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

OPEN FILE REPORT

WASTE GATE FORMATION

PART ONE

Hydrogeologic Framework and Potential Utilization of the Brine Aquifers of the Waste Gate Formation, a New Unit of the Potomac Group Underlying the Delmarva Peninsula

by

Harry J. Hansen
Maryland Geological Survey

and

PART TWO

Palynology of Continental Cretaceous Sediments, Crisfield Geothermal Test Well, Eastern Maryland

by

James A. Doyle
University of California, Davis

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PART ONE

HYDROGEOLOGIC FRAMEWORK AND POTENTIAL UTILIZATION OF THE BRINE AQUIFERS OF THE WASTE GATE FORMATION, A NEW UNIT OF THE POTOMAC GROUP UNDERLYING THE DELMARVA PENINSULA

by

Harry J. Hansen
Maryland Geological Survey

ABSTRACT

The Lower Cretaceous Waste Gate Formation is a new name proposed for a subsurface unit of the Potomac Group occurring beneath the eastern Delmarva Peninsula; the top of the unit occurs at depths ranging from about 3,500 feet at its up-dip edge to 5,670 feet at the Coast. It consists chiefly of unconsolidated to moderately lithified, light gray to whitish, arkosic to subarkosic sandstones and drab, often finely laminated silty shales (or clays). It ranges up to 1,500 feet thick at the Coast with sand percentages characteristically 50 to 70 percent. The unit is tentatively dated Neocomian [Berriasian to Hauterivian (?)] on the basis of limited palynological data. An apparent absence of Clavatipollenites and other Zone I (mid-Barremian to early Albian) palynomorphs implies the Waste Gate Formation is older than the Patuxent Formation, which comprises the basal beds of the outcropping Potomac Group.

Sandstone porosities of the Waste Gate Formation, estimated from geophysical logs, range between 19 and 27 percent. Analysis of production test data for a Waste Gate sandstone in the DOE Crisfield Airport No. 1 well yielded permeabilities in the 75 to 118 millidarcy range. The formation waters of the Waste Gate are brines of the sodium-calcium-chloride type. The Crisfield Airport well produced brine with a chloride concentration of 42,000 mg/L (71,000 mg/L total dissolved solids). Elsewhere on the Peninsula, geophysical log estimates of NaCl salinity range from 53,700 mg/L to 97,000 mg/L. Below 3,000 feet Waste Gate fluid pressures increase under a hydrostatic pressure gradient of about 0.44 to 0.46 psi/foot. Temperature gradients appear to fall between 1.3° and 1.75° F/100 ft. Waste Gate formation temperatures range from about 124° F in up-dip areas to about 172° F near the base of the formation at the Coast; temperatures as high as 190° F are possible, but are less likely.

Possible utilization of the Waste Gate aquifer includes extraction of chemical commodities from brines, geothermal heat production, and disposal of hazardous wastes. The former is least likely, because commerical sodium-calcium chloride type brines have salinities three or four times greater than Waste Gate water. Because of the relatively low formation temperatures associated with the Waste Gate aquifers, large volumes of water are required to satisfy the energy requirements for geothermal heating. For example, about 300 gpm of 175° F water would be required to provide a 5×10^6 BTU/hr. peak requirement.

Although this yield from one well may be possible, the relatively low aquifer permeabilities would necessitate opening to production a number of sands totaling hundreds of feet of section (e.g., about 370 feet for an 85 millidarcy sand). Conversely, only modest injection rates would be possible, if it is required to confine the waste stream within one aquifer of the formation. It is estimated that injection rates in the 30 to 115 gpm range may be possible without risk of fracturing the confining beds.

INTRODUCTION

The Lower Cretaceous Waste Gate Formation that underlies the eastern portion of the Delmarva Peninsula is a newly erected subsurface unit of the Potomac Group. Until recently, the hydrogeologic characteristics of the Lower Cretaceous sediments underlying the Peninsula were poorly understood and were inferred largely from the stratigraphic descriptions of three deep oil test wells drilled in the 1940's (Anderson and others, 1948). In 1979 the completion of a deep (5,562 feet) geothermal test well located near Crisfield in Somerset County, Maryland, provided new information bearing on the stratigraphy, petrophysics, and interstitial water of the Waste Gate Formation (e.g., Hartsock, McCoy, and Radford, 1980). With the availability of these data, a modern reappraisal of the hydrogeologic characteristics of the deeper Potomac Group units became possible. One of these, the Waste Gate Formation, is discussed in the following sections of the report with emphasis on its potential utilization as:

1. brines for commercial and industrial applications
2. sources of low-temperature geothermal energy
3. subsurface space for the disposal and long-term storage of hazardous wastes.

POTOMAC GROUP

The Potomac Group underlying the Eastern Shore of Maryland (Maryland portion of the Delmarva Peninsula) is a largely non-marine fluvio-deltaic complex of interbedded sands and silt/clays which exceeds 5,200 feet in thickness at the Atlantic Coast. The unit is chiefly Lower Cretaceous to Cenomanian in age, but may include Upper Jurassic beds at its base. The basal beds of the Potomac Group thin up-dip by onlap with their age younging westward from Berriasian (or older) at the Coast to Barremian at their type locality in the Baltimore-Washington corridor. In its type area the Potomac Group is subdivided into the Patuxent and Arundel Formations of Barremian to early Albian age and the Patapsco Formation of Albian age. Elsewhere the formations are less distinct lithologically and the Potomac Group is often treated as an undivided unit. The toplapping upper beds of the Potomac Group are erosionally truncated by Santonian age sediments (Magothy Formation), which mark the beginning of a major cycle of marine sedimentation.

The areal distribution of individual sands within the Potomac Group is very complex and usually allows only local delineation, well control permitting. Informal groups of sands can often be correlated more widely and may define a hydraulically continuous aquifer system extending over two or three counties. In vertical profile the Potomac Group sands frequently exhibit fining upward cycles characteristic of meandering stream deposition (Hansen, 1969). Blocky profiles suggestive of braided or stacked channel sand deposits are also

common and may dominate locally. Eastward, the fluvio-deltaic complex becomes increasingly distributary (Robbins, Perry, and Doyle, p. 64, 1975) and includes, rarely, marginal marine elements. The thickness of individual sand beds varies widely, but usually does not exceed 150 feet without a significant (10 ft.) clay/silt break.

Potomac Group sands along the inner margin of the Maryland Coastal Plain are characteristically light-colored and quartzose, unconsolidated and porous (>35 percent). Field hydraulic conductivities are generally in the 20 to 250 ft/day range. Although only sparse data are presently available, it is clear that extrapolation of these parameters into the deeper subsurface should be avoided, particularly for basal onlapping units like the Waste Gate Formation. For example, sands of the Waste Gate Formation are typically feldspathic and often partially cemented with kaolinite or calcite, forming friable sandstones. Porosities can be expected to be significantly lower (19 - 24 percent), with aquifer permeabilities perhaps two to three orders-of-magnitude lower than the shallower Potomac Group sands currently in production.

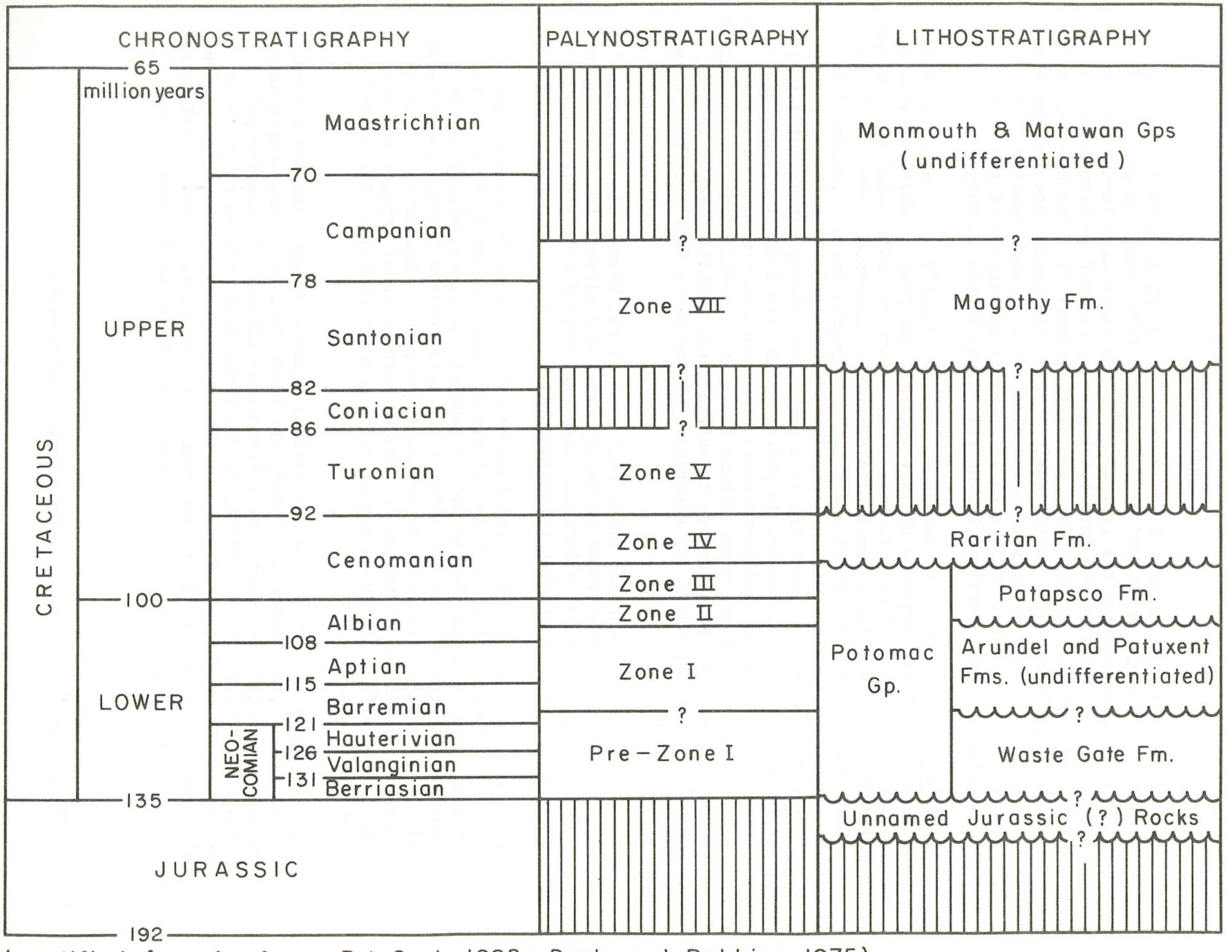
The only current utilization of the Potomac Group is for fresh water supplies, except in outcrop areas where sand and brick clay are quarried. At present, the Potomac Group is the largest source of potable (<250 ppm chloride) ground water in Maryland with production in the 35 to 40 million gallons per day range. Although much of this pumpage is from west of the Chesapeake Bay, Potomac Group aquifers in the 1,000 to 1,500 feet range yield fresh water to several southern Eastern Shore communities, including Cambridge and Crisfield. Generally speaking, however, the Potomac Group beneath the lower Delmarva Peninsula is saturated with salty water, ranging from slightly brackish to brines with salinities considerably greater than sea water.

None of the several deep test wells drilled in the area have shown any traces of oil or natural gas. Although the Potomac Group may contain commercial quantities of hydrocarbons, the general consensus is that production, if it occurs, will be off-shore along the outer edge of the continental shelf. Thus, any future onshore utilization of the saline aquifers of the Potomac Group will probably be focused on brine extraction, geothermal heat, or hazardous waste injection.

WASTE GATE FORMATION
STRATIGRAPHY

Nomenclature: The Waste Gate Formation is a new stratigraphic name introduced herein to identify a correlative sequence of subsurface beds underlying the eastern Delmarva Peninsula (table 1). These beds were previously included in the Potomac Group (undivided) (e.g., Robbins, Perry, and Doyle, 1975) or, if given formation rank, assigned to the lower part of the Patuxent Formation (Anderson, and others, 1948). Because, however, this stratal sequence differs significantly in age, lithology, and petrophysics from the Patuxent Formation at its type locality, a new stratigraphic ranking is

Table I. Proposed stratigraphy of the Potomac Group beneath the eastern Delmarva Peninsula



(modified from Am. Assoc. Pet. Geol., 1982; Doyle and Robbins, 1975)

warranted. The Ohio Oil Company L. G. Hammond No. 1 (Wi-Cg 37*) located in central Wicomico County (N 38° 20' 48", W 75° 29' 13"), near the cross-roads of Waste Gate, is designated the type well for the Waste Gate Formation. At this site, the Formation is 615 feet thick and was penetrated between 4,745 feet and 5,360 feet K.B. (Altitude: +70 feet) (figure 1). The Hammond well was drilled in 1944 and cored continuously through the Waste Gate section with good recovery. The core descriptions and electric logs were published by Anderson and others (1948). Only a small archival collection of the Waste Gate core remains in the Maryland Geological Survey sample library.

Lithology: The Waste Gate Formation consists largely of an unconsolidated to moderately lithified sequence of interbedded light gray to white arkosic to feldspathic sandstones and drab to occasionally mottled, silty shales (or clays), often finely laminated with carbonaceous material. Anderson (1948, p. 14) reports that the sandstones (sands) are relatively poorly sorted, ranging from fine to very coarse-grained with an occasional pebbly bed. The feldspars are often strongly kaolinized, resulting in a pervasive, clayey matrix sufficiently binding to form friable sandstones in places. The more indurated sandstones are associated with occasional occurrences of calcareous cement. Core descriptions provided by Anderson and others (1948, p. 408-412) indicate that about 27 percent of the arenaceous footage is sufficiently lithified to be called "sandstone", a figure perhaps representative of the Waste Gate Formation elsewhere in Maryland.

In addition to the Hammond well, 89.5 feet of the Waste Gate Formation was cored in the U. S. Department of Energy Crisfield Airport No. 1 well (Som-Dd 47) (figure 2). Similar lithologies were encountered (table 2), although the sands are not as feldspathic (<10 percent).

The Waste Gate Formation in the Hammond well is about 70 percent sandstone (sand); however, each unit is relatively thin and rarely exceeds 100 feet in thickness. In profile the self-potential (S.P.) signatures of the arenaceous beds (figure 1) do not exhibit the well-defined fining upward cycles generally ascribed to deposition by meandering streams. Rather they have a blocky aspect suggestive of braided or stacked sand channel deposition, perhaps associated with a higher energy alluvial complex (Robbins, Perry, and Doyle, 1975, p. 62).

Age and Biostratigraphy: In the earlier studies of Anderson and others (1948) and Spangler and Peterson (1950), the Waste Gate beds were lumped into the Patuxent Formation and dated Lower Cretaceous without biostratigraphic evidence. Later work by Maher (1971, p. 39) tentatively placed the beds in the Trinitian (?) or Aptian (?) stage of the Lower Cretaceous based on regional correlations with a deep well at Cape Fear, North Carolina. Brown, Miller, and Swain (1972, pl. 35), again largely on the basis of regional correlations,

* Well number assigned by the Maryland Geological Survey.

Figure 1a. Geologic cross-section from Sandy Point (Anne Arundel County, Maryland) to near Salisbury (Wicomico County, Maryland) showing proposed subdivision of the Potomac Group.

