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Inference of Tectonic Evolution from LANDSAT-1 Imagery*

A possible relationship of LANDSAT-1 lineaments to Cenozoic tectonics of the area of the Delmarva Peninsula is suggested.

(Abstract on next page)

INTRODUCTION

THE FALL LINE SEPARATES the Piedmont Province to the northwest from the Atlantic Coastal Plain Province to the southeast (Figure 1). The Delmarva Peninsula is entirely in the Atlantic Coastal Plain physiographic province. It is the land area of the contiguous parts of Delaware, Maryland, and Virginia that lie south of Delaware Bay and between the Atlantic Ocean to the east and Chesapeake Bay to the West (shaded area on Figure 1). The portion of the Piedmont Province just northwest of the Delmarva Peninsula is underlain by complex crystalline rocks of the Glenarm Series of early Paleozoic age. These are represented here principally by the Wissahickon Formation. The eastern part of the Piedmont in Delaware is composed mainly of mafic banded gneisses comprising the Wilmington Complex which has been described by Ward (1957) and mapped by Woodruff and Thompson (in press). The relationship between the Complex and the Glenarm Series rocks of the Wissahickon Formation is not clear. The possibility of a strike-slip fault at or near the contact of these two rock masses has been suggested by Spoljaric (1974).

The basement under the sedimentary rocks is thought to be composed of crystalline rocks similar to those outcropping in the Piedmont Province northwest of the Fall Line. Fresh crystalline rocks are separated from the overlying sediments by their weathered products. This weathered material shows considerable variation in composition and its thickness may locally exceed 100 feet (Spoljaric, 1972). Most of the weathered material seems to have been formed before the deposition of the Mesozoic sediments, at least in the northern part of the Peninsula. For example, in several holes drilled to the basement the weathered material is interbedded with the Mesozoic sediments. The beds of the weathered material are believed to represent slumps that occurred concurrently with the deposition of the overlying fluvial Mesozoic deposits (Spoljaric, 1972).

Knowledge of the basement complex on the Peninsula is poor and the significance of the contact between this complex and the overlying sedimentary rocks, a major unconformity, is uncertain. However, recent detailed studies of the basement complex in the northern part of the Peninsula (Spoljaric, 1973) are beginning to shed light on the structural make-up of these complex rocks.

The sedimentary rocks range in age from possibly Triassic to Holocene and reach a maximum thickness of about 8000 feet in the east-central part of the Peninsula. The bulk of the sedimentary sequence is composed of Cretaceous deposits of sand, silt, and clay. These sediments seem to have been deposited in complex fluvial deltaic environments (Groot, 1955; Spoljaric, 1967). Not much is known about them at depth primarily because sufficient deep drilling control is not available. In addition, they are charac-

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terized by frequent vertical and lateral lithologic changes that make subsurface correlation of individual layers, or groups of layers, very difficult (Spoljaric, 1967; Jordan, 1968). These nonmarine sediments are separated from the marine deposits of Late Cretaceous age by the transitional sediments of the Magothy Formation. The Late Cretaceous marine units generally contain significant amounts of the mineral glauconite and are often referred to as "greensands". Most of the overlying Tertiary sediments appear to be of marine origin, although some may be considered transitional. With the exception of the Miocene series, they are all highly glauconitic. It should be pointed out here that the Tertiary sequence on the Peninsula is incomplete because no sediments of Oligocene, Early Miocene, and Pliocene age have been recognized. The youngest deposits, excluding the Holocene sediments, are gravels, sands, silts, and clays of Pleistocene age. They largely cover older deposits on the Peninsula.

The LANDSAT-1 imagery of the Peninsula (Figure 2) shows the presence of at least three different sets of lineaments trending N-S, NE-SW, and NW-SE. These lineaments are not as apparent as those one can observe in the crystalline rocks of the Piedmont but a careful examination of the imagery does indeed reveal the presence of the lineaments.

The purpose of this study is to discuss the tectonic disturbances in the area of the Delmarva Peninsula that occurred during the Holocene and part of Tertiary time utilizing the LANDSAT-1 imagery, subsurface geology, and geomorphology.

ABSTRACT: *A study of geomorphologic features of land surface, drainage patterns, and subsurface geology, as they appear on LANDSAT-1 imagery, suggests that the area of the present Delmarva Peninsula has been undergoing tectonic evolution at least since early Tertiary times. Several NE-SW and NW-SE trending lineaments can be correlated with the subsurface basement faults and surface geomorphologic features. Several other lineaments, however, do not seem to correspond to any known surface or subsurface features. Lack of correlation also exists for several surficial features and for several subsurface features which are not apparent on the LANDSAT-1 imagery. The most notable example is a very distinct subsurface linear anomaly manifested by an abrupt change in the thicknesses of several Tertiary sedimentary units which cannot be observed on the LANDSAT-1 imagery.*

One of the major tectonic events that has been taking place for a considerable period of time is southeastward or eastward tilt of the Peninsula. This is evident in the regional drainage patterns of present-day streams, coastal geomorphology, the distribution of subsurface geologic units and surfaces of unconformities. The evidence for significant regional vertical movements that affected not only the area of the Peninsula but also other parts of the Coastal Plain is provided by two major unconformities between Eocene and Middle Miocene and between Late Miocene and Pleistocene, respectively. It is believed that the area was continuously or intermittently uplifted during these hiatuses.

A conceptual model for the block-fault origin of the Atlantic Continental Terrace appears to be compatible with the fault systems and other structural features observed on the Peninsula. Assuming that the model, which relates marginal faulting to the impingement of oceanic fracture zones, is correct and that rifting at the Mid-Atlantic Ridge is presently occurring, it can be concluded that the tectonic evolution of the Delmarva Peninsula is still in progress. This is supported by studies of recent earthquakes in the northern and central parts of the Peninsula. It is suggested that a system of conjugate compressional and tensional shears extends from the Piedmont to the north across the Coastal Plain and onto the Shelf in the south.

