fork River	15	N43W	?	N.A.	Yes	(nearby)	Yes	(3)	PROBABLY TECTONIC	
3 Collins Rive.	28	N35W	No	N.A.	No	(far away)	No		Judgement Reserved	(Too far from joint observations)
4 Roaring River	23	N65W	Yes?	N.A.	No	(far away)	No		Judgement Reserved	(Too far from joint observations)
5 Sink Creek	29	N80E	No	N.A.	No	(nearby)	Yes	(3)	PROBABLY NOT TECTONIC	
6 Charles Creek	22	N65W	No	N.A.	No	(nearby)	No		PROBABLY NOT TECTONIC	
7 Hickman Creek	31	N50E	Yes	?	Yes	(nearby)	Yes and a Mine!	(6)	TECTONIC	
8 Town Creek	22	N24E	No	N.A.	No	(far away)	No		NOT TECTONIC	(Probably Cuesta-Controlled)
9A Middle Fork Stones R.	16	N39W	Yes	?	Yes	(nearby)	No		PROBABLY TECTONIC	(Trends into Beech Grove Disturbed Zone)
9B Panhandle Creek	16	N45W	No	N.A.	Yes	(nearby)	No		POSSIBLY TECTONIC	
10 Flat Creek	43	N45W	?	N.A.	Yes	(far away)	No		POSSIBLY TECTONIC	(Based mainly on parallelism with 9A)
11 Stewart Creek	30	N32E	?		Yes	(nearby)	Yes	(5)	PROBABLY TECTONIC	
12 Harpeth River	25	N50W	No	N.A.	Yes	(far away)	Yes	(1)	Judegment Reserved	(Too far from joint observations)
13 Rutherford Creek	23	N62E	No		Yes	(far away)	No		Judgement Reserved	(Too far from joint observa vations)

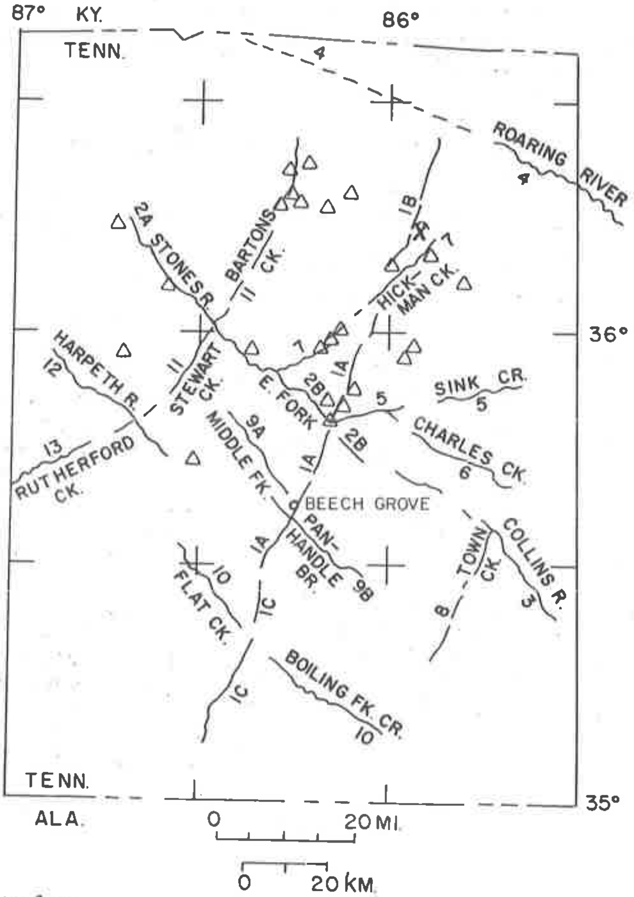

Figure 6. Twenty-four mineral prospects in relation to linears on Figure 5. All but six localities are close to the linears.

to Saunders Creek portion), and a southern curving one 25-miles long (Mulberry Creek portion), 1B, A, C on Fig. 5.

Mineralization and the "System" of Linears

Mineralization along the BGL was cited by Hollyday and others (1973) as evidence for the possible structural significance of the BGL. Jewell (1947) described 28 mineral vein prospects and mines in Middle Tennessee, eight of which are nearby pairs yielding the 24 mapped sites located on Figure 6. Note that only six of the localities are more than five miles from a lineament, too distant for any assumed association with those particular lineaments. However, 15 are relatively close. Most of the accessible prospects displayed vertical veins containing limestone breccia and some combination of fluorite, barite, galena, and sphalerite. In some of these veins the wallrock is slickensided with nearly horizontal striations, and some of the veins are sheeted. This is evidence for minor episodic adjustments to tectonic stress with and subsequent to mineral emplacement. It also suggests that renewed movement can occur preferentially along pre-existing zones of weakness.

Six prospects are on or near the BGL. Four of these lie on or near the lineament near its intersection with the Stones River Lineament (SRL), and two of these are on that lineament. Two more lie on or near the Hickman Creek line at the Gordonsville Knot (one on the east and one on the west side). Just north of these prospects and also at the knot is the large active Elmwood Mine north of Gordonsville.

Six of the 24 sites occur along and within three miles to the north of the SRL; however, three of these occur close to the junction with the BGL and so have already been counted there. Indeed one occurs at the intersection. All prospects along the BGL are at or north of the intersection, and all prospects on the SRL are at or west of the intersection of the two.

Nine of the eleven prospects in the 15-mile wide zone along the BGL have breccia veins striking NE. Seven show horizontal slickensides, and six show northeast movement of the eastern side (Jewell, 1947). This is important because it suggests north-directed compression shown by transverse offset of left-lateral sense along the trend.

The area shown in Figure 6 is about 9550 square miles. Because all of the prospects are in pre-Mississippian carbonates, the area can be reduced to about 5060 square miles if Mississippian and younger outcrops are excluded. If the 24 mineral prospects and the mine are distributed randomly, the average area per prospect is 202 square miles.

The length of the linears on Figure 6 in the pre-Mississippian outcrop area is about 400 miles. If the effective width of each feature is considered to be four miles (2 miles on each side), the total area within this zone is 1600 square miles less 112 square miles for intersections (7 overlapping areas of 16 square miles each) for an area of 1488 square miles (29% of the pre-Mississippian map area). Only nine of the 25 sites on Figure 5 lie outside this distance; 16/25 or 64% are within 29% of the area.

The 16 localities that lie within the 1488-square-mile area along the lineaments have a density of 93 square miles per locality; whereas, the nine localities away from the lineaments are distributed within an area of 3570 square miles for an average of about 400 square miles per location. The enrichment factor (prospects per unit area near lineaments divided by prospects per unit area far away) between the linear and non-linear zones is over four.

We conclude from this comparison that Hollyday and others (1973) were correct in correlating mineral occurrences with the BGL and that this correlation is applicable to other lineaments such as the SRL. It is possible to infer that the mineralized lineaments follow zones of fractures in pre-Mississippian rocks, and that sheeted mineral deposits occur in once open fractures developed over zones of wrench faulting at depth. The next subsection is an attempt to look at greater depths.

Relationship of the System of Linears to Regional Gravity and Magnetic Maps

We now have a system of linear features defined by relatively straight and aligned stream valleys. The BGL is one. If there is a basement-related tectonic significance to these, it might be manifested by some systematic relationship to geophysical map patterns.

The BGL is roughly parallel to the regional gravity gradient (Keller, and others, 1980). However, this map is based on gravity stations three or more miles apart, so detailed relationships are not discernible.

Regional magnetic maps (Johnson, and others, 1979) are more detailed (being controlled by details along flight lines about a mile apart), and relationships emerge. On Figure 7 the BGL appears to separate two magnetic terrains. To the east of the BGL the magnetic field shows broader and lower amplitude anomalies; but west of the BGL, to the general position of the Stewarts Creek Lineament, anomalies are narrower and have a higher amplitude. The narrow, steep gradients suggest that magnetically susceptible basement is higher here. The BGL appears to coincide with individual anomalies only near its north end (north of 36°10'). This is where the mine is located. West of the BGL, the Stones River Lineament follows a narrow magnetic high for about 20 miles and touches the south end of a large anomaly. East of the Beech Grove Lineament, this lineament appears unrelated to magnetics. The Roaring River Lineament (RRL), which crosses the north end of the BGL, runs just south of, and parallel to, a large magnetic high along the Kentucky-Tennessee line. The Middle Fork Stones River Lineament crosses the BGL at a low (this is the site of the disturbed zone in the road cut at Beech Grove).

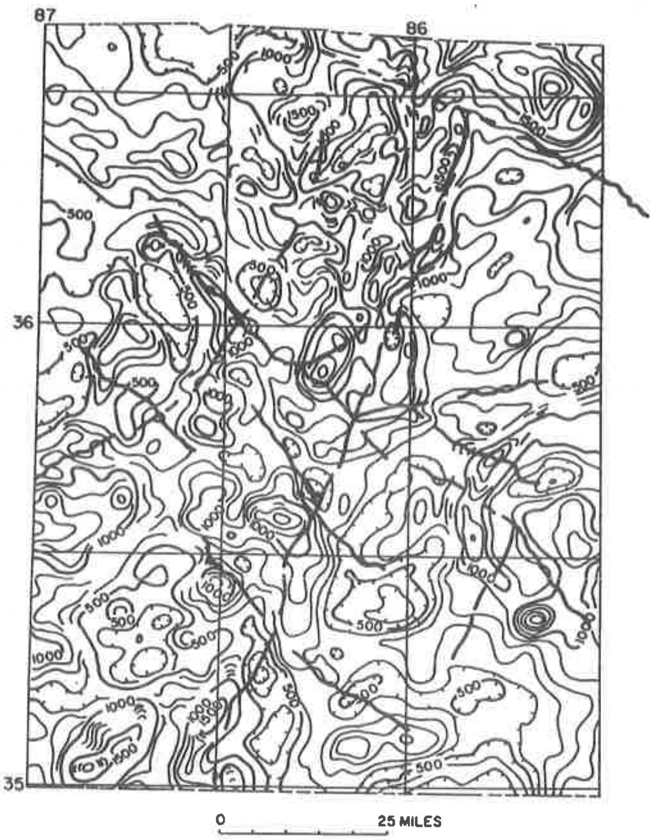

Figure 7. The Beech Grove and other lineaments (pattern from Figure 5) compared to regional magnetic pattern. The Beech Grove Lineament coincides with elongated anomalies only north of 36°10′. Stones River Lineament follows the crest of a narrow magnetic high west of 86°25′. Just to the south, the Middle Fork of Stones River follows a magnetic low.

Relationships of the Linears to the Knox, Carters, and Chattanooga Structure Contours

We have recently redrawn structure maps of the area contoured on top of the Cambro-Ordovician Knox Dolomite, top of the Middle Ordovician Carters Limestone, and base of the Devonian Chattanooga Shale at a scale of 1:250,000 employing all available data. No systematic vertical offset was found across any of these lineaments. If there is any coincidence of the lineaments with normal or reverse faulting, it must occur in deeply buried rocks, older than upper Knox. Some parallelism of lineaments and magnetic features is suggestive of basement faulting.

The Gordonsville-Carthage Area — The Gordonsville Knot

General

The complex area near Gordonsville, referred to as the Gordonsville Knot, is interesting in the context of this study because this mineralized area that relates to magnetic and gravity anomalies was discovered by using streams. If the stream-related complexities of the knot are related to other geologic features, then it is easier to consider it possible, even likely, that the more lengthy straight portions of the lineaments are also related to geologic features.

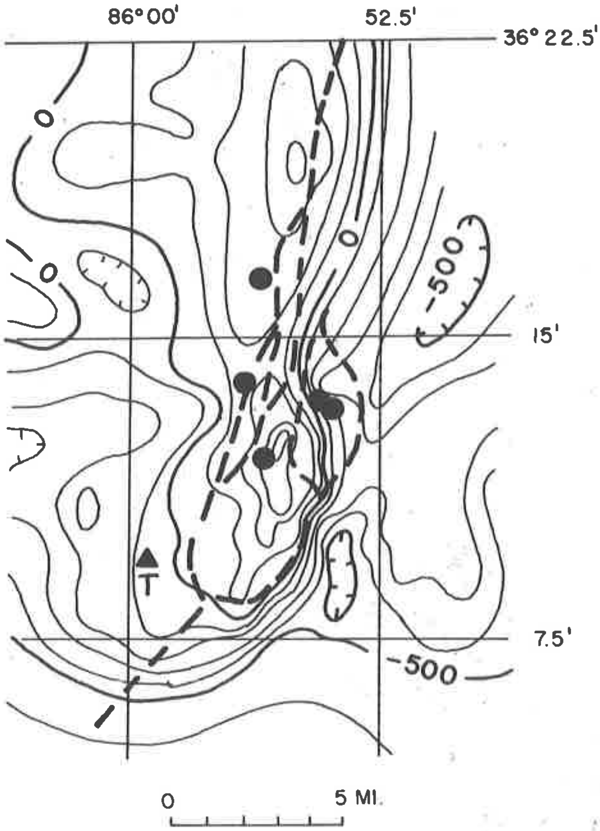

Figure 8. The "Gordonsville Knot", magnetic anomaly, and mine shafts. Solid circles are mine shafts. "T" is the old Terry Prospect (Jewell, 1947). The magnetic anomaly is from Ganster (1969).

When the BGL was drawn northward from Beech Grove, the lineament either had to end south of its limits as defined by the discoverers or had to break up into several equally likely choices near Gordonsville. Reesman drew this trace, and in "forcing" the BGL by a devious route through the knot his alternate choices precisely bracketed the magnetic anomaly discovered by Ganster (1969), and included in the Johnson and others (1979) map of the region. The patterns also correspond with a gravity anomaly identified by Stearns. Of course, Reesman was aware of the mining district in the Gordonsville-Carthage area but at the time was unaware of the magnetic and gravity anomalies. Had Stearns drawn this knot, it would be easy to allege bias.

Magnetics, Gravity, and Structure

Figure 8 shows the Gordonsville Knot superimposed on the vertical magnetic intensity map of Ganster (1969), along with the location of the five mine shafts. The magnetic anomaly represents a source buried below the Knox and below the ore bodies. The ore probably postdates all the rocks in the area, certainly those surface rocks that contain the exposed mineral prospects. This coincidence of relationships in pattern and location of geologic features of varying depth and age suggests a recurrent causal relationship. However, Ray Gilbert, who was Chief Geologist for New Jersey Zinc in the Carthage area until 1983, stated that there is no evidence for faulting along the BGL in this area (personal communication). His information comes from intensive surface studies, numerous exploration cores in the area, and observations within the mines. Although the possibility remains that some sort of fracture system or zone

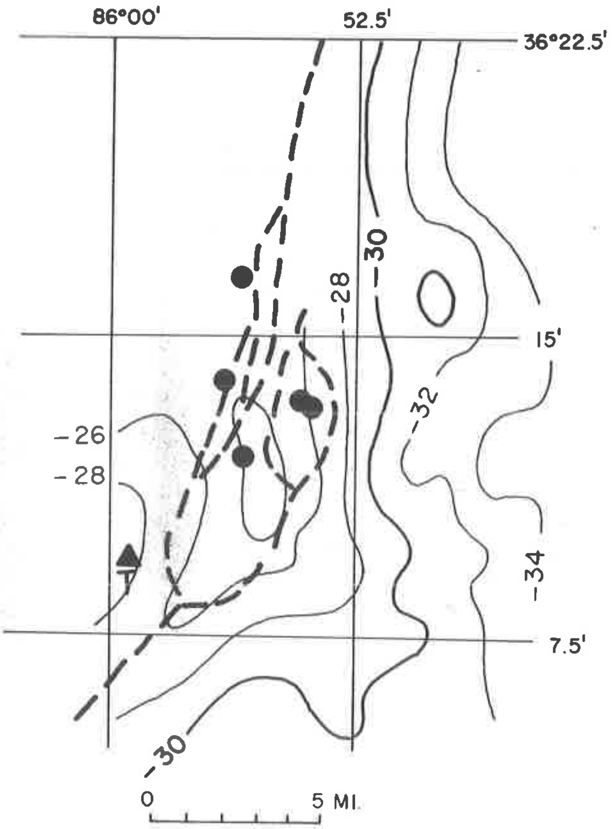

Figure 9. The "Gordonsville Knot", gravity anomaly, and mine shafts. The gravity anomaly is from unpublished work by Stearns. On the "knot" and to the south the Beech Grove Lineament follows a positive gravity anomaly.

could exist in the knot, there is no indication of near-surface faulting of measurable stratigraphic offset or Gilbert would have found some evidence for it. By the same reasoning, it would appear that obvious faulting is not to be expected elsewhere along the lineament.

An unpublished detailed gravity survey by Stearns in 1970 covers the Gordonsville area (see Figure 9). A gravity high corresponds with Ganster's (1969) magnetic anomaly near Gordonsville. South of Gordonsville to Alexandria the lineament follows an extension of the Gordonsville high. From Carthage to Difficult the lineament is roughly parallel to the gravity gradient, a general relationship seen from the regional map.

Unpublished structure contour maps drawn in 1972 by Stearns and C. W. Wilson, Jr. on the top of the Carters Formation shows only a rough parallelism between the lineament and structure. The knot area does not stand out.

Ground Water Hydrology of the Knox in the Knot

In the knot the surface rocks are Middle Ordovician limestones and the mineralized zone is in the underlying Knox Group. Newcome and Smith (1962) studied the ground-water potential of the Knox in Middle Tennessee and Fischer and Hoagland (1970) did a detailed study of the potentiometric surface of the water in the Knox in the Elmwood Mine area (in the Knot). Their patterns were discovered to be related to topography. Thus, Rima and Hollyday (quoted by Fischer, 1977) and Fischer (personal communication) concluded that recharge is essentially local. Vertical recharge into the Knox must take place primarily through joint systems with some lateral movement occurring along bedding planes.

Conceptually, the Gordonsville Knot should be one of the best areas to prospect for ground water along the BGL because, if fracture related, this area should be the most highly fractured, and water should penetrate more freely here than elsewhere along the lineament. However, it does not.

Four 12-foot-diameter mine shafts were sunk by the New Jersey Zinc Company into the upper Knox paleoaquifer system. During the sinking of the Elmwood number 1 shaft, the ground water flow never exceeded 0.4 gpm (Fischer, 1977). The four mine shafts in the knot are now interconnected by drifts at depths ranging from about 950 to 1300 feet below land surface. Most of the mining activity is under the relatively low lying region along the Caney Fork River. The drifts must pass under the river at two or more locations and cross several of the possible branches of the lineament. At present, the total mine water output from all the workings is probably less than 200 gpm (Fischer, personal communication). Clearly, the area is not one of abundant open fractures. By the same token parts of the lineament elsewhere may not be bands of abundant open fractures.

THE LINEAMENT AND JOINTS

The lack of joints that trend along the strike of the BGL was cited by the Tennessee Valley Authority (1975) as evidence against the lineament being an expression of a significant structural feature. To verify these findings a limited study was initiated to examine the creek bed for joints upstream from Beech Grove in the "type area" of the lineament. This is the narrowest and straightest portion of Garrison Fork, and it includes the part of the stream nearest to the disturbed zone found by Hollyday and others (1973). Results were clear; the N 21^{o}E lineament direction is a conspicuous minimum in the distribution of joint strikes as TVA asserted in 1975.

A study of jointing over a large are including this part of the Beech Grove was made by Conway Hughes (1982). Hughes measured 3772 joints in Ordovician limestones at 78 locations in seven quadrangles along and near a 25-mile stretch of the central portion of the BGL. He found that the lineament trend (N 21^{o}E) has the least number of joints.

Both of these studies agree with the TVA results, so the TVA conclusion stands that there are no abundant joints parallel to the BGL. If one still wishes to maintain that fractures control the lineament, they must be few and must occupy the portion of the stream bed or valley concealed from view, maybe weathered out and filled with alluvium so as to be difficult to find. We have looked at the stream bed in the type area and have found many exposures and many joints, so we prefer to believe (in accordance with the evidence) that the lineament is not controlled by joints trending parallel to the lineament.

TENTATIVE CONCLUSIONS FROM THE REEVALUATION

1. If it is real and continuous, the Beech Grove Lineament is 96 miles long and remarkably straight.

2. The BGL is not unique in the region. Other lineaments are as straight and long. The Stones River Lineament because of correspondance to geophysical anomalies and mineralized localities on it is a strong candidate for tectonic feature. If joined to the Collins River Lineament it too is over 90 miles long.

3. The Beech Grove lineament does not coincide with elongate magnetic anomalies or trend parallel with joints along most of its length. Other lineaments that trend NE and NW are parallel with abundant joints, and so are far more likely to be joint controlled.

4. The Beech Grove is related to gravity and magnetics only near its north end, where commercial zinc mineralization occurs. This northernmost 20 miles of so is most apt to be tectonically controlled. However, the low ground water yields from the Elmwood Mine suggest that any tectonic fractures that may have existed have been healed by subsequent cementation.

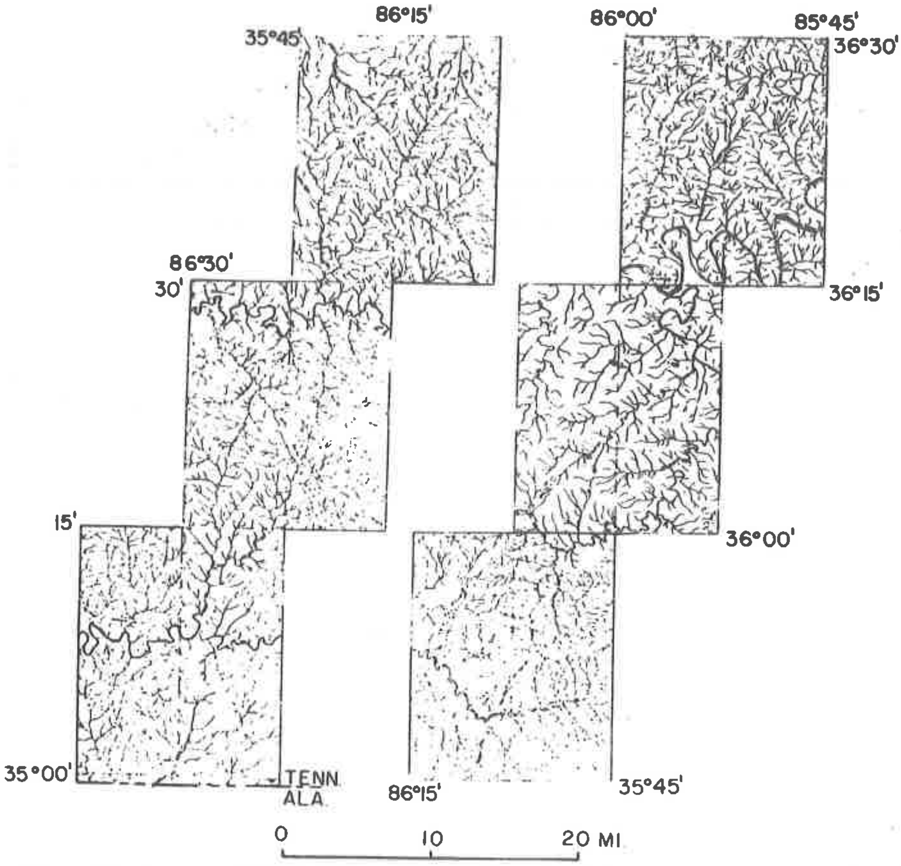

Figure 10. All stream courses from twenty-four 7 1/2' quadrangles straddling the Beech Grove Lineament. All the lineaments in the 24 quadrangles that are drawn on Figure 5 are visible here too. This map is the data base from which Figures 11 and 12 are drawn.

AN ALTERNATE WORKING HYPOTHESIS: SEARCH FOR A NON-TECTONIC ORIGIN OF THE LINEAMENT

General

So far, the working hypothesis has been that the lineament does exist as the 96-mile long feature proposed by Hollyday, and others (1973). There is a positive correlation with geophysical patterns for a part of the lineament, but not with structure contour patterns or joints. Segments of the lineament correlate with nothing. Correlation of only part of the lineament with geophysical anomalies leads to a possible conclusion that the lineament may well be partly tectonic in origin, and partly imaginary, fortuitous, or of non-tectonic origin. Now we will attempt to redraw lineaments with no assumption of continuity. That way it could emerge as a discontinuous feature.