(See page 8)

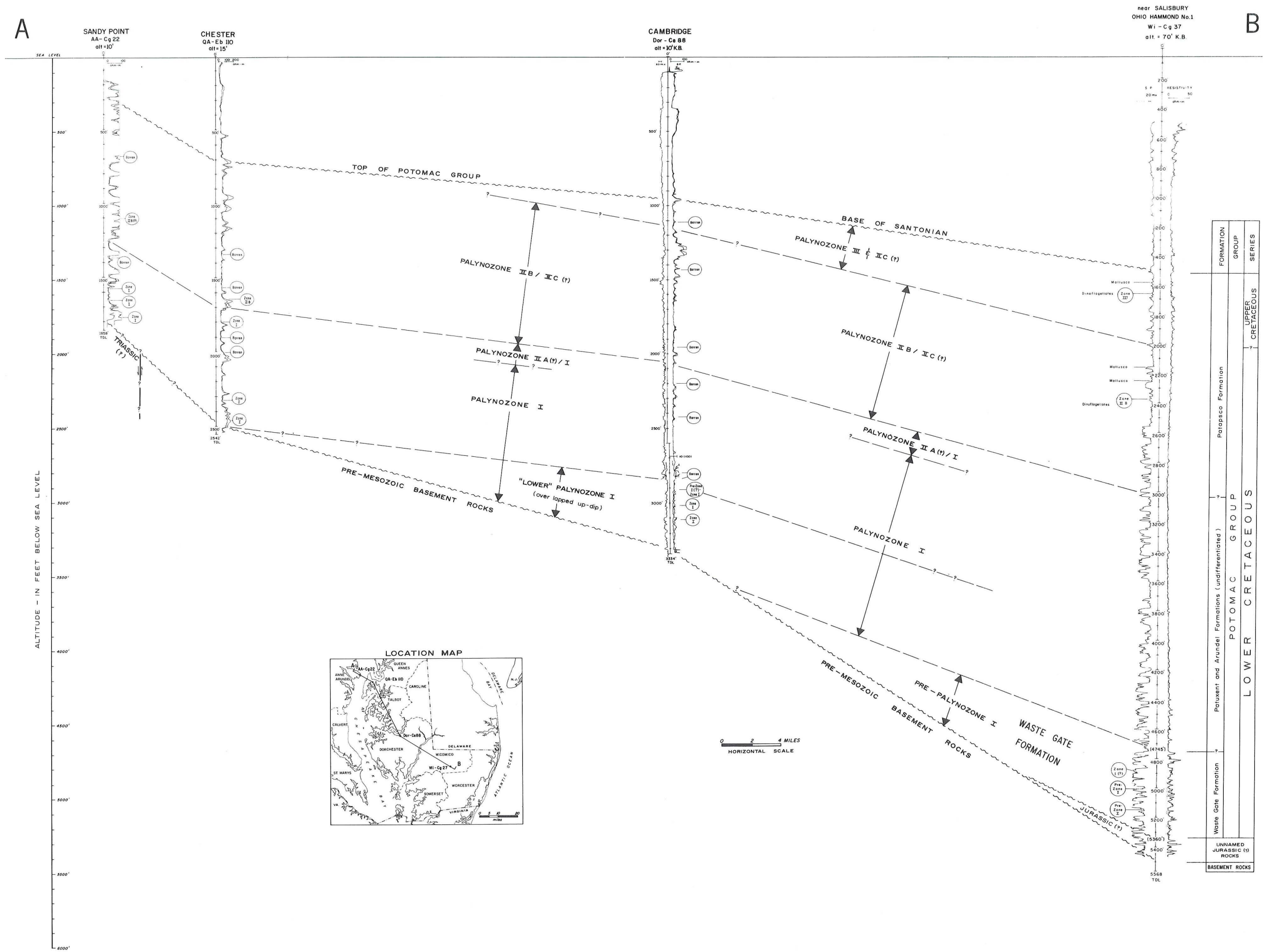

A
B
SANDY POINT
AA-Cg 22
alt.=10'
CHESTER
QA-Eb 110
alt.=15'
CAMBRIDGE
Dor-Ce 88
alt.=10' K.B.
near SALISBURY
OHIO HAMMOND No.1
Wi-Cg 37
alt. = 70' K.B.
SEA LEVEL
ALTITUDE - IN FEET BELOW SEA LEVEL
TOP OF POTOMAC GROUP
BASE OF SANTONIAN
PALYNOZONE IIB / IIC (?)
PALYNOZONE IIA(?)/ I
PALYNOZONE I
"LOWER" PALYNOZONE I
(over lapped up-dip)
PRE-MESOZOIC BASEMENT ROCKS
TRIASSIC (?)
PALYNOZONE III & IIC (?)
PALYNOZONE IIB / IIC (?)
PALYNOZONE IIA(?)/ I
PALYNOZONE I
PRE-PALYNOZONE I
WASTE GATE FORMATION
JURASSIC (?)
Barren
Zone IIB
Zone I
Zone II
Mollusca
Dinoflagellates
Pre-Zone I (?)
Pre-Zone II
Pre-Zone III
(4745')
(5360')
5568 TDL
0 2 4 MILES
HORIZONTAL SCALE
LOCATION MAP
QUEEN ANNES
ANNE ARUNDEL
CAROLINE
TALBOT
CALVERT
DORCHESTER
DELAWARE
WICOMICO
ST MARYS
SOMERSET
WORCESTER
VA.
VIRGINIA
ATLANTIC OCEAN
DELAWARE BAY
CHESAPEAKE BAY
FORMATION
GROUP
SERIES
Patapsco Formation
Patuxent and Arundel Formations (undifferentiated)
Waste Gate Formation
POTOMAC GROUP
UPPER CRETACEOUS
LOWER CRETACEOUS
UNNAMED JURASSIC (?) ROCKS
BASEMENT ROCKS

Figure 1b. Geologic cross-section from near Salisbury (Wicomico County, Maryland) to Ocean City (Worcester County, Maryland) showing proposed subdivision of the Potomac Group.
(See page 10)

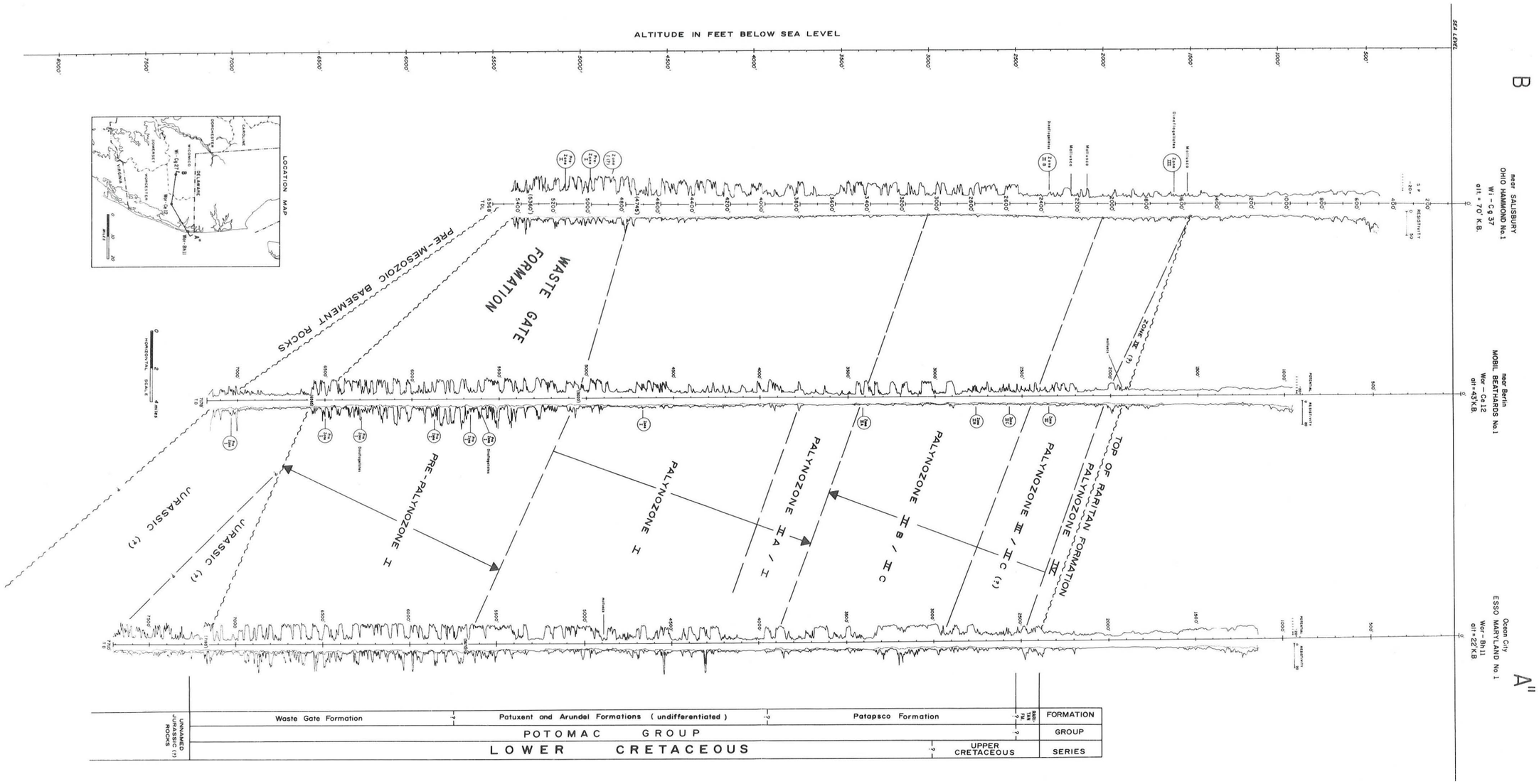
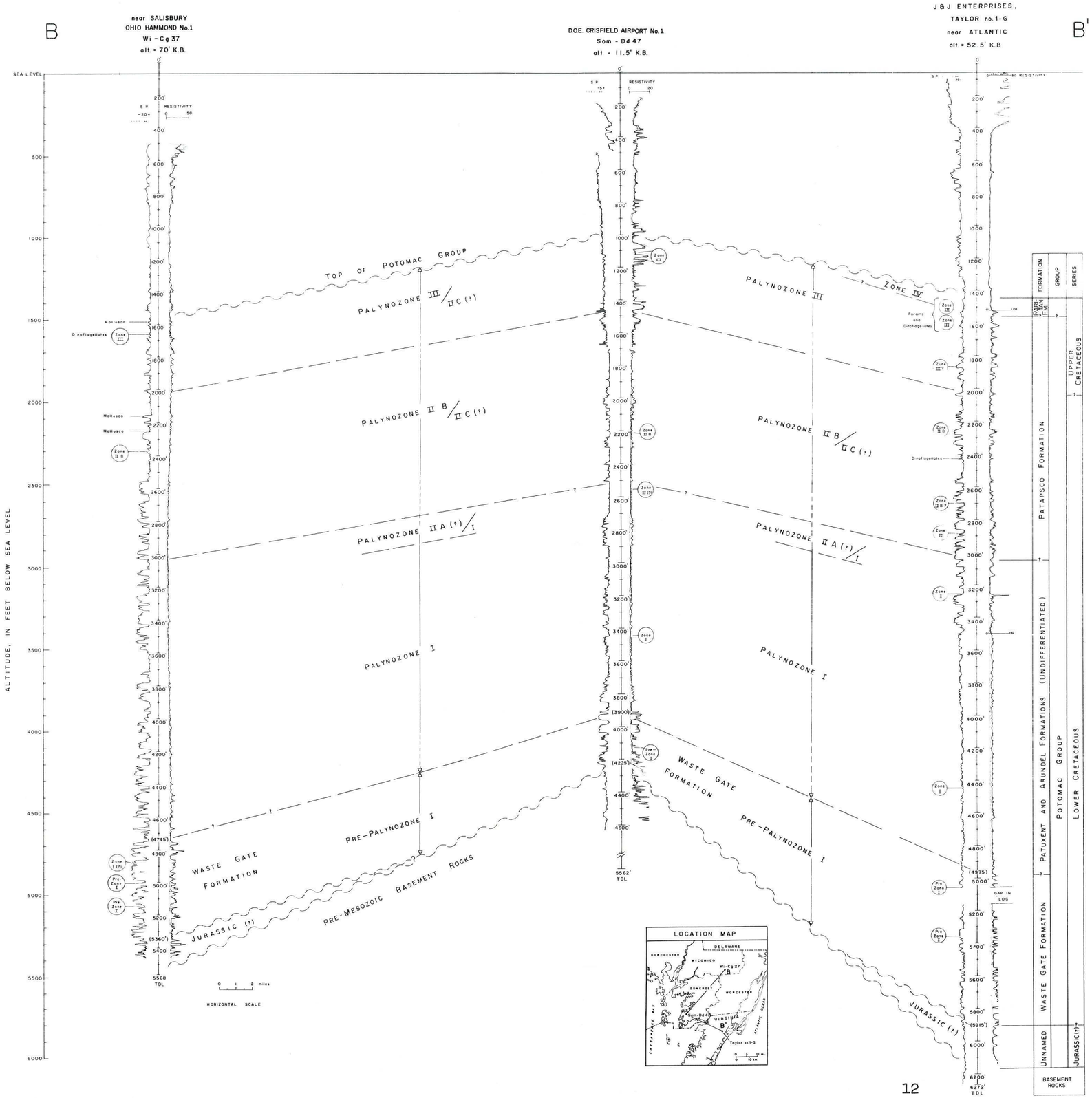

B
near SALISBURY
OHIO HAMMOND No.1
Wi – Cg 37
alt. = 70' K.B.
near Berlin
MOBIL BEATHARDS No.1
Wor – Ca 12
alt=43'K.B.
Ocean City
ESSO MARYLAND No 1
Wor – Bh 11
alt=22' K.B.
A''
ALTITUDE IN FEET BELOW SEA LEVEL
SEA LEVEL
LOCATION MAP
HORIZONTAL SCALE
PRE-MESOZOIC BASEMENT ROCKS
WASTE GATE FORMATION
JURASSIC (?)
PRE-PALYNOZONE I
PALYNOZONE I
PALYNOZONE II A / I
PALYNOZONE II B / II C
PALYNOZONE II / II C (?)
TOP OF RARITAN FORMATION
PALYNOZONE III
ZONE IX (?)
Waste Gate Formation
Patuxent and Arundel Formations (undifferentiated)
Patapsco Formation
RARITAN
FORMATION
POTOMAC GROUP
GROUP
LOWER CRETACEOUS
UPPER CRETACEOUS
SERIES
UNNAMED JURASSIC ROCKS

Figure 2. Geologic cross-section from near Salisbury (Wicomico County, Maryland) to near Atlantic (Accomack County, Virginia) showing proposed subdivision of the Potomac Group.
(See page 12)


B
near SALISBURY
OHIO HAMMOND No.1
Wi - Cg 37
alt. = 70' K.B.
DOE CRISFIELD AIRPORT No.1
Som - Dd 47
alt = 11.5' K.B.
J & J ENTERPRISES,
TAYLOR no. 1-G
near ATLANTIC
alt = 52.5' K.B
B'
SEA LEVEL
ALTITUDE, IN FEET BELOW SEA LEVEL
TOP OF POTOMAC GROUP
PALYNOZONE III / IIC (?)
PALYNOZONE IIB / IIC (?)
PALYNOZONE IIA (?) / I
PALYNOZONE I
PRE-PALYNOZONE I
WASTE GATE FORMATION
JURASSIC (?)
PRE-MESOZOIC BASEMENT ROCKS
ZONE IV
Forams and Dinoflagellates
Dinoflagellates
Mollusca
GAP IN LOG
5568 TDL
5562' TDL
6272' TDL
HORIZONTAL SCALE
LOCATION MAP
DELAWARE
DORCHESTER
WICOMICO
SOMERSET
WORCESTER
VIRGINIA
ATLANTIC OCEAN
CHESAPEAKE BAY
FORMATION
GROUP
SERIES
PATAPSCO FORMATION
UPPER CRETACEOUS
PATUXENT AND ARUNDEL FORMATIONS (UNDIFFERENTIATED)
POTOMAC GROUP
LOWER CRETACEOUS
WASTE GATE FORMATION
UNNAMED
JURASSIC(?)
BASEMENT ROCKS

placed the Waste Gate beds in the lower part of their Unit H. Although Unit H of Brown, Miller, and Swain (1972, pl. 2) included beds as young as Aptian, the lower part was probably older and may have included strata of Barremian/Neocomian age. The first palynological study of the Waste Gate section of the Potomac Group in Maryland was undertaken by Robbins, Perry, and Doyle (1975). Using core material from the Ohio L. G. Hammond No. 1, the Socony-Vacuum J. B. Bethards No. 1 (Wor-Ce 12) and the J. and J. Enterprises E. G. Taylor No. 1-G (from neighboring Accomack County, Virginia) they established a Lower Cretaceous age for the Waste Gate beds (figs. 1a, 1b, 2). Furthermore, they strongly suggested that the beds were pre-Barremian (i.e., pre-Zone I of Brenner, 1963) based on the absence of Clavatipollenites hughesii and other Zone I palynomorphs found in the outcropping Patuxent and Arundel Formations.