FIG. 1 Location map of the Delmarva Peninsula (shaded).

DISCUSSION

LINEAMENTS AND BASEMENT FAULTS

The LANDSAT-1 lineaments in the northern part of the Peninsula marked 2 and 5 (Figure 2) can be related to known faults in the basement complex. Lineament number 2 corresponds to a fault originally found by drilling just south of the Fall Line (Spoljaric, 1972). The northeastern side of the fault is downdropped with a maximum known vertical displacement of about 50 feet. The northwestern extension of this fault was later found in the Piedmont (J. C. Miller, personal communication) and its possible southeastward extension is suggested by the lineament on the LANDSAT-1 imagery.

Lineament number 5 appears to be a surface expression of a graben fault system identified in the basement complex (Spoljaric, 1973) and trending in the same direction as the lineament. The graben faults were originally found by drilling approximately in the area of the northeastern portion of the lineament and were later confirmed by a detailed vibroseis survey carried out by Dames and Moore, Consulting Engineers in the Applied Sciences. Although the lineament suggests that the fault system extends both to the northeast and the southwest for several miles, supporting subsurface evidence is not available. The vibroseis survey carried out along the lineament just southwest of the graben fault system was inconclusive. However, several faults trending in the same direction as the lineament have been found in proximity to the lineament. A detailed study of one of these faults suggests that the sediments of Early Cretaceous age and early Late Cretaceous age have been affected by faulting but not younger strata. If this interpretation is correct, then the faulting occurred sometime early in the Late Cretaceous.

The lineaments marked 3 and 4 (Figure 2) correlate with a postulated major fault recently proposed by Higgins, Zietz, and Fisher (1974). The evidence for the presence of a fault is inconclusive so that the significance of the lineament is unknown.

SUBSURFACE TERTIARY STRUCTURAL FEATURES

The discussion of the subsurface geology is limited to the Eocene sediments of Claiborne and Jackson ages, and to the deposits of Middle and Late Miocene age (Figure 3) because a sufficient amount of data, to indicate earlier geologic times, are presently not available. The cross-section (Figure 3) shows the general relationships of the units to be discussed and also two major unconformities within this sedimentary sequence.

The depositional basin of the Claiborne sediments trends NE-SW across the Peninsula and the deposits thin both to the northwest and the southeast (Figure 4). The southeastern margin of this depositional basin correlates with an abrupt change in the configuration and elevation of the surface of the Claiborne sediments, as well as with the sudden change of the thickness of the same unit. This flexure-like feature extends both to the northeast and the southwest and it seems to have limited the westward extent of the overlying Jackson sediment of Eocene age (Figure 5).

The Jackson sediments are present only in the east-central part of the Peninsula. They also might be present in the southernmost part of the Peninsula but this has not been confirmed. The contact of the Claiborne-Jackson deposits with the overlying sediments of Middle Miocene is a major uncon-

