Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 29

UPPER CRETACEOUS (SENONIAN) AND PALEOCENE (DANIAN) PINCHOUTS ON THE SOUTH FLANK OF THE SALISBURY EMBAYMENT, MARYLAND, AND THEIR RELATIONSHIP TO ANTECEDENT BASEMENT STRUCTURES

by
Harry J. Hansen

Prepared in cooperation
with the
Geological Survey
United States Department of the Interior
and the
Maryland Energy and Coastal Zone
Administration

1978

ENGLISH-METRIC CONVERSION TABLE

INCHES x 0.0254	=	METERS
FEET x 0.3048	=	METERS
MILES x 1.609	=	KILOMETERS
FEET PER MILE x 0.1894	=	METERS PER KILOMETERS
FEET PER SECOND x 0.0003048	=	KILOMETERS PER SECOND

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UPPER CRETACEOUS (SENONIAN) AND PALEOCENE (DANIAN) PINCHOUTS ON THE SOUTH FLANK OF THE SALISBURY EMBAYMENT, MARYLAND, AND THEIR RELATIONSHIP TO ANTECEDENT BASEMENT STRUCTURES

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ABSTRACT

Upper Cretaceous (Santonian to Maestrichtian) and Lower Tertiary (Danian) pinchouts on the southern flank of the Salisbury Embayment in Maryland coincide broadly with a change in aeromagnetic pattern believed to be associated with the contact between two distinct crustal blocks. On regional maps the central part of the Embayment is dominated by a "featureless" aeromagnetic belt called the Richmond-Brandywine trend. In Virginia, Maryland, and Delaware, this trend is characterized by a generally planar, down-dip decrease in total intensity, punctuated by broad-amplitude closures. It is bordered on the west and north by a complex, ropy pattern of steep-sided highs and lows which correlates with the schistose, ultramafic and gabbroic rocks of the outcropping eastern Piedmont. Southward the NE to NEE Richmond-Brandywine trend abuts against a N- to NNE- striking en echelon series of aeromagnetic highs and lows, dominated by the Sussex-Currioman Bay anomaly which extends from Sussex County, Virginia, into St. Mary's County, Maryland.

In Virginia the Richmond-Brandywine aeromagnetic trend strikes oblique to the Fall Line where it is coincident with an extensive granite-gneiss pluton containing one large and several small, downfaulted Triassic basins. Beneath the Coastal Plain, the association of the Richmond-Brandywine trend with Triassic rocks has been confirmed by basement core data as far north as Prince George's County, Maryland. Extension of the Richmond-Brandywine trend across the Delmarva Peninsula suggests that downfaulted Triassic rocks may occur there as well, although several vibratory seismic lines failed to record primary reflections from below top-of-basement.

It is proposed that general downwarping of the continental margin during late Jurassic, Cretaceous, and early Tertiary times was accentuated in the Salisbury Embayment and Baltimore Canyon Trough because those areas correspond broadly with Triassic rift basins functioning as antecedent zones of crustal weakness. The Upper Cretaceous and Lower Paleocene pinchouts described herein coincide broadly with the southern margin of the Salisbury Embayment (as defined by the Richmond-Brandywine aeromagnetic trend). The association of Upper Cretaceous and Lower Paleocene pinchouts with the boundary of the Richmond-Brandywine trend suggests that the Salisbury Embayment was rooted in a residually active Triassic rift system, sporadically readjusting to stress during the downwarping of the continental margin.

Faulting within the Richmond-Brandywine trend in Prince George's County, Maryland, was first proposed by Jacobeen (1972) who mapped a high-angle, up-to-the-SE reverse fault system affecting strata as young as Lower Tertiary. Seventy miles of reflection seismic lines were run across the margins of the Richmond-Brandywine trend in Kent, Queen Anne's, Talbot, Dorchester, and St. Mary's Counties, Maryland to investigate the possibility of Coastal Plain structures associated with the edges of juxtaposed basement blocks.

A potentially significant fault was recorded on a seismic profile in central St. Mary's County on the southern margin of the trend near its contact with the Sussex-Currioman Bay anomaly. This fault, herein called the Hillville Fault, is a high angle, up-to-the-south reverse fault with an estimated offset of about 250 feet. A marked change in the seismic signature from the top-of-basement occurs across the fault, suggesting that two distinct basement terranes are involved. Conversely, seismic profiles run in Talbot and Dorchester Counties on the Eastern Shore of Maryland failed to establish a comparable fault on the

southern edge of the Richmond-Brandywine trend, even though Coastal Plain pinchouts along the same traverse are well documented. These apparently conflicting data appear to eliminate the possibility of a single, transcurrent border fault but may be compatible with an en echelon series of up-to-the-south, scissor faults oblique to regional strike.

Faults, involving at least the lower part of the Coastal Plain, were mapped on seismic profiles near the northern margin of the Richmond-Brandywine trend in Kent and Queen Anne's Counties. These were consistently up-to-the-north faults and had offsets of less than 100 feet, imparting a subdued stair-step configuration to the top-of-basement. Stage-level Upper Cretaceous and Lower Tertiary pinchouts are not associated with this faulting in Maryland.

INTRODUCTION

The Maryland Coastal Plain occupies a south central position within the Salisbury Embayment. The southern flank of the Salisbury Embayment is defined by a pronounced change in strike of the basement contours at about 38° 30′ N. which is broadly coincident with a major change in aeromagnetic pattern (fig. 1). Outcropping formations of Upper Cretaceous (Senonian) to Lower Paleocene (Danian)* age thin, and in some cases pinch out, across the southern flank of the Salisbury Embayment. This study was undertaken to investigate the possible association of Coastal Plain pinchouts with sporadically active basement structures.

As part of a hydrogeologic investigation of the Magothy Formation (Mack and Mandle, 1977), an important Upper Cretaceous aquifer, additional well control was established in Anne Arundel, Prince George's, Charles, and Calvert Counties, Maryland. Cores and selected cuttings from these and other previously drilled wells were given to Gilbert J. Brenner of the State University of New York (New Paltz) who dated the samples on the basis of their palynological assemblages. These data were used in conjunction with geophysical logs to establish a correlation grid from which new isopach (thickness) maps of the Upper Cretaceous-Lower Paleocene interval were prepared.

A review of regional aeromagnetic data (U.S. Naval Oceanographic Office, 1964-1966; Taylor and others, 1968) suggested that the zero-isopach lines associated with the Upper Cretaceous-Lower Paleocene interval in southern Maryland were broadly correlative with the northwestern boundary of the Sussex-Currioman Bay magnetic trend (LeVan and Pharr, 1963). Inasmuch as the association of stratigraphic pinchouts with a boundary separating two regional aeromagnetic patterns is suggestive of a possible zone of crustal rupture, 70 miles of vibratory seismic reflection lines were run to investigate the structural significance of these features. Furthermore, it was hoped that the acquisition of new stratigraphic and geophysical data from the Maryland part of the Salisbury Embayment would provide a basis for evaluating recently proposed tectonic theories (Mattick and others, 1974; Schlee and others, 1976) concerning the evolution of the Atlantic continental margin.

The author wishes to acknowledge the assistance given by William Peterson and Terry Durham of the Seismograph Service Corp. who provided advice during the field acquisition and processing of the siesmic data and aided in its geologic interpretation. The latter was chiefly responsible for preparing the synthetic seismograms illustrated in this report. Drafts of the report were reviewed by Kenneth Schwarz of the Maryland Geological Survey and Robert Mattick and Harold Gill of the U.S. Geological Survey who made constructive editorial and technical suggestions. Data acquisition costs were funded by the U.S. Geological Survey, the Maryland Geological Survey, and the Maryland Energy and Coastal Zone Administration. Irwin Kantrowitz, Kenneth Weaver, and Paul Massicot, respectively, worked with the author to coordinate this aspect of the project. The illustrations were drafted, with color separation, by John Goodell. The report manuscript, which included several earlier drafts, was typed by Margaret Little.

REGIONAL SETTING

Regional structure contours drawn on top of basement rocks exhibit a pronounced change in strike beneath the Maryland Coastal Plain at approximately latitude N. 38° 30′ (fig. 1). At this latitude the strike of the basement contours shifts from a NE orientation, which dominates the structural surface of the basement rocks from the Long Island Platform southward, to a S to SSE trend (fig. 2). This change in strike defines a flank position separating the more axial parts of the Salisbury Embayment† (Richards, 1948) from the Norfolk Arch (Gibson, 1967), a locally prominent, eastward-plunging structural high. The Norfolk Arch appears to lose definition offshore where it merges into the monoclinal south flank of the Baltimore Canyon Trough (fig. 2).

*Some of the stratigraphic names and age determinations used in this report do not agree fully with those of the U.S. Geological Survey.

†These features have also been called the Chesapeake-Delaware Embayment (Murray, 1961) and the Fort Monroe High (Richards, 1948).

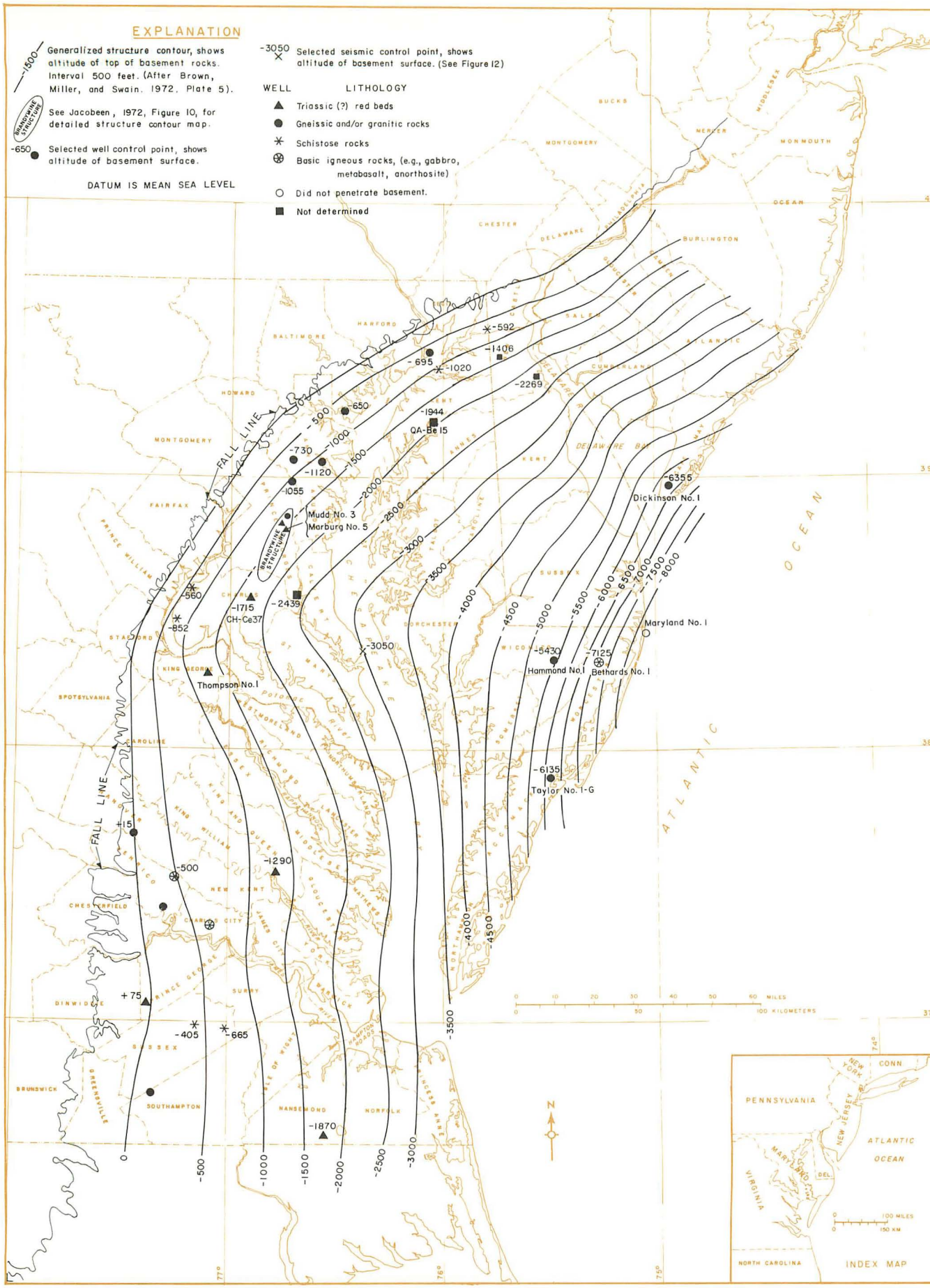


Figure 1. **Generalized structure contour map on top-of-basement surface beneath middle Atlantic Coastal Plain and location of selected deep test holes (modified after Brown, Miller, and Swain, 1972, pl. 5)**

A series of structural contour maps prepared by Otton and others (1969) and Brown, Miller, and Swain (1972) show Lower Cretaceous to Paleocene (Midway) units either terminating or shifting strike as they approach the flank of the Norfolk Arch in southern Maryland. Between 38° 30′ N. and 39° N. the older Coastal Plain units change strike from dominantly NE to dominantly S to SSE, reflecting in a muted, less angular way, the configuration of the top-of-basement surface. Post-Midwayan sediments seem to traverse the Norfolk Arch with progressively less structural warping (Brown, Miller, and Swain, 1972), and by Middle Miocene time appear to strike across it largely unaffected by deeper structures.

In the Maryland part of the Salisbury Embayment regional structure maps (for example, Brown and others, 1972, pl. 5) drawn on the top-of-basement rocks exhibit two changes in gradient. One usually occurs within 15 to 20 miles of the Fall Zone and reflects, in part, distal flattening of the original erosional gradient. The break also coincides in a very broad sense with a major change in aeromagnetic grain. Beneath the inner edge of the Coastal Plain, the top-of-basement rock surface has a regional dip of about 75 to 90 feet per mile. Eastward the slope flattens so that beneath most of the Coastal Plain the dip ranges between 50 to 75 feet per mile. Within 10 to 15 miles of the present coast line, however, the slope of the basement rocks steepens to 90 to 150 feet per mile. This change in gradient is suggestive of a tectonic hinge zone and may define the shoreward edge of the Baltimore Canyon Trough.

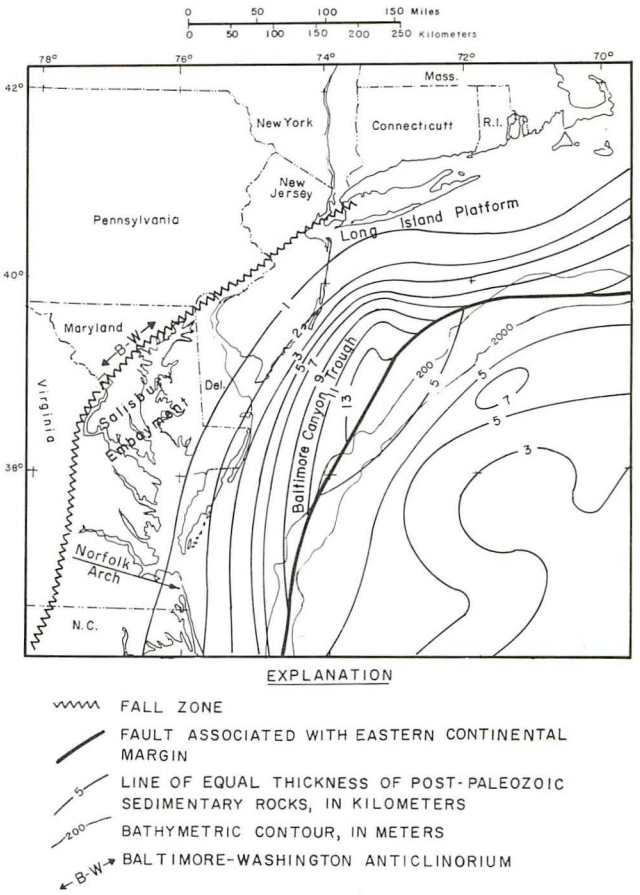


Figure 2. Generalized map showing major tectonic features in the middle Atlantic area (modified from U.S Geol. Survey, 1975, pls. 1 and 3).

BASEMENT ROCKS

The Piedmont rocks in Maryland outcropping adjacent to the Fall Zone are dominated by the Baltimore-Washington Anticlinorium (fig. 2, 3). Several Precambrian gneiss domes crop out along the axis of the anticlinorium. The Baltimore Gneiss, which is exposed in the core of the domes, is overlain unconformably by a thick sequence of early Paleozoic(?), metasedimentary (quartzites, marbles, schists) rocks comprising the Glenarm Series. On the eastern flank of the anticlinorium, the Glenarm rocks are associated with a lithologically complex suite of mafic and metavolcanic rocks (gabbros, greenschist, amphibolites) exhibiting a complex, ropy aeromagnetic texture characterized by sinuous, short-amplitude closures. The structural mechanism juxtaposing the Glenarm rocks with the eastern metavolcanic suite is moot, some investigators favoring in situ plutonic emplacement (Southwick, 1969, p. 71), others thrusting from a distal eugeosynclinal terrane (Crowley, 1975; Rankin, 1975, p. 322-325).

Even though the axis of the Baltimore-Washington Anticlinorium exhibits a gentle concavity to the Fall Zone, the structural strike of the Piedmont rocks in Maryland broadly subparallels the inner margin of the Coastal Plain. As a consequence, the strike belts established in outcrop cannot be projected beneath the Coastal Plain with any confidence. Southward into Virginia, however, the strike of the Fall Zone swings N-S, obliquely traversing major NE trending Piedmont strike belts (fig. 3). From Washington to Richmond one encounters, first, a belt of Wissahickon-type rocks, including pebbly gneisses formerly mapped as "granite,"

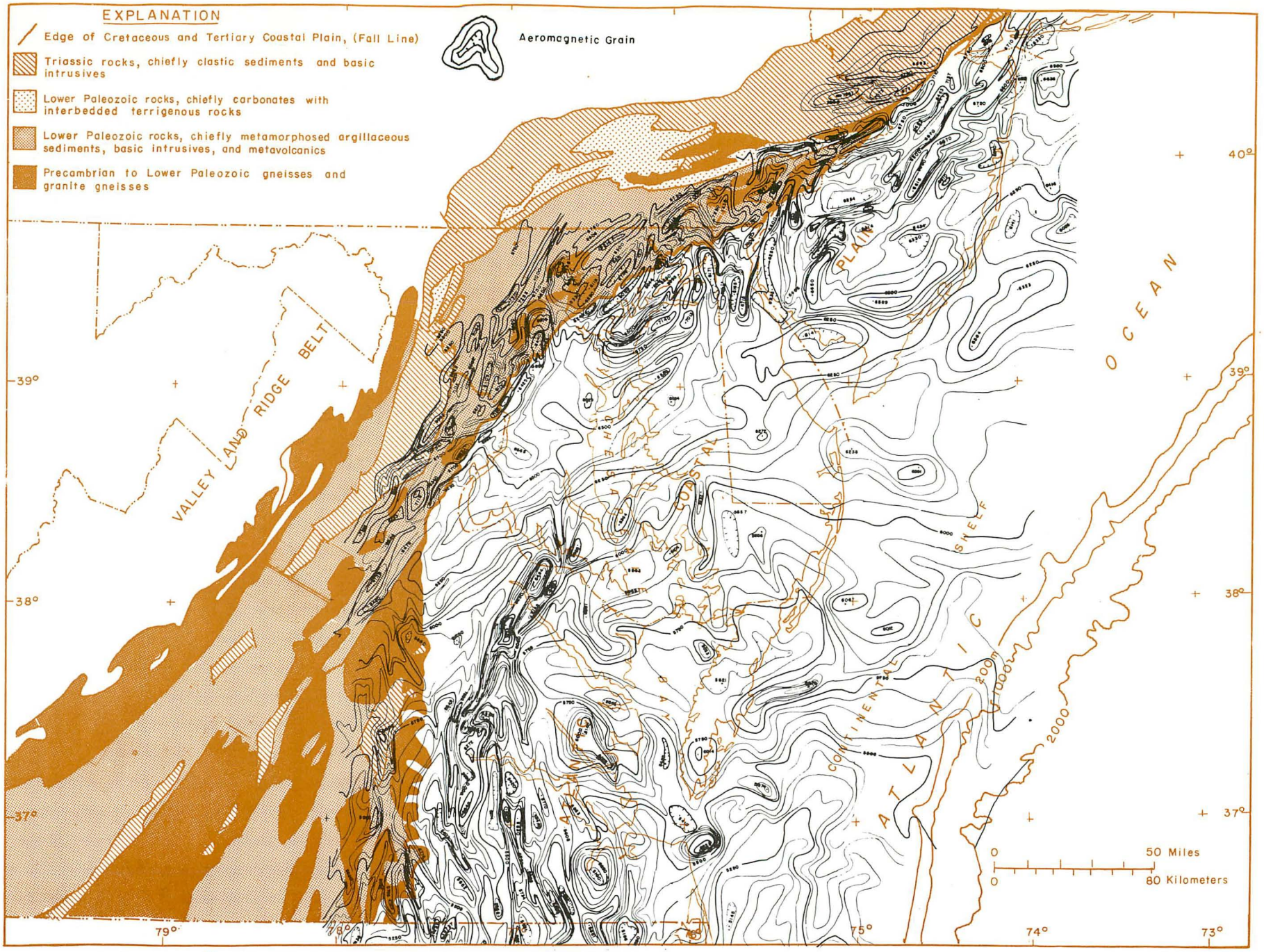


Figure 3. Broadly generalized geologic map of the middle Atlantic Piedmont, including generalized aeromagnetic trends in Coastal Plain areas (modified from U.S. Geol. Survey, 1974c; and U.S. Naval Oceanographic Office, 1964-66)

and associated metavolcanics (Pavlides, 1974); second, a granite-gneiss pluton of uncertain origin; and, third, one large and several small downfaulted Triassic basins underlain on their eastern margins by granitic rocks mapped as Petersburg Granite; (Calver, 1963). The inner margin of the Coastal Plain overlaps the latter two strike belts with pronounced angularity.

South of Richmond the structural grain of the Piedmont again swings subparallel to the Fall Zone, making projection of the outcropping Piedmont units beneath the Coastal Plain sediments more problematic. In any event the Piedmont units south of Richmond become increasingly dominated by Wissahickon - type schists, gneisses, and metavolcanic rocks which may, in part, underlie the inner margin of the southern Virginia Coastal Plain.

In the absence of adequate well data, geophysical methods have been used to map the distribution of pre-Cretaceous basement rocks beneath the Coastal Plain (fig. 4). Beginning in the Richmond-Petersburg areas, Woollard (1940) ran several magnetic transverses southeastward subparalleling the James River. From these and other data Woollard (1940, p. 303) noted:

> "On all three traverses in the Coastal Plain, a marked magnetic low exists near the Fall Line over areas which, from available well data, appear to be underlain by granite. A marked area of magnetic "highs" about eight miles wide, however, occurs just to the east of the zone and these lie in the same area which is charcterized by high basement-seismic velocity and also high gravitational values."