Habib (1977) reviewed Robbins, Perry, and Doyles' work and considered their pre-Zone I beds to correlate with his Ephedripites multicostatus Zone of Berriasian to Hauterivian (Neocomian) age. More recent work on the D.O.E. Crisfield Airport No. 1 well by J. A. Doyle (1982) and G. J. Brenner (per comm., 1981) confirms a pre-Barremian age for the Waste Gate beds. In a study of core samples between 4,121 feet and 4,148 feet Doyle reports in Part Two that the schizaeaceous and verrucate spores correlate with mid-Berriasian assemblages reported by Norris (1969), Hughes and Croxton (1973), and Doring (1965).

Brenner made a preliminary evaluation of two core samples from the Crisfield Airport No. 1 well (table 3). He reported that for sample 4,139.5 to 4,140 feet the most conservative evaluation of the age would be Late Berriasian to Hauterivian (?). Typical Barremian forms such as Clavatipollenites were not found in this sample. Nor were they found in a second core (4,121.6 feet to 4,122.1 feet) from the Crisfield Airport well or in a core from the Socony-Mobil Bethards well (5,612 - 5,628 feet) (figure 1). Brenner dated the latter sample pre-Zone I, conservatively placing it between the Berriasian and the lowermost Barremian. Table 3 contains Brenner's discussion of the palynology of the three cores. Although the available palynological data strongly suggest that the Waste Gate Formation is largely of Berriasian to Hauterivian (?) age, Brenner (1981, per comm.) also reported the presence of Peromenoletes peroreticulatus, an early angiosperm type common in Zone I, in a core (4,927 - 4,933 feet) from the Ohio Hammond No. 1 well (figure 1). This evidence retains the possibility that the upper beds of the Waste Gate Formation may extend into the early Barremian.

Areal Distribution, Thickness and Lithofacies: The Waste Gate Formation is a subsurface unit on the Delmarva Peninsula. It is known to occur beneath parts of Somerset, Wicomico, and Worcester Counties, Maryland, and Accomack County, Virginia (figure 3). The Waste Gate probably underlies a portion of Sussex County, Delaware, and, based on the correlations of Brown, Miller, and Swain (1972, pl. 54), and Maher (1971, pl. 9) may extend at least as far north as the Anchor Dickinson No. 1 at Cape May Point, New Jersey. Glaser (per comm., 1982, 1969) has noted that the outcropping "Patuxent Formation" of Virginia is lithologically similar to the Waste Gate. Although correlation of the two units is not possible with existing data, a lithologically similar source area is implied.

Table 2. Lithologic description of Lower Cretaceous cores from the U. S. Department of Energy Crisfield Airport No. 1 Well (D. Drummond, per comm., 1981).

Depth in feet below K.B.	Core Description
4,119.5 - 4,120.4	Clayey silt, yellow-gray; silt portion mostly quartz, subangular, clear, well sorted; micaceous, pyritiferous, lignitic; possibly some plagioclase grains
4,120.4 - 4,122.1	Shale, medium gray, highly lignitic, micaceous; rythmic banding of light and dark gray; feldspar grains intermixed toward bottom of interval
4,122.1 - 4,123.7	Sand, light gray-tan, poorly indurated, very poorly sorted (grain size varies from very fine sand to medium gravel; mostly quartz, angular to subangular, clear, some frosted, sparsely iron-stained; also some organic chips, muscovite, oxidized pyrite; cemented with white, powdery, noncalcareous cement which disaggregates readily in water (kaolinite ?)
4,123.7 - 4,130.0	Silty clay, light gray to dark brown-gray faintly laminated in places, mottled with yellow clay
4,130.0 - 4,131.2	Siltstone, medium gray-green, well indurated; grains silt-sized, mostly quartz, some muscovite, dark minerals
4,131.2 - 4,134.2	Clayey silt, light gray-tan, poorly indurated, laminated on a 1 mm scale; laminations consist of dark bands of organic rich layers; silt portion is mostly quartz, subangular to well-rounded, clear, sparsely frosted, colorless; some muscovite
4,134.2 - 4,141.2	Silty clay, dark gray, non-structured, dense, micaceous; some organic material in slender rods (1 mm x 10 mm); hard, indurated toward bottom of interval; shaley from 4,138.1 - 4,141.2
4,142.0 - 4,146.9	Clayey silt; medium gray-green, poorly indurated; orange iron-stained patches; micaceous; sparse lignite; possibly some feldspar
4,146.9 - 4,149.9	Silty clay, medium brown, non-structured, micaceous; lignitic
4,149.9 - 4,155.0	Sandstone, light gray-tan, well indurated, slightly stratified; grains fine sand-sized, quartz, subangular, clear; some layers and patches of orange-brown, consisting of well-rounded iron-stained quartz fine sand; some patches of organic material; calcareous (4,152.1 - 4,155.0)
4,158.0 - 4,166.3	Sandstone, light gray-tan, well indurated, well stratified; grains mostly fine to medium sand-sized, with layers of coarse sand to medium gravel; poorly sorted; sand grains subangular, very clear to frosted, colorless, some iron-stained; cement consists of white, powdery, noncalcareous material, disaggregates in water; bands of well-rounded iron-stained quartz sand; numerous layers and patches of lignite; micaceous; sparse pyrite in the coarse layers; sparse grains of feldspar in coarse layers
4,166.3 - 4,170.7	Siltstone, tan and brown, irregularly banded with light and dark areas; lignite abundant; subangular to well-rounded quartz, clear and frosted; micaceous; grades downward to fine sand grains; at 4,169.4 dark gray-black, hard pyrite and clay cemented aggregate (15 x 12 mm); calcareous material 4,167.4 - 4,167.8; cement white, clayey
4,196.0 - 4,199.0	Sandstone, light gray, moderately to poorly indurated, weakly stratified, fine to medium; mostly quartz, some white feldspar, rounded to subangular, well-sorted; cement white, powdery; disaggregates moderately in water (kaolinite ?); quartz pebbles up to 15 mm

Table 3. - Palynological discussion of Lower Cretaceous core samples from the U. S. Department of Energy Crisfield Airport No. 1 Well, Socony-Mobil Bethards No. 1 Well, and Ohio Hammond No. 1 Well (G. J. Brenner, per comm.)

U. S. Department of Energy Crisfield Airport No. 1 Well
(Som-Dd 47)
4,121.6 - 4,122.1 feet
Stage Determination: Upper Berriasian - Hauterivian
Stratigraphic Correlation: Pre-Zone I
Paleoecology: Nonmarine

Diagnostic Plant Microfossils	Range	Frequency[1]
1. Alisporites spp.	LR*	
2. Callialasporites dampieri	Valang.-Turonian (ACP)**	R
3. Cerebropollenites mesozoicus	Berrias.-Aptian (ACP)	R
4. Cicatricosisporites australensis	Berrias.-Barremian (ACP)	R
5. Classopollis torosus	LR	A
6. Cyathidites minor	LR	A
7. Densoisporites velatus	LR	R
8. Eucommiidites troedssonii	LR	A
9. Exesipollenites tumulus	LR	O
10. Pilosisporites sp. 2 (115)	Berrias.-Albian	R
11. Podocarpidites sp.	LR	O
12. Taurocusporites reduncus	LR	O

Discussion

The absence of typical Zone I spores of the genera Trilobosporites, Cicatricosisporites and the absence of Clavatipollenites suggest a pre-Zone I horizon. Pilosisporites both in England (Norris, 1969) and the Netherlands (Burger, 1966) does not enter the section until the late Berriasian. Unfortunately, the above sporomorphs do not permit a more confined dating.

[1] R=Rare (<1%); O=Occasional (1-5%); C=Common (6-10%); A=Abundant (>10%)

* Long-Ranging

** Atlantic Coastal Plain

U. S. Department of Energy Crisfield Airport No. 1 Well
(Som-Dd 47)
4,147 - 4,147.5 feet
Stage Determination: Late Berriasian to Hauterivian
Stratigraphic Correlation: Post Jurassic - Pre-Zone I
Paleoecology: Nonmarine

Diagnostic Plant Microfossils	Range	Frequency
1. Aequitriradites spinulosus	Berriasian-Cenom. (ACP, Europe)	R
2. Aequitriradites verrucosus	Upper Berrias.(Europe)	R
3. Callialasporites trilobatus	Berrias.-Aptian (ACP)	R
4. Cerebropollenites mesozoicus	LR	R
5. Converrucosisporites variverrucatus	Upper Jurassic-Valang.	R
6. Denoisporites microrugulatus	LR	R
7. Densoisporites cf. velatus	Late Berrias.-Valang. (Europe)	R
8. Ephedripites multicostatus	Berrias.-Cenomanian	R
9. Gleicheniidites circinidites	LR	
10. Parvisaccites radiatus	Upper Jurassic-Albian?	C
11. Pilosisporites sp. 2 (115) Bebout	Berrias.-Albian (ACP)	O
12. Pilosisporites trichopapillosus	Berrias.-Albian (ACP)	R
13. Trilobosporites sp. 2 (133) Bebout	Valang.-Hauterivian	C
14. Vitreisporites pallidus	Valang.-Maestricht.	R

Discussion

In 1969, Norris published a palynological study of the Upper Jurassic - Lowermost Cretaceous section from Southern England. If one applies Norris' ranges to the above list of palynomorphs, the above sample is younger than the Lower Purbeck from southern England. The following species first appear in the Middle Purbeck (Berriasian) and are not found in the underlying Portlandian (Tithonian):

1. Pilosisporites spp.
2. Pilosisporites trichopapillosus
3. Callialasporites trilobatus
4. Aequitriradites spinulosus
5. Ephedripites multicostatus

Dr. John W. Bebout (1981) of the U. S. Geological Survey has recently finished an informal zonation of palynomorphs from some Mid-Atlantic (OCS) wells. Based on his data, the following species places this sample above the Berriasian and below the Barremian:

1. Trilobosporites sp. 2 (133) Bebout — Valang.-Hauterivian
2. Vitreisporites pallidus — Valang.

Based on Dorhofer, (1979) the following species do not occur in Europe before the Upper Berriasian or Valanginian:

1. Aequitriradites verrucosus
2. Aequitriradites spinulosus
3. Densoisporites microrugulatus

Although Parvisaccites radiatus first appears in the Upper Jurassic of Europe, it does not beome persistent until the Berriasian. This species is a common element in the palynoflora of this sample.

On the basis of the above comparisons with the pertinent literature, the most conservative evaluation of the age of this sample would be Late Berriasian to Hauterivian.

Typical Barremian forms such as Clavatipollenites spp. are not found in this sample.

Table 3 (continued)

Ohio Hammond No. 1 Well
(Wi-Cg 37)
4,927 - 4,933 feet
Stage Determination: Barremian-Aptian
Stratigraphic Correlation: Zone I
Paleoecology: Nonmarine

Diagnostic Plant Microfossils	Range	Frequency[1]
1. Araucariacites australis	LR*	R
2. Callialasporites dampieri	Valang.-Turonian (ACP)**	R
3. Classopollis torosus	LR	C
4. Converruosisporites cf. variverrucatus	LR	C
5. Cyathidites sp.	LR	C
6. Klukisporites sp.	LR	R
7. Matonisporites sp.	LR	R
8. Peromonoletes peroreticulatus	Zone I & II (ACP)	R

Discussion

The palynomorphs present in this sample are typical of the Lower Cretaceous of the Atlantic Coastal Plain. Although the population is sparse, the presence of Peromonoletes peroreticulatus, an early angiosperm type, is common in Zone I. The small (sparse) population prevents more precise correlation. No marine forms were found.

Socony-Mobil Bethards No. 1 Well
(Wor-Ce 12)
5,612 - 5,628 feet
Stage Determination: Lowermost Barremian-Berriasian
Stratigraphic Correlation: Post Jurassic - Pre-Zone I
Paleoecology: Nonmarine-marginal marine (?)

Diagnostic Plant Microfossils	Range	Frequency
1. Acanthotriletes varispinosus	LR	O
2. Cicatricosisporites australiensis	Berriasian-Barremian	C
3. Cicatricosisporites purbeckensis	Berriasian-Barremian	C
4. Converruscosisporites cf. variverrucatus	LR	R
5. Cyathidites sp.	LR	C
6. Densoisporites perinatus	Zone I & II	R
7. Eucommiidites troedssonii	Zone I & II	C
8. Parvisaccites sp.	Zone I & II	O
9. Phyllocladidites microreticulites	Zone I & II	R
10. Pilosisporites trichopapillosus	Berriasian-Albian	O
11. Pinuspollenites sp.	LR	R
12. Podocarpidites sp.	LR	R
13. Reticulatisporites cf. sp. 2 (Bebout sp. 138)	Berriasian	R
14. Rogalskisporites cicatricosus varirotundus - typical form of Rogalskisporites cicatricosus peak zone of Berriasian	Berriasian-Albian	R
15. Taxodiaceaepollenites hiatus	LR	O
16. Vitreisporites pallidus	Valang.-Maestricht.	O

Discussion

The absence of typical monosulcate angiosperms typical of Zone I and common occurrence of Cicatricosisporites australensis and C. purbeckensis coupled with the occurrence of Rogalskisporites cicatricosus strongly suggests a pre-Zone I horizon for this sample. The first occurrence of Clavatipollenites in the Wealden Section of England is Middle Barremian (Hughes and Croxton, 1973). Based on the study by Bebout (1981) of the subsurface palynology of the Baltimore Canyon area, I would conservatively place the age of this sample in pre-Zone I, between lowermost Barremian to Berriasian.