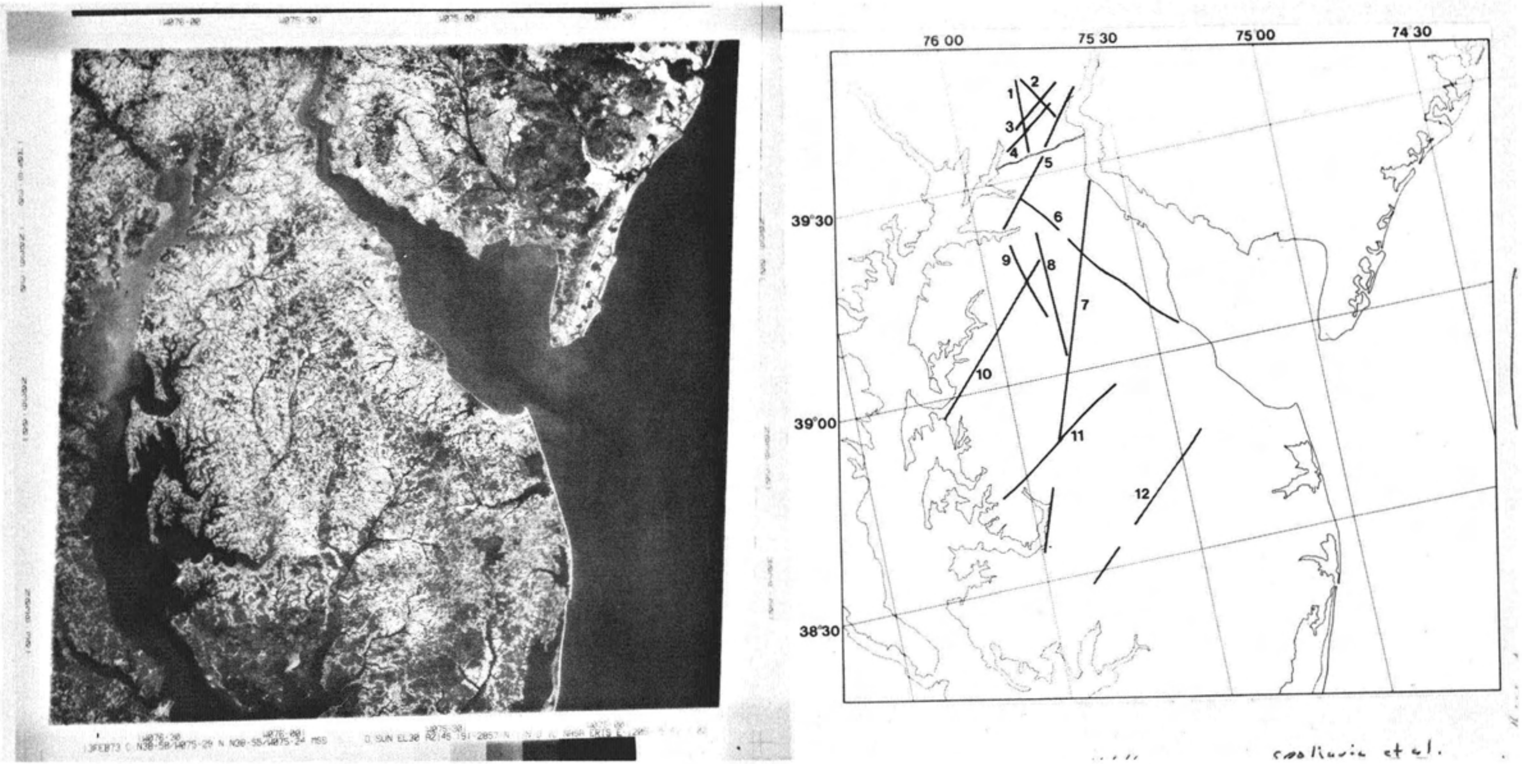

FIG. 2 Color composite LANDSAT-1 imagery of the Delmarva Peninsula (left); major lineaments are shown on the right.

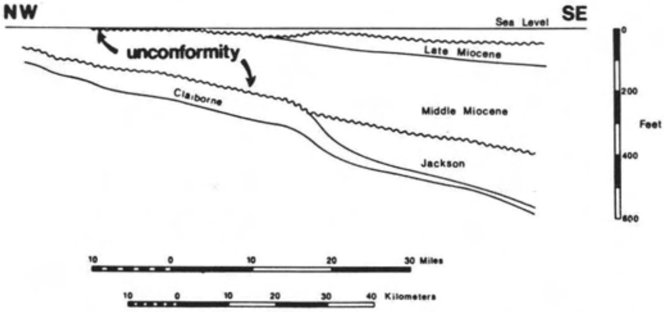

FIG. 3 Generalized cross-section of the stratigraphic units and unconformities discussed in the text.

formity (Figure 3). There is also a possible minor unconformity separating the Claiborne from the Jackson. Nevertheless, in view of the fact that both are time-stratigraphic units, the relationship between the Jackson sediments of Late Eocene age and laterally adjacent Claiborne sediments of Middle Eocene age is anomalous and two possible explanations for this anomaly are suggested.

The first possibility is the presence of a fault. The problem with this interpretation is

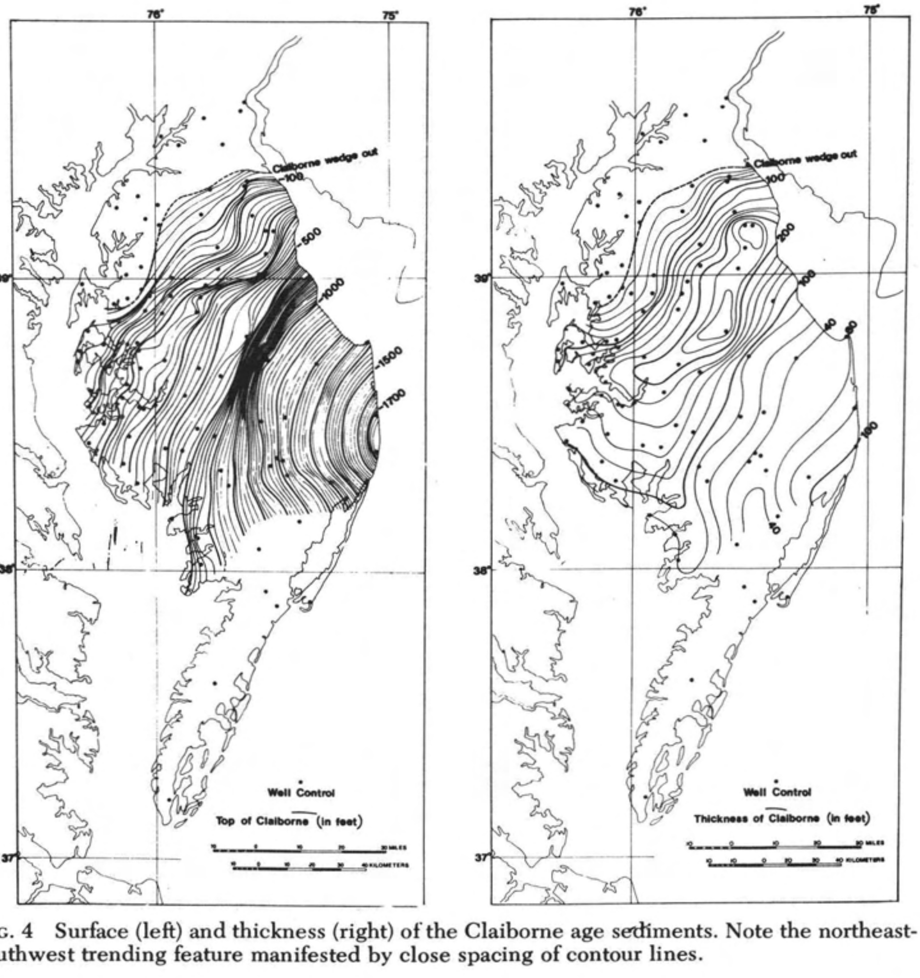

FIG. 4 Surface (left) and thickness (right) of the Claiborne age sediments. Note the northeast-southwest trending feature manifested by close spacing of contour lines.

that the difference of the thickness of the Claiborne sediments on opposite sides of the postulated fault cannot be satisfactorily accounted for without invoking reversal in the sense of movement along the fault. During the initial activation the northwestern block should have moved downward and the southeastern block upward. In the reactivation the movements along the fault should have been reversed. Although a reversal in the sense of movement along reactivated faults has been observed elsewhere by other workers, most recently by Chowdhary (1975), no firm evidence is presently available to prove this interpretation.

