Department of Natural Resources

MARYLAND GEOLOGICAL SURVEY

Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 21

SEDIMENTARY FACIES OF THE AQUIA FORMATION IN THE SUBSURFACE OF THE MARYLAND COASTAL PLAIN

by

Harry J. Hansen

Prepared in cooperation with
Geological Survey
U. S. Department of the Interior

1974

Department of Natural Resources

MARYLAND GEOLOGICAL SURVEY

Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 21

SEDIMENTARY FACIES OF THE AQUIA FORMATION IN THE SUBSURFACE OF THE MARYLAND COASTAL PLAIN

by

Harry J. Hansen

Prepared in cooperation with
Geological Survey
U. S. Department of the Interior

1974

COMMISSION OF
MARYLAND GEOLOGICAL SURVEY

Ernst Cloos, *Chairman* . . . . . Baltimore

S. James Campbell . . . . . Towson

Richard W. Cooper . . . . . Salisbury

John C. Geyer . . . . . Baltimore

Robert C. Harvey . . . . . Frostburg

TABLE OF CONTENTS

	Page
Purpose	3
Previous investigations	3
Method of study	7
The Aquia outcrop	9
The subsurface Aquia	12
Structure	12
Thickness	12
Stratigraphic boundaries	15
Selected facies trends	19
Sand distribution	19
Sand texture	21
Sand mineralogy	21
Transmissivity	30
Depositional environment	32
Earlier investigations	32
Sand distribution and texture	35
Mineralogic diagnostics	37
Conclusions	43
References	44

LIST OF ILLUSTRATIONS

			Page
Figure	1.	Map showing generalized outcrop of the Aquia Formation and location of wells that penetrate the Aquia and have geophysical logs	4
	2.	Stratigraphic cross-sections A-A'through D-D'	6
	3.	Stratigraphic cross-sections Y-Y' and Z-Z'	8
	4.	Location map showing wells that penetrate the Aquia Formation and have drill cuttings	10
	5.	Diagram showing increase in grain size of the Aquia Formation from southwest to northeast (after Drobnyk, 1965, fig. 1, 2)	11
	6.	Map showing extent of Chesapeake - Delaware Embayment (after Maher, 1971, pl. 3)	12
	7.	Structure contour map of the Aquia Formation in Maryland	13
	8.	Isopach map of the Aquia Formation	14
	9.	Sand thickness map of the Aquia Formation using geophysical log data	16
	10.	Map showing stratigraphic units sub-cropping beneath Aquia Formation	17
	11.	"Worm's eyeview" map showing formations overlying Aquia Formation	18
	12.	Sand percentage map of Aquia Formation using geophysical log data	20
	13.	Stratigraphic cross-section N-N', showing subsurface sand build-up	22
	14.	Stratigraphic cross-section S-S', showing subsurface sand build-up	23
	15.	Map showing the percentage of Aquia sands described as medium- or coarse-grained in drillers' logs	24
	16.	Map showing the footage of Aquia drill cuttings which contain greater than 50 percent medium to coarse sand	26
	17.	Six vertical well profiles showing trends in several environmentally diagnostic parameters	28
	18.	Contoured cross-section O-O', showing distribution of medium and coarse quartz sands in Aquia Formation	29
	19.	Contoured cross-section R-R', showing distribution of medium and coarse sand in Aquia Formation	30-31
	20.	X-ray diffraction trace of agglomeratic goethite pellets (from well Cal-Db 36, 523-533 ft.)	32
	21.	Map showing distribution of goethite + glauconite expressed as a percentage of the total sand fraction	33

22. Map showing well footages in which the goethite/goethite + glauconite ratio (X100) exceeds 25 percent 34

23. Contoured cross-section T-T', showing distribution of goethite/goethite + glauconite ratio (X100) between Waldorf and Hambleton 35

24. Map showing distribution of iron-stained quartz in Aquia Formation 36

25. Map showing localities where at least one interval from each set of Aquia sample cuttings contains 25 or more percent shell fragments or cemented sand aggregates 38

26. Map showing generalized transmissivity distribution in the Aquia Formation of Maryland (from Hansen, 1971, fig. 7) 39

27. Map showing the composite distribution of near shore marine facies during Aquia time 40

28. Proposed model for fecal pellet authigenesis 43

Plate 1. Photomicrograph of thin section of epoxy-impregnated drill cuttings from well Tal-Ce 62 (639' - 649') 25

2. Photomicrograph of thin section of epoxy-impregnated drill cuttings from well Ch-Bf 127 (302' - 321') 25

3. Photomicrograph of thin section of epoxy-impregnated drill cuttings from well Tal-Ce 62 (639' - 649'), showing agglomeratic goethite pellet 27

4. Photomicrographs comparing recent, agglomeratic fecal pellets voided by polychaete worms with goethite and glauconite grains from the Aquia Formation 42

SEDIMENTARY FACIES OF THE AQUIA FORMATION IN THE SUBSURFACE OF THE MARYLAND COASTAL PLAIN

by

Harry J. Hansen

ABSTRACT

The marine Aquia Formation of Paleocene age outcrops in Maryland as an irregular band extending from the Potomac River bluffs in western Charles County to the upper reaches of the Sassafras River in southeastern Cecil County. The Formation thickens and becomes more coarsely-textured toward the northeast, traversing at least two first-order facies. The oblique relationship between the outcrop belt and several lithofacies trends suggests that post-Eocene tilting has imparted to the Formation a structural strike that is demonstrably different from its depositional strike.

In the subsurface the Aquia Formation exhibits a tripartite facies pattern: 1 ,a thick, coarser-textured sandy facies extending southwesterly in outcrop from Kent County to about the Patuxent River valley where it swings south into the subsurface toward southern St. Mary's County; 2 ,a finely textured sand to silt-clay facies, occurring chiefly in Charles and southern Prince George's County; and 3, a thinner, very muddy facies that appears to underlie much of the Eastern Shore seaward of the Choptank River; it does not outcrop.

Facies 1 is interpreted to be an offshore sand bank complex. In addition to being thicker and more coarsely textured than facies 2 , it exhibits consistently greater transmissivity values, higher goethite/goethite + glauconite ratios, more intense iron staining of quartz grains, and thicker accumulations of calcareously cemented, sand-packed shell beds.

The fine, muddy, glauconitic sands dominating facies 2 were apparently deposited in a lower energy, inner shelf environment occurring landward of the sand bank complex (facies 1). The predominately silt-clay character of facies 3 is suggestive of outer shelf sediments occurring seaward of the sand bank complex; sand thickness vaules based on geophysical log data are consistantly less than 25 feet. Texturely, the sands are chiefly very fine to fine-grained and exhibit very little iron-staining.

The Aquia Formation, particularly facies 1 , contains appreciable amounts of pelletal goethite. The goethite grains differ from associated glauconite grains by being generally irregular to ellipsoidal-shaped rather than polylobate or accordian-shaped; by being generally agglomeratic, rather than microcrystalline; and by being generally more coarsely textured. Both, however, are believed to be derived from fecal pellets, albeit pellets voided by organisms having distinctly different physiological, ecologic, and/or tropic processes.

PURPOSE

The Aquia Formation is an important source of ground water in several Southern Maryland (Calvert, St. Mary's) and Eastern Shore (Kent, Queen Anne's, Talbot) Counties. Prior to constructing a digital simulation model for predicting hydrologic responses to future pumping arrays (Kapple and Hansen, in prep.), a stratigraphic study was undertaken to determine both the internal (fabric) and external (boundaries) characteristics of the formation. Inasmuch as both are to a considerable extent the products of antecedent sedimentary processes, an attempt was also made to reconstruct a generalized paleogeographic setting for the formation.

PREVIOUS INVESTIGATIONS

Clark in 1896 first employed the name "Aquia Formation" to describe marine, lower Tertiary "greensands and greensand marls" outcropping in Virginia, Maryland, and Delaware. Five years later Clark, Martin, and others (1901) published a very thorough systematic report in which the "Eocene" section was subdivided as follows:

Group	Formation	Member
Pamunkey	Nanjemoy	Woodstock
		Potapaco
	Aquia	Paspotansa
		Piscataway

At the same time nine faunal zones, chiefly molluscan, were proposed for the Aquia Formation and eight for the overlying Nanjemoy. Although the formations Clark erected remain, with some modification, viable stratigraphic units, both the members and zones have proven parochial to modern workers (Nogan, 1964; Drobnyk, 1965; Glaser, 1971) and, consequently, have limited applicability.

Later foraminiferal studies by Shifflett (1948) and Bennett and Collins (1952) identified Paleocene strata at the base of the Pamunkey sequence in Southern Maryland. These beds were assigned to the Brightseat Formation. Subsequently, Loeblich and Tappan (1957) using planktonic Foraminifera extended the Paleocene-Eocene time line upwards to include parts of the Aquia Formation previously considered Eocene. Hazel (1969) carried the change further and considered most, if not all, of the Aquia Formation Paleocene in age.

Darton (1948), abandoning Clark's subnomenclature, suggested that the distinctive but thin (30 feet), pinkish clay-silt beds at the base of the Nanjemoy Formation (Claiborne) be given member status. He proposed the name Marlboro Clay Member which was generally accepted. Going a step further, Glaser (1971) argued that the Marlboro "member" should be raised to formational rank because of its role in Southern Maryland as a persistent and easily recognized marker bed. Recently, Brown and others (1972, p. 47) suggested that the Marlboro Clay is early Eocene in age and consequently should be assigned to the Sabine (Upper Wilcox) stage, rather than to the Claiborne.

Cooke (1952) suggested that the Aquia Formation be called a "Greensand" because of the near ubiquitous occurrence of the mineral glauconite. This nomenclature provides a useful descriptor and, consequently, appears often in the literature.

Finally, Otton (1955) described a post-Nanjemoy (Jackson) sequence of Eocene sands occurring only in the subsurface which he named the Piney Point Formation. This unit is now recognized in Virginia, Delaware, and New Jersey. Recently, however, Brown and others (1972, p. 49) have argued that the Piney Point Formation is Claiborne in age. If this interpretation is correct, the Piney Point may be, at least in part, a facies of the Nanjemoy.

Thus, a concensus of modern opinion would subdivide the Paleocene-Eocene sediments of Coastal Plain Maryland as follows:

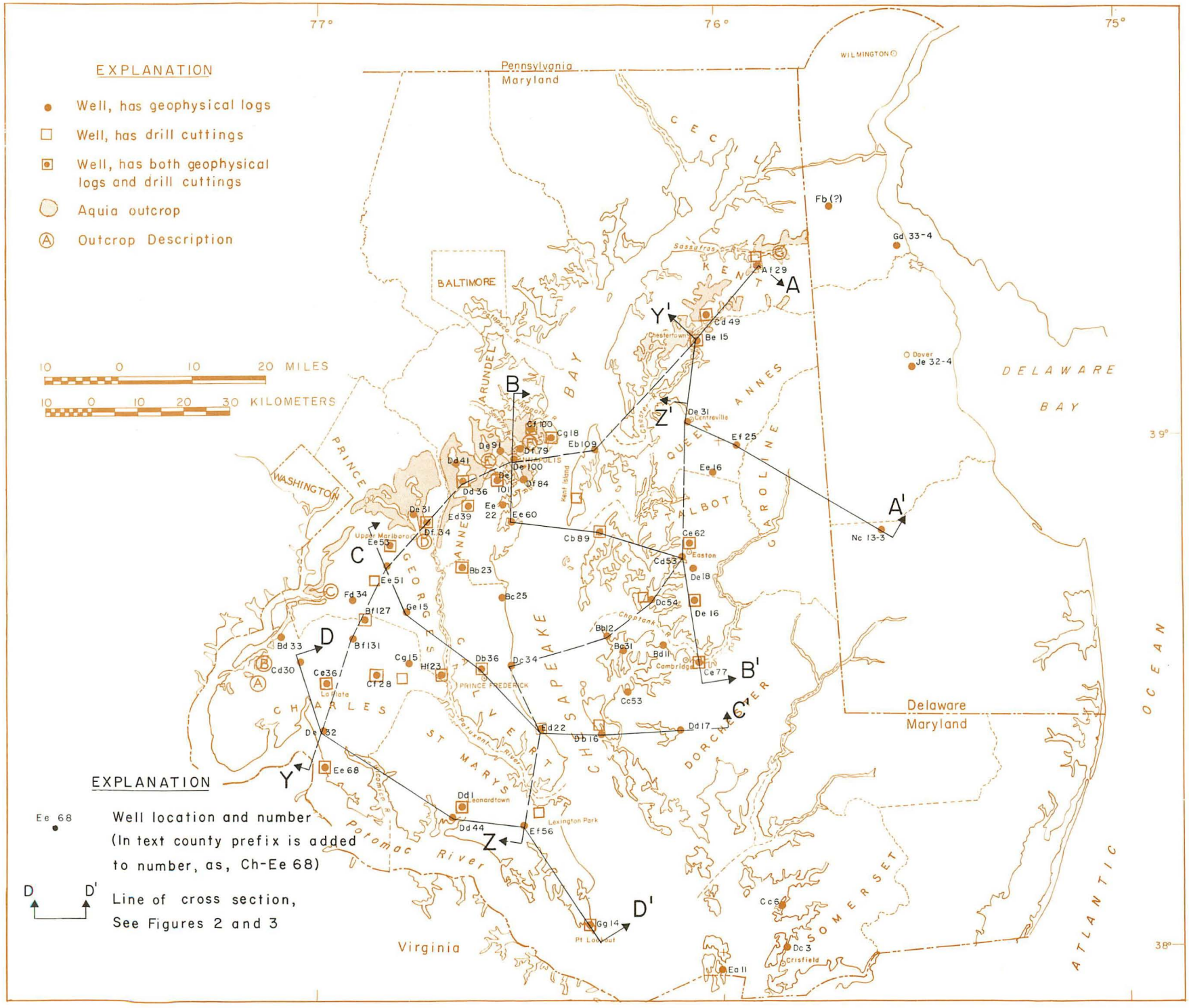


Figure 1.—Map showing generalized outcrop trend of the Aquia Formation and location of wells that penetrate the Aquia and have geophysical logs.

Series	Stage	Formations	Group
Eocene	Jackson	Piney Point	Pamunkey
	?		
	Claiborne	Nanjemoy	
	Upper Wilcox (Sabine)	Marlboro Clay	
	?		
Paleocene	Lower Wilcox		
		Aquia (Greensand)	
	Upper Midway		
	Lower Midway	Brightseat	

In addition to the stratigraphic-paleontologic studies undertaken to fix the Aquia Formation within the geologic time scale, other investigations have focused on the sedimentary aspects of the of the unit, notably those of Drobnyk (1965) and Glaser (1971). Both document in some detail Clark's original suggestion (1901, p. 57) that the Aquia sands, particularly in the quartz fraction, tend to coarsen northeastward along the outcrop belt. The sands are chiefly quartzose with glauconite ranging between 5 and 70 percent, but usually less than 50 percent. Lesser amounts of feldspar, muscovite, phosphate pellets, calcite and clay-silt aggregates are reported. Foraminiferal sands are very rare, molluscan coquinas less so. The heavy minerals are chiefly black opaques with ilmenite predominating. Other heavy minerals commonly reported include staurolite, garnet, chloritoid, tourmaline, zircon, and kyanite.

Environmental reconstructions are somewhat vague chiefly because textural and mineralogic patterns mapped in outcrop have not been extended into the deeper subsurface. Nonetheless, important generalizations have been made; as Drobnyk (1965, p. 626) comments:

> "The Aquia was probably deposited in inner neritic marine waters where generally slow rates of deposition varied from time to time.. Irregularities in the coastline and changing patterns of current activity resulted in deposition of sediments with varying texture and and mineralogy (note: Drobnyk illustrates this with three lithofacies maps).
>
> "Continuous shoaling during Aquia deposition culminated in the deposition of the pink Marlboro Clay . . . in brackish water."

Along similar lines Nogan (1964, p. 5) notes:

> "Paleoecologic analyses indicate that the Brightseat Formation, the Aquia Formation and the . . . (Marlboro Clay) . . . were deposited in a gradually shoaling sea. The Brightseat was deposited in water not exceeding 300 feet in depth, the Aquia in progressively shallower water and the (Marlboro Clay) in shallow brackish water."

The first attempt to describe the subsurface distribution of the Aquia Formation was made by Clark, Mathews, and Berry in 1918 as part of a general survey of ground-water usage in the State. Their discussions (pp.245-247) were necessarily based on sparse data and, as a consequence, several instances of miscorrelation occurred; more specifically, at several Eastern Shore localities, the Aquia was confused with younger Eocene sands now assigned by Rasmussen and Slaughter (1957) to the Piney Point Formation.

After the publication of the Clark *et al* volume, subsurface investigations remained fallow until after 1942 when a series of county-oriented ground-water projects were initiated. Several investigators, Overbeck (1948, 1951, 1958) in particular, carefully studied many sets of drill cuttings, thus providing the lithologic data necessary to erect a stratigraphic framework. Others contributing subsurface hydrogeologic data include Brookhart (1949), Meyer (1952), Ferguson (1953), and Otton (1955) for Southern Maryland; and Rasmussen and Slaughter (1955, 1957) for the Eastern Shore counties. Each of these reports usually provided annotated well logs, structure contour maps, potentiometric data, aquifer coefficients, and hydrochemical data. Isopach and lithofacies maps were generally absent and few environmental reconstructions were attempted. Later hydrogeologic reports such as those by Mack (1962, 1966); Mack, Webb, and Gardner (1971); and Weigle, Webb, and Gardner (1970) emphasized quantitative geohydrologic techinques. Nevertheless, their investigations contributed useful stratigraphic data because they employed extensively for the first time geophysical logs to develop local correlations. The author of this study has benefited greatly by having available to him the electric and gamma-ray logs obtained during the last decade by these workers.

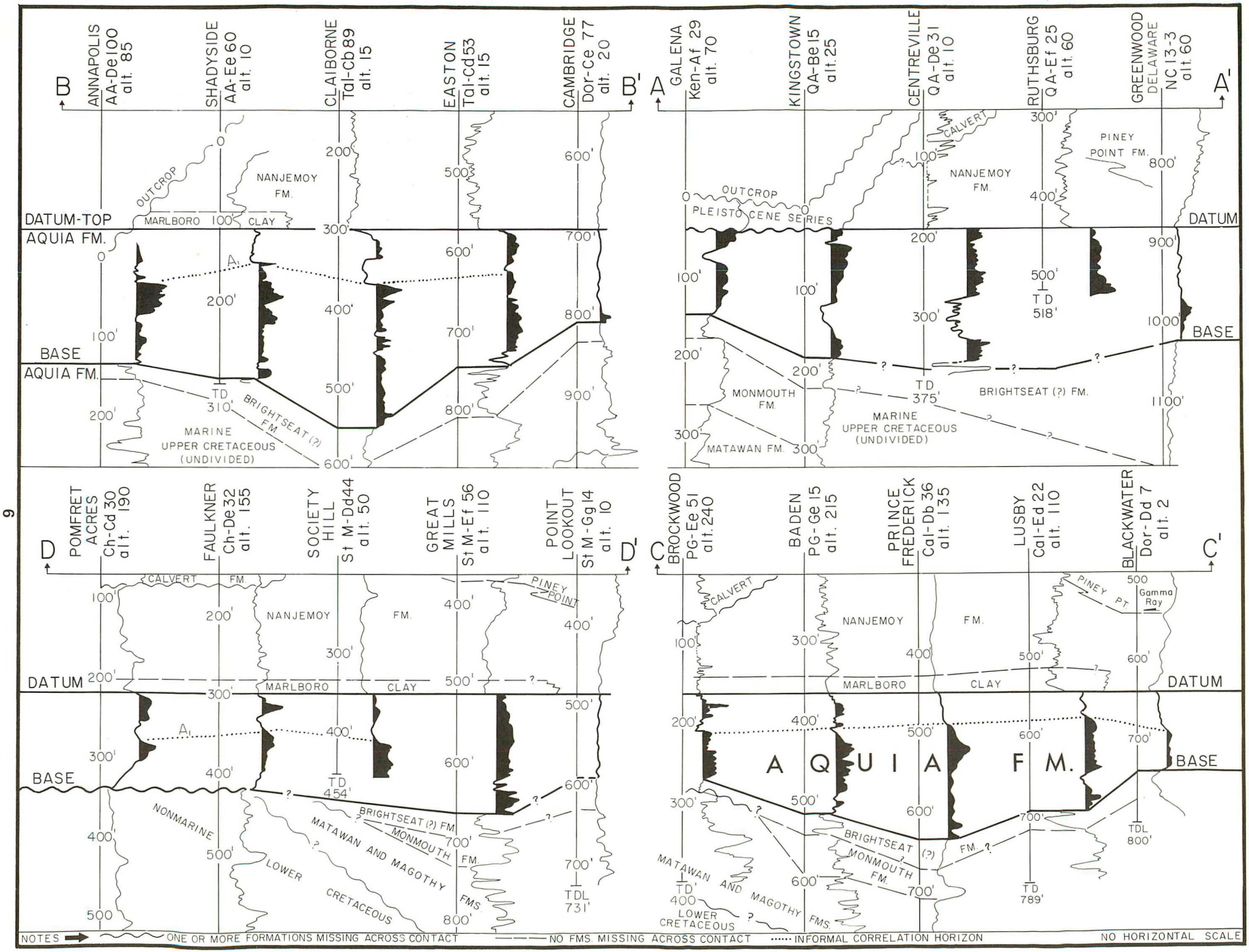


Figure 2.—Stratigraphic cross-sections A-A' through D-D'.

METHOD OF STUDY

Single-point resistivity logs, supplemented by gamma-ray logs, were used to establish an Aquia correlation grid across the Maryland Coastal Plain. In all, more than 50 wells were included in the grid. Figure 1 is a map locating the wells; also shown are the traverses of six stratigraphic cross-sections, included herein as figures 2 and 3.[1] Written logs and sample cuttings were also studied so that prominent "kicks" on the geophysical logs could be related to lithology in a broad sense. Both lithologic and informal geophysical marker beds, such as the Marlboro Clay or the "Al"-horizon (in figs. 2 and 3), were used to correlate from well to well. Inasmuch as no single Aquia marker bed is present across the entire Coastal Plain, other informal horizons were erected to "tie" the grid. Therefore, one can be reasonably sure that the Aquia beds depicted in figs. 2 and 3 have not been miscorrelated with either younger (Piney Point) or older (Monmouth) glauconitic sequences. In this report the beds defined as Aquia Formation represent an areally correlative lithostratigraphic unit, having identifiable upper and lower boundaries within which demonstrable facies changes occur. Marker beds serve to establish local time-stratigraphic relationships. Regional correlations using microfaunal data were not attempted. Thus time-lines defined paleontologically may not correspond in detail to the formational boundaries used in this report. Nevertheless, as Payne (1968, p. 2) observed for the Sparta Sand of the Gulf Coast, "correlations based primarily on electrical characteristics . . . define what may be considered . . . (a) . . . hydraulic system and give a consistent interval for the calculation of sand content of the system".

Thus the correlation grid serves a two-fold purpose: One, it defines the external geometry of the formation, thereby fixing its position within the wedge of Coastal Plain sediments which, in turn, facilitates the construction of cross-sections, structure contour, subcrop, and thickness maps. Two, the grid provides a consistent set of datum planes between which various textural and lithologic properties can be contoured to produce sand thickness, sand percentage, and lithofacies maps.

Geophysical logs were most useful for structure contouring and for broad lithofacies mapping based on the inflection point method of calculating sand-clay ratios (Lynch, 1962, p. 168). Drillers' logs provide additional information sometimes useful to map textural variations within sandy beds and to identify the occurrences of cemented or coquinoid strata. Drill cuttings are required to define mineralogical trends, such as glauconite-quartz percentages and the presence of goethite or phosphate pellets; also, cuttings serve as a useful check of the textural and lithologic inferences made on the basis of geophysical and (or) drillers' logs. Cores are necessary to identify bedding characteristics, such as burrowed zones, and to calculate such in situ parameters as permeability and grain fabric; very few Aquia cores were available to the author during the current study.

Nearly all the wells used in the Aquia correlation grid had, in addition to a geophysical log, a written driller's or geologist's log made at the well site. A few had more detailed mineralogic and textural descriptions based on a binocular microscope study of washed cuttings.

To supplement these data 28 new sample sets were described using estimation techniques modified after Ingram (1965, pp. 619-625). More precise, sieving and point count methods were not undertaken in view of the "homogenized" quality of cuttings retrieved from rotary-drilled bore holes. Sample intervals varied from well to well, ranging from consistent, 5- or 10-foot increments to erratic footages with gaps. Arenaceous samples were washed to remove drilling mud and other fines. Each sample was studied briefly with limited objectives in mind; estimates of the following parameters were recorded:

1) Percent ratio of detrital (chiefly quartz), authigenic (glauconite, goethite, phosphate),and biogenic (Foraminiferal, shell fragments) clasts.