Stream Courses as a Guide to Lineament Studies

The BGL was originally defined as a series of aligned cleared stream valleys, so it and the other lineaments (Figs. 1 and 5) were compiled from streams on 1:250,000-scale maps. Although the use of streams appears to be a proper approach, lineaments drawn from the 1:250,000 maps may be biased, because at 1:250,000 scale only the

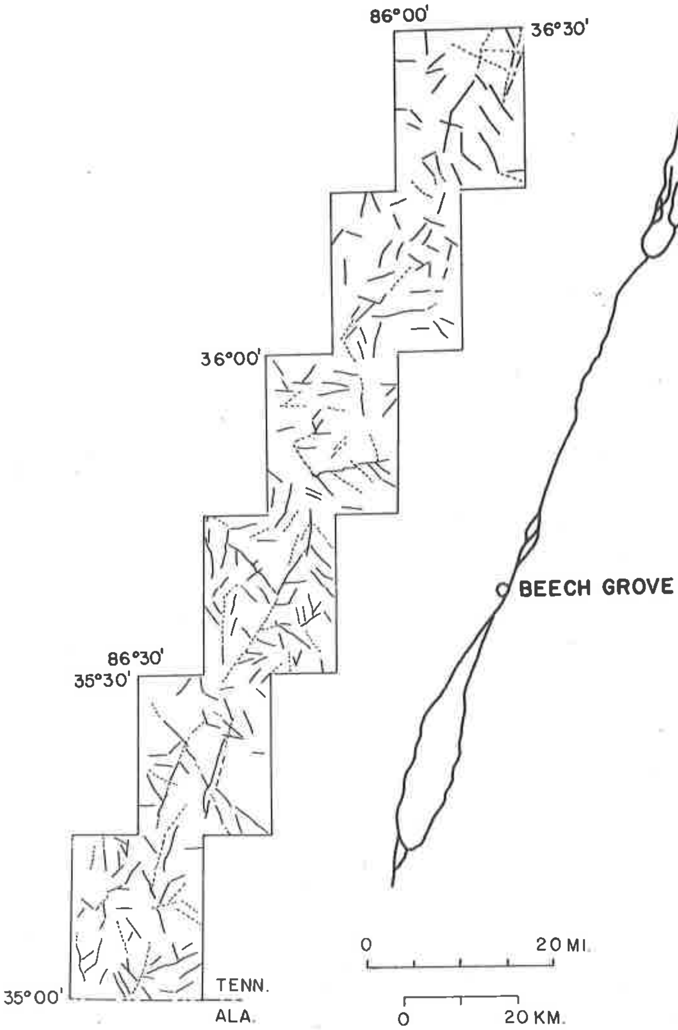

Figure 11. Straight stream courses selected from Figure 10. Dashed lines are sinuous streams in straight valleys. The continuous trace is shown for comparison. Note that much of the Beech Grove Lineament disappears.

larger streams will be included on the map and there may also be an artistic slection by the cartographer of streams from the many that are actually present. These factors could result in stream courses being represented as more continuous in a given direction than they are.

To remove the possibility of such biases and to add detail, *all* blue stream courses plotted as constant weight lines (intermittent as well as permanent) on 7 1/2-minute quadrangles were drawn. At this scale no significant streams are omitted. Stream maps were drawn for 24 quadrangles that span and straddle the entire length of the BGL. For Figure 10, these maps were combined and reduced.

Map of all Stream Courses

Figure 10 is interesting because it can be examined without enhancement. Being aware of the general location and direction of the BGL by the arrangement of chosen quadrangles, the BGL should be apparent. On the contrary, it is fair to say that the entire length of the BGL does *not* stand out. Rather, some segments do; but also there

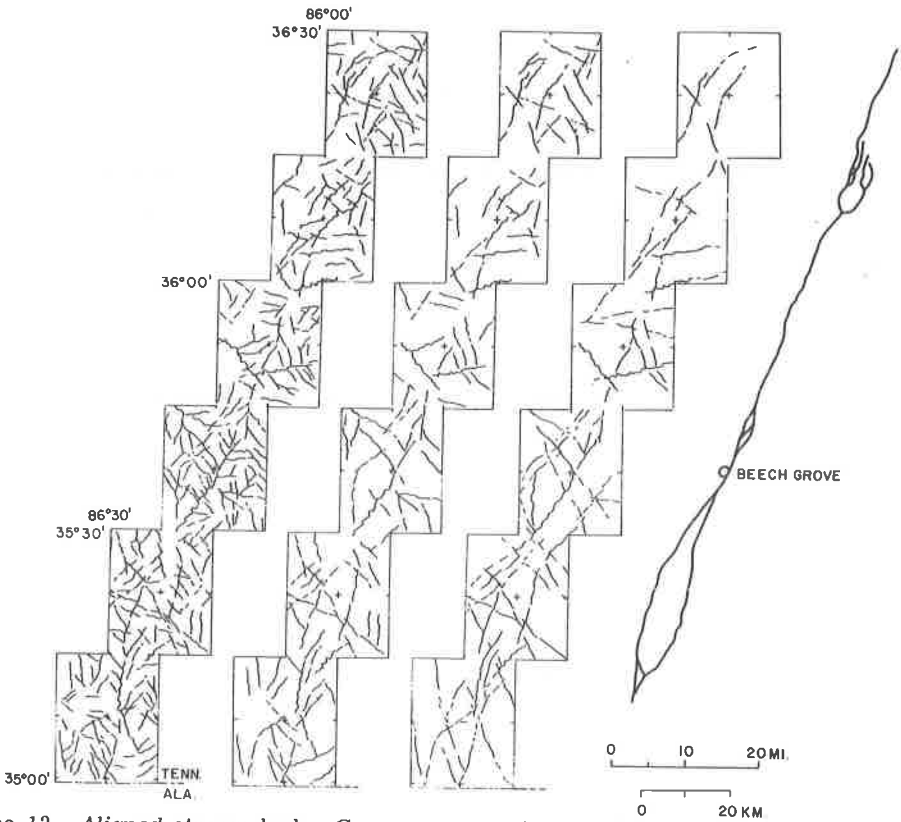

Figure 12. Aligned stream beds. Curves are permitted as long as end-to-end alignment is preserved. Viewed this way, the Beech Grove Lineament does not disappear but it breaks into segments as much as 30 miles in length.

are other lengthy relatively straight, end-to-end stream sets with other orientations that appear. Streams on this map compare well with the lineaments on Figure 5 drawn from the 1:250,000-scale maps. All the lineaments drawn on Figure 5 that are in this area are prominent trends. There are also others.

Two approaches were tried in manipulating the map. Neither assumes continuity of the BGL or any other lineament. One emphasizes straightness, the other end-to-end continuity of trend.

Straightness

Both the relatively straight portions of water courses and straight valleys in which the streams wander a bit were drawn on Figure 11. The resulting map minimizes the continuity of the BGL. Much of it between 35°45' and 36°15' disappears.

End-to-End Continuity

It is not necessary that fractures or fracture zones be straight. Taking this into account, an approach emphasizing end-to-end continuity was tried. The full set of streams on Figure 10 was modified to preserve only those streams that trend toward each other. Others were omitted. In addition to straight lines, curved lines appear in this approach (Figure 12). This set of maps preserves all streams that occur singly or in disjointed but end-to-end sets aggregating two, four, and ten miles in length. The gaps are gaps in the actual stream courses. The BGL, as a single 90-mile-long feature, again is not evident on any of these maps.

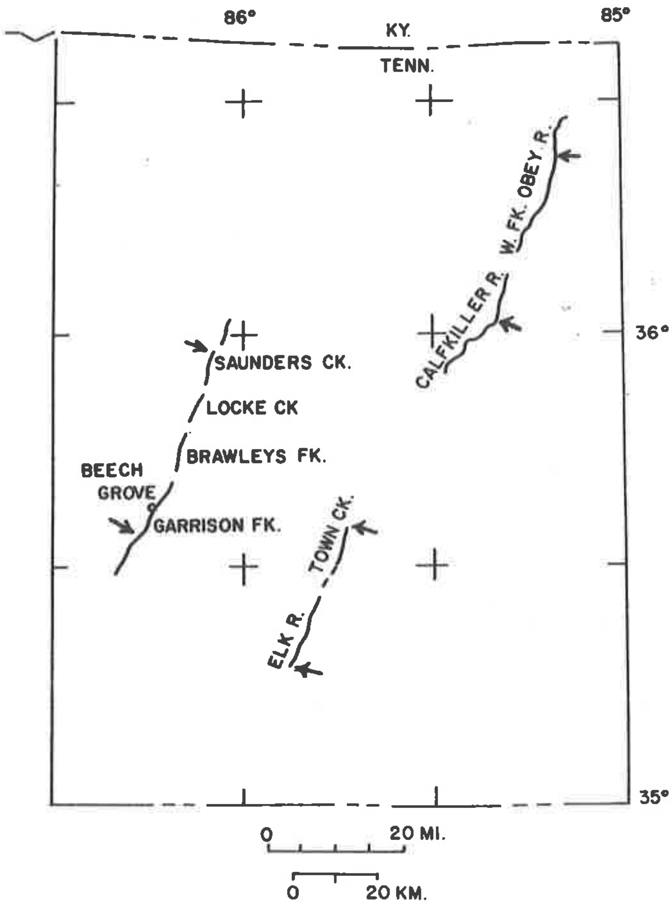

Figure 13. The central portion of the Beech Grove Lineament and two other parallel stream sets at the edge of the Cumberland Plateau. These are both parallel to strike of nearby cuesta-forming Pennsylvanian sandstone. The arrows indicate the straightest portions with parallel trends.

Although there is more apparent continuity on the four- and 10-mile maps, the impressionistic view of multiple lineaments obtained by looking at all streams on Figure 10 carries through all versions.

Using streams as a guide, it seems justified to assert that the BGL is not one feature. Rather, it probably is several features originally connected because of interpretive bias toward straight and long lines. Comparison of the 10-mile and longer feature map with the continuous trace map (the two right panels on Figure 12) suggests that the lineament may be a joining of six to ten stream-valley sets. The pieces need not have the same origin or a common relationship to geological phenomena.

THE BEECH GROVE LINEAMENT AS A SET OF DISMEMBERED STREAMS

The Central Straight Portion

The 35-mile long part of the Beech Grove Lineament between about 35°30' N and 36°00' N (Garrison Fork, Brawleys Fork, Locke Creek, and Saunders Creek) is the most striking part of the lineament as viewed on the ERTS image. This portion of the lineament is the N 21° E portion demonstrated to be unrelated to joints or to the magnetic map. Yet this aligned set of streams exists; why? We are reluctant to ascribe this situation to pure chance.

Search for Analog Ancestral Streams

If the continuity of the streams can not be explained from the underlying rocks, perhaps it was superimposed. If superimposed drainage is inferred, it seems appropriate to search eastward for analogs of comparable stages of erosion along the north-northeast-trending escarpment of the Cumberland Plateau where upper Mississippian and lower Pennsylvanian rocks that once covered the area of the BGL are now being eroded. On the Cumberland Plateau an alternating sequence of non-resistant shales and resistant sandstones dips to the southeast forming northeast-trending cuestas. It is probable that some streams began by flowing along the foot of the cuestas. Thus, they would flow parallel to strike and also parallel to the BGL.

One possible analog of an ancestral "Beech Grove River" is the pair consisting of the West Fork of the Obey River and headwaters of the Calfkiller (N 22° E for 27 miles). Both of these streams head at 36°10' N, 85°20' W on Pennsylvanian sandstones of the Cumberland Plateau (Figure 13), and cut into Mississippian rocks within the straight reach. Just east of here the Pennsylvanian strikes between N 13° E and N 23° E. Another analogous pair (plotted on Figure 13) is the head of Elk River-Town Creek pair (35°25' N, 85°50' W) that trend N 23° E for 22 miles (Figure 13). Just east of here the Pennsylvanian strikes N 25° E.

Dismemberment of the Ancestral Beech Grove Rivers

The elevations of gaps at stream divides between now-divided segments of the BGL can provide some insight into the hypothetical paleodrainage course. Because the highest gap (1300 feet) is in the middle of the BGL, between the Cumberland (Stones) and the Tennessee (Duck) drainages, it is easy to rationalize the BGL as once consisting of two streams, like the proposed analogs, that headed up north of Beech Grove near the present Duck-Stones Basin divide. The southwest part (Garrison Fork) has its original flow direction toward the southwest, and Saunders Creek at the north also has its original flow direction to the northwest. The Stones River may well have captured the drainage of the two middle streams, Brawleys Fork and Locke Creek, so Locke Creek flow direction was reversed. The result is four streams where there used to be two.

CONCLUSIONS

1. The Beech Grove Lineament, a 96-mile long feature and a supposed fracture trace, is actually a combined series of several separate and real lineaments having different origins.

2. The readily apparent 30-mile-long central portion of the lineament from near 35°30' N to 36° N is not a tectonic feature; rather, it is a superimposed pair of streams that originated by flow parallel to cuestas during erosion of the now eroded resistant and non-resistant Pennsylvanian sandstone and shale.

3. The lineament is not unique. There are several others as long and as straight as the central part of the BGL. Unlike the central part of the BGL, many of these are parallel to joints, parallel to geophysical anomalies, and are close to mineral localities. The following list is proposed for the degree of tectonic certainty (Table 1).

A. The most probable candidates for tectonic lineaments are the Hickman Creek Lineament at the "Gordonsville Knot" and the northwestern 30-mile portion of the Stones River Lineament. Both are parallel to known joints nearby and to mapped geophysical anomalies and both are close to mineralized localities.

B. Lineaments with possible tectonic control include the Middle Fork of Stones River, Stewart Creek, East Fork of Stones River, and Panhandle Creek. These are close to and parallel to abundant joints but lack either observed association with geophysical anomalies or mineral prospects.

4. If the interpretations herein are correct, superimposition of linear drainage should be a standard explanatory hypothesis for linear stream trends in areas of deep erosion. Also, viewing drainage patterns alone should be a regular working method in compiling linear features. Finally, lengthy straight features should be viewed with suspicion and alternative explanations sought.

REFERENCES

Fischer, F. T., and Hoagland, A. D., 1970, Hydrologic investigation of the Middle Tennessee zinc district: AIME World Symposium on Mining and Metallurgy of Lead and Zinc, D. O. Rausch and B. C. Mariacher, eds., Chap. 4, p. 95-107.

Fischer, F. T., 1977, The geologic setting of a persisting paleoaquifer - The Elmwood Mine, Middle Tennessee zinc district: AIME Lead-Zinc Update, D. O. Rausch, F. M. Stephens, and B. C. Mariacher, eds., Chap. 1, p. 3-19.

Ganster, M. W., II, 1969, Analysis and interpretation of a magnetic anomaly at Gordonsville, Smith County, Tennessee: Unpublished Master's Thesis, Vanderbilt University, 36 p.

Hollyday, E. F., Moore, G. K., and Burchett, C. R., 1973, Preliminary assessment of a Tennessee lineament: Remote Sensing of Earth Resources, v. 2, F. Shahrokhi, ed., 2nd Ann. Remote Sensing of Earth Resources Conf., Tullahoma, Tenn., Univ. of Tenn. Space Inst., p. 119-128.

Hughes, C. T., III, 1982, Fracture analysis in the vicinity of the Beech Grove Lineament, East Central Tennessee: Unpub. Master's Thesis, Memphis State University, 47 p.

Jewell, W. B., 1947, Barite, fluorite, galena, sphalerite veins of Middle Tennessee: Tenn. Div. of Geology, Bull. 51, 114 p.

Johnson, R. W., Jr., Haygood, C., and Kunselman, P. M., 1979, Residual total intensity aeromagnetic map of Tennessee west-central sheet: Tenn. Div. of Geology.

Keller, G. R., Russell, D. R., Hinze, W. J., Reed, J. E., and Geraci, P. J., 1980, Bouguer gravity anomaly map of the East-central Midcontinent of the United States: Nuc. Reg. Com. Rept., NUREG/CR-1663, 12 p.

Manning, R. A., and Statler, A. T., 1975, Structure map on top Knox Group: Tenn. Div. of Geology.

Moore, G. K., 1976, Lineaments on Skylab photographs - detection, mapping, and hydrologic significance in Central Tennessee: U.S.G.S. Open-File Report 76-196, 81 p.

Moore, G. K., and Hollyday, E. F., 1976, Discovery and significance of the Beech Grove Lineament of Tennessee: U.S.G.S. Prof. Paper 929, p. 164-168.

Newcome, R., Jr., and Smith, O., Jr., 1962, Geology and ground-water resources of the Knox Dolomite in Middle Tennessee: Tenn. Div. Water Resources, Water Resources Ser. No. 5, 43 p.

Tennessee Valley Authority, 1975, Additional response to question 323.42, Report to U.S. Nuclear Regulatory Commission on the Hartsville Nuclear Plant Site: 26 p., 11 figures.

THE GEOLOGY OF THE FLORIDAN AQUIFER SYSTEM IN EASTERN MARTIN AND ST. LUCIE COUNTIES, FLORIDA

JOHN R. ARMSTRONG[1] — *Department of Geology, Florida State University, Tallahassee, Florida 32306*

MICHAEL P. BROWN[2] — *South Florida Water Management District, P. O. Box V, West Palm Beach, Florida 33402*

SHERWOOD W. WISE, JR. — *Department of Geology, Florida State University, Tallahassee, Florida 32306*

ABSTRACT

The mid Tertiary formations which comprise the upper portion of the Floridan aquifer system and its confining beds in eastern Martin and St. Lucie Counties, Florida, have been studied through the analysis of lithologic well samples and geophysical logs. At least three distinct lithologic units make up the Floridan aquifer system within the study area. From oldest to youngest, they are: the Ocala Limestone of the upper Eocene Series, and an unnamed limestone which has been divided into two units, U-B (lower) and A-U (upper). The calcareous clays and sands of the Hawthorn Formation comprise the upper confining unit of the system.

A normal fault which runs parallel to the barrier islands, Hutchinson Island, is delineated in northeastern Martin County. Thickening of units on the downthrown (eastern) side of the fault suggests that movement along the fault had begun by Ocala time and continued into Hawthorn time.

In the area of investigation, the upper portion of the Ocala Limestone is usually a coarse biocalcarenite, but east of the Hutchinson Island fault, the Ocala is finer grained and sparsely fossiliferous. This change in lithology is attributed to deposition in deeper water on the downthrown side of the fault.

The unnamed, fine-grained, post-Ocala, pre-Hawthorn limestone has been assigned an early Oligocene age based on its assemblage of planktonic foraminifers and coccoliths. The presence of a layer of phosphorite in this interval may record the first deposition of phosphates in Florida.

East of the Hutchinson Island fault, the lower part of the Hawthorn Formation has been dated as late Oligocene, using planktonic foraminifers. These appear to be the oldest Hawthorn beds yet dated in Florida. It is believed that deposition of the Hawthorn Formation began in structurally low areas following a large scale mid-Oligocene sea level drop. The entire sequence of strata seems to have been affected by minor faulting or warping during Hawthorn time.

INTRODUCTION

Study Area

The study area is located in east central peninsular Florida and consists of the eastern third of Martin and St. Lucie Counties. Figure 1 shows the geographic location of the study area. Figure 2 shows the location of wells used in the study. Table I provides more detailed information about the location and depth of each well.

The study area is part of the Coastal Plain physiographic province. Within the Coastal Plain province is the Atlantic Coastal Ridge which covers most of the study area. The easternmost margin of the area is comprised of two large linear barrier islands, Hutchinson Island to the north and Jupiter Island to the south. These islands are separated from the mainland by the shallow waters of the Indian River. The barrier islands were probably formed as offshore sand bars during higher stands of sea level (Lichtler, 1960, p. 145). The elevation of the barrier islands varies from mean sea level (MSL) up to 30 feet above MSL on Jupiter Island.

[1]Current address: Department of Environmental Regulation, St. John's District Office, 1600 Wycliff Drive, Orlando, Florida 32303

[2]Current address: Geraghty and Miller, Inc., P. O. Box 271173, Tampa, Florida 33688

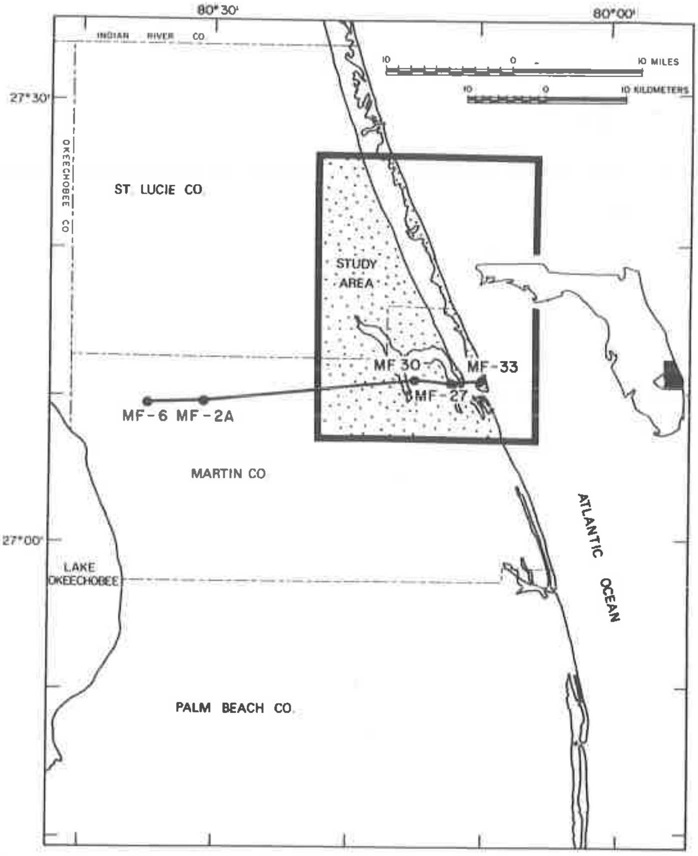

Figure 1. General location map with well locations and cross-section line for Figure 4 (after Mooney, et al., 1980).

Table I. Location and depth of study wells.

Well No.	Latitude	Longitude	Owner or Name	Total Depth Feet Below Land Surface	Elevation MSL
MF-3	27°12'48"	80°10'44"	Indian River Plant Standby	980	+5'
MF-4	27°11'04"	80°09'04"	Mobil Oil Estates #1	1525	+6'
MF-27	27°10'25"	80°12'55"	Martin Co. Golf & Co. Clubs	991	+15'
MF-28	27°11'46"	80°12'06"	Seawalls Point	1088	+27'
MF-31	27°12'46"	80°10'48"	Indian River Plant W/S	1010	+5'
MF-32	27°13'13"	80°13'55"	River Club Condominium	1008	+10'
MF-33	27°10'44"	80°10'02"	Mobil Oil Estates #2	1110	+5'
MF-35	27°14'17"	80°11'36"	Joe's Point #1	1705	+5'
SLF 26	27°23'23"	80°18'39"	Savannahs Co. Park	958	+10'
SLF 28	27°20'28"	80°16'35"	Mr. Cast Low	883	+31'
AG 106	27°20'15"	80°18'50"*	Florida Power & Light	711	+15'

*Approximate location

Methods

The majority of the wells used in this study were drilled into the Floridan aquifer system as water supply wells. All were drilled by either the percussion or hydraulic rotary method except for wells AG-104, -105, and -106 which were cored into the

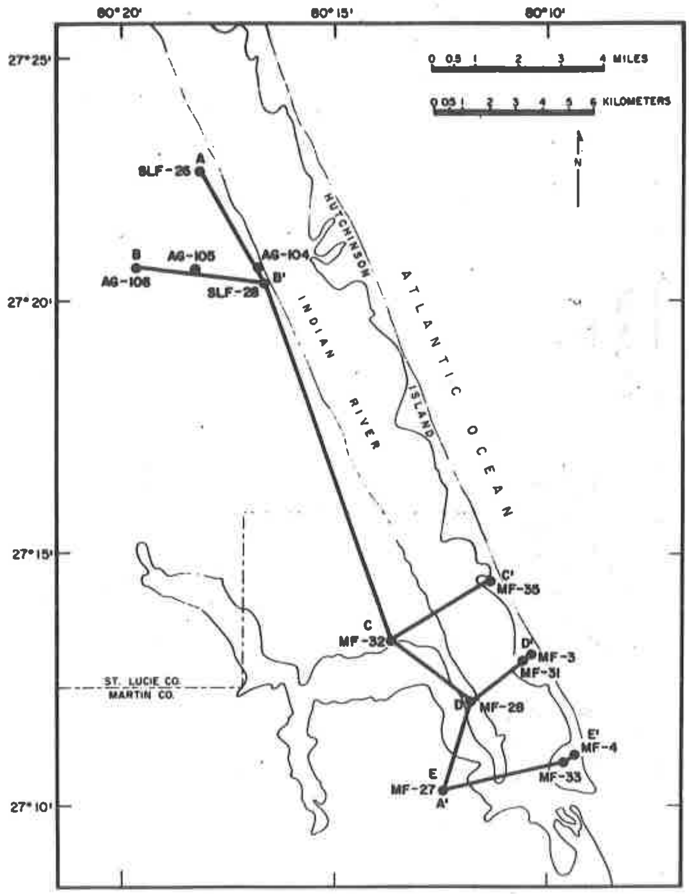

Figure 2. Map of study area showing well locations and cross-section lines for Figures 7-11.

strata of the aquifer system. For the other wells, cutting samples were collected at intervals of from ten to twenty feet.