The second possible explanation of the Claiborne anomaly is a slump. A slump could account for the difference in the thickness of the Claiborne sediments on the opposite sides of the feature, but this would be very difficult to prove.

The same anomalous feature is also quite apparent in the thickness of the sediments of Middle Miocene age, but it seems to be absent from the surface of the same unit (Figure 6). It is concluded that the feature exerted some control on the deposition of the lower part of the Middle Miocene sequence only.

The thickness and the surface of the Late Miocene deposits (Figure 7) give no indication of the presence of the same anomalous feature in these sediments. This is most probably the reason why this conspicuous subsurface feature is not recognized on the LANDSAT-1 imagery. With the exception of the lower part of the Middle Miocene, the feature apparently had no influence on de-

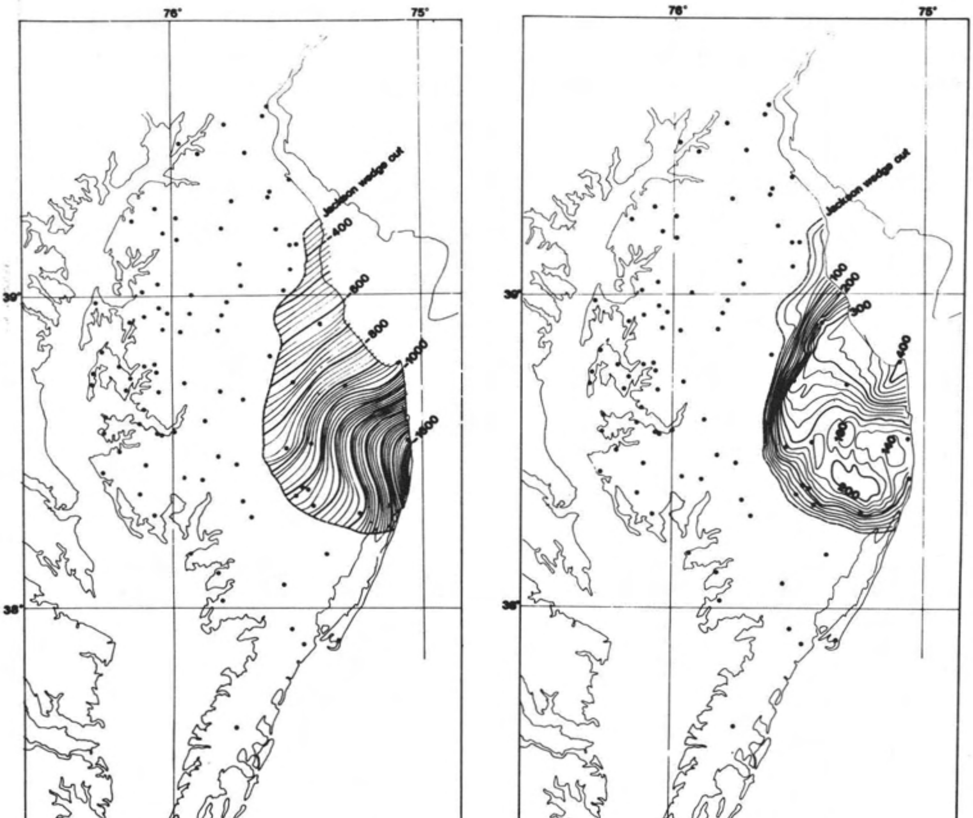

FIG. 5 Surface (left) and thickness (right) of the Jackson age sediments. The northeast-southwest trending feature (Figure 4) seems to have limited the westward extent of the Jackson sediments.

position of the remaining Miocene and younger sediments.

EVIDENCE FOR VERTICAL MOVEMENTS AND THE TILT OF THE PENINSULA

Regional vertical movements of the Peninsula area that affected other parts of the Coastal Plain as well are indicated by at least two major unconformities in the Tertiary sedimentary sequence (Figure 3). The first unconformity is found between Eocene sediments of Claiborne-Jackson age and Middle Miocene deposits. The other is observed between Middle-Late Miocene and Pleistocene sediments. In the northern part of the Peninsula these two unconformities merge, thus increasing the hiatus from Eocene to Pleistocene to about 40 million years of geologic time. It is not known what events took place during that time. However, the area must have been emergent for a sufficiently long period of time to account for the unconformities. It is also not known whether the sediments of Oligocene, Early Miocene, and Pliocene ages, which seem to be missing from the Peninsula, were first deposited here and later eroded or not deposited at all.

The evidence for the southeastward or eastward tilt of the Delmarva Peninsula is provided by the subsurface geology, drainage patterns, and coastal geomorphology. For example, the surface of the individual stratigraphic units and the surface of the two