2) Sand particle-size percentages in the detrital and authigenic fractions.

3) Goethite - glauconite ratios.

4) Occurrences of cemented strata, generally as calcareous aggregates and coquinoid debris.

5) Evidence of weathering, as either altered glauconite or iron-stained quartz.

Of the 28 sample sets studied 20 were part of the Aquia correlation grid (fig. 4). The remaining eight lacked geophysical logs, but were reasonably close to wells having them and could, therefore, be correlated into the grid with confidence.

[1] In figures 2 and 3, the wavy unconformity line is introduced only after a formation has been completely overlapped along the line of section and is, therefore, totally missing. Disconformable contacts, separating stratigraphically contiguous formations are not differentiated.

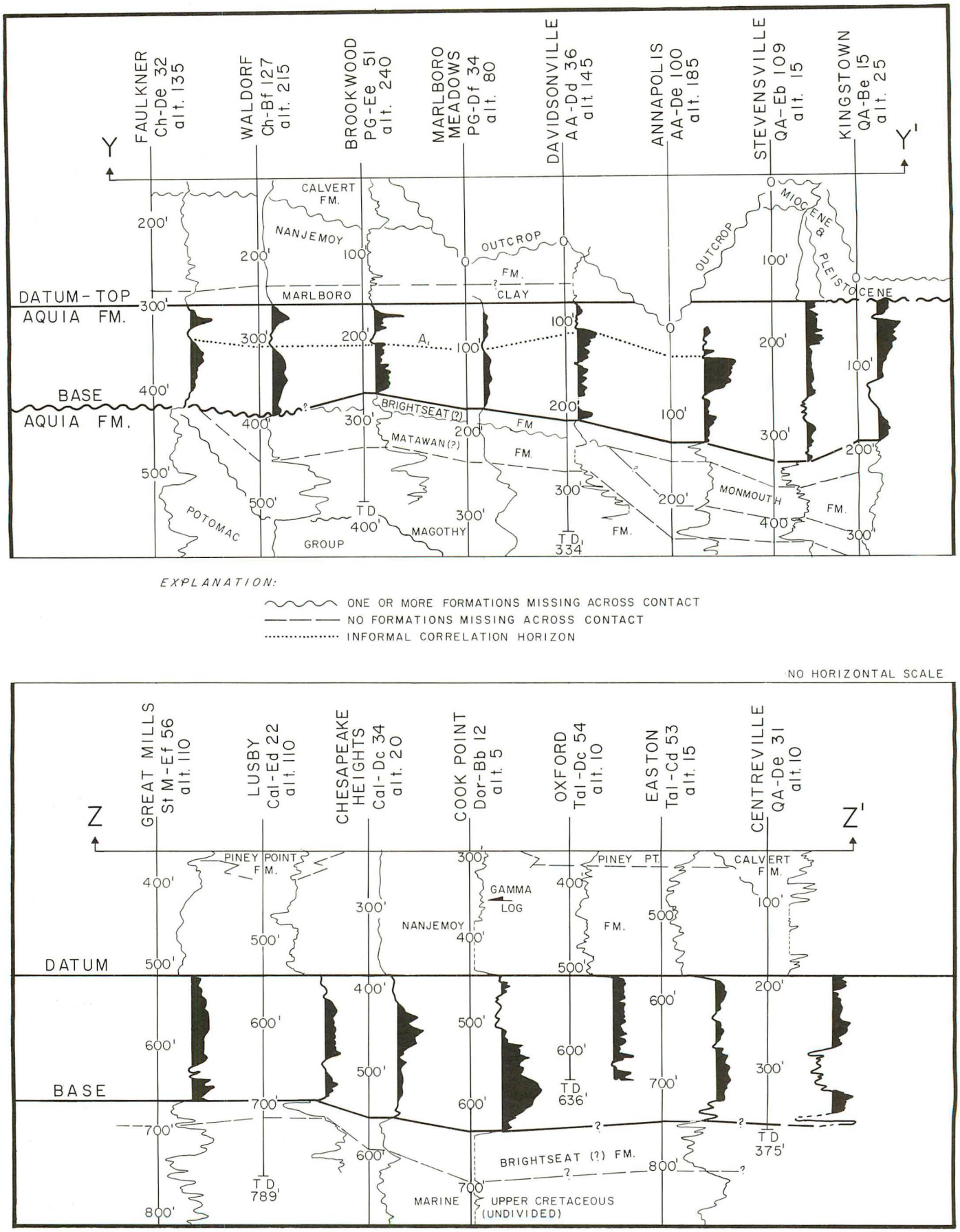


Figure 3.—Stratigraphic cross-sections Y-Y' and Z-Z'.

THE AQUIA OUTCROP

The Aquia Formation outcrops in Maryland as an irregular band extending from the Potomac River bluffs in western Charles County to the upper reaches of the Sassafras River in southeastern Cecil County (fig. 1). Fewer exposures of the Aquia Formation occur east of Chesapeake Bay where it subcrops beneath fluvio-estuarine deposits of Pleistocene and younger age (Cleaves and others, 1968).

The outcrop belt is quite narrow in southern Maryland, but flairs broadly between the western branch of the Patuxent River and the Magothy River in Anne Arundel County. Data from wells near outcrop suggest an accompanying increase in thickness, from 90 to 95 feet in Charles County. to 145 to 160 feet in Anne Arundel County.

Outcrops on the Eastern Shore are restricted to the bluffs bordering the Chester and Sassafras Rivers and their tributaries. Elsewhere the Formation subcrops beneath relatively thin (less than 50 feet) Pleistocene sediments. Wells near outcrop suggest an Aquia thickness comparable to that occurring in Anne Arundel County. However, because the Marlboro Clay, a marker bed, is absent from the Eastern Shore section, the possibility exists that the Aquia-Nanjemoy contact has been inadvertently shifted upwards; in which case, the Aquia Formation may appear somewhat thicker than it actually is, but probably by no more than 20 feet.

Drobnyk (1965) studied the petrology of the Aquia outcrop belt in Maryland, concentrating his sampling on exposures west of Chesapeake Bay. He concluded on the basis of sieve and hydrometric analyses that the formation coarsened and became better sorted northward along strike (fig. 5). Also, Drobnyk (1965, figs. 9-11) suggested that the formation became increasingly glauconitic in Kent and Cecil Counties where glauconite was believed to exceed 50 percent of the mineral content of the formation. While perhaps true for selected beds available for study in outcrop, subsurface data do not support this generalization entirely.

Glaser (1968, 1971) has recently published several newly measured Aquia sections from southern Maryland. They corroborate the textural inferences Drobnyk had made earlier. Glaser's sections from south to north follow; some details have been condensed (fig. 1).

A. Old Md. 224 near Rison, Charles County (Glaser, 1971, p. 69)

Upland Deposits:
Coarse gravel succeeded by loamy reddish sand . . . . . 6 ft

Nanjemoy (?) Fm.:
Pale-gray, fine-grained clayey sand, reddish-brown in upper part, impressions of small bivalves throughout 7

Sand as above, very clayey, transitional into clay below, shell impressions, burrows, and lignite fragments 2

Marlboro Clay:
Steel-gray, plastic clay 4

AQUIA FM.:
Fine-grained, greenish-brown sand, sparsely glauconitic 42

B. Md. 224 near Mason Springs, Charles County (Glaser, 1968, p. 43)

Nanjemoy (?) Fm.:
Sand, fine-grained, silty, micaceous, very sparingly glauconitic, mottled reddish-brown iron-oxide crusts near top, casts of pelecypods near base 10

Marlboro Clay:
Clay, plastic, sticky; silvery to medium-gray to pinkish brown; bears lignite as well as chips and twigs; sporadic tubular burrows filled with fine glauconite; rare impressions of small pelecypods 14

AQUIA FM.:
Sand, fine-grained, sparsely-glauconitic; pale-gray to greenish gray, brownish mottles in upper protion; upper 5 inches yellow-brown silty micaceous clay containing scattered gypsum casts 10

Sandstone, fine to medium-grained, calcite-cemented rare glauconite, medium gray; abundantly fossiliferous; *Turritella mortoni* in large numbers 1½

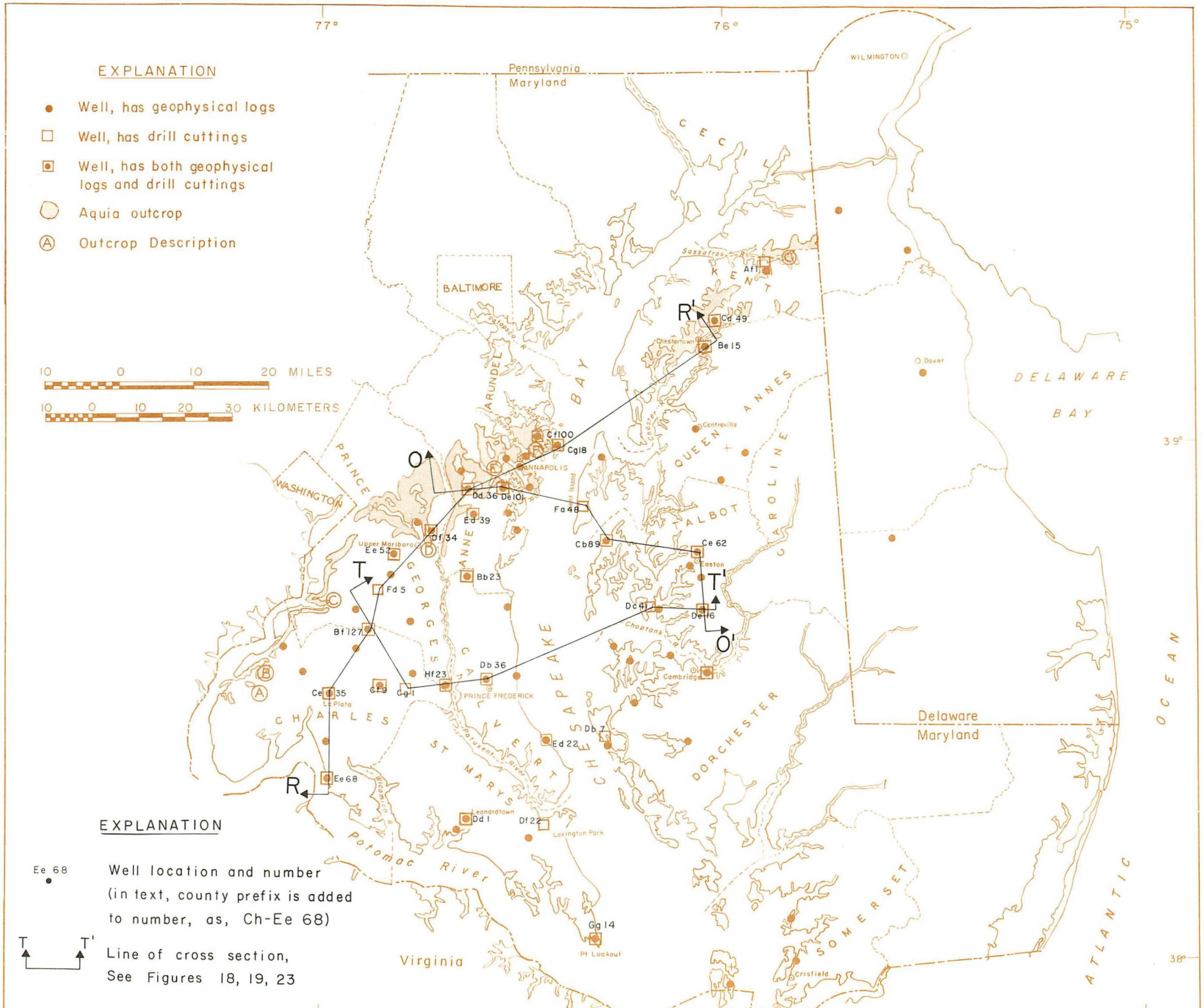


Figure 4.—Location map showing wells that penetrate the Aquia Formation and have drill cuttings.

C. Piscataway Creek near intersection with Md. 210, Charles County (Glaser, 1968, p. 41).

AQUIA FM.:
Sand, fine to medium-grained, argillaceous, glauconitic; gray-green; patchy calcite cementation; fossiliferous; with *Turritella mortoni* most abundant 15

Sandstone, pale, brownish-gray, calcite-cemented; sparsely fossiliferous 2

Sand, fine to medium-grained, argillaceous; mottled pale-brown and gray-green; abundantly fossiliferous; shells much decomposed . . 18

The following series of measured sections which were compiled by several earlier workers, traverses Prince George's, Anne Arundel and Kent Counties. Note the coarsening of the Aquia sands and the persistence of cemented strata.

D. Md. 202 near Md. 408, Prince George's County (Overbeck, 1950, p. 29).

Nanjemoy Fm.:
Glauconitic clay 22

Marlboro Clay
Pink clay 22

AQUIA FM.:
Coarse, glauconitic sand; 35-40 percent glauconite; limonite concretions 32

Shell marl; abundant fossils 2

Indurated ledge; abundant fossils 5

Glauconitic sand; shell fragments including bryozoa, echinoid spines, and Foraminifera . 5

E. Bluffs at confluence of Broad Creek and South River, Anne Arundel County (Little, 1916, p. 85).

AQUIA FM.:
Ferruginous sandstone full of casts of *Turritella mortoni*, *Venericardia "planicosta"*, *Bathytormus alaeformis* 10

Coarse, oxidized greensand, with occasional casts of *Venericardia planicosta* 24

Talus 24

F. Bluffs along north bank of Severn River 1 mile north of railroad bridge, Anne Arundel County

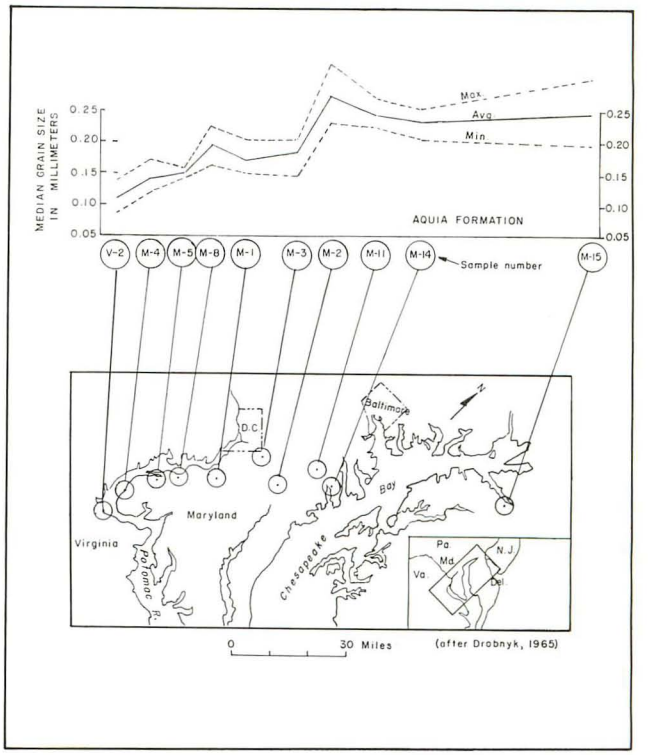


Figure 5.—Diagram showing increase in grain size of the Aquia Formation from southwest to northeast (after Drobnyk, 1965, fig. 1, 2).

(Little, 1916, p. 85).

Pleistocene:
Sand and loam 5

AQUIA FM.:
Coarse red, glauconitic sand; partly indurated; with *"Ostrea compressirostra"*, *Cucullaea gigantea*, *Pitar ovatus*, *Turritella mortoni* . . . 20

Red glauconitic sand and talus 50

G. Wilson Point on the Sassafras River, Kent County (Miller, 1926, p. 72).

Pleistocene:
Coarse, brown sand, very compact, containing isolated gravel lenses 11

AQUIA FM.:
Coarse, glauconitic sand; upper part intensely green and lower 5 to 8 feet lighter in color, somewhat consolidated 27

Structure

In large measure the subsurface structure of the Aquia Formation reflects deeper, basinal patterns associated with the axial parts of the Chesapeake-Delaware Embayment, a major depocenter beneath the modern Middle Atlantic bight (Maher, 1971; Kraft and others, 1971) (fig. 6). A series of contour maps drawn on top of several Cretaceous and lower Tertiary formations characteristically shows a shift in strike from predominantly NE beneath the upper Eastern Shore to nearly N-S beneath Southern Maryland (Otton and others, 1969). A generalized contour map drawn on the top of the Aquia Formation conforms to this sculpturing (fig. 7). Dips measured normal to strike between Chestertown in Kent County and Denton in Caroline County average about 25 feet per mile. On the western shore dips are less. For example, between Upper Marlboro and Chalk Point, dips average slightly less than 20 feet per mile; the gradient decreases noticeably, however, from Chalk Point southeastward to the mouth of the Patuxent River, averaging only about 10 feet per mile. To some extent this change in gradient is due to an elongated thickening of the formation which extends southward from outcrop in Anne Arundel County to the deeper subsurface beneath Calvert County and central St. Mary's County (fig. 8). Note, however, that as the formation thins eastward between Lexington Park in St. Mary's County and Crisfield in Somerset County an accompanying increase in dip occurs.

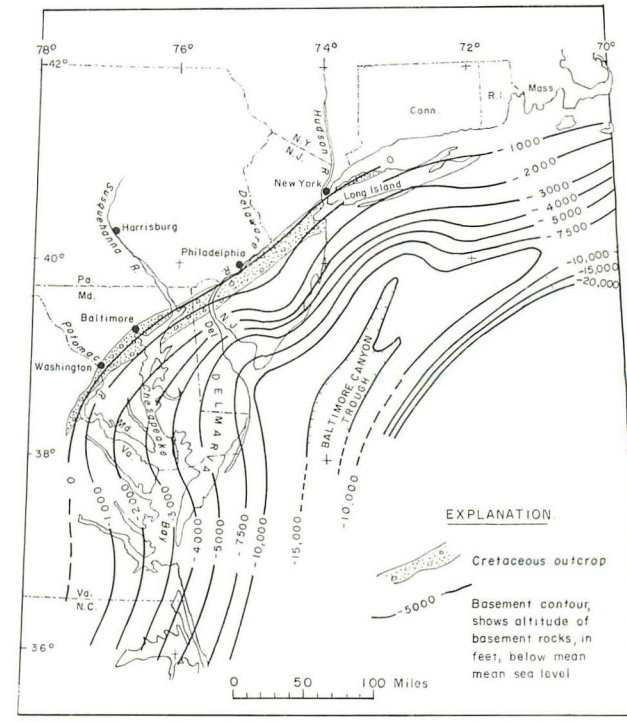


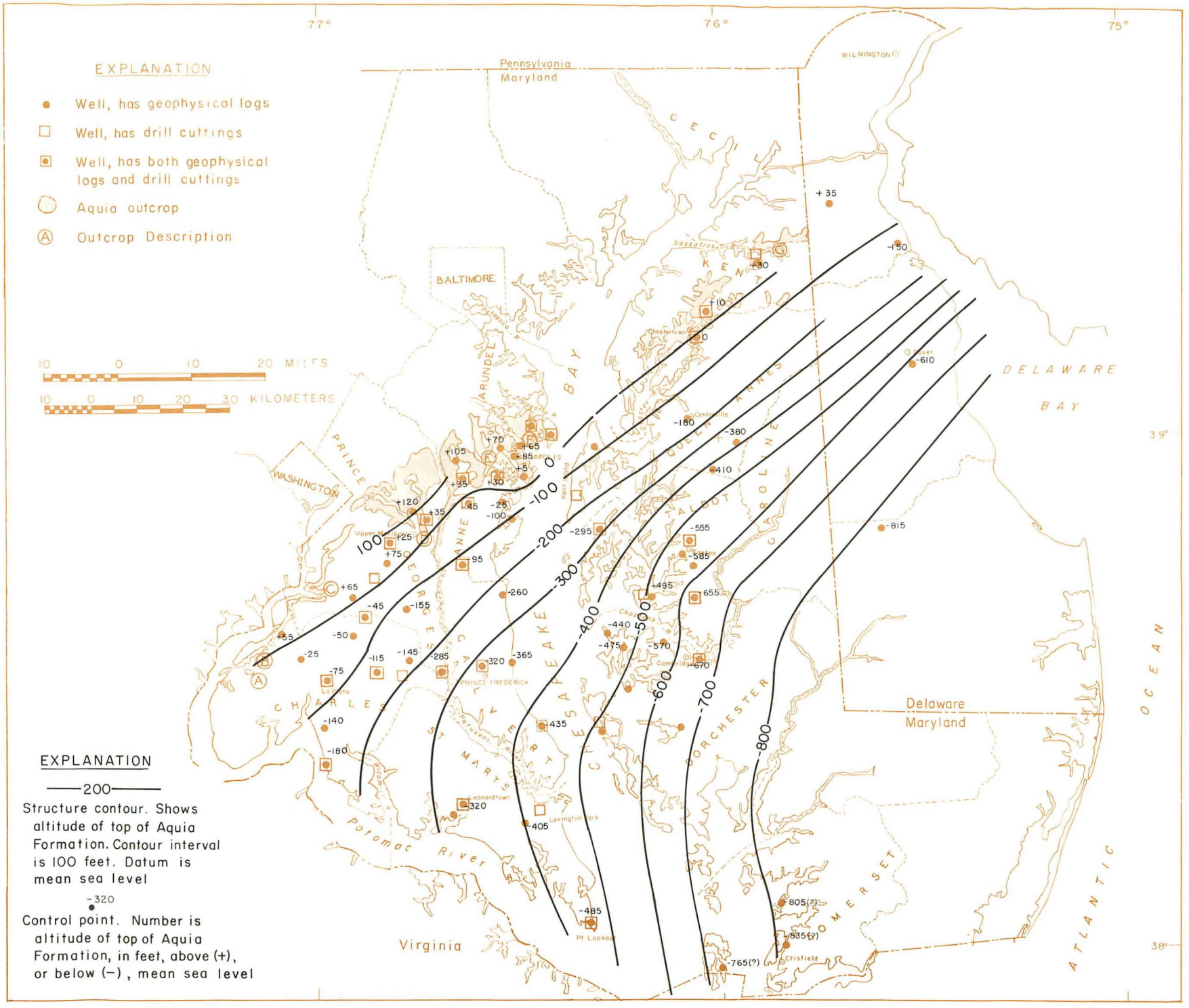
Figure 6.—Map showing extent of Chesapeake-Delaware Embayment (after Maher, 1971, pl. 3).

Thickness

In outcrop the Aquia thins from central Prince George's County (140 feet) southward to the Potomac River (90 feet). On the Eastern Shore the Aquia outcrop is poorly exposed beneath Pleistocene overburden, but probably is comparable in thickness to the well exposed Anne Arundel County section (150 feet).

Contoured well data are shown in figure 8, a thickness (isopach) map. In Southern Maryland the isopach lines diverge obliquely from outcrop and extend deep into the subsurface. The thickest part of the Formation occurs as an irregularly shaped pod and, as defined by the 200-foot line, extends from central Queen Anne's County to perhaps northern Calvert County. The thickest, fully penetrated, Aquia section occurs beneath Claiborne (Tal-Cb 89) where it is 240 feet thick (fig. 2, 3, 8). It is about 190 feet thick at both Shadyside in Anne Arundel County (AA-Ec 60) and at Stevensville in Queen Anne's Coutny (QA-Eb 109). In Southern Maryland the thickest part of the Aquia underlies portions of Prince George's County (Chalk Point), Calvert County (Prince Frederick and Lusby), and St. Mary's County (Great Mills). Westward across Charles County the Formation thins from 185 feet at Hughesville to 95 feet at Pamunkey near its outcrop. As a consequence, the thickness lines, which subparallel the outcrop belt on the Eastern Shore, swing sharply oblique to it in Southern Maryland.

Downdip the Aquia Formation thins as it changes to an argillaceous, outer shelf facies. In figure 2 the wells at Greenwood, Delaware (NC 13-2), Cambridge (Dor-Ce 77), Blackwater (Dor-Dd 7) and Point Lookout (StM-Gg 14) demonstrate this eastward thinning of the Aquia section.



EXPLANATION

—200—

Structure contour. Shows altitude of top of Aquia Formation. Contour interval is 100 feet. Datum is mean sea level

-320

Control point. Number is altitude of top of Aquia Formation, in feet, above (+), or below (−), mean sea level

Figure 7.—Structure contour map of the Aquia Formation in Maryland.