All samples were examined and described using a binocular microscope, and detailed lithologic logs were prepared (see Armstrong, 1980, Appendix, for long descriptions). In some instances x-ray diffraction techniques were utilized to determine mineralogy and the amount of some constituents. The foraminiferal content of each sample was also studied and key species were noted.

Geophysical logs are available for all wells included in this study and have proved a valuable tool for correlation. The natural gamma-ray log proved to be the most useful and widely available log other types including the electrical resistivity, spontaneous potential, neutron, caliper, fluid resistivity, temperature and flowmeter logs were also utilized. Through examination of geophysical logs and comparison with lithological samples, distinctive geophysical patterns were discerned which enabled the identification of various subsurface units with confidence even in the absence of lithologic samples. Information from the units thus delineated was then used in the development of cross-sections, structure contour maps and isopach maps. In several instances where cutting samples were of poor quality or were affected by excessive lag time, geophysical logs allowed precise placement of unit boundaries. Geophysical logs also allow the recognition of very thin units difficult to recognize in cuttings collected as a composite to represent up to 20 feet of section. A characteristic gamma ray log for the study area is shown in Figure 3 along with a corresponding lithologic log.

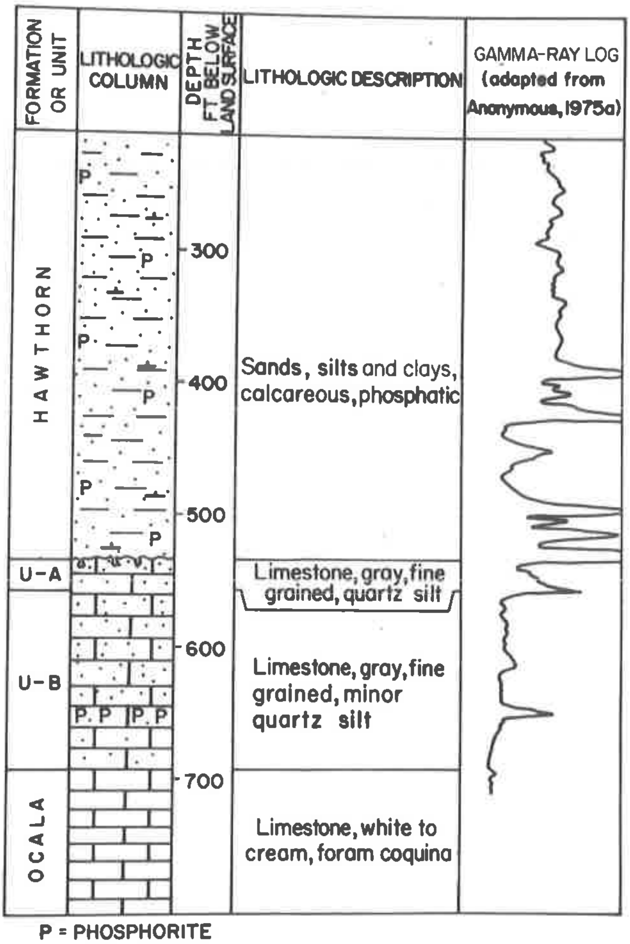

Figure 3. Lithologic columnar section and gamma-ray log for core AG-106 (after Anonymous, 1975a).

Previous Studies

The first detailed observations on the geology of Florida began during the late 1800's on surface exposures in the central and northern peninsular part of the state. By the late 1920's and 1930's, researchers had begun work on the subsurface stratigraphy of Florida. These early studies have been summarized in detail by Mooney, *et al.* (1980) and will not be reviewed here.

The mid-1940's saw the publication of two important papers concerning the stratigraphy of the mid Tertiary carbonates of Florida. Applin and Applin (1944) described a number of subsurface units using lithologic characteristics and benthic foraminiferal content. The following year Applin and Jordan (1945) outlined a series of faunizones, and gave lists of diagnostic species of foraminifers from the formations described by the Applins in 1944. Although a number of changes have been suggested subsequently, the stratigraphic column proposed in these papers has survived as the basic framework for the present-day division of the mid Tertiary carbonates of Florida.

Publication of the 1961 Code of Stratigraphic Nomenclature (ACSN, 1970) has caused recent workers to question the validity of a number of these subsurface formations because they are described at least in part in terms of biostratigraphy. Definition of a formation on the basis of its faunal content is not allowed under the present code. Although it can be argued that many currently defined Florida "formations" are really biostratigraphic units, rather than true formations defined on their lithologic properties, the traditional nomenclature is so well ingrained in the literature that revision of the present scheme will inevitably be slow. For purposes of this report, an attempt will be made, where possible, to correlate units within the study area with units traditionally recognized in Florida.

Workers researching the groundwater system of Florida discovered that the principal artesian aquifer crossed a number of formational boundaries. To facilitate discussion of the aquifer, Parker, *et al.* (1955, p. 189) stated that the principal artesian aquifer is "designated as the Floridan aquifer and includes parts or all of the middle Eocene (Avon Park and Lake City limestones), upper Eocene (Ocala limestone) and Oligocene (Suwannee limestone), and Miocene Tampa and permeable parts of the Hawthorn formation that are in hydrologic contact with the rest of the aquifer." Brown and Reece (1979) have since found in the area of interest that the aquifer consists of a number of producing zones separated by semi-permeable zones, all of which they designate as the Floridan upper to middle aquifer system.

The geology and groundwater resources of Martin County were studied by Lichtler (1960). He used electric logs and well cuttings to describe the character of the subsurface formations, as well as the properties of the deep and shallow aquifers. He also identified a major subsurface fault with a vertical displacement between 300 and 400 feet, striking parallel to the coast and located about five miles inland. The movement along the fault was postulated to have begun in the late Oligocene and to have continued perhaps into the Miocene, resulting in a thickened section of Oligocene on the downthrown (eastern) side of the fault. These Oligocene sediments were identified as Suwannee Limestone by Lichtler (1960).

Chen (1965) used cuttings, cores and electric logs to study the lithostratigraphy of the Florida Paleocene and Eocene on a regional basis. He presented his findings in the form of structure maps, lithofacies maps and isopach maps. Unfortunately Chen's study included only one well in St. Lucie County and none in Martin County.

Vernon (1970, p. 7) extended the fault proposed by Lichtler (1960) northward through St. Lucie County and southward into Palm Beach County where it intersects with the coastline near the city of West Palm Beach. Vernon relied on hydrologic data to extend the fault.

Bermes (1958), in a study of Indian River County, proposed the presence of several faults running parallel or sub-parallel to and within several miles of the coast, and reported 280 feet of "Oligocene" sediments in the northeast part of the county (Bermes, 1958, p. 15). Bermes reported that the thickened section of Oligocene beneath the southeast part of the barrier beaches had low permeability and that the Eocene rocks there yielded poor quality water (Bermes, 1958, p. 40).

As a prerequisite for the construction of the Florida Power and Light nuclear power plant on Hutchinson Island in St. Lucie County, Law Engineering Testing Company produced a report concerning the geology of Hutchinson Island (Anonymous, 1975a). A number of shallow borings were taken and three deep core holes were drilled into the top of the Ocala Limestone. These deep core holes were drilled along a line west of the plant site and were intended to cross the fault line proposed by Vernon (1970). Seismic surveys were also conducted along sections of the St. Lucie and Indian Rivers. On the basis of the seismic and core data, Law Engineering concluded that no faults were present and that folding was responsible for the offset in marker beds.

The engineering firm of Black, Crow and Eidsness, Inc. produced a report on the drilling and testing of a deep disposal and monitoring well for the city of Stuart in Martin County (Anonymous, 1975b). This report postulates a fault just west of Lichtler's (1960) fault based on the offset of key gamma marker beds. The trend and movement along this fault was similar to that of the fault proposed by Lichtler (1960).

Mooney, *et al.* (1980), in a reconnaissance study, examined the structure, stratigraphy and hydrology of the Floridan aquifer system east of Lake Okeechobee. Of particular interest in this study is a post-Ocala, pre-Hawthorn gray calcilutite which Mooney, et al., referred to as the "unnamed calcilutite" or "unnamed limestone". They reported that the unnamed limestone was generally thin and contained some quartz sand and silt, but were unable to determine the age of the unit or whether it could be correlated with any established Florida formations.

The present study, in part, was designed as a follow-up to the investigation of Mooney, *et al.* (1980). The size of the study area was narrowed so that a number of unresolved problems and questions posed by Mooney, et al., could be examined in more detail. Where possible, the stratigraphic usage of those authors has been followed.

STRATIGRAPHY

Lithostratigraphy

The upper confining beds of the Floridan aquifer system consist of the lower beds of the Hawthorn Formation. Within the study area the lithology of the lower Hawthorn is variable, ranging from soft calcareous clays to hard moldic limestone. All Hawthorn rock types, however, contain some quartz sand and phosphorite and are characterized by a green to greenish-gray color. The lower contact of the Hawthorn is sharp. Core AG-106 shows that the contact between the Hawthorn and underlying limestones is erosional with coarse sands of the basal Hawthorn washed into solution cavities developed in the underlying limestone (Fig. 3). Well data in east central St. Lucie County and from one site in northeastern Martin County show that the Hawthorn Formation is underlain by a relatively thin unit of limestone. This unit ranges in thickness from 20 to 30 feet and has been identified in core AG-106 and wells SLF-26, SLF-28 and MF-28. In core AG-106 this limestone extends from 523 to 545 feet below MSL and varies from a hard, vuggy fossiliferous limestone at the top to a soft, fine-grained, calcarenite near the base. This limestone contains fairly abundant quartz sand and phosphorite and has a gray-green cast which distinguishes it from the underlying limestones which are white to cream in color. This unit is designated in this paper as the unnamed limestone A (U-A) and is equivalent to the upper portion of the unnamed calcilutite of Mooney, *et al.* (1980).

In areas where unit U-A is not present, the Hawthorn Formation is underlain by a white sandy to silty textured limestone. This limestone rarely contains a few fossil molds but generally is non-fossiliferous. Small amounts of quartz silt and traces of phosphorite may be present. In some instances this limestone contains microscopic black specks of undetermined composition. This limestone unit is referred to here as the unnamed limestone B (U-B), and is correlated with the lower portion of the unnamed calcilutite of Mooney, *et al.* (1980).

A distinctive feature of unit U-B is the presence of a layer of white to brown, soft, tabular, microlaminar phosphorite in the lower third of the unit. This zone of phosphorite is about 10 feet thick and is traceable throughout the study area. In peak abundance this microlaminar phosphorite makes up about 40% of the total rock volume. The tabular plates of phosphorite are generally about 1 mm thick and about 10 mm wide. They show many laminae in cross-section (Pl. 1, Figs. 1 and 2). Core AG-106 shows that the phosphorite fragments have a sub-horizontal orientation and are contained within a calcilutite matrix.

The fragments of phosphorite have rounded edges and often contain inclusions of smaller phosphorite fragments. The fact that this phosphorite does not show a distinctive x-ray diffraction pattern may be due to the dilution or masking effects of the large amount of calcite present or to the amorphous nature of this material. The phosphorite does, however, react positively with a phosphate reagent. This layer of phosphorite usually occurs in the lower part of unit U-B and serves as an excellent marker on gamma-ray logs.

Below this layer of phosphorite, in some places unit U-B grades downward into a biocalcarenitic unit containing benthic foraminifers and bryozoans, but little or no quartz silt. Unit U-B ranges in thickness from a maximum of 390 feet at well MF-4 to a minimum 123 feet at well MF-27.

The base of unit U-B is marked by its contact with the Ocala Limestone. Lithologically the contact may not appear sharp in cuttings, and geophysical evidence may be needed to confirm its precise location. The contact in core AG-106 at a depth of -680 feet MSL is very sharp and is probably erosional. The appearance of abundant, large *Lepidocyclina* species marks the top of the Ocala. The contact is less distinct in Martin County, especially near the coast at wells MF-35 and MF-4; here the contact appears gradational and faunal differences are less distinct.

The Ocala Limestone is generally a cream biocalcarenite containing many large species of foraminifers. Two wells on Hutchinson Island (MF-35 and MF-4) show an

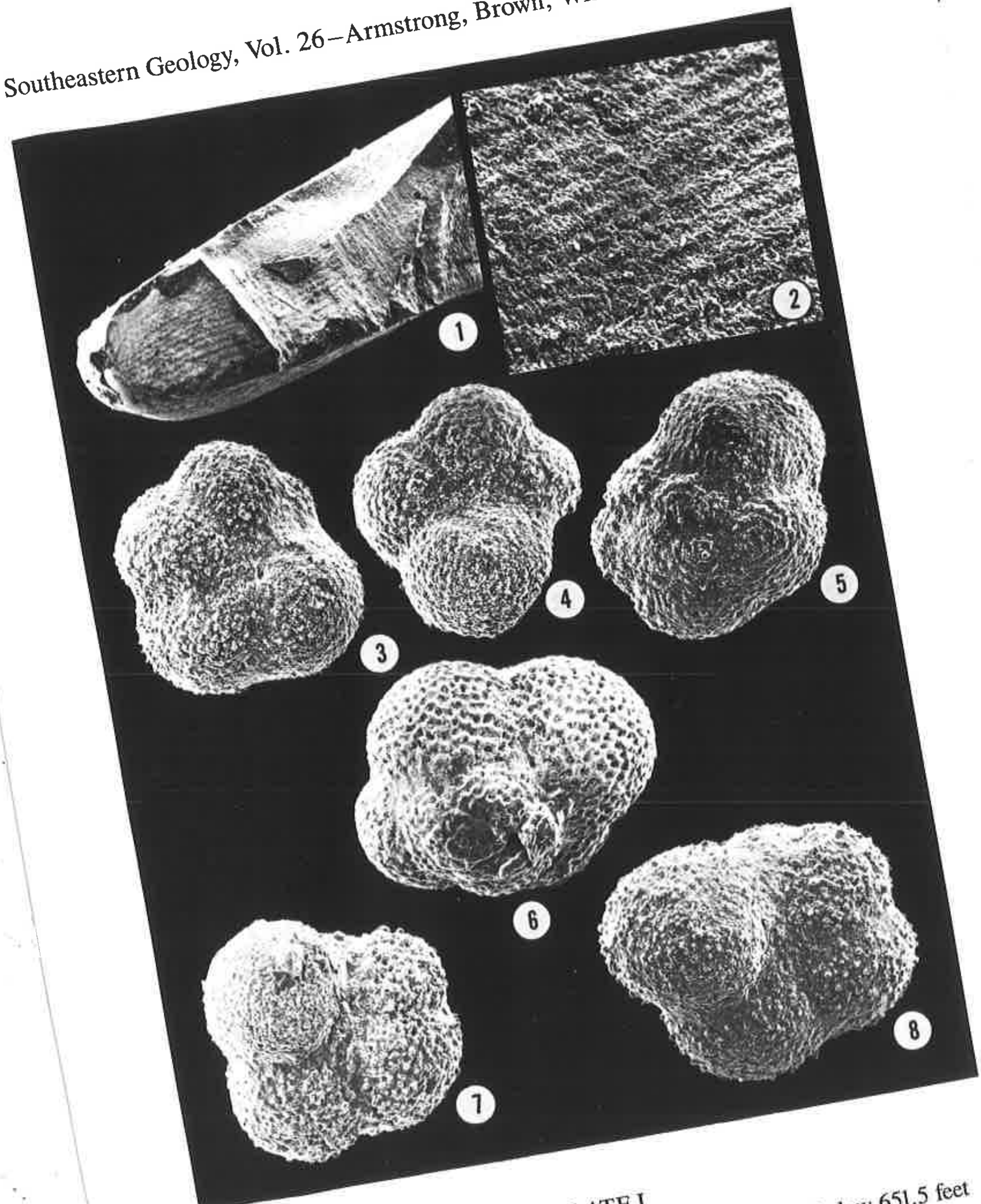

PLATE I

Figures 1 and 2: Microlaminar phosphorite, core AG-106, below 651.5 feet MSL: (1) X 64; (2) X 416.
Figure 3-8: *Globorotalia opima nana* Bolli well MF-35, 875-880 feet below MSL: (3) umbilical view, X 224; (4) umbilical view, X 192; (5) spiral view, X 152; (6) spiral view, X 144; (7) umbilical view, X 160; (8) umbilical view, X 224.

characteristic upper Eocene forms such as *Discoaster barbadiensis* Tan Sin Hok, *Discoaster saipanensis* Bramlette and Riedel or *Reticulofenestra reticulata* (Gartner). A similar date was obtained at about this level in core AG-106 (640 feet). A note of caution is attached to these dates because discoasters are quite rare in wells of this area, but *R. reticulata* has been noted in the upper Eocene penetrated by other wells in the vicinity.

Geophysical Characteristics of Formations

As mentioned previously, borehole geophysical logs have proven to be a valuable and reliable tool in the identification and correlation of subsurface units within the study area. Through a comparison of lithologic units with geophysical logs, a geophysical signature for each subsurface unit was recognized. Although many types of logs can be useful in distinguishing subsurface units, the gamma-ray and electrical resistivity logs proved to be the most useful and most commonly available. They are the only two logs discussed here although the additional log types served to reinforce or verify interpretations of the gamma-ray and resistivity logs.

The gamma-ray log was used most extensively for this study. This log is basically a measure of the natural radioactivity of a unit. It is quite useful for the delineation of clays, phosphorites and, to a lesser extent, dolomites. It is also valuable because it may be run in a cased hole. Since water supply wells in the study area are often cased to the base of the Hawthorn, it is commonly the only log available for this interval.

The electrical resistivity log measures the bulk or saturated electrical properties of a formation by passing an electrical current through the rocks via an array of electrodes. Electrical resistivity logs are especially useful in distinguishing the presence of limestone.

The base of the Hawthorn is marked by a very sharp decrease in gamma-ray activity, usually just below a large gamma peak (Fig. 3). Below the Hawthorn Formation, unit U-A can be readily distinguished by a gamma-ray activity which is much lower than that of the lower Hawthorn but higher than that of the subjacent limestone of unit U-B. The base of unit U-A is usually marked by a sharp gamma peak.

Unit U-B is generally characterized by a very low gamma activity except near the base of the unit, where a sharp gamma peak marks the presence of the microlaminar phosphorite bed mentioned previously. A small resistivity peak may also be associated with this bed. This phosphorite layer is a key marker bed recognizable throughout the study area.

The boundary between unit U-B and the underlying Ocala Limestone is marked by both a small gamma-ray and electrical resistivity peak. Of all the unit boundaries recognized, the Ocala top is the most difficult to distinguish on geophysical logs. When considered along with lithologic samples, however, it can be readily discriminated. The Ocala shows low gamma-ray activity. The base of the Ocala is recognized only in wells SLF-26 and SLF-28, using geophysical criteria established by Mooney, et al. (1980) and made in any of the wells included in this study.

STRATIGRAPHIC-STRUCTURAL INTERPRETATIONS AND CORRELATIONS

Structure

Structure contour maps, isopach maps, and geologic cross-sections have been constructed using the data given in Table II. This table shows the depth below mean sea level to the tops of units U-A, U-B, and the top of the Ocala Limestone as well as the depth to the gamma-ray marker within unit U-B.

Figure 4 is a cross-section across northern Martin County. Data for the three westernmost wells on this cross-section (MF-6, MF-2A, and MF-30) were taken from Mooney, *et al.* (1980). For the location of Mooney's wells, see Figure 1. Note particularly the thickening of the post-Ocala/pre-Hawthorn limestone to the east in the offshore shelf edge direction.

Table II. Depth below mean sea level of unit boundaries and the gamma-ray marker bed.

Well No.	Top of Unit U-A	Top of Unit U-B	Top of Gamma-ray Marker Bed	Top of Ocala	Thickness of U-A and U-B
MF-3	Not present	715	875	Not Reached	?
MF-4	Not present	804	1019	1200	390
MF-27	Not present	767	870	890	123
MF-28	763	788	898	933	145
MF-31	Not present	690	815	855	165
MF-32	Not present	770	850	890	140
MF-33	Not present	705	870	990	285
MF-35	Not present	915	1075	1215	300
SLF-26	610	635	730	770	135
SLF-28	574	604	707	744	140
AG-106	523	550	636	680	130

All depths in feet below MSL

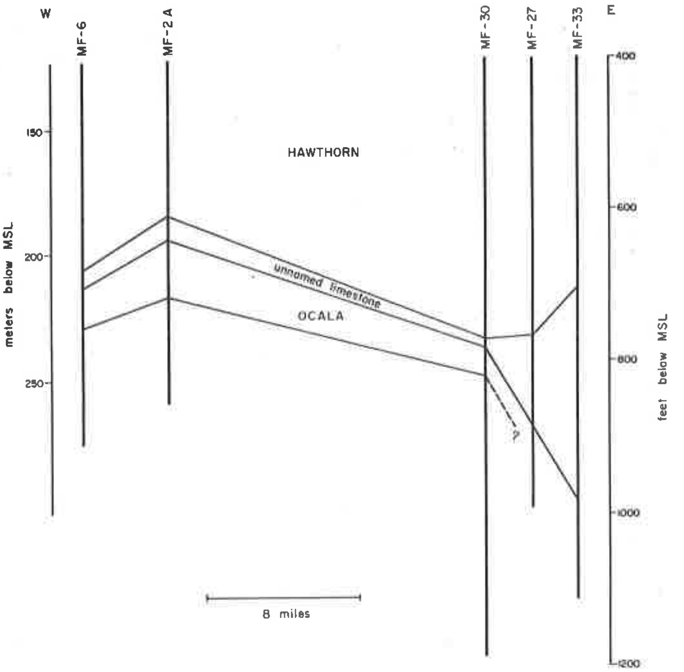

Figure 4. Stratigraphic cross-section across northern Martin County, Florida.

Structure contour maps for the top of the Ocala, the gamma-ray marker near the base of units U-B, and for the base of the Hawthorn (Fig. 5) all show a similar configuration with beds dipping to the east southeast. Two notable exceptions to this trend occur in northeast Martin County where beds in well MF-31 reflect a structural high, and wells MF-35, MF-3 and MF-4 are offset sharply downward. This offset is interpreted as a fault which is here called the Hutchinson Island fault. Thickening of units on the downthrown side of the fault (example, Fig. 5) suggests that movement along the fault began at least as early as Ocala time. Offsets of 100 feet at the base of the Hawthorn between wells MF-33 and MF-4 as well as a thickening of unit U-B across the fault suggest that movement along the fault continued during the deposition of unit U-B and into Hawthorn time. The apparent offset of the top of the Ocala, between wells MF-33 and MF-4, shows a minimum of 200 feet of movement. This does not take into account movement along the fault which may have occurred prior to the end of Ocala time.

The fact that the base of the Hawthorn is offset 100 feet between MF-33 and MF-4 but only 25 feet between MF-31 and MF-3 suggests that movement along the downthrown block may not have been uniform along the length of the fault. An alternative explanation is that the study wells are located within a fault zone where movement of many small blocks presents an irregular pattern. An attempt has been made to contour the downthrown side of the fault block, within the limits of well control to the east of the fault.

The northwest extension of the Hutchinson Island fault cannot be documented due to the lack of well control in St. Lucie County. One could speculate, however, that this fault or fault system extends northward along the eastern margin of St. Lucie County and connects with the fault system proposed by Bermes (1958) in Indian River County.