Speculating further Woollard (1940, p.304) observed:

> On the basis of known magnetic susceptibilities for various rocks, it would appear that the rocks giving rise to the observed high magnetic anomalies might be similar to gabbro or basalt. Such rocks are known to occur in the Wissahickon gneiss lying to the west of the Petersburg granite, which is the basement-rock at the Fall Line, but such an extensive band as the one indicated beneath the Coastal Plain is not known."

Later LeVan and Pharr (1963, p. 14, pl. 2) prepared a total intensity aeromagnetic map of the Virginia Coastal Plain. Elaborating on Woollard's earlier observation they concluded:

> "The most prominant feature determined is a major trend of positive magnetic anomalies that extend in a northeasterly direction from Sussex, Sussex County to Currioman Bay, Westmoreland County, a distance of 100 miles. High values of total magnetic intensity obtained over the Potomac River. . .indicate that the trend continues northward into Maryland.
>
> "This major feature ranges in width from four to 12 miles and follows a somewhat sinuous course."

Eschewing Woollard's proposed Wissahickon affinity, LeVan and Pharr (1963, p. 15) speculated that at least part of the Sussex-Currioman Bay trend (fig. 4) might "represent one or more basic igneous rock bodies situated within a downfaulted Triassic basin or perhaps along the eastern region of such a basin." Although noting that prior to their writing no well had actually penetrated the basement rocks along the magnetic trend, LeVan and Pharr cited the occurrence of buried Triassic sedimentary rocks in King William County, approximately five miles west of the magnetic high, to support their view.

Using new well data, Teifke (1973, p. 8, pl. 1) reviewed briefly the distribution of basement lithologic types underlying the Virginia Coastal Plain (fig. 1). In Sussex County several miles east of the Sussex-Currioman Bay trend, two wells (Nos. W-3220, W-2253) were drilled into Wissahickon-type rocks described as biotite schist. In eastern Henrico County, Well No. W-2071, located on the west flank of the magnetic high, penetrated 12 feet of "gabbro or anorthosite" considered by Teifke (1973, p. 68) to be a Triassic intrusive. More recently, however, Teifke (personal comm., 1975) has reevaluated this age assignment in light of the fact that in Charles City County a well drilled into the magnetic high has yielded metavolcanics (Johnson, 1975, p. 5) more diagnostic of the lower Paleozoic rocks of the eastern Piedmont than of the Triassic. This reappraisal supports Woollard's previously expressed skepticism "that if the gabbro-type rock (of the magnetic high) were Triassic diabase, it would be the widest continuous exposure known in the Atlantic area" (1940, p. 305). A magnetic strike belt having the dimensions of the Sussex-Currioman Bay trend (100 miles long, four to 12 miles wide) is much more suggestive of the linear magnetic anomalies of the Piedmont of south-central Virginia and adjacent North Carolina (Reed, Owens, and Stockard, 1967, p. 182; Lidiak and Zietz, 1976, p. 3).

Gravity data reported recently by Johnson (1975, p. 7) defines the Sussex-Currioman Bay trend in corroborative terms: "The most prominent north trend is a broad positive (Bouguer) anomaly with the central area located at about 77°08′ W. longtitude and extending from (the Potomac River) to its southern terminus

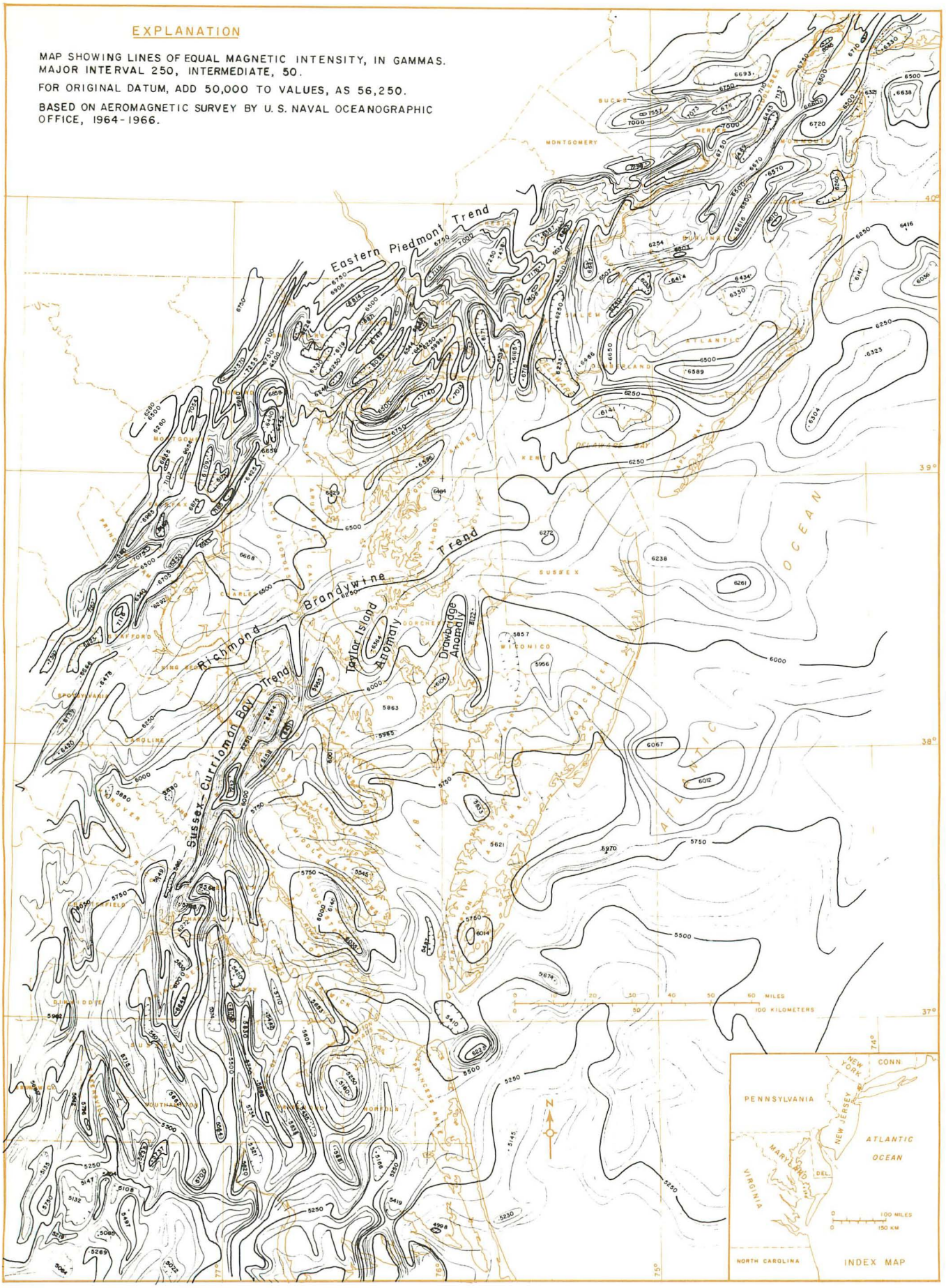


Figure 4. Generalized total magnetic intensity map of the middle Atlantic Coastal Plain (modified from U.S. Naval Oceanographic Office, 1964-66).

northeast of Sussex;...it is attributed to dense intrusives, at least as mafic as gabbro. Steep gradients occur on the east and west flanks of this anomaly, but the gradients become more gradual toward the southern terminus" (see also Johnson, 1973, p. 7-8). Detailed gravity data are presently unavailable north of the Potomac River, but regional Bouguer maps compiled by Woollard and Joesting (1964) and Maher (1971) leave little doubt that the Sussex-Currioman Bay gravity anomaly extends into Southern Maryland.

The Sussex-Currioman Bay trend is bordered on the northeast by a "featureless" aeromagnetic belt, characterized by a generally planar eastward decrease in total intensity. This belt, which is about 20 to 25 miles wide, strikes into (and is apparently coincident with) the gneissic, granitic, and Triassic rocks which dominate the Virginia Fall Zone from about Fredericksburg southward to Petersburg (Woollard, 1940, p. 350). The Sussex-Currioman Bay trend extends northeastward, crossing the Potomac River in the vicinity of central St. Mary's County, Maryland (Taylor, Zietz, and Dennis, 1968, fig. 1; U.S. Naval Oceanographic Office, 1964-66, sheet 6) (fig.4). From here it swings easterly across Chesapeake Bay, becoming less sharply defined, but still identifiable in southern Dorchester County as an en echelon series of magnetic highs and lows (U.S. Geol. Survey, 1974a, 1974b).

At this writing a basement test of the Sussex-Currioman Bay trend has not been drilled in Maryland so that speculation concerning lithologic identity parallels the discussion offered above for the Virginia segment of the trend. The relatively "featureless" magnetic terrain north and west of the Sussex-Currioman Bay trend has, however, been sampled in several wells drilled to basement (fig. 1). The most extensive drilling has been done in the Brandywine area of southern Prince George's County. As discussed by Jacobeen (1972), fourteen wells were drilled to basement, nine encountered granitic and gneissic rocks and five penetrated variegated Traissic(?) sandstones and shales, containing thin lenses of coal (Edwards, 1970). Consolidated red beds believed to be of Triassic age were also encountered farther south in the La Plata area of Charles County (Mack, 1973, pers. comm.; Richards, 1974, p. 1662). The juxtaposition in southern Maryland of Triassic sedimentary rocks, including coal, and granitic basement rocks is reminiscent of the outcropping Richmond basin which is located along the same aeromagnetic strike belt. Several wells drilled into basement along the strike belt between Brandywine and Richmond confirm the presence of similar rock types in at least parts of King George, King William, and Henrico Counties, Virginia, (LeVan and Pharr, 1963; Brown, Miller, and Swain, 1972; Teifke, 1973). The occurrence of volcanic rocks within the trend was established by the Thompson No. 1 well located in King George County (Johnson, p. 7, 1973) (Fig. 1). An isolated 400 gamma anomaly in eastern Anne Arundel County suggests that volcanics may also occur elsewhere within the trend.

Contrary to the relatively subdued magnetic signature of the Richmond-Brandywine trend (fig. 4), the schistose, ultramafic, and gabbroic rocks of the eastern Piedmont of Maryland exhibit higher magnetic susceptibilities (Bromery, 1968, p. 60) which define a complex, ropy pattern of steep-sided highs and lows (fig. 4). The contact (E-NE) between these contrasting magnetic grains is oblique to the Fall Line (NE) so that the Piedmont pattern extends about 20 miles east of the inner margin of the Coastal Plain in Cecil County whereas farther south, in Charles County, the break in pattern is within five miles of the Fall Line. A pronounced E-W "offset" of the contact occurs in northern Anne Arundel County which is, at least superficially, suggestive of wrench faulting.

COASTAL PLAIN STRATIGRAPHY

In the up-dip portions of the Maryland Coastal Plain, major unconformities occur at or near the base of the Aptian-Barremian (Patuxent Formation), Santonian (Magothy Formation), Midway (Aquia Formation) and Middle Miocene (Calvert Formation) (tab. 1). As reviewed in the previous section, the Lower Cretaceous beds of the basal Coastal Plain overlie a complex suite of basement rocks including strata as young as Triassic. Jurassic units appear to be missing north of the Norfolk Arch, although Brown, Swain, and Miller (1972, p. 37) have recently suggested, on the basis of ostracod affinities, that consolidated red beds as old as Portlandian (?) may be present in the deep wells drilled along the coast of Maryland and New Jersey. However, Robbins, Perry, and Doyle (1975, p. 54) counter using floral taxa and suggest that the basal

Coastal Plain beds are no older than Lower Cretaceous Neocomian (?)- Aptian.

From northeast (Kent County) to southwest (Charles County), the Aquia Formation truncates rocks as young as Danian and as old as Albian (Patapsco Formation), although not successively inasmuch as the Upper Cretaceous section is itself complicated by unconformable relationships on the south flank of the Salisbury Embayment.

In Maryland, Middle Miocene beds of the Calvert Formation overlie units as young as Late Eocene (Jackson) and as old as Middle Paleocene (Midway). Farther south in Virginia, the Calvert Formation overlaps Lower Cretaceous units and in many places rests directly on the Piedmont rocks. Heretofore, neither Oligocene nor Lower Miocene beds have been identified in the emergent Coastal Plain north of the Norfolk Arch. However, R.K. Olsson has recently suggested that basal "Calvert" beds from the shallow subsurface of Caroline County are strongly associated with the *Globorotalia kugleri-Globoquadrina dehiscens* (Early Miocene) and *Globogerina ampliapertura* (Upper Oligocene) foraminiferal zones (personal comm., 1976, 1977). Offshore, Oligocene beds are known to wedge into the section; for example, Weed and others (1974, p.4) have noted their occurrence in several widely spaced dredge samples from the edge of the continental shelf, and Smith and others (1976) have logged 286 feet of Oligocene sediments in the C.O.S.T. No. B-2 well.

Of the unconformities the one occurring at or near the base of the Aquia Formation is most clearly related to the pronounced shift in basement contours occurring approximately at latitude 38°30′ N. Upper Cretaceous and Danian units thin severely across this structural grain and eventually zero out. Less is known about the Lower Cretaceous units because of sparse well control. Although the section thins southward in response to the Norfolk Arch, Aptian and Albian beds of the nonmarine Potomac Group clearly extend across the structure (Brown, Miller, and Swain, 1972, pl. 7, 8; Weed and others, 1974, sheet 2). Likewise, the major Tertiary units (except for the apparently absent Oligocene) extend south of Lat. 38°30′ N., although again some thinning occurs, particularly in the basal beds (Lower Midwayan) of the Paleocene.

In Maryland between Lat. 38° N. and 38°30′ N., the distribution of beds above and below the major Coastal Plain unconformities suggest: (1), the northern flank of the Norfolk "Arch" was a negative structural element during Lower Cretaceous times, but accumulated sediments much less rapidly than the Salisbury Embayment; (2), during Upper Cretaceous (Senonian) to Lower Midway (Danian) times, the area was tectonically positive, causing marine sediments encroaching southward from the Salisbury Embayment to pinch out; and (3), during later Tertiary times, its structural importance was diminished as several marine transgressions swept across it with progressively less stratigraphic thinning.

Possible Occurrences of Jurassic and Triassic (?) Rocks

The Maryland Coastal Plain comprises a relatively small part of the Salisbury Embayment, a major coastal structure which is dominated by the offshore Baltimore Canyon Trough (fig. 2). Using recently obtained geophysical data, Mattick and others (1974) speculated that the Baltimore Canyon Trough is a faulted, graben-like structure containing as much as 40,000 feet of Mesozoic and Tertiary sediments. This estimate approximately doubles earlier computations of sedimentary thickness (Drake, Ewing, and Sutton, 1959) and was accomplished largely by a redefinition of acoustical basement. Formerly, seismic velocities of 5.0 to 5.9 km/sec. (16,000 to 19,000 ft./sec.) were assumed to represent crystalline basement. However, Jurassic sedimentary rocks (consolidated red beds, carbonates and evaporites) with comparable velocities have been found beneath the continental shelf off both Cape Hatteras, North Carolina, and southern Nova Scotia, Canada (Mattick and others, 1974). On this basis, Schlee and others (1976) have considered rocks of their "lower acoustical unit," defined by interval velocities of 3.9 to 5.9 km/sec. (13,000 to 19,000 ft./sec.) to be Triassic (?) and Jurassic in age (table 2). The lower acoustical unit has a maximum thickness of about 9 km in the Baltimore Canyon Trough. A multi-channel seismic-reflection profile run off central New Jersey suggests that the Triassic (?) and Jurassic rocks of lower acoustical unit pinch out shoreward; however, a line run off the Maryland-Virginia portion of the Delmarva Peninsula reveals an up-dip wedge of the lower acoustical unit extending far enough west to be present onshore (Schlee and others, 1976, figs. 7, 12).

Three deep wells drilled near the coast have penetrated as much as 585 feet of consolidated red beds above crystalline basement rocks (Anderson, 1948; Onuschak, 1972). The red beds were until recently thought to be Triassic in age, but now are considered either Early Cretaceous (Neocomian)

Table 1. Correlation chart of stratigraphic units occurring in Maryland, northern Virginia (after Teifke, 1973), and Atlantic Continental Shelf (after Schlee and others, 1976)

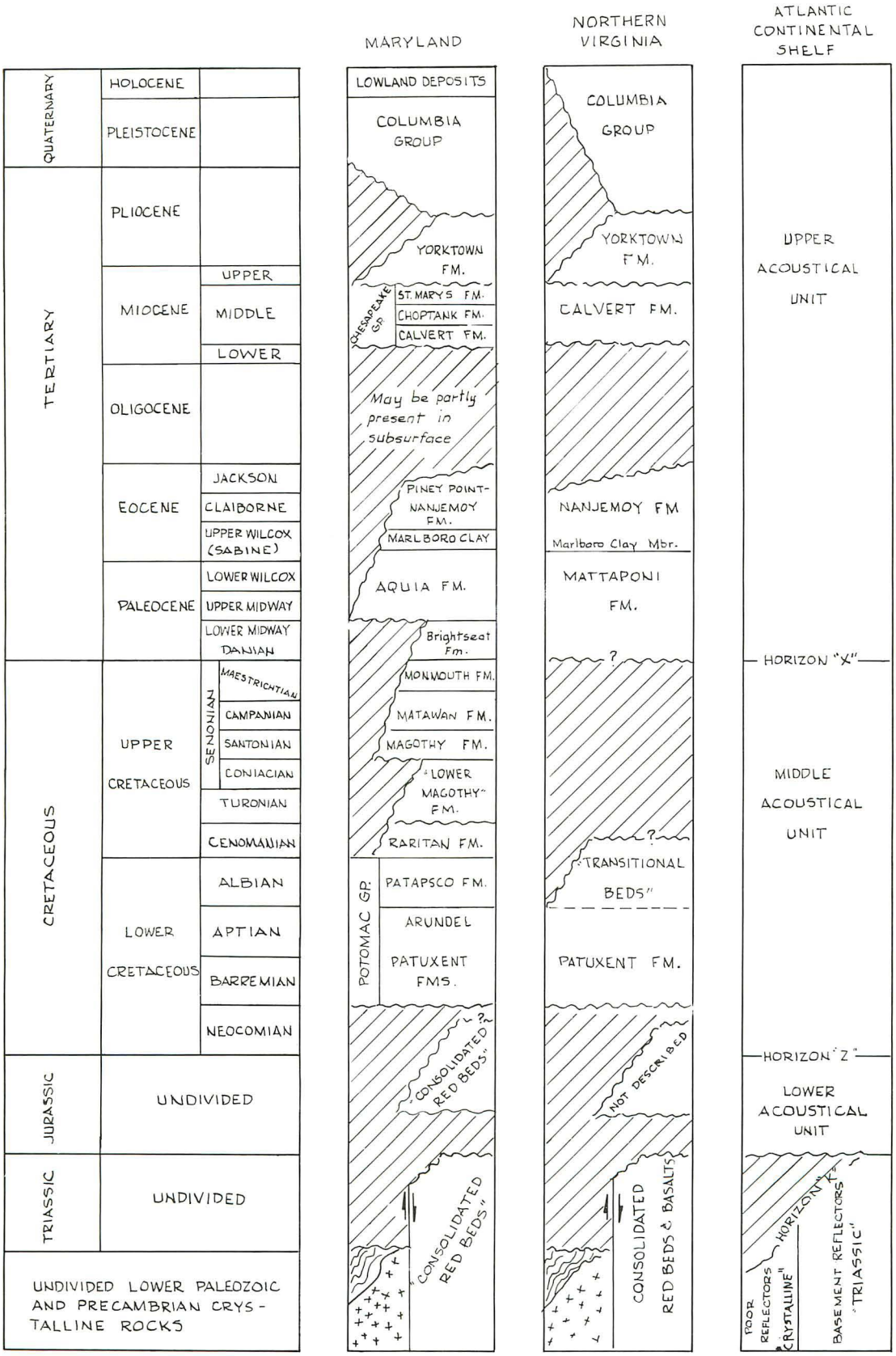


Table 2. Range of acoustic velocities of Maryland, eastern Virginia, and adjacent continental shelf

Area	Age	Range of Acoustic Velocities	Reference
Inner Coastal Plain	Tertiary	1.6-2.4 km/sec*	(1)
	Lower Cretaceous	1.7-2.7 km/sec	(1), (2)
	Triassic (?) (weathered)	2.5-3.9 km/sec	(1)
	Crystalline basement (weathered)	2.5-5.0 km/sec	(3)
Outer Coastal Plain	Tertiary	1.5-2.5 km/sec	(4)
	Upper Cretaceous	1.5-2.8 km/sec	(4)
	Lower Cretaceous	1.7-3.5 km/sec	(4)
	Consolidated "red beds"	4.1-5.1 km/sec	(4)
	Crystalline basement	>6.0 km/sec	(4)
Continental Shelf	Tertiary	1.8-2.6 km/sec	(5)
	Upper Cretaceous	2.7-3.2 km/sec	(5)
	Lower Cretaceous	3.3-4.6 km/sec	(5)
	Jurassic/Triassic (?)	3.9-5.9 km/sec	(6)

(1) Well; Ch-Ce 37; Birdwell 3-D velocity log

(2) Well; WGL Marbury No. 5; Schlumberger bore hole compensated sonic log

(3) Well; Ce-Dc 2; Core Laboratories, Inc. acoustic velocity test (core plug)

(4) Well; J & J Enterprises Taylor 1-G; Schlumberger bore hole compensated sonic log

(5) Well; Ocean Production Co. C.O.S.T. No. B-2; Seismic Reference Service digital velocity conversion log

(6) Multichannel seismic velocity-spectra display; Schlee and others (1976)

* km/sec x 3,281 = ft/sec

(Robbins and others, 1975) or Late Jurassic (?) (Brown, Miller, and Swain, 1972). There is a strong likelihood that these rocks represent a relatively thin shoreward edge of the lower acoustical unit of the Baltimore Canyon Trough section. Sonic logs were not run in the old (1944-1946) Maryland wells but are available for a recent (1971) stratigraphic test (J & J Enterprises, E.G. Taylor 1-G) drilled to basement in Accomack County, Virginia. Onuschak (1972) logged a shaly, "red bed" sequence between -6,018 feet and -6,134 feet, immediately overlying crystalline basement rocks. Sonic log velocities for the interval range from 3.2 km/sec. to 5.8 km/sec. (10,000 to 19,000 ft./sec.) immediately above basement (table 2). This rather wide spread in velocities suggests that Lower Cretaceous Potomac Group sediments may have been included in the upper part of the "red beds" and weathered basement rocks in the lower. Nevertheless, in the interval between -6,060 feet and -6,110 feet, velocities consistently range between 4 and 5 km/sec. and accord reasonably well with the velocities (4.5-6.3 km/sec.) (15,000-21,000 ft./sec.) Schlee and other (1976, tab.1) associate with the "lower acoustical unit" (which occurs at greater depths beneath the outer continental shelf). Raritan and Potomac Group sediments overlying the "red bed" sequence in the Taylor 1-G well have sonic log velocities that range largely between 1.7 and 3 km/sec. (5,600 and 9,900 ft/sec.). Cenozoic sediments, which occur to a depth of about -1,325 feet, exhibit velocities which usually fall in the 1.5 to 1.7 km/sec. (4,900 to 5,600 ft./sec.) range, except for an occasional higher velocity bed thought to be calcareously cemented.