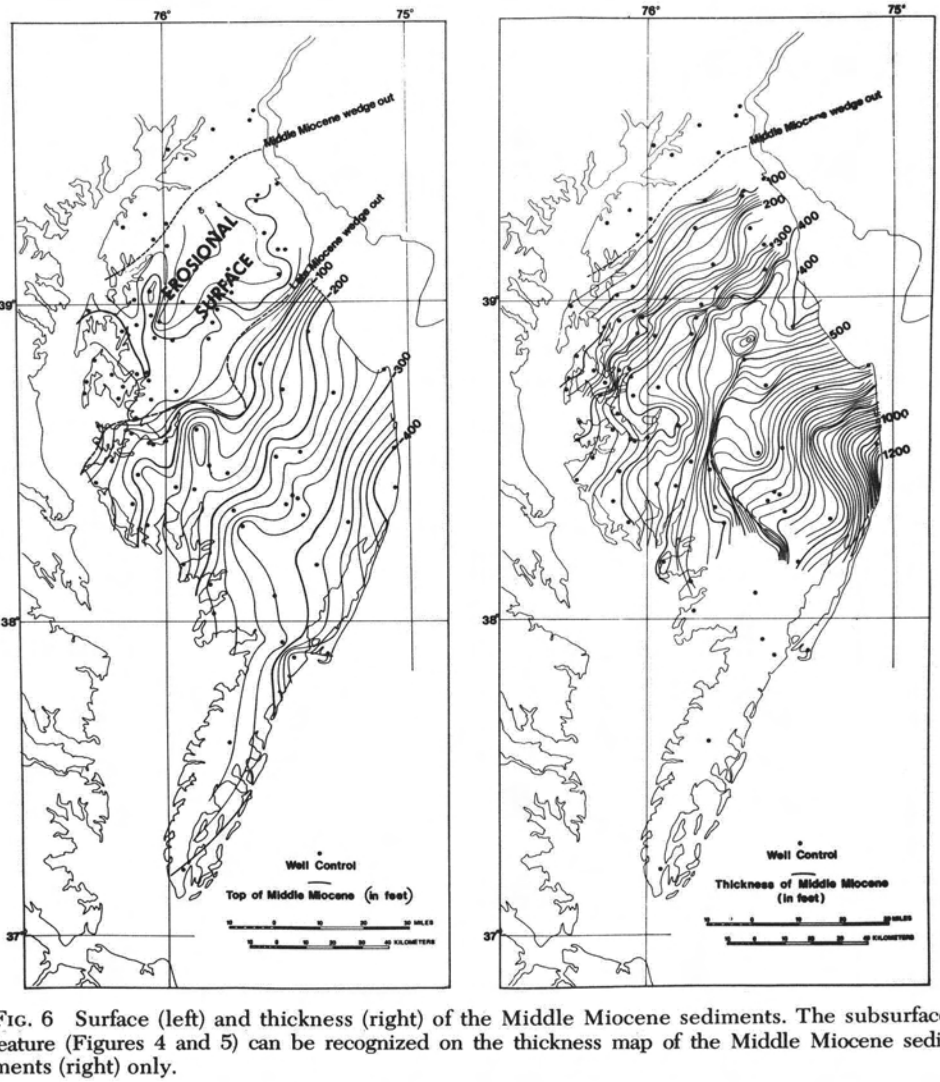

FIG. 6 Surface (left) and thickness (right) of the Middle Miocene sediments. The subsurface feature (Figures 4 and 5) can be recognized on the thickness map of the Middle Miocene sediments (right) only.

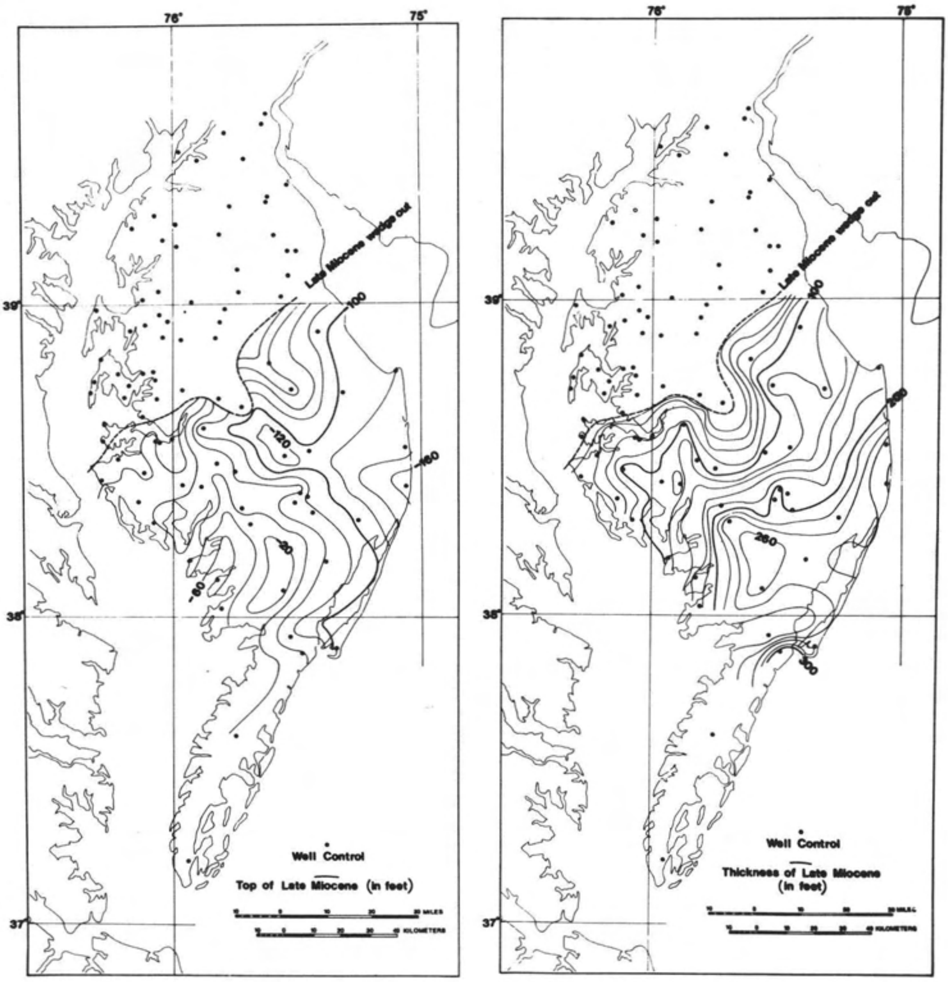

FIG. 7 Surface (left) and thickness (right) of the Late Miocene sediments. No presence of the subsurface feature (Figures 4, 5, and 6) is indicated.

major unconformities dip to the east-southeast. The drainage map (Figure 8) provides a more apparent evidence for the postulated tilt.