Faulting along the western margin of the study area has been proposed in a number of earlier studies but cannot be documented in this study without further well control (Lichtler, 1960; Vernon, 1970; Anonymous, 1975a). The presence of a thickened sequence of post-Ocala/pre-Hawthorn limestones (units U-A and U-B) is confirmed by this study however, suggesting possible downwarping or faulting near the western margin of the study area (Fig. 4).

An isopach map of units U-B and U-A (Fig. 6) shows that the combined thickness of these units ranges from 120 feet thick at well MF-32 to 390 feet at well MF-4. In St. Lucie County and the area in Martin County west of the Hutchinson Island fault, unit U-B generally ranges in thickness from about 120 to 140 feet near the fault; on the downthrown side unit U-B thickens to about 390 feet.

Cross-section (Figs. 7-11) and isopach maps show that unit U-B in St. Lucie County and the area in Martin County west of the Hutchinson Island fault is relatively uniform in thickness, thickening slightly to the east in Martin County. This rather uniform thickness suggests that units U-A and U-B were laid down on a relatively smooth surface. If the unit had been deposited on a surface with much local relief, deposition would have created local variations in thickness.

The fact that structure maps for the top of the Ocala, the gamma-ray marker bed within unit U-B and the base of the Hawthorn all show a similar configuration suggests that deformation of these beds (warping, not faulting) did not occur until after their deposition, i.e., during Hawthorn time or later.

Stratigraphy

The Hawthorn Formation and the Ocala Limestone have been recognized within the study area. The base of the Hawthorn is easily recognized by virtue of its distinctive lithology and geophysical signature. The Ocala Limestone is also easily distinguished where it occurs as a coarse foraminiferal biocalcarenite on the upthrown side of the Hutchinson Island fault. The intervening interval of post-Ocala/pre-Hawthorn rocks (units U-A and U-B), however, is much more difficult to correlate with historically recognized units within Florida. Mooney, et al. (1980) discuss several possibilities concerning the nomenclatural affinities of their "unnamed calcilutite", which corresponds to units U-A and U-B of the present study. These possibilities include the following:

(1) The limestone is part of the lower Hawthorn Formation,
(2) It is part of the Tampa Limestone,
(3) It is part of the Suwannee Limestone,
(4) The limestone represents a new formation.

When Mooney, *et al.* (1980) made these speculations, they did not have the benefit of knowing the age of the calcilutite. Examination of cuttings and core samples during the present study has yielded datable assemblages of coccoliths and planktonic foraminifers which help to clarify the status of these post-Ocala/pre-Hawthorn limestones.

The base of unit U-B has been dated as early Oligocene by coccoliths from core AG-105, 694 feet. In well MF-35, the lowermost Hawthorn is late Oligocene in age. If the base of the Hawthorn lies above an unconformity throughout the study area as it does in core AG-105, then the presence of Oligocene age Hawthorn in MF-35

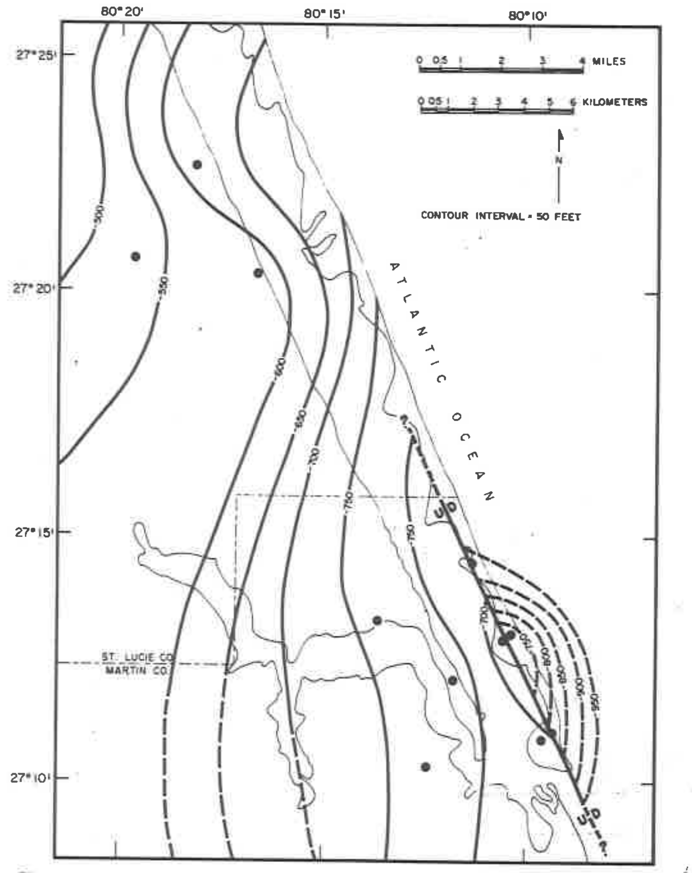

Figure 5. Structural contour map of the base of the Hawthorn Formation. Elevations are in feet below mean sea level.

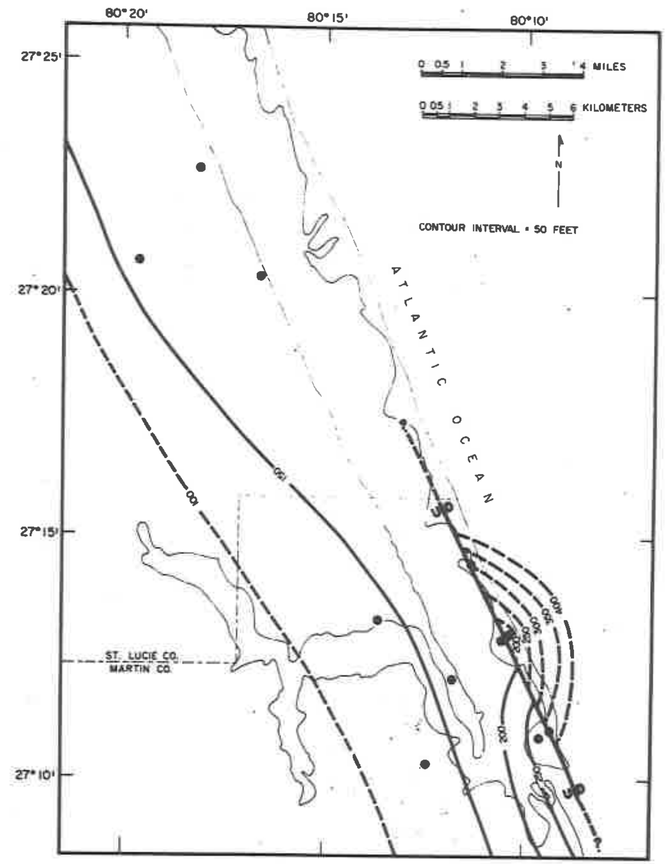

Figure 6. Isopach map of units U-A and U-B.

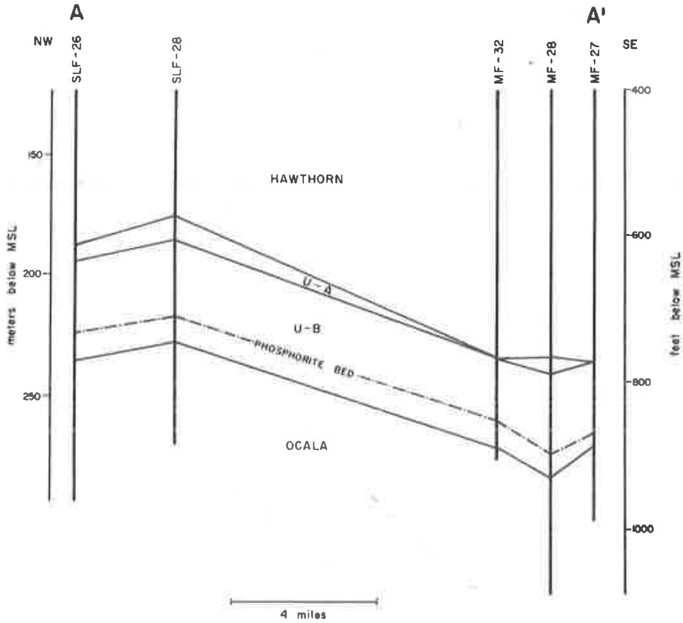

Figure 7. Stratigraphic cross-section A-A'.

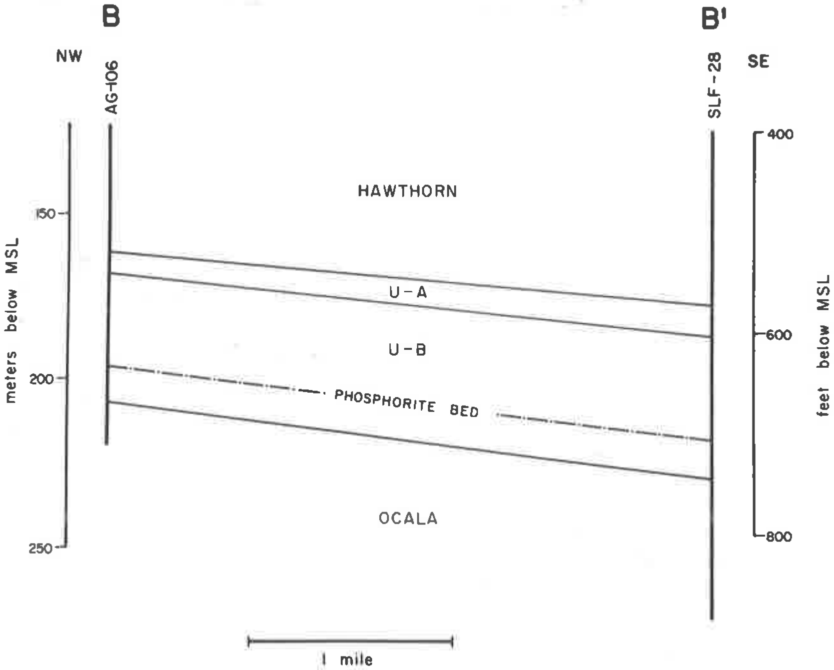

Figure 8. Stratigraphic cross-section B-B'.

suggests that the erosional event which preceeded the deposition of Hawthorn sediments must have occurred during the late Oligocene.

A major worldwide eustatic sea level drop and erosional event during the middle of the late Oligocene (29 Ma) has been suggested by Vail, *et al.* (1977). This, the largest sea level drop proposed by these authors for the Cenozoic, would have caused widespread erosion across the Florida peninsula and the erosional boundary (shoreline)

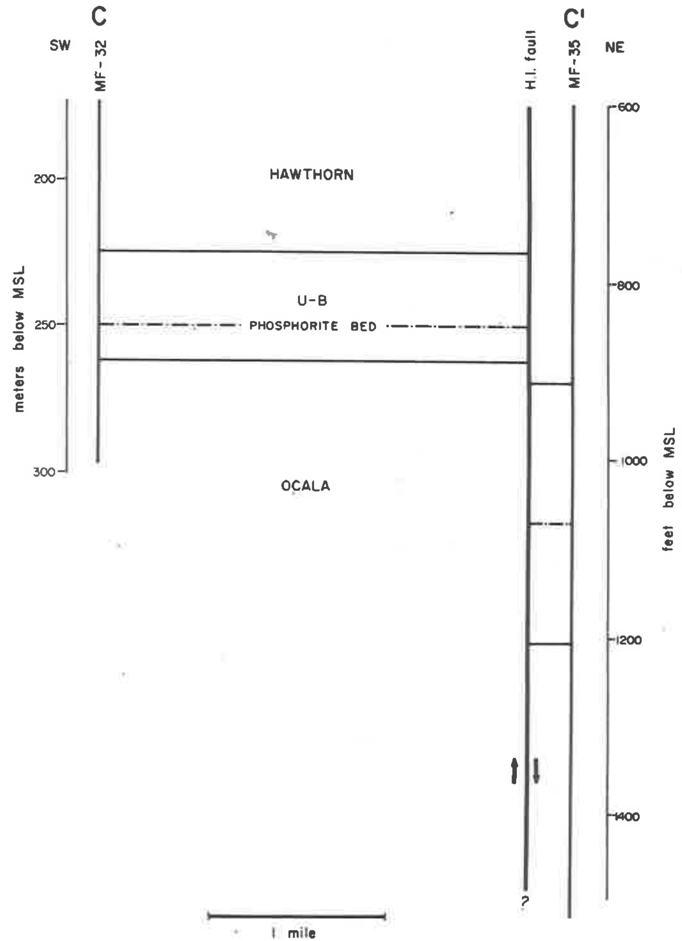

Figure 9. Stratigraphic cross-section C-C'.

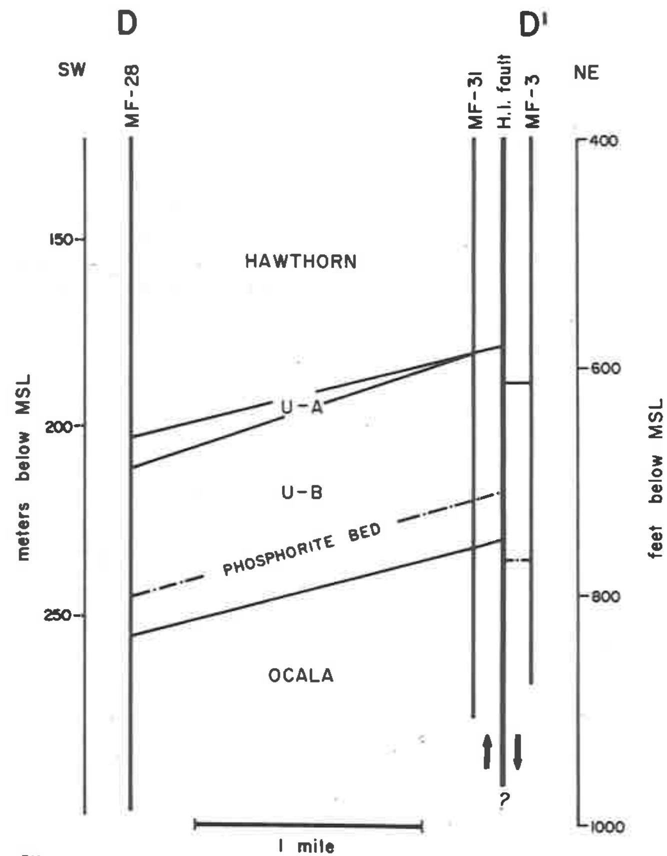

Figure 10. Stratigraphic cross-section D-D'.

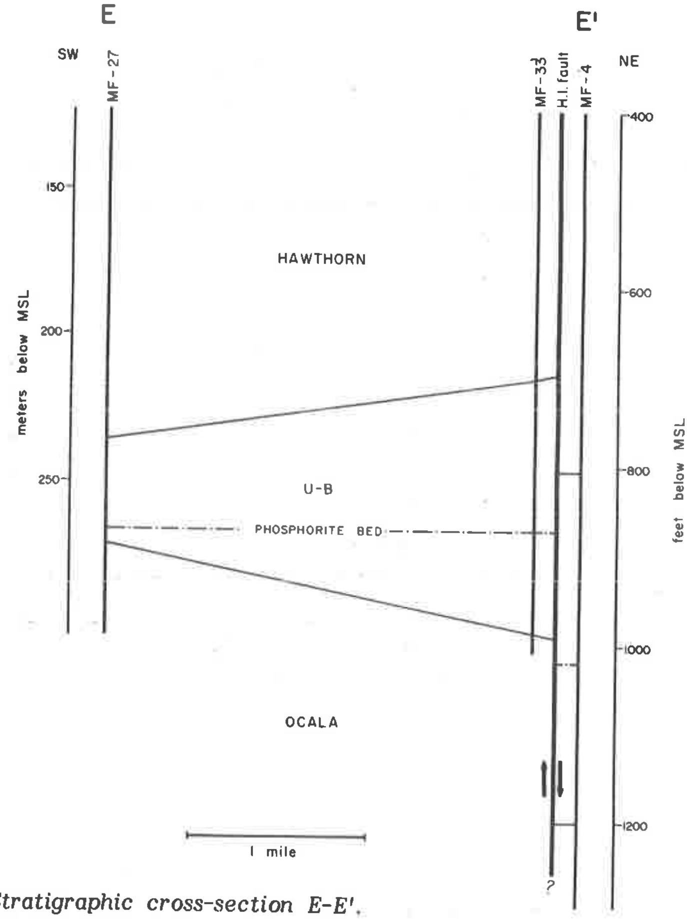

Figure 11. Stratigraphic cross-section E-E'.

would have moved far seaward of the present coastline.

The survival of thick sequences of early Oligocene age rocks (units U-A and U-B) in Martin and St. Lucie Counties suggests that these areas were structurally low relative to the rest of the peninsula, and were protected from erosion. Structurally higher areas to the west were stripped entirely of this Oligocene cover, or only a thin residuum remained, as is the case in most of central and western Martin and St. Lucie Counties (Mooney, et al., 1980).

Subsequently, during late Oligocene time sea level began to recover. As sea level rose, deposition of the Hawthorn Formation began first in structurally low areas. Thickened sections of Hawthorn sediments which accumulated on the downthrown side of the Hutchinson Island fault show that this area was still structurally low. Thus the late Oligocene Hawthorn preserved at well MF-35 may represent some of the oldest Hawthorn preserved beneath the present peninsula of Florida. Figure 12 is an interpretative diagram which shows the proposed depositional sequence in relation to the sea level changes proposed by Vail, *et al.* (1977).

It is interesting to note that the major change from a carbonate environment to a detrital depositional regime follows this large-scale episode of regression. A worldwide regression of this magnitude would surely expose extensive areas to subaerial erosion, thus providing a logical source for the large amounts of Hawthorn clastics.

If the data concerning the beginning of Hawthorn deposition are correct, then the age of the post-Ocala/pre-Hawthorn limestone is bracketed to the interval between the early Oligocene date obtained from coccoliths near the base of unit U-B and the time of the late Oligocene regression which was followed by the onset of Hawthorn deposition. Units U-A and U-B, then, would have been deposited between about 29 and

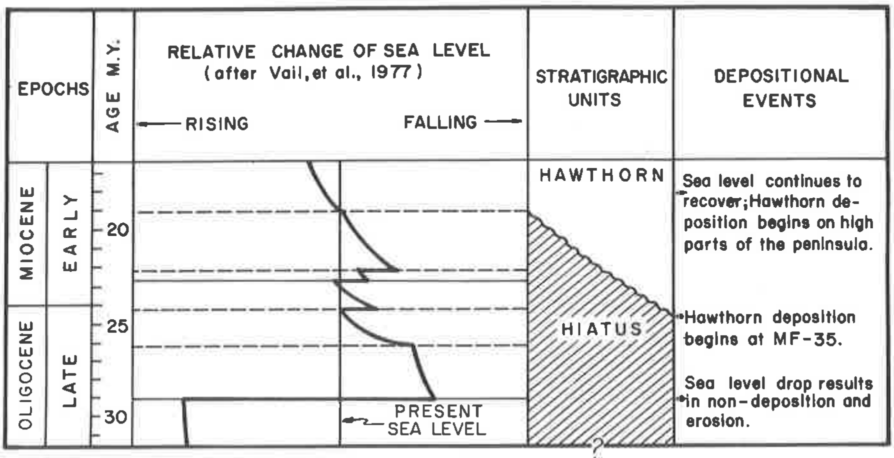

Figure 12. Comparison of eustatic sea level changes during the mid-Tertiary (from Vail, et al., 1977) with the proposed depositional sequence on the Florida platform.

37 m.y. BP, assuming the Vail curve shown in Figure 12 applies to south Florida.

It is important to note that the first stratigraphic occurrence of phosphorite encountered in the section is in the lower part of unit U-B. As far as is known, this is the first report of phosphorite in the lower Oligocene of Florida.

Assignment of an early Oligocene age to units U-A and U-B helps to clarify the correlation of these units with established Florida formations. These units are somewhat older than the Tampa and Hawthorn Formations which are considered to be no older than late Oligocene or early Miocene, respectively (King and Wright, 1979). The ages determined in this investigation suggest that the Suwannee Limestone may be an equivalent of units U-A and U-B. Although quartz, as found in units U-A and U-B is more common in the Tampa and Hawthorn formations, it is not unknown from the Suwannee (Boggess, *et al.*, 1977). The microfaunal content of units U-A and U-B, however, differs significantly from that described for the Suwannee Limestone by Applin and Jordan (1945). If further studies can establish the physical relationships between the Suwannee and these Oligocene units, it should be possible to resolve the problem of whether these units should be referred to as a facies of the Suwannee or whether they deserve a separate and new formational name.

As previously mentioned, examination of lithologic cuttings from depths of about 1200 feet in wells MF-4 and MF-35 on the downthrown side of Hutchinson Island fault reveal a fine-grained, sparsely fossiliferous limestone. The stratigraphic position of this limestone (subjacent to unit U-B) suggests that it is an equivalent of the Ocala Limestone, characteristic examples of which occur nearby in wells on the upthrown side of the fault. This limestone differs from the typical Ocala in containing few species of larger foraminifers such as *Lepidocyclina* and *Operculinoides*. Also species of *Dentalina*, *Miogypsina*, rare *Heterostegina* and *Gypsina* are present.

In a study of the geology of Jackson County in panhandle Florida, Moore (1955, pp. 42-43) noted the presence of a similar limestone which he called the Gadsden Limestone. He reported that it was a fine grained equivalent of the upper Ocala which contained no, or few, larger foraminifers such as *Lepidocyclina*, *Asterocyclina*, or *Operculinoides*. Moore interpreted the Gadsden Limestone as a deep water facies of the Ocala deposited in a structural low. He estimated a maximum difference in depositional depths of 181 feet between the shallow-water Ocala and deeper-water Gadsden Limestone, based on an analysis of structure- and of depth-dependent benthic foraminiferal assemblages (Moore, 1955, pp. 74-76).

Puri (1957, pp. 38-41) also recognized this facies of the Ocala but did not recognize the name Gadsden Limestone proposed by Moore. Puri referred to the limestone as the downdip facies of the Ocala Group.

Moore (1955) felt that the high percentage of foraminifers typical of the outer neritic and inner bathyal zones in the Gadsden Limestone suggested deep water deposition. In the study area considered here, the relative absence of such deep water species suggests that differences in water depth may not have been as great as in the case of the Gadsden Limestone. However, the absence of large species of foraminifers in the study area suggests a parallel to the Gadsden Limestone (see Moore, 1955, p. 74).

The fine-grained limestones which lie to the east of the Hutchinson Island fault are inferred to be deep-water equivalents of the Ocala Limestone, deposited in a stuctural low created by movement along the Hutchinson Island fault during the Eocene. Well MF-35 penetrated approximately 500 feet of this unit without reaching the base. If the entire 500 feet of this deep water limestone is indeed equivalent to the Ocala, then there was significant movement along the fault during late Eocene (Ocala) time.

An alternative explanation for the thickened Eocene sequence is that movement along the fault began prior to Ocala time, thus we may be looking at a deep-water equivalent of the middle Eocene Avon Park Limestone which normally underlies the Ocala in Florida. Such an explanation, however, does not explain the absence of the characteristic upper Ocala in well MF-35.

Hydrogeology

The Floridan aquifer system consists of the permeable limestones that lie below the confining beds of the Hawthorn Formation and range in age from Oligocene to middle Eocene. The oldest part of the aquifer system encountered in the present study is in the upper Eocene Ocala Limestone.

The Floridan aquifer system in east central Florida is generally characterized by several relatively thick, laterally continuous producing zones. These zones are usually associated with lithologic changes (Brown and Reece, 1979). Local drillers often report hitting "hard spots" associated with increased flows.

Within the study area, the most prolific water producing zone is the upper portion of the Ocala Limestone. Lithologically, this producing zone consists of the coarse biocalcarenite of the upper part of the Ocala Limestone. This biocalcarenite usually has a high intergranular porosity. In contrast the limestones above and below this producing zone generally are much finer-grained, have lower porosity, and contribute only small amounts of water to the total production of a given well.

The upper Ocala producing zone seems to be fairly consistent throughout the study area, except along the extreme northeastern portion of Martin County in wells MF-4 and M-35. The producing zone in these wells is poorly defined and its overall yield is poor. This poor production lies east of the Hutchinson Island fault and may be the result of a number of factors.