The westernmost well of the three Maryland oil tests is the Ohio L. G. Hammond No. 1 located in central Wicomico County (fig. 1). Beginning at -5,295 feet, Anderson (1948, p.13) logged 135 feet of indurated "red beds," speculating that they were an up-dip wedge of Triassic rocks. However, later work by Robbins and others (1975, p.54-59) provides evidence for a Neocomian or Late Jurassic (?) age which accords reasonably well

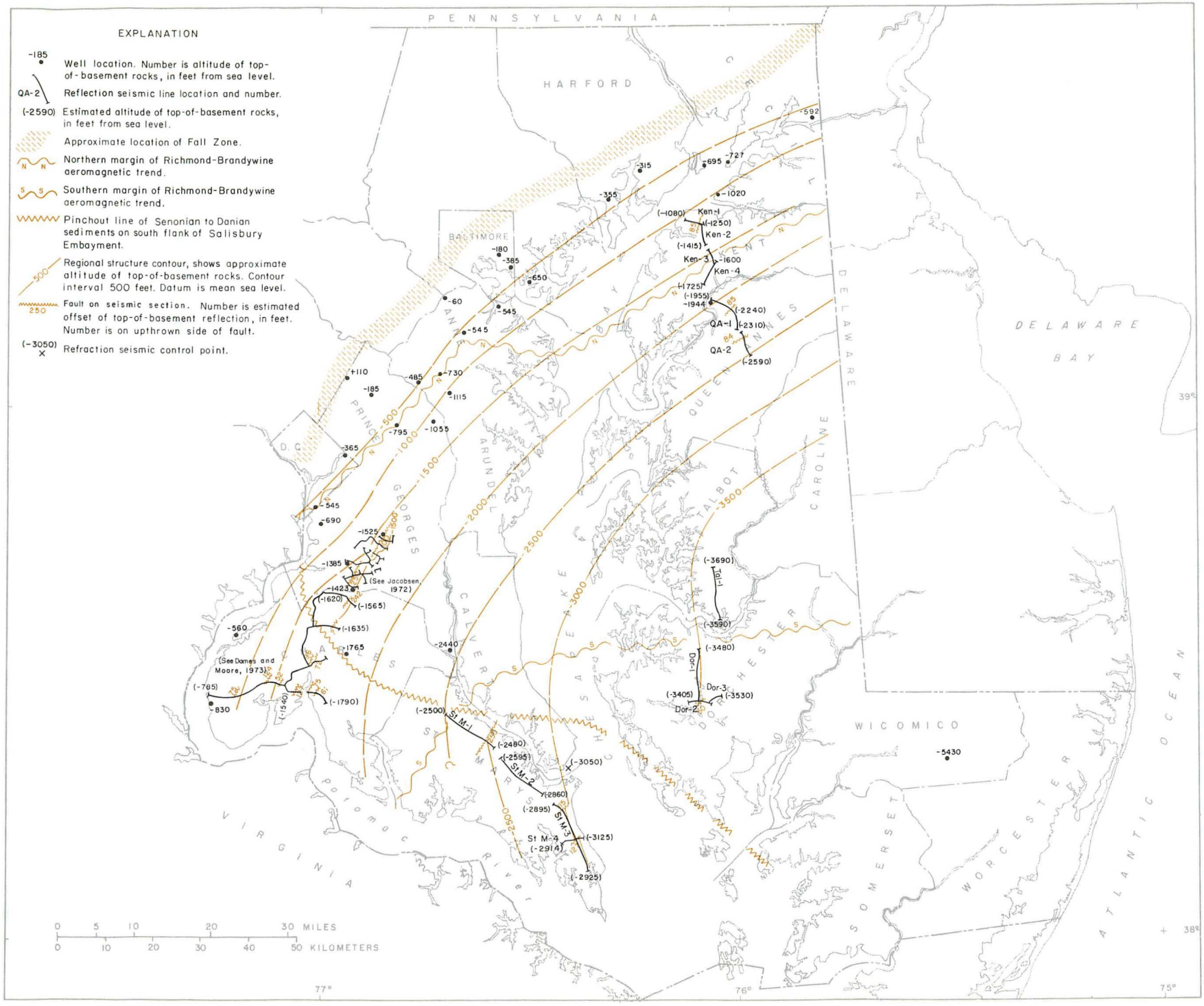


Figure 5. Map of eastern Maryland showing location of reflection seismic lines, possible faults, and depth to top-of-basement.

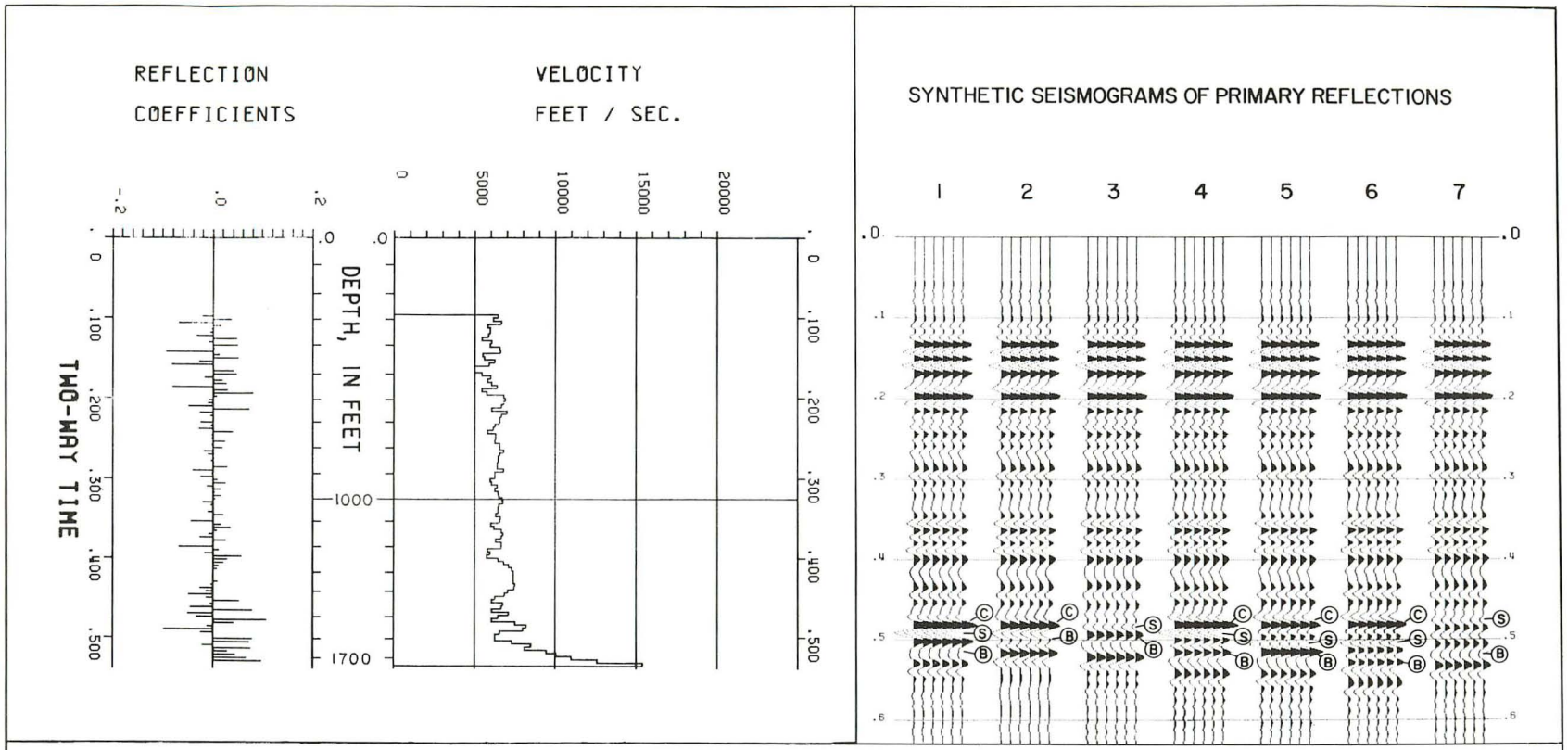
with a thin, landward extension of Schlee's "lower acoustic zone." It is problematic as to how much farther west the feathering edge of the "lower acoustic zone" extends. Limited subsurface data, chiefly seismic, suggests that, if present at all, it occurs as a disconnected series of indurated outliers.

Vibroseis lines run in Kent, Queen Anne's, Talbot, and Dorchester Counties exhibited several distinctive wavelet patterns associated with the basement reflection (Seismograph Service Corp., 1976a; undated) (figs. 5, 6). Synthetic seismograms were prepared by Seismograph Service Corporation in an attempt to model each of the several basement signatures. One characteristic pattern featured a sharp, high amplitude peak-trough-peak wavelet followed by a broad trough and lesser peak. The natural amplitude synthetic seismogram (fig. 6, no. 1) which best fit this signature was obtained by modeling a stratal sequence consisting of one, a higher velocity (2.5 km/sec.) (8,200 ft./sec.) "indurated layer"; two, a lower velocity (1.9 km/sec.) (6,200 ft./sec.) layer of saprolitic rock; and three, a high velocity layer (4.5 km/sec.) (15,000 ft./sec.) of fresh crystalline rock. The synthetic was modeled using times compatible with a thickness of 50 to 100 feet for both the "indurated layer" and saprolite. A synthetic seismogram (no. 2) modeled without the "indurated layer" exhibited a basement event consisting of two lower amplitude peaks separated by a broad trough.

At present, only one calibration point is available on the Eastern Shore to test whether the top-of-basement stratigraphy occurring in the vibroseis record sections is consistent with the assumptions used to simulate the data synthetically. Well QA-Be 15, located near Chestertown, encountered saprolitic crystalline rocks at -1,945 feet. Above basement interbedded sands and tough, but unlithified, clays typical of the Cretaceous Potomac Group, were logged (Kantrowitz and Webb, 1971, p. 8-9); indurated beds immediately above basement were not present. Between VP 105 and 155, record section QA-1 (fig. 7) exhibits a peak-trough basement event which lacks the strong double peak signature simulated in synthetic seismograms by adding an indurated layer. Well QA-Be 15 projects into record section QA-1 at about VP 125, thereby providing bore hole verification for a wavelet pattern generated by a relatively simple saprolite-crystalline rock basement stratigraphy. Beginning at about VP 155, the character of the basement reflection changes to a strong double peak seismic response, simulated in synthetic seismograms by a consolidated bed immediately above basement. In this case bore hole calibration between seismic response and synthetic seismogram is unavailable. Nevertheless, the structure of the basement event is consistent with this interpretation, inasmuch as the first appearance of the "indurated layer" coincides with a monoclinical downwarping of "top-of-basement" (between VP 145 and 155). In the structurally higher area north of the warp, lack of the double-peak event suggests that the "indurated layer" may have been eroded prior to deposition of the Potomac Group.

Similar seismic evidence for the patchy occurrence of consolidated beds immediately above basement has been observed in vibroseis records from Kent, Talbot, and Dorchester Counties. In the absence of confirmatory well data, the lithologic and stratigraphic significance of the "indurated layers" is speculative. Without these data a reasonable alternative is possible which argues that the strong double peak event can also be explained by a complex saprolite stratigraphy. Nevertheless, correlation with the Neocomian or Upper Jurassic (?) "red beds" discussed earlier must be given consideration inasmuch as similar rocks are known to occur as far west as the Ohio Hammond No. 1 well in central Wicomico County. If true, outliers of Schlee's "lower acoustical zone" are present farther up-dip in the Salisbury Embayment than heretofore suspected.

The possibility of Jurassic(?) rocks at the base of the Coastal Plain section challenges the *a priori* assumption that all consolidated red beds encountered at or near total depth in wells on the Coastal Plain are evidence of thick accumulations of Triassic (?) rocks downfaulted into the basement complex (Brown, Miller, and Swain, 1972, pl. 5). Nevertheless, it does not, of course, rule out the likelihood of buried Triassic (?) basins occurring beneath the Maryland Coastal Plain, particularly along the Richmond-Brandywine aeromagnetic trend which forms a strike-belt with the outcropping Richmond Basin. Within the trend, consolidated red beds have been drilled in King George County, Virginia, and Charles and Prince George's Counties, Maryland (fig. 1). For example, the J.S.C. Thompson No. 1 located about 20 miles east of the Fall Line at King George, Virginia, penetrated several hundred feet of indurated rocks including a basaltic section near total depth (3,307 feet) (Johnson, 1973, p. 7). A thick accumulation of consolidated red beds



Data Source: Schlumberger Borehole Compensated Sonic Log.

Well Name: Washington Gas Light Co., Marbury No. 5.

Location: Prince Georges County, Maryland, (N 38° 42' 16", W 76°55'02").

Reference: Maryland Geological Survey, Information Circular No. 13, (Plate 1).

Zero Datum: Land Surface, (206 feet above sea level).

Log Interval: 10 feet. Filter: 25-25-70-70 Hz.

Correction to datum: 6000 feet per second.

Data Processing and Interpretation: Seismograph Service Corporation.

SYNTHETIC SEISMOGRAMS

1 Unmodeled Sonic Log of WGL Marbury No. 5

2 Modeled with no saprolite.

3 Modeled with no "consolidated bed" above saprolite.

4 Modeled with double thickness of saprolite.

5 Modeled with double thickness of "consolidated bed."

6 Modeled with double thickness of saprolite and "consolidated bed."

7 Modeled with double thickness of saprolite and no "consolidated bed."

SEISMIC SIGNATURES

Ⓒ "Consolidated bed."

Ⓢ Saprolite, (weathered basement rock).

Ⓑ Basement Rock.

Figure 6. Synthetic seismograms modeled to show range of seismic signatures associated with the top-of-basement reflection (from Seismograph Service Corp.).

occurring relatively close to the Fall Line strongly suggests the presence of a buried Triassic (?) basin. It is considered highly unlikely that Neocomian or Upper Jurassic (?) rocks wedging into the Coastal Plain section from the east, could be that thick so close to the Fall Line, inasmuch as equivalent beds penetrated in the Accomack County well were less than 150 feet. Evidence from Charles County, Maryland, is less persuasive because well Ch-Ce 37, located near La Plata penetrated less than 100 feet of weathered rock (2.5-3.9 km/sec.) yielding red shaly cuttings (table 2). However, in Prince George's County, Maryland, the Washington Gas Light Mudd No. 3, located near Brandywine, selectively cored about 235 feet of steeply dipping (45°- 50°), gray to reddish brown sandstones and shales containing coaly partings. Although biostratigraphic corroboration is lacking, the lithology, thickness, and dip of these rocks are again very suggestive of a buried Triassic basin.

It is, at present, conjectural whether the Triassic (?) rocks known to underlie parts of King George, Charles, and Prince George's Counties are part of a single basin or whether they occur as a linear series of small, complexly faulted basins. Vibroseis profiles run in the latter two Counties (Jacobeen, 1972; Dames & Moore, 1973) have failed to reveal coherent events below the top-of-basement surface, leaving the structure of the Triassic rocks unresolved. The lack of coherent data may be interpreted to support a series of small, complexly faulted basins, but operational considerations, such as energy absorption and lack of velocity contrast below the base of the Coastal Plain, must also be considered.

Nevertheless, the occurrence of Triassic (?) rocks within the Richmond-Brandywine aeromagnetic trend is well established both in outcrop and beneath the inner margin of the Coastal Plain. The formation of graben-like structures in Triassic (?) times identifies the trend as a tectonically active belt of subsidence during the early Mesozoic. Recent investigations by Jacobeen (1972), Dames & Moore (1973), and Mixon and Newell (1976) along the inner margins of the Maryland and Virginia Coastal Plain have identified structures within the Richmond-Brandywine trend that imply continuing, although diminishing, fault movements into at least the middle Tertiary. The trend appears to define a relatively negative belt of basement instability within which a thicker accumulation of sediments was deposited during parts of Mesozoic and Early Tertiary times.

The implications of this association become more obvious on the Delmarva Peninsula where the Richmond-Brandywine aeromagnetic trend (figs. 3, 4, 18) coincides in general with the thicker parts of the Salisbury Embayment (Bain, 1972). Identification of downfaulted Triassic rocks underlying the Eastern Shore of Maryland has, however, not been established either by drilling or vibroseis. Rocks formerly considered Triassic (?) in the Ohio Hammond and Mobil Bethards wells have been shown to contain Neocomian or Upper Jurassic (?) palynomorphs and, as argued previously, may correlate with the up-dip edge of the "lower acoustical unit." Significant basement tests elsewhere are lacking. Vibroseis profiles run on the north and south margins of the Brandywine-Richmond trend failed to record structure below top-of-basement. At several locations on the profiles, the possibility of primary reflections below top-of-basement existed, but a review of the data by Seismograph Service Corporation showed that the stacking velocities for these events were lower than the velocity of basement rocks and were, therefore, more likely to be multiples. It should be recalled, however, that vibroseis surveys in Prince George's and Charles Counties which traversed known occurrences of Triassic (?) rocks failed also to record mappable reflections from below top-of-basement (Jacobeen, 1972; Dames & Moore, 1973). In summary it can be said that presently available subsurface data are inadequate to prove or disprove the occurrence of downfaulted Triassic (?) rocks beneath the Eastern Shore. Nevertheless, the known association of downfaulted Triassic (?) rocks with the Richmond-Brandywine aeromagnetic trend strongly suggests that where the trend crosses the Delmarva Peninsula similar basins can be expected to occur. As noted previously, this belt, which includes all of Queen Anne's, Caroline, and Talbot Counties, Maryland, and parts of Kent and Sussex Counties, Delaware (fig. 4), coincides broadly with the axial part of the Salisbury Embayment.

Paleocene (Danian)—Upper Cretaceous (Senonian) Pinchouts

Minard, et al, (1969) and Owens, et al, (1970) have argued persuasively that in outcrop beds of the basal Tertiary successively overlap older Upper Cretaceous units southward from New Jersey to northern Maryland. In southern Maryland Dryden and Overbeck (1948) and Glaser (1974) have shown that Lower Tertiary beds continue to overlap older units so that in the

Potomac River bluffs of western Charles County, the Aquia Formation rests directly on Lower Cretaceous (Albian) beds of the Patapsco Formation.

South of the Potomac River in Fairfax, Prince William, and Stafford Counties, Virginia, similar stratigraphic relationships are mapped in outcrop (Calver, 1963), although Cederstrom (1957) and Teifke (1973) have suggested that in the subsurface the Mattaponi Formation and underlying "transitional beds" span the Paleocene to Upper Cretaceous interval. However, subsurface correlations across the Potomac (for example, Glaser, 1968, fig. 6; Brown, Miller, and Swain, 1972, pl. 35) show that the Maryland stratigraphy carries at least into the first tier of Virginia Counties and that a major unconformity separates Tertiary and Cretaceous beds in northern Virginia.

Figures 8, 9, and 10 are stratigraphic cross-sections using the base of the Aquia Formation as datum. The geophysical logs displayed on the cross-sections are electrical resistivity logs unless otherwise noted. Figure 8 extends from east central Anne Arundel County to western St. Mary's County and includes wells in Prince George's and Charles Counties. The two other sections extend approximately N-S along the eastern and western shores of Chesapeake Bay and cross Lat. 38°30′ N. where a pronounced shift in basement strike has been noted (fig. 1). Figure 11 is a stratigraphic cross section, which extends approximately normal to strike from near Annapolis in eastern Anne Arundel County to Cambridge in northern Dorchester County, Maryland. Core hole AA-De 100 (fig. 11) was studied by Brenner (in Mack, 1974, p. 65-75) who established a tentative time-stratigraphic zonation using marine microplankton, pollen, and spores. He was able to distinguish five palynological zones: Lower Tertiary (Paleocene-Eocene), basal Tertiary (Danian or Lower Midway), Upper Cretaceous (Campanian-Maestrichtian), Upper Cretaceous (Santonian to perhaps Upper Turonian), and Lower Cretaceous (Albian) (table 3).

The Lower Tertiary zone, which is correlated with the shallow marine Aquia Formation, contains abundant *Castanea* and Alnoid type pollen as well as less common occurrences of marine microplankton (acritarchs). The basal Tertiary (Danian) zone correlates largely with the Brightseat Formation, although formational contacts established on lithologic and geophysical criteria do not coincide perfectly with Brenner's biostratigraphic zonation.

As shown below, the Brightseat pollen assemblage from well AA-De 100 is post-Cretaceous whereas the acritarchs may have Upper Cretaceous affinities, suggesting to Brenner the occurrence of a thin section of "transitional beds" beneath the Aquia.

Marine Microplankton

Palaeotetradinium hyalodermum
Pterospermopsis cf. *ginginensis*

Pteridophyta

Osmundacidites
Laevigatospontes
Cicatricosporites

Angiospermae

Tricolporopollenites sp. (*Castanea* type)
Pseudo-alnoid type
Triatriopollenites
Tetrapollis
Piolencipollis cf. *piolencensis*

Upper Senonian (Maestrichtian (?)) beds occurring immediately beneath the Brightseat Formation are assigned to the Monmouth Formation and have yielded the following palynological assemblage:

Marine Microplankton

Hystrichosphaeridium sp. (tuberose type)
Hysterichosphaeridium
Deflandrea sp.
Microdinium sp.
Pterospermaopsis ginginensis

Pteriodophyta

Camarozonosporites sp.
Cicatricosisporites sp.
Deltoidospora halii

Gymnospermae

Abietineaepollenites
Podocarpidites sp.
Pinuspollenites sp.

Angiospermae

Minorpollis sp.
Tricolporopollenites sp.
Tricolporate "reticulate type"

Campanian beds assigned largely to the Matawan Formation have been identified in core hole AA-De 100 (208-212 ft., 241-242 ft.) and are noted by increasing numbers of small triporates (*Minorpollis*), the first down-hole occurrence of *Rugubivesticulites reductus*, and the presence of *Protocarya* type triporate forms.

Upper Campanian Plant Microfossils:

Marine Microplankton

Micrhystridium sp.
Chlamydophorella cf. *hyei*
Fromea amphora
Microdinium sp.
Deflandrea sp.

Pteridophyta

Gleicheniidites sp.