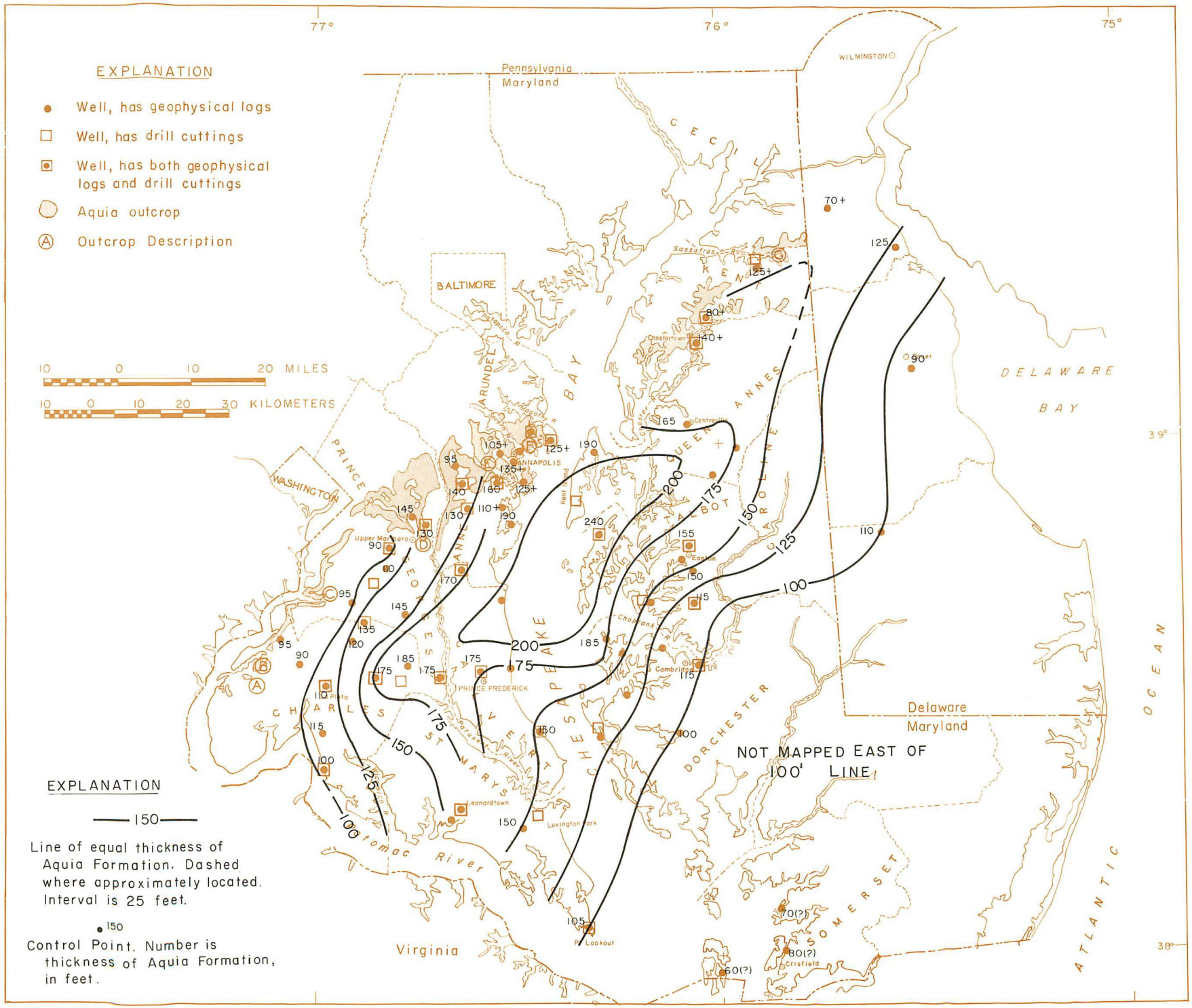


Figure 8.—Isopach map of the Aquia Formation.

Stratigraphic Boundaries

Updip (Outcrop): Beginning at the Potomac River and trending northeastward to the Patuxent River, the outcropping Aquia Formation is often mantled by thin, coarse-textured Quaternary deposits (Glaser, 1971, plate 1). In valley areas, where both formations are water saturated, they form a single hydrostratigraphic unit (as defined by Maxey, 1964). Between the Patuxent River and the Chesapeake Bay the Aquia outcrops in a broad band which reaches a maximum width of 11 miles (Cleaves and others, 1968). Except for the alluvial sediments associated with the present drainage system, this area generally lacks the extensive surficial cover of Quaternary deposits characteristic of more southerly terrains. Isolated outliers of the Calvert Formation (Miocene) do, however, cap several upland areas where they unconformably rest on Aquia sediments (Darton, 1951, p. 761).

The Aquia Formation is present beneath Chesapeake Bay and is overlain unconformably by Quaternary sediments. Mantling Pleistocene and Holocene deposits range in thickness from 10 to over 100 feet; the deposits are texturally variable, fining upwards from basal sands and gravels to semi-liquid silts and clays at the water-sediment interface (Ryan, 1953, plate 2).

Coarse Quaternary alluvium mantles the subcropping Aquia Formation across the Upper Eastern Shore, forming a single hydrostratigraphic unit (Overbeck, 1958, p. 79). Thin wedges of Calvert Formation are reportedly encountered along the subcrop belt of the Aquia. Like the Calvert outliers on the Western Shore, these occurrences document a major Miocene overlap. The Nanjemoy Formation, which usually overlies the Aquia, is truncated in the subsurface and apparently does not outcrop on the Upper Eastern Shore (Cleaves and others, 1968). Recent mapping suggests, however, that the Nanjemoy may outcrop on Kent Island in westernmost Queen Anne's County (oral comm., J. P. Owens).

Downdip (Facies Change): As is characteristic of many marine shelf units, the Aquia Formation exhibits a seaward (eastward) decrease in both total and sand thickness (figures 8, 9). East of the 50-foot sand thickness line the Aquia Formation is no longer considered an aquifer, inasmuch as the sands have both thinned and become finer-textured. On the cross-sections depicted in figure 2 wells NC 13-3, Dor-Ce 77, Dor-Dd 7, and StM-Gg 14 illustrate these trends. The facies change is not abrupt and in a hydrologic sense defines a transmissivity gradient, rather than a barrier.

Lower Contact (Unconformity): Using outcrop data Minard and others (1969) have mapped a regional unconformity at the base of the Paleocene section. They have demonstrated (1969, fig. 5) that several of the Upper Cretaceous beds occurring beneath the unconformity are successively truncated from New Jersey to the upper Eastern Shore of Maryland. This unconformity is extended southward in figure 3 (cross-section, Y-Y') which is a stratigraphic cross-section trending from Kingstown, Queen Anne's County to Faulkner in Charles County. It shows the Aquia and Brightseat Formations overlapping successively older beds. At Faulkner Paleocene strata rest directly on beds of the Lower Cretaceous Potomac Group.

Jordan (1963, p. 195), citing foraminiferal and lithologic data from wells at Dover, Salisbury, and other localities on the lower Eastern Shore, suggested that the Cretaceous-Tertiary contact was conformable. Much of his data were from sites at or near the depositional axis of the Salisbury Embayment where marine sedimentation was certainly more continuous than along the margins of the basin now revealed in outcrop. One indication of this is the expanding Brightseat section shown on A-A' (fig. 2) between Kent County, Maryland and Greenwood, Delaware.

In figure 10, between outcrop and the 25-foot sand thickness line, the Aquia Formation usually overlies a finer-textured unit herein identified as the Brightseat Formation. This unit is consistently correlative in the subsurface (e.g., as a high "kick" on gamma-ray logs) and appears to be the geophysical analog of the Brightseat Formation described in outcrop by Bennett and Collins (1952) and Hazel (1969) (fig. 10). Because, however, the type Brightseat is to a large extent paleontologically defined, equivalence with the subsurface unit may not be exact. In the outcrop belt southwest of Washington, Hazel (1969, fig. 2) has mapped the Aquia Formation successively overlapping older Brightseat, marine Cretaceous, and Potomac Group beds. There the stratigraphic relationships can be traced into the subsurface to a line at least as far downdip as cross-section Y-Y', where

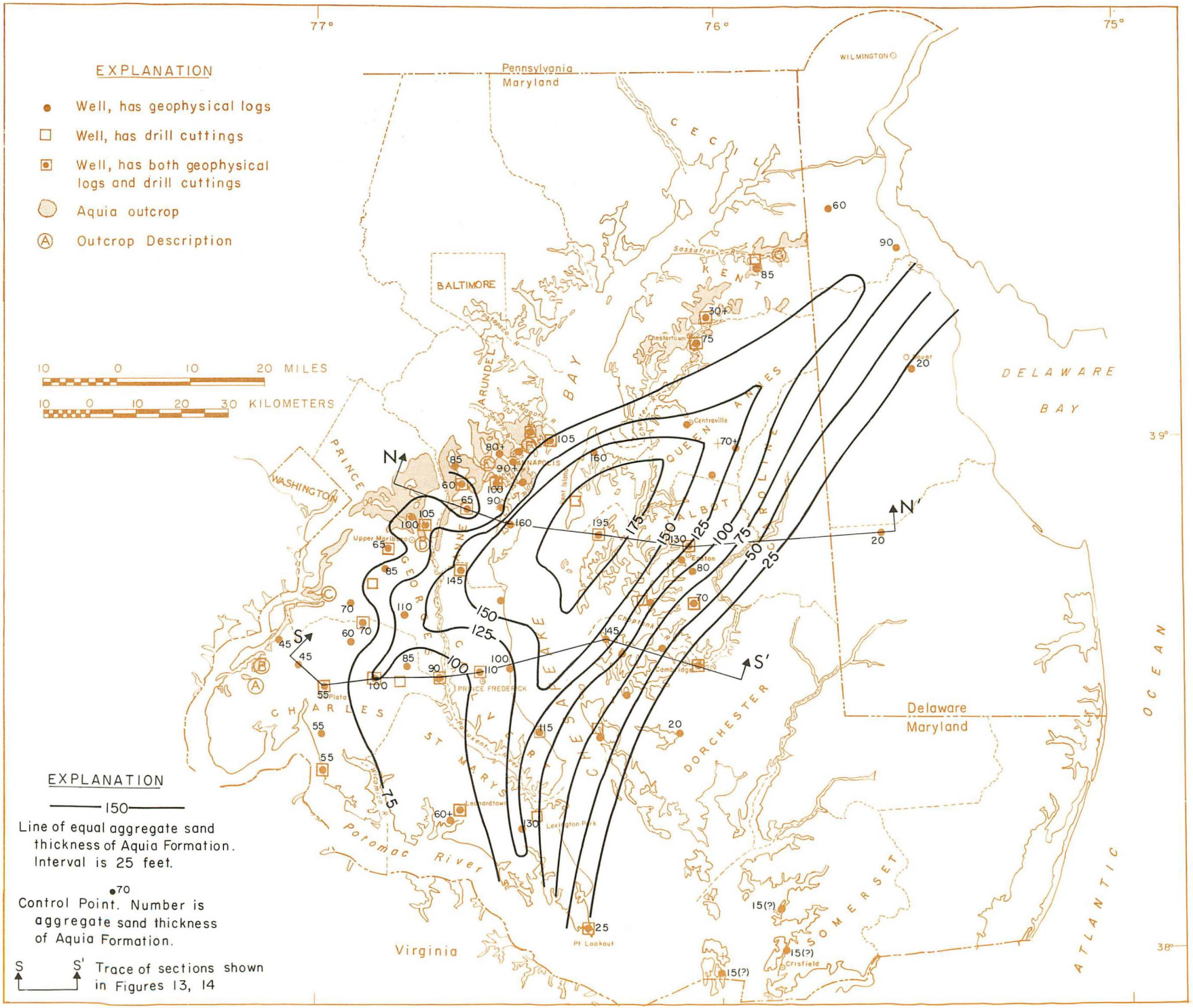


Figure 9.—Sand thickness map of the Aquia Formation using geophysical log data.

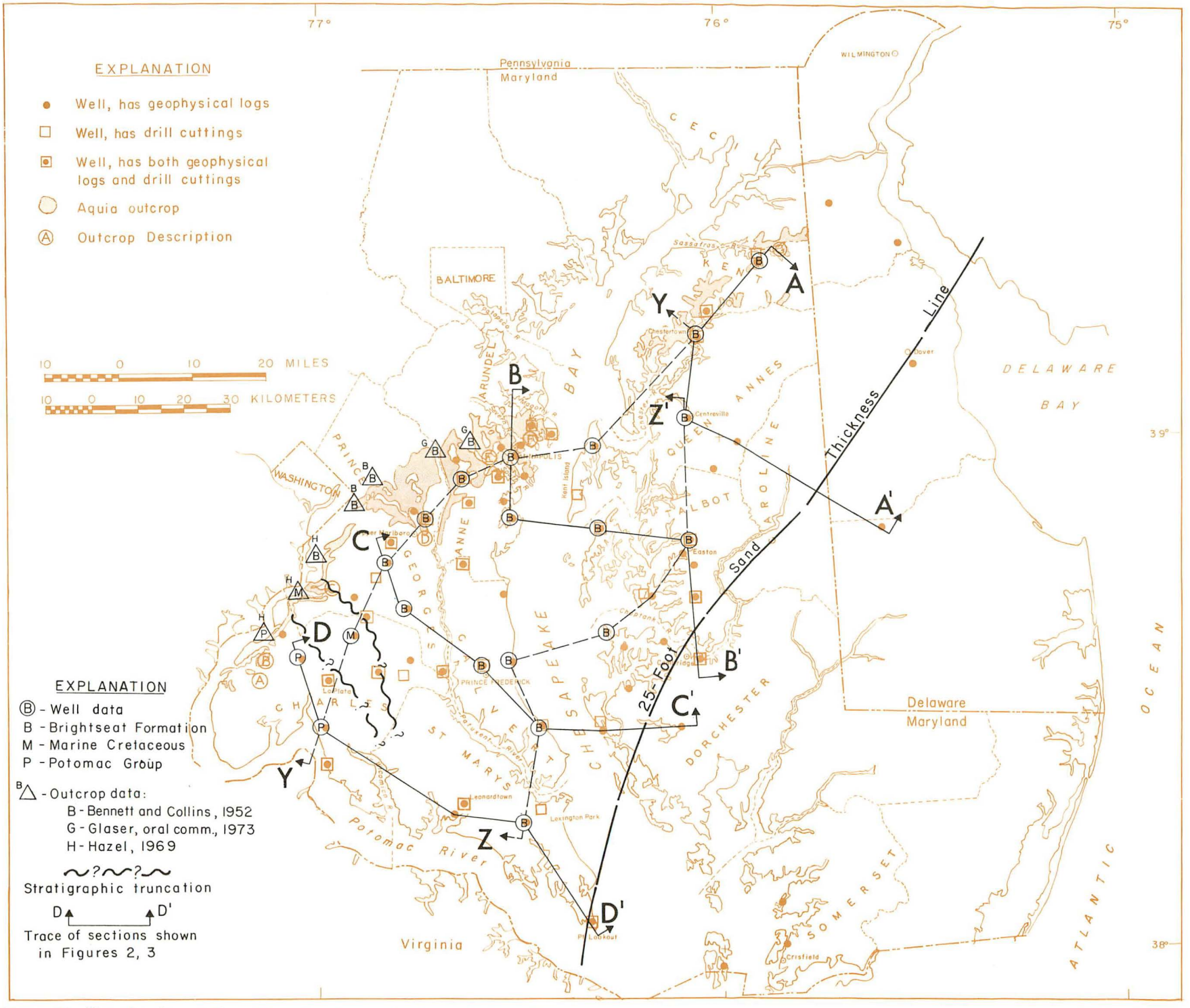


Figure 10.—Map showing stratigraphic units sub-cropping beneath Aquia Formation.

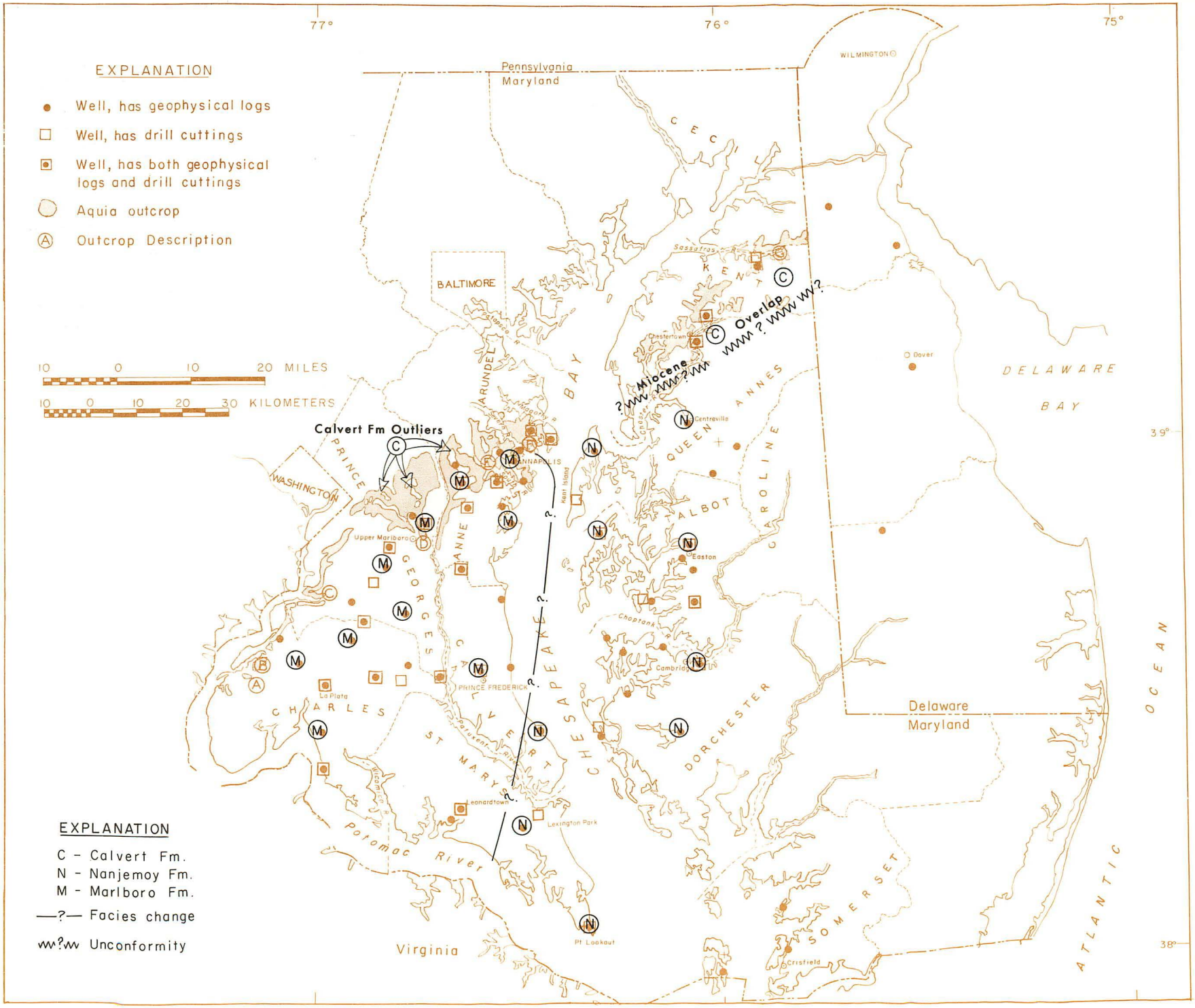


Figure 11.—"Worm's eyeview" map showing formations overlying Aquia Formation.

at Faulkner (Ch-De 32) and Waldorf (Ch-Bf 127) the Aquia rests on beds assigned to the Potomac Group and marine Cretaceous respectively (fig.3, 10). Deeper into the subsurface, at localities such as Great Mills (StM-Ef 56) and Lusby (Cal-Ed 22), a thin wedge of Brightseat strata underlies the Aquia Formation. Cross-section Z-Z' (fig. 3) suggests that this stratal sequence can be correlated with similar beds occurring along strike at Cook Point (Dor-Bb 12) and Easton (Tal-Cd 53) beneath the Eastern Shore.

Although the distribution of the Brightseat Formation is imperfectly mapped, some general conclusions from the correlation network can be stated:

1) Between outcrop and the 25-foot Aquia sand thickness line the Brightseat Formation ranges in thickness from a feather's edge to about 60 feet.

2) The Brightseat Formation functions as the lower confining bed for the Aquia aquifer except in parts of southern Prince George's County and western Charles County where it pinches out between the base of the Aquia and the truncated edges of succesively older Cretaceous beds.

Upper Contact (Conformable): Over much of the Coastal Plain the Aquia Formation is overlain by either the Nanjemoy Formation or the Marlboro Clay, which is a restricted basal lithofacies of the Nanjemoy (fig. 11). The contact as viewed in outcrop ranges from gradational to slightly disconformable. Thus Glaser (1971, p. 13) notes for the general Southern Maryland case:

> "This contact in updip exposures probably records a minor hiatus since the uppermost few inches of Aquia sand are limonite-cemented and contain gypsum casts. Downdip, however, the same contact is marked by a transition zone several inches thick of interlaminated glauconitic sand and silvery-gray Marlboro Clay."

Insofar as the Marlboro Clay is missing from southernmost Calvert and St. Mary's Counties, as well as the Eastern Shore, a generalized facies boundary trending north-south can be drawn as depicted in figure 11. The pinkish, mud-flat clays and silts of the Marlboro are characteristic of the areas west of the line; eastward of it gray-green, open shelf sediments of the basal Nanjemoy Formation overlie the Aquia Formation (fig. 2).

West of the Chesapeake Bay the Miocene overlap is evidenced only by a series of outliers which rest upon successively older sediments (Darton, 1951). Recent erosion has stripped away the bulk of Miocene sediments, thereby allowing the truncated edges of older Tertiary units to outcrop.

East of Chesapeake Bay in Kent and northern Queen Anne's County the Miocene Calvert Formation rests directly on the Aquia Formation (fig. 11). Nanjemoy beds are truncated in the subsurface and, apparently, do not crop out, except perhaps on the Kent Island. Downdip they begin to wedge into the section and are believed to be present at Centreville (QA-De 31) and Stevensville (QA-Eb 109) (fig. 3).

On the Eastern Shore and in Southern Maryland the Aquia outcrop belt is often mantled by a veneer of Quaternary sand and gravel, forming a single hydrostratigraphic unit utilized by shallow wells.

Selected Facies Trends

Subsurface data, usually in the form of geophysical logs, lithologic logs made at the well site, and drill cuttings (ditch samples), are sufficiently available in Maryland to map broad Coastal Plain facies trends. Although the applicability of each type of data is limited, a combination of the three often provides the necessary lithologic and mineralogic data to map lithofacies and, in turn, define ancient sedimentary environments. For example, electric logs are particularly useful for constructing sand percentage maps and sand thickness maps. Well-site logs record additional information sometimes useful for mapping textural variations in sand beds, as well as for identifying more unique strata such as cemented or coquinoid layers. Drill cuttings are required to define mineralogic trends, such as the glauconite/quartz + glauconite ratio, and to establish the presence of environmental indicators such as goethite or phosphate pellets.

Sand Distribution: Using electric-log data from the correlation grid, sand thickness and sand percentage maps were constructed (figs. 9, 12). Both bear a strong resemblance to the Aquia thickness map (fig. 8), suggesting that stratigraphic thickening of the Aquia interval is accomplished by a build-up of its sandy facies. Like the thickness map, the lines drawn in figures 9 and 12 increasingly diverge from the Aquia outcrop belt as they swing from NE to N. Such a configuration implies strongly that post-Eocene tilting has caused the Aquia outcrop belt to trend obliquely across the original depositional strike of the Formation.