The paleoecology of this sample based on the relative amounts of nonmarine and marine elements suggests a nonmarine to marginal depositional site. The proximity of the marine environment is indicated by a few rare fragements of cysts of acritarchs.

[1] R=Rare (<1%); O=Occasional (1-5%); C=Common (6-10%); A=Abundant (>10%)

* Long-Ranging

** Atlantic Coastal Plain

Offshore of New Jersey, partially coeval Berriasian to Hauterivian beds have been identified by Scholle and others (1980, figures 23, 24) in both the COST B-2 and COST B-3 wells (figure 3). In the COST B-2 well drilled about 91 miles east of Atlantic City on the outer continental shelf these strata are nonmarine, except for a mid-shelf Berriasian section. On the continental slope 32 miles south of B-2, however, COST well B-3 penetrated an uninterrupted marine Berriasian to Hauterivian section.

In Maryland, the Waste Gate Formation has been penetrated in only four wells; two in Worcester County and one each in Wicomico and Somerset Counties (figure 4). At the Coast, the unit is about 1,515 feet thick in the ESSO Maryland No. 1. Although correlation of the Waste Gate Formation into the COST B-2 and B-3 wells is tentative, the Berriasian to Hauterivian section appears to show only a modest increase in thickness offshore (1,925 feet and 1,750 feet respectively) (Scholle and others, 1980, p. 48-49). Up-dip the Waste Gate Formation thins relatively rapidly by onlap. It is, for example, only 615 feet thick in the Ohio Hammond No. 1 and even thinner, 325 feet, in the DOE Crisfield Airport No. 1. The feather-edge trend of the unit is undetermined because of a lack of data, but probably does not extend west of the Nanticoke River. Dor-Ce 88 drilled at Cambridge, for example, encountered lower Barremian beds overlying crystalline (gneissic) basement rocks* (figures 1 and 4). Nevertheless, it remains possible that patchy outliers of the Waste Gate Formation may occur west of the Nanticoke River, but are probably not as widespread as the reflection seismic data interpreted by Hansen (1978, p. 14) may have suggested.

The Waste Gate Formation in Maryland is a nonmarine alluvial sequence of interbedded feldspathic sandstones (sands) and shales (clays). The sands are poorly sorted ranging from fine to pebbly. The unit is characterized by high sand percentages (49% to 71%), particularly the northern wells that are nearer the axis of the Salisbury embayment (figure 4). The Waste Gate Formation in Maryland contains both carbonaceous laminae and calcareous sandstones, but does not exhibit coaly seams or limestones. Although rare occurrences of marine or brackish water fossils have been noted**, the evidence generally favors a high-energy, alluvial setting dominated by fluvial channel facies proximal to the early Cretaceous Fall Line.

The COST B-2 well also penetrated a dominately nonmarine Hauterivian-Valanginian section dominated by feldspathic sandstones and shales. But the presence of coaly seams, calcareous shales, and occasional limestones coupled

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* Gneissic basement rocks at Cambridge provide a local, feldspathic source area for the Waste Gate sandstones occurring in eastern Maryland.

**Brenner (per comm., 1981) suggested the proximity of a marine environment on the base of the rare occurrence of acritarch cysts in the Mobil-Bethards well (see tab. 3).

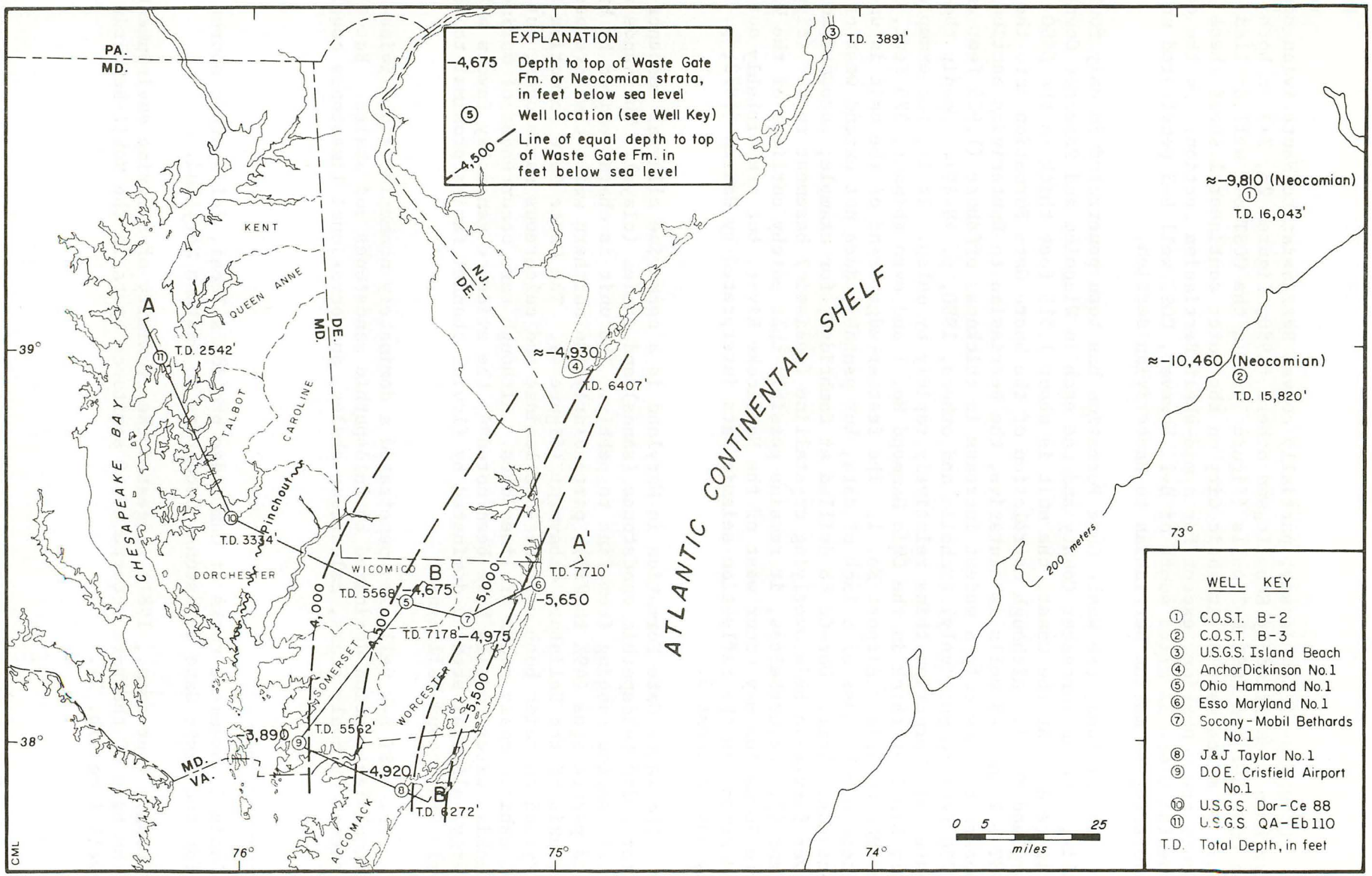

Figure 3. Contour map showing altitude of the top of the Waste Gate Formation beneath the Delmarva Peninsula and vicinity

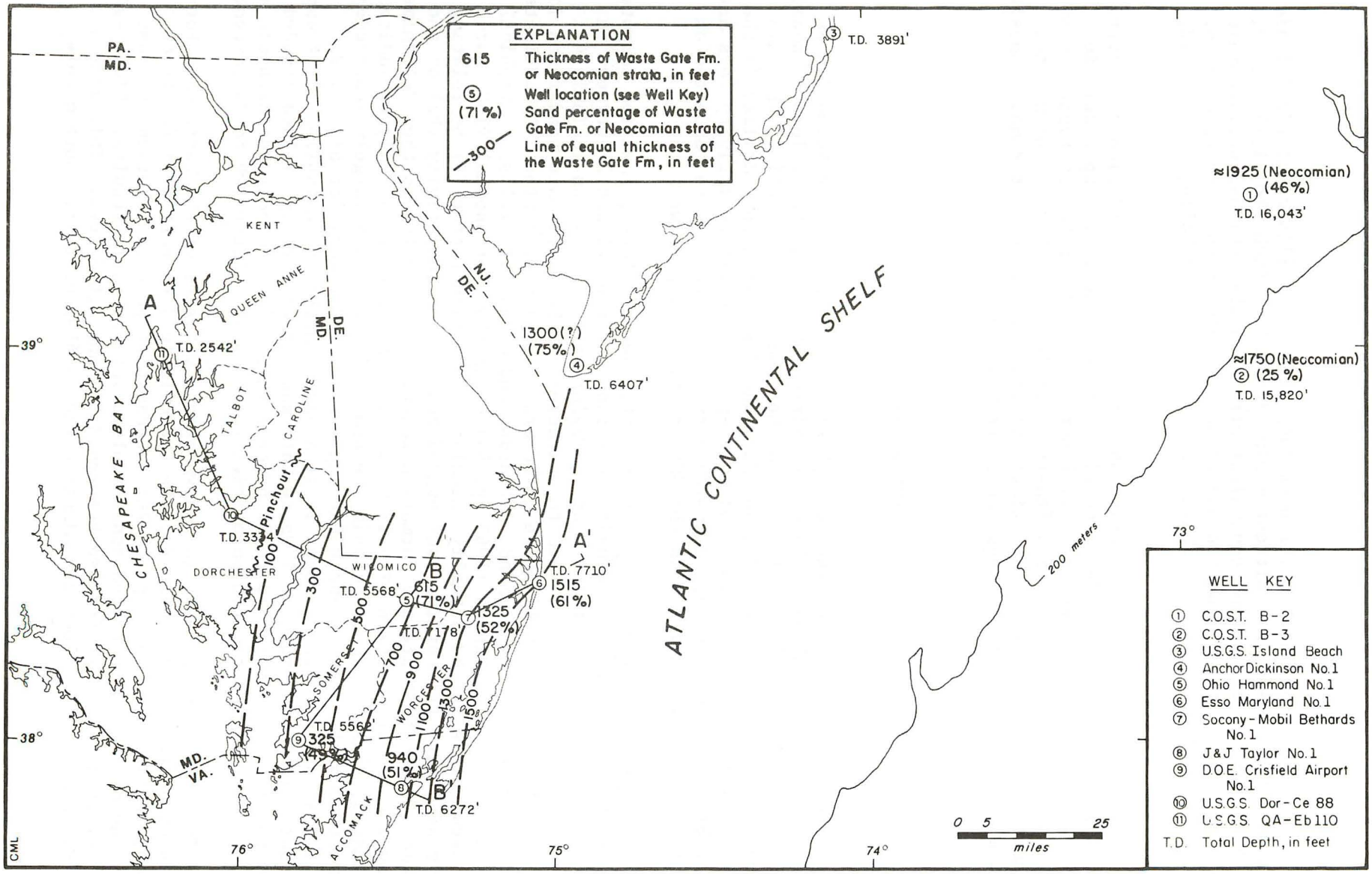

Figure 4. Well location map showing total thickness and cumulative sand percentage of the Waste Gate Formation beneath the Delmarva Peninsula and vicinity

with rare dinoflagellate occurrences suggest a lower (distributory) deltaic setting with perhaps intermittent marine incursions (Scholle, 1977, p. 19, 33, 42). On the other hand equivalent strata in the COST B-3 well contain inner to mid-shelf foraminifera and calcareous nannofossils in association with limy sandstones, marine shales, and limestones (Scholle, 1980, p. 22, 76).

Thus, the Waste Gate Formation and its off-shore Berriasian to Hauterivian (?) equivalents include three first order facies: 1) Upper deltaic fluvial facies (onshore wells), 2) Lower deltaic distributory facies (COST B-2), and 3) marine shelf or delta-front facies (COST B-3). Because the onshore and off-shore wells are widely separated, however, it remains possible that more than one deltaic sequence is represented.

PETROPHYSICS

Information regarding the petrophysics of the Waste Gate Formation is largely based on geophysical logs. A fairly complete suite of logs is available for the DOE Crisfield Airport and the J and J Taylor wells. The Ohio Hammond, Socony-Mobil Bethards, and Maryland Esso wells were drilled in the 1940's and only self-potential and multi-point electric resistivity logs are available. In addition, drawdown-recovery pumping tests were conducted on several Waste Gate aquifers in the DOE Crisfield Airport well.

Porosity and Permeability: Representative sandstone porosities computed from compensated formation density logs range between 21 and 27 percent in the DOE Crisfield Airport and J and J Taylor wells. As shown in Table 4 slightly higher porosities seem to characterize the Waste Gate sandstones in the Crisfield Airport well where it occurs at shallower depths. To estimate porosity values in the Hammond, Bethards, and Ocean City wells, a graphical method described by Pirson (1963, p. 94) using the short-normal (16") curve was used. This method actually calculates formation factor (F) by relating the resistivity (Ri) of the mud-invaded zone to the resistivity (Rz) of the mixture of mud filtrate and formation water. Porosity (θ) is then determined using the Archie equation ($F = 1/\theta^m$, $m = 2$). Because Rz can only be indirectly estimated, this method of porosity determination has been largely superceded by more accurate density and sonic log methods. However, for old wells lacking a modern suite of logs, it is a useful method to establish first approximations. In the Hammond well Waste Gate sandstones largely yielded invaded zone porosities of about 23 to 27 percent (table 4). In both the Bethards and Ocean City wells, estimated porosities were somewhat lower (19 to 24 percent).

The only pumping tests (drawdown recovery tests) of the Waste Gate Formation conducted to date were for the DOE Crisfield Airport well (Hartsock, McCoy, and Radford, 1980, p. 10-26). Because of pump calibration problems only one of the three tested zones yielded interpretable results. Eighty-six feet of casing were perforated between 3,901 and 4,032 feet. This zone yielded about 118 gallons per minute during a 48-hour test. Bottom hole

Table 4. Estimated petrophysical characteristics of the Waste Gate Formation.