Gymnospermae

Rugubivesiculities reductus
Abietineaepollenites microreticulatus

Table 3. Palynological zones and core descriptions for well AA-De 100, Anne Arundel County, Maryland (modified from Brenner, 1974; and Glaser, 1974)

CORE DEPTH	CORE DESCRIPTION	ZONE
95-96′ 117-118′	Sand, olive-black to olive-gray, speckled; fine to medium, moderately glauconitic, very clean; evenly interlaminated with very clayey fine sand, dusky blue-green	Lower Tertiary
135-136′	Silt, clayey, greenish-black, dense, conspicuously micaceous, scattered shell fragments, otherwise structureless	Danian
143-144′	Sand, olive-black, fine to medium, clean to slightly clayey, moderately glauconitic; interbedded with very clayey fine sand, dusky blue-green	Upper Senonian (Maestrichtian (?)
193-194′	Sand, dark gray to olive-gray sporadically mottled green, slightly clayey, sparsely glauconitic	Maestrichtian (?)
208-212′	Clay, silty, tough, micaceous, plastic in part, olive-black, mottled with fine to medium sand, clayey, grayish olive-green; very sparsely glauconitic; scattered molluscan fragments; sparsely lignitic	Campanian (?)
241-242′	Clay, silty, olive-black, tough, irregularly interlaminated with very clayey sand; greenish-black; micaceous; rare shell fragments; pyritic concretions common	Campanian (?)
280-282′	Sand, pale-gray, fine-grained, clayey; interlaminated with silty clay, dark-gray, lignitic	Santonian
303-305′	Sand, light-gray, fine-grained, clayey; interlaminated with clay, plastic, dark-gray; lignitic	Santonian
354-359′	Sand, pale-gray to dark-gray, fine to coarse; interbedded with clayey silt, mostly dark-gray; pyrite-cemented aggregates common	Santonian (?) to Turonian
376-382′	Sand, pale to medium-gray, coarse to very coarse pebbly; two thin beds of interlaminated fine clayey sand and dark-gray silt; lignite very scarce	Santonian (?) to Turonian
404-436′	Clay, mottled dark reddish-brown, pale red, light olive-brown, medium gray, and light gray; dense with thin irregular lenses and partings of very fine sand and silt, light gray	Albian (by correlation with nearby well)

Angiospermae

Minorpollis sp.
"Protocarya" type
Suemegipollis triangularis
Tricolpopollenites sp. *(psilate)*

Lower Campanian Plant Microfossils:

Marine Microplankton

Palaeotetradinium hyalodermum
Dinogymnium cf. *nelsonensa*
Microdinium sp.
Deflandrea sp.
Fromia amphora

Gymnospermae

Rugubivesiculites reductus

Angiospermae

Tetracolporopollenites globosus
Tricolpollenites cf. *retiformis*
Minorpollis sp.
Momipites cf. *tenuipolus*

Glauconite grains from 240 feet have yielded a potassium-argon date of 70.3$\pm$2.7 million years, which supports Brenner's Campanian age assignment (Geol. Soc. London, 1964, p. 261; Van Hinte, 1976, fig. 2).

The first nonmarine beds encountered in core hole AA-De 100 are assigned to the upper part of the Magothy Formation and are considered by Brenner to be Santonian in age. The floral taxa of the upper Magothy are differentiated from overlying materials by the absence of marine microplankton, by an increase in normapolle type angiosperms, and by large numbers of varied Liliacidites type. Two cores (280-282 ft.; 303-305 ft.) from the upper part of the Magothy yielded the following assemblages:

Upper Magothy Plant Microfossils:

Pteridophyta

Rotaspora rugulatus
Laevigatosporites sp.
Deltoidospora sp.
Gleicheniidites sp.

Gymnospermae

Abietineaepollenites microreticulatus

Angiospermae

Tricolpites sp.
Minorpollis sp.
Triatriopollenites sp.
Tricolporate "reticulate type"
Vitaceae

and

Pteridophyta

Deltoidospora sp.
Zonalapollenites dampieri
Cicatricosisporites sp.
Matonisporites sp.

Gymnospermae

Pinuspollenites sp.
Rugubivesiculites sp.
Abietineapollenites sp.
Araucariacites australis

Angiospermae

Liliacidites sp.
Minorpollis sp.
Tricolpites retuculatus
Momipites sp.
Tricolpopollenites platyreticulatus
Triatriopollenites sp.
Sporopollis pseudosporites
Tricolporate "reticulate type"
Trudopollis sp.

The nonmarine "lower Magothy Formation" may be as young as Santonian and as old as Turonian, but appears largely to post-date the type Raritan Formation which is considered Cenonanian (Robbins, Perry, and Doyle, 1975, p. 13). The lower part of the Magothy Formation is distinguished by the common occurrence of small (8-12 microns) oblate tricolporates and triporates and by the presence of Porocolpopollenites. Two cores from AA-De 100 (354-359 ft.; 376-382 ft.) contained the following floral assemblages:

Pteridophyta

Laevigatosporites sp.
Gleicheniidites sp.
Camarozonosporites
Perotriletes sp.
Cicatricosisporites sp.

Gymnospermae

Araucariacidites sp.
Abietineaepollenites sp.
Rugubivesiculites sp.
Podocarpidites sp.

Angiospermae

Tricolpites reticulatus
Many small oblate 8-12 micron
Tricolporates and *Triporates*
Liliacidites sp.
Tricolporate "recticulate type"
Porocolpopollenites sp.

and

Pteridophyta

Aequitriradites spinulosus
Camarozonotriletes sp.
Deltoidospora sp.
Sphagnumsporites sp.

Gymnospermae

Araucariacites australis
Pinuspollenites sp.
Rugubivesiculites sp.

Angiospermae

Tricolpites reticulatus
Numerous very small oblate
Tricolporates and *Triporates*
Tricolporate "reticulate type"
?Vacuapollis sp.
Tricoloporate sp.
Porocolpopollenites orbiformis

Variegated beds below the Magothy in the vicinity of AA-De 100 have yielded a sparse flora, but the presence of *Appendicisporites potomacensis* and *Ephedripites multicostatus* suggests an Albian age and they are correlated with the Patapsco Formation (Brenner, 1963).

Electric and gamma ray log correlations between the Annapolis well (AA-De 100) and the Thomas Point well (AA-Df 90) are reasonably convincing (fig. 11) and establish a time-stratigraphic reference section for N-S cross-section B-B′ (fig. 9). Although a direct correlation into cross-section C-C′ (fig. 10) from AA-De 100 is more difficult using geophysical logs, the tie between the Thomas Point well (AA-Df 90) and the Stevensville well (QA-Eb 109) suggested in figure 9 provides a time-stratigraphic reference for C-C′ at its northern end.

In cross-section B-B′ (fig. 9) beds ranging from Danian (lower Midway) (Brightseat Formation) to perhaps as old as Turonian (?) ("lower Magothy Formation") can be traced southward from Stevensville to Randle Cliff with slight loss of section. Maestrichtian sands, which are well developed at Stevensville and Thomas Point, grade southward into a fine-grained sequence at Randle Cliff. In well Cal-Cc 55 the Maestrichtian-Campanian section cannot be easily separated on geophysical logs. Both the upper and lower parts of the Magothy Formation carry through, albeit thinner, and, in the case of the Santonian beds, noticeably less sandy.

Between Randle Cliff and Scientist Cliffs (Cal-Dc 35), a distance of 6.7 miles, an abrupt thinning of the Upper Cretaceous occurs as Campanian and Maestrichtian beds are apparently eroded from the section. A core from Cal-Dc 35 cut at 643 feet yielded a Santonian (Upper Magothy) assemblage,* suggesting that in this well Lower Tertiary beds rest directly on the Magothy Formation. The Magothy, itself, has thinned noticeably between Cal-Cc 55 and Cal-Dc 35 with florally diagnostic Albian beds (Patapsco Formation) occurring at least as high as 832 feet in the latter well and, as suggested, in figure 9, probably higher.

The pre-Aquia unconformity cuts progressively deeper into the section at Calvert Cliffs (Cal-Ed 22) and Cove Point (Cal-Fe 19). The basal beds of a truncated Magothy section may perhaps survive into well Cal-Ed 22, but at Cove Point, 3.8 miles farther south, the Aquia Formation rests directly on lithologically distinctive beds of the Patapsco Formation. Thus, from Thomas Point to Cove Point about 325 feet of section, spanning beds

*Diagnostic forms include *Tricolpopollenites crassinurus, Tricolpopollenites subtiles,* Tricolporate type 5 (Doyle, 1969), Tricolporate type 6 (Doyle, 1969), *Rugubivesiculites reductus, Plicopollis* sp.

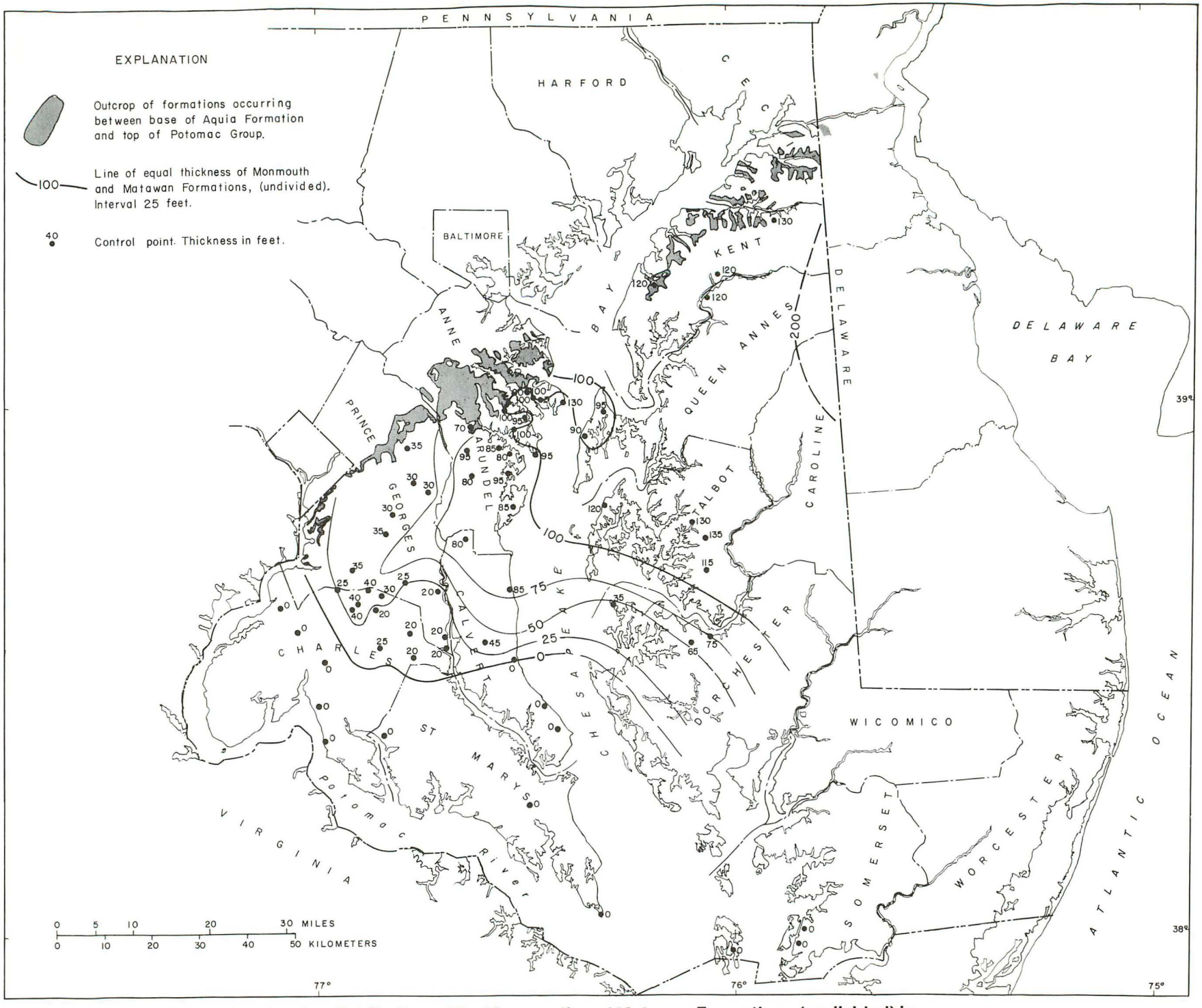


Figure 12. Isopach map showing the distribution of the Monmouth and Matawan Formations (undivided) in Maryland.

tentatively dated as old as Turonian and as young as Danian, have been the truncated beneath the Aquia Formation. Uplift and erosion is implied because the truncated edges of the marine units overlying the Magothy Formation fail to exhibit the shallow water facies characteristic of strandline sedimentation.

Similar stratigraphic trends are evident along cross-section A-A′ (fig. 8) which runs from Henekes Corner (AA-Cf 108) in Anne Arundel County southward to Wicomico Shores (St. M-Ca 5) in western St. Mary's County. Electric and gamma ray logs from well AA-Cf 108, which anchors the north end of A-A′, correlate strongly with logs from AA-De 100, Brenner's (1974, p. 65-75) type well (fig. 11, tab. 3). On this basis formational picks establish in AA-De 100 can be carried into AA-Cf 108 with reasonable confidence. In AA-Cf 108 the section from the base of the Aquia Formation to the top of the Potomac Group is about 290 feet. As in AA-De 100, the sandy facies of the Monmouth Formation and the upper and lower parts of the Magothy Formation are well developed. A thin edge of the Monmouth may extend into AA-Dd 41 at Rutland Road, but south of that site, it ceases to be a mappable subsurface unit (fig. 8). Sands assigned to the (upper) Magothy Formation are well developed as far south as Marlboro Meadows. Between Marlboro Meadows (PG-Df 34) and Baden (PG-Ge 15), the Upper Magothy thins and begins to assume an e-log signature dominated by silt/clay "kicks." This facies change becomes increasingly evident in wells PG-Hf 40 (Eagle Harbor) and Ch-Cg 18 (Hughesville). In contrast, the sands of the "lower Magothy" Formation, which occur at least as far south as Hughesville, consistently exhibit a fining upward e-log signature by which the unit can be correlated.

Brenner studied the palynology of several cores from PG-Hf 40 and Ch-Cg 18. Using AA-De 100 as a standard section, he established the presence of Danian, Santonian, and "lower Santonian"* age beds in PG-Hf 40 and Santonian beds in Ch-Cg 18. As correlated in A-A′ (fig. 8), the occurrence of Maestrichtian or Campanian units is considered problematic in PG-Hf 40 and unlikely in Ch-Cg 18. In the Hughesville well (Ch-Cg 18) the section between the base of the Aquia and the top of the Potomac Group, which was 290 feet thick at Henekes Corner (AA-Cf 108), has thinned to 120 feet and probably only includes beds assigned to the "lower Magothy" Formation. At the southern end of A-A′ (fig. 8), between Hughesville and Wicomico Shores (St. M-Ca 5), the Santonian age beds appear to be truncated so that the middle Paleocene Aquia Formation rests unconformably on Albian age beds of the Potomac Group. It should be noted that between Eagle Harbor and Wicomico Shores, where the older units drop from the section, the Aquia Formation correlates across with only minor change in thickness or facies.

Stratigraphic relationships are less clear on the eastern N-S section (fig. 10). The palynology of these wells has not been systematically studied, consequently, correlation with Brenner's type well (AA-De 100) must be made indirectly using electric and gamma ray logs. Nevertheless, as shown in figure 9, correlation into the Stevensville well (QA-Eb 109) can be made with some confidence, providing a reference section for the northern end of the cross-section. Less certain is the extension of the geophysical log picks southward into the Claiborne well (Tal-Cb 89) (fig. 11), although correlation back to AA-De 100 via the Thomas Point well (AA-Df 90) eliminates the possibility of an obvious mistie.

Microfaunal studies of well Tal-Cb 89 by Todd (1957, p. 46) and Brown, Miller, and Swain (1972, pl. 58) largely corroborate the formational correlations shown in figure 10, although Todd's time-stratigraphic zonation of the Lower Tertiary has been superceded (Loeblich and Tappan, 1957; Hazel, 1968). Todd suggests a Paleocene-Upper Cretaceous contact between 581 and 607 feet while Brown, Miller, and Swain put the contact at about 655 feet. Brown, Miller, and Swain also noted a Lower Senonian (Austinian) marine assemblage at about 750 feet which is placed in the upper part of the Magothy Formation in figure 10. It should be noted that equivalent beds in Brenner's type well (AA-De 100) are nonmarine (fig. 11).

S. M. Herrick (pers. comm., 1968) studied the foraminiferal assemblages of well Tal-De 18

*The "Lower Santonian" palynomorph assemblage contains numerous *Plicapollis* sp. and *Vacuapollis* pollen grains which Brenner (pers. comm.,1975) believes to be less advanced than those which occur in the type Magothy (Santonian). The "Lower Santonian" assemblage also includes numerous grains of small oblate triangular reticulate tricolporates and small rectangular shaped *Liliacidites* types. Although tentatively dated "Lower Santonian", the range of this assemblage may eventually be shown to include the Turonian and Coniacian as well.

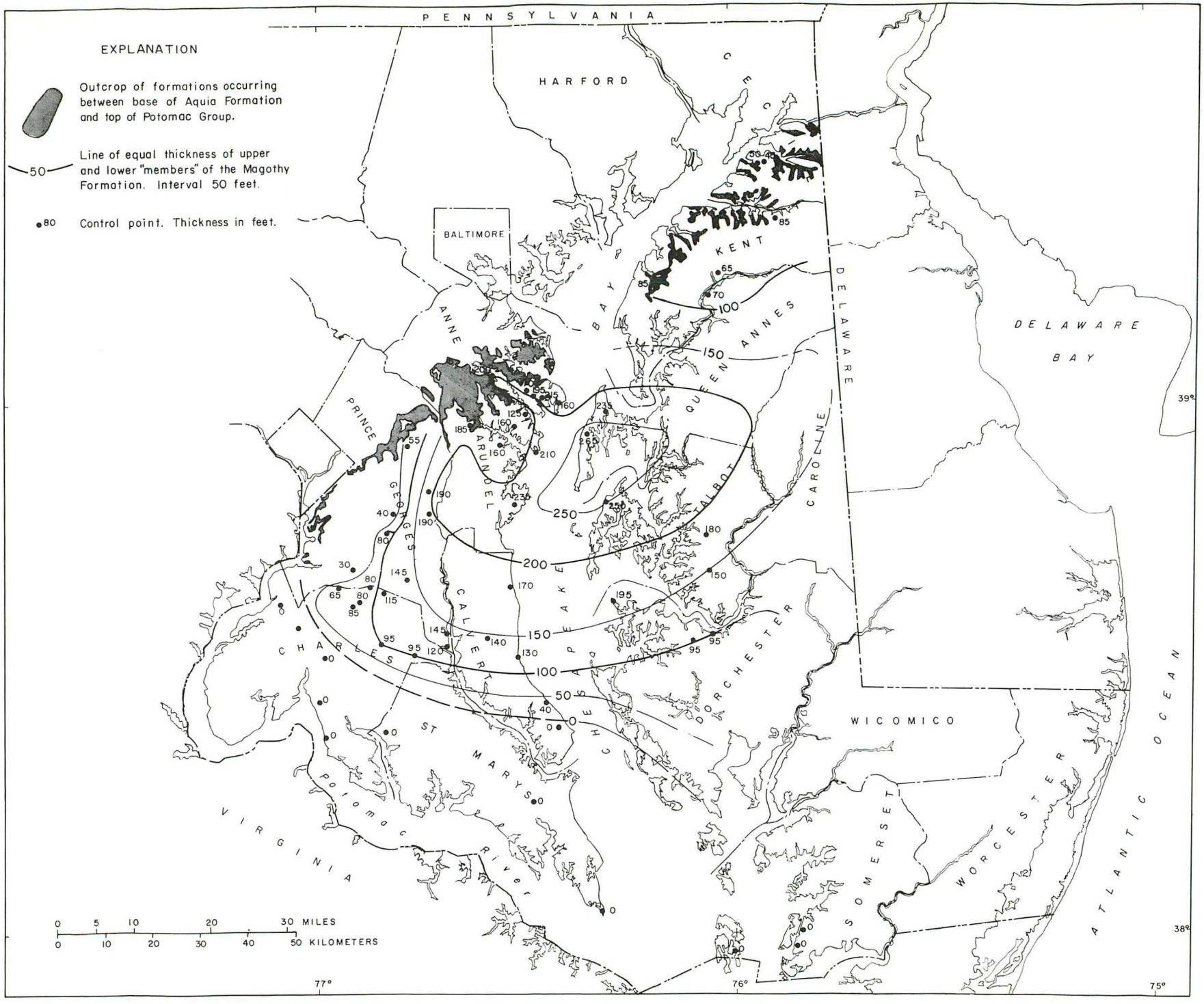


Figure 13. Isopach map showing the distribution of the upper and lower "members" of the Magothy Formation in Maryland.

drilled near Easton and reported the following occurrences suggestive of the Lower Tertiary:

Marginulina huneri, Cibicidina blanpiedi (360-370 ft.)
Marginulina vacavillensis (493-504 ft.)
Dentalina winniana (524-534 ft.)
Cyclammina cf., *C. caneriverensis* (566-576 ft.)
Vaginulinopsis hatchetigbeensis (576-587 ft.)
Nodosaria affinis, Robulus clagshamnensis, Frondiculana howei (627-637 ft.)
Dentalina annloomisae (648-658 ft.)
Cibicides neelyi (658-699 ft.)
Polymorphina subrhombica (689-700 ft.)
Planulania limbata (700-710 ft.)
Anomalina longa (783-793 ft.)

In the same well at 1018-1028 ft., Herrick reported occurrences of *Citharina* sp. and *Citharina texana,* a Lower Senonian (Austinian) form associated with the marine facies of the upper part of the Magothy Formation in Maryland. Younger Cretaceous units (upper Senonian) are shown occurring in well Tal-De 18, based, in part, on the report by Brown, Miller and Swain (1972, pl. 58) of *Veenia arachoides* and *Anomalina rubiginosa* in a nearby well, which has excellent geophysical correlation with Tal-De 18.

Correlation of the Lower Tertiary units between Easton (Tal-De 18) and Cambridge is complicated by a sand to silt/clay facies change in the Aquia Formation. From well Tal-De 18 to well Dor-Ce 77 the Aquia changes from a predominately arenaceous, inner shelf facies to a predominately fine-grained, outer shelf facies (Hansen, 1974). In well Dor-Ce 77 both Herrick (pers. comm., 1968) and Brown, Miller, and Swain (1972, pl. 58) pick the base of the Paleocene (including pre-Aquia, Brightseat equivalents) at about 835 feet. The first occurrence of the tough, mottled red and gray clays generally associated with the Potomac Group, occurs at about 995 feet in well Dor-Ce 77. Thus, Senonian beds, which are about 315 feet thick at Easton and 370 feet thick at Claiborne, are represented here by a maximum of 160 feet of section. Apparently, however, in the Cambridge section beds are not simply lost from the top. Rather the presence of both Upper (*Veenia archoides*) and Lower (*Citherina texana*) Senonian beds suggests that some thinning and overlap may have occurred during deposition of these units and prior to the main episode of uplift and truncation recorded at the base of the Aquia.