The coastal area along the Delaware Bay is rather monotonous, low flat and characterized by abundant marshes. Streams draining to the Delaware Bay are short and tidal for the greater part of their length. On the other hand, the coastal area of the Peninsula along the Chesapeake Bay is characterized by numerous bays, is higher than the Delaware Bay coast, and has small cliffs. The streams draining into the Chesapeake Bay are relatively long and their valleys are generally deeper than those of the streams draining into the Delaware Bay. The coastal geomorphology of the Delaware Bay and the Chesapeake Bay sides of the Peninsula are indeed quite different although they developed on the same kinds of sediments. It is important to note that the drainage divide of the Peninsula is considerably closer to the Delaware Bay than the Chesapeake Bay. The difference in the coastal geomorphology and the "eastward shift" of the regional divide are to be expected if the Peninsula is tilting eastward or southeastward. Tilting may also provide the mechanism for conversion of chains of lagoons into the longer southwestward flowing streams following the drainage evolution suggested by Rasmussen and Slaughter (1955) and mentioned by Jordan (1966, 1974a).

The drainage map (Figure 8) also provides explanation for a number of the LANDSAT-1 lineaments not explained before. The lineaments marked 6, 7, 9, 11, and 12 (Figure 2) correspond to stream valleys. It is not known whether or not some of these stream valleys are in fact structurally controlled.

ATLANTIC MARGINAL GEOSYNCLINE

Following is a brief discussion of a conceptual model of the block-fault origin of the Atlantic Marginal Geosyncline, orginally developed and discussed by Sheridan (1974a), as it may relate to the structural features observed on the Delmarva Peninsula.

Recently new geological and geophysical data have become available through petroleum exploration drilling and seismic studies of the Atlantic continental margin. These studies revealed the basement structure to be block-faulted, rifted style, overlain with as much as 25,000 to 33,000 feet of Triassic and younger shallow-water facies sediments (Sheridan, 1974b). This structure is compatible with the interpretation that North America and Africa, once contiguous during the late Paleozoic, have rifted apart along lines close to their continental slopes to spread laterally with the formation of the Mesozoic and Cenozoic Atlantic Ocean (Pitman and Talwani, 1972).

The basement structure map (Figure 9) shows basins as isolated fault bounded troughs (Sheridan, 1974a). Fundamental tensional basement faults were inferred from the hinge zones (Figure 10), and complementary transverse faults were inferred from linear magnetic features. The interpreted fault-block structure (Figure 11) can be simply illustrated as 17 blocks (A to Q) separated by major graben structures of the basins and right-lateral shear faults of oceanic fracture zones.

An analysis of these major fault trends seems to suggest their grouping into four general trends: nearly due north, nearly due northwest, nearly due northeast, and nearly due east. Using the hinge zones of the continental margin basins to define the axes of extension, there appear to be three distinct minimum stress axes: one due north, one due east, and one due northwest. The complementary compressional stresses would produce right-lateral shear on the northwest trending Atlantic fracture zones, the nearly north trending White Mountain fault zones, and the northeast trending Labrador Sea fracture zones. Three stress systems can therefore be defined: the Atlantic Ocean stress system with north-south compression and east-west tension, the Labrador Sea stress system with east-west compression and north-south tension, and the White Mountain stress system with northeast-southwest compression and northwest-southeast tension (Figure 10).

These three stress systems appear to overlap spatially and to act independently at times. Thus, as Brown and others (1972) have shown, northeast trending basement faults in the Delmarva Peninsula (Block M) acted as shear faults part of the time, then became tensional faults at other times when the northwest trending shear faults became dormant. This reflects the alternation between the Atlantic Ocean and White Mountain stress systems, both of which have affected the Delmarva Peninsula.

The simple block subdivisions (A through Q) were manipulated to reduce the extension of the marginal faults (Figure 11, left side) (Sheridan, 1974a). The reconstruction

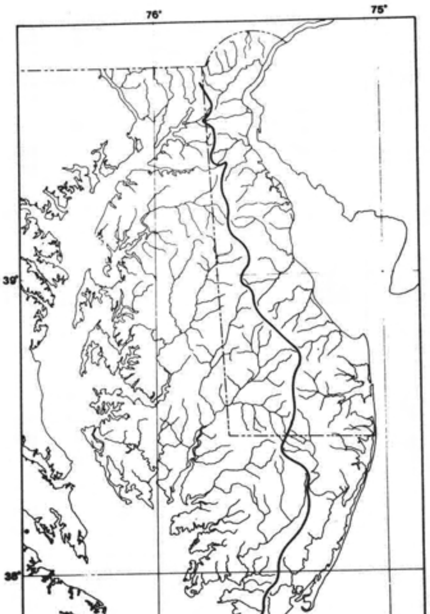

FIG. 8 Drainage map of the Delmarva Peninsula. Note the "eastward shift" of the drainage divide and the distinct difference in the coastal geomorphology between the eastern and western coasts of the Peninsula.