It is possible that the total volume of water flowing through the aquifer system remains the same on either side of the fault, but that the flow must expand to fill a larger volume of rock east of the fault so that wells drilled into these units yield less production per foot drilled. This explanation does not, however, seem entirely satisfactory in the case of well MF-35 which yielded less than 50 gallons per minute from nearly 800 feet of section within the Floridan aquifer. Characteristic yields from the Floridan aquifer are generally much greater than this, and are produced from much thinner sections. The poor water production may possibly be related to either the primary or secondary effects of faulting. Poor production may be related to the finer-grained nature of the deep-water facies of the Ocala that is present on the downthrown (eastern) side of the fault. The fine-grained sediments are much less porous than the typical upper Ocala Limestone. In addition, continuous downward movement along the fault from Ocala time (or earlier) through early Hawthorn time may have inhibited the formation of distinct flow zones. A final possibility is that the fault acts as a structural barrier across which flow from the Floridan aquifer is inhibited or disrupted.

SUMMARY AND CONCLUSIONS

The geology of the Floridan aquifer system has been studied using lithologic well samples and geophysical logs. These studies have allowed the delineation of several subsurface units and the following conclusions:

1. The "unnamed calcilutite" delineated by Mooney, *et al.* (1980) has been recognized within the present study area and has been subdivided into two units, units U-A (upper) and U-B (lower). The age of this unnamed limestone has been bracketed between early Oligocene and mid-late Oligocene through the use of microfaunal dating techniques. The phosphorite which occurs in unit U-B may be the oldest such deposit in Florida.

2. Faulting in the western portion of the study area as reported in some earlier studies cannot be confirmed with the well control used in this study. A new fault, the Hutchinson Island fault, has been recognized from well data on Hutchinson Island in eastern Martin County. Movement along the fault began at least as early as late Eocene Ocala time and continued into early Hawthorn time. Movement along the Hutchinson Island fault created structurally negative areas where thickened accumulations of sediments were deposited. Well yields in the Floridan aquifer east of this fault are low.

3. A deep-water facies of the Ocala Limestone has been recognized in Martin County east of the Hutchinson Island fault.

4. A late Oligocene age has been demonstrated for the lower part of the Hawthorn Formation east of the fault. This suggests that deposition of the Hawthorn Formation had begun in structurally low areas by late Oligocene.

5. Structural contour maps and cross-sections show that the study area was affected by faulting or folding as late as Miocene time.

ACKNOWLEDGEMENTS

This study was condensed from a masters thesis submitted by the senior author to the Department of Geology, Florida State University, in partial fulfillment of degree requirements (Armstrong, 1980). We are especially grateful to members of the South Florida Water Management District, particularly to Mr. Abe Kreitman, Director of the Groundwater Division, who was instrumental in providing funds and logistical support for the project. Drs. J. B. Cowart and Ramil C. Wright (FSU) kindly read early drafts of the paper and Ms. Muriel Hunter provided helpful discussion. We particularly thank James A. Miller (U.S. Geological Survey, Atlanta) for his meticulous review of the final draft. Rosemarie Raymond, Louise Cox, Dennis Cassidy, Tom Fellers, and Steve Peacock (all FSU) provided valuable assistance in preparing the manuscript.

We are pleased to acknowledge the Florida Bureau of Geology which provided important samples and assistance. We particularly thank Messrs. Tom Scott, Michael Knapp, Ed Lane and Ron Hoenstein.

In addition, we are grateful to the Florida Power and Light Company for permission to examine their cores taken in connection with the construction of the Hutchinson Island nuclear power plant.

REFERENCES CITED

American Commission on Stratigraphic Nomenclature (ACSN), 1970 Code of stratigraphic nomenclature: Am. Assoc. Petrol. Geol. Tulsa, 22 p.

Anonymous, 1975a, PSAR St. Lucie unit 2 (Rev. 26 - 1/8/75), Docket No. 50-335: engineering report, Law Engineering Company, Tampa, Florida, p. 2. 5-1 through 2.8 (unpublished).

Anonymous, 1975b, Drilling and testing of deep disposal and monitoring wells, the city of Stuart, Martin County, Florida, Project No. 307-74-52: engineering report, Black, Crow and Eidsness, Inc., Gainesville, Florida, 51 p. (unpublished).

Applin, P. L., and Applin, E. R., 1944, Regional subsurface stratigraphy and structure of Florida and southern Georgia: Am. Assoc. Petrol. Geol. Bull., v. 28, p. 1673-1753.

Applin, E. R., and Jordan, L., 1945, Diagnostic foraminifera from subsurface formations in Florida: Jour. Paleo. v. 19, p. 129-148.

Armstrong, J. R., 1980, The geology of the Floridan Aquifer System in eastern Martin and St. Lucie counties, Florida: Master's Thesis, Department of Geology, Florida State University, 72 p. (unpublished).

Bermes, B. J., 1958, Interim report on geology and ground water resources of Indian River County, Florida: Florida Geol. Surv. Information Circular No. 18, 74 p.

Boggess, T. M., Missimer, T. M., and O'Donnell, T. H., 1977, Saline-water intrusion related to well construction in Lee County, Florida: U.S. Geological Survey Water-Resources Investigations 73-33.

Brown, M. P., and Reece, D. R., 1979, Total dissolved solids of Floridan Aquifer Systems waters for September, 1977, Upper East Coast Planning Area: South Florida Water Management District: Hydrogeologic Map Atlas, Map Series 79-1.

Chen, C. S., 1965, The regional lithostratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geol. Surv. Bull. 45, 105 p.

King, K. C. and Wright, R. C., 1979, Revision of the Tampa Formation West Central Florida: Gulf Coast Assoc. Geol. Soc. Transactions, 29.

Lichtler, W. F., 1960, Geology and ground water resources of Martin County, Florida: Florida Geol. Surv. Report of Investigations 23, 149 p.

Martini, E., 1971, Standard Teritary and Quarternary calcareous nannoplankton zonation: *in* Farinacci, A., 1971, Proceedings of the II Planktonic Conference, Roma, Tecnoscienze (Rome), 739-785.

Mooney, R. T., Brown, M. P., and Wise, S. W., 1980, The Stratigraphy of the Floridan Aquifer System east and northeast of Lake Okeechobee, Florida: Southeastern Geology, 21, 261-277.

Moore, W. E., 1955, Geology of Jackson County, Florida: Florida Geol. Surv. Bull. 37, 101 p.

Parker, G. G., Ferguson, G. E., and Love, S. K., 1955, Water Resources of Southeastern Florida: U.S. Geol. Surv. Water-Supply Paper 1255, 965 p.

Puri, H. S., 1957, Stratigraphy and zonation of the Ocala Group: Florida Geol. Surv. Bull. 38, 248 p.

Reece, D. E., Brown, M. P., Hynes, S. D., 1980, Hydrogeologic data collected from the upper east coast planning area, South Florida Water Management District, SFWMD Technical Publication 80-5, 117 p.

Stainforth, R. M., Lamb, J. L., Luterbacher, H., Beard, J. H., and Jeffords, R. M., 1975, Cenozoic planktonic foraminiferal zonation and characteristics of index forms: The University of Kansas Paleontological Contributions, Article 62, 425 p.

Vail, P. R., Mitchum, R. M., Jr., and Thompson, S., III, 1978, Relative changes of sea level from coastal onlap, *in* Payton, C., ed., Stratigraphic interpretations of seismic data: Am. Assoc. of Petrol. Geol. Mem. 26, p. 63-81.

Vernon, R. O., 1970, The beneficial use of zones of high transmissivities in the Florida subsurface for water storage and waste disposal: Florida Geol. Surv. Information Circular 70, 39 p.

PALEOECOLOGY OF A DELTA SLOPE COMMUNITY FROM THE LOWER MISSISSIPPIAN BORDEN FORMATION IN CENTRAL KENTUCKY

THOMAS W. KAMMER
KENYON D. COX

Department of Geology and Geography, West Virginia University, Morgantown, WV 26506

ABSTRACT

An Early Mississippian delta slope fauna from the Nancy Member of the Borden Formation in central Kentucky is analyzed in terms of faunal composition and paleoecology. The fauna occurs at two sites near St. Francis, Kentucky. At one site, IU10884, only 10 taxa, all brachiopods, were found. The other site, IU10885, had 47 taxa of brachiopods, crinoids, bryozoans, corals, gastropods, conularids, trilobites, and sponges. The first site records an early successional stage of community development, whereas the second site records an advanced successional stage of community development. Community succession resulted from the process of taphonomic feedback, whereby the skeletal debris of pioneering brachiopods provided larval settlement sites for later generations.

This Nancy fauna is the most diverse fauna recorded from the delta slope environment of the Borden delta. The relatively high diversity is the result of community succession. The fauna does not contain endemic taxa, rather the fauna consists of taxa that migrated from the prodeltaic and delta platform environments.

INTRODUCTION

The Lower Mississippian Borden Formation in Kentucky and Indiana comprises deltaic sediments deposited by a rapidly prograding deltaic complex termed the Borden delta (Kepferle, 1977; Ausich and others, 1979; Kammer and others, 1983). Ausich and others (1979) reported that each depositional environment of the Borden delta was characterized by a unique community, or communities, of benthic invertebrates. On the basis of community composition and structure, they were able to recognize basinal, prodeltaic, delta slope, and platform communities. All the delta slope faunas studied were from southern Indiana.

In 1979 Alan Horowitz of Indiana University brought to Kammer's attention a collection of fossils from the Nancy Member of the Borden Formation at two sites near St. Francis, Kentucky (Fig. 1). The Nancy Member consists of Borden delta slope deposits (Kepferle, 1977). The sites were originally collected by Horowitz and Kepferle in 1969. Kepferle reported the sites on the geologic map of the Raywick Quadrangle (Kepferle, 1973). From 1982 to 1984, Kammer made additional collections at the sites.

The present paper is a report on the paleoecology of these fossil faunas from the Nancy Member in central Kentucky. These faunas represent the best developed, and most diverse, Borden delta slope community known. The community at one of the sites (IU10885) in this study is twice as diverse as any of the delta slope sites in southern Indiana (47 species vs. 23 species). Thus, information from these delta slope sites constitutes a valuable addition to the body of knowledge on the Borden delta communities.

All the specimens upon which this report is based are in the paleontological collections of the Department of Geology, Indiana University under the catalog numbers IU10884 and IU10885.

GEOLOGIC SETTING

The overall depositional history of the Borden delta and its constituent facies in north-central Kentucky is discussed in Kepferle (1977), Ausich and others (1979), Kammer and others (1983), and Kammer (1985a). The Nancy Member of the Borden Formation was deposited in the delta slope environment (Fig. 2). The Nancy Member

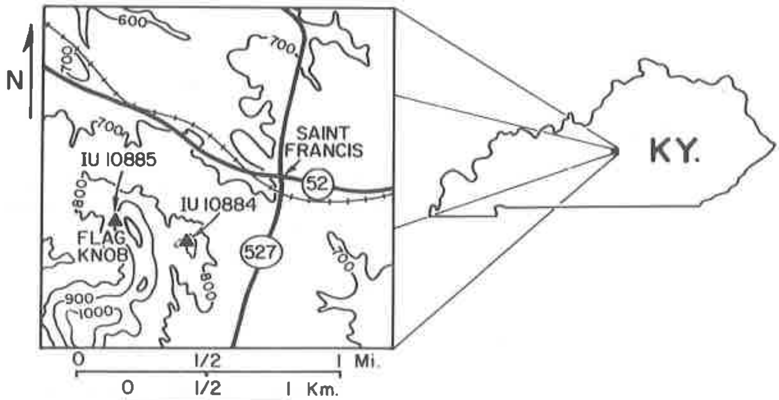

Figure 1. Locality map showing the two sites near St. Francis, Kentucky, where the Nancy fauna was collected. Contour interval is 100 ft.

consists of light-olive-gray to greenish-gray silty shales and siltstones. Typically, primary bedding is not preserved because of bioturbation. Kepferle (1977) reported obscurely ripple-laminated bedding in the Nancy, although it is usually disturbed by bioturbation. The fossils were enclosed in soft, silty shale in an approximately two-meter thick zone at both sites. At site IU10885 the silty shale was overlain by thin-bedded siltstones containing scattered fossil debris consisting mostly of crinoid columnals and bryozoans. The two sites are stratigraphically located within the middle part of the 36 m thick Nancy. Their stratigraphic position was determined by plotting their geographic location on the Raywick Quadrangle geologic map (Kepferle, 1973). Construction of a stratigraphic section showing the precise horizon(s) of the two localities is not possible because the fossiliferous outcrops are limited exposures on densely forested slopes.

Depositional conditions within the Nancy were characterized by a moderate to rapid rate of deposition and weak current energy (Kepferle, 1977). By comparison, the prodelta had a slow rate of deposition and little or no current energy (Kepferle, 1977; Kammer, 1985a), whereas the delta platform exhibited a range of sedimentary facies including cross-bedded and channelled sediments indicating high current energy and associated rapid deposition on some parts of the platform (Ausich and Lane, 1980). The lack of obvious physical sedimentary structures and the abundance of bioturbation in the Nancy Member indicates deposition was below normal wave base (Howard, 1978).

FAUNA OF THE NANCY MEMBER

The fauna consists of 47 taxa of macroinvertebrates (Table 1). Brachiopods are

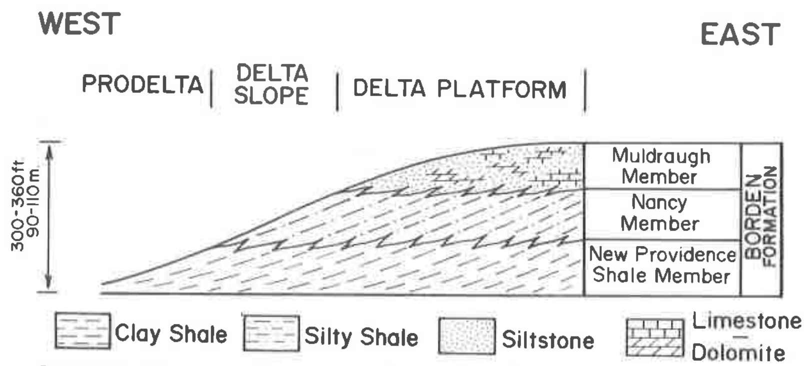

Figure 2. Generalized depositional model for the Borden delta in central Kentucky. The Muldraugh Member contains sediments deposited in both a delta platform environment and a later carbonate platform environment.

Table 1. Fauna of the Nancy Member near St. Francis, Kentucky; occurrence of taxa in the prodelta and delta platform environments of the Borden delta is also indicated.

TAXA	PRODELTA	PLATFORM
CRINOIDS		
Eretmocrinus sp.	X	X
Dorycrinus gouldi (Hall)		X
Eucladocrinus millebrachiatus (Wachsmuth and Springer)	X	
Platycrinites cf. P. planus (Owen and Shumard)	X	
Halysiocrinus tunicatus (Hall)	X	X
Catillocrinus turbinatus Springer	X	X
Cyathocrinites nodosus (Wachsmuth and Springer)	X	
C. parvibrachiatus (Hall)	X	X
Forbesiocrinus sp.	X	
BRACHIOPODS		
Rhipidomella oweni (Hall and Clarke)	X	
Schuchertella sp.	X	X
Rugosochonetes shumardianus (DeKoninck)	X	
Echinoconchus alternatus (Norwood and Pratten)		X
Marginatia crawfordsvillensis (Weller)	X	X
Athyris cf. A. lamellosa (Leveille)		X
Cleiothyridina parvirostra (Meek and Worthen)	X	X
C. cf. C. obmaxima (McChesney)		X
Voiseyella? sp.	X?	
Tylothyris sp.		X
Prospira floydensis (Weller)	X	X
Imbrexia mortonanus (Miller)		X
Brachythyris suborbicularis (Hall)	X	X
BRYOZOANS		
Hederella sp.	X	
Fistulipora sp.	X	X
stenoporids	X	X
Leioclema sp.	X	
trepostome A		
trepostome B		
Fenestella spp.	X	X
Penniretopora sp.	X	X
Cystodictya lineata (Ulrich)	X	X
Nicklesopora sp.	X	X
rhabdomesid A		
rhabdomesid B		
Streblotrypa sp.	X	X
Worthenopora spinosa Ulrich	X	X
CORALS		
Amplexus fragilis White and St. John	X	
A. rugosus Weller	X	
Amplexizaphrentis centralis (Milne-Edwards and Haime)	X	
Cladochonus crassus (M'Coy)	X	X
C. beecheri (Grabau)	X	X
MISCELLANEOUS		
Paraconularia newberryi (Winchell)	X	X
Platyceras (Platyceras) equilateralis Hall	X	X
P. (Orthonychia) acutirostre (Hall)	X	X
Phillibole conkini Hessler	X	
sponges	X	X
echinoid spine base		X

numerically abundant and dominate the fauna both in number of individuals and number of species. Other taxa, in order of decreasing abundance, include crinoids, bryozoans, corals, gastropods, conularids, and one specimen each of a trilobite, sponge, and echinoid.

The fauna is age equivalent to the fauna of the late Osagian Keokuk Limestone in the Upper Mississippi Valley. The crinoids are particularly age definitive as all nine taxa have been previously reported from the Keokuk Limestone or its chronostratigraphic equivalents (Bassler and Moodey, 1943; Van Sant and Lane, 1964; Kammer, 1985a). The brachiopods are not as age definitive. Most taxa range through the Osagian and some range into the other Mississippian stages. However, four species, *Marginatia crawfordsvillenis* (Weller), *Cleiothyridina parvirostra* (Meek and Worthen), *Prospira floydensis* (Weller), and *Imbrexia mortonanus* (Miller), are known only from the Keokuk Limestone or its equivalent (Carter and Carter, 1970). Other faunal elements, such as bryozoans and corals, cannot be used as rigorously for biostratigraphy, but it should be noted that most of these other faunal elements are found in the Keokuk-equivalent New Providence Shale Member of the Borden Formation in Kentucky (Kammer, 1985a) and the Edwardsville Formation of the Borden Group in Indiana (Ausich, 1983).

The Nancy fauna is closely allied to other Borden faunas. Typical Borden faunas contain crinoids, brachiopods, and bryozoans as the dominant elements (Ausich and others, 1979). The Nancy fauna, however, consists of a unique grouping of taxa composing a community that is not strongly similar to other Borden communities.

PALEOECOLOGY

The collections of the Nancy fauna from the two sites near St. Francis, Kentucky (Fig. 1), are significantly different. At site IU10884 brachiopods were the only fossils found. The other site, IU10885, contained the same brachiopods as the first site, plus three additional brachiopod species, and all the other taxa listed in Table 1. The difference in faunal composition between the two sites is inferred to be the result of autogenic succession within a single community type. Site IU10884 appears to be in an arrested, early stage of community succession, whereas site IU10885 represents an advanced successional stage with a more complex community structure. The two keys to understanding the paleoecology of this delta slope community are the brachiopod autecology and the process of taphonomic feedback (Kidwell and Jablonski, 1983).

The brachiopod autecology can best be understood by considering the absolute abundance of each taxon (Table 2) and the mode of stabilization on the substrate (Table 3). At site IU10884, which only contained brachiopods, the primary mode of stabilization on the substrate was by interarea stabilization with 86 percent of all individuals utilizing this adaptation (primarily *Voiseyella?* sp. and *Prospira floydensis).* In general, brachiopods from this site were smaller than those from IU10885, and there was only one specimen of the large and heavy-shelled *Imbrexia mortonanus*, whereas there were 77 individuals of this species from site IU10885. The dominance of brachiopods with interarea stabilization, and their generally small size, suggests an adaptation to a soft and probably fluid substrate. Ausich and others (1979) found that brachiopods were the dominant organisms on the delta slope in Indiana because of substrate instability, which is characteristic of this environment. However, the dominant brachiopods in the siltstones of the Carwood Formation in Indiana were the large, broad brachiopods *Orthotetes* and *Syringothyris*, but these brachiopods are adapted to coarser lithologies and are not common in silty shales, such as those of the Nancy.

At site IU10885 only 64 percent of the brachiopods utilized interarea stabilization, and an additional 32 percent were tethered by pedicles. Inspection of Table 2 indicates that there was a sharp increase in the number of *Athyris* cf. *A. lamellosa* and *Cleiothyridina parvirostra* at site IU10885. These athyrids were tethered by, and presumably could rotate around, their pedicle (Alexander, 1977). They did not have an interarea to sit upon. This suggests that they needed a firm anchor for their pedicle. Such an anchor probably was shell debris from other organisms. Kammer (1985a) found that the distribution of the orthid *Rhipidomella oweni* (Hall and Clarke), in the New Providence Shale, was strongly controlled by the availability of shell debris that

Table 2. Brachiopod abundance data for sites IU10884 and IU10885.

SPECIES	IU10884 No. of inds.	IU10884 Percent	IU10885 No. of inds.	IU10885 Percent
Rhipidomella oweni (Hall and Clarke)	-	-	1	0.1
Schuchertella sp.	2	0.4	4	0.4
Rugosochonetes shumardianus (DeKoninck)	16	3.1	36	3.3
Echinoconchus alternatus (Norwood and Pratten)	-	-	2	0.2
Marginatia crawfordsvillensis (Weller)	2	0.4	6	0.6
Athyris cf. A. lamellosa (Leveille)	42	8.3	282	25.7
Cleiothyridina parvirostra (Meek and Worthen)	1	0.2	63	5.7
C. cf. C. obmaxima (McChesney)	-	-	4	0.4
Voiseyella? sp.	317	62.3	339	30.9
Tylothyris sp.	1	0.2	4	0.4
Prospira floydensis (Weller)	121	23.8	271	24.7
Imbrexia mortonanus (Miller)	1	0.2	77	7.0
Brachythyris suborbicularis (Hall)	6	1.2	7	0.6
	509	100.1	1096	100.0

Table 3. Modes of stabilization on the substrate for brachiopods from the Nancy Member; interpretations based on Moore (1965), Rudwick (1970), Alexander (1977), and this study.

FUNCTIONAL PEDICLE, COMMISSURE VERTICAL		FREE LIVING, COMMISSURE HORIZONTAL		
Tethered	Interarea Stabilization	Cemented in Juvenile Stage	Pedicle in Juvenile Stage	Anchored by Spines
Rhipidomella Athyris Cleiothyridina	Voiseyella? Tylothyris Prospira Imbrexia Brachythyris	Schuchertella	Rugosochonetes	Echinoconchus Marginatia

provided an attachment site for the pedicle. Curiously, *R. oweni* is very rare in the Nancy fauna and may have been limited by additional factors other than pedicle attachment sites. The brachiopod data suggests a greater density of shell debris on the sea floor at site IU10885.

In addition to providing substrates for pedicle attachment, the shell debris at site IU10885 also provided settling sites for the larvae of crinoids, bryozoans, corals, conularids, and sponges. Kidwell and Jablonski (1983) described the process of shell debris providing settling sites for new organisms as taphonomic feedback. Thus, the death assemblage exerted an influence on the life assemblage and brought about an autogenic change in the community composition. The IU10884 site apparently never achieved a density of shell debris to allow successful settlement of organisms other than brachiopods. At the IU10885 site shell debris density reached a level that may have approached a shell pavement. As bryozoans, crinoids, and corals successfully settled on brachiopod shell debris, the debris of these organisms then provided settling sites for later generations, thus also contributing to the feedback mechanism. On the soft Nancy substrate, achievement of a critical level of shell density was necessary for development of a complex suspension feeding community. Kammer (1985a) reported another example of this process in the prodeltaic environment of the New Providence Shale where larval settlement sites were provided by the skeletal debris of earlier generations.