About 40 miles south of Cambridge in the Crisfield area of Somerset County, several microfaunal studies have failed to establish the presence of Upper Cretaceous marine beds (e.g., McLean, 1950, p. 133-138; McLean *in* Hansen, 1967, p. 22-24; Herrick, 1968, pers. comm.; Brown, Miller, and Swain, 1972, pl. 53). Well Som-Dc 3 is representative of the area and contains fossiliferous Lower Paleocene (Danian?) strata overlying a nonmarine sequence tentatively dated Cenomanian on the basis of spot palynological determinations offered by Brenner (*in* Hansen, 1967, p. 16). Using foraminiferal indices the contact has been picked as high as about 910 feet (Herrick; Brown and others) and as low as 1,060 feet (McLean). This range is attributable, in part, to the dependence of each worker on drill cuttings for his sample material.

Using the stratigraphic control displayed in cross-sections A-A′ through D-D′, several isopach maps (figs. 12, 13, 14) were prepared to show the areal distribution of the units occuring between the base of the Aquia Formation and the top of the Potomac Group. Figure 12 shows that the Monmouth and Matawan Formations (undivided), which are estimated to be 200 feet thick in eastern Queen Anne's County, thin southward and westward before terminating along an irregular line extending from extreme SW Prince George's County to central Dorchester County. In contrast an isopach map (fig. 13) of the upper and lower "members" of the Magothy Formation exhibits a pronounced thickening in western Queen Anne's County and adjacent parts of Anne Arundel and Talbot Counties. The northward thinning of the unit in Maryland appears to reflect sedimentary trends associated with deltaic deposition in the Salisbury Embayment (Hansen, 1969). Southward, however, the Magothy is bevelled off at the base of the Aquia, implying an episode of late Cretaceous to early Paleocene uplift and erosion. Figure 14 is a composite of figures 12 and 13 and, consequently, exhibits characteristics of both.

In summary, it should be noted that along each N-S cross-section (figs. 8, 9, and 10) Upper Cretaceous (Senonian) beds are truncated beneath a pre-Aquia unconformity so that at their southern end, Paleocene strata rest directly on the Potomac Group. Thinning and overlap within the Upper Cretaceous interval suggests that the north flank of the Norfolk Arch was tectonically active during late Cretaceous times. However, uplift and erosion must have extended into the lowermost Tertiary, inasmuch as beds of suspected Danian (lower Midway) age are also truncated in places.

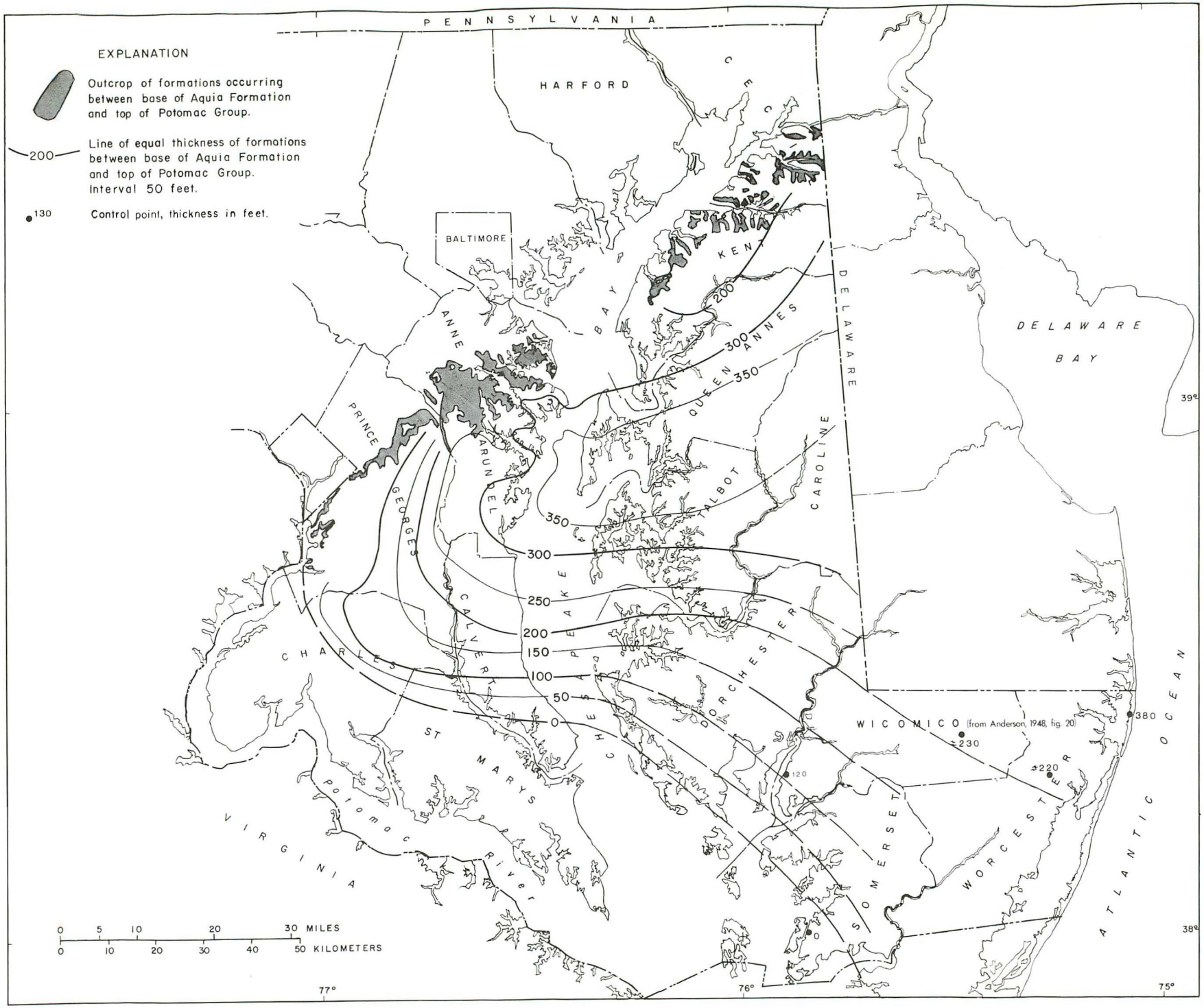


Figure 14. Isopach map showing the distribution of the formations occurring between the base of the Aquia Formation and the top of the Potomac Group in Maryland.

GEOPHYSICAL EVIDENCE FOR BASEMENT STRUCTURES

Southern Maryland

Electric-log correlations, supported by biostratigraphic evidence, show that units of Senonian to Danian age pinch out in the subsurface of southern Maryland. Structural control was initially suspected because on regional contour maps of the top of basement surface (fig. 1), the pinchouts coincide in a broad sense with a major NE to N-NNW strike change occurring at about lat. 38° 30′ N. In St. Mary's and Calvert Counties both the pinchouts and the change in basement strike are generally coincident with a major change in aeromagnetic pattern (fig. 4). The northern parts of the two Counties are within the Richmond-Brandywine aeromagnetic belt which is characterized by a NE-ENE trending pattern of broad, relatively smooth contours thought to be characteristic of a gneissic-granitic terrane containing downfaulted Triassic rocks. Southward the Brandywine-Richmond trend abuts against an en echelon series of aeromagnetic highs and lows striking NNW to NNE. In St. Mary's County the boundary is defined by the northern terminus of the steep-sided Sussex-Currioman Bay aeromagnetic trend, a suspected metavolcanic lineament which defines the eastern margin of the Richmond-Brandywine trend in Virginia (Le Van and Pharr, 1963). Southern Calvert County occupies a saddle separating the Sussex-Currioman Bay trend from a smaller, en echelon aeromagnetic high extending from the Taylor Island area of western Dorchester County SSW to the mouth of the Patuxent River. The Taylor Island anomaly is ellipsoidal in shape and conforms to the N-NNE aeromagnetic grain which increasingly dominates eastern Southern Maryland and the Eastern Shore south of lat. 38°30′. Wells have not been drilled to basement in either Calvert or Dorchester Counties so that the lithologic source of the Taylor Island anomaly remains unresolved. The anomaly is worth noting because, like the Sussex-Currioman Bay trend, it helps to define the boundary between two regional aeromagnetic patterns which may, in turn, suggest a zone of weakness separating crustal blocks. Thus, marginal faults operating sporadically along this zone of weakness during Late Cretaceous and Early Tertiary time may have provided structural control for the stratigraphic pinchouts (figs. 8, 9) which occur in the vicinity of the Sussex-Currioman Bay trend in St. Mary's County.

To test this hypothesis, a vibratory reflection seismic survey was run along Md. Route 235 (fig. 4, 5) normal to the Sussex-Currioman Bay aeromagnetic trend to determine whether basement offsets were associated with either of its steep-gradient flanks. A six-fold common-depth-point (CDP) stack was obtained by vibrating at 200-foot intervals along a split spread with geophone stations 100 feet apart (Seismograph Service Corp., 1976a). Three synchronized, truck-mounted vibrators were used 50 feet apart in line over a 200 feet pattern. Sixteen 7-second sweeps were made during each pattern using a frequency of 80 to 20 Hz. These data were processed using the Seismograph Service Corporation (SSC) Phoenix system and displayed as a 25-50-25 three-trace mix, variable area record section.

A portion of annotated record section St. M-1 is reproduced as figure 15. At the NW end of the section the basement reflection comes in at about 740 milliseconds, occurring as a strongly continuous trough between two sharp crests. Continuity is enhanced because the basement signature is characteristically overlain by a complex but continuous wavelet in this part of the record. Depths calculated from velocity-time picks using the Dix (1955) approximation show little variation between vibration points 350 and 400. The basement surface is essentially planar, varying approximately between 2,675 feet and 2,700 feet below sea level. Near vibration points 405 and 410, a noticeable discontinuity in the basement event occurs which may be interpreted as a small graben-like structure with offsets of 50 feet or less. South of this feature, the basement signature resumes a planar trend to about VP 422. At this point the continuity and character of the basement reflection begins to break up. A zone of discontinuity occurs to about VP 430 where a new basement event comes in at a calculated depth of 2,460 feet. This seismic feature is called the Hillville Fault Zone inasmuch as the small community of Hillville occurs adjacent to the fault zone along Md. Route 235. Although this top-of-basement signature is not as continuous as the signature encountered north of the fault zone, it is considered sufficiently correlative to pick. This characteristic, coupled with the loss of the preceding complex wavelet, suggests strongly that a basement-rock interface having different acoustic properties occurs on the up-thrown side of the fault.

Although seismic line St. M-1 traverses normal to the Sussex-Currioman Bay aeromagnetic trend (fig. 5), generalized top-of-basement structure contour maps (fig. 1) suggest that the line was run subparallel to regional strike. The latter is confirmed by the relatively small dip (25-30 feet per mile) of the strong basement event north of VP 405. The north flank of the aeromagnetic trend appears to be unbroken at top-of-basement where a strong, essentially planar event characterizes the record. In contrast the south flank of the trend is associated with a zone of marked discontinuity and offset. The basement signature south of the fault zone, although correlative, is in general a weaker, less continuous event. This occurrence suggests that the basement rocks south of the fault have less acoustical contrast with the overlying Potomac Group sediments than those of the north block. For example, a deep saprolite, grading to fresh rock, might produce a weak, attentuated basement signal such as that observed in the record section (fig. 6, seismogram 7).

Faulting within the zone of seismic discontinuity is probably too complex to illustrate on the record section, except in a schematic way. Although the up-to-the-south movement across the zone appears clear enough, the precise placement and apparent dip of individual faults within the zone are not. A reasonable interpretation of the record section suggests that two basement terranes have been juxtaposed by high angle faulting with the south block uplifted about 250 feet relative to the north. Extension of the Hillville fault zone up into the Coastal Plain section is difficult because discontinuous ("wormy") reflections associated with the nonmarine Potomac Group inhibit correlation across the structure. There is a tendency, however, for several of the more coherent events to suggest dragging at the fault margins. These can be traced to a depth of about 1,700 feet (500 milliseconds). Signal recovery above that depth is generally poor. Reflections from the shallow marine beds shown in figures 8 and 9 could not be discriminated with the geophone spread used during the survey.

The suggestion of a fault zone in central St. Mary's County is compatible with previous speculation that Upper Cretaceous pinchouts occurring along the south flank of the Salisbury Embayment were basement controlled. The association of the Hillville fault zone with the Sussex-Currioman Bay aeromagnetic trend (fig. 5) further suggests that the juxtaposition of two regional aeromagnetic patterns on the south flank of the Salisbury Embayment may define a broad zone of crustal instability, sporadically active during, at least, Santonian to Danian times. If so, the regional top-of-basement strike change occurring at approximately 38° 30′ N may be shown ultimately to represent an en echelon series of up-to-the-south offsets rather than a simple warping.

A further suggestion of up-to-the-south faulting occurs near St. James in southern St. Mary's County (fig. 5, 16). Vibroseis line St. M-3 was run along Route 235 between Lexington (Patuxent) Park and Ridge using the same acquisition and processing parameters as St. M-1. Because the St. M-3 traverse subparallels regional strike, the basement reflection is essentially flat, deepening only slightly from about 2,895 feet (800 milliseconds) at the north end of the line to about 2,925 feet (808 milliseconds) at the south. Unfortunately, signal recovery is on the whole poor with the basement event breaking through as a continuous reflector only sporadically. Figure 16 reproduces a portion of St. M-3 between VP 340 and 525. Between approximately VP 400 and VP 445, the basement event is obscured within a noisy interval dominated by a group of strong, but discontinuous events. Southward the basement reflector is reestablished, albeit weakly. Across the zone of discontinuity the basement event shows a net, up-to-the-south offset of about 125 feet. Local structural control is suggested inasmuch as this amount of displacement is incompatible with the small apparent dip shown along the section north and south of St. James. In figure 16 several faults are tentatively mapped and collectively identified as the "St. James Anomaly." Because of the marginal quality of the seismic record, additional seismic or drill-hole corroboration is needed to confirm these results. For the present, one can only point out that up-to-the-south displacement across the St. James anomaly is compatible with its position on the south flank of the Salisbury Embayment.

Eastern Shore

The NE-ENE trending Richmond-Brandywine aeromagnetic belt, which appears to truncate the Sussex-Currioman Bay trend in St. Mary's and Calvert Counties, also abuts obliquely against an en echelon feature in western Dorchester County (named for reference, the Taylors Island anomaly) (fig. 4). The Taylors Island anomaly trends NNE between the mouths of the Patuxent

and Choptank rivers. It is areally much smaller than the Sussex-Currioman Bay trend and its flanks lack the steep magnetic gradients exhibited by the latter. The two features are separated by several small, aeromagnetic lows which are similarly oriented.

Truncation of the Taylors Island anomaly by the Richmond-Brandywine trend extends the juxtaposition of two regionally different aeromagnetic patterns eastward across Chesapeake Bay. Although not sharply defined, the contact zone between the two grains can be projected across northern Dorchester County and into Delaware. A stratigraphic cross-section (fig. 10) traversing normal to the contact shows that Danian and Santonian age sediments thin from about 390 feet at Easton to 160 feet at Cambridge. South of Cambridge the entire interval thins to zero thickness, although a lack of well control prevents detailed isopaching. Extrapolation of the western shore data suggest that the zero-isopach passes through central Dorchester County (fig. 14). The occurrence of stratigraphic pinchouts in association with a change of aeromagnetic grain raises the possibility of sporadic differential movement between structurally discrete blocks of basement rocks.

Vibratory reflection seismic lines were run across the break in aeromagnetic pattern to investigate the structural characteristics of the top-of-the-basement (Seismograph Service Corporation, 1976a). Lines were run north (Tal-1) and south (Dor-1) of Cambridge (fig. 5) using field and processing parameters similar to the St. Mary's County survey. Although broken and weak in places, the basement signal in seismic line Tal-1 can be correlated with reasonable confidence (not illustrated). The top-of-basement surface exhibits little change in elevation (about -3,590 to 3,690 feet), suggesting that the seismic line was run subparallel to strike (fig. 5). Although a dominant NNW-N strike is implied by these data, there is a hint at the north end of the line that a NE strike is beginning to be established. Even so, seismic line Tal-1 suggests that the regional shift in basement strike actually may occur closer to 38°42′, than 38°30′ as previously mapped using scattered bore-hole data. The basement event in Tal-1 is offset by a series of minor (<100 feet), high angle (normal) faults that do not appear to offset strong reflectors in the overlying Potomac Group. In some cases the "offsets" may actually represent erosional irregularities on the basement rock surface. There is no evidence for a major fault with offsets comparable to the Hillville fault of seismic line St. M-1.

The basement signature in seismic line Dor-1 occurs consistently as a sharp, trough-peak, wavelet (fig. 17) that is easily correlative across the record. It is also a strike (NNW-N) section and only shows about 80 feet (-3420 to -3500 feet) of relief attributable to the regional slope of the basement rocks. The basement event is an unfaulted, planar surface. The event has a slightly undulatory aspect across the section, but nowhere exhibits a step-like discontinuity that is suggestive of faulting (fig. 15). The strength and coherency of the event implies a sharp acoustical boundary between Coastal Plain and basement.

As noted above, seismic lines Tal-1 and Dor-1 record basement events with sharply different wavelet characteristics. Inasmuch as the field acquisition and processing parameters for each line were essentially the same, a geologic interpretation requiring two basement terranes seems reasonable. This interpretation supports speculative conclusions made previously using regional aeromagnetic data. Seismic line Tal-1 traverses the southern margin of the Richmond-Brandywine trend. In Tal-1 the basement surface is not a sharply defined acoustic event. Although in places the reflection has a strong trough-peak signature, the wavelet often shows attenuation and a general loss of coherency. Basal Potomac Group sediments overlying a deep basement saprolite could account for this characteristic wavelet as might the occurrence of increasingly consolidated (Jurassic (?)) Coastal Plain beds overlying acoustically slow basement (e.g. Triassic rocks) (fig. 18).

South of the Choptank River a different and dominantly N-NNE aeromagnetic grain, associated in a broad sense with the Sussex-Currioman Bay trend, is encountered. Within this terrane seismic line Dor-1 traverses a broad flatish aeromagnetic pattern located between en echelon highs; the Taylors Island anomaly lies to the west while east of Dor-1 a complexly shaped high, informally named the Drawbridge Anomaly, occurs subparallel to the Nanticoke River (fig. 4, 5). Juxtaposition of the two regional aeromagnetic patterns is more easily observed where the Taylors Island and Drawbridge anomalies abut against the NE-E Richmond-Brandywine trend. In the flatish areas between the anomalies, however, the contours swing into alignment much less abruptly so that a "break" in the grain is not closely observable. Although seismic line Dor-1 traverses such an area, its sharply coherent base-

ment signature seems to require an acoustically different rock than that producing the weak, phasing signal encountered along Tal-1.

In contrast to the St. Mary's County survey, the seismic evidence does not support the existence of a major fault zone separating the two aeromagnetic terranes. Nothing comparable to the Hillville fault was observed in Tal-1 or Dor-1, nor does contouring of the basement event require an offset between the lines. The absence of a continuous fault zone separating the two regional aeromagnetic patterns does not eliminate the possibility of local faulting, perhaps associated with smaller scale features such as the Taylors Island or Drawbridge anomalies but does seem to limit the possibility of a major transcurrent fault of the type described by Drake and Woodward (1963) and Sheridan (1974).

The possibility of faulting on the north flank of the Richmond-Brandywine trend was investigated by a series of NW-SE vibroseis lines run through central Kent (Ken-1, 2, 3, and 4) and Queen Anne's (QA-1, QA-2) Counties (figs. 5, 7, 19, 20). Faulting which involved both the top-of-basement reflection and events assigned to the Lower Potomac Group appear to be consistently high angle reverse faults, up-thrust from the north or west. None had a basement offset exceeding 100 feet, but three were in the 75 to 100 feet range. For example, between VP 250 and VP 260 on vibroseis line QA-1 (fig. 7), the basement event is offset by an estimated 80 feet. This fault is informally named the Hambleton Creek fault for ease of reference. The fault crosses State Route 213 near the headwaters of Hambleton Creek (fig. 7). Interestingly, the character of the basement event differs on either side of the proposed fault. On the down-to-the-south side of the fault, the basement signature has a relatively sharp double-peak event, whereas on the north wall the top-of-basement is marked by an attenuated to absent upper peak (fig. 7). As discussed earlier, synthetic seismogram models of several different reflection responses suggest that the double-peak event may represent the occurrence of a relatively thin consolidated bed overlying saprolitic basement (fig. 6). Regional considerations suggest that the consolidated bed may be an outlier of Jurassic (?) rocks erosionally detached from an eastward thickening continental wedge. An implication of this stratigraphy is that faulting prior to deposition of the Lower Cretaceous Potomac Group caused Jurassic (?) rocks to be stripped from the up-thrown wall of the fault. The Lower Potomac Group reflectors are clearly warped across the structure but do not exhibit displacements that are as obvious. Faulting, if present, seems to diminish up-section, never exceeding 70 feet.

A second example of down-to-the-SE faulting on the north flank of the Richmond-Brandywine trend is found between VP 125 and 145 on vibroseis line QA-2 (figs. 5, 19). This fault is herein called the Church Hill fault. The town of Church Hill is about one mile northwest of the fault via State Route 405. The fault is marked by a high noise level with basement continuity poorly established for approximately 2,000 feet. Displacement across the zone of discontinuity is about 85 feet. Offsets within the Coastal Plain section are difficult to establish and may be minimal. In this case the top-of-basement signature appears the same on both sides of the fault zone.

The Coleman fault (fig. 20) appears on seismic line Ken-1 (fig. 5) near the small community of the same name. A strong top-of-basement reflection can be established at the west end of the line at about -1,080 feet (360 milliseconds). The surface dips southeasterly so that at VP 195 it is estimated to be about -1,195 feet deep (387 milliseconds). The signal is essentially lost for the next 1,000 feet before emerging again as a strong event at VP 207. The reestablished reflection comes in structurally lower than projected regional dip allows, therby strongly suggesting a down-to-the-SE offset of about 85 feet. Due to poor seismic data at shallow depths, evidence for continuance of the fault into the Potomac Group is lacking.