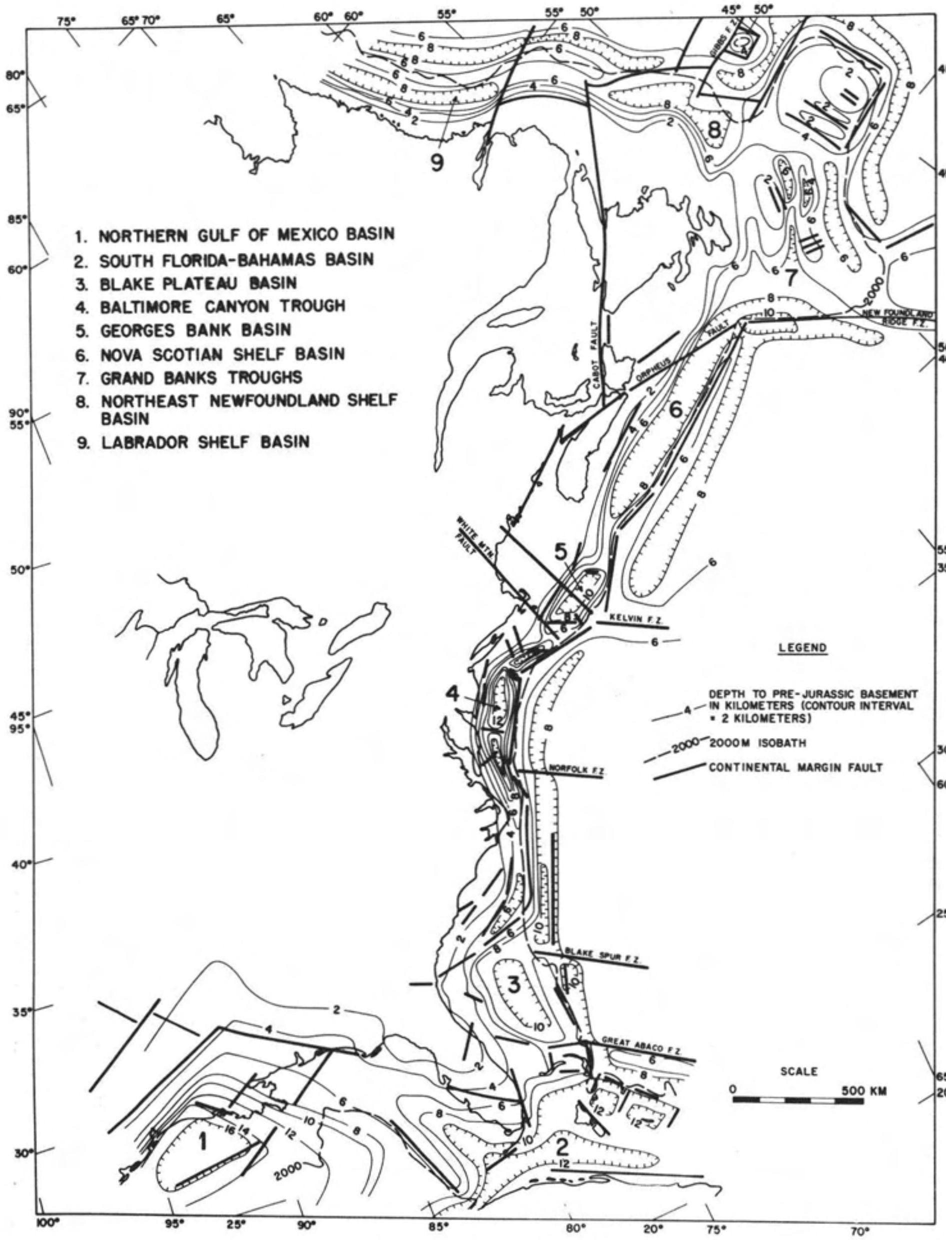

FIG. 9. Structural map of pre-Jurassic basement of Atlantic continental margin (after Sheridan, 1974b).

is considered a hypothetical unit structural block, and the motions of the subdivision blocks, which give the appropriate right-lateral shear and tension for the continental margin faults, would result in the clockwise rotation of the unit structural block (Figure 11, right side). This would be compatible with sea-floor spreading of the Labrador Sea and the Atlantic Ocean and the clockwise rotation of North America away from Africa. The drastic reorientations in spreading directions in the north Atlantic through the Mesozoic and Cenozoic (Pitman and Talwani, 1972) and the independent opening of the Labrador Sea have caused the alternation of stress directions along the margin depending on North America's direction of movement away from Africa-Europe.

This conceptual model for the block-fault origin of the Atlantic Marginal Geosyncline

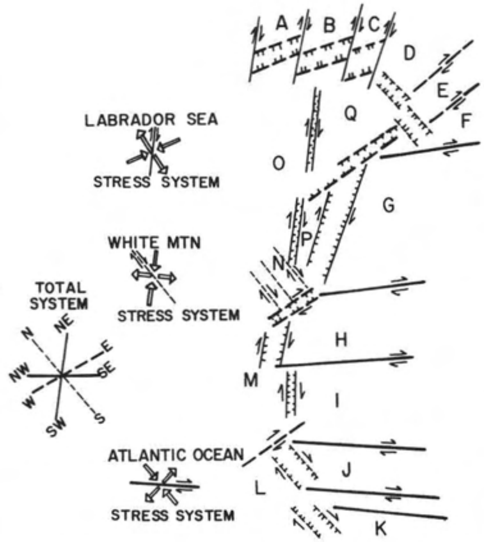

FIG. 10 Fundamental fault pattern of Atlantic continental margin with deduced stress systems (after Sheridan, 1974a).

is compatible with the observed basement structures and stratigraphy of the Delmarva Peninsula. As pointed out by Brown and others (1972) and Sheridan (1974a), the stress systems deduced for the Delmarva Peninsula should have been sporadically active throughout the Mesozoic and Cenozoic Eras, as long as sea-floor spreading has continued in the Atlantic. Indeed, because rifting is still occurring along the Mid-Atlantic Ridge, the continental margin fault systems should be considered active.

TECTONIC ACTIVITY AND RECENT EARTHQUAKES

It has been suggested elsewhere in this report that the continental margin fault system should be considered active if rifting along the Mid-Atlantic Ridge is indeed taking place. Indirect evidence that supports this activity is provided by recent earthquakes on and near the Peninsula (Figure 12) (summary of the earthquakes given by Jordan and others, 1974a).

The first known damaging earthquake occurred on October 9, 1871 near Wilmington at the northern margin of the Peninsula. The intensity of the modified Mercalli Scale was estimated to be about VII. An earthquake with an estimated intensity of V took place in March of 1879 near Dover in the northern part of the Peninsula. Not much is known about this event except that it was felt strongly. The May 8, 1906 earthquake, with an estimated intensity of V occurred in the central part of the Peninsula and it was also described as strong.