A downdip build-up of sand in the Aquia Formation can be readily seen in cross-sections N-N' and S-S' (figs. 13, 14), which use the base of the formation as datum. Both sections are normal to the depositional strike of the Aquia. Sand build-ups are exhibited in wells Cal-Dd 36 (Prince Fred-

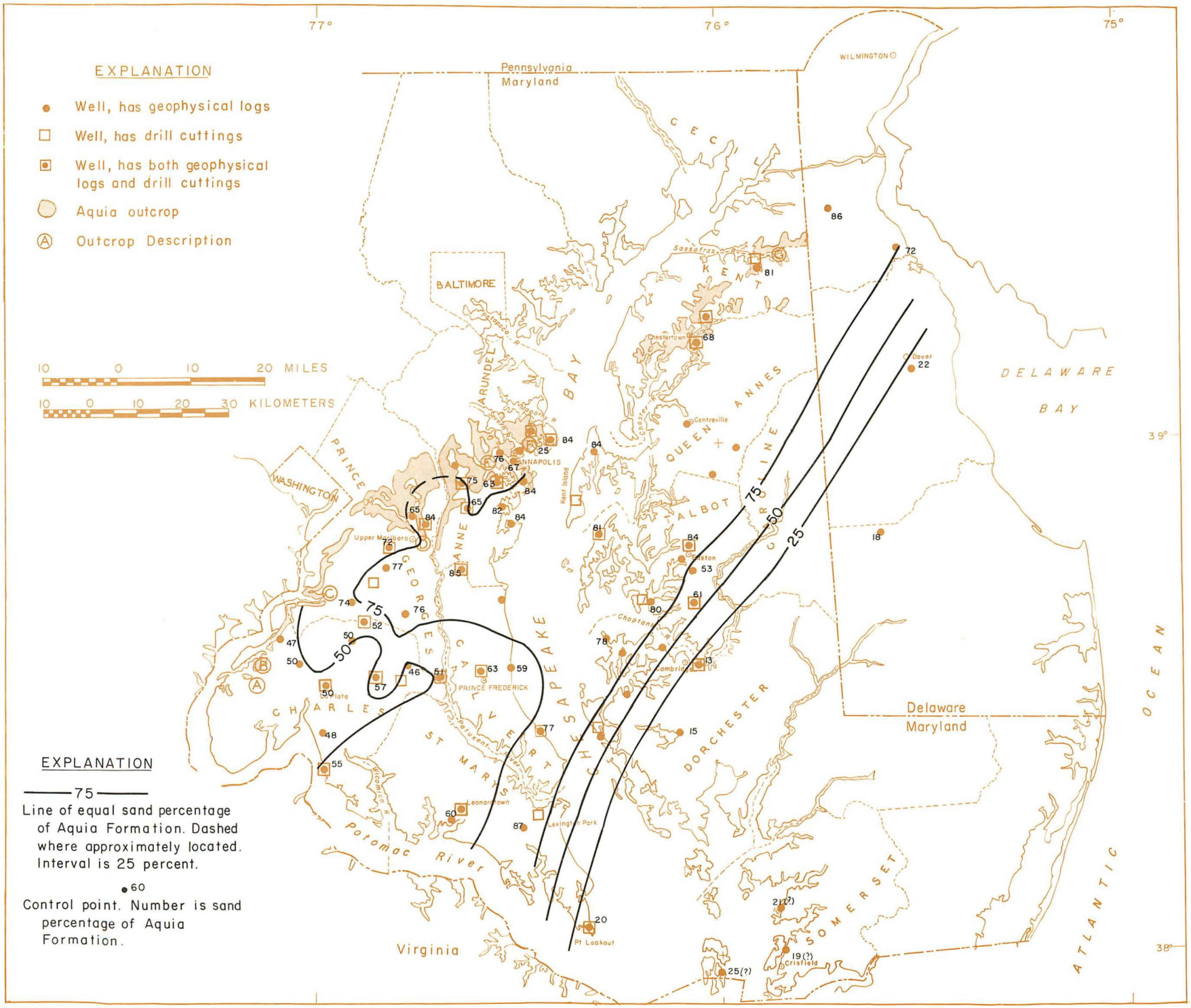


Figure 12.—Sand percentage map of Aquia Formation using geophysical log data.

erick), Dor-Bb 12 (Cook Point), AA-Ee 60 (Shadyside), Tal-Cb 89 (Claiborne), and Tal-Cd 53 (Easton). Updip from these sites, as depicted along cross-sections N-N' and S-S' (figs. 13, 14), the Aquia thins and becomes less sandy. Strata in wells at Pomfret (Ch-Cd 30), La Plata (Ch-Ce 36), and Harwood (AA-Ed 39) are examples. Downdip the formation also thins by grading into a predominantly finer-grained outer shelf facies as, for example, at Greenwood, Delaware (NC 13-3) and Cambridge (Dor-Ce 77).

Drillers' logs were also used to construct subsurface thickness and lithofacies maps of the Aquia Formation. The data depicted in these maps were used to corroborate thickness and sand thickness trends defined previously using geophysical logs.

Sand Texture: Drillers' logs were used to gain a first approximation of the textural trends occurring within the sandy facies of the Aquia. Figure 15 is a map of the percentage of Aquia sands described as being either medium or coarse-grained. A comparison of figures 8 and 15 demonstrates that the thickest part of the Aquia Formation coincides approximately with the areal distribution of its coarsest-grained facies. This association is common in modern marine sediments and is usually attributable to such constructual sedimentary features as sand bank complexes and offshore bars.

In southern Prince George's County and in Charles County Aquia sands are typically described as fine or very fine in drillers' logs. This is consonant with outcrop descriptions from the area. Coarser textured sands are encountered both northeastward along the erosional strike and southeastward, down the dip; within this facies of the Aquia Formation medium- to coarse-textured sands described in the drillers' logs usually exceed 75 percent of the arenaceous section. Typical sections are recorded at Prince Frederick (Cal-Dd 36) and Lusby (Cal-Ed 22) in Calvert County and at Claiborne (Tal-Cb 89) and Easton (Tal-Cd 53) in Talbot County (figs. 13, 14). Eastward (seaward) thin, fine to very fine-textured sands wedge into a predominantly argillaceous section.

Washed drill cuttings were inspected to corroborate the sedimentary patterns inferred from the drillers' logs. Figure 16 depicts footages in which medium or coarse sand constitute more than 50 percent of the sample. In their general configuration figures 15 and 16 are similar and reenforce the existence of sedimentary patterns already established by other means. As is common with lithologic data from rotary drilled holes, differences in detail occur; for example, washed cuttings from the Sandy Point (AA-Cg 18) and Kingstown (QA-Be 15) wells are coarser-textured than their drillers' logs had suggested. Nevertheless, the same tripartite facies pattern is again prominently displayed: these are 1, a thick, coarser-textured sandy facies extending southwesterly in outcrop from Kent County to about the Patuxent River valley where it swings south into the subsurface; 2, finer-textured sands and silts in Charles and southern Prince George's County; and 3, a thinner, very muddy facies that appears to underlie much of the Eastern Shore seaward of the Choptank River.

Figure 17 contains six well-cutting profiles that show vertical trends in several environmentally diagnostic parameters. Wells Ch-Ee 68 and Ch-Bf 127 are representative of facies 2 (as defined above); wells Cal-Dd 36, AA-De 101, and Tal-Ce 62 of facies 1, and well Tal-De 16 of facies 3.

The data presented in figure 17 suggest strongly that textural changes occur vertically within each facies. To gain an understanding of how these changes relate areally, several stratigraphic cross-sections were drawn oblique to the facies trends already established using geophysical log and drillers' log data. The parameter selected for delineating on the cross-sections is the percentage of quartz grains in each sample interval that is medium and (or) coarse-textured. The values were plotted using contours, rather than depicted more conventionally, because washed cuttings are at best composite samples useful for identifying textural trends. Clearly, the lines shown on figures 18 and 19 perform this function only and do not imply specific stratigraphic correlations.

Cross-section O-O' (fig. 18) defines a central pod-shaped accumulation of coarser textured detritus in which medium-coarse sands usually constitute at least 70 percent of the quartz fraction. This facies of the Aquia Formation coarsens rapidly upward from its base, maintains its texture with only minor fluctuations, and then exhibits a slight tendency to fine near its upper contact with the Marlboro Clay. Outward, in both directions, the central pod of coarse detritus grades into consistently finer grained sediments.

Cross-section R-R' (fig. 19) subparallels the present strike of the Aquia Formation and, like the measured outcrop sections discussed earlier, coarsens northward. The interdigitated pattern developed between Cheltenham (PG-Fd 5), Marlboro Meadows (PG-Df 34), and Davidsonville (AA-Dd 36) suggests that the landward side of the sand bank complex was very irregular, having recorded several minor transgressive-regressive events during Aquia sedimentation.

Sand Mineralogy: The Aquia sands are predominantly quartzose. In washed drill cuttings glauconite occurs ubiquitously, although rarely in excess

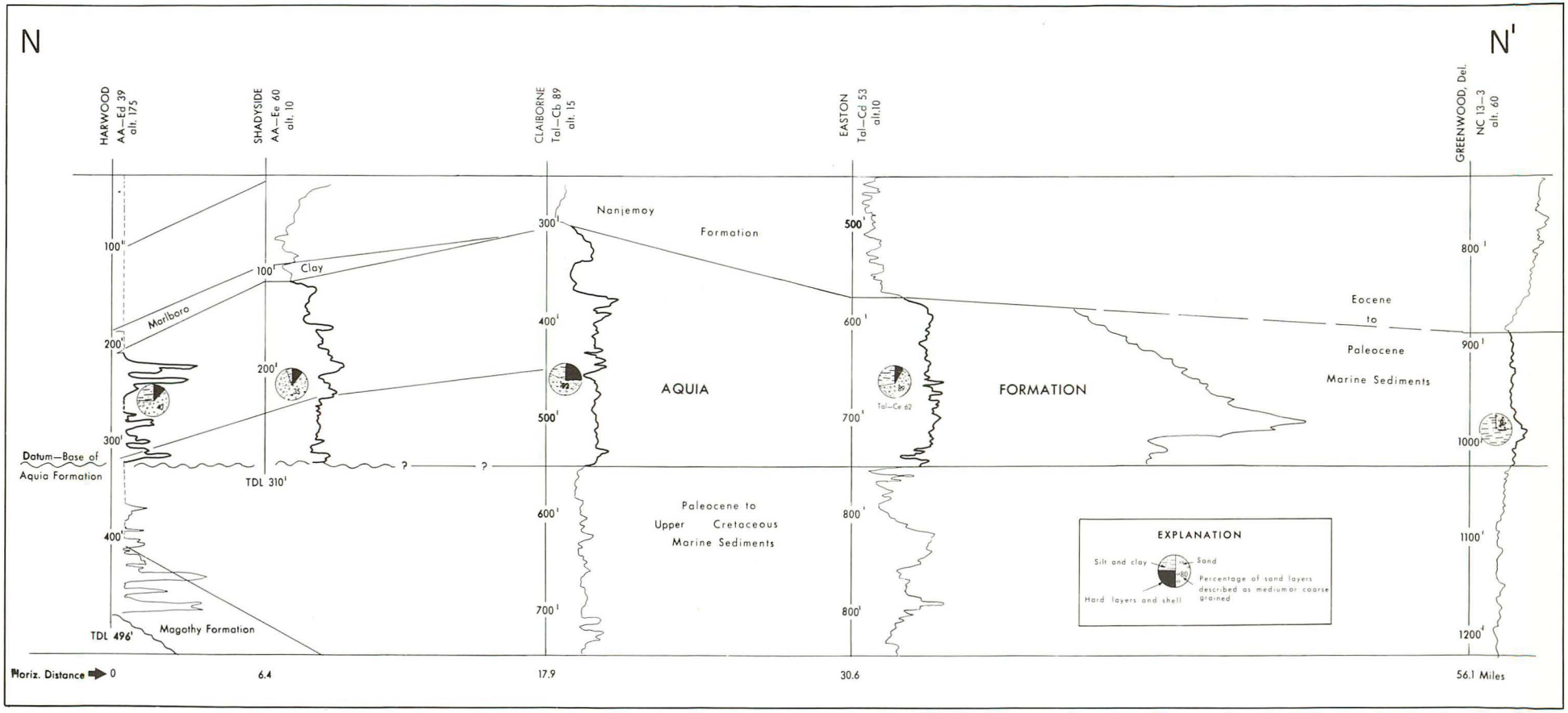


Figure 13.—Stratigraphic cross-section N-N', showing subsurface sand build-up.

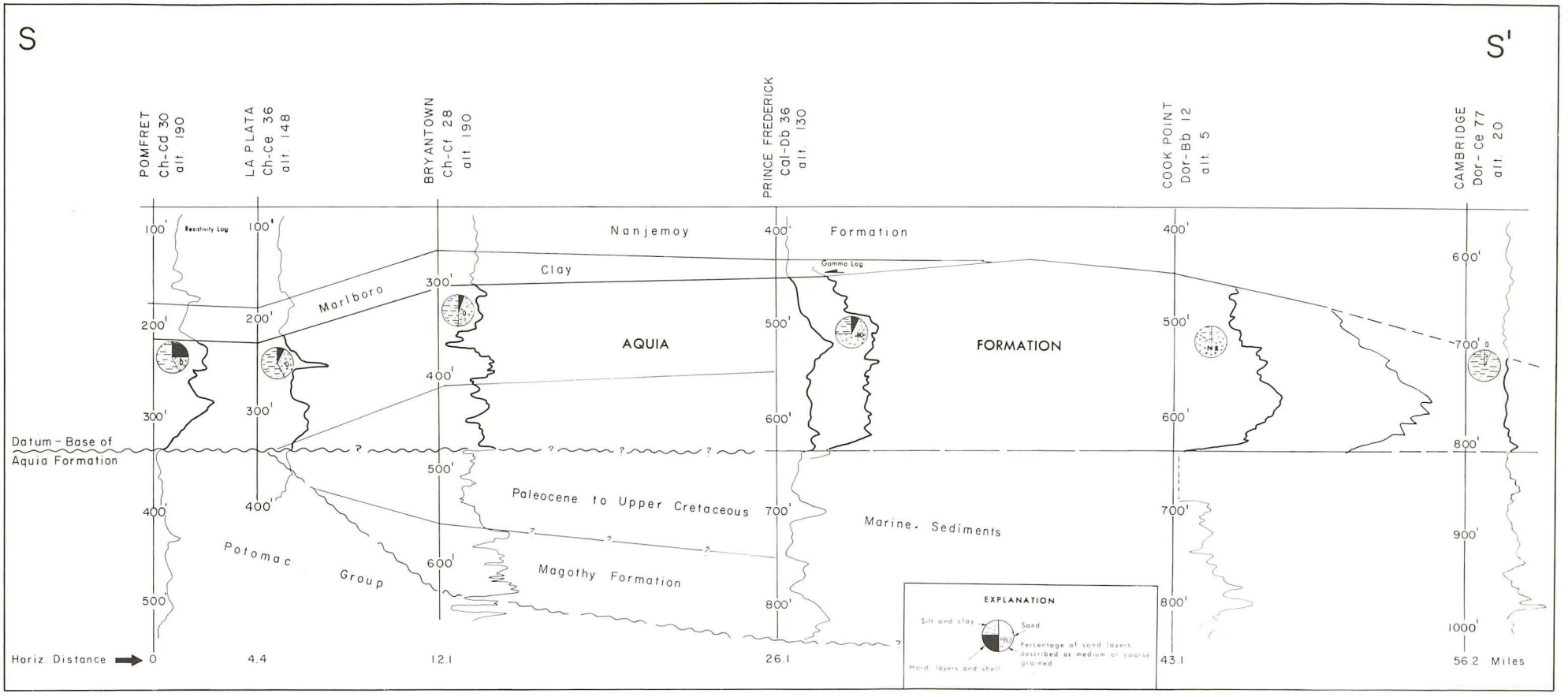


Figure 14.—Stratigraphic cross-section S-S', showing subsurface sand build-up.

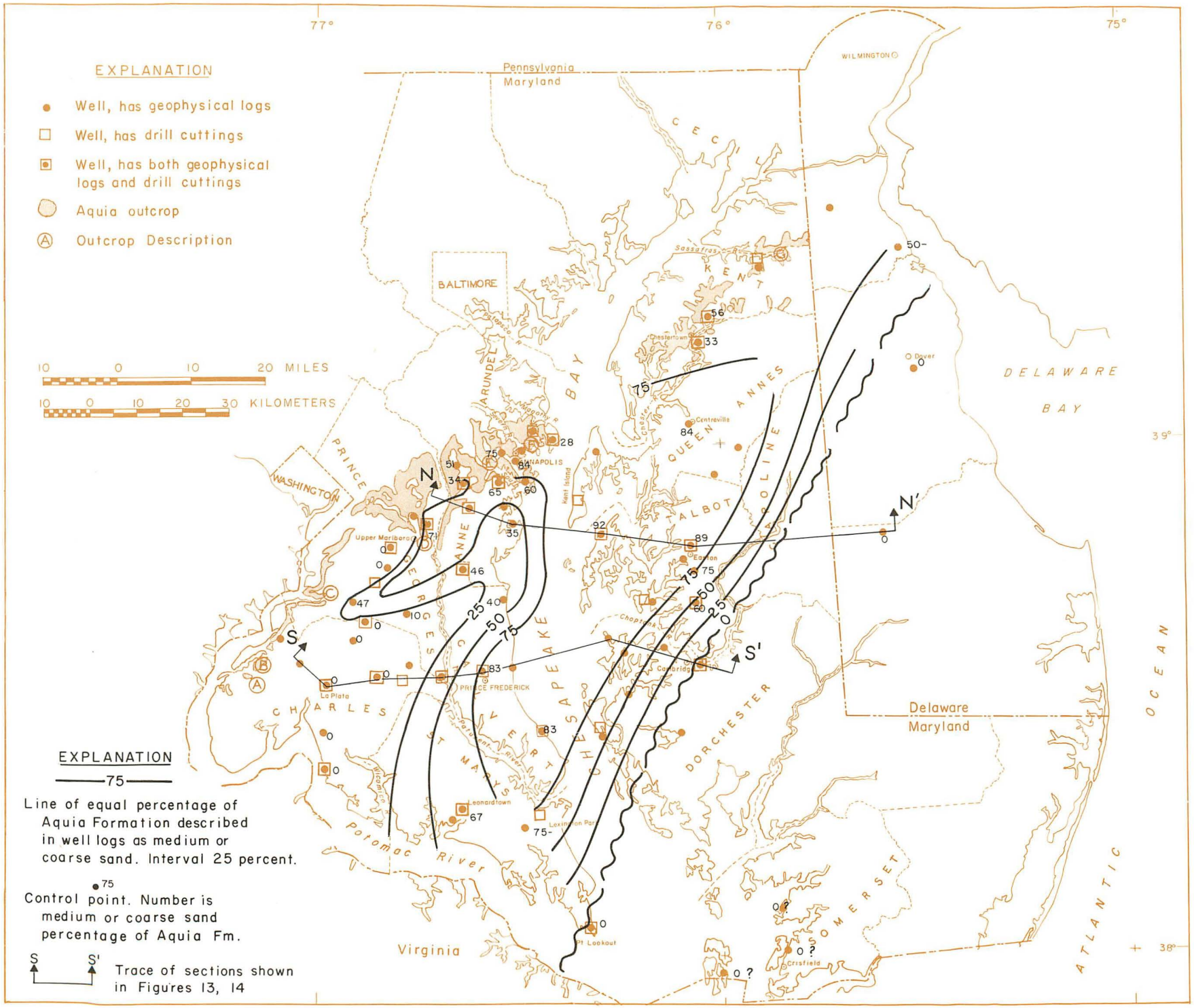


Figure 15.—Map showing the percentage of Aquia sands described as medium- or coarse-grained in drillers' logs.

Plate 1. Thin-section photomicrograph of Facies 1: Prepared with epoxy-impregnated drill cuttings from well Tal-Ce 62 (639'-649'). The light-colored grains are detrital quartz, chiefly medium to very coarse grade-size. Iron-staining occurs as surficial crusts and along fracture surfaces. The darker minerals are glauconite grains, chiefly very fine to medium grade-size. The grains are typically ovoid to lobate. "Limonite" rinds are common and in some cases alteration approaches completion. (The dark flecks in the epoxy ground-mass are polishing abrasives. The long view is approximately 2 mm.)

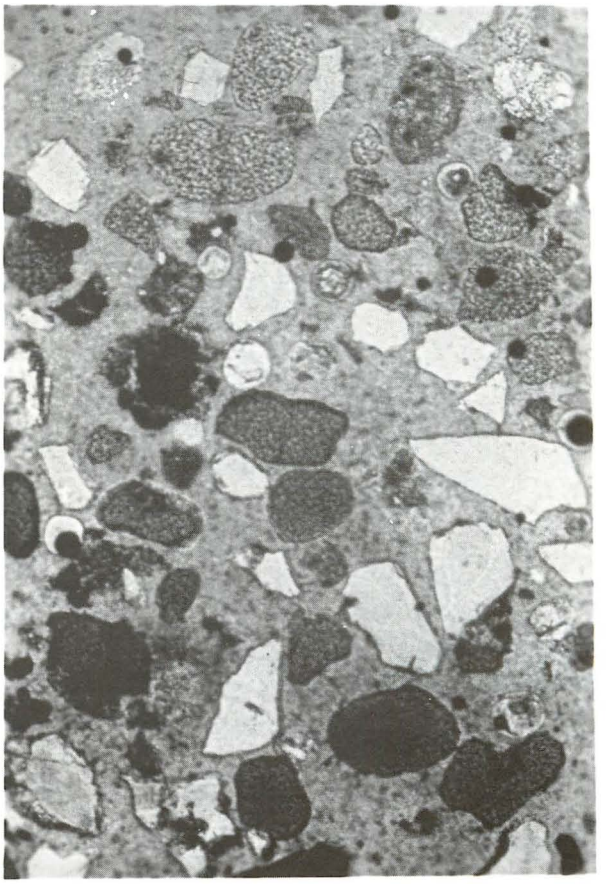


Plate 2. Thin-section photomicrograph of Facies 2: Prepared with epoxy-impregnated drill cuttings from well Ch-Bf 127 (302'-321'). The light-colored quartz grains are chiefly in the very fine to fine size range; the grains exhibit only minor iron-staining. The glauconite grains show evidence of "limonite" alteration, but much less than in Facies 1 (Plate 1). (The dark flecks in the epoxy ground-mass are polishing abrasives. The long view is approximately 2 mm.)

of 50 percent of the sand fraction. Glauconite particles most commonly occur as green to blackish green, polylobate grains (or aggregates), chiefly in the fine to medium grade sizes. Less frequently observed, but still common, are elongated stacks of glauconite platelets and calcareously cemented aggregates of glauconite and quartz. Glauconite ghosts of macro-shell debris are extremely rare to absent; so too are ostracod valves or foraminiferal tests packed with glauconite.

In facies 1 more than half of the glauconite grains show some degree of limonitic alteration; glauconites in the two flanking facies exhibit less. The grains studied in five epoxy-impregnated thin sections (plates 1, 2, 3) suggest that alteration usually occurs as patchy rinds. Although deeper penetration along the furrows of polylobate grains was commonly observed, few grains are completely altered. The glauconite grains are generally microcrystalline and, unlike the goethite pellets associated with them, normally do not contain included mineral detritus large enough to be observed under standard binocular magnification.