Kammer and others (1983, Table 2) summarized the macroinvertebrate species diversity of the various communities on the Borden delta and showed that the most diverse delta slope fauna previously reported contained 23 taxa and is from Millport Knob in southern Indiana (Ausich and others, 1979). The Nancy fauna, or community, is most similar to the prodeltaic Button Mold Knob community (96 taxa) (Kammer, 1985a) and the delta platform mudstone community of the Edwardsville Formation (113 taxa) (Ausich, 1983). Nearly all of the taxa of the Nancy fauna are found in either or both of these communities (Table 1). Ausich and others (1979) pointed out that the delta slope faunas in southern Indiana were not unique to the slope environment, but rather were a mixture of prodeltaic and platform organisms. This is also the case for the Nancy fauna. Organisms migrated up from the prodelta and down from the platform to form low diversity communities in the high-stress delta slope environment. Diversity remained low because of the high physiological stress caused by high rates of sedimentation and the associated unstable substrate. Thus, community development was not as extensive as in more physically stable environments. Other low-diversity communities on the Borden delta include the basinal Coral Ridge community with 29 taxa (Kammer and others, 1983; Kammer, 1985a), and the submarine channel sandstone community on the delta platform with 49 taxa (Ausich, 1983). The basinal community was stressed by dysaerobic oxygen levels, whereas the submarine channel sandstone was stressed by high current velocities and the resultant mobile sand substratum.

Another aspect of the paleoecology of the Nancy fauna is the crinoid autecology. The nine species of crinoids in the fauna (Table 1) represent most of the major groups of Lower Mississippian crinoids and include the monobathrid camerates *Eretmocrinus* sp., *Dorycrinus gouldi* (Hall), *Eucladocrinus millebrachiatus* (Washsmuth and Springer), and *Platycrinites* cf. *P. planus* (Owen and Shumard); the disparid inadunates *Halysiocrinus tunicatus* (Hall) and *Catillocrinus turbinatus* (Springer); the *Cyathocrine inadunates Cyathocrinites nodosus* (Wachsmuth and Springer) and *C. parvibrachiatus* (Hall); and the flexible *Forbesiocrinus,* sp. The monobathrids had pinnules on their arms, whereas the other groups were all nonpinnulate. In numbers of individuals collected, there are approximately even proportions of pinnulate and nonpinnulate crinoids. Kammer (1985b) applied aspects of aerosol filtration theory (Rubenstein and Koehl, 1977) to crinoid distribution on the Borden delta and found that nonpinnulate crinoids were dominant on the prodelta because they used a feeding mode adapted to low-velocity currents. Kammer also found that in the higher-energy facies on the delta platform, pinnulate crinoids were often dominant because they were adapted to feeding in higher-velocity currents. Although the isolated calyx plates of less than 30 individual crinoids were found, the approximately equal proportions of pinnulate and nonpinnulate crinoids suggests current energies intermediate between the prodelta and the delta platform. The silty shale lithology of the Nancy also indicates deposition by current velocities between those associated with the clay shales of the prodelta and the siltstones of the delta platform.

SUMMARY

The Nancy Member of the Borden Formation, near St. Francis, Kentucky, contains a fauna with 47 taxa of macroinvertebrates. This is the most diverse fauna yet found from the delta slope environment of the Borden delta. The benthic community represented by this fauna was dominated by brachiopods with crinoids, bryozoans, and corals, among others, being subordinate. Analysis of the community paleoecology indicates that brachiopods were dominant because of their adaptations to the soupy, unstable substrate of the delta slope. The most common brachiopods were those that utilized interarea stabilization. When brachiopod shell density approached that of a shell pavement, the larvae of other faunal elements were able to settle on the brachiopod shell debris. This is an excellent example of taphonomic feedback, which is the process responsible for community succession at site IU10885.

Compositionally, the fauna is a mixture of prodeltaic and delta platform species. The fauna consists of those species best adapted to the high rate of sedimentation and moderate current energies associated with the delta slope environment.

ACKNOWLEDGMENTS

Original collections of the Nancy fauna were made by Alan Horowitz and Roy Kepferle. Gary Lane and Heidi Kammer asssisted the senior author in making additional collections. John Carter of the Carnegie Institute provided taxonomic assistance with the brachiopods. William I. Ausich and Charles L. Rice critically reviewed the manuscript and offered many useful comments. Tom Bjerstedt drafted the figures.

REFERENCES

Alexander, R.R., 1977, Generic longevity of articulate brachiopods in relation to the mode of stabilization on the substrate: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 21, p. 209-226.

Ausich, W.I., 1983, Component concept for the study of paleocommunities with an example from the Early Carboniferous of southern Indiana (U.S.A.): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 44, p. 251-282.

Ausich, W.I., Kammer, T.W., and Lane, N.G., 1979, Fossil communities of the Borden (Mississippian) delta in Indiana and northern Kentucky: Journal of Paleontology, v. 53, p. 1182-1196.

Ausich, W.I., and Lane, N.G., 1980, Platform communities and rocks of the Borden siltstone delta (Mississippian) along the south shore of Monroe Reservoir, Monroe County, Indiana, *in* R.H. Shaver (ed.), Field Trips 1980 from the Indiana University Campus: Bloomington, Indiana University, p. 36-67.

Bassler, R.S., and Moodey, M.W., 1943, Bibliographic and faunal index of Paleozoic pelmatazoan echinoderms: Geological Society of America Special Paper 45, 734 p.

Carter, J.L., and Carter, R.C., 1970, Bibliography and index of North American Carboniferous brachiopods (1898-1968): Geological Society of America Memoir 128, 382 p.

Howard, J.D., 1978, Sedimentology and trace fossils, *in* P.B. Basan (ed.), Trace Fossil Concepts, SEPM Short Course No. 5: Oklahoma City, Society of Economic Paleontologists and Mineralogists, p. 13-47.

Kammer, T.W., 1985a, Basinal and prodeltaic communities of the Early Carboniferous Borden Formation in northern Kentucky and southern Indiana (U.S.A.): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 49, p. 79-121.

Kammer, T.W., 1985b, Aerosol filtration theory applied to Mississippian deltaic crinoids: Journal of Paleontology, v. 59, p. 551-560.

Kammer, T.W., Ausich, W.I., and Lane, N.G., 1983, Paleontology and stratigraphy of the Borden delta of southern Indiana and northern Kentucky (Field Trip 2), *in* R.H. Shaver and J.A. Sunderman (eds.), Field Trips in Midwestern Geology: Bloomington, Indiana, The Geological Society of America, Indiana Geological Survey, and Indiana University, p. 37-71.

Kepferle, R.C., 1973, Geologic map of the Raywick Quadrangle, central Kentucky: U.S. Geological Survey Quadrangle Map GQ-1048.

Kepferle, R.C., 1977, Stratigraphic, petrology, and depositional environment of the Kenwood Siltstone Member, Borden Formation (Mississippian), Kentucky and Indiana: U.S. Geological Survey Professional Paper 1007, 49 p.

Kidwell, S.M., and Jablonski, D., 1983, Taphonomic feedback: ecological consequences of shell accumulation, *in* M.J.S. Tevesz and P.L. McCall (eds.), Biotic Interactions in Recent and Fossil Benthic Communities: New York, Plenum Press, 195-248.

Moore, R.C. (ed.), 1965, Treatise on Invertebrate Paleontology, Part H, Brachiopoda: Boulder, Colorado, Geological Society of America and University of Kansas, 937 p.

Rubenstein, D.I., and Koehl, M.A.R., 1977, The mechanisms of filter feeding: some theoretical considerations: American Naturalist, v. 111, p. 981-994.

Rudwick, M.J.S., 1970, Living and Fossil Brachiopods: London, Hutchinson University Library, 199 p.

Van Sant, J.F., and Lane N.G., 1964, Crawfordsville (Indiana) crinoid studies: University of Kansas Paleontological Contribution, Article 7, 136 p.

TERRACE STRATIGRAPHY ALONG THE LOWER RED RIVER, LOUISIANA

JOHN J. ALFORD — *Geography Department, Western Illinois University, Macomb, Illinois 61455*

CHARLES R. KOLB[1], JOSEPH C. HOLMES[2] — *Institute for Environmental Studies, Louisiana State University, Baton Rouge, Louisiana 70803*

ABSTRACT

Nearly 50 years ago H. N. Fisk attempted to relate Pleistocene terrace formation in the lower Red River Valley to glacial events taking place far to the north. According to his well known model the Williana, Bentley, Montgomery, and Prairie terraces were respectively Aftonian, Yarmouthian, Sangamonian, and mid-Wisconsinan alluvial fills. More recent investigators have recognized a post-Prairie Deweyville Terrace and have assigned the Prairie Terrace to the Sangamonian Stage. However, ^{14}C dates from Fisk's paratype Montgomery section indicate a Farmdalian age for this fill. These data suggest that much of the surface that has been mapped as Prairie Terrace is much younger than previously thought.

TERRACE STRATIGRAPHY ALONG THE LOWER RED RIVER, LOUISIANA

The terraces along the lower Red River have been of interest to Pleistocene scientists ever since Harold N. Fisk (1938, 1940) worked in the area and developed his well known model of fluviatile terrace formation for Gulf Coast streams. According to Fisk (1938) alluvial material was deposited during interglacial periods when sea level was rising and aggrading streams built up their beds in response to a rising base level. During glacial periods when sea level was dropping streams adjusted their gradient by down cutting, and leaving their former floodplains as terrace surfaces. Terrace surfaces, thought to represent several glacial-interglacial cycles, are preserved because of the regional uplift that is taking place north of a coastwise hinge line.

Fisk (1938), in accord with the wisdom of his day, recognized four terrace formations. The oldest and highest was named Williana and was thought to be Aftonian; while in descending order he recognized a Yarmouthian Bentley, a Sangamonian Montgomery, and a mid-Wisconsinan Prairie. All of these formations were named after type localities in the lower Red River Valley.

OTHER VIEWS

Modification of Fisk's model became necessary when Bernard (1950) recognized the Deweyville Terrace. Situated below the Prairie surface but above the modern floodplain and characterized by very large meander scars, the Deweyville has been identified along a number of Gulf Coast and Atlantic Coast streams (Bernard, 1950; Gagliano and Thom, 1967). Originally, Bernard (1950) considered the Deweyville to be Holocene in age. However, a few ^{14}C dates taken from what was thought to be Deweyville fill indicated an age of between 33,000 and 17,000 B.P. for this unit. Gagliano and Thom (1967) after reviewing these dates suggested that the Deweyville might be the result of a possible high sea level stand occurring during the Farmdalian Substage.

Following up on this idea, Saucier (1968) suggested a new chronology for the lower Mississippi Valley. He agreed that the Deweyville might be Farmdalian (c. 30,000-22,000 B.P.) and thought the Prairie Terrace was formed during the Sangamonian

[1]Deceased

[2]Louisiana Department of Natural Resources, Baton Rouge, Louisiana 70803

Figure 1. Location map.

interglacial (c. 125,000-75,000 B.P.). In a later paper (Saucier and Fleetwood, 1970), this model was modified when studies along the Ouachita River suggested that late Deweyville surfaces were as young as early Woodfordian.

Although the age of the Deweyville Terrace has remained uncertain a number of Gulf Coast geologists (e.g. Gagliano and Thom, 1967; Hoyt and others, 1968; Saucier, 1968; Otvos, 1972; Delcourt and Delcourt, 1977) have been willing to assign a Sangamon age to the Prairie Terrace fill. The wide acceptance of a Sangamonian Prairie is based upon a minimum amount of isotopic dating. A scattering of dead dates on samples taken from core holes in what was thought to be Prairie fill along the Mississippi River (McFarlan, 1961) provides the bulk of the ^{14}C evidence that the terrace, in Louisiana, is pre-Wisconsinan.

In an effort to more firmly date the late Pleistocene terraces in the lower Mississippi Valley the authors returned to Fisk's type area with hopes of collecting ^{14}C datable material from the type sections. Despite an extensive search, datable material was recovered from only one section. However, this exposure, located at Waddel Bluff, does provide some answers to the ages of the late Pleistocene terraces along the lower Red River.

WADDEL BLUFF

Waddel Bluff is located 9.6 kilometers southeast of Montgomery in sec. 8, T. 7N., R. 4W., in Grant Parish, Louisiana (Fig. 1). Although Fisk (1938) considered Waddel Bluff the paratype section for the Montgomery Terrace more recent studies (Smith and Russ, 1974; Russ, 1975) indicate that Waddel Bluff is part of the Prairie fill. According to Russ (1975), Fisk (1938) failed to recognize that there were two Prairie surfaces and incorrectly mapped parts of the upper Prairie (including Waddel Bluff) as Montgomery.

Russ (1975) argues that the basal units of the upper Prairie were laid down during waning Illinoian times, and that the surface of this terrace was the active Red River floodplain during most of the Sangamonian Stage. He believes the low Prairie was

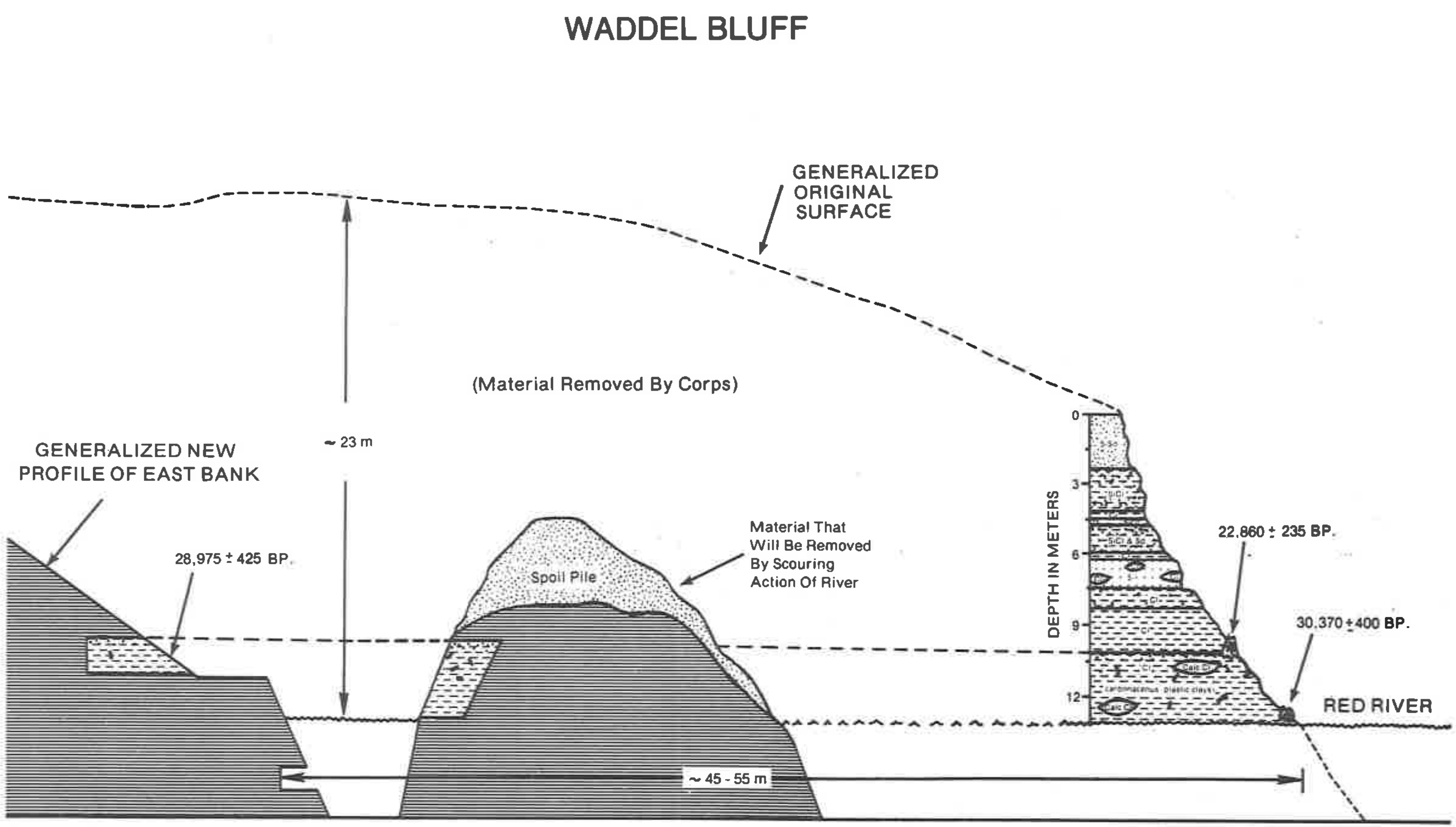

Figure 2. Stratigraphy at Waddel Bluff (modified from Fisk, 1938).

Table 1. ^{14}C Dates Associated with Waddel Bluff.

Lab No.	Date	Material Dated	Source
Beta-1220	22,860 ± 235	stump 3m above low water	This Paper
Beta-1221	30,370 ± 400	stump 0.3m above low water	This Paper
Beta-1856	28,975 ± 425	wood 1.2m above low water, exposed by cut 46m back from original face	This Paper

formed during the late Sangamonian when the Mississippi River shifted westward and caused a shortened Red River to degrade its bed.

Regardless of which terrace cycle Waddel Bluff belongs to it is one of the most intriguing exposures in the Central Gulf Coast area. As Fisk (1938, p. 161) reported, the lower portion of this deposit, which is exposed only during extremely low-water stage, is:

> composed of bluish-gray clays and contains many upright stumps ... and knees of cypress trees. The sediments surrounding the stumps contain leaf impressions, coprolites of large animals, freshwater (?) ostrocodes, a few pelecypod and many gastropod shells of small size.

Unusually low-water stages during the summers of 1979 and 1980 allowed us to examine the site in detail. Channelization work done in these two summers by the U.S. Army Corps of Engineers not only provided a fresh cut-face to work with but also allowed us to examine the stratigraphy some distance back into the bluff face (Fig. 2).

Three samples were collected for ^{14}C dating (Table 1). The dates show excellent stratigraphic agreement (Fig. 2); and they reveal that the fossiliferous unit, which is buried by 10 to 20 meters of fill, dates in age from 30,000 B.P. to 23,000 years B.P. Since Fisk (1938) mapped Waddel Bluff as Montgomery Terrace and Russ (1975) mapped it as part of the high (classical) Prairie Terrace, these dates are suprisingly young. At first glance the dates suggest that the Waddel Bluff fill is part of the Deweyville complex; however, this is not so certain. Russ (1975) has recognized, with large meander scars, a Deweyville surface in this area at a level well below the Waddel Bluff surface.

Although it is possible that Waddel Bluff is part of a series of Deweyville surfaces such as was identified by Saucier and Fleetwood (1970) in the Ouachita Valley, the available evidence does not support this interpretation. First, the Waddel Bluff surface lacks the large meander scars that characterize most Deweyville surfaces. Secondly, the vertical separation between the Deweyville surface and the Waddel Bluff surface is much greater than the greatest separation between the highest and lowest Deweyville surfaces along the Ouachita River. (At Waddel Bluff the separation is about 23 meters while along the Ouachita it is less than 7 meters).

DISCUSSION

The evidence indicates that what has been thought to be a Sangamonian terrace (the upper Prairie of Smith and Russ, or the Montgomery of Fisk) is actually a Farmdalian fill. Thus, the lower Prairie Terrace is probably Woodfordian in age and the Deweyville, at least along the Red River, is either waning Woodfordian or Holocene in age.

Significantly, evidence exists in other parts of Louisiana for a relatively youthful Prairie Terrace. It is generally recognized that in the Mississippi Valley the Wisconsinan Stage is represented by two loess falls (Wascher, H. L., and others, 1948; Leighton and Willman, 1950; Willman and Frye, 1970). Thus any surface in the loess belt that is Sangamonian or older should carry two loess sheets. Touchet and Daniels (1970) in their detailed loess study near Ville Platte, Louisiana (about 110 km south, southeast of Waddel Bluff) found only one loess unit capping what has been identified as Prairie Terrace. This is not surprising if one accepts a mid-Wisconsin age for the Prairie surface; however, it requires some explanation for those who argue that the Prairie is Sangamon in age.

Although it is possible that the valley trains that produced the early Wisconsin loess did not reach the latitude of Ville Platte; it should be noted that Touchet and Daniels (1970) found an older loess on older terrace surfaces in the same general area. Thus, the loess stratigraphy in the part of the loess belt nearest to Waddel Bluff strongly supports the ^{14}C dates and the assignment of fluviatile deposits that Fisk (1938) mapped as Montgomery and Smith and Russ (1974) mapped as upper Prairie to a Farmdalian time slot.

In summary, it is recognized that the Waddel Bluff sediments have not been directly traced to other areas that have been mapped as Prairie. Nevertheless, this preliminary study raises the possibility that other Louisiana terraces that are thought to be Sangamonian (Prairie) are younger than that. Although extensive study with good ^{14}C control is necessaary before the terrace stratigraphy in the Central Gulf Coast area can be accepted with any degree of confidence, a well dated bench mark has been established at Waddel Bluff.

ACKNOWLEDGEMENTS

Although Dr. Kolb died before the final draft of this paper was written, the conclusions of this study are very much his. The junior author's wish to acknowledge the time and patience that Dr. Kolb spent as he attempted to educate them in some of the finer points of Gulf Coast geology. We will miss him greatly.

REFERENCES CITED

Bernard, H. A., 1950, Quaternary geology of southern Texas: Ph.D. Dissertation, Louisiana State Univ., Baton Rouge.

Delcourt, P. A. and Delcourt, H. R., 1977, The Tunica Hills, Louisiana-Mississippi: late glacial locality for spruce and deciduous species: Quaternary Research, V. 7, p. 218-257.

Fisk, H. N., 1938, Geology of Grant and LaSalle parishes: Louisiana Dept. of Conservation Geologic Survey Bull. no. 10, 246 p.

Fisk, H. N., 1940, Geology of Avoyelles and Rapides parishes: Louisiana Dept. of Conservation Geologic Survey Bull. no. 18, 240 p.

Gagliano, S. M., and Thom, B. G., 1967, Deweyville terrace, Gulf and Atlantic coasts: Coastal Studies Bull. no. 1, Louisiana State Univ., Baton Rouge, p. 23-41.

Hoyt, J. H., Weimer, R. J., and Henry, V. J., Jr., 1968, Age of late-Pleistocene shoreline deposits, coastal Georgia: Means of Correlation of Quaternary Successions, ed. R. B. Marrison and H. E. Wright, Jr., Proceedings of the International Assoc. for Quaternary Research, v. 8, p. 381-393.

Leighton, M. N, and Willman, H. B., 1950, Loess formation of the Mississippi Valley: Journal of Geology, v. 58, p. 599-623.

McFarlan, E., Jr., 1972, Mississippi Gulf Coast Pleistocene beach barriers and the age problem of the Atlantic-Gulf Coast "Pamlico"—"Ingleside" beach ridge system: Southeastern Geology, v. 14, p. 241-250.

Russ, D. P., 1975, The Quaternary geomorphology of the lower Red River Valley, Louisiana: Ph.D. Dissertation, Louisiana State Univ., Baton Rouge.

Saucier, R. T., 1968, A new chronology for braided stream surface formation in the lower Mississippi Valley: Southeastern Geology, v. 9, p. 65-76.

Saucier, R. T., and Fleetwood, A. R., 1970, Origin and chronologic significance of late Quaternary terraces, Ouachita River, Arkansas and Louisiana: Geological Society of America Bull. v. 81, p. 869-890.

Smith, F. L., and Russ, D. P., 1974, Geologic investigation of the lower Red River-Atchafalaya Basin area: Technical Report no. S-74-5, U.S. Army Corps of Engineers, Waterway Experiment Station, 40 p.

Touchet, B. A., and Daniels, R. B., 1970, A post-Montgomery, pre-Prairie age loess near Ville Platte, Louisiana: Southeastern Geology, v. 12, p. 83-93.

Wascher, H. L., Humbert, R. P., and Cady, J. G., 1948, Loess in the southern Mississippi Valley-identification and distribution of the loess sheets: Soil Science Society of America, Proceeding, v. 12, p. 389-399.

William, H. B., and Frye, J. C., 1970, Pleistocene stratigraphy of Illinois: Illinois State Geological Survey Bull. Series 94, 204 p.

GEOCHEMICAL CHANGES OF STREAMS ASSOCIATED WITH SURFACE MINING OF COAL ON THE CUMBERLAND PLATEAU

PETER K. GOTTFRIED *Natural Systems Analysts, Inc., 917 W Fairbanks Avenue, Winter Park, Florida 32789*

ABSTRACT

Ten streams and nine small watersheds on the Cumberland Plateau in east Tennessee were studied from 1975 to 1979 to determine the impacts of coal surface mining on water chemistry. Results indicate that (1) streams draining undisturbed areas were acidic, (2) streams draining unreclaimed mine sites were generally well within pH effluent limitations established by the Surface Mining Control and Reclamation Act of 1977, and (3) rocks of the eastern coal-bearing portion of the Cumberland Plateau are generally more alkaline than western plateau rocks, producing a more alkaline drainage from mine sites. The data strongly suggest that effluent limitations contained in surface mine regulations should reflect the unique characteristics of coal-producing regions.