Between VP 154 and VP 160 a basement high, interpreted as an erosional remnant, can be picked on line Ken-1 (fig. 20). A change in top-of-basement signature across the anomaly may be explained by local variations in the thickness of weathered material (saprolite). A complex double wavelet is present east of the high and absent above and west of it. Synthetic seismogram No. 7 (fig. 6), modeled by doubling the thickness of the saprolite layer shown in synthetic seismogram No. 3, suggests that the more complex reflections occurring east of the anomaly may be associated with more deeply weathered basement rocks.

As the examples cited above imply, minor basement faulting may be associated with the northern margin of the Richmond-Brandywine trend. However, unlike the southern margin, faulting does not appear to have influenced significantly the distribution of Upper Cretaceous or Lower Tertiary strata (figs. 12, 13, 14).

TECTONIC EVOLUTION OF THE RICHMOND—BRANDYWINE AEROMAGNETIC BELT AND ITS RELATIONSHIP TO THE SALISBURY EMBAYMENT

During Triassic to perhaps early Jurassic (?) time the Richmond-Brandywine strike belt was the locus for a series of complexly faulted graben or half-graben basins infilling largely with nonmarine, terrigenous rocks. Although drilling along the inner margins of the Coastal Plain has established the occurrence of buried Triassic (?) rocks within the belt, penetration has been inadequate to define their total thickness. If the outcropping basins may be used for comparison, hundreds, if not thousands, of feet of accumulation may be expected (Fisher, 1964).

The Richmond-Brandywine belt of Triassic (?) rocks is one segment of two great regional trends (fig. 18). The outcropping western trend, which is defined from south to north by the Dan River, Culpeper, Newark-Gettysburg and Connecticut Valley Basins, shows clearly a pronounced change in strike conformable to the Appalachian structures of central Pennsylvania. On the other hand, the eastern trend can be defined in outcrop only by the Deep River and Richmond Basins. Drill hole data confirm the northward extension of the trend into Maryland where it is associated with the Richmond-Brandywine aeromagnetic trend. From Richmond to Dorchester County, Maryland, the aeromagnetic trend changes strike from dominantly north to dominantly east, mimicking the change in strike of the western alignment of Triassic basins in Maryland, Pennsylvania, and New Jersey (fig. 4). Extension of the Richmond-Brandywine trend offshore to include the Baltimore Canyon trough (figs. 4, 18) suggests reestablishment of a northeast strike that is subparallel with the outcropping Newark Basin in New Jersey. Farther north, Triassic rocks, which may be part of the same trend, are believed to underlie Georges Bank (Schlee and others, 1976), the Gulf of Maine and the Bay of Fundy (Ballard and Uchupi, 1974).

Present theories of continental drift and sea floor spreading suggest that the Triassic basins originated along tensional rift zones associated with the early phases of the separation of North America and Africa (e.g., Heezen, 1968). As illustrated by Dietz and Holden (1970), Europe and Africa rotated counterclock-wise from North America so that the proto-North Atlantic widened progressively from north to south, perhaps involving transcurrent wrench faults as proposed by Drake and Woodward (1963). As rifting continued into the Jurassic, the proto-Atlantic Ocean widened, causing tensional stress along the

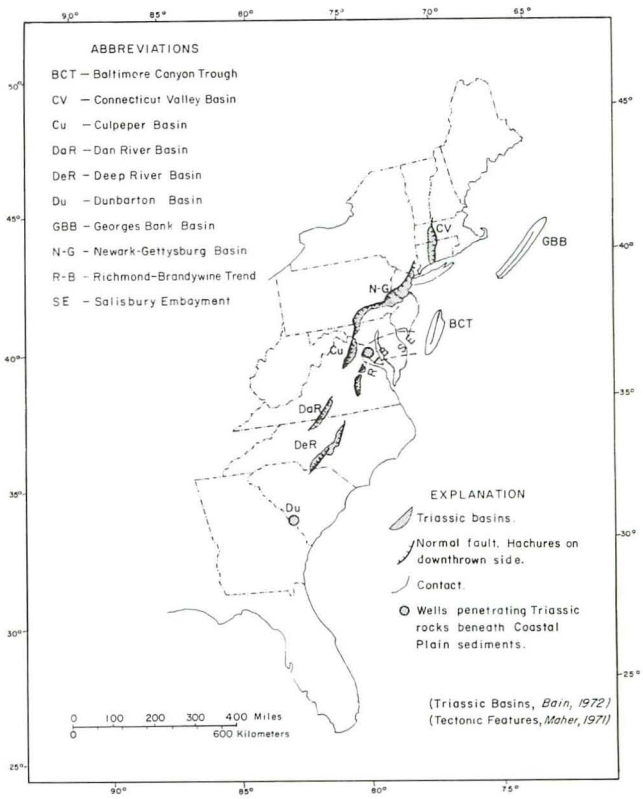


Figure 18. Map of eastern United States showing distribution of Triassic basins (including tectonic structures believed to be associated).

continental margins to diminish with movement on the border faults farthest from the Mid-Atlantic Ridge becoming less active.

Following directly from this tectonic reconstruction is the possibility that tensional faulting associated with the northern and easternmost Triassic rift basins continued to be a significant structural force further into the Mesozoic than elsewhere along the continental margin. Thus in areas where the rift basins remained residually active, notably the Baltimore Canyon Trough and the Georges Bank Basin, thick Jurassic and Cretaceous deposits occur. Sedimentation spread beyond the initial basins so that an irregular wedge of Jurassic rocks, becoming progressively marine eastward, fringes the continental margin. These rocks, which are rooted in Triassic rift basins, have been identified seismically beneath the present outer continental shelf by Schlee and others (1976) and referred to as the "lower acoustical zone."

Seismic sections published by Schlee and others (1976, figs. 5 and 13) show primary reflections

below the base ("horizon K") of the "lower acoustical zone" (Jurassic) which appear to infill graben or half-graben structures. Near the top of these structures, the reflections seem to be structurally conformable to "horizon K," giving the appearance of a progressive overlap of rift basin sediments onto the subsiding continental margin. Although largely developed as a continental wedge, sediments of the "lower acoustical zone" are rooted in rift structures which continued to function as depocenters during Jurassic sedimentation. The outcropping southern and western Triassic rift basins lack Jurassic "roofs" because by Middle Mesozoic time, the North America continent had rotated far enough from the Mid-Atlantic to render their border faults inactive except for local readjustments which continued into at least the Middle Cenozoic (Jacobeen, 1972; Mixon and Newell, 1976). For this reason Jurassic rocks are largely confined to the continental shelf, although, as discussed previously, their feather-edge may extend beneath the outer Coastal Plain and patchy outliers even farther west.

Whereas the Jurassic rocks merge downward into deep, graben-like structures at their base (Schlee and others, 1976, figs. 6 and 11), the overlying Cretaceous and Cenozoic section generally thickens seaward as a marginal wedge punctuated by broad, transverse embayments. In areas such as the Salisbury Embayment and Baltimore Canyon Trough, which are broadly coincident with Triassic rift structures, general downwarping of the continental margin was accentuated. Fault complexes associated with the basins were sporadically reactivated throughout the Cretaceous and Lower Tertiary to permit stress adjustments in response to continued, though diminishing, subsidence of the continental margin. By Middle Tertiary time, the sediments appear to prograde across the continental shelf with little response to deeper, antecedent structures.

In Maryland the easternmost known Triassic (?) rift system is associated with the Richmond-Brandywine aeromagnetic trend. The Richmond-Brandywine belt occupies the central part of the Salisbury Embayment and, after a major strike change, the Baltimore Canyon Trough. Facies and thickness trends associated with the up-dip portions of the Salisbury Embayment suggest strongly that it was a sporadically active depocenter up through at least the Lower Tertiary (Hansen, 1971). As heretofore discussed, stratigraphic pinchouts involving Santonian to Danian sediments on the southern flank of the Embayment are well documented (figs. 8, 9, and 10). Subsurface efforts, chiefly seismic, to establish structural control involving basement faulting for the pinchouts has met with inconclusive results. In central St. Mary's County a potentially significant, up-to-the-south, border fault (the Hillville Fault) is suggested in vibroseis line St. M-1 (fig. 15). Reflections associated with the Potomac Group appear to be offset across the fault, supporting the assumption that structural adjustments were occurring on the southern flank of the Salisbury Embayment during Late Cretaceous and Early Tertiary deposition. Conversely, a vibroseis profile run in Talbot (Tal-1) and Dorchester (Dor-1, Dor-2, Dor-3) Counties failed to establish a significant border fault on the southern margin of the Richmond-Brandywine trend (fig. 17). Inasmuch as currently available seismic evidence is restricted to several relatively short lines, these data should not be viewed as ruling out the possibility of significant up-to-the-south faulting near the southern margin of the Richmond-Brandywine trend elsewhere beneath the Eastern Shore.

The Brandywine fault system first identified by Jacobeen (1972) in southern Prince George's County and extended into Charles County by Dames & Moores (1973), is a significant up-to-the-SE reverse fault system. It is located within the Richmond-Brandywine aeromagnetic trend, however, rather than near the southern margin and may represent compressional readjustments along its axis. Also, the Brandywine fault system occupies an area of the Richmond-Brandywine trend in which a major strike change occurs from predominantly NE-SW to predominantly E-W. The east striking segment which coincides broadly with the axis of the Salisbury Embayment was a focus of subsidence during the Mesozoic and Early Tertiary, whereas the SW striking segment was less affected by warping along the continental margin. Seismic evidence suggests that the junction in Southern Maryland of these tectonically distinct segments of the Richmond-Brandywine trend is marked by complex basement faulting. Because the dominant stress was compressional within the curvature of the trend, a system of en echelon, high angle reverse faults having known rotational offsets of as much as 250 feet has apparently developed. It would also be somewhat surprising if the faults did not have a strong strike-slip component, although available subsurface data are insufficient to demonstrate this possibility.

CONCLUSIONS

A review of subsurface information for Coastal Plain Maryland, including recently obtained stratigraphic, palynologic, and geophysical data, suggests the following:

1) In southern Maryland, the south flank of the Salisbury Embayment at about lat. 38°30′ N. is characterized by (a) a change in strike of the pre-Miocene units from dominantly NE-SW to dominantly N-S; (b) a series of well documented Upper Cretaceous (Senonian) to Lower Paleocene (Danian) pinchouts; and (c) a major change in aeromagnetic pattern.

2) West of the Chesapeake Bay, the Senonian to Danian section reaches a maximum thickness of 325 feet in the subsurface of southern Anne Arundel County. Biostratigraphic evidence, chiefly palynological, from a series of stratigraphic test wells drilled along the west margin of the Bay shows progressive thinning of these strata so that in southern Calvert County the Aquia Formation (Late Midway-Early Wilcox) rests unconformably on Albian beds of the Potomac Group. Uplift and erosion is implied because the truncated edges of the marine units fail to exhibit the facies characteristics associated with strand lines.

3) The Richmond-Brandywine aeromagnetic trend strikes oblique to the Fall Zone in Virginia where it correlates with an extensive granite-gneiss pluton containing one large and several small, downfaulted Triassic basins. The Richmond-Brandywine trend strikes NE into Southern Maryland where basement cores confirm its association with Triassic (?) rocks, subcropping beneath the Coastal Plain. Between lat. 38°N. and lat. 39°N. the aeromagnetic trend changes strike to NEE and extends across the Delmarva Peninsula where it is broadly coincident with the central part of the Salisbury Embayment.

4) The association of stratigraphic pinchouts with the boundary between two regional aeromagnetic patterns suggests a zone of crustal weakness sporadically readjusting along one or more border faults. A potentially significant fault (Hillville Fault) was mapped seismically in central St. Mary's County near the southern margin of the Richmond-Brandywine trend. In profile, it is a high-angle up-to-the-SE reverse fault having an estimated offset at top-of-basement of 250 feet. The magnitude and tectonic significance of its strike-slip component remains unresolved.

5) Synthetic seismograms used to model the top-of-basement signature can be interpreted to show the irregular occurrence of consolidated rocks above saprolitic basement in parts of Queen Anne's, Talbot, and Dorchester Counties. If this interpretation is correct, outliers of Jurassic (or perhaps Neocomian) strata, encountered as a feather-edge in deep coastal wells, occur at least 35 miles farther west than heretofore believed; these strata may correlate with Schlee's (1976) Jurassic (?) "lower acoustical zone" which fills the basal part of the Baltimore Canyon Trough.

6) It is proposed that the Salisbury Embayment is part of an eastern Triassic rift system that conforms to the curvature of the Appalachians. The rift system consists of the outcropping Deep River Basin-Richmond Basin, Salisbury Embayment, and the Baltimore Canyon Trough. Rotational drift of the North American plate caused the northern and easternmost Triassic rift basins to remain a significant structural force further into the Mesozoic than elsewhere along the Continental margin. Consequently, as the margin subsided in association with a general deepening of the Atlantic, anomalously thick depocenters developed where the rift basins remained residually active, notably the Salisbury Embayment and the Baltimore Canyon Trough. During Jurassic time sediments spread out of the rift basins to form an irregular continental wedge. Beneath coastal Maryland, these strata occur only as a thin, patchy veneer, but are kilometers thick offshore [Schlee's (1976) "lower acoustical zone"] where they are rooted in deep, graben-like structures. As shown on the south flank of the Salisbury Embayment, faults associated with the old rift system were sporadically reactivated during the Cretaceous and early Tertiary to permit stress adjustments caused by sea floor spreading and continued subsidence of the continental margin. By Middle Tertiary time, Coastal Plain sediments appear to prograde eastward with little influence from deeper, antecedent structures.

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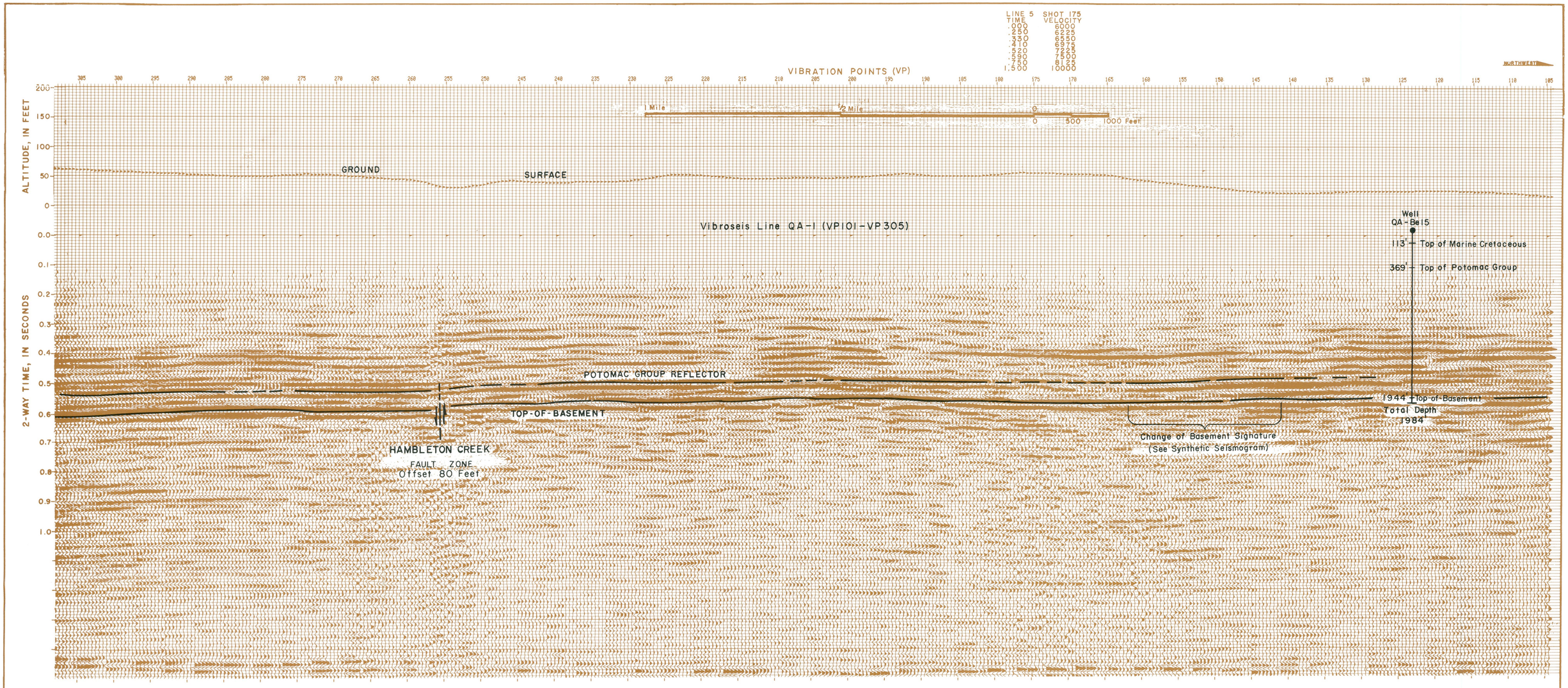
Maryland Residents Add 5% Sales Tax

Figure 7. Reflection seismic line QA-1 (VP 101 to VP 305) showing Hambleton Creek fault

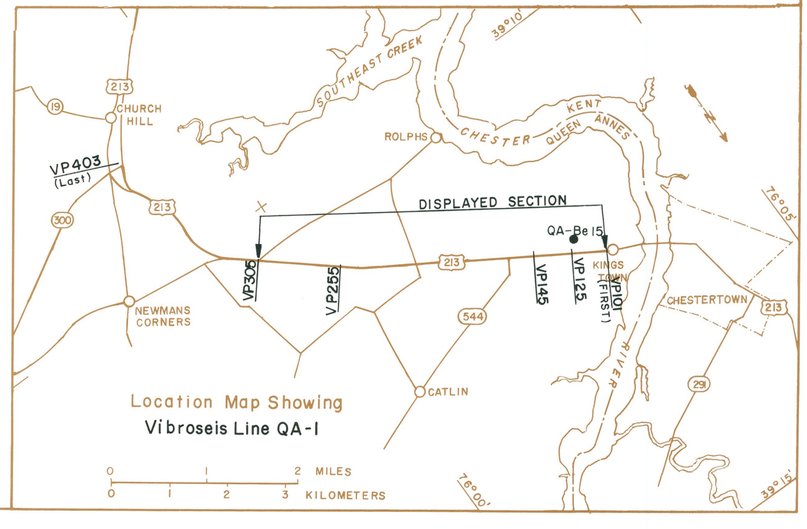


RECORDING PARAMETER
(Contractor- Seismograph Service Corp.)

Energy Source - 2 or 3 Vibrators.
VP Interval - 200 Feet.
Geophone Interval - 100 Feet.
Offsets - 400-1500 Feet.
Stack - 600 Percent.
Sweep Length - 7 Seconds.
Sweep Frequency - 80 to 20 Hz.
Number of Sweeps - 16.

TIME-DEPTH FUNCTION

Z = 441 - 4230t.
Z = Depth in Feet to Top-of-Basement.
t = 2-Way Time in Seconds.



Location Map Showing
Vibroseis Line QA-1

Figure 8. Stratigraphic cross-section A-A′ extending from eastern Anne Arundel County to SW St. Mary's County

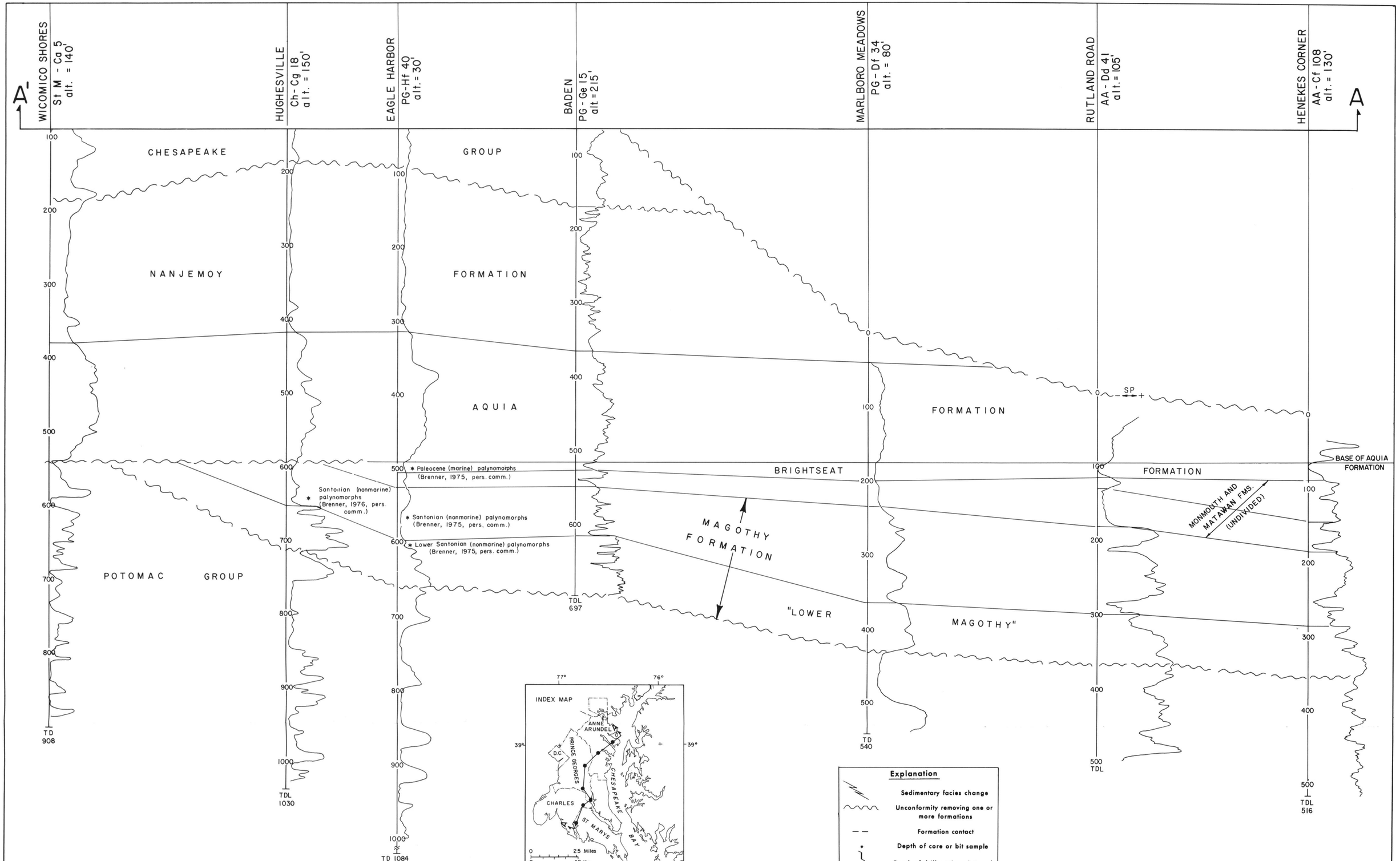


Figure 9. Stratigraphic cross-section B-B′ extending from western Queen Anne's County to SE Calvert County