Less ubiquitous, but still extensively found in facies 1 are brown, irregular to ellipsoid-shaped pellets, usually in the medium to coarse grade size

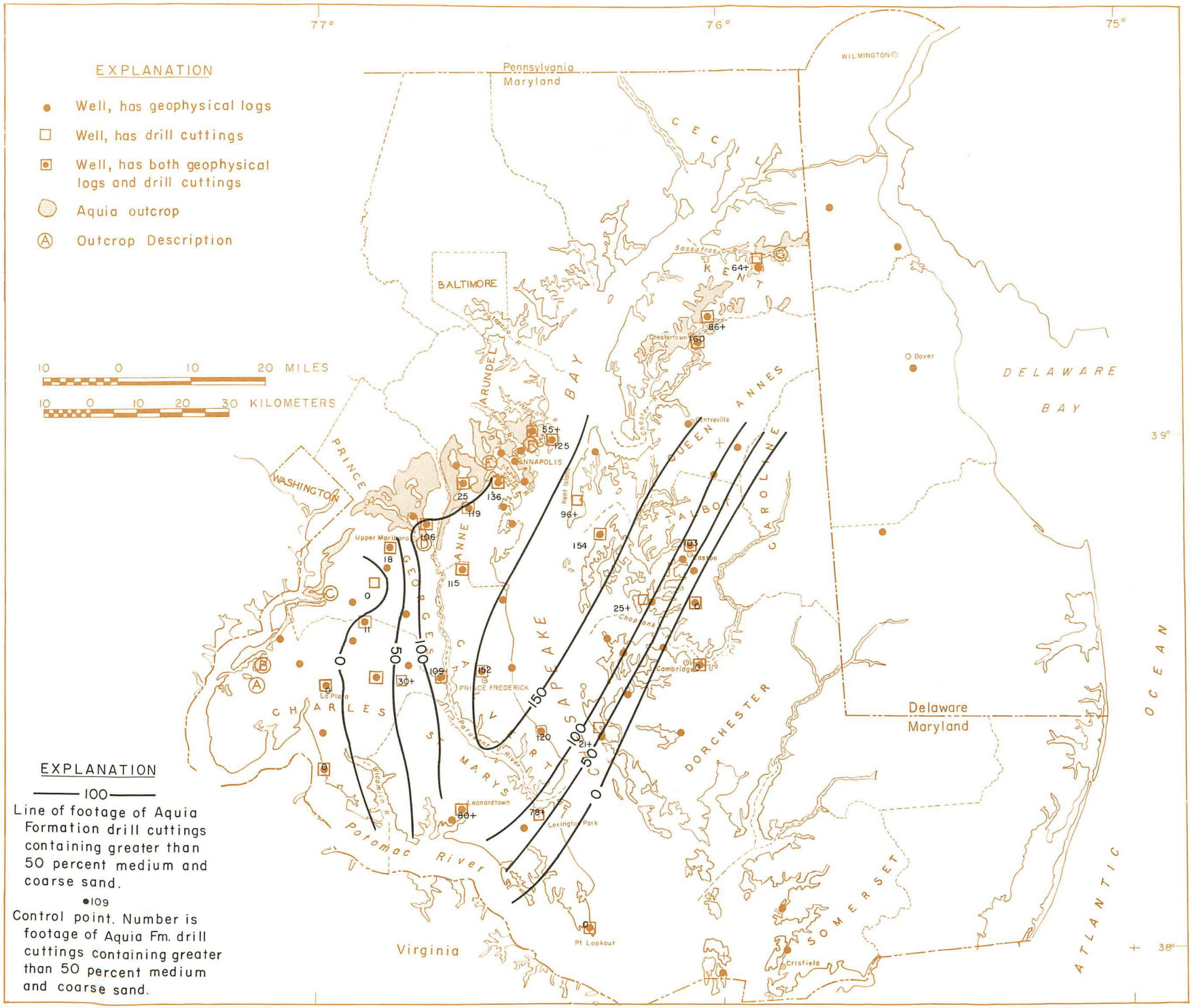


Figure 16.—Map showing the footage of Aquia drill cuttings which contain greater than 50 percent medium to coarse sand.

(plate 3). On the basis of color, shape, size, and internal structure these pellets are readily differentiated from each of the several glauconite types and their alteration products; such distinctions argue persuasively that the pellets are not second-cycle, limonitically altered, glauconite grains (Trumbull, 1972, p. 15). X-ray diffraction analysis shows the pellets to have a weak goethite crystallinity (fig. 20).[1] Goethite pellets occur deep in the subsurface and are clearly not a Quaternary weathering product, a relationship often implied by outcrop workers. Altered glauconite grains produced by Quaternary weathering do occur in some updip wells, but they are characteristically earthy in aspect; this is sharply in contrast to the smooth, lustrous appearance of the goethite pellets (Alexander, 1934, p. 20).

In thin section a diagenetic continuum is visible only between morphologically similar grains of glauconite and goethite (plate 1). Thus many of the deeply furrowed polylobate and spheroidal grains of goethite, particularly in the very fine and fine grade sizes, probably have passed through a glauconitic stage. Much of the goethite logged in samples from the shelf facies flanking the sand bank complex (facies 1) may have this origin. How ever, in these facies goethite is quite subordinate, with the goethite/goethite + glauconite ratio rarely, if ever, exceeding 25 percent.

On the other hand, in facies 1 the goethite/goethite + glauconite ratio increases to as much as 50 percent, chiefly by the introduction of medium- to coarse-textured brown, irregular to ellipsoidal shaped pellets. In thin section these pellets are characteristically composite in morphology, consisting of silty to fine quartz and, more rarely, glauconite grains floating in a goethite matrix (plate 3); matrix-grain contacts are not deeply serrated or anastomosing, suggesting that little diagenetic replacement has occurred. Usually each pellet has smooth, lustrous veneer, imparting to it a polished aspect. These pellets are believed to be authigenic (Porrenga, 1967) rather than detrital (Van Andel and Postma, 1954, pp. 77, 136) insofar as they are less spherical and much better sorted than the quartz fraction associated with them; furthermore, the particles within the pellet "float" rarely exhibiting the serrated grain-to-cement contacts commonly associated with sandy limonite crusts (plate 3). Interestingly, some invertebrates shed agglomeratic fecal pellets morphologically similar to the geothite grains found in facies 1 (Kraeuter and Haven, 1970; Bathurst, 1971, p. 85).

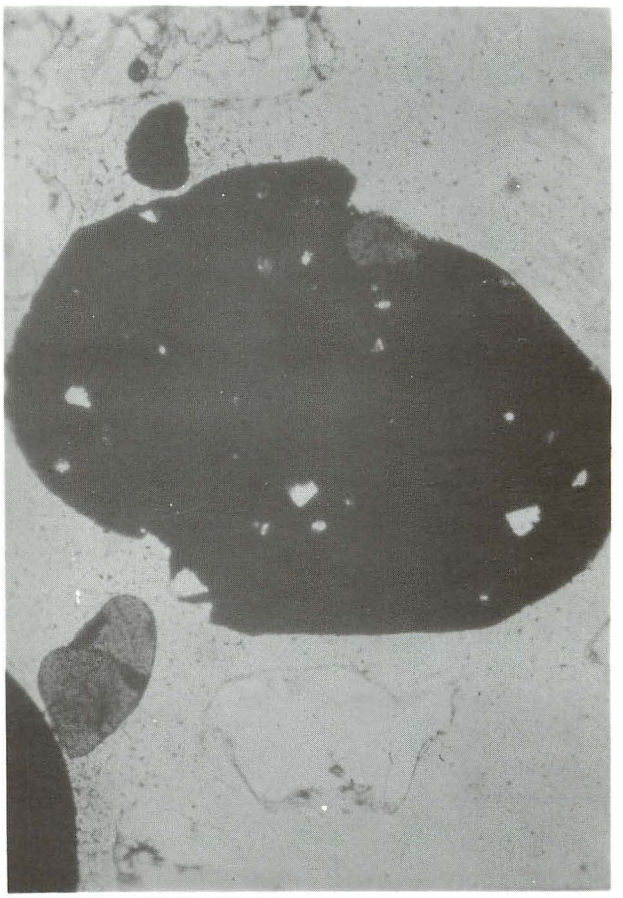


Plate 3. Thin-section photomicrograph of agglomeratic goethite pellet from Facies 1: Prepared with epoxy-impregnated drill cuttings from well Tal-Ce 62 (639'-649'). The long axis of this large ellipsoidal-shaped pellet exceeds 1 mm. It contains silt to very fine-sized quartz grains; also visible is a very fine, darker-colored, lobate grain of glauconite, only slightly altered. The occurrence of relatively "fresh", detrital grains of glauconite within the pellets suggests that the goethite cement was derived driectly from fecal-pelleted muds rather than as an alteration product of glauconite. (Long view is approximately 2 mm.)

In this writer's opinion, the Aquia Formation particularly facies 1, contains not one, but two common authigenic minerals, glauconite and goethite. On the other hand, phosphate nodes or replacements are very rarely observed in the cuttings, although a substantial accumulation was recorded at the base of the Aquia in the Waldorf well (Ch-Bf 127).

Figure 21 is a map showing the distribution of goethite and glauconite expressed as a percentage

[1] Although consisting largely of goethite, x-ray patterns suggest the occurrence of smaller amounts of quartz, illite, and mixed-layer clays.

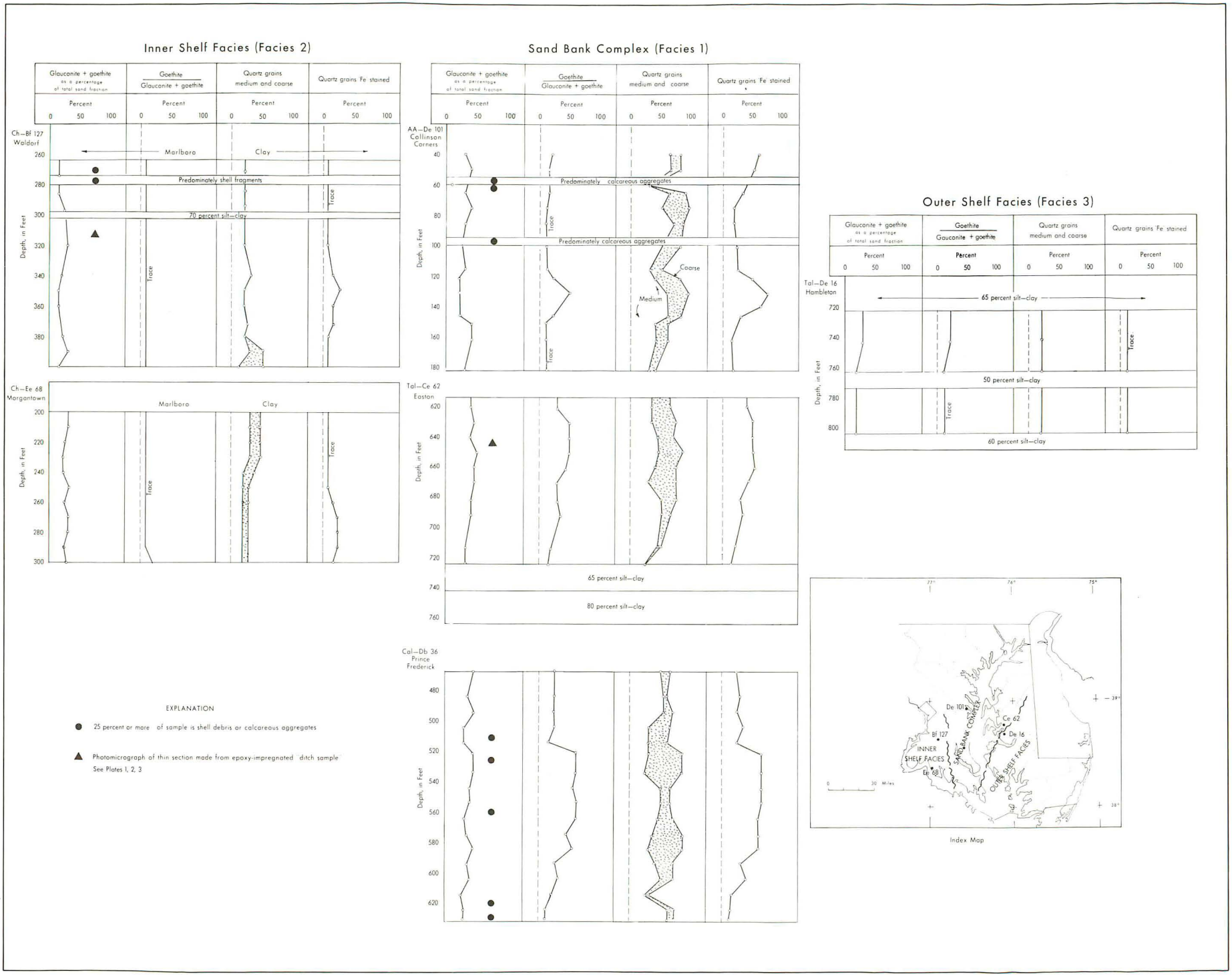


Figure 17.—Six vertical well profiles showing trends in several environmentally diagnostic parameters.

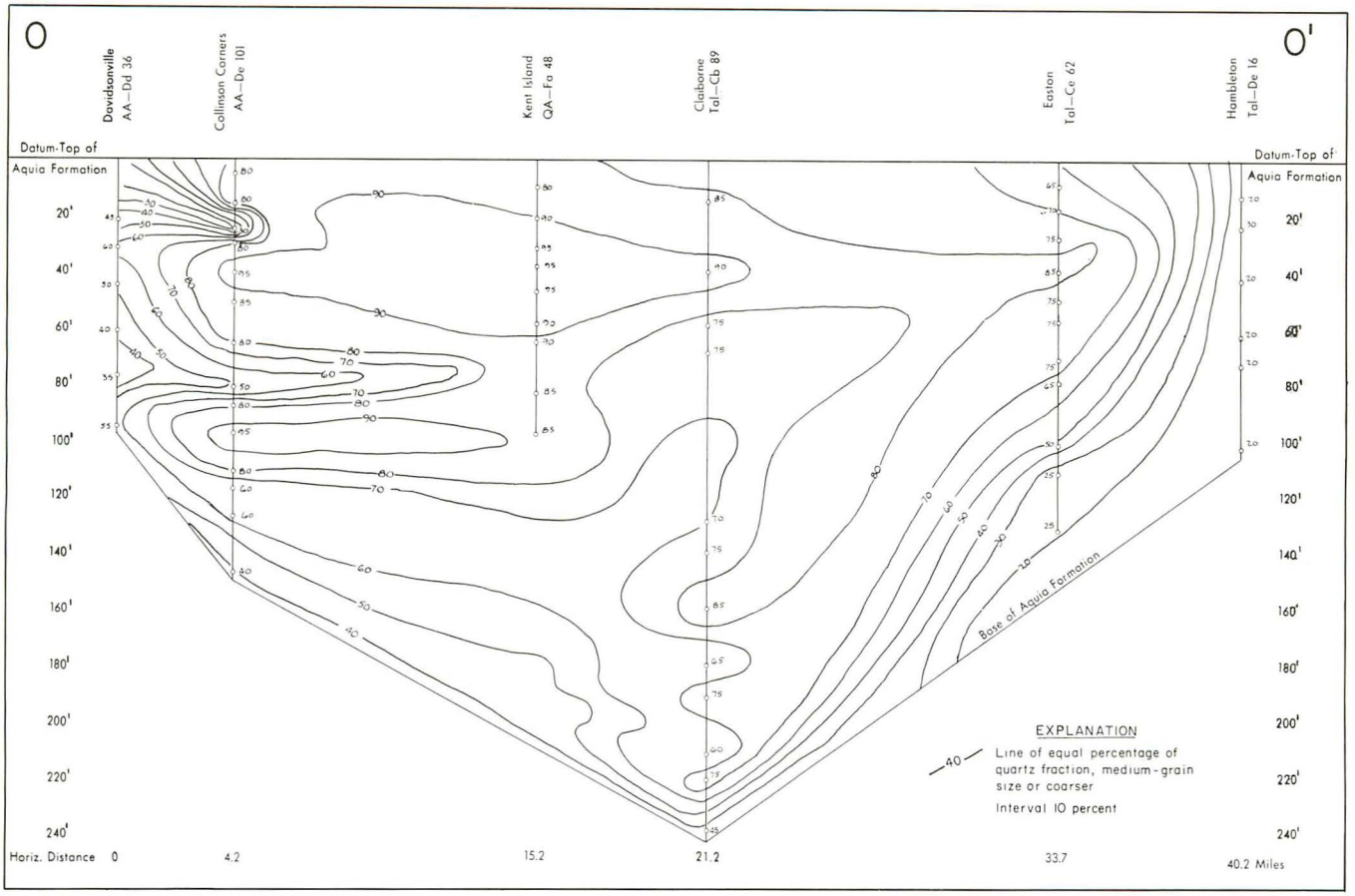


Figure 18.—Contoured cross-section O-O', showing distribution of medium and coarse quartz sands in Aquia Formation.

of the total sample. For each set of Aquia well samples an average value and a high-low range were plotted on the map. Inasmuch as the sampling interval often varies widely from well to well, the percentages do not represent individual beds in any precise stratigraphic sense. Thus these data, like all parameters derived from washed drill cuttings, are useful primarily as a means to identify trends.

Figure 21 is a map showing where in the subsurface glauconite and goethite are most abundant in the Aquia Formation. It shows that the highest concentrations coincide largely with the thickest (fig. 8) and coarsest-textured (fig. 15, 16) facies of the formation. A comparison with figure 22 suggests that the rise in the authigenic fraction is caused chiefly by increasing occurrences of goethite. Where goethite, expressed as a percentage of the total authigenic fraction (goethite + glauconite), exceeds 25 percent, well footages plot in a consistent pattern and coincide with the sedimentary trends characteristic of facies 1. Thus, in the Aquia Formation, authigenic goethite is an important mineral constituent beneath southeast Anne Arundel County, Calvert County and contiguous parts of St. Mary's County, Dorchester County, Talbot County, and Queen Anne's County. It is much less common beneath the upper Eastern Shore, western Prince George's County, and most of Charles County.

Cross-section T-T' (fig. 23) suggests that the vertical distribution of goethite is complex. There is a tendency, however, for the goethite concentrations to peak in mid-Formation, rather than be concentrated near either the upper or lower contact. This is particularly true of wells such as PG-Db 36, which penetrate facies 1 of the Formation. Unlike concentrates of phosphate debris, goethite pellets are not uniquely associated with hiatal unconformities. Rather, like glauconite, the common occurrence of goethite pellets is indicative of depositional processes, albeit slow and chiefly biogenic.

Iron-staining of the quartz fraction may occur deep into the subsurface and is clearly unrelated to Quaternary weathering effects. The iron-staining occurs chiefly as surficial crusts covering the quartz grains or as films coating hair-line fractures (plate 1). Lesser amounts of primary, "rosy" quartz also occur, but not in the peak concentrations logged in

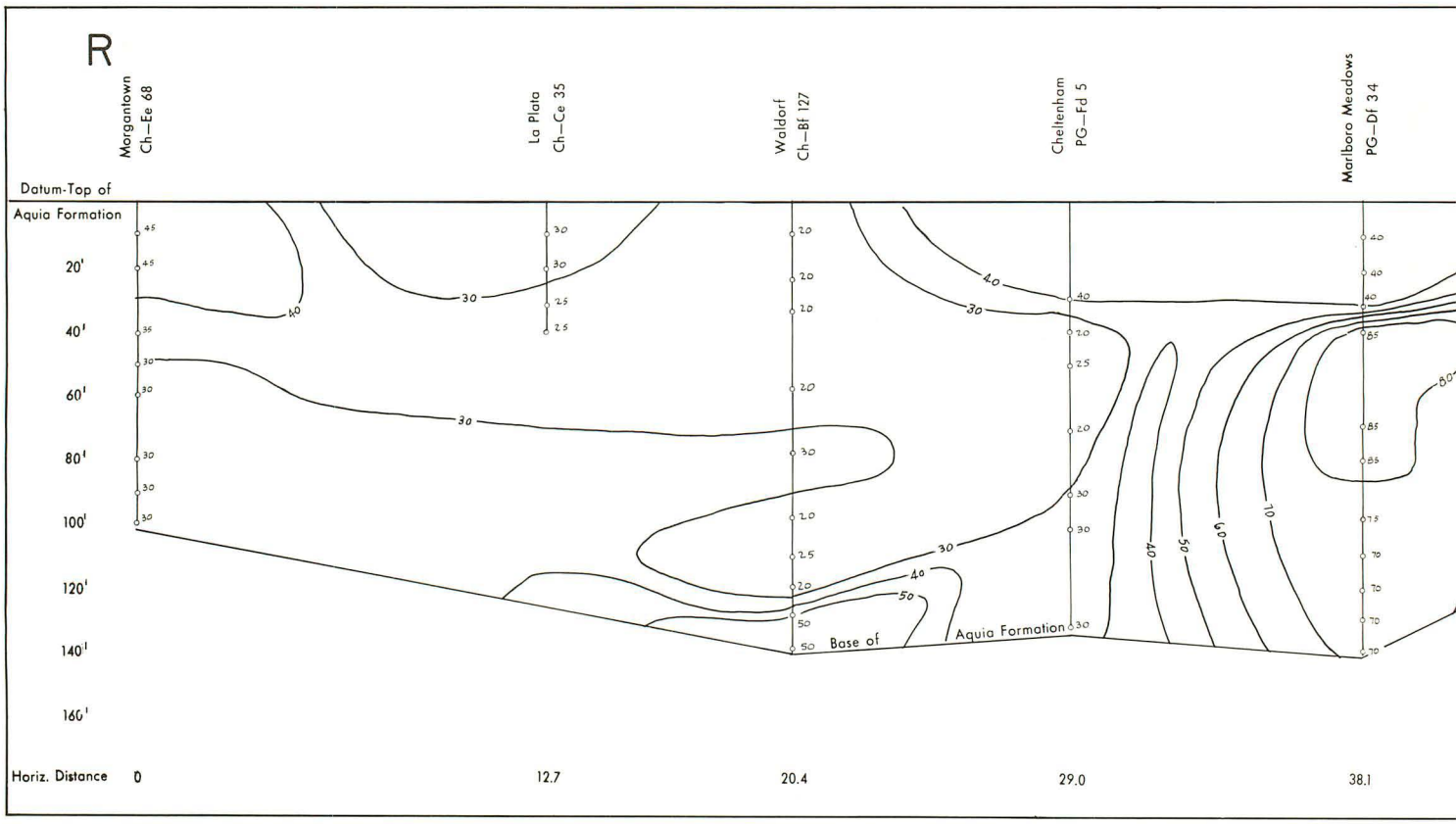


Figure 19.—Contoured cross-section R-R', showing distribution of medium and coarse quartz sands in Aquia Formation.

figure 17 and depicted in figure 24.

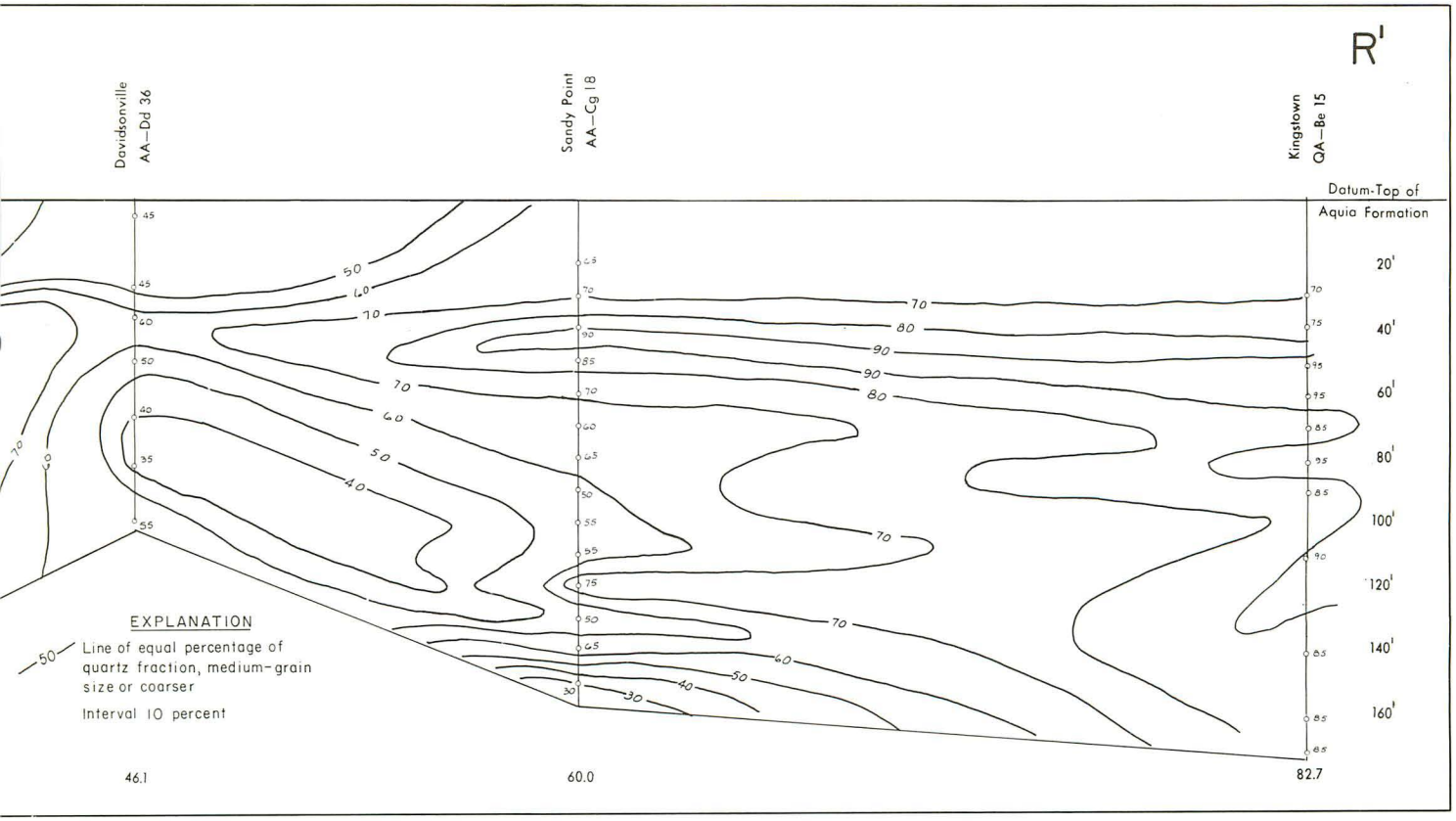
Figure 24 maps the distribution of iron-stained quartz grains in the Aquia Formation. The parameter selected for mapping represents for each set of drill cuttings the footage in which iron-stained grains exceed 50 percent of the quartz fraction. Admittedly, this parameter is an arbitrary one; therefore, its quantification has limited significance, except as a means of showing where the subsurface Aquia Formation contains appreciable amounts of iron-stained quartz sand. The pattern revealed in figure 27 is reminiscent, however, of other previously outlined trends. For example, figure 8, a thickness map of the formation, and figure 16, a sand texture map, both mimic figure 24, suggesting a positive correlation between surficial iron-staining and the accumulation of thick, medium- to coarse-textured quartz sands. Too, the common presence of goethite pellets in the Aquia Formation (fig. 22) is broadly correlative with the predominant occurrence of iron-stained quartz grains.