Well Name	Depth (K.B.) feet	Estimated Sandstone Porosities (Total)		Estimated Formation Factors		Estimated Permeability, Millidarcies	
		Percentage	Method	F	Method	K	Method
DOE Crisfield Airport	3,900-4,225	24-27	Compensated Formation Density Log	10.9	$F = R_o/R_w$	75-120	pumping test
				10.4-13.3	Humble* Formula	63-122	Schlumberger Formula•
J & J E. J. Taylor	4,975-5,915	21-24	do	13.3-17.7	do	29-63	do
Ohio Hammond	4,745-5,360	23-27	Short Normal Electric log Method▲	10.4-14.6	do	49-122	do
Socony-Mobil Bethards	5,020-6,565	19-24	do	13.3-22.1	do	16-63	do
Esso Ocean City	5,670-7,180	19-24	do	13.3-22.1	do	16-63	do

$*F = \frac{0.62}{\theta^{2.15}}$

▲Graphic Solution (Pirson, 1963)

$•K = \left[\frac{100\ \theta_e^{2.25}}{SW_{irr}}\right]^2$

pressure declined 121 psi from an initial value of 1718 psi (water density = 1.031). Analysis of the straight part of the pressure build-up curve using the van Everdingen method gave a slope of 51 psi/cycle and a permeability of 75 millidarcies (Hartsock, McCoy, and Radford, 1980, p. 12-46). Achmad (per comm., 1979) analyzed the same drawdown and recovery data using standard ground-water techniques (Jacobs semi-log method). Over one time cycle (100-1000 minutes) the drawdown was 29.9 psi which yielded a transmissivity of 430 gallons/day/foot and a hydraulic conductivity of 5 gallons/day/foot^2 at field temperature (135° F). Analysis of the pressure recovery data using a plot of time versus extended drawdown minus residual drawdown yielded a calculated recovery of 38 psi over one time cycle (100-1000 minutes). Transmissivity and hydraulic conductivity values of 340 gallons/day/foot and 4 gallons/day/foot^2 were calculated from these data. These data converted to oil-field units suggest formation permeabilities in the range of 93 to 118 millidarcies.

Because formation tests were not conducted in the other wells penetrating the Waste Gate Formation, comparable permeability data are lacking elsewhere. Furthermore, even though the Ohio Hammond well was extensively cored, laboratory permeabilities were not run, or if so, were not reported publically. Lacking better data, an estimate of permeability can be obtained using the Schlumberger formula, which although useful, is at best only a semi-quantitative method. The formula is

$$K = \left[\frac{100\ \theta^{2.25}}{SW_{irr}} \right]^2 \qquad (1)$$

where K = permeability, in millidarcies
θ = effective porosity
SW_{irr} = irreducible water saturation

The values calculated from this formula are tabulated in table 4. Effective porosities were obtained by reducing the log-derived values by 5 percent, in accordance with Levorsen's (1967, p. 101) suggestion that effective sandstone porosities are usually 5 to 10 percent less than total porosities. In each case, the irreducible water saturation was assumed to be 30 percent. On this basis, average sandstone permeabilities were estimated to range from a low of 16-63 millidarcies in the Esso Ocean City and Socony-Bethards wells to a high of 49-122 millidarcies in the Ohio Hammond well. Bear in mind that these values are offered only as order-of-magnitude approximations.

Pressure and Temperature: At present on the Delmarva Peninsula only one well, the DOE Crisfield Airport No. 1, has been completed in the Waste Gate Formation and systematically tested for bottom hole pressures and temperatures. To estimate regional gradients for these parameters, the Crisfield Airport well

data must be supplemented by other, less reliable information. Evidence at hand suggests that with increasing depth normal hydrostatic pressures prevail and that the geothermal gradient is probably within the expected range (1.3 to 1.75° F per 100 feet) for the Coastal Plain area.

Bottom hole shut-in pressures for the three zones tested in the Crisfield Airport well were reported to range between 1,679 psi at 3,822 feet (a sand immediately above the Waste Gate Formation) to 1,863 psi at 4,185 feet (Hartsock, McCoy, and Radford, 1980, p. 10-17). Using a reported specific gravity of 1.04, comparable salt-water heads are estimated to be -94 and -48 feet below sea level, respectively. It should be borne in mind that the tested zones were inadequately developed so that entrained mud or sand in the well bore could result in an imprecise pressure to head conversion. These data are graphically displayed in figure 5 along with representative static water-level information for the shallower, fresh-water part of the Coastal Plain. For comparison to the deep Crisfield data, fresh-water heads are also displayed as calculated bottom hole pressures in figure 5. An approximate best-fit line through these points yields a slope of about 0.44 psi/ft., a hydrostatic gradient slightly less than the Crisfield brines (0.45 psi/ft.), but more than fresh-water (0.433 psi/ft.).

The actual gradient between the upper and lower zones (363 feet) tested at Crisfield is 0.51 psi/ft. The value is significantly greater than hydrostatic and would imply a geopressured condition, if extrapolated to greater depth. Although some porosity reduction is evident in the Waste Gate Formation, it is probable that this is not representative of the regional condition. For example, the COST B-2 well drilled offshore reported a hydrostatic pressure gradient (0.435 psi/ft.) between 6,000 and 15,000 feet (Smith and others, 1976, fig. 8).

Figure 6 shows the range of bottom hole pressures likely to be characteristic of the Waste Gate Formation between its up-dip top (3,500 feet) and down-dip base (7,180 feet). The solid line is the expected trend and is based on a hydrostatic pressure gradient increasing with depth from 0.433 to 0.46 psi/ft. in accordance with increasing salinity. For comparison a high and low range is given. The low range assumes a constant gradient of 0.433 psi/ft. while the high range posits an unlikely geopressured condition (0.50 psi/ft.) below 4,000 feet depth.

Based on temperatures reported by Dashevsky and McClung (1979, p. A22-29) the average temperature gradient at Crisfield between 965 feet and 4,180 feet is approximately 1.74° F/100 ft. (figure 7), significantly lower than the average gradient above 965 feet (2.3° F/100 ft.). The Crisfield Airport well was drilled through the base of the Coastal Plain and penetrated several hundred feet of basement rock, reported by Gleason (1979, p. A-5) to be a grey-green, fine-grained metamorphic rock. An equilibrium bottom hole temperature of 152.5° F was measured at 5,553 feet. Also plotted on figure 7 is the log bottom-hole temperature for the J and J Taylor No. 1 located in Accomack County,

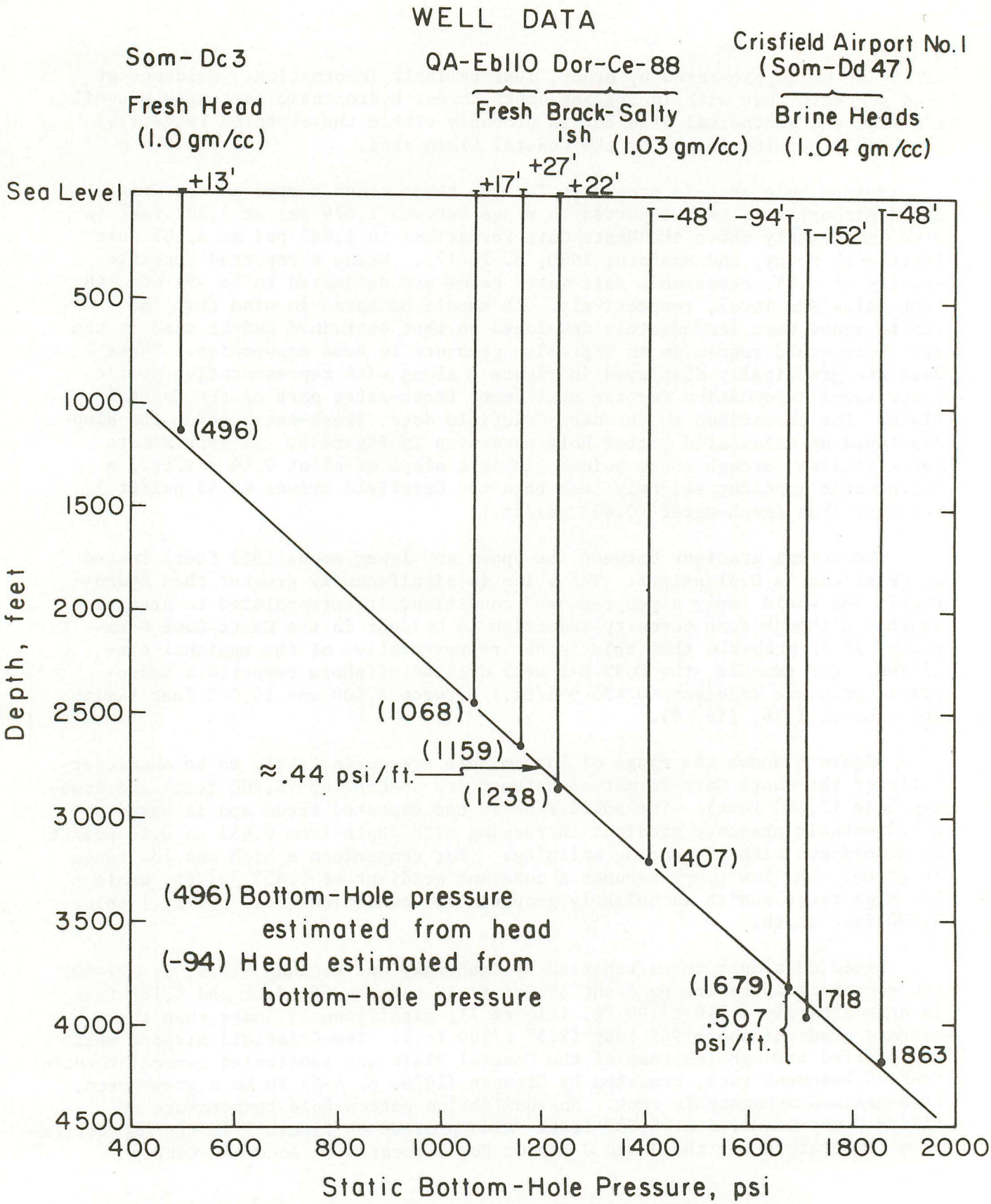

Figure 5. Graph showing the relationship between depth and bottom-hole pressure for several wells on the Delmarva Peninsula

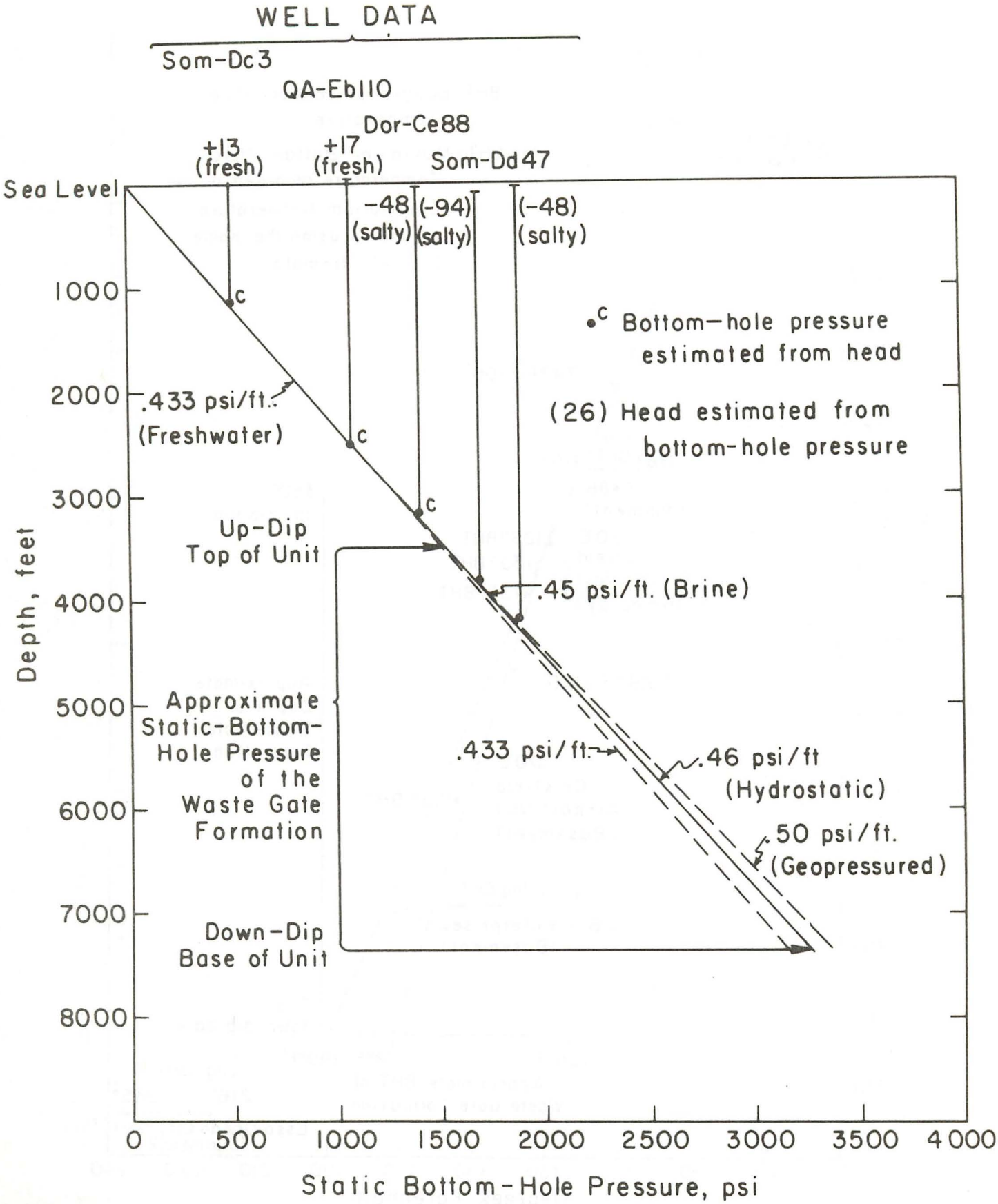

Figure 6. Graph showing estimated bottom-hole pressures of the Waste Gate Formation between 3,500 feet and 7,180 feet

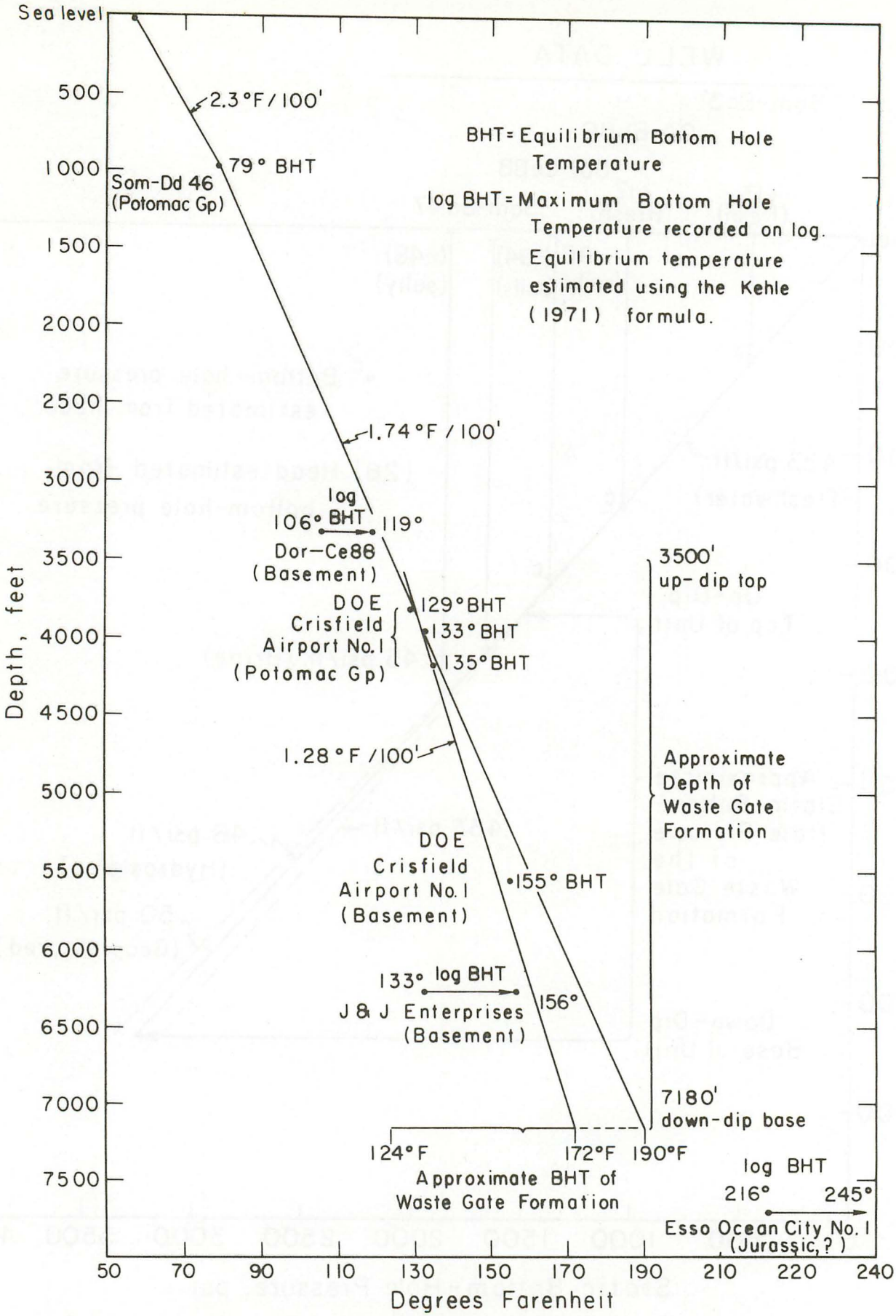

Figure 7. Graph showing estimated bottom-hole temperatures of the Waste Gate Formation between 3,500 feet and 7,180 feet