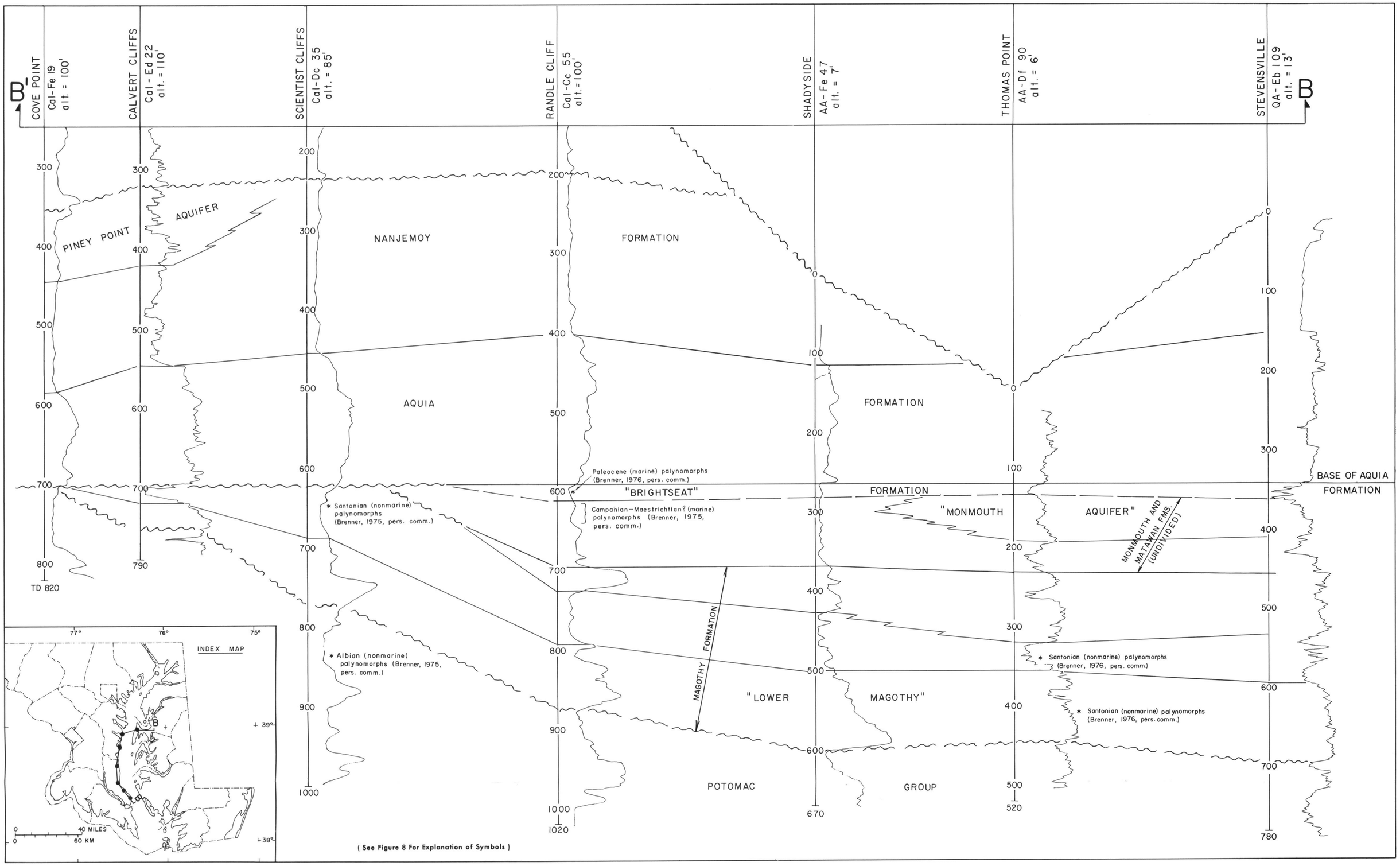


Figure 10. Stratigraphic cross-section C-C′ extending from western Queen Anne's County to SW Somerset County

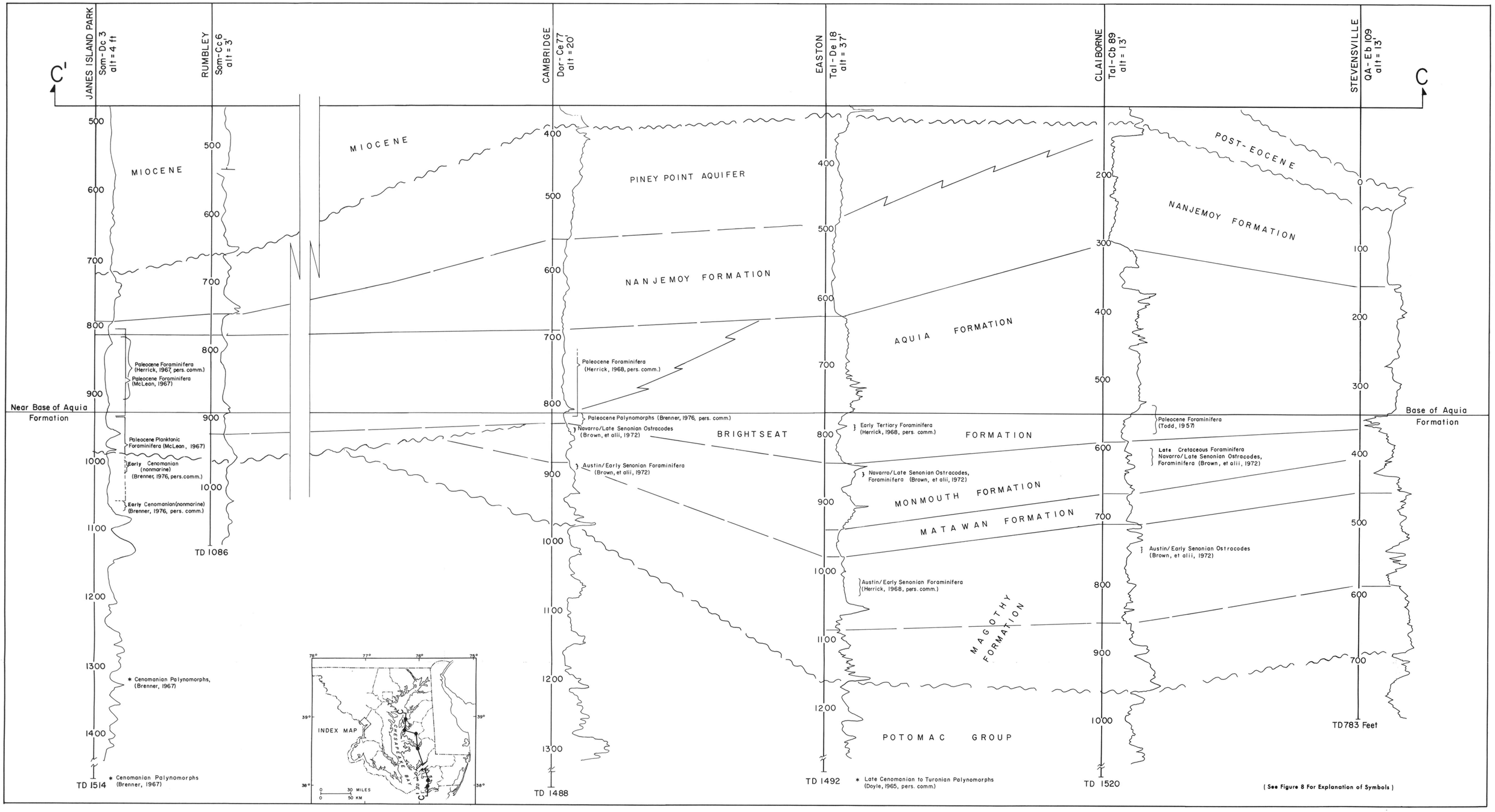


Figure 11. Stratigraphic cross-section D-D′ extending from east central Anne Arundel County to northern Dorchester County

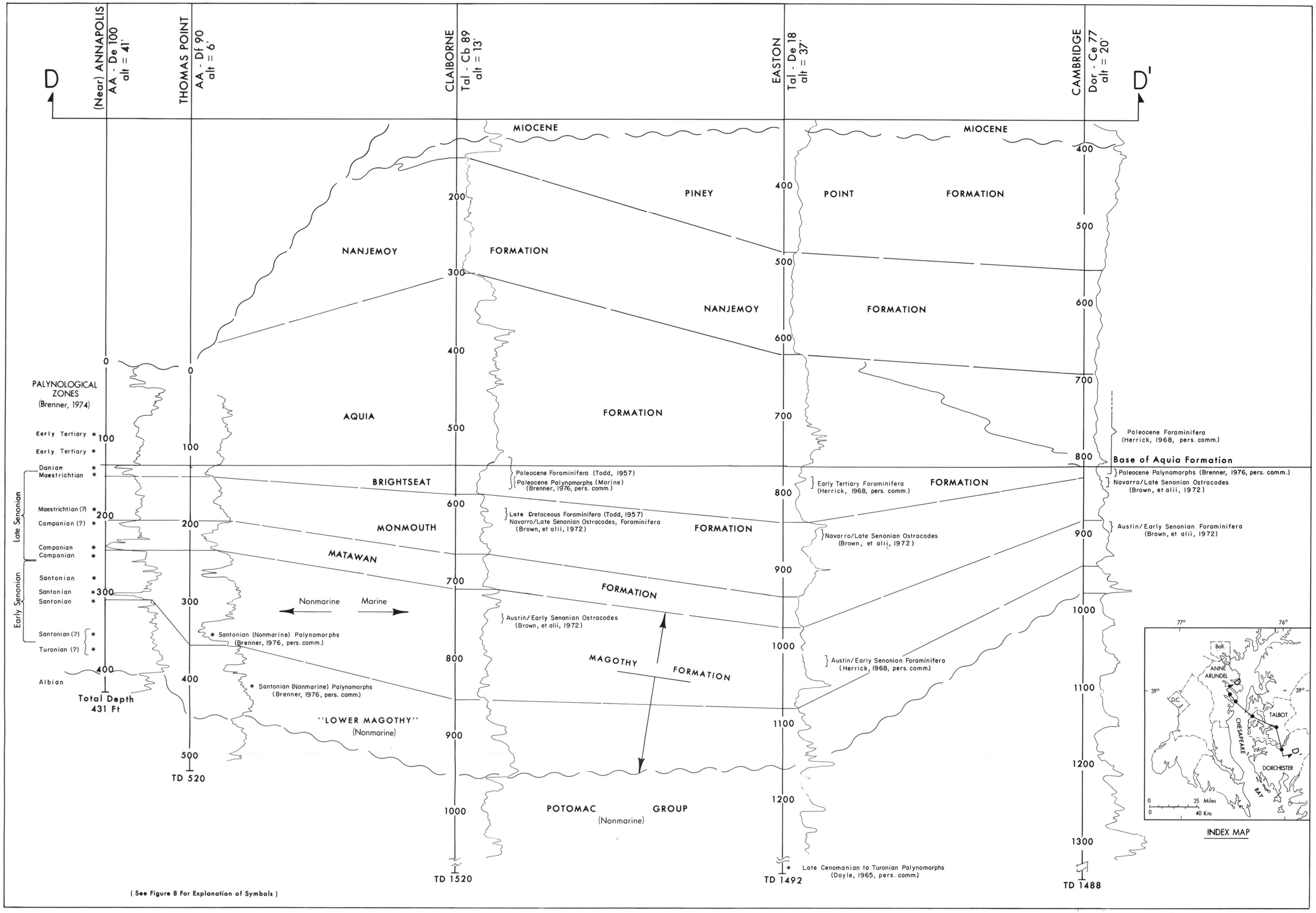
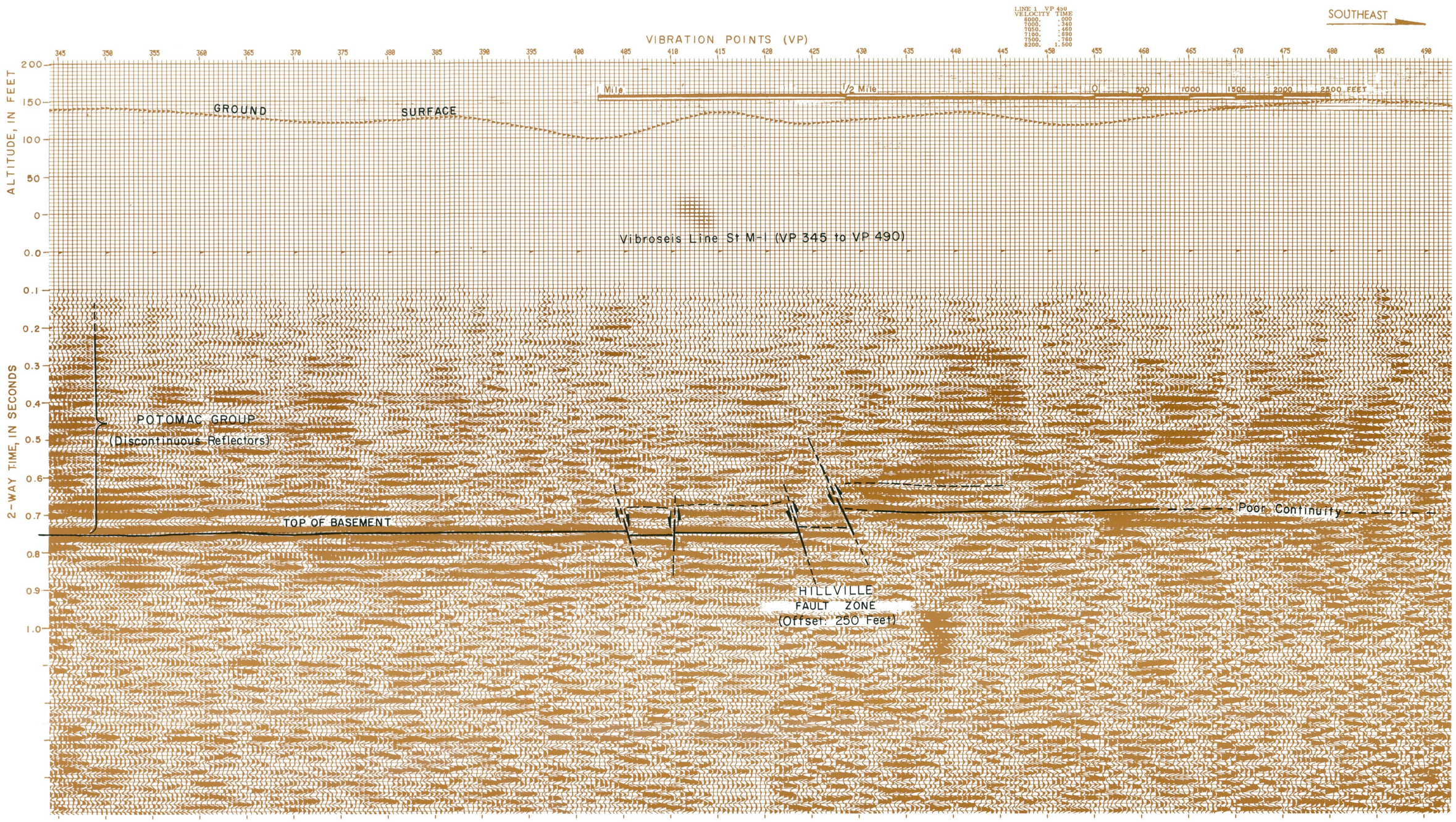


Figure 15. Reflection seismic line St. M-1 (VP 345 to VP 490) showing the Hillville fault



RECORDING PARAMETERS

(Contractor – Seismograph Service Corp.)

Energy Source – 2 or 3 Vibrators
VP Interval – 200 Feet
Geophone Interval – 100 Feet
Offsets – 400-1500 Feet
Stack – 600 Percent
Sweep Length – 7 Seconds
Sweep Frequency – 80 to 20 Hz.
Number of Sweeps – 16

TIME – DEPTH FUNCTION

$Z = 491 - 4230t$
Z = Depth in Feet to Top-of-Basement
t = 2-Way Time in Seconds

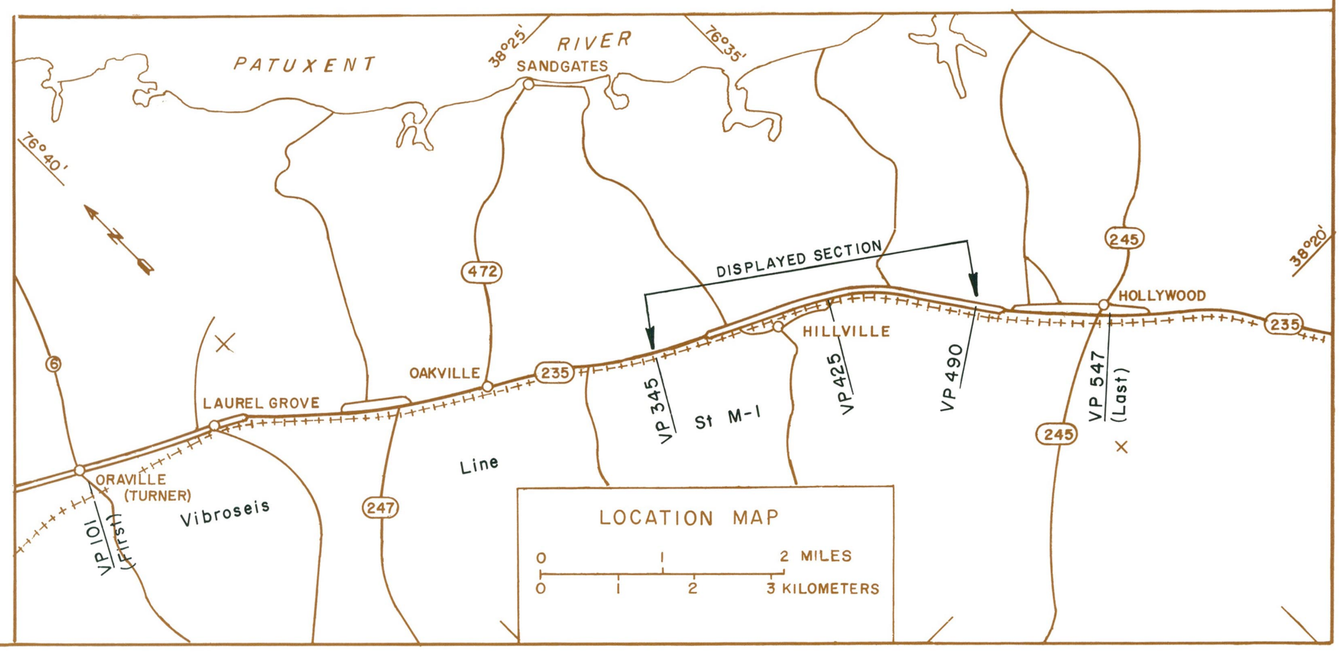
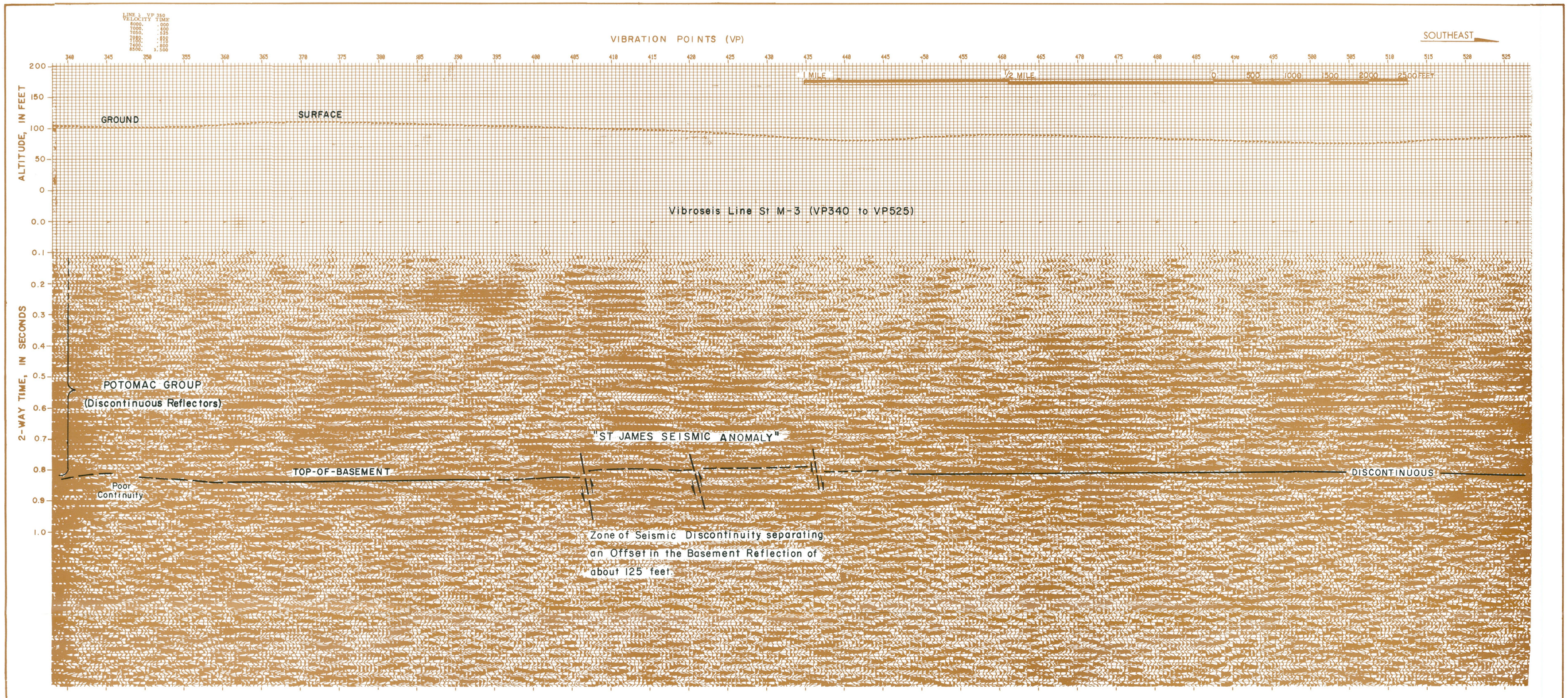


Figure 16. Reflection seismic line St. M-3 (VP 340 to VP 525) showing the St. James seismic anomaly



RECORDING PARAMETERS

(Contractor - Seismograph Service Corp.)