Calcareously cemented layers occur throughout much of the Aquia Formation, having been observed in outcrop as well as in numerous wells. The degree of cementation ranges from a loose pasty filling of pore spaces to hard layers of cemented sand and coquinoid debris.

Figure 25 was prepared to show the areas in which cemented and (or) coquinoid strata are most frequently encountered. At each of the keyed localities at least one sample interval contained 25 or more percent shell fragments or cemented sand aggregates; cumulative well footages are also recorded for each locality. These data suggest that the incidence of cemented and (or) coquinoid strata diminishes both east and west of the tract broadly mapped in figure 25.

Transmissivity: Insofar as it affects hydraulic gradients within the fluid system, one aspect of geologic framework is particularly important to the ground-water hydrologist. This is transmissivity, a hydrologic parameter equal to an integration of hydraulic conductivity across the saturated thickness of an aquifer; it is essential for predicting the time-yield-drawdown relationships associated with ground-water withdrawals. In the Aquia Formation high transmissivity values are associated with the thicker, more coarsely textured facies of the Formation, particularly in area where porous coquinoid beds are commonly encountered (fig. 25).

Aquia transmissivity values range from less than 1,000 to nearly 40,000 gpd/ft. The highest values occur in an elliptical-shaped tract underlying most of southern Queen Anne's and northern



Talbot Counties where porous shelly beds are common (figure 26); representative values include 37,500 gpd/ft. at Queenstown (Queen Anne's County) and 25,000 gpd/ft. at Wades Point (Talbot County). The long axis of the Aquia transmissivity tract broadly conforms to facies 1 of the formation. Transmissivity values decrease along strike both northeast and southwest of the high transmissivity tract, as for example at Smyrna, Delaware (16,500 gpd/ft.) (Sundstrom and Pickett, 1968) and Chesapeake Beach in Calvert County (10,000 gpd/ft.) (Otton, 1955).

In Southern Maryland values range from less than 1,000 gpd/ft. at La Plata in Charles County to 10,000 gpd/ft. at Chesapeake Beach in Calvert County. In southern Calvert and St. Mary's Counties Aquia transmissivity values diminish downdip toward the facies boundary, being, for example, 7,000 gpd/ft. at Lusby and 7,500 gpd/ft. at Lexington Park (Otton, 1955; Weigle and others, 1970).

Earlier Investigations

The presence of molluscan fossils and the near ubiquitous occurrence of authigenic glauconite quickly led early workers to assign a marine origin to the Aquia sediments (Clark, and others, 1901). Finds of sea turtle and crocodile remains (Case, 1901, p. 95-97) suggests a semi-tropical or warm temperate habitat. Shallow-water deposition was evidenced by the common occurrence of oysters ("Ostrea") in some outcrops of the Aquia Formation. Both the thinness of the formation and its comparatively high percentage of authigenic minerals suggests further a relatively stable, marine shelf setting which received terrigenous debris at a slow rate. Too, early workers recognized that the formation became thicker and more coarsely textured northeastward along its outcrop from Charles County to Anne Arundel County (Clark and others, 1901, p. 57). However, the oblique relationship between present structural strike and regional depositional strike was not adequately understood.

Later workers have embroidered additional details onto this basic framework, often using modern sedimentary analogues to affect new interpretations. Particular emphasis in recent years has been on microfaunal studies of the outcropping Aquia-Brightseat sequence, for both stratigraphic and paleoecologic purposes (Nogan, 1964; Hazel, 1968, 1969). These investigations are typically concerned with the intensive study of a few selected outcrop samples. Their results are often contradictory in detail, perhaps because of the emphasis assigned to specific organisms by the specialists studying them. Paleoecologic factors such as bathymetry, water temperature, or rate of sedimentation are established to the satisfaction of each author, but because only a small number of areally restricted outcrop samples are studied, paleogeographic considerations remain vague at best.

By means of well data Shifflett (1948) and Otton (1955) extended the outcrop data into the subsurface, constructing thickness and structure contour maps of the Aquia Formation. Neither, however, mapped lithologic or mineralogic distributions; as a consequence, important lithofacies trends which bear upon the depositional history of the Formation went unrecognized to a large extent.

Subsurface data presented in this report suggest that the Aquia Formation exhibits three first-order lithofacies: Facies 1 is a thicker, coarser-textured deposit extending southwesterly in outcrop from Kent County to about the Patuxent River where it swings south into the subsurface. Facies 2 consists of finer-textured sands and clays

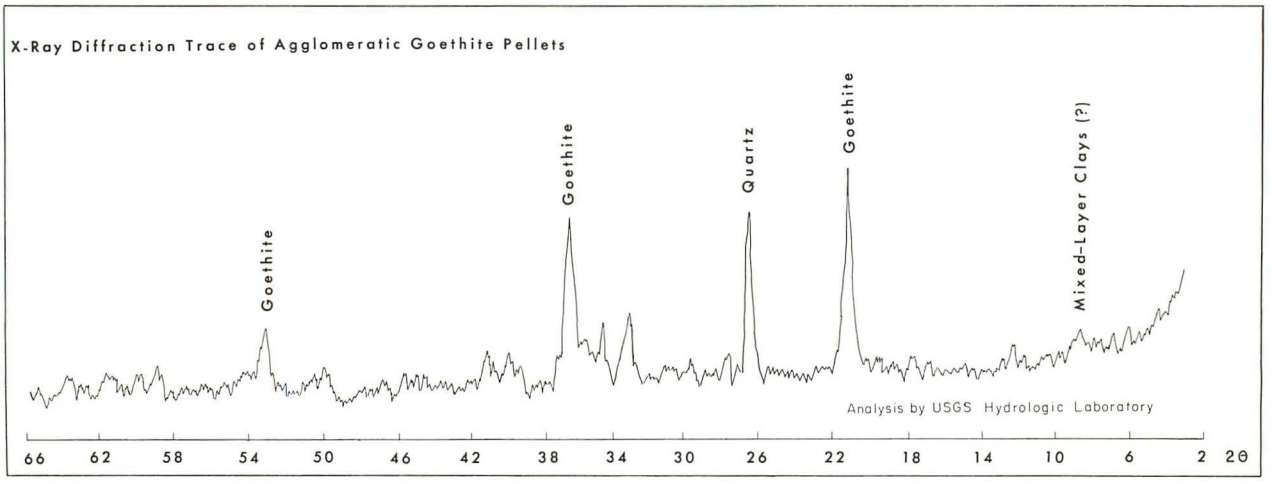


Figure 20.—X-ray diffraction trace of agglomeratic goethite pellets (from wells Cal-Db 36, 523-533 ft.)

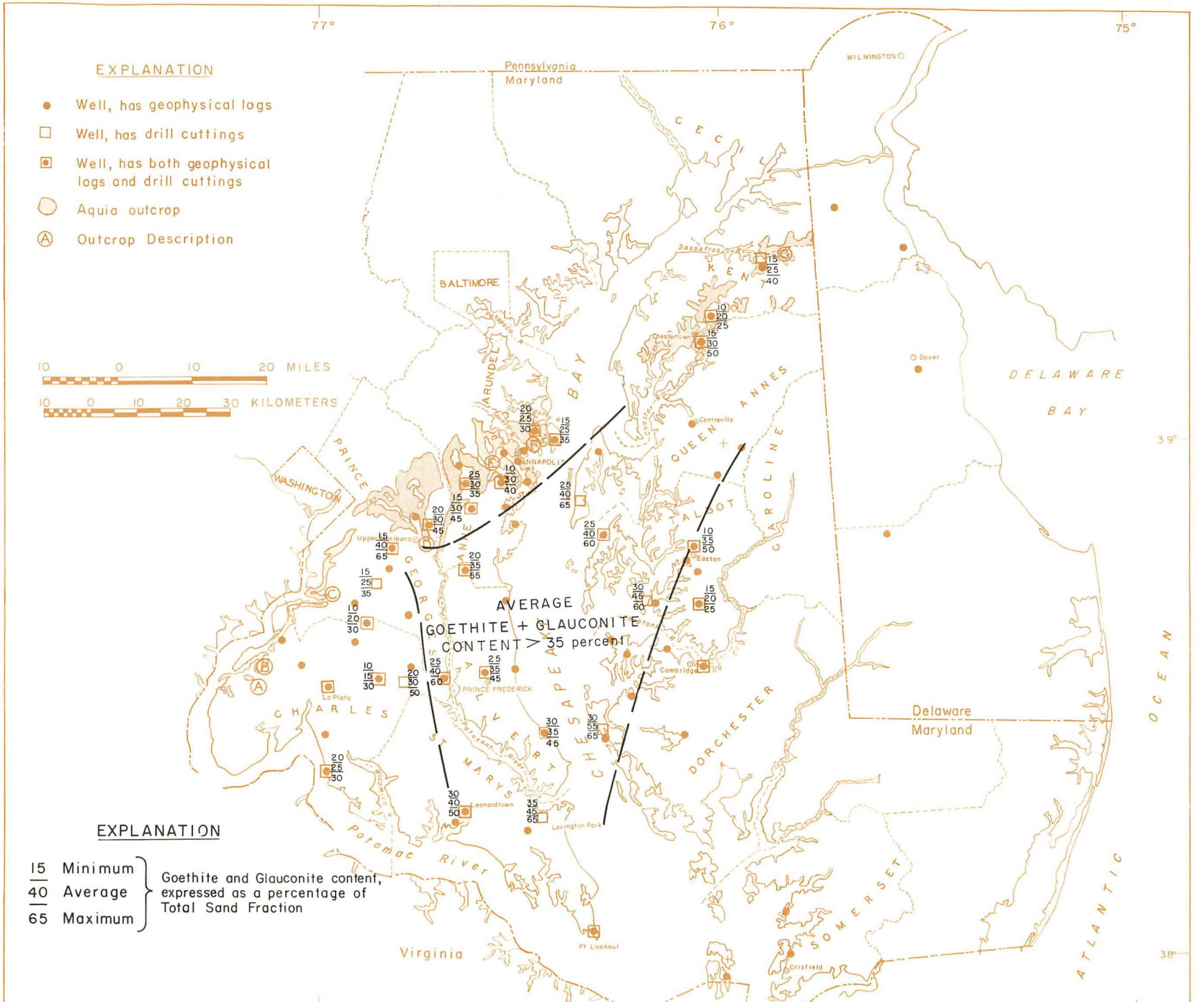


Figure 21.—Map showing distribution of goethite + glauconite expressed as a percentage of the total sand fraction.

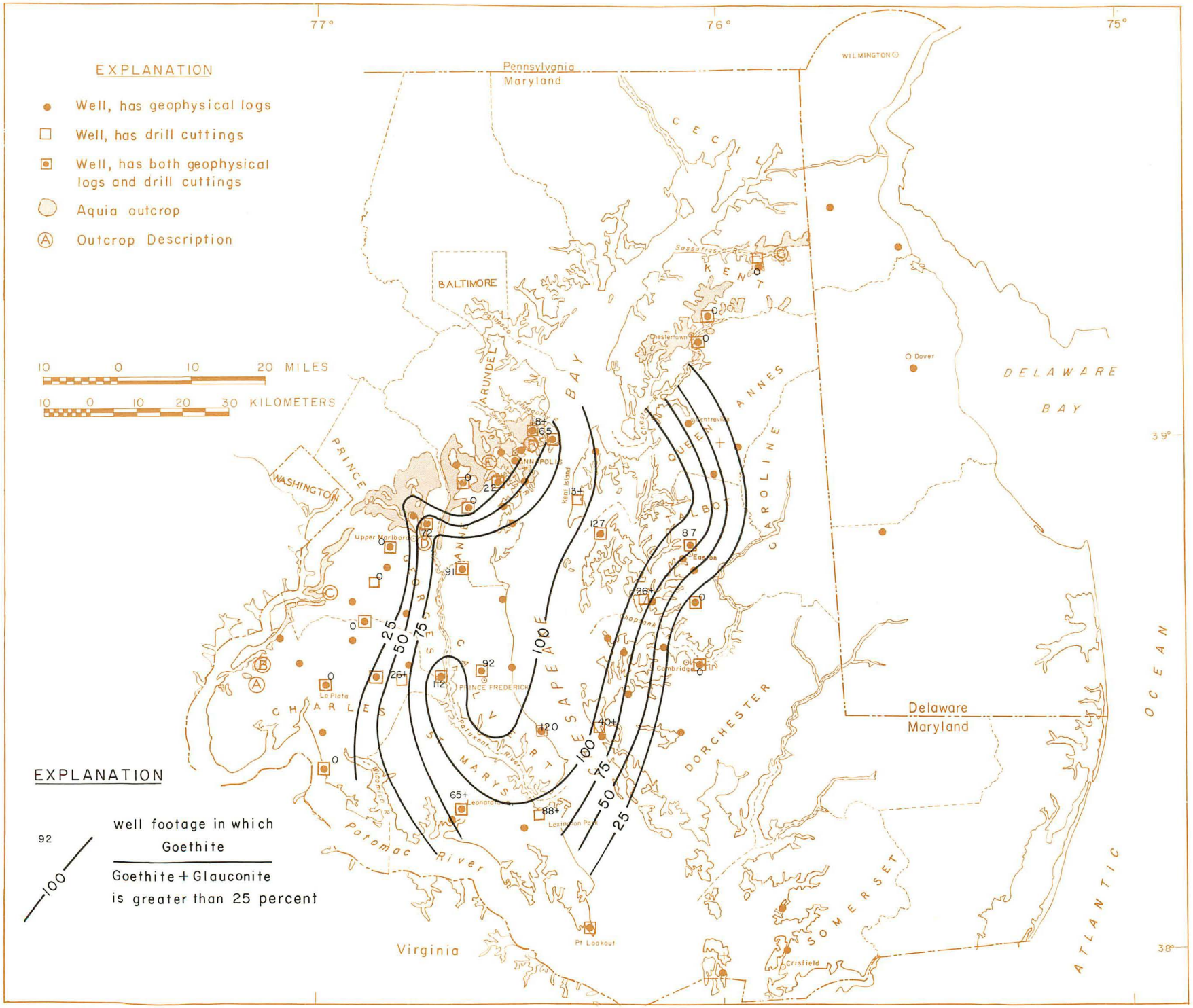


Figure 22.—Map showing well footages in which goethite/goethite + glauconite ratio (X100) exceeds 25 percent.

and is largely confined to Charles County, southern Prince George's County and western St. Mary's County; and facies 3 is a thin, very muddy facies that seems to underlie much of the Eastern Shore seaward of approximately the Choptank River. Figure 27 is an environmental map of Aquia times showing the composite distribution of the three first-order lithofacies. Inasmuch as the facies interrelate complexly (fig. 18, 19) the isolith lines shown on figure 27 are useful as facies boundaries only in a broad sense.

For the reasons discussed below facies 1 of the Aquia Formation is considered to be the depositional product of a shoaling sand bank complex; facies 2 represents an inner shelf setting shoreward of facies 1; and facies 3 defines an outer shelf environment extending seaward from the sand bank complex. Inasmuch as the areal extent of the three facies has already been reviewed, the following comments will briefly discuss how these patterns might relate to a modern marine shelf setting.

Sand Distribution and Texture

Diagnostic sand patterns associated with offshore bars or sand bank complexes have been established using both modern (Shepard and Moore, 1955) and ancient (Fisher and McGowen, 1969) prototypes. In addition, vertical profiles of offshore bar facies have been studied resulting in both textural and bedding criteria useful for differentiating them (Visher, 1965; Davies, and others, 1971). The geophysical logs, drillers' logs, and well cuttings used in the Aquia study were sufficient to map diagnostic sand patterns; textural variations could also be recognized, although not rigorously quantified. In the absence of cores, bedding characteristics of the Formation could not be observed and, therefore, were not used in this study.

Sand thickness and sand percentage maps (fig. 9, 12) generated from electric log and drillers' log data define the areal extent of the Aquia sand bank complex in Maryland. This complex, like its modern equivalents, is a linear deposit which thins in both the landward and seaward direction. It often parallels the shore line and can be areally extensive. For example, Nelson and Bray (1970, p. 62) have described two offshore sand bank complexes near Galveston, Texas:

> "Heald Bank is a sinuous asymmetrical, slightly biconvex mass of sand that has a straight line of approximately 25 miles and a width of 4 to 11 miles."

and

> "Within the area of study (Sabine Bank) is an elongated mass of sand and mud . . . the main axis plus the lobes form a bank that is more than 26 miles long and 4 to 11 miles wide."

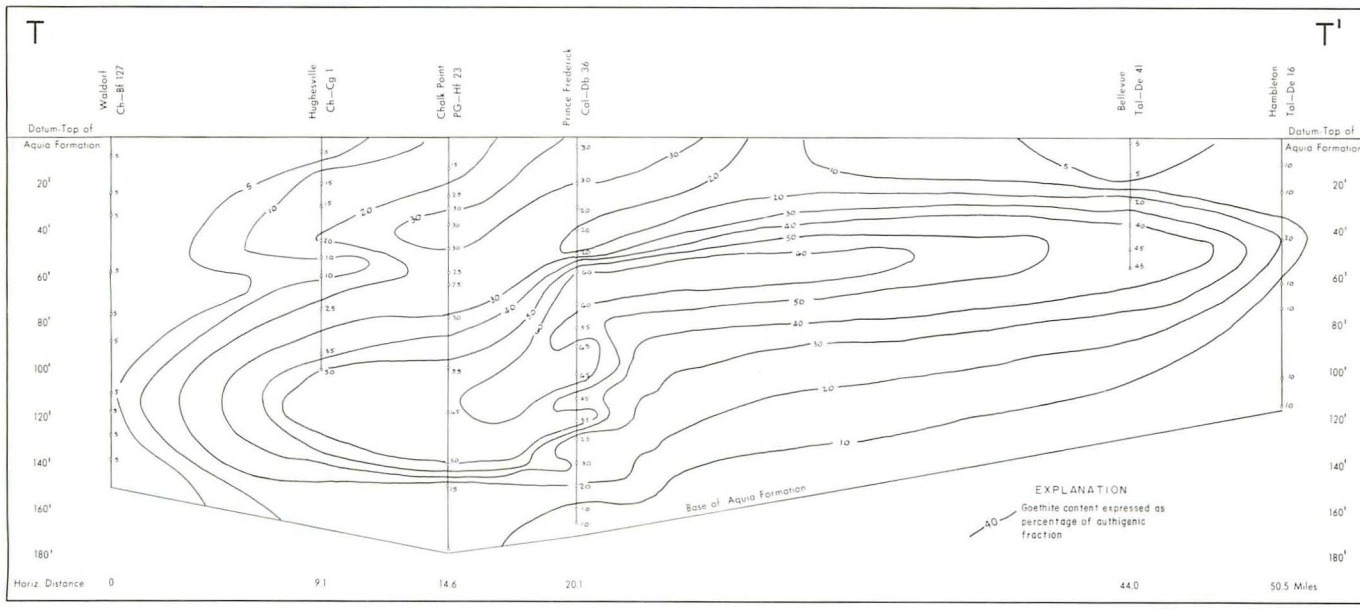


Figure 23.—Contoured cross-section T-T', showing distribution of goethite/goethite + glauconite ratio (X100) between Waldorf and Hambleton.

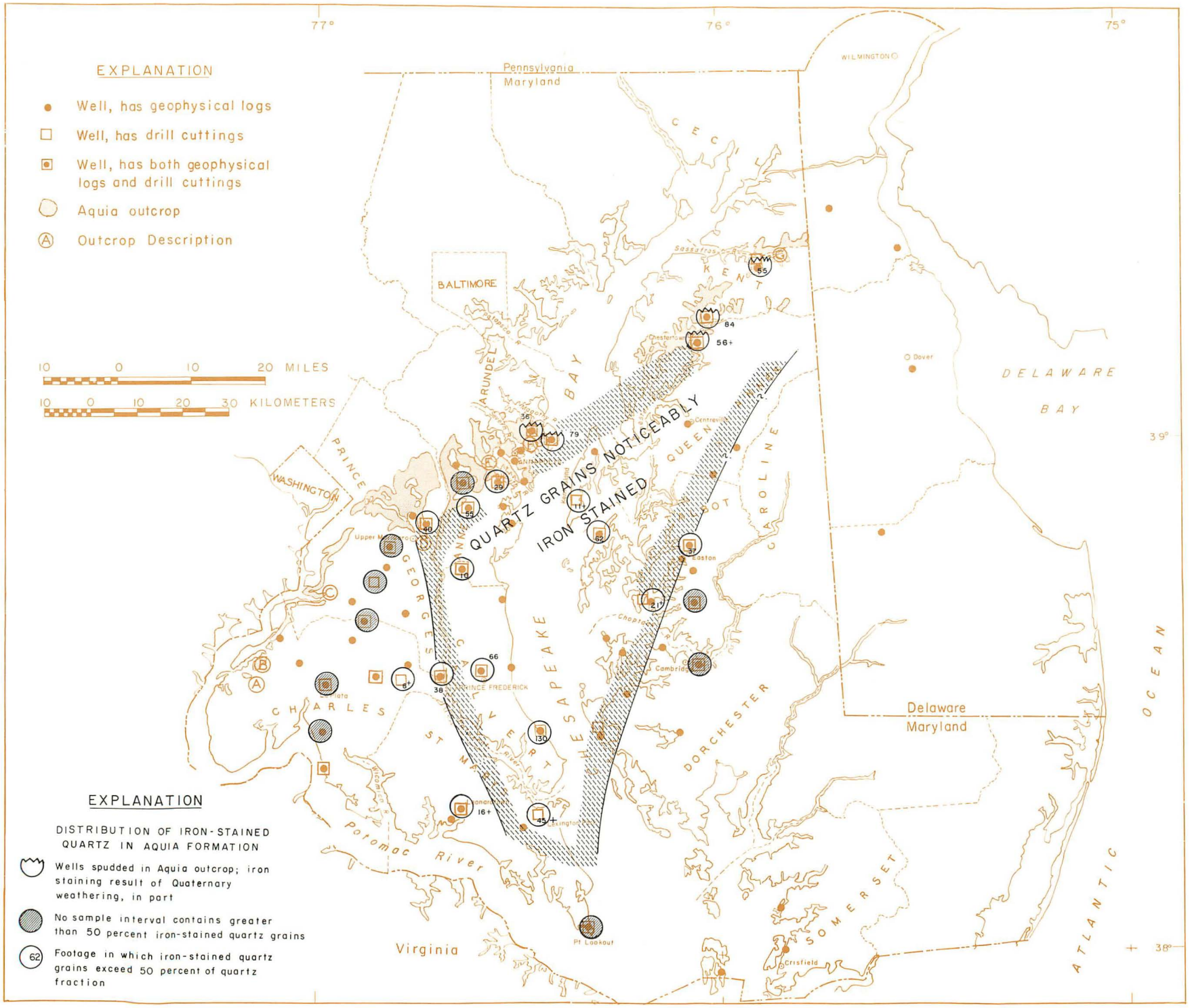


Figure 24.—Map showing distribution of iron-stained quartz in Aquia Formation.

The width of facies 1, which exceeds 20 miles in places, reflects a composite origin during all of Aquia time and not the paleogeography of a specific "instant". Thus cross-section N-N' and S-S' (figs. 13, 14) do not depict a specific paleogeographic setting, but rather define a broad tract within which the sand bank facies predominated during Aquia sedimentation. In this writer's opinion facies 1 of the Aquia Formation represents a multistory sequence of offshore sand bank deposits. As suggested above, these deposits may be areally extensive and, although relatively thin at any one instant, may stack up with time to form a deposit consonant with the isopach and isolith maps contained herein. Inasmuch as Sonu (1973, p. 45) has shown that "outer-bar" systems are relatively stable after formation and exhibit little movement normal to shore, stacking in a locally subsiding depocenter may be expected.