Virginia. A recorded temperature of 133° F at 6,271 feet was adjusted using Kehle's formula* (Bebout, Loucks, and Gregory, 1978, p. 74) for converting Gulf Coast log temperatures to equilibrium temperatures. This results in an adjusted temperature of 156° F, a useful but approximate value at best. A trend line through these points yields a geothermal gradient of about 1.28° F/100 ft. between 3,816 feet and 6,217 feet. What appears to be an anomalously high log bottom-hole temperature was recorded for the Esso Ocean City No. 1. An uncorrected temperature of 216° F was logged at 7,710 feet; application of the Kehle relationship produces an equilibrium temperature of 243° F, significantly hotter than what might have been expected by projecting the shallower geothermal gradients discussed above (figure 7). The gradient could be steeper in the Ocean City area, but the possibility of an unreliable temperature reading cannot be ruled out. Temperature logs run in the COST B-2 well (16,043 feet T.D.) 26 to 31 hours after cessation of mud circulation recorded a geothermal temperature gradient of about 1.5° F/100 ft. without any noteworthy anomalies (Smith and others, 1976, p. 23).

The anticipated range of bottom-hole temperatures through the Waste Gate section beneath the Delmarva Peninsula is also shown in figure 7. The values range from about 124° F in up-dip areas where the unit is overlapped to about 172° F near the base of the Formation near the Coast. Temperatures as high as 190° F are possible, although less likely.

Salinity: Although regional studies have suggested the occurrence of brines in the Waste Gate Formation (Manheim and Horn, 1968), the only water samples thus far collected for analysis are from the DOE Crisfield Airport No. 1 (table 5). The formation waters from two Waste Gate aquifers are brines with chloride concentrations (42,000 mg/l) over twice that of ocean water (18,980 mg/l). The following comparison of ion ratios by weight suggests that the brines probably evolved by concentrating connate ocean water which had intruded the formation after deposition.

Ionic Ratio	Ocean Water (from White, 1965, Tab. 1)	Waste Gate Formation Water
Ca/Cl	0.021	0.170
Mg/Cl	0.067	0.012
Na/Cl	0.53	0.46
K/Cl	0.020	0.015
SO_4/Cl	0.14	0.20

*The Kehle formula is an empirically-derived relationship based on a statistical study of Gulf Coast wells:

$$T_e = T_1 - 8.819 \times 10^{-12} D^3 - 2.143 \times 10^{-8} D^2 + 4.375 \times 10^{-3} D - 1.018 \qquad (2)$$

where T_e = equilibrium temperature (°F)
T_1 = bottom-hole well log temperature (°F)
D = depth (feet)

Table 5. Chemical analyses of three water samples from the Waste Gate and Lower Patuxent (?) Formations, Crisfield, Maryland

Well Number	SOM Dd 47	SOM Dd 47	SOM Dd47
Sample Date	6/23/79	6/28/79	7/5/79
Aquifer	Waste Gate	Waste Gate	Patuxent (?)
Sampling Depth (Ft.)	4,148-4,200	3,901-4,032	3,798-3,846
Elevation of Land Surface Datum (Ft. NGVD)	3.50	3.50	3.50
Temperature (Deg. C)	42.0	52.0	36.0
Density (Gm/ml at 20° C)	1.043	1.042	1.040
Agency Analyzing Sample (10/16/79)	U. S. Geol. Survey	U.S. Geol. Survey	U. S. Geol. Survey
Color (Platinum-Cobalt Units)	80	290	150
pH (Units)	6.7	6.3	6.7
Carbon Dioxide, Dissolved (Mg/l as CO_2)	16	40	---
Alkalinity (Mg/l as $CaCO_3$)	41	41	29
Nitrogen, Nitrite Total (Mg/l as N)	.02	.00	.01
Chloride (Mg/l as Cl)	42,000	42,000	41,000
Sulfate (Mg/l as SO_4)	870	820	1,000
Fluoride (Mg/l as F)	.8	.7	.5
Silica (Mg/l as SiO_2)	16	17	15
Arsenic (µg/l as As)	0	0	1
Barium (µg/l as Ba)	100	100	500
Beryllium (µg/l as Be)	0	0	20
Boron (µg/l as B)	9,200	8,600	1,000
Cadmium (µg/l as Cd)	0	0	0
Chromium (µg/l as Cr)	7	7	7
Cobalt (µg/l as Co)	0	0	0
Nitrogen, Nitrate Total (Mg/l as N)	.08	2.7	.05
Nitrogen, NO_2 + NO_3 Total (Mg/l as N)	.10	2.6	.06
Phosphorus (Mg/l as P)	.01	.01	.01
Hardness (Mg/l as $CaCO_3$)	20,000	20,000	19,000
Hardness, Noncarbonate (Mg/l as $CaCO_3$)	20,000	20,000	19,000
Calcium, (Mg/l as Ca)	7,200	7,100	6,900
Magnesium (Mg/l as Mg)	490	510	470
Sodium (Mg/l as Na)	18,000	21,000	26,000
Sodium Adsorption Ratio	55	65	82
Sodium Percent	66	70	75
Sodium-Potassium (Mg/l as Na)	18,000	21,000	---
Potassium (Mg/l as K)	62	60	120
Strontium (µg/l as Sr)	270,000	270,000	260,000
Zinc (µg/l as Zn)	3,800	410	800
Lithium (µg/l as Li)	670	590	600
Selenium (µg/l as Se)	0	0	0
Solids, Residue at 180° C. (Mg/l)	70,300	68,900	65,100
Solids, Sum of Constituents (Mg/l)	69,000	71,900	75,800
Specific Conductance (Micromhos)	90,000	90,000	---
Iodide (Mg/l as I)	.01	.00	.02
Mercury (µg/l as Hg)	1.0	1.0	.8
Copper (µg/l as Cu)	4	29	3
Iron, Suspended Recoverable (µg/l as Fe)	0	16,000	9,300
Iron, Total Recoverable (µg/l as Fe)	25,000	23,000	18,000
Iron, Dissolved (µg/l as Fe)	25,000	7,200	8,700
Lead (µg/l as Pb)	0	0	1
Manganese, Suspended, Recoverable	1,000	0	1,000
Manganese, Total Recoverable (µg/l as Mn)	12,000	13,000	13,000
Manganese, Dissolved (µg/l as Mn)	11,000	13,000	12,000
Molybdenum (µg/l as Mo)	0	0	0
Nickel, (µg/l as Ni)	3	---	0
Silver (µg/l as Ag)	0	0	---

It should be noted that the Ca/Cl ratio of the formation water is significantly greater than the equivalent ocean water ratio, a condition commonly associated with deep aquifer brines. The composition of the water is characteristic of Back's (1966, p. 13) sodium-calcium cation facies with Ca + Mg totalling 32 percent (expressed as equivalents per million) of the major cations. Although the mechanisms involved are incompletely understood, most observers agree that chloride brines, typically with a relatively high proportion of calcium, do not necessarily require an evaporite association to develop (White, 1965, p. 344). Other explanations include the release of adsorbed ions during early diagenesis (Levorsen, 1967, p. 173) and concentration due to the selective diffusion of ions through clayey semi-permeable membranes (Bredehoeft and others, 1963; White, 1965, p. 348). Increase in the Ca/Cl ratio requires a calcium source, which in the case of the nonmarine Waste Gate Formation might be calcic feldspar grains in the sands or interstitial calcite cement associated with the sandstones.

The detailed chemical characteristics of the Waste Gate brines elsewhere beneath the Delmarva Peninsula are unknown, but estimates of salinity are possible using standard electric log calculations (table 6). For comparison, formation water resistivities were calculated using both the self-potential (S.P.) (Manheim and Horn, 1968; Meisler, 1980) and resistivity methods as follows:

$$Rw = \frac{Ro}{F} \quad \text{(e.g., Gearhart-Owen, 1974, p. 40)} \qquad (3)$$

where Rw = Resistivity of formation water, in ohm-m
Ro = Resistivity of formation, in ohm-m
F = Formation factor

$$SSP = K \log \frac{Rmfe}{Rwe} \quad \text{(e.g., Gearhart-Owen, 1974, p. 40)} \qquad (4)$$

where SSP = Static self potential
K = Constant dependent on temperature = $-70.7 \left(\frac{460+T}{537}\right)$
T = Temperature of formation in degrees Fahrenheit
Rmfe= Equivalent resistivity in mud filtrate, in ohm-m
Rwe = Equivalent resistivity of formation water, in ohm-m

and

$$NaCl = \left(\frac{3647.5}{Rw-0.0123}\right)^{1.047} \quad \text{(Hartsock, McCoy, and Radford, 1980, p. 5)} \qquad (5)$$

where NaCl = Salinity expressed as ppm
Rw = Resistivity of formation water at 77° F, in ohm-m

Of the two methods, the resistivity (Rw) calculation consistently yields higher equivalent NaCl concentrations. The resistivity (Rw) method is considered the more accurate estimation by virtue of its closer calibration with the water analyses from the DOE Crisfield Airport well (table 6). Total dissolved solids (TDS) by analysis are about 71,000 ppm in the Waste Gate Formation at

Table 6. Estimated salinities of the Waste Gate Formation using electric log data.

Well	Depth (ft.)	Est. Bore Hole Temperature (°F)	Self Potential Method						Resistivity Method				
			SP	Rm	Est. Rmf / Rmfe	Rwe / Rw	Rw @ 77° F	Equivalent NaCl (ppm)	Ro	Ro @ 77°F	F	Rw / Rw @ 77°F	Equivalent NaCl (ppm)
Ohio Hammond	4,950	135°	-115	2.75 (4.4@ 77°)	2.34 / 1.98	.073 / .079	.130	50,400	0.9	1.6	12.6	.071 / .125	53,700
J & J Taylor	5,340	140°	-100	3.2 (3.3@ 133°)	2.72 / 2.31	.128 / .140	.245	24,700	0.7	1.28	15.5	.045 / .079	91,300
Esso Ocean City	6,925	160°	-120	1.4 (2.0@ 88°)	1.19 / 1.01	.035 / .047	.094	73,800	0.65	1.29	17.7	.038 / .077	94,300
Socony-Mobil Bethards	6,430	155°	-115	1.45 (2.4@ 89°)	1.23 / 1.05	.04 / .053	.098	70,200	0.65	1.28	17.7	.038 / .075	97,400
DOE Crisfield	4,010	122°	-97	2.55 (4.7@ 74°)	2.15 / 1.84	.10 / .12	.185	33,700	0.70	1.09	11.9	.058 / .088	80,000
									0.70	1.10	10.9	.064 / .096	72,000

Where Rm = Resistivity of mud, ohm-m
Rmf = Resistivity of mud filtrate
Rmfe = Equivalent resistivity of mud filtrate
Rw = Resistivity of formation water
Rwe = Equivalent resistivity of formation water
Ro = Resistivity of formation

SP = Self potential, millivolts
F = Formation factor
NaCl = Salinity expressed as sodium chloride, ppm

Crisfield. Depending on which Formation Factor is used, the Rw calculation produces an equivalent NaCl concentration of about 72,000 ppm to 80,000 ppm. Because the Waste Gate formation water is actually a sodium calcium type, the equivalent NaCl values underestimate total dissolved solids by several thousand parts per million (Birdwell Division, 1972, p. B-110). Thus, the values calculated by the Rw method yield adjusted TDS values in the range of 75,000 ppm to 83,000 ppm, which compares favorably with the laboratory value of 71,000 ppm.

Using an average Formation Factor calculated from estimated porosities (table 4), equivalent NaCl concentrations were computed for the other four deep wells. Values range from a low of 53,700 ppm in the Ohio Hammond well to a high of 97,400 ppm in the Socony-Mobil Bethards well. Again, the equivalent NaCl values probably underestimates TDS. No attempt was made to adjust these values because the ionic composition of the water is unknown, although similarity to the Crisfield analyses could be assumed as a first approximation.

The SP method for determining Rw consistently produced lower salinity values than the resistivity method. As reviewed by Manheim and Horn (1968, p. 217-218), the SP method includes a number of possible sources of error. These include 1) shaliness of the bed, 2) mud filtrate invasion of the bed, 3) uncertainty of bore-hole temperatures, 4) assumption of standard relationships between mud resistivity and mud filtrate resistivity and between the latter and equivalent mud filtrate resistivity, 5) bore-hole diameter, 6) assumption of NaCl dominance of the fluids, and 7) streaming-potential effects due to pressure differences between formation and bore-hole.

Perhaps foremost of these potential sources of error is the assumption of a "clean", shale-free sand, particulary for the arkosic Waste Gate formation which exhibits a clayey matrix resulting in part from the decomposition of feldspar grains. The shaliness of the Waste Gate aquifer at 4,010 feet in the Crisfield Airport well was estimated using the sonic-density cross-plot contained in Gearhart-Owen (1974, p. 126). Using representative values of 2.2 gm/cc and 110 microseconds/ft. obtained from compensated sonic and formation density logs, a shaliness factor of about 20 percent was obtained. This value includes both laminar and interstial clay. An alternate method is offered by Schlumberger (1970, p. 23) to estimate the clay-filled fraction of total sand porosity (or q-factor). In this method, the q-factor for dispersed clay is estimated using a nomograph that solves the ratio,

$$q = \frac{\phi z - \phi e}{\phi z}$$

where,

ϕz = Sonic log porosity, percent
ϕe = Density log porosity, percent
q = Clay-filled pore fraction, percent

At Crisfield, the q-factor of the Waste Gate aquifer ranges between 23 and 31.5 percent, using an estimated ϕz of 35 percent and a ϕe range of 24 to 27 percent.