INTRODUCTION

Coal has been a valuable energy resource of the Cumberland Plateau of eastern Tennessee since the early nineteenth century. Accessible outcrops along the streams and rivers and the close proximity to growing urban markets, such as Nashville and Knoxville, have served to intensify mining activities throughout the region.

The southern Appalachian region, of which the Cumberland Plateau is a part, presently contains approximately 16 percent of the total U.S. coal reserves on a tonnage basis, or 20 percent on a uniform, Btu-adjusted basis (Murray, 1978). Increased domestic and foreign energy needs and new fluidized bed combustion techniques will intensify demands made on the regional coal resources and the environment as a whole.

The purpose of this paper is to discuss results of studies relating to the water quality of ten streams draining nine mined and unmined watersheds on the Cumberland Plateau.

STUDY AREAS

The Cumberland Plateau is a broad, relatively flat-topped tableland which extends diagonally across eastern Tennessee (figure 1). The Plateau ranges in width from 60 to 90 kilometers and has an area of approximately 13,000 square kilometers. It is part of the Appalachian Plateau physiographic province of the eastern United States, which extends from the southern border of New York to central Alabama (Luther, 1959).

Nine small watersheds, located on the coal-bearing region of the Cumberland Plateau in northeastern Tennessee were studied (figure 1, Table 1). Three study watersheds were located in the western, area-mined portion of the plateau, while six were located in the eastern, contour-mined portion of the plateau. The rocks in this region are principally easily weathered sandstones, shales, and conglomerates. Present geochemical interpretation of water analyses has confirmed earlier observations (Shoup, 1944) concerning the poor buffering action of natural waters draining this area of the plateau as indicated by the low pH and alkalinity of the reference (control) streams. Glenn (1925) presents an excellent historical, geological, and economic account of the study areas in his description of the northern Tennessee coal fields. A more recent geological interpretation of this region, as well as a description of the updated stratigraphic nomenclature, is presented by Wilson and others (1956).

General Geology of Western Sites

The sites mined by the "area" method are situated on the western coal-bearing portion of the Cumberland Plateau in Fentress County. The plateau surface in this

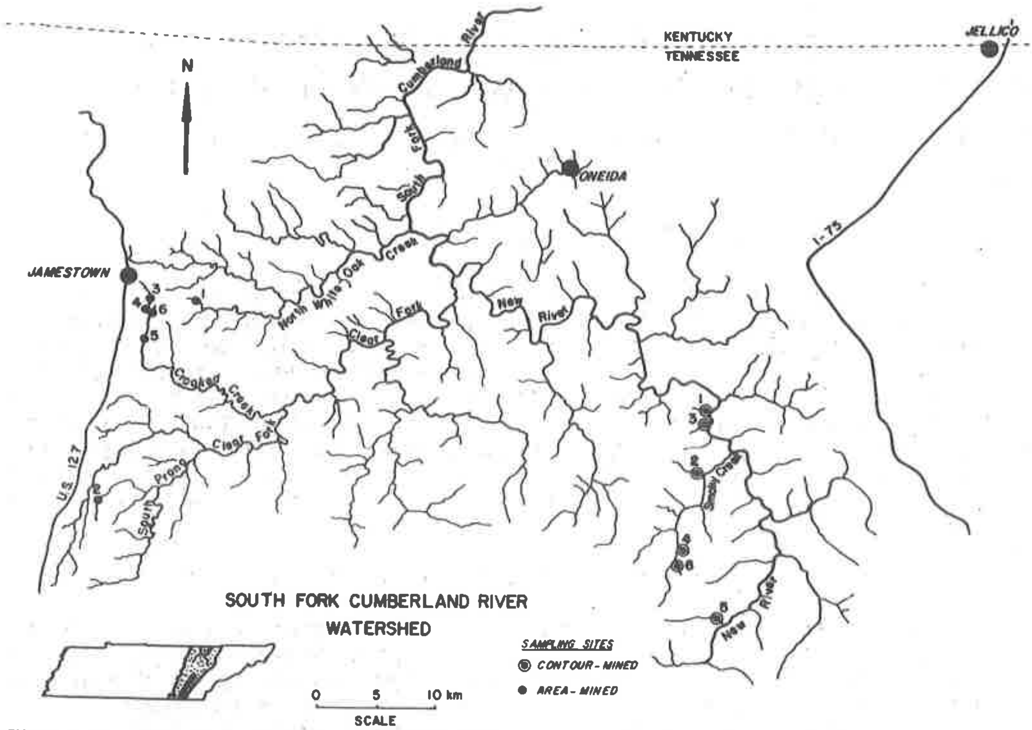

Figure 1. Location of area (western) and contour-mined (eastern) sites in upper east Tennessee. The Cumberland Plateau is indicated by shaded area within the Tennessee map.

region is gently rolling with streams flowing through valleys ranging from small grooves to profound gorges. Typically, stream headwaters have not cut deeply beneath the plateau surface but lower steatches have cut precipitous gorges 60 to 120 meters deep.

The rocks of the area-mined sites consist of conglomerates, sandstones, shales, and coals of the Gizzard and Crab Orchard Mountain Groups. They directly overlay Mississippian age limestones. Study streams drain the sanstones and shales of the Rockcastle conglomerate, a part of the Crab Orchard Mountain Group. The nemo coal seam is the major coal of this conglomerate and is actively mined in the region. Figure 2 presents a cross section of Crooked Creek illustrating the major coal seams and formations through which it flows.

General Geology of Eastern Sites

Six contour-mined sites were located in Scott and Anderson counties on the eastern edge of the Cumberland Plateau, approximately 40 miles southeast of the area-mined sites. The topography of this region is substantially different from the area-mined sites and is composed of narrow, winding ridges separated by narrow, deeply cut stream gorges. The roughness of the terrain is primarily due to the erodibility of softer shales and thin sandstones through which the streams flow. These rocks are a part of the middle Pennsylvanian series which includes the Vowell Mountain, Redoak Mountain, Graves Gap, Indian Bluff, and Slatestone Formations, previously referred to collectively as the Briceville Formation. Economically recoverable coal seams in these formations include the Pewee, Walnut Mountain, Big Mary, Windrock, Joyner, and Jellico seams, although all may not be accessible or present in any one study watershed. A cross section of Anderson Branch illustrating the predominant coal seams and formations through which it flows is presented on figure 3.

Table 1. Watershed characteristics of study streams with primary land use characteristics.

	Study stream	Site Code	Watershed area (ha)	Land use (%) Mined	Rural-residential	Forested
			Western Sites			
1.	Lynn Branch	LY 0.4	103	0	11	89
2.	Long Branch	LB 4.0	280	0	11	89
3.	Crooked Creek	CC 18.5	180	0	69	31
4.	Crooked Creek	CC 16.7	725	13	56	31
5.	Crooked Creek	CC 15.9	950	13	55	32
6.	Unnamed Tributary	UT 0.01	52	43	52	5
			Eastern Sites			
1.	Lowe Branch	LOW	238	0	0	100
2.	Bowling Branch	BOW	764	0	0	100
3.	Anderson Branch	AND	210	7.5	0	92.5
4.	Bills Branch	BIL	174	9.0	0	91.0
5.	Indian Branch	IND	1119	18.9	0	81.1
6.	Green Branch	GRE	357	24.1	0	75.9

Note: Watershed areas are determined from the area upstream of each sampling site. Land use data are accurage as of January 1979.

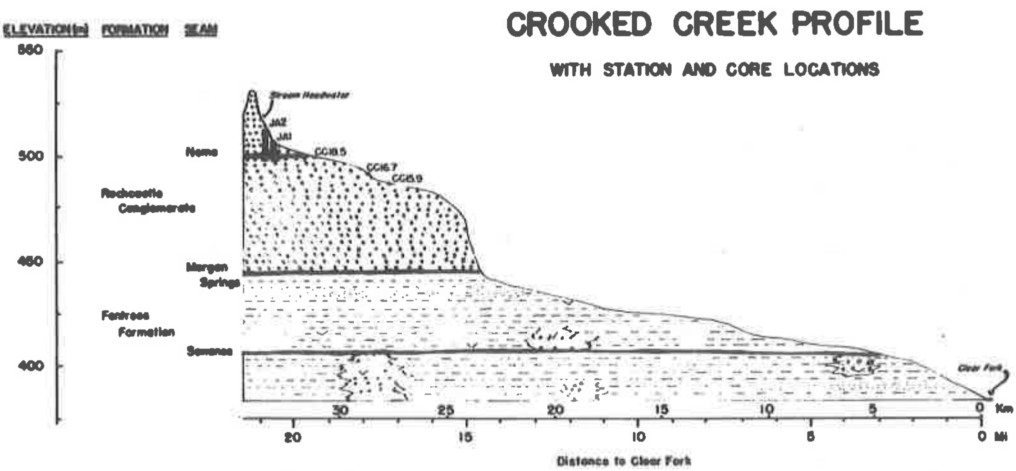

Figure 2. Elevation profile of Crooked Creek with station and core locations. (Vertical exaggeration 100 X)

ANALYTICAL PROCEDURES

An analysis of the stratigraphy and water quality was performed on nine small watersheds to observe the relationship between rock and stream chemistry. Core sampling was conducted at area- and contour-mined sites to characterize the rock overlying the coal seams. Cores were drilled at four locations in the area-mined study area and at three locations in the contour-mined study area. Of the four area-mined cores, two (JA1 and JA2, figure 2) were collected from an undisturbed area drained by Crooked Creek. One (GR1) was collected from the Long Branch watershed, and one (JA3) was collected from spoil material in the unnamed tributary watershed. All three contour mine cores (NR1, NR2, and NR3) were collected in the Anderson Branch watershed (figure 3) and each contained 20 to 30 meters of rock overlying coal seams that were being mined simultaneously.

After the core samples were logged, composite samples were taken to represent strata that were lithologically similar. The characteristics used in determining

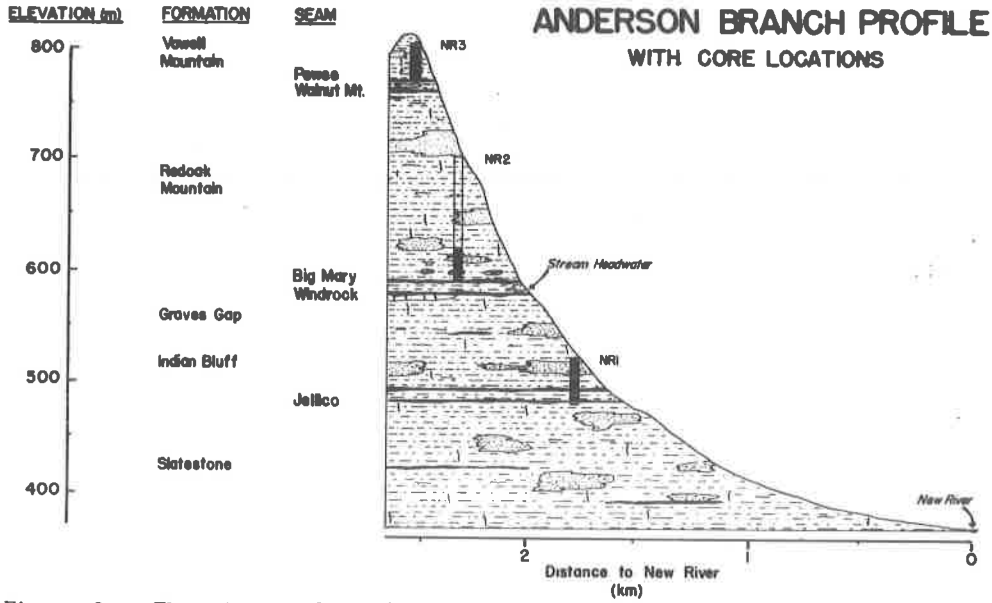

Figure 3. Elevation profile of Anderson Branch with core locations. (Vertical exaggeration, 5 X)

similarity included color, texture, and mineral composition. About 220 grams of each composite sample were ground to pass through a No. 50 sieve, yet be retained by a No. 100 sieve, and were analyzed for total sulfur, pyritic sulfur, cation exchange capacity (CEC), calcium carbonate, soil pH, potential acidity with peroxide, and total neutralization potential. Excess neutralization potential (ENP) was calculated by subtracting potential acidity from total neutralization potential. Composite samples of about 2 kg, ground to pass through a No. 10 sieve, were retained for the leaching study.

In a modification of the methods of Caruccio (1968) and Geidel (1976), a 100-g portion from each of the 42 strata identified was placed in a leaching chamber with moist air continually pumped across the strata at a rate of 100 cubic feet per minute. At 7-day intervals, the strata were washed with 100 ml of de-ionized water, filtered, and then returned to the leaching chamber with the filter pad. The leachate (filtrate) was then analyzed for oxidation reduction potential (ORP), pH, alkalinity, and acidity. Each stratum was subjected to this procedure for approximately 63 days or nine washings.

A wide water quality data were collected at approximately monthly intervals at the western area sites beginning in February 1976 and continuing through December 1978. Analysis for pH, acidity, and alkalinity were carried out in the field whenever possible. Other analyses were conducted in the laboratory by standard methods established by the U.S. Environmental Protection Agency (1976). Six contour-mined stream sites were sampled at approximately weekly intervals from January 1975 to December 1979. All contour-mined analyses were conducted in the laboratory.

RESULTS AND DISCUSSION

Stratigraphy and Geochemistry

Stratigraphic sections of the six cores are presented on figures 4 and 5. Sandstone was the dominant rock type of the western, area-mined sites. These creamy white to tan to gray sandstones ranged from slightly weathered to highly weathered. Claystones were present in cores JA1 and GR1, close to the coal seam. Shale was present only in core JA1, also located close to the coal seam. Siltstone was distributed

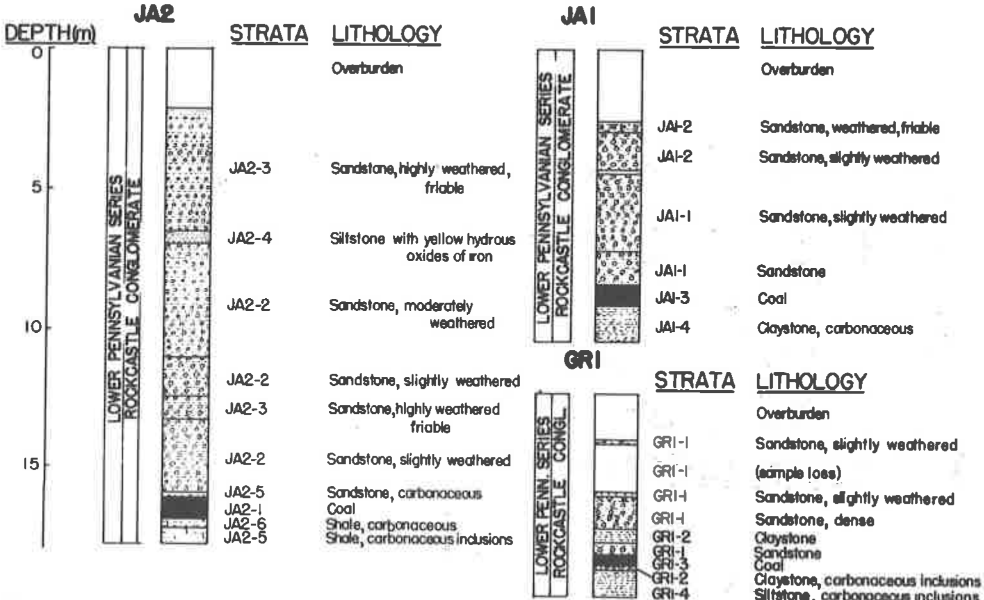

Figure 4. Core descriptions of western sites.

throughout the length of cores JA2 and GR1. Nemo coal was sampled from each core and varied in thickness from 30 to 80 cm.

Shale dominated the strata found in the eastern, contour-mined sites. These shales were either carbonaceous or calcarious in nature, depending on depth and location. Oil shale was found in cores NR2 and NR3. Sandstones varied from very dense and carbonaceous to very porous and friable. Colors ranged from tan to medium gray. Siltstone varied from highly weathered to unweathered and dense and was present only at the upper and lower ends of core NR1. Coal was present in all cores, but only analyzed in core NR1. Two seams were present, the Joyner and the Jellico seams, spaced aproximately 10 meters apart. The Jellico seam was approximately 40 cm thick; the Joyner seam was not analyzed.

Strata at eastern sites were generally more alkaline than western strata, reflected by higher soil pH, $CaCO_3$ concentrations, and excess neutralization potentials (table 2). This more alkaline character of the overburden and coal would seem to explain the higher pH and alkalinity of eastern reference streams.

Pyritic sulfur concentrations were low, averaging less than one percent of each rock type analyzed. Pyritic sulfur concentrations were predictably higher in the coal seam, although the relative proportions of pyritic sulfur to total sulfur varied from seam to seam and from core to core. Pyritic sulfur comprised 93 to 100 percent of the total sulfur content of the Nemo seam compared to 39 percent of the Jellico seam.

Although calcium and magnesium are the principal causes of hardness, their geochemical behavior is substantially different. Magnesium ions, being smaller than sodium or calcium, have a stronger charge density and a greater attraction for water molecules (Hem, 1970). Sedimentary sources of calcium and magnesium include carbonates such as limestone ($CaCO_3$), magnesite ($MgCO_3$), and dolomite ($CaMg(CO_3)_2$) and sulfates such as gypsum ($CaSO_4{\cdot}2H_2O$) and Epsom salt ($MgSO_4$). Magnesium concentrations were significantly higher than calcium concentrations in most of the samples analyzed. In addition, magnesium concentrations, as well as calcium concentrations, were higher at the contour-mined sites.

Primary sources of iron in sedimentary rock are the disulfides, pyrite and marcasite, siderite, and magnetite. Ferric oxides and hydroxides (Fe_2O_3 or $Fe(OH)_3$) give sandstones their red or yellow colors. Iron concentrations were significantly greater in the eastern strata.

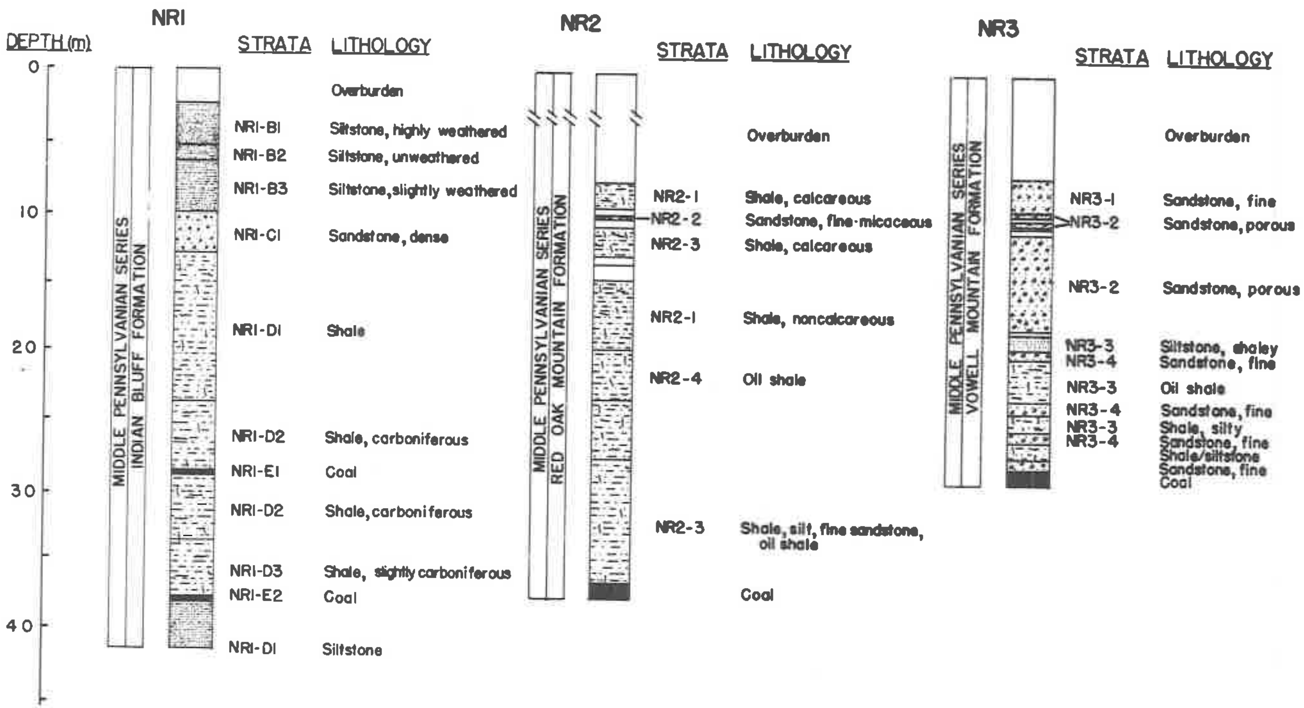

Figure 5. Core descriptions of eastern sites.

Table 2. Average geochemical concentrations of rock types sampled at western and eastern sites.

Rock Type	# of Samples	Total Rock Type Sampled (Percent)	Soil pH	$CaCO_3$ (meg/100g)	Excess Neutralization Potential+	Pyritic Sulfur (Percent)	Total Sulfur (Percent)	Ca (ug/g)	Mg (ug/g)	Mn (ug/g)
					Western Sites					
Sandstone	6	65.7	4.6	0.28	0.70	0.02	0.04	200	351	41
Claystone	2	5.7	4.2	0.25	3.28	0.05	0.09	513	2460	210
Siltstone	2	5.3	4.4	0.33	0.58	0.04	0.09	129	976	44
Shale	1	1.1	3.0	0.20	-0.30	0.06	0.03	500	480	30
Coal	3	5.1	3.4	0.38	2.50	0.35	0.35	990	769	32
Overburden	-	17.1	-	-	-	-	-	-	-	-
Spoil	-	-*	4.7	0.13	0.09	.02	-	63	220	18
		100.0								
					Eastern Sites					
Sandstone	4	18.0	5.3	3.17	28.28	0.02	0.08	3500	3163	338
Siltstone	5	8.9	5.7	2.57	12.43	0.02	0.03	817	4400	383
Shale	7	61.1	7.8	3.09	22.70	0.05	0.17	4176	5634	380
Coal	2	0.4	3.8	4.55	0.70	0.31	0.79	640	1600	33
Overburden	-	11.6	-	-	-	-	-	-	-	-
		100.0								

Note: Average pH values calculated from hydrogen ion concentrations.
*Sample from different core.

+Tons $CaCO_3$ equivalent/1000 tons rock

Table 3. Average chemical concentrations of leachate from western and eastern core samples.

Rock Type	pH	Alkalinity (mg/l)	Acidity (mg/l)	Oxidation-reduction potential (mv)
		Western Core Samples		
Sandstone	4.7-4.0	3.0- 3.0 (25.0)	9.4- 3.1 (156.3)	150-240
Claystone	4.0-4.0	1.5- 0.8 (12.8)	14.1- 0.0 (262.5)	170-140
Siltstone	4.6-3.4	1.5- 0.8 (13.0)	0.0- 23.4 (268.8)	170-190
Shale	2.9-3.0	0.0- 0.0 (1.0)	100.0- 146.9 (297.1)	330-260
Coal	3.0-2.0	0.0- 0.4 (1.7)	1000.0-4500.0 (15,625.0)	240-540
Spoil	5.4-4.0	5.1- 0.6 (12.8)	14.0- 18.8 (287.5)	150-150
		Eastern Core Samples		
Sandstone	8.9-7.3	30.0-27.9 (200.0)	2.7- 3.2 (25.7)	0- 95
Siltstone	6.8-6.1	5.2-11.4 (75.5)	0.0- 0.0 (117.9)	45- 70
Shale	6.8-6.7	24.8-16.6 (186.8)	4.2- 5.3 (66.3)	115- 95
Coal	2.9-2.0	0.0- 0.0 (0)	857.1-3535.7 (17,946.0)	375-500

Note: Beginning, ending, and cumulative values are given reflecting any changes which occurred during the nine wash leaching test with de-ionized water. First number is value after first wash; value in parenthesis is cumulative after all nine washings.