Within the sand bank facies aggregate sand thicknesses usually exceed 100 feet and sand percentages exceed 65 percent. Seaward, sand thickness and percentage decline, and are less than 25 feet and 25 percent at such outer shelf localities as Point Lookout, Cambridge (fig. 14), Greenwood, Del. (fig. 13), and Dover, Del. where the Aquia Formation is chiefly argillaceous. Landward of the sand bank complex sand thickness and percentage values diminish also, but less abruptly (figs. 9, 12). Apparently, the offshore bar system of facies 1 was never emergent long enough to establish true lagoonal conditions in which estuarine silts and clays accumulated shoreward of it. Although much of the incoming wave energy must have been absorbed across the tract, currents sweeping westward still had the capacity to transport finer textured detritus (plate 2) into Southern Maryland where the Aquia is a relatively thin, muddy sand of shallow marine origin. The regressive Marlboro Clay which overlies the Aquia Formation is Southern Maryland marks the first appearance of a tidal-flat clay into the Paleocene-Eocene section.

The distribution of Aquia facies is suggestive of the three "energy belts" Irwin (1965, p. 450) associates with shoaling seas marked by wide, very gently sloping shelves. Beginning farthest offshore these are:

1. "A wide, low-energy zone . . . occurring in the open sea beneath wave depth where marine currents are the only form of hydraulic energy acting upon the bottom." (Outer shelf facies of this report.)

2. "An intermediate, high-energy belt, tens of miles wide, beginning where waves first impinge upon the sea floor and thus expend their kinetic energy on the bottom, extending landward to the limit of tidal action." (Sand bank complex of this report.)

3. "An extremely shallow, low-energy zone in which there is little circulation of water, where tides are essentially wanting and in which the only wave action is that produced by local storms." (Inner shelf facies of this report.)

Although Irwin illustrated his model with examples from carbonate settings, Heckel (1972, p. 255) has pointed out that terrigenous analogs exist.

Mineralogic Diagnostics

Because of their potential importance as environmental diagnostics, several aspects of Aquia mineralogy which could be evaluated using washed drill cuttings were mapped. Maps were prepared showing the distribution of iron-stained quartz sand (fig. 24), of glauconite and goethite (figs. 21, 22), and of calcareously cemented sand and coquinoid strata (fig. 25).

In Anne Arundel County both the outcrops exposed in the Severn River bluffs (Little, 1916, p. 85) and shallow water wells (Brookhart, 1949, p. 45) reveal a thick Aquia profile containing iron-stained quartz sands. The conventional interpretation views these occurrences as a deep weathering profile, possibly of Pleistocene or Holocene origin. A Coastal Plain-wide study of Aquia drill cuttings demonstrates, however, that the incidence of iron-stained quartz grains extends deep into the subsurface (fig. 24), suggesting a much earlier, perhaps penecontemporaneous, component.

In general form the pattern depicted in figure 24 approximates the extent of the sand bank complex defined by sand thickness and textural data. The concentration of iron-stained quartz sand in an offshore bar or bank facies (Rusnak, 1960, p. 183) is a common occurrence. In these environments the preservation of inherited iron-staining, as well as the precipitation of primary ferric coatings, is favored. In the crestal sands of a bar tract the movement of oxygenated pore waters is maximized because these sands are usually more coarsely textured (hence permeable) and are usually subject to greater wave turbulence (Swift and Boehmer, 1972, p. 880). Inasmuch as the goethite associated with the sand bank facies occurs as authigenic pellets (Porrenga, 1967) rather than reworked stratified crusts (Van Andel and Postma, 1954, p. 77), the iron-staining found in facies 1 is probably an in situ characteristic diagnostic of a shoaling marine environment, rather than solely an antecedent characteristic acquired during erosion and transport. The occurrence of unaltered to slightly altered glauconite grains suggests, however, that the sand bank complex was rarely, if ever, emergent.

Figure 25 shows the subsurface distribution of wells in which at least one sample interval consists

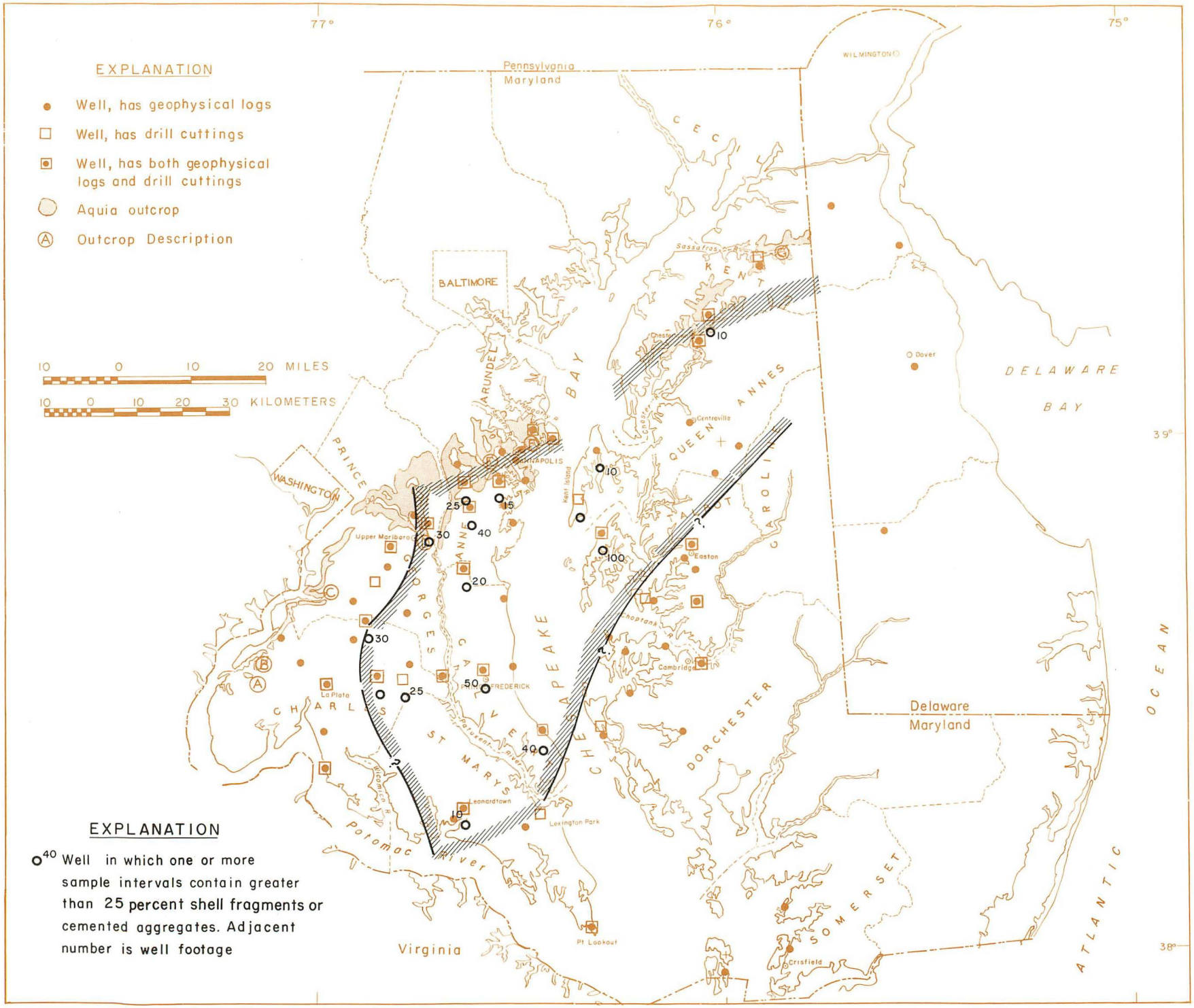


Figure 25.—Map showing localities where at least one interval from each set of Aquia sample cuttings contains 25 or more percent shell fragments or cemented sand aggregates.

of 25 percent or more of cemented sand or shell detritus. Again there is a strong similarity between the areal distribution of these wells and the distribution of the sand bank facies. Sand-packed shell concentrates are commonly associated with marine shoals (Curray, 1960; Nelson and Bray, 1970). For example, Nelson and Bray (p. 63) describe shell patches more than 20 miles long and 2 miles wide in the Saline-High Island area of the Texas Gulf Coast. The chalky cement lithifying the Aquia "ledges" probably was derived from these shell heaps. The mechanism by which lithification occurs is moot, although some evidence suggests that it may be "beach rock" as defined by Russell (1971, p. 2343). The three requisites for modern beach rock to form are: 1, a source of calcium carbonate; 2, warm temperatures which allow near-surface pore water to remain above 21° C (70°F) at least 8 months of the year; and 3, partial dewatering of the land causing the release of carbon dioxide and the precipitation of calcium carbonate. Also, beach rock is relatively thin insofar as it reflects the tidal range existing during lithification. Bricker (1971, p. 2) has noted that beach rock forms very rapidly, thereby implying that it may form on periodically emergent shoals as well as "permanently" emerged beaches.

Cemented strata in the Aquia Formation are usually thin, usually 2 or 3 feet thick, and coquinal debris is conspicuously present. The other two requisites, warm annual temperatures and periodic dewatering are not as easily established, although some evidence is very suggestive. Fossil vertebrates, such as crocodiles and sea turtles (Case, 1901, p. 95), argue for tropical or at least warm temperate conditions. Furthermore, corroborating evidence is provided by the occurrence of authigenic goethite which Porrenga (1967, p. 498) concludes to be an indicator of warm, shallow marine environments having bottom waters of greater than 20°C (67°F). It is more difficult to establish that shoals within the sand bank complex were episodically emergent. The occurrence of iron-stained quartz sands and goethite pellets (Bell and Goodell, 1967, p. 194) is strongly suggestive, but no more. Invertebrate evidence such as oyster fossils and more rarely, *Callianassa* burrows (J. D. Glaser, oral comm., 1972) found within the lithified strata indicate a very shallow marine environment (Seilacher, 1967). Therefore, one can at least say that the conditions were amenable to emergent shoaling inasmuch as minor changes in either sedimentation or sea level could have accomplished it. Even if the sand bank complex was never emergent it would still be a

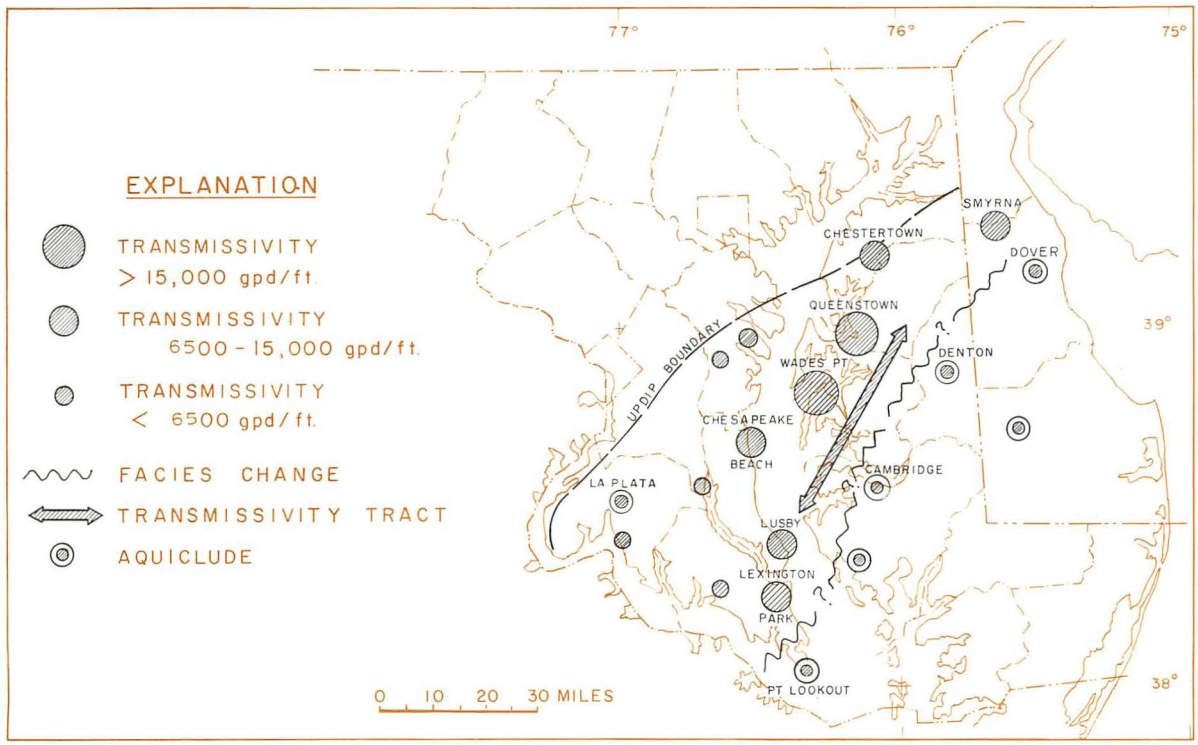


Figure 26.—Map showing generalized transmissivity distribution in the Aquia Formation of Maryland (from Hansen, 1971, fig. 7).

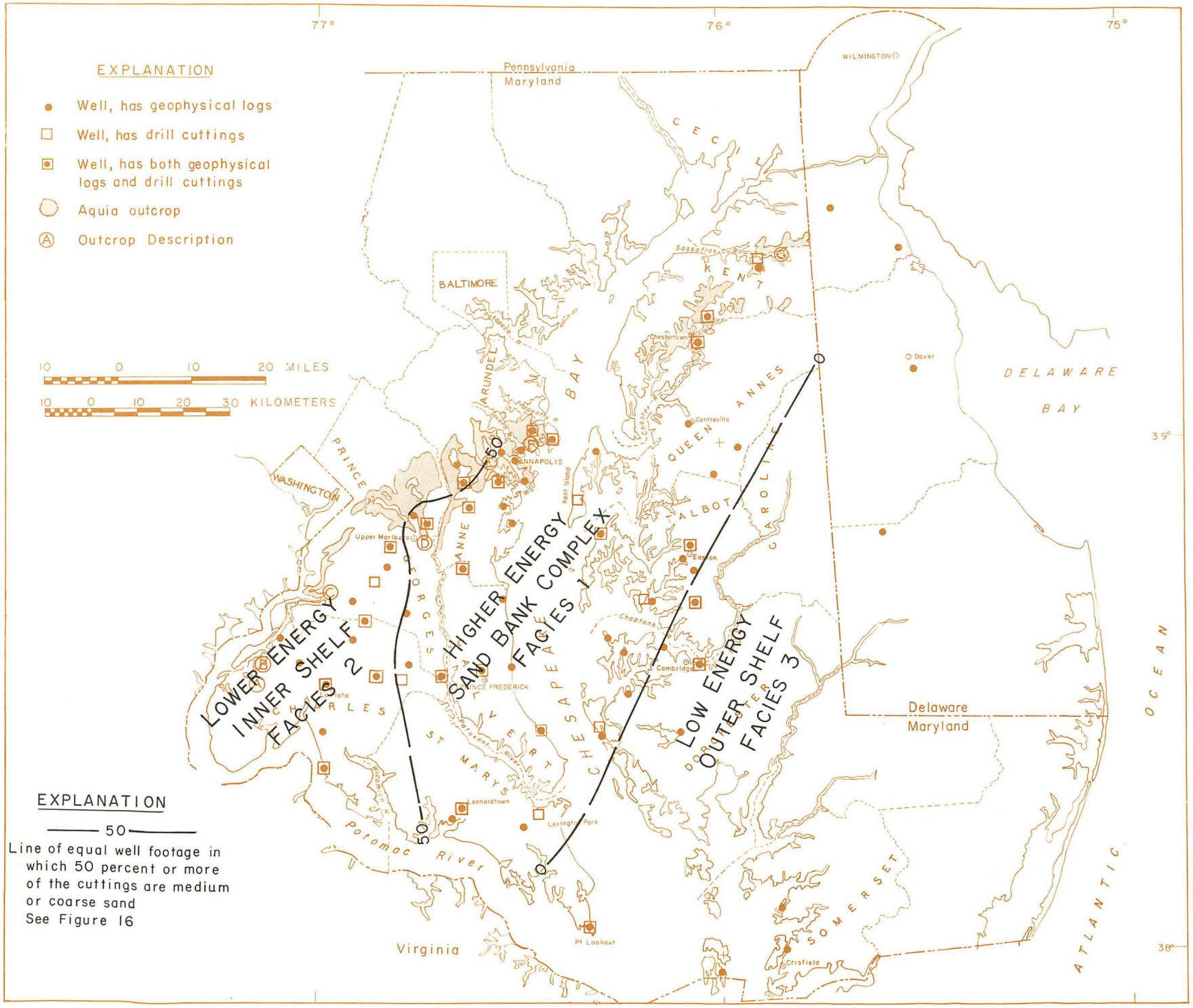


Figure 27.—Map showing the composite distribution of near-shore marine facies during the Aquia time.

more favorable place for lithification because (1) as a locus for the deposition of shell heaps it optimized the chances for carbonate supersaturation and (2) as a shoaling area greater wave agitation induced a more rapid exchange of pore fluids. Although the origin of the Aquia ledges remains moot, their relative concentration within facies 1 implies a very shallow marine, if not periodically emergent, lithification.

As logged in figure 17 the authigenic minerals, glauconite and goethite, are generally more abundant in facies 1 where the minerals often comprise 25 percent or more of the sand fraction. As remarked upon earlier, this change is accomplished chiefly by the introduction of goethite into the sediments and not by significant increases in the glauconite percentage.

Morphologically, the glauconite grains are overwhelmingly spheroidal to polylobate types and deeply furrowed (Triplehorn, 1966a, figs. 3, 4; 1966b, p. 94). Obvious ghosts of foraminiferal tests, ostracodes, or molluscan detritus are very rare and, in fact, usually absent. Triplehorn (1966a, p. 251) suggests that mammillated to lobate types result from the aggregation of smaller, rounded pellets while the pellets are still soft. During later solidification the shallow sutures connecting the the individual pellets may be accentuated to form deep cracks, a characteristic commonly displayed by the Aquia glauconites. The goethite grains are, in contrast, rarely polylobate, being instead smooth surfaced irregular ellipsoidal-shaped pellets, which in thin section are shown to contain inclusions of detrital quartz (plate 3). Some recent workers (Bell and Goodell, 1967, p. 199; Boyer, 1972, p. 5) have suggested that those glauconite species having ellipsoid or mammillate forms originated as fecal pelleted muds. For example, some polychaete worm and gastropod species void pellets having similar shapes and sizes (Kraeuter and Haven, 1970, fig. 12). Decomposing protoplasm in the fecal pellets is thought to be responsible for creating the microchemical environment necessary for glauconitization (Emery, 1960, p. 213); redox conditions would appear to be particularly favorable in abandoned, fecal-packed burrow tubes.

In shallow marine shelf areas characterized by relatively slow rates of terrigenous input, biogenic activities are proportionally more important; burrowing organisms disrupt stratification, shell heaps form, and fecal pellets become an important constituent of the sediments. Examples of the latter situation abound. For example, Allen (1970, p. 149) reports for the Nigerian shelf that "some cores display more than a metre of slightly compacted fecal pellets"; Haven and Morales-Alamo (1967) report that bottom sediments in the York River (Va.) estuary contain as much as 25 percent fecal pellets; and Reineck (1967, p. 205) reports that in the German North Sea "fecal pellets are present . . . in both tidal flat and shallow shelf sediments, whereas they are completely absent in beach samples".

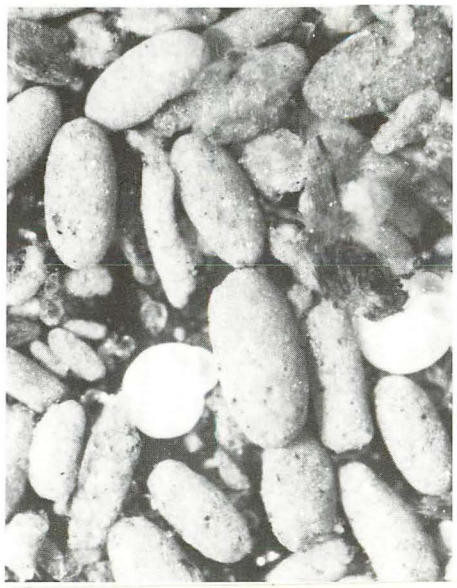
Authigenic glauconite is an imprecise bathymetric indicator, eliminating only the beach zone (Cloud, 1955). Insofar as the Aquia glauconites are mineralized fecal pellets, their presence merely signifies a biologically active marine setting, receiving terrigenous sediments at a relatively slow rate. An inner shelf setting with water depths certainly less than 300 feet is implied. However, other evidence, such as the occurrence of *Ostrea*, *Callianassa*, goethite pellets, iron-stained quartz sands, and perhaps "beach rock", suggest a much shallower depth, particularly for the sand bank complex.

Although limonite is a common subaerial weathering product of glauconite (Bentor and Kastner, 1965, p. 163), the pelletized form is considered authigenic (Porrenga, 1967, p. 496; Allen, 1970, p. 141). As discussed earlier, the known modern occurrences of pelletized goethite are restricted to warm shelf areas where they are found at shallow depths above the thermocline (Porrenga, 1967); they are usually associated with fecal pellets.

Morphologically, the ellipsoidal goethite pellets are distinctly different from the accordian, mammillated, or lobate-shaped glauconite grains. Insofar as both probably represent mineralized fecal pellets, the organisms shedding them must have certainly been different. At the present level of analysis it is moot as to whether this differentiation is primarily systemic (for example, polychaete worms versus gastropods), ecologic (epifaunal vs. infaunal), or trophic (for example, deposit versus suspension feeders) (Kornicker, 1962; Pryor, 1972; Rhoades and Young, 1970). Differences in morphology and internal composition of the grains suggest several distinctions, however. For example, the goethite grains are often 1 to 2 millimeters in their long dimension and in thin section contain very fine inclusions of detrital quartz and, less commonly, glauconite, suggesting that the fecal pellets from which they were derived were shed by large, nonselective deposit-feeding organisms. Furthermore, inasmuch as goethite is necessarily the product of an oxidizing environment at equilibrium with depoistional waters (Curtis and Spear, 1968, p. 261), the life mode of the organisms from which the pellets were derived was probably epifaunal or, perhaps, that of a very shallow infaunal plower (fig. 28). Accumulation in burrow tubes seems unlikely because their pore waters often exhibit negative Eh values. Modern agglomeratic fecal pellets having similar morphologies are reported by Harrison (1971, p. 53-59) to be an important constituent of the coastal bottom sediments of north-

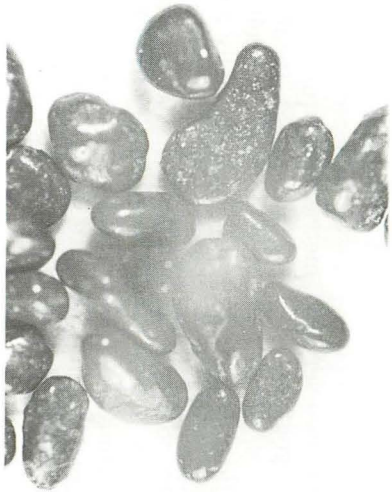
Polylobate glauconite grains found in Facies 1 of the Aquia Formation, (well cuttings from Cal-Db 23 at 400-415 feet).

0 1 mm
approx.



Modern, agglomeratic fecal pellets, probably shed by polychaete worms, (from Harrison, 1971, figure 12).

0 0.5 mm
approx.



Agglomeratic goethite pellets found in Facies 1 of the Aquia Formation, (well cuttings from Tal-Ce 62 at 619-629 feet).

0 1 mm
approx.

Plate 4. Photomicrographs comparing recent, agglomeratic fecal pellets voided by polychaete worms with goethite and glauconite grains from the Aquia Formation.

ern Virginia (plate 4).

If the oxidized, agglomeratic nature of the goethite pellets points intuitively toward deposit-feeding organisms which void at or just beneath the water-sediment interface, then conversely the microcrystalline texture of the smaller glauconite grains suggests production by selective suspension-feeding (syphonate) burrowers. Insofar as fecal-packed burrow tubes generally contain microreducing niches, the coprophagic muds deposited in the burrows are more favorably disposed to glauconization than goethite authigenesis.

Although the side by side production of glauconite and goethite pellets is geochemically improbable at the pore water level, data from modern marine cores suggest that substantial Eh-pH contrasts can occur in adjacent microenvironments, such as between abandoned, fecal-packed burrow tubes and the agitated carpet of detritus at the sediment-water interface (Emery, 1960, p. 264; Swanson and others, 1972, p. 19).