Even though the standard geophysical log methods for estimating the shaliness are approximations at best, it seems reasonable to conclude that the Waste Gate aquifers at Crisfield are not "clean" sands. As a result, the theoretical value of K (-76.6) used in the SSP solution of Rw is probably incorrect (Lynch, 1962, p. 218). An empirical value of K can be estimated as follows:

$$SP = -K \log \frac{Rxo}{Ro}, \text{ where } Rxo = F \cdot Rmf \qquad (6)$$

and where
SP = Log self potential, millivolts
K = Constant dependant on temperature
Rxo = Resistivity of flushed zone, ohm-m
Ro = Resistivity of formation, ohm-m
Rmf = Resistivity of mud filtrate, ohm-m

$$-97 = -K \log \frac{25.58}{.9} \quad \text{where } Rxo = 11.9 \times 2.15$$

$$-97 = -K\ (1.45)$$

$$K = 66.7$$

Using this value of K and an Rwe value derived from the relationship Rw = Ro/F, a pseudostatic self potential (PSP) value may be calculated for the shaly sand occurring at 4,010 feet in the Crisfield Airport well:

$$PSP = -K \log \frac{Rmfe}{Rwe} \qquad (7)$$

$$PSP = -66.7 \log \frac{1.84}{.075}$$

$$PSP = -66.7 \times 1.38$$

$$PSP = -92.0$$

A calculated PSP value of -92.0 is close to the log SP which was measured at -97. This relationship suggests that the log SP values are significantly effected by shaliness and do not accord well with the theoretical SSP method for calculating Rw.

An estimate of the theoretical static self potential (SSP) for a clean sand can be made by substituting the value Rwe obtained using the resistivity method into the standard equation:

$$SSP = -K \log \frac{Rmfe}{Rwe} \qquad (8)$$

$$SSP = -76.6 \log \frac{1.84}{.075}$$

$$SSP = -106.5$$

The SP reduction factor (α) for the Waste Gate sand at Crisfield is:

$$\alpha = \frac{\text{(Log SP)}}{\text{(Theoretical SP for clean sand)}} \qquad (9)$$

$$\alpha = \frac{-97}{-106.5} = 0.91$$

Although the Waste Gate Formation in each of the wells analyzed in table 6 is probably effected by shaliness, the S.P. reduction factor (α) worked out for the Crisfield well is site-specific and should not be indiscriminantly applied elsewhere. All in all, the many poorly measured factors effecting the SP make it an imprecise method for calculating formation salinity. The Rw values presented in table 6 using the resistivity method are considered more representative, even though some uncertainty remains concerning the effect of shaliness on the formation factor (F).

In summary, the Waste Gate brines increase in salinity with depth and are of a calcium/sodium chloride type that is typical of deep subsurface waters in many areas (Dickey, 1966). These waters are at normal hydrostatic pressure and exhibit very lethargic to stagnant flow systems. As in the case of the Waste Gate Formation, which is overlapped by younger units of the Potomac Group, brines of this type are isolated by confining beds from sources of meteoric or ocean water. Because the system is essentially at hydrostatic pressure, hydraulic gradients across the confining beds are small, precluding the transport of large volumes of water into or out of the stagnant zone. Over geologic time, fluid migration within the stagnant zone is largely controlled by the amount of subsidence and compaction occurring in the basin. As Jones (1981, p. 113-114) points out, "the overall water movement is into the basin and downward, rather than out of the basin and upward". As subsidence occurs, the formation waters move downward into higher temperature and pressure zones, but upward stratigraphically. It is probable that this flux mechanism, active at least since the Cretaceous, has contributed to the downward concentration of brines in the Waste Gate Formation.

POTENTIAL UTILIZATION

With salinities exceeding sea water there is little likelihood that the Waste Gate aquifers will be developed for potable or industrial water supplies on the Delmarva Peninsula. The amount of fresh water perennially available to the Delmarva Peninsula is estimated to be 1.5 billion gallons per day by Cushing, Kantrowitz, and Taylor (1973, p. 55), which is about six times the projected water demand for the year 2010. In addition, a relatively unlimited amount of salty water is available from the contiguous Chesapeake Bay, Delaware Bay, and Atlantic Ocean. If the Waste Gate aquifers are exploited, it is much more likely that they will be utilized in one of three areas: commercial brines, low to moderate temperature geothermal applications, and/or repositories for deep waste disposal.

Commercial brines: Mineral commodities extracted commercially from brines or sea water include bromine, calcium, chloride, iodine, lithium, and magnesium (Fulton, 1975, tab. 1). Commercial brines of the NaCl type generally have salinities close to saturation (>300,000 ppm) with total dissolved solids probably three or four times greater than the Waste Gate brines. On the other hand, the concentrations of magnesium and iodine are actually greater in sea water than in the Waste Gate brine sampled at Crisfield (tab. 5).

Based on the data offered for comparison in table 7 it seems unlikely that the Waste Gate Formation will become a competitive source of commercial brines. Although the brines may have specialized industrial applications, particularly if developed as a by-product of geothermal production (Saleem and Mott, 1980, p. xx-5), the economic feasibility of such projects would have to be carefully considered.

Geothermal Applications: Beneath the Maryland portion of the Delmarva Peninsula reservoir temperatures for the Waste Gate aquifers probably range from a low of 120° F to perhaps as high as 175° to 190° F (fig. 7). These temperatures are considered low for geothermal utilization, but can be used for space heating and for various agricultural and horticultural purposes. As a comparison, the lowest temperature for binary cycle electricity-generation is about 285° F. Based on information obtained in Iceland, where geothermal heat is diversely utilized, Lindal (1973) compiled a list of threshold temperatures for various geothermal applications (cited in National Conference of State Legislatures, 1981). This list is presented as a frame-of-reference, with the realization that technological advances could revise it materially.

Table 7. Ionic concentration of Waste Gate Formation water compared to ocean water and commercial brines.

Constituent ppm	Waste Gate Sdst. Crisfield, Md.[1]	Ocean Water[2]	Sylvania Sdst. Michigan Basin[3]	Pliocene Sdst. Salton Sea, Calif.[4]
Bromine	Not reported	65	2,910	146
Calcium	7,200	400	74,800	40,000
Chloride	42,000	18,980	208,000	185,000
Iodine	0.01	0.05	40	22
Lithium	0.67	0.1	70	300
Magnesium	490	1,272	9,960	730 (?)
Total Dissolved Solids	70,300	34,475	331,000	309,877

[1] table 5.

[2] White (1965, tab. 1)

[3] White, Hem, and Waring (1963, tab. 13)

[4] White (1965, tab. 1)

Required Temperature (approximate)		Application
	70° F	Fish Farming
	85°	Swimming pools; composting; fermentation; deicing
	105°	Soil warming
Expected Range of Waste Gate Reservoir Temperatures	120°	Therapeutic baths; mushroom growing
	140°	Space heating combined with fossil-fuel burners
	< 160°	Refrigeration (low temperature limit)
	175°	Space heating
	195°	Drying of stock fish
	212°	Drying of grains, vegetables, seaweed, wool, etc.
	285° (saturated steam)	Power generation using binary cycle

For direct geothermal applications, two resource factors determine whether the energy requirements of the potential user can or cannot be met. The factors to be considered are the flow rate and temperature drop of the hot water through the heat exchange area, expressed approximately as:

$$E = 500\ Q\Delta T \quad \text{(EG \& G Idaho Inc., 1979)} \qquad (10)$$

where E = Energy, Btu/hr.
ΔT = Temperature drop, $^{\circ}$F
500 = Constant $\frac{\text{Btu/hr.}}{\text{gpm/}^{\circ}\text{F}}$
Q = Flow rate, gpm

As a rule of thumb, EG & G Idaho (1979) suggests that ΔT can be related to the useable resource temperature (Tr) by the approximate relationship, $\Delta T = 0.6Tr - 70$ expressed in $^{\circ}$F. As a conservative estimate the Tr of the Waste Gate Formation probably ranges between 125° and 175° F (fig. 7), yielding potential ΔT's between 5° and 35° F. Estimated flow rates required to provide a range of energy requirements are summarized:

Maximum Energy Requirement (Btu/hr)	Tr (° F)	ΔT (° F)	Approximate Flow Rate (gpm)
1×10^6	133°	10°	200 gpm
(e.g., small school building)	175°	35°	55 gpm
5×10^6	142°	15°	665 gpm
(e.g., large school building)	175°	35°	285 gpm
15×10^6	158°	25°	1200 gpm
(e.g., small college campus)	175°	75°	855 gpm

As can be seen the well production requirements sharply increase as reservoir temperature (and ΔT) decreases. For this reason many geothermal space heating projects are designed so that either heat pumps or fossil fuel burners can be used to supplement direct heat transfer during intervals when the outside ambient temperature falls below a design value. The technical and economic feasibility of using low-temperature geothermal energy to heat specific installations has been addressed by Paddison and Yu (1979); Ryback (1979); Von Briesen and Yu (1980); Meyer, Coe, and Dick (1981); and Leffel (1981).

Because relatively large flow rates are required to offset small ΔT's in low temperature geothermal applications, the productive capacity of the reservoir rocks is a critical constraining factor. Although the Potomac Group aquifers (Patuxent and Patapsco) often yield large volumes of fresh water in up-dip areas, their hydrologic characteristics are quite different from the Waste Gate Formation. Whereas the Patuxent Formation sands often exhibit permeabilities in the 10^3 to 10^4 millidarcy range (e.g., Bennett and Meyer, 1952, p. 51), average permeabilities of the Waste Gate Formation probably fall between 15 and 125 millidarcies (table 4). The large difference in permeability between the units reflects their contrasting textural and mineralogical characteristics. For example, the Patuxent aquifer consists of quartzose, relatively well sorted, unconsolidated, sand and pebbly sand, with effective porosities exceeding 30 percent. In contrast, the Waste Gate aquifers are relatively poorly sorted, feldspathic, matrix-rich (clayey) sands with subordinate interbeds of limy sandstone. The effective porosities of the Waste Gate sands are estimated to be in the 15 to 25 percent range.

Although permeabilities of the Waste Gate Formation are relatively low for a Coastal Plain aquifer, the unit is hundreds of feet thick with sand beds accounting for 50 to 75 percent of the section (fig. 4). Because the transmissive properties of an aquifer are a function of both permeability and thickness, the possibility of a reasonably productive hot water well should not be rejected without further consideration. The modified non-equilibrium formula (Ferris and others, 1962, p. 92) which relates drawdown to discharge can be

used to test the productivity of the Waste Gate under a set of given conditions. The relationship, stated in petroleum engineering units, is

$$\Delta p = \frac{162.6Q\mu}{Kb}\left[\log\frac{Kt}{\phi\mu cr^2} - 3.23\right] \quad \text{(Warner and Lehr, 1977 (11)}$$

where Δp = Reservoir pressure change at radius (r) and time (t), psi
Q = Well yield, bbl/day
μ = Viscosity, centipoise
K = Permeability, millidarcies
b = Aquifer thickness, feet
t = Time since pumping began, hours
c = Aquifer compressibility, psi^{-1}
r = Distance from well, feet
ϕ = Porosity, decimal

The formula provides only an approximate solution because it assumes several ideal conditions not encountered in the field. The most important are 1) the aquifer is infinite without recharge or discharge boundaries, 2) the aquifer is homogeneous, isotropic, and of uniform thickness, and 3) flow across the confining beds (clays) is negligible. Furthermore, the well is assumed to be 100 percent efficient with no head losses allowed for "formation damage" or poor well design.

In the analysis that follows thickness of the production zone (b) is treated as a variable that can be increased to meet production requirements with total net sand thickness (B) representing the limiting value. If b is greater than B, the aquifer can not meet production requirements from one well. In a production well b represents the formation thickness opened by screens or by casing perforations. A production rate of 300 gpm (10,285 bbl/day) was chosen because it could satisfy the maximum energy requirements of a relatively large building (5×10^6 Btu/hr) with $\Delta = 35°$ F over a 3 month (2,160 hr.) peak heating period. The pump setting was assumed to be sufficiently deep to accommodate a 500 ft (225 psi) head loss at the end of the 3 month period. The well was assumed to have an effective radius of one foot. The analysis was applied to four potential sites represented by the Ohio Hammond well (Salisbury), the DOE Crisfield Airport well, the Mobil Bethards well (Berlin), and the Esso Ocean City well. Table 4 summarizes estimated sandstone porosity and permeability data for the Waste Gate Formation at each of these sites. Values for the viscosity of the formation water was estimated using a graph presented by Lynch (1962, p. 412-413), which expresses viscosity as a function of temperature and salinity. As suggested by Warner and Lehr (1977, p. 40), aquifer compressibility was assumed to be 6×10^{-6}/psi.

Equation (11) was rearranged to determine whether the Waste Gate Formation could meet the hypothetical production requirements summarized in table 8. Restated

$$b = \frac{\frac{162.6Q\mu}{K}\left[\log \frac{Kt}{\phi\mu cr^2} - 3.23\right]}{\Delta p} \qquad (12)$$

where the terms are as previously defined. In two cases the actual net sand thickness (B) is exceeded by the calculated sand thickness (b) needed to satisfy the production criteria of the hypothetical geothermal well. At the DOE Crisfield site B>b by 200 feet strongly suggesting that a 300 gpm production well is not feasible at the site if drawdown is restricted to 500 feet. At the Mobil Bethards site B exceeds b by 29 feet, perhaps not enough to declare the venture infeasible but still sufficient to warrent caution. At the Ohio Hammond and Esso Ocean City sites B>b by 67 and 206 feet respectively. Although the hypothetical well is theoretically feasible at these two sites, it should be borne in mind that in both cases large sections of the Waste Gate Formation would have to be opened for production. At the Ohio Hammond site 384 feet of screen or perforated casing would be required while at Ocean City the total reaches 745 feet.

Using the same aquifer and production parameters as above, equation (12) can be rearranged to solve for yield (Q) for the limiting case when b = B.

$$\frac{1}{Q} = \frac{\frac{162.6\mu}{Kb}\left[\log \frac{Kt}{\phi\mu cr^2} - 3.23\right]}{\Delta p} \qquad (13)$$

In this solution, the total sand thickness (B) of the Waste Gate Formation is opened for production. Solution of the above expression yields maximum well yields for the four sites given the assumptions made. The maximum yields for the four sites are:

Area	Theoretical Maximum Yield From One Well
Crisfield Airport	135 gallons per minute
Salisbury	354 gallons per minute
Berlin	288 gallons per minute
Ocean City	386 gallons per minute

Table 8. Aquifer parameters used to estimate thickness of Waste Gate production zone needed for a 300 gpm (5×10^6 BTU/hr.) geothermal well.