Results of Leaching Study

Closely correlated to the geochemical analysis were the results of the leaching study, the purpose of which was to determine the short-term weathering characteristics of the various rock types. Changes in pH, alkalinity acidity, and ORP of the leachate during the experiment are presented in table 3 for each area and rock type.

Values of pH usually declined through the nine washings due possibly to the increase in the rate of the oxidation of pyrite and other minerals present in the strata or to the rapid leaching of neutralizing materials throughout the weathering processes. Generally, pH values of leachate from eastern strata were higher than those from western strata leachate, except for coal in which values were comparably low. At both sites, the pH of the leachate was highest for sandstone reflecting higher excess neutralization potentials and lower pyritic sulfur content.

Alkalinity, like pH, was higher in the eastern strata and strongly correlated to excess neutralization potential and pyritic sulfur content based on linear regression analysis. Alkalinity peaked early in the leaching process simulation for the western claystone and coal, and for eastern shale samples, but peaked later in the process for western sandstone and siltstone samples. Cumulative alkalinities were greatest for western and eastern sandstones, eastern shales, and western spoil. Alkalinity for eastern and western coal samples was negligible, as well as for western shale.

Acidity was highest for all coal samples, exceeding 4,000 mg $CaCO_3$ per liter and 3,500 mg $CaCO_3$ per liter after the ninth washing of western and eastern coal, respectively. Cumulative values were also high for western shale and eastern siltstone. Differing rates of H^+ production were also observed for each strata with acidity values peaking either early, late, or gradually increasing throughout the simulated weathering process.

ORP was positive for all strata leachates except for eastern shale leachate, which was less than zero at the fifth wash. ORP was highest for coal leachate - 0.78 volts by the sixth wash of the eastern coal leachate. Eastern sandstone peaked at 0.63 volts by the seventh wash, then dropped to 0.03 volts by the eighth wash. Western sandstone leachate also peaked by the seventh wash.

Statistical Interdependence of Overburden Geochemistry

Pearson correlation coefficients (r) were calculated in order to explain the statistical interdependence of the average values of geochemical parameters analyzed. Values for eastern and western samples were pooled prior to analysis. A list of significant correlation coefficients where r is greater than or equal to 0.5 and the probability that r=0 is less than or equal to 0.001 for geochemical variables is given in table 4.

Correlations between parameters generally reflect similar geochemical behavior or lattice substitutions by atoms or ions of similar atomic or ionic size or like ionic charge (Bogner and others, 1979). For these data, calcium and magnesium concentrations were positively correlated with excess neutralization potential, $CaCO_3$, alkalinity, and pH. This suggests that calcium and magnesium carbonates are a major source of buffering capacity in the strata. Pyritic and total sulfur concentrations were likewise positively correlated with acidity and H^+ concentrations and negatively correlated with soil and leachate pH.

Water Chemistry

Mean values and standard errors of the mean, for mine-related water quality parameters are presented in table 5.

pH and Alkalinity

It is well known that acid-mine drainage arises in Appalachian mining regions from the oxidation of sulfide minerals, primarily pyrite. Other sulfide minerals,

Table 4. High positive and negative Pearson correlation coefficients (r) for average core sample and leachate values from pooled eastern and western samples. Values given are those where |r| - .5 and where the probability that r=0 is - .001.

Variable A	Variable B	r
soil pH	alkalinity*	.86
	ENP	.82
	Mn	.79
	Mg	.74
	$CaCO_3$	.73
	ORP*	-.67
	Ca	.67
pH of leachate	ORP*	-.80
	alkalinity*	.71
	ENP	.60
	acidity	-.60
	pyritic sulfur	-.60
	Mn	.58
	Mg	.52
Hydrogen ion concentration*	acidity*	.95
	ORP*	.86
	pyritic sulfur	.76
acidity*	ORP*	.85
	pyritic sulfur	.72
alkalinity*	ENP	.92
	Ca	.78
	Mg	.78
	Mn	.78
	pH*	.71
	$CaCO_3$	.70

*From leachate data

Table 5. Means and Standard errors of water-quality variables from western and eastern sites.

Variable		WESTERN SITES						EASTERN SITES					
		UT 0.01	CC15.9	CC 16.7	CC 18.5	LY 0.4	LB 4.0	GRE	IND	BIL	AND	BOW	LOW
% mined*		43	13	13	0	0	0	24.1	18.9	9.0	7.5	0	0
pH	Mean+	6.3	5.5	6.5	6.2	5.3	4.4	7.0	6.5	6.7	6.2	6.2	6.1
(s.u.)	Range	5.8-7.8	5.7-8.5	5.6-7.9	4.8-7.9	3.8-8.2	3.0-7.3	6.4-7.8	5.2-8.0	6.0-7.6	4.7-8.0	4.8-7.6	5.1-7.6
Alkalinity ($mg/l\ CaCO_3$)	Mean	11.5	16.3	17.8	22.9	3.8	4.4	31.0	24.7	15.4	26.0	9.0	6.7
	S.E.	0.81	1.14	1.46	1.4	0.49	0.8	0.54	1.07	0.50	2.44	0.47	0.29
Acidity	Mean	9.2	5.5	6.0	5.3	5.8	9.9	--	--	--	--	--	--
($mg/l\ CaCO_3$)	S.E.	1.15	0.67	1.20	0.90	1.21	1.38	--	--	--	--	--	--
Ca	Mean	9.3	10.4	10.1	12.4	2.5	3.0	32.8	67.7	8.4	6.2	1.3	1.2
(mg/l)	S.E.	0.44	0.45	0.33	0.45	0.14	0.67	1.06	2.67	0.35	0.74	0.09	0.04
Mg	Mean	2.5	2.0	1.7	1.7	0.6	0.8	18.1	27.3	6.1	2.8	1.7	1.5
(mg/l)	S.E.	0.08	0.09	0.06	0.05	0.03	0.06	0.45	1.04	0.22	0.20	0.07	0.03
Mn	Mean	1.1	0.05	0.4	0.1	0.03	0.1	0.3	1.0	0.1	0.1	0.1	0.0
(mg/l)	S.E.	0.09	0.07	0.10	0.01	0.01	0.04	0.02	0.05	0.02	0.01	0.01	--
Fe	Mean	3.4	1.5	1.2	2.0	0.4	1.0	4.4	8.1	2.6	2.6	1.9	0.2
(mg/l)	S.E.	0.41	0.12	0.16	0.46	0.09	0.20	0.87	0.61	0.74	0.50	0.39	0.01
SO_4	Mean	17.4	16.8	10.4	9.9	3.3	5.2	150.0	381.9	40.4	12.6	10.2	10.6
(mg/l)	S.E.	1.0	1.10	0.64	0.65	0.36	0.6	4.52	19.16	1.37	0.63	0.53	0.38

Note: Mean values were calculated from data collected between 1975 and 1979 and are expressed as mg/l unless otherwise indicated.

* Indicates percentage of watershed area disturbed upstream from sample site.

+ Calculated from hydrogen ion concentrations.

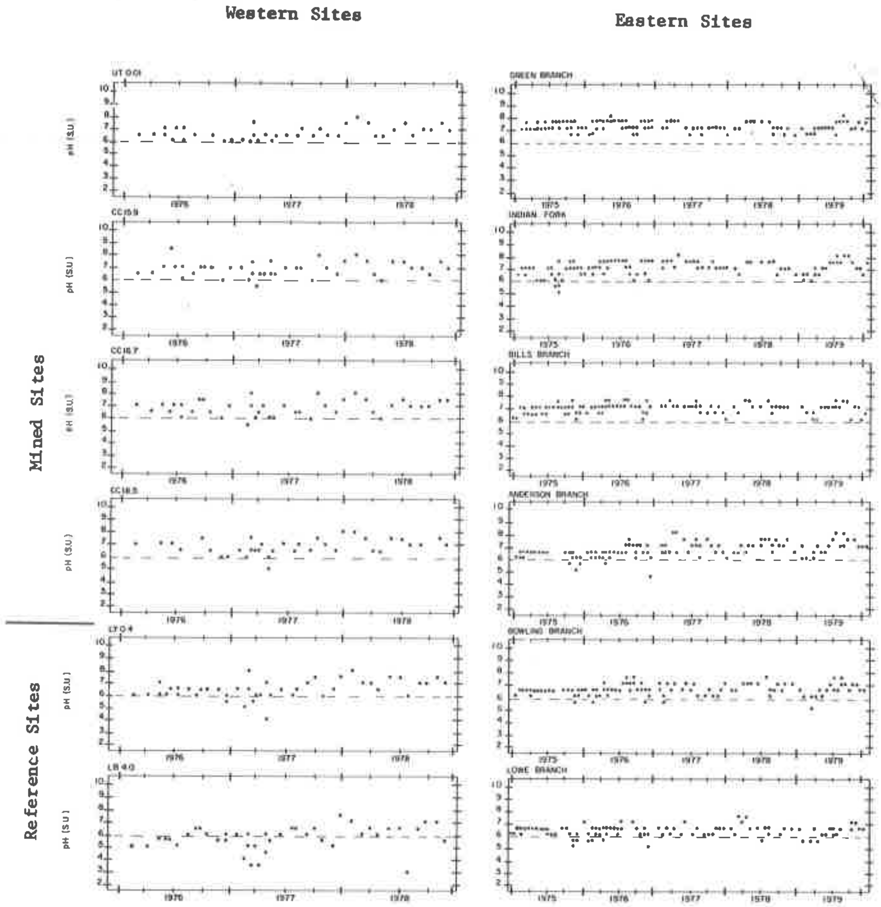

Figure 6. pH of western and eastern streams between 1975 and 1979. Dashed line is lower pH effluent limitation established under the Surface Mine Control and Reclamation Act of 1977.

cuprite, sphalerite, or galena (Cu_2S, ZnS, and PbS) may also be associated with coal deposits (Herricks and Cairns, undated). In the western and eastern areas of the Cumberland Plateau, however, alkaline-mine drainage seems to be the rule rather than the exception. Mean pH values (calculated from average hydrogen-ion concentrations) were significantly higher at the mined sites than at the reference sites. Eastern reference sites invariably had higher pH and alkalinity than western sites, due most likely to higher excess neutralization potentials, and $CaCO_3$ concentrations of the eastern strata. Acidity, measured only at western sites, was discernibly different between mined and reference sites.

In order to observe seasonal trends, values of pH and total alkalinity were plotted throughout the sampling periods and are presented in figures 6 and 7. Seasonal trends were observed only for total alkalinity, which was usually highest during the summer months when stream flows are low and when photosynthesis is at its peak and lowest during the winter months. A significant number of pH values were below the lower effluent limitation (pH = 6) estabished by the Surface Mine Control and Reclamation Act of 1977 (SMCRA). Approximately 63 percent of the pH values measured at the LB4.0 reference site were below a pH of 6, whereas 10 percent of the values were below a pH of 6 at the Bowling Branch reference site. Most mined-site values were above this limit.

Numerous other investigators have also observed alkaline-mine drainage in the Appalachian region (Minear and Tschantz, 1976; Geidel and Caruccio, 1977; Caruccio

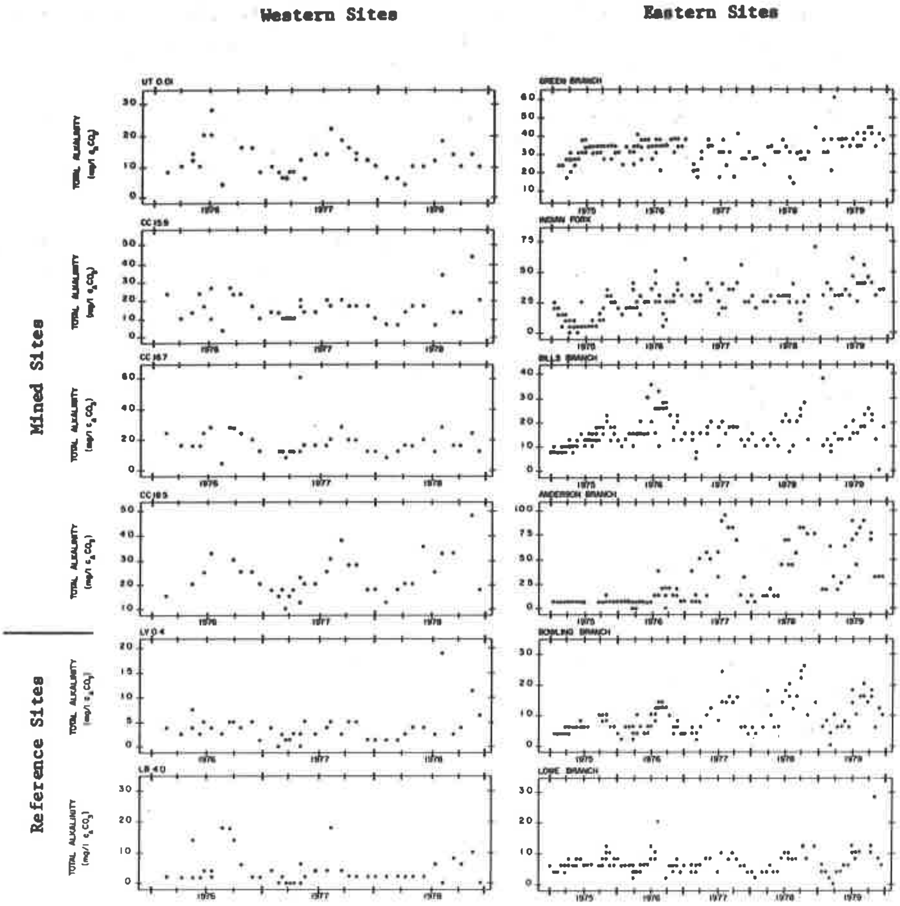

Figure 7. Total alkalinity of western and eastern streams between 1975 and 1979.

and others, 1980; Carccio and others, 1976). These investigators have identified several factors important in alkaline-mine drainage production: (1) the calcium carbonate and clay content and cation exchange capacity of the rock strata, (2) the pH and buffering capacity of ground water, and (3) the morphology and quantity of the pyrite mineral.

All rock strata analyzed contained varying quantities of alkalinity-producing materials and cation-exchange capacity sufficient to cause alkaline drainage. The following section discusses the results of iron and sulfate analysis and the importance of these elements relating to increased acidity.

Iron, Sulfate, and the Production of Acidity

The presence of alkalinity-producing strata can be particularly important in regions where acid-forming iron disulfide (pyrite) minerals occur. Without the neutralization and buffering effects of alkalinity, acid production can become particularly severe. The resulting drop in stream pH can increase the solubility of not only calcium and magnesium, but also heavy metals such as iron, manganese, copper, and zinc causing further pollution.

The most useful indicator of acid-mine drainage according to Herricks and Cairns (undated) is sulfate. A sulfate concentration greater than 250 mg/1 is given as a criteria for the presence of acid mine drainage, although values greater than 20 mg/1 are cause for concern especially in Appalachian water, which naturally contain less than 20 mg/1 sulfate.

Mean sulfate concentrations were significantly higher for sites receiving mine effluent than reference sites, but most were well below the 250 mg/1 criteria. Only at Indian Fork (IND) were sulfate values consistently high, 77 percent of which exceeded 250 mg/1. Green Branch (GRE) also had high sulfate values, 4.5 percent of which exceeded 250 mg/1.

Total iron concentrations can be highly elevated in strip mine environments due to the release of Fe^{+2} during the oxidation of pyrite. SMCRA established a maximum effluent limit of 7.0 mg/1 total iron from strip mine operations. In addition the U.S. Environmental Protection Agency proposed a 1 mg/1 criteria for fresh-water aquatic life (USEPA, 1976).

Mean total iron concentrations were all below the 7.0 mg/1 limit at sites except for the 8.1 mg/1 mean value observed at Indian Fork. Although mean values were well below the effluent limit in most cases some individual values, however, were significantly higher. Thirty-three percent of the values exceeded the effluent limit at CC18.5 (an agricultural site), whereas 43.5 percent exceeded the limit at Indian Fork. Total iron at Green Branch was also relatively high, with 15.7 percent of the values exceeding 7.0 mg/1 over the 5-year sampling period. Lowest values (actual and mean) were observed at the mined sites CC15.9 and CC16.7 and at the reference sites LYO.4, LB4.O, and Lowe Branch (LOW).

Acidity, a major reaction product of iron pyrite oxidation, was measured only at the western sites. Acidity was highest at reference site LB4.0 for the 3-year sampling period. Mean values for all area mine sites were significantly higher than the acidity criteria of 3.0 mg/1 for determining acid mine drainage established by Herricks and Cairns. Since pH and alkalinity values were significantly higher at all sites, however, sufficient neutralization and buffering could have been taking place. If pyrite was being oxidized, the reaction products, acidity, sulfate, and iron were quickly tempered by carbonates or cation exchange within the strata or in streams so as to yield an alkaline-mine drainage. On the other hand, the pyrite could be in a form that dissolves slowly, yielding little or no acidity. Acid production in the leaching studies could be more a function of the physical rather than chemical properties of the crushed samples.

Manganese, Magnesium, and Calcium

Manganese is a transition element and closely related to iron. Manganese is also an important reactant in redox processes in natural waters and is an essential micronutrient of freshwater flora and fauna (Wetzel, 1975). Water-quality standards proposed by the U.S. Public Health Service (1962) recommend an upper limit of 0.05 mg/1 because small concentrations of manganese in water may be objectionable. Concentrations of manganese greater than 1 mg/1 are common in streams receiving acid mine drainage and can persist in water for greater distances downstream from the pollution source than iron because of greater solubility at neutral pH. Average manganese concentrations were low at all sites. None of the observed values exceeded the 4.0 mg/1 effluent limit established by the SMCRA. Apparently little manganese-containing minerals were present in the study areas.

Calcium and magnesium concentrations were significantly greater at sites affected by mine effluent than at reference sites. This observation was probably the result of calcium and magnesium carbonates being dissolved from rock strata disturbed by mining and would help to explain elevated alkalinity at sites affected by mine drainage.

Statistical Interdependence of Water Quality Parameters

Pearson correlation coefficients (r) were calculated in order to determine the statistical interdependence of various water quality parameters analyzed. A list of significant correlation coefficients for water chemistry variables at area-mined and contour-mined sites is presented in table 6. Like the correlations between geochemical parameters, correlation coefficients between water-quality parameters generally reflect similar geochemical behavior or lattice substitution by atoms or ions or similar atomic or ionic size or like ionic charge. The analyses revealed close association between the anions and cations of the common salts found in Cumberland Plateau strata. Calcium and magnesium concentrations were positively correlated with sulfate

Table 6. High positive and negative Pearson correlation coefficients for area-mined and contour-mined site water quality variables. (/r/ - .5; p - .001)

Variable A	Variable B	Western sites	Eastern sites
pH	Alkalinity	(.39)	.57
Alkalinity	Ca	.65	(.35)
Ca	Mg	.72	.96
	SO_4	.52	.92
	Mn	(.35)	.84
Mg	SO_4	.77	.91
	Ca	.72	.97
	Mn	.72	.84
Mn	SO_4	.66	.88
	Mg	.72	.84
	Ca	(.35)	.84
SO_4	Ca	.52	.92
	Mg	.77	.91
	Mn	.66	.88

Note: Values in parenthesis, which are less than 0.5, are given for comparative purposes.

an alkalinity. Manganese was also correlated with sulfate.

SUMMARY AND CONCLUSIONS

Water quality and geochemical analyses were performed in nine east Tennessee watersheds on the eastern and western portions of the Cumberland Plateau to determine the impact of coal surface mining on the aquatic environment. Streams draining eastern and western sites were only slightly acidic with mean pH values ranging between 6.2 and 7.0. Reference (undisturbed) streams were significantly more acidic, having mean pH values ranging from 4.4 to 6.2. Stratigraphic and geochemical analysis of overburden within study watersheds indicated the presence of buffering agents, which when exposed by mining, could increase the pH and alkalinity of affected streams. In general, streams affected by mining were generally more alkaline than reference streams. Eastern mined sites were also found to be more alkaline than western mined sites.

The results suggest that modification in existing regulatory effluent limitations may be a consideration in regions where unique geological and geochemical characteristics exist. Modifications would have to be based on an evaluation of overburden chemistry, not on water quality, since water quality may not reflect what lies beneath the surface. This evaluation would have to be fullproof and accurate and one that could be easily used by regulatory agencies. These modifications would permit greater utilization of Appalachian coal at reduced costs as domestic and world-wide demand grows, while simultaneously ensuring that appropriate regulatory controls continue to protect the environment.

ACKNOWLEDGEMENTS

This research was part of a larger study supported under Federal Interagency Agreement numbers EPA-IAG- 08-E721 and TV-41967A between the Tennessee Valley Authority and the Environmental Protection Agency for energy-related environmental research. The purpose of the larger study was to provide background data for the development and demonstration of regional mathematical models for predicting the impacts of coal surface mining on the aquatic environment. This data can be found in the TVA/EPA report by Gottfried, Bales, and Precious (1984), available by writing

to Natural Systems Analysts, 917 W Fairbanks Ave., Winter Park FL 32789.

REFERENCES CITED

Bogner, J. E., Henricks, J. D., Olsen, R. D., Schubert, J. P., Sobek, A. A., Wilkey, M. L., and Johnson, D. O., 1979, Environmental control technology survey of selected U.S. strip mine sites. Vol. 2A: Ohio. Argonne National Laboratory, Argonne, IL. 135 pp.

Caruccio, F. T., 1968, An evaluation of factors affecting acid mine drainage production and the ground water interactions in selected areas of western Pennsylvania. Presented at the Second Symposium on Coal Mine Drainage Research. Mellon Institute, Pittsburgh, Pennsylvania.

Caruccio, F. T., Geidel, G., and Pelletier, A., The assessment of a stratum's capability to produce acidic drainage. Presented at the Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation, Lexington, KY. December 1-5, 1980.

Caruccio, F. T., Geidel, G., and Sewell, J. M., 1976, The character of drainage as a function of the occurrence of framboidal pyrite and ground water quality in eastern Kentucky. Presented at the Sixth Symposium on Coal Mine Drainage Research, Louisville, KY.

Geidel, G., and Caruccio, F. T., 1977, Time as a factor in acid mine drainage pollution. Presented at the Seventh Symposium on Coal Mine Drainage Research, Louisville, KY. October 18-20, 1977.

Glenn, L. C., 1925, The northern Tennessee coal field. Bulletin 33-B. Tennessee Divison of Geology, Nashville, TN.

Gottfried, P. K., Bales, J., and Precious, T. W., 1984, The influence of coal surface mining on the aquatic environment of the Cumberland Plateau. EPA-600/7-84-043. Tennessee Valley Authority, Muscle Shoals, AL.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water. U.S. Geological Survey Water-Supply Paper 1473, Washington, D.C.

Herricks, E. E., and Cairns, J., Jr., Undated, Rehabilitation of streams receiving acid mine drainage. Center for Environmental Studies, Bulletin 66. Virginia Polytechnic Institute and State University, Blacksburg. 284 pp.

Luther, E. T., 1959, The coal reserves of Tennessee, Bulletin 63. Tennessee Department of Conservation and Commerce, Division of Geology, Nashville, TN. Bogner, and others, 1979.

Minear, R. A., and Tschantz, B. A., 1976, The effect of coal surface mining on the water quality of mountain drainage basin streams. Journal of the Water Pollution Control Federation. Vol. 48, No. 11, pp. 2549-2569.

Murray, F. K., Editor, 1978, Where we agree - Report of the National Coal Policy Project. Vol. 2. Westview Press, Boulder, CO.

Shoup, C. S., 1944, Geochemical interpretation of water analysis from Tennessee streams. Transactions of the American Fisheries Society, Vol. 74. pp. 223-229.

U.S. Environmental Protection Agency, 1976, Quality criteria for water. EPA-440/19-76-023, Washington, D.C.

U.S. Public Health Service, 1962, Public health service drinking water standards, 1962. PHS Pub. No. 956, Washington, D.C.

Wetzel, R. R., 1975, Limnology. W.B. Saunders Company, Philadelphia.

Wilson, C. W., Jr., Jewell, J. W., and Luther, E. T., 1956, Pennsylvanian geology of the Cumberland Plateau. Tennessee Division of Geology, Nashville, TN.

Patchin Crandall Curtis