Between July 1971 and March of 1975 more than 20 earthquakes have been felt or instrumentally recorded (Delaware Geological Survey files). Most of them occurred in southwestern Wilmington and close to the Fall Line. The majority of these events had estimated intensities of less than III with the

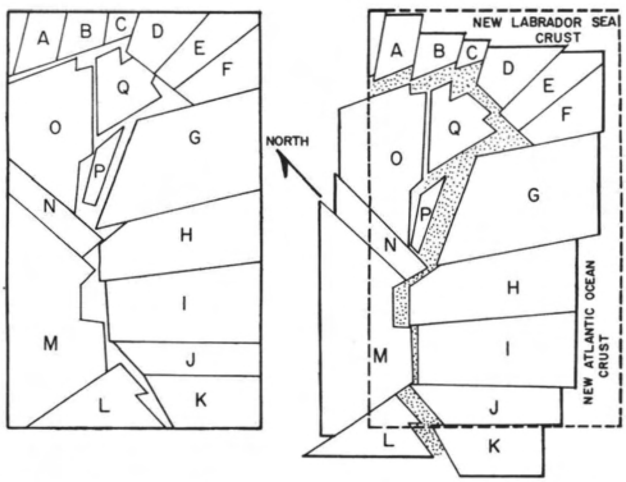

FIG. 11 Conceptual reconstruction of unit-structural block of Atlantic continental margin (left) and clockwise rotation into present configuration (right). Speckled pattern represents extensional structure of block-faulted Atlantic Continental Margin Geosyncline subsequently opened by rotation (after Sheridan, 1974a).

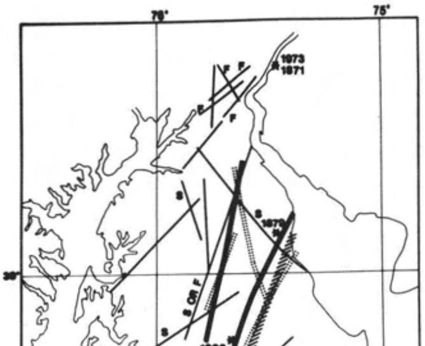

FIG. 12 Interpretation of linear features on the Delmarva Peninsula. Note close correspondence between the earthquake epicenters and some linear features.

exception of the November 10, 1972 event with an estimated intensity of III; June 1, October 10, November 27, 1972 and July 10, 1974 earthquakes with estimated intensities of IV; and the February 28, 1973 earthquake with an estimated intensity of VI (Woodruff and others, 1973) and a magnitude of 3.8 on the Richter Scale as determined by NOAA scientists.

The fault-plane solution for the February 28, 1973 earthquake computed by Sbar and others (1975) indicates a dip-slip motion on a nearly vertical plane with the southeastern side downdropped. The strike of the fault-plane was determined to be about N 28° E. It lies along the possible northeastward extension of the basement graben fault-system (Spoljaric, 1973) and the LANDSAT-1 lineament.

Two other earthquakes have been noted on the Peninsula, one in 1774 and the other in 1937. The 1774 event occurred somewhere in the southermost part of the Peninsula and very little is known about it. The 1937 earthquake took place in the central part of the Peninsula, in southern Delaware, and again very little is known about it.

Spoljaric (1974) studied geology, geomorphology, aeromagnetic data, and LANDSAT-1 imagery of the Piedmont Province in northern Delaware and southeastern Pennsylvania (Figure 13) following the February 28 earthquake, and concluded that most of the lineaments seen on the LANDSAT-1 imagery are probably faults that have previously been unknown. Jordan and others (1974b) reached similar conclusions in their study of the Piedmont in Delaware. It is interesting to note that the

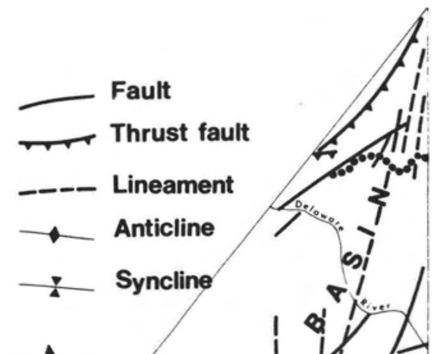

FIG. 13 The trends of the LANDSAT-1 lineaments and structural features in the S.E. Pennsylvania and northern Delaware are similar to those observed on the Peninsula (Figure 2, right) and on the Atlantic continental margin (Figure 9) (modified after Spoljaric, 1974).

trends of the LANDSAT-1 lineaments and the known faults here correlate with the trends of the similar linear features on the Peninsula, and also with the trends of the fundamental faults along the continental margin of the Atlantic Marginal Geosyncline. This correlation is perhaps suggestive of a system of compressional and tensional shears (Brown and others, 1972) extending from the Appalachian Piedmont to the north across the Coastal Plain and onto the Continental Shelf in the south.

The approximate locations of the epicenters of the 1879 and 1906 (Figure 12) earthquakes closely correspond to the location of the Tertiary subsurface anomalous feature. If this feature and the earthquakes are related, then it is quite possible that the feature developed as a result of some tectonic disturbance and its interpretation as a fault becomes quite probable.

Conclusions

Most LANDSAT-1 lineaments, faults and other linear features on the Delmarva Peninsula seem to be related to a system of compressional and tensional shear zones that extend from the Piedmont to the north, across the Coastal Plain, and onto the shelf in the south. Tectonic activity along these shear zones has been going on at least since the Tertiary time. The most recent activity is manifested by numerous earthquakes that occurred mainly at the northern margin of the Peninsula, but also in its central and southern parts. These earthquakes clearly suggest that the tectonic evolution of the Peninsula is still in progress.

Acknowledgments

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