CONCLUSIONS

1. In outcrop the Aquia Formation becomes thicker and more coarsely textured northeastward from Charles County to Anne Arundel and Queen Anne's Counties. A study of geophysical logs and drill cuttings from water wells demonstrates the persistence of these trends into the subsurface.
2. Thickness, sand thickness, and sand percentage contours (figs. 8, 9, 12) diverge increasingly from the Aquia outcrop belt as they swing from northeast to south. The oblique relationship between these sedimentary trends and the Aquia structure contour map (fig. 7) suggests that post-Eocene tilting has modified the original strike of the formation.
3. The subsurface Aquia Formation consists of three first-order facies: 1, a thick coarse-textured sandy facies extending southwesterly in outcrop from Kent County to about the Patuxent River valley where it swings south into the subsurface; 2, a finely textured sandy and clayey facies which occurs chiefly in Charles and southern Prince George's County; and 3, a thinner, very muddy

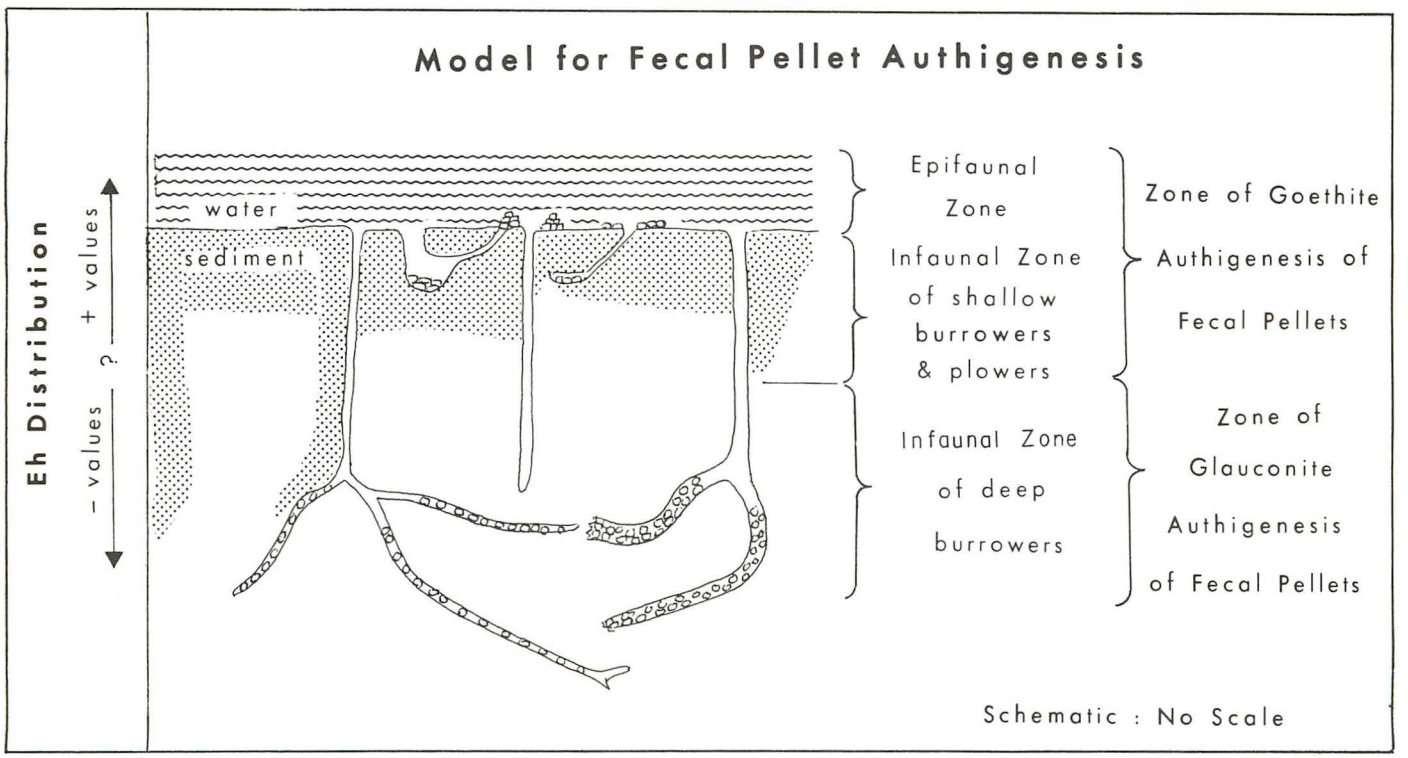


Figure 28.—Proposed model for fecal pellet authigenesis.

facies that appears to underlie much of the Eastern Shore seaward of the Choptank River.

4. Facies 1, in addition to being thicker and more coarsely textured, exhibits consistently higher transmissivity values, greater goethite concentrations, more intense iron-staining, and a somewhat greater occurrence of calcareously cemented, sand-packed shell beds.

5. Facies 1 exhibits the elongate isopach and lithofacies patterns characteristic of a sand bank complex. The occurrence of authigenic goethite, iron-stained quartz sand, and "beach rock" implies deposition in warm, very shallow marine waters.

6. The sand bank complex was, however, never sufficiently emergent for either beach or dune sands to form or lagoonal silts and clays to accumulate landward of it. Instead, a marine facies consisting predominately of muddy, fine, glauconitic sand was deposited in a lower energy, inner shelf environment occurring west (landward) of the sand bank complex.

7. Seaward of the sand bank complex, sand thickness values decline sharply, being consistently less than 25 feet. This thin very muddy facies probably represents an outer shelf deposit.

8. The Aquia Formation, particularly the sand bank complex, contains two important authigenic minerals, glauconite and goethite. Textural and morphological differences suggest strongly that the latter is not simply an alteration product of glauconite. Both are believed to be derived from fecal pellets which were voided by organisms having distinctly different systemic, ecologic, and (or) trophic processes.

REFERENCES

ALEXANDER, A. E., *1934, A petrographic and petrologic study of some continental shelf sediments: Jour. Sed. Petrol. Vol. 4, No. 1, pp. 12-22.*

ALLEN, J. R. L., *1970, Sediments of the modern Niger Delta, a review and summary* in *Delta sedimentation modern and ancient, ed. J. P. Morgan: Soc. Econ. Paleo. and Min. Special Publ. No. 15. pp. 138-151.*

BATHURST, R. G. D., *1971, Carbonate sediments and their diagenesis: American Elsevier Publ. Co., New York, 620 p.*

BELL, D. L. and GOODELL, H. G., *1967, A comparative study of glauconite and the associated clay fraction in modern sediments: Sedimentology, vol. 9, pp. 169-202.*

BENNETT, R. R. and COLLINS, G. G., *1952, Brightseat Formation, a new name for sediments of Paleocene age in Maryland: Wash. Acad. Sci. Jour., V. 42, pp. 114-116.*

BENTOR, Y. K. and KASTNER, M., *1965, Notes on the mineralogy and origin of glauconite: Jour. Sed. Petrol., Vol. 35, No. 1, pp. 155-166.*

BOYER, P. S., *1972, Cretaceous and Tertiary greensands and their faunas, New Jersey Coastal Plain: Guidebook for field trips of East Sect. Nat. Assoc. Geol. Teachers, pp. 5:1-5:22.*

BRICKER, O. P., *1971, Beach rock and intertidal cement, Introduction* in *Carbonate Cements: Johns Hopkins Univ. Studies in Geol. No. 19, pp. 1-3.*

BROOKHART, J. W. and others, *1949, The water resources of Anne Arundel County: Maryland Department of Geology, Mines and Water Resources Bull. 5, 149 p.*

BROWN, P. M., MILLER, J. A., and SWAIN, F. M., *1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U. S. Geological Survey Prof. Paper 796, 79 p.*

CASE, E. C., *1901, Reptilia in Eocene volume, ed. W. B. Clark: Maryland Geological Survey, pp. 95-98.*

CLARK, W. B., *1896, The Eocene deposits of the Middle Atlantic Slope in Delaware, Maryland and Virginia: U. S. Geol. Survey, Bull. 141, 167 p.*

---------, MARTIN, G. C., and others, *1901, Eocene volume: Maryland Geological Survey, 331 p.*

---------, MATHEWS, E. B., and BERRY, E. W., *1918, The surface and underground water resources of Maryland, including Delaware and the District of Columbia: Maryland Geol. Survey, Spec. Publ. Vol. 10, Part 2, 542 p.*

CLEAVES, E. T., WEAVER, K. N., EDWARDS, J., and GLASER, J. D., *1968, Geologic Map of Maryland: Maryland Geol. Survey, Baltimore, Md.*

CLOUD, P. E., *1955, Physical limits of glauconite formation: Amer. Assoc. Petroleum Geologists Bull. Vol. 39, No. 4, pp. 484-492.*

COOKE, C. W., *1952, Sedimentary deposits in Geology and water resources of Prince Georges County: Maryland Dept. Geology, Mines and Water Resources Bull. 10, pp. 1-53.*

CURRAY, J. R., *1960, Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico* in *Recent sediments northwest Gulf of Mexico ed. F. P. Shepard and others: Amer. Assoc. Petroleum Geol., Tulsa, Okla., pp. 221-226.*

CURTIS, C. D., and SPEARS, D. A., *1968, The formation of sedimentary iron minerals: Econ. Geol. Vol. 63, pp. 257-270.*

DARTON, N. H., *1948, The Marlboro Clay: Econ. Geol. Vol. 43, pp. 154-155.*

---------, *1951, Structural relations of Cretaceous and Tertiary Formations in part of Maryland and Virginia: Geol. Soc. America Bull. Vol. 62, No. 7, pp 745-779.*

DAVIES, D. K., ETHRIDGE, F. G., and BERG, R. R., *1971, Recognition of barrier environments: Amer. Assoc. Petroleum Geol. Bull. Vol. 55, No. 4, pp. 550-565.*

DROBNYK, J. W., *1965, Petrology of the Paleocene-Eocene Aquia formation of Virginia, Maryland and Delaware: Jour. Sed. Petrol., Vol. 35, pp. 626-642.*

EMERY, K. O., *1960, The sea off Southern California: John Wiley and Sons, New York, 366 p.*

FERGUSON, H. F., and others, *1953, The water resources of St. Marys County: Maryland Dept. Geology, Mines and Water Resources Bull. 11, 195 p.*

FISHER, W. L. and McGOWEN, J. H., *1969, Depositional systems in Wilcox Group (Eocene) of Texas and their relationship to occurrence of oil and gas: Amer. Assoc. Petroleum Geol. Bull. Vol. 53, No. 1, pp. 30-54.*

GLASER, J. D., *1968, Coastal Plain geology of Southern Maryland: Maryland Geol. Survey Guide Book No. 1, 56 p.*

---------, *1971, Geology and Mineral resources of Southern Maryland: Maryland Geol. Survey Rept. Invest. No. 15, 85 p.*

HANSEN, H. J., *1971, Transmissivity tracts in the Coastal Plain aquifers of Maryland: Southeastern Geology Vol. 13, No. 3, pp. 127-149.*

HARRISON, S. C., *1971, The sediments and sedimentary processes of the Holocene tidal flat complex, Delmarva Peninsula, Virginia: Unpubl. Ph. D. Dissert., Johns Hopkins Univ., Baltimore, Md., 202 p.*

HAVEN, D. S., and MORALES-ALAMO, R., 1967, *Occurrence and transport of fecal pellets in suspension in a tidal estuary: Sed. Geology Vol. 2, pp. 141-151.*

HAZEL, J. E., *1968, Ostracodes from the Brightseat Formation (Danian) of Maryland: Jour. Paleontology, Vol. 42, pp. 100-142.*

---------, *1969, Faunal evidence for an unconformity between the Paleocene Brightseat and Aquia Formations (Maryland and Virginia): U. S. Geol. Survey Prof. Paper 650-C, pp 58-65.*

HECKEL, P. H., *1972, Recognition of ancient shallow marine environments* in *Recognition of ancient sedimentary environments, ed. J. K. Rigby and W. K. Hamblin: Soc. Econ. Paleon. Mineral. Sp. Publ. No. 16, pp. 226-286.*

INGRAM, R. L., *1965, Facies maps based on the megascopic examination of modern sediments: Jour. Sed. Petrol. Vol 35, No. 3, pp. 619-625.*

IRWIN, M. L., *1965, General theory of epeiric clear water sedimentation: Amer. Assoc. Petroleum Geol. Bull. Vol 49, No. 4, pp. 445-459.*

JORDAN, R. R., *1963, Configuration of the Cretaceous-Tertiary boundary in the Delmarva Peninsula and vicinity: Southeastern Geology Vol. 4, No. 4, pp. 187-198.*

KAPPLE, G. W. and HANSEN, H. J., *in prep., A digital simulation model of the Aquia aquifer in southern Maryland: Maryland Geol. Survey.*

KORNICKER, L. S., *1962, Evolutionary trends among mollusk fecal pellets: Jour. Paleon. Vol. 36, No. 4, pp. 829, 834.*

KRAEUTER, J., and HAVEN, D. S., *1970, Fecal pellets of common invertebrates of lower York River and lower Chesapeake Bay, Virginia: Chesapeake Science Vol. 11, No. 3, pp. 159-173.*

KRAFT, J. C., SHERIDAN, R. E., and MAISANO, M., *1971, Time-stratigraphic units and petroleum entrapment models in Baltimore Canyon Basin of Atlantic continental margin geosyncline: Amer. Assoc. Petroleum Geol. Bull. Vol. 55, No. 5, pp. 658-679.*

LITTLE, H. P., *1916, Physical features of Anne Arundel County: Maryland Geol. Survey, 232 p.*

LOEBLICH, A. R., and TAPPAN, HELEN, *1957, Planktonic foraminifera of the Gulf Coastal region of the United States and adjacent areas: U. S. Nat. Mus. Bull. 215. pp. 173-198.*

LYNCH, E. J., *1962, Formation evaluation: Harper and Row, Inc., New York, pp. 83-226.*

MACK, F. K., *1962, Ground-water supplies for industrial and urban development in Anne Arundel County: Maryland Geol. Survey Bull. 26, 90 p.*

---------, *1966, Ground-water in Prince Georges County: Maryland Geol. Survey Bull. 29, 101 p.*

---------, WEBB, W. E., and GARDNER, R. A., *1971, Water resources of Dorchester and Talbot Counties, Maryland - with special emphasis on the ground-water potential of the Cambridge and Easton areas: Maryland Geol. Survey Rept. Invest. No. 17, 107 p.*

MAHER, J. C., *1971, Geologic framework and petroleum potential of the Atlantic Coastal Plain and Continental Shelf: U. S. Geol. Survey Prof. Paper No. 659, 98 p.*

MAXEY, G. B., *1964, Hydrostratigraphic units: Jour. Hydrology, Vol. 2, No. 2, pp. 124-129.*

MEYER, G., *1952, Ground-water resources in Geology and ground-water resources of Prince Georges County: Maryland Dept. Geol., Mines and Water Resources Bull. 10, pp. 82-254.*

MILLER, B. C., *1926, The physical features of Kent County: Maryland Geological Survey, 184 p.*

MINARD, J. P., and others, *1969, Cretaceous-Tertiary boundary in New Jersey, Delaware, and Eastern Maryland: U. S. Geol. Survey Bull. No. 1274-H, 33 p.*

NELSON, H. F. and BRAY, E. E., *1970, Stratigraphy and history of the Holocene sediments in the Sabine-High Island Area, Gulf of Mexico* in *Deltaic sedimentation modern and ancient, ed. J. P. Morgan: Soc. Econ. Paleon. and Min. Special Publ. No. 15, pp. 48-77.*

NOGAN, D. S., *1964, Foraminifera, stratigraphy, and paleoecology of the Aquia Formation of Maryland and Virginia: Cushman Foundation for Foraminiferal Research Spec. Publ. No. 7, 50 p.*

OTTON, E. G., *1955, Ground-water resources of Southern Maryland coastal plain: Maryland Dept. of Geology, Mines and Water Resources Bull. 15, 347 p.*

---------, and others, *1969, Ground-water aquifers and minerals commodities of Maryland: State Planning Dept. Publ. No. 152, 36 p.*

OVERBECK, R. M., *1948, The physical features of Charles County: Maryland Dept. of Geology, Mines and Water Resources, 267 pp.*

---------, *1950, The coastal plain geology of Southern Maryland: Johns Hopkins Univ. Studies Geology, No. 16, Pt. 3, pp. 15-56.*

---------, and others, *1951, The water resources of Calvert County: Maryland Dept. of Geology, Mines and Water Resources Bull. 8, 100 p.*

---------, and SLAUGHTER, T. H., *1958, The water resources of Cecil, Kent, and Queen Annes Counties: Maryland Dept. of Geology, Mines and Water Resources Bull. 21, 478 p.*

PAYNE, J. N., *1968, Geohydrology of the Claiborn Group: U. S. Geol. Survey Prof. Paper 569-A, 17 p.*

PORRENGA, D. H., *1967, Glauconite and chamosite as depth indicators in the marine environment: Marine Geology Vol. 5, No. 5/6, pp. 495-502.*

PRYOR, W. A., *1972, Biogenic pelletization and alteration of suspended argillaceous sediments (abst.): Amer. Assoc. Petroleum Geol. Bull. Vol. 56, No. 3, p. 645.*

RASMUSSEN, W. C. and SLAUGHTER, T. H., *1955, The water resources of Somerset, Wicomico, and Worcester Counties: Maryland Dept. of Geology, Mines and Water Resources Bull. 16, 535 pp.*

---------, *1957, The water resources of Caroline, Dorchester, and Talbot Counties: Maryland Dept. of Geology, Mines and Water Resources Bull. 18, 465 pp.*

REINECK, H. E., *1967, Layered sediments of tidal flats, beaches, and shelf bottoms of the North Sea:* in *Estuaries, ed. G. L. Lauff: Amer. Assoc. Advan. Sci. Publ. No. 83, p. 191-206.*

RHOADES, D. C., and YOUNG, D. K., *1970, The influence of deposit-feeding organisms on sedment stability and community trophic structure: Jour. Marine Res. Vol. 28, No. 2, pp. 150-178.*

RUSNAK, G. A., *1960, Sediments of Laguna Madre, Texas* in *Recent sediments northwest Gulf of Mexico ed. F. P. Shepard and others: Amer. Assoc. Petroleum Geol., Tulsa, Okla., pp 153-196.*

RUSSELL, R. J., *1971, Water-table effects on sea coasts: Geol. Soc. Amer. Bull., Vol. 82, No. 8, pp. 2343-2348.*

RYAN, J. D., *1953, The sediments of Chesapeake Bay: Maryland Dept. of Geology, Mines and Water Resources Bull. 12, 120 p.*

SEILACHER, A., *1967, Bathymetry of trace fossils: Marine Geology vol. 5, No. 5/6, pp. 413-428.*

SHEPARD, F. P., and MOORE, D. G., *1955, Central Texas Coast sedimentation: Characteristics of sedimentary environments, recent history, and diagenesis: Amer. Assoc. Petrol. Geol. Bull. Vol. 39, No. 8, p. 1463-1593.*

SHIFFLETT, E., *1948, Eocene stratigraphy and foraminifera of the Aquia Formation: Maryland Dept. of Geology, Mines and Water Resources Bull. 3, 93 p.*

SONU, C. J., *1973, Three-dimensional beach changes: Jour. Geol. Vol. 81, No. 1, pp. 42-64.*

SUNDSTROM, R. W. and PICKETT, T. E., *1968, The availability of ground-water in Kent County, Delaware, with special reference to the Dover area: Univ. Delaware Water Resources Center, 123 p.*

SWANSON, V. E., LOVE, A. H., and FROST, I. C., *1972, Geochemistry and diagenesis of tidal-marsh sediments, northeast Gulf of Mexico: U. S. Geol. Survey Bull. 1360, 83 p.*

SWIFT, D. J. P. and BOEHMER, W. R., *1972, Brown and gray sands on the Virginia shelf: Color as a function of grain size: Geol. Soc. Amer. Bull. Vol. 83, No. 3, p. 877-884.*

TRIPLEHORN, D. M., *1966a, Morphology, internal structure, and origin of glauconite pellets: Sedimentology Vol. 6, pp. 247-266.*

---------, *1966b, Glauconite provides good oil search data: World Oil Vol. 162, No. 1, pp. 94-97.*

TRUMBULL, J. V. A., *1972, Atlantic continental shelf and slope of the United States - sand size fraction of bottom sediments, New Jersey to Nova Scotia: U. S. Geol. Survey Prof. Paper 529-K, 45 p.*

VAN ANDEL, T. and POSTMA, H., *1954, Recent sediments of the Gulf of Paria: Reports of the Orinoco Shelf expedition Vol. 1, North-Holland Pub. Co., Amsterdam, 245 p.*

VISHER, G. S., *1965, Use of vertical profile in environmental reconstruction: Bull. Amer. Assoc. Petroleum Geologists Vol. 49, No. 1, pp. 41-61.*

WEIGLE, J. M., WEBB, W. E., and GARDNER, R. A., *1970, Water resources of Southern Maryland: U. S. Geol. Survey Hydrol. Invest. Atlas HA-365, 3 sheets.*

MARYLAND GEOLOGICAL SURVEY
214 Latrobe Hall
The Johns Hopkins University
Baltimore, Maryland 21218

Reports of Investigation:

1. Chemical quality of water and trace elements in the Patuxent River Basin, by S. G. Heidel and W. W. Frenier, 1965, 52 p. $1.00
2. Pleistocene stratigraphy of the Salisbury area, Maryland and its relationship to the lower Eastern Shore: a subsurface approach, by H. J. Hansen, 1966, 56 p. 2.25
3. Water resources of the Salisbury area, Maryland, by D. H. Boggess, and S. G. Heidel, 1968, 69 p. 3.00
4. Expandable clay in the St. Mary's Formation of Southern Maryland, by M. M. Knechtel, H. P. Hamlin, and J. W. Hosterman, 1966, 19 p. 1.00
5. Chemical quality reconnaissance or water of Maryland streams, by J. D. Thomas, 1966, 61 p. 2.00
6. Revision of stratigraphic nomenclautre—Glenarm Series of the Appalachian Piedmont, by D. L. Southwick and G. W. Fisher, 1967, 19 p. 1.50
7. Geophysical log cross-section network of the Cretaceous sediments of Southern Maryland, by H. J. Hansen, 1968, 56 p. 4.00
8. Piedmont and Coastal Plain geology along the Susquehanna Aqueduct: Baltimore to Aberdeen, Maryland by E. T. Cleaves, 1968, 45 p. 2.00
9. Chemical and physical character of municipal water supplies in Maryland, by J. D. Thomas and S. G. Heidel, 1969, 52 p. 1.00
10. Ground-water occurrence in the Maryland Piedmont, by L. J. Nutter and E. G. Otton, 1969, 56 p. 2.50
11. Petrology and origin of Potomac and Magothy (Cretaceous) sediments, Middle Atlantic Coastal Plain, by J. D. Glaser, 1969, 101 p. 3.50
12. Paleoecology of the Choptank Formation (Miocene) of Maryland and Virginia, by R. E. Gernant, 1970, 90 p. 4.50
13. Extent of brackish water in the tidal rivers of Maryland, by W. E. Webb and S. G. Heidel, 1970, 46 p. 1.50
14. Geologic and hydrologic factors bearing on subsurface storage of liquid wastes in Maryland, by E. G. Otton, 1970, 39 p. 2.75
15. Geology and mineral resources of Southern Maryland, by J. D. Glaser, 1971, 84 p. . . . 4.75
16. Flow characteristics of Maryland streams, by P. N. Walker, 1971, 160 p. 2.50
17. Water resources of Dorchester and Talbot Counties, Maryland with special emphasis on the ground-water potential of the Cambridge and Easton areas, by F. K. Mack, W. E. Webb, and R. A. Gardner, 1971, 107 p. 5.25
18. Solid-waste disposal in the geohydrologic environment of Maryland, by E. G. Otton, 1972, 59 p. 3.00
19. Hydrogeology of the carbonate rocks, Frederick and Hagerstown Valleys, Maryland, by L. J. Nutter, 1973, 70 p. 3.50
20. Hydrogeology of the formation and neutralization of acid waters draining form underground mines of western Maryland, by E. F. Hollyday and S. W. McKenzie, 1973, 50 p. 2.25
21. Sedimentary facies of the Aquia Formation in the subsurface of the Maryland Coastal Plain, by H. J. Hansen, 1974, 47 p. 3.50

Maryland Residents Add 4% Sales Tax

Sedimentary Facies of the Aquia Formation in the Subsurfaces of the Maryland Coastal Plain

R.I. No. 21, 1974