Energy Source – 2 or 3 Vibrators
VP Interval – 200 Feet
Geophone Interval – 100 Feet
Offsets – 400-1500 Feet
Stack – 600 Percent
Sweep Length – 7 Seconds
Sweep Frequency – 80 to 20 Hz.
Number of Sweeps – 16

TIME – DEPTH FUNCTION

Z = 491 – 4230 t
Z = Depth in Feet to Top-of-Basement
t = 2-Way Time in Seconds

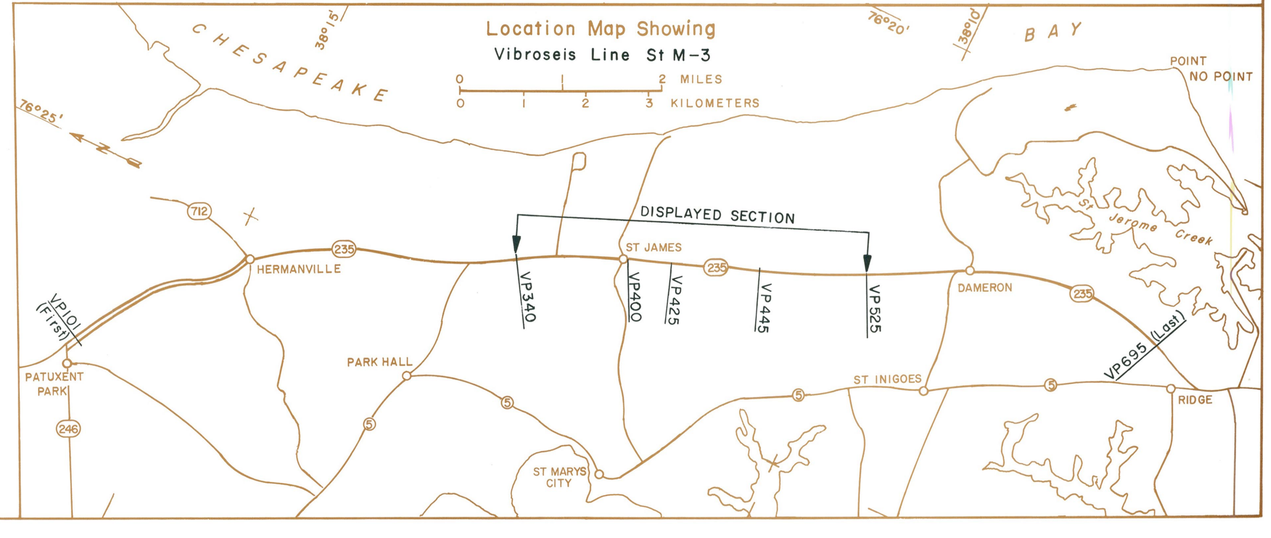
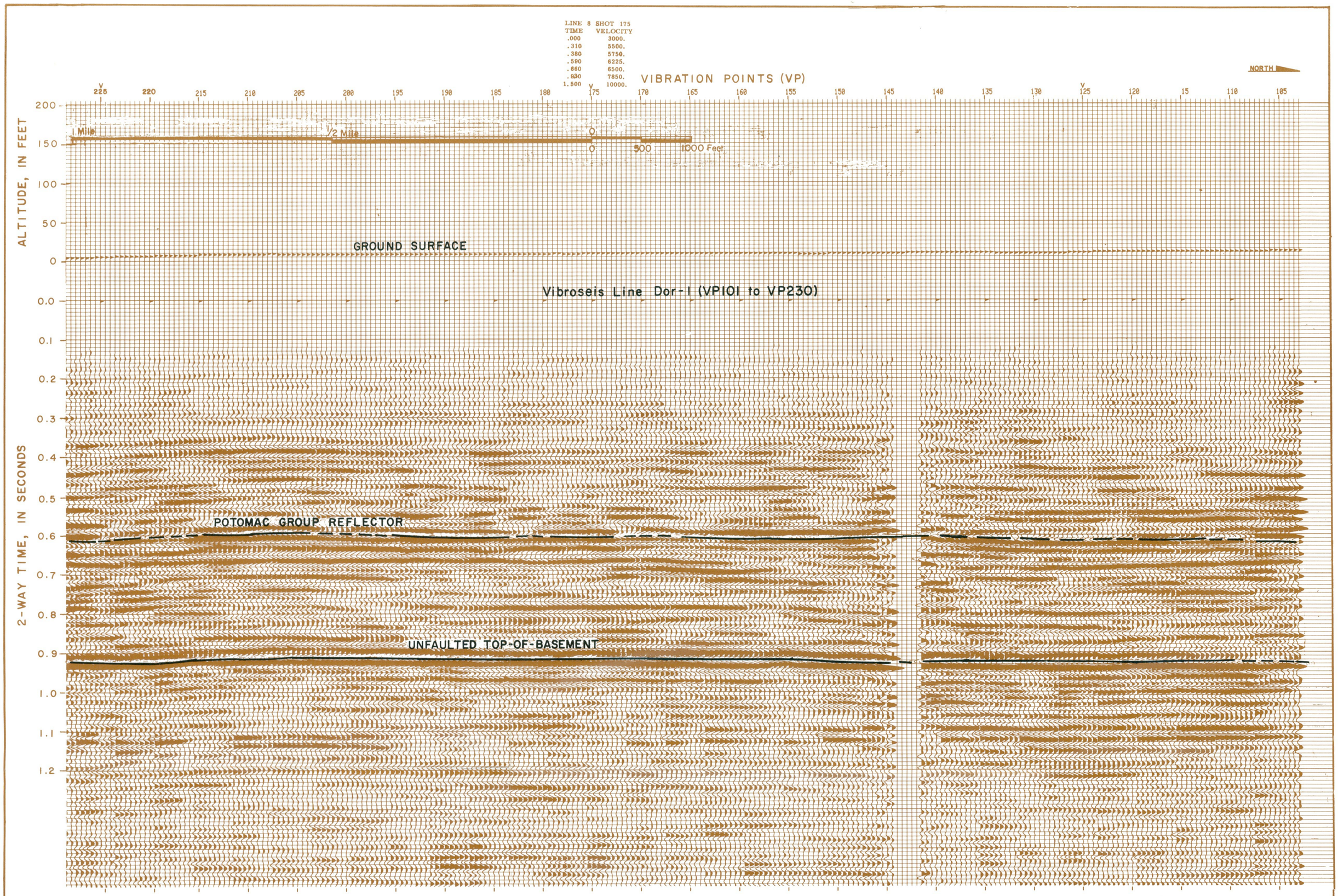


Figure 17. Reflection seismic line Dor-1 (VP 101 to VP 230) showing unfaulted top-of-basement



RECORDING PARAMATERS

(Contractor-Seismograph Service Corp.)

Energy Source - 2 or 3 Vibrators.
VP Interval - 200 Feet.
Geophone Interval - 100 Feet.
Offsets - 400 - 1500 Feet.
Stack - 600 Percent.
Sweep Length - 7 Seconds.
Sweep Frequency - 80 to 20 Hz.
Number of Sweeps - 16.

TIME-DEPTH FUNCTION

Z = 441 - 4230 t.
Z = Depth in Feet to Top-of-Basement.
t = 2-Way Time in Seconds,

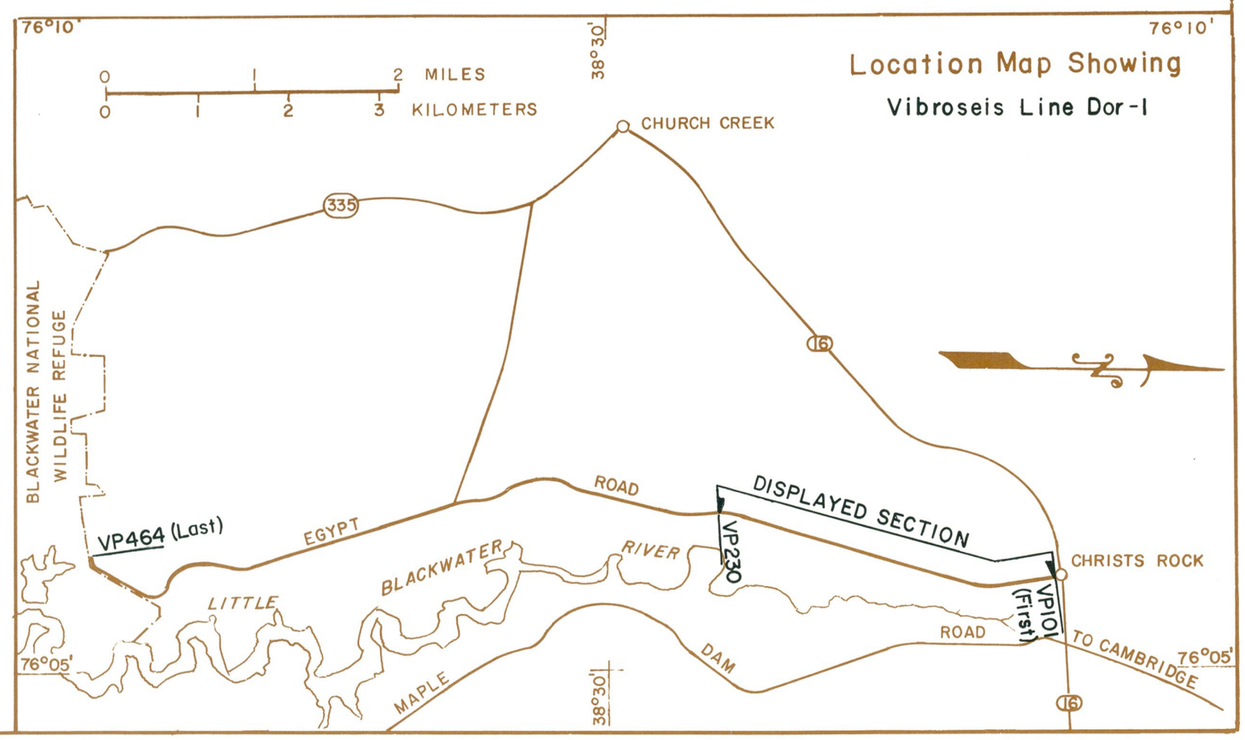
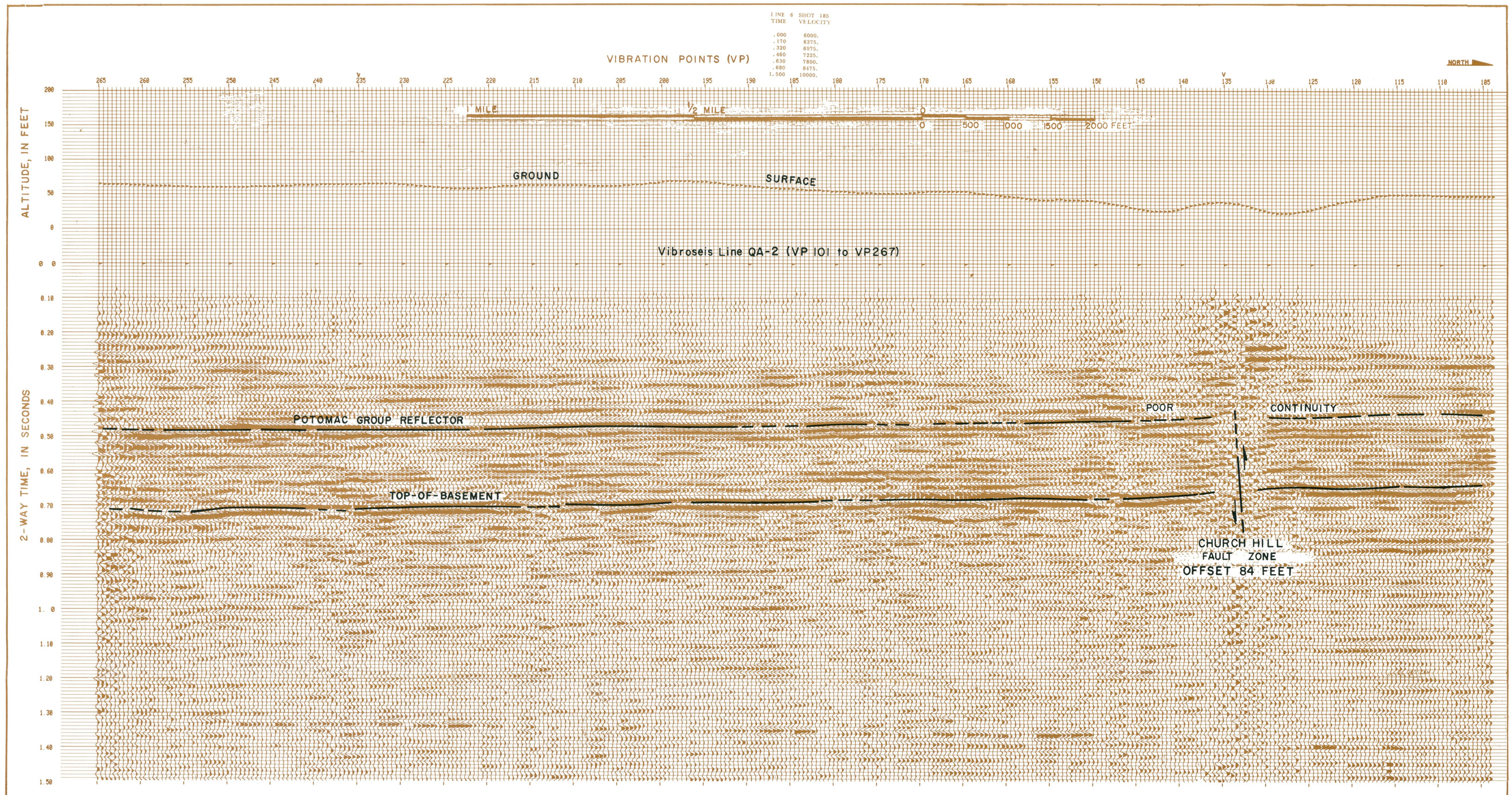


Figure 19. Reflection seismic line QA-2 showing Church Hill fault



RECORDING PARAMETERS

Contractor- Seismograph Service Corp.

Energy Source - 2 or 3 Vibrators.
VP Interval - 200 Feet.
Geophone Interval - 100 Feet.
Offsets - 400-1500 Feet.
Stack - 600 Percent.
Sweep Length - 7 Seconds.
Sweep Frequency - 80 to 20 Hz.
Number of Sweeps 16.

TIME - DEPTH FUNCTION

Z = 441 - 4230t.
Z = Depth in Feet to Top-of-Basement.
t = 2-Way Time in Seconds.

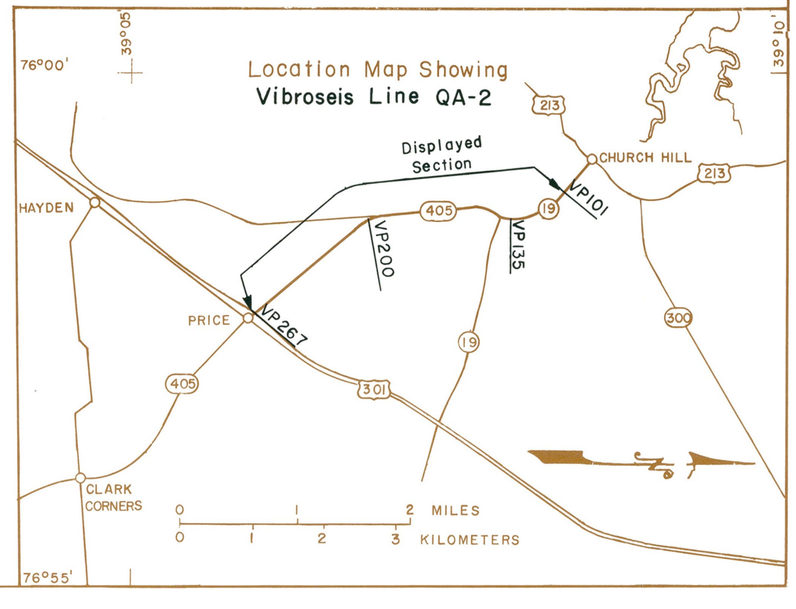
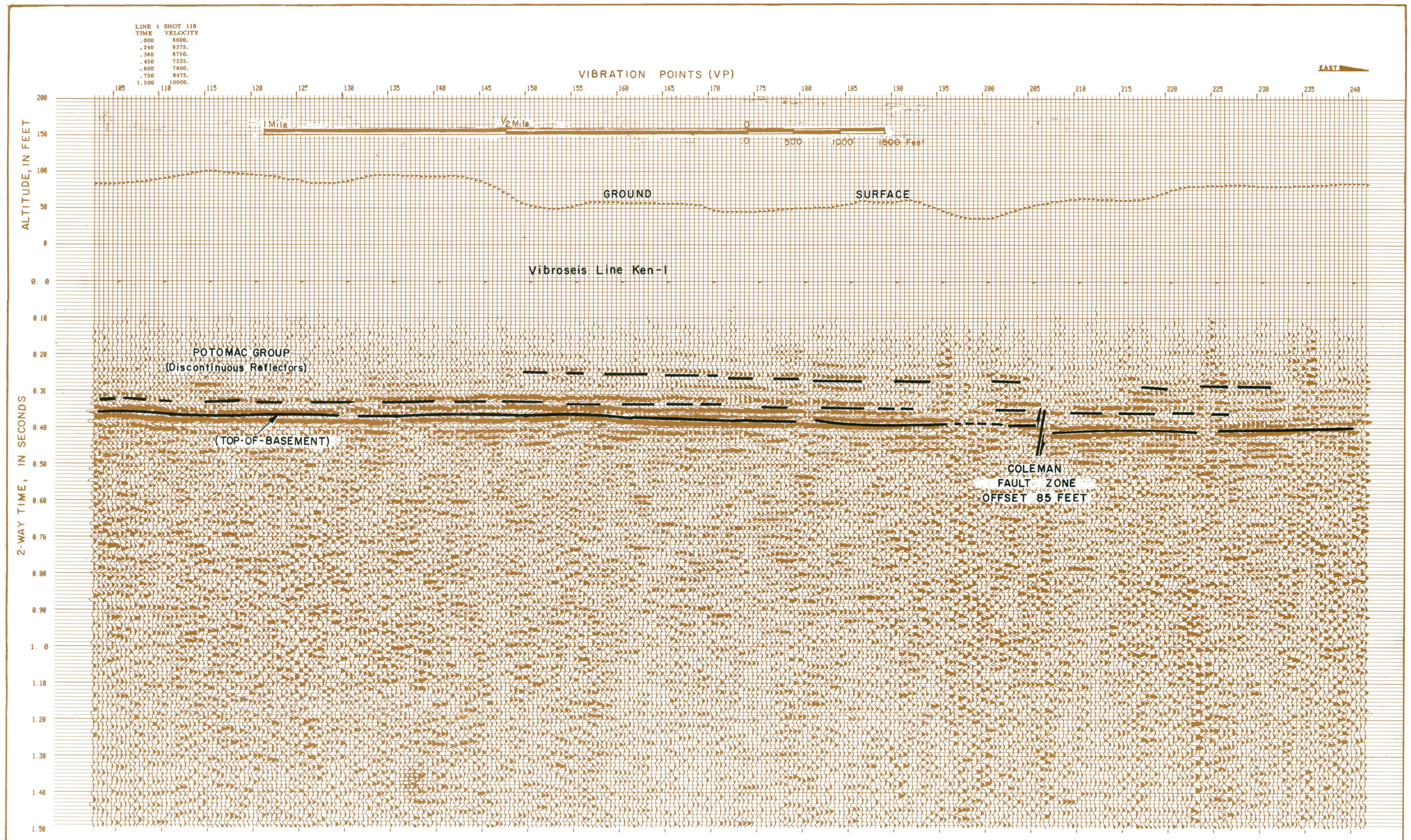


Figure 20. Reflection seismic line Ken-1 showing Coleman fault



RECORDING PARAMETERS

(Contractor-Seismograph Service Corp.)

Energy Source- 2 or 3 Vibrators.
VP Interval- 200 Feet.
Geophone Interval- 100 Feet.
Offsets- 400-1500 Feet.
Stack - 600 Percent.
Sweep Length - 7 Seconds.
Sweep Frequency - 80 to 20 Hz.
Number of Sweeps - 16.

TIME-DEPTH FUNCTION

Z = 441 - 4230 t.
Z = Depth in Feet to Top-of-Basement.
t = 2-Way Time in Seconds.

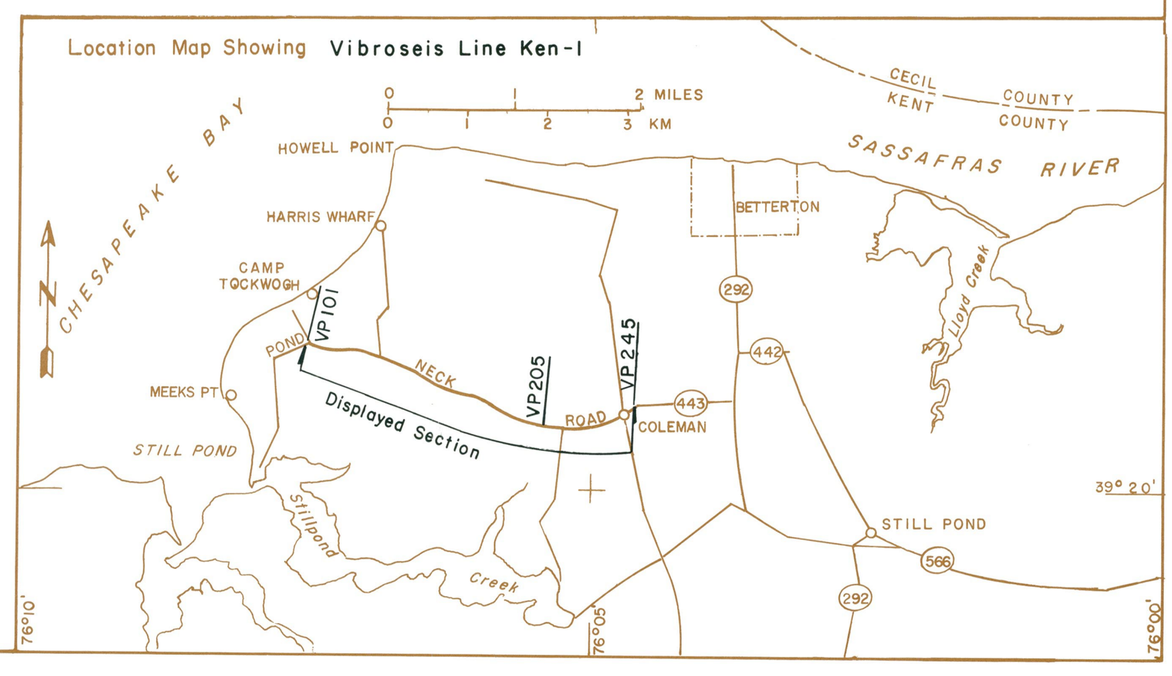


Figure 16. Reflection seismic line St. M-3 (VP 340 to VP 525) showing the St. James seismic anon

Upper Cretaceous (Senonian) and Paleocene (Danian)
Pinchouts on the South flank of the Salisbury Embayment,
Maryland, and their Relationship to Antecedent Basement Structures

R.I. No. 29, 1978