Well Site	Fm. Depth (ft.)	B (ft.)	Q bbl/day	Δp psi	t (hr.)	r (ft.)	k milli-darcies	ϕ %	μ cp.	C_6 10^{-} / psi	b (ft.)	Remarks
Ohio Hammond @ Salisbury	4,757-5,360	436	10,285	225	2160	1	85	26	.52	6.0	369	B>b; feasible
DOE Crisfield Airport	3,900-4,225	159	10,285	225	2160	1	93	25	.55	6.0	358	B<b; not feasible
Mobil Bethards @ Berlin	5,020-6,565	689	10,285	230	2160	1	40	21.5	.5	6.0	718	B<b; not feasible
Esso Ocean City	5,670-7,180	924	10,285	230	2160	1	40	21.5	.5	6.0	718	B>b; feasible

From the above analysis it seems apparent that geothermal wells yielding several hundred gallons per minute can be completed in the Waste Gate Formation in most areas. To compensate for its relatively low permeability, however, the developer should be prepared to open for production as many of the interbedded sands as economically feasible. This will entail perforating hundreds of feet of casing, or, alternatively, installing long sections of interspersed blank and slotted casing. For example, at Ocean City, the Waste Gate Formation is 1,510 feet thick with a potential net production interval of 924 feet (table 8).

Deep Well Disposal of Hazardous Wastes: The U.S. Environmental Protection Agency has defined an underground source of drinking water as "an aquifer or its portion which either currently provides water for human consumption or is capable of yielding water containing fewer than 10,000 mg/l of total dissolved solids" (U. S. Environmental Protection Agency, 1980, p. 42,480). By this definition water from the Waste Gate Formation is nonpotable because it is a brine with NaCl salinities ranging between about 50,000 and 100,000 mg/l. In addition, the Waste Gate Formation is separated from the fresh-water flow system by overlapping units of the Potomac Group, which also contains salty water. Because the Waste Gate contains nonpotable water and is isolated from the fresh-water flow system it may be therefore considered a potential reservoir for subsurface disposal of liquid wastes. This setting corroborates Otton's (1970) preliminary evaluation of the salty aquifers of the outer Coastal Plain as potential deep well disposal zones in Maryland.

Deep well waste disposal is, of course, a pre-emptive useage. In areas where the Waste Gate Formation is committed to deep well disposal, alternative utilization of the resource will be locally precluded, or at least, made more difficult. Although the Waste Gate brines are probably not a commercial source of chemicals, their heat value may eventually be used in low temperature geothermal applications. Nevertheless, in an area as large as the eastern half of the Delmarva Peninsula multi-purpose utilization of the Waste Gate is probably feasible with careful design and monitoring of the operating facilities.

The fluvial-deltaic Waste Gate Formation is not ideal for well injection because of its complex sand stratigraphy. Individual aquifers and confining beds are only locally correlative. The geometry of each sand body is complex. With sparse well control, it is impossible to predict unequivically whether a potential reservoir is laterally connected with an adjacent sand or whether it wedges out within a clayey confining bed. As a consequence, the isolation of an individual sand can never be assured. In practical terms the waste disposal reservoir should be viewed as including not only the injection zone, but one or two of the adjacent sands as well. Because the Waste Gate Formation is hydrologically isolated from the shallow fresh water flow system, this contingency should not preclude waste injection unless local conjunctive use of the Waste Gate brines is anticipated.

To a considerable extent the success of any waste injection program is dependent on the design of the well and the effectiveness of the pre-injection treatment (see Cook, 1972; Warner and Lehr, 1977; Brown and Silvey, 1977).

Excess head build-up can be minimized through effective well screen and gravel pack design and by a well development program to remove drilling fluids from the injection face. Pretreatment of the waste prior to injection is often required to prevent the deterioration of formation permeability due to precipitate reactions between the waste water and the formation matrix and brine. For example, certain types of acidic wastes may react with the feldspathic aquifer material:

$$\text{Feldspar(s)} + H^{+}\ \text{(aqueous)} \rightleftharpoons \text{Clay(s)} + \text{Cations (aqueous)},$$

producing clays that might reduce aquifer permeability near the disposal well. At the very least entrained gasses and suspended solids must be removed from the waste water prior to injection.

Although the operational factors mentioned above are important, the transmissive and storage properties of the aquifer must be sufficiently large to accept economical volumes of wastewater within prescribed injection pressures. The following preliminary analysis is intended to provide order-of-magnitude estimates of the Waste Gate's capacity for deep well waste disposal.

Hubbert and Willis (1972, p. 251) have estimated the minimum pressure gradient at which vertical hydraulic fracturing will occur according to the relationship;

$$\frac{Pi}{Z} = \frac{\frac{Sz}{Z} + \frac{2\ Po}{Z}}{3} \qquad (14)$$

where Pi/Z = Fracture initiation pressure gradient, psi/ft.
Sz/Z = Lithostatic stress gradient, psi/ft.
Po/Z = Formation fluid pressure gradient, psi/ft.

This relationship assumes that under conditions of incipient normal faulting the least principal stress will be horizontal and will have a value of approximately one-third the effective overburden pressure. Under normal lithostatic (1 psi/ft) and hydrostatic (0.46 psi/ft) conditions, the minimum fracture initiation gradient is 0.64 psi/ft. A conservative regulatory policy would restrict injection pressures to less than 0.64 psi/ft to prevent rupturing the confining beds. However, in a fluvio-deltaic sand sequence such as the Waste Gate Formation, injection pressure restrictions imposed solely to prevent waste-water from "bleeding" into adjacent sands may have only a palliative value. Nevertheless, a limiting gradient of 0.64 psi/ft is used in table 9 to estimate the allowable pressure build-up for four hypothetical sites.

Equation (15) (Warner and Lehr, 1977, p. 104) can be used to estimate the maximum injection rates sustainable within the limiting build-up pressures (i.e., allowable pressure build-up) cited in table 9:

Table 9. Data used to estimate allowable pressure build-up at four hypothetical waste water injection sites.

Well	Site	Waste Injection Zone: Average Depth of Injection Zone (ft.)	Waste Injection Zone: Hydrostatic Pressure (psi)	Waste Injection Zone: Fracture Initiation Pressure (psi)	Allowable Pressure Build-up (psi)
D. O. E. Airport	Crisfield	4,100	1,886	2,624	738
Ohio Hammond	Salisbury	5,100	2,346	3,264	918
Mobil Bethards	Berlin	5,800	2,668	3,712	1,044
Esso Ocean City	North Ocean City	6,400	2,944	4,096	1,152

$$\frac{1}{Q} = \frac{\frac{162.6u}{Kb}\left[\log \frac{Kt}{\phi ucr^2} - 3.23\right]}{\Delta p} \qquad (15)$$

where Q = Maximum injection rate (barrels per day)
K = Aquifer permeability (millidarcies)
b = Aquifer thickness (feet)
u = Viscosity of injection fluid (centipoises)
c = Aquifer compressibility (psi^{-1})
ϕ = Aquifer porosity (percent)
r = Effective well radius (feet)
t = Time sine injection began (hours)
Δp = Allowable pressure build-up,(psi)

Assigned aquifer parameters (porosity, permeability, and compressibility) for the four sites are listed in table 8. The aquifer is assumed to be 75 feet thick; at least one Waste Gate sand, or dominantly sandy zone, is 75 or more feet thick at each site. Analyses were made for two hypothetical injection fluids having viscosities of 1.0 and 2.2 centipoises. The latter value is comparable to an iron-rich, waste pickling liquor (Waller, Turk, and Dingman, 1978, p. 23). Build-up pressures were calculated over a five year project life. The results are summarized below:

A. Waste stream viscosity = 1.0 centipoise (water at 20.2° C)

Site	Allowable Pressure Build-up psi	Approximate Injection Rate Bbl/day	gpm	Approximate Minimum Radial Migration*, (ft) r	R
Crisfield	738	3,461	101	802	915
Salisbury	918	3,867	113	865	982
Berlin	1,044	2,180	64	702	808
Ocean City	1,152	2,405	70	734	842

$$* \; r = \sqrt{\frac{V}{3.14.b.\phi.E}} \qquad \text{(Heidari and Cartwright, 1981, p. 615)} \qquad (16)$$

where r = minimum radius of wastewater front, ft.
V = cumulative volume of wastewater, ft^3
b = aquifer thickness, ft
ϕ = aquifer porosity
E = displacement efficiency (.9)

$$R = r + 2.3\sqrt{Dr} \qquad \text{(Warner and Lehr, 1977, p. 112)} \qquad (17)$$

R = radius with dispersion, ft.

D = dispersion coefficient (3 ft.)

B. Waste stream viscosity = 2.2 centipoises (pickling liquor)

Site	Allowable Pressure Build-up psi	Approximate Injection Rate Bbl/day	gpm	Approximate Minimum* Radial Distance (ft) r	R
Crisfield	738	1,625	47	560	655
Salisbury	918	1,860	54	590	685
Berlin	1,044	1,025	30	480	565
Ocean City	1,152	1,130	33	505	595

Although these values are clearly no more than order-of-magnitude estimates, the analysis strongly implies that only a relatively modest wastewater stream can be injected into the reservoir sand without hydraulically fracturing the unit and its immediate confining beds. Hydraulic fracturing may, in fact, be necessary in order to develop adequate porosity and permeability to make waste injection feasible. Fracturing would necessarily create more uncertainty about the movement and distribution of the wastewater and probably result in leakage into adjacent Waste Gate sands. However, the isolation of the Waste Gate Formation from the shallow fresh-water flow system would lessen considerably the impact of such outward migration.

The minimum radial distances shown above are based on a uniform outward movement of the wastewater from the injection well. In actual practice, the wastewater will selectively move through zones of higher permeability, creating a very irregular wastewater front around the well. Plumes could easily extend two or three times farther than the simple volumetric analysis suggests. Nevertheless, the total area encroached by the wastewater from the four hypothetical injection wells would be comparatively small (about 0.2 square miles for the pickling liquor). With careful planning, conjunctive use of the Waste Gate brines for their geothermal heat appears to be a reasonable possibility.

Bredehoeft and Maini (1981) have offered an alternate strategy for the disposal of radioactive wastes. In their scheme, the deeper Potomac Group units, including the Waste Gate Formation, would function as an undisturbed "sedimentary rock blanket" overlying a waste repository excavated in crystalline basement rocks. They argue (p. 296) that "under favorable circumstances the flow system can work as an active barrier, so that a long migration and very slow path for the wastes to the biosphere can be assumed".

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* See footnote, preceding page.

SUMMARY AND CONCLUSIONS

The name Waste Gate Formation is proposed for an overlapped, subsurface sequence of interbedded sandstones (sands), and shales (clays) occurring near the base of the Lower Cretaceous Potomac Group beneath the eastern Delmarva Peninsula. The unit is dated Berriasian to Hauterivian (?) because it contains pre-Zone I palynomorphs apparently older than the mid-Barremian to early Albian assemblages characteristic of the overlapping Patuxent Formation. The Waste Gate formation ranges in thickness from an up-dip feather's edge to about 1,500 feet at the Coast. Cumulative sand percentages are in the 50 to 70 percent range. The arenaceous beds are unconsolidated to moderately lithified and consist largely of light gray to whitish, arkosic to feldspathic sandstones. The sandstones often exhibit a pervasive, clayey (kaolinitic) matrix. The more indurated sandstones are calcareously cemented. Sandstone porosities estimated from geophysical logs are largely in the 19 to 27 percent range. These characteristics suggest that the Waste Gate sandstones typically have relatively low permeabilities, perhaps an order-of-magnitude of 15 to 150 millidarcies.

The Waste Gate aquifers yield brines of the sodium-calcium chloride type, with total dissolved solids in the 50,000 to 100,000 mg/l range. Below 3,000 feet fluid pressures approach a hydrostatic condition, exhibiting a gradient of about 0.44 to 0.46 psi/ft. Below about 1,000 feet, a normal geothermal gradient (1.3° to 1.7° F/100 ft.) seems to characterize the area. Formation temperatures may be as high as 190° F (at the Coast), but are more likely in the 124° F (at 3,500 feet) to 172° F (at 7,180 feet) range.

Potential utilization of the Waste Gate aquifers include:

1. Extraction of chemical commodities: This possibility is least likely because the Waste Gate brines are not competitive with commercial brines produced elsewhere (e.g., Michigan) that have salinities close to saturation (>300,000 ppm).

2. Extraction of geothermal heat: A combination of modest formation temperatures (124° F to 172° F) and relatively low permeabilities (15 to 150 millidarcies) combine to diminish the geothermal potential of the Waste Gate aquifers. Production of 300 gallons per minute of 170° F water may be feasible from one well, but it would require opening for production hundreds of feet of section (e.g., 370 cumulative feet of 85 millidarcy sand) at well depths of about 6,200 to 7,200 feet.

3. Disposal of hazardous wastes: The Waste Gate Formation is isolated from the shallow fresh-water flow system by overlapping saline to brackish units of the Potomac Group. Its hydrogeologic setting is suitable for liquid waste disposal. It is estimated that a 30 to 115 gallon per minute waste stream could be injected into a typical Waste Gate sandstone without fracturing the aquifer and its confining beds. Larger volumes could be injected by increasing the number of sandstones receiving the waste and/or by increasing the allowable pressure build-up to exceed the fracture initiation pressure of the formation.

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PART TWO

PALYNOLOGY OF CONTINENTAL CRETACEOUS SEDIMENTS, CRISFIELD GEOTHERMAL TEST WELL, EASTERN MARYLAND

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ABSTRACT

Palynological study indicates that core samples from 4148', 4138', and 4121' in the Crisfield Geothermal Test Well of eastern Maryland, near the base of the Waste Gate Formation of the Potomac Group of Hansen, are mid-Berriasian in age, much older than the basal Potomac Group at the outcrop belt west of Chesapeake Bay (Barremian-Aptian). A variety of spores allow correlation with Suite C of Norris in the Purbeck Beds of England, while detailed comparisons of striate Schizaeaceae (Cicatricosisporites) and verrucate spores (Concavissimisporites, Trilobosporites, etc.) indicate the samples are more precisely equivalent to the lower part of Suite C and the Hils 1 assemblage of northwestern Germany, and near but slightly older than the "Wealden A" of northeastern Germany. The typical Southern Laurasian aspect of the flora suggests a humid subtropical climate; the lack of marine plankton and the variable quantitative composition of the three samples are consistent with the inferred fluvial environment of deposition of the Waste Gate Formation. Ditch and core samples from higher in the Potomac Group correlate as follows: 3430', Zone I (Barremian-Aptian); 2550' and 2200', lower and upper Subzone II-B, respectively (middle-late Albian?); 1143', 1127', and 1113', middle Zone III (early Cenomanian?); environments are continental (floodplain) throughout.

INTRODUCTION

In an effort to correlate the continental Cretaceous (Potomac Group) sediments penetrated by the Crisfield Geothermal Test Well of eastern Maryland (Som-Dd 47), core samples from all four cored intervals and several ditch samples were prepared for palynological analysis. Unfortunately, samples from the middle two cored intervals (2620'-2701', 3114'-3144') proved to be barren, and most of the ditch samples were too heavily contaminated with younger material to be useful for precise correlation. However, samples from the lowest and highest cored intervals (4119'-4199', 1109'-1146') were richly fossiliferous and allow the continental Cretaceous sequence to be dated as extending from Berriasian, the earliest stage of the Early Cretaceous, to early Cenomanian, at the beginning of the Late Cretaceous. The Berriasian age of the basal samples, from the new Waste Gate Formation of the Potomac Group of Hansen (1982), is of considerable interest in showing that Cretaceous sedimentation in this area began at least three stages before it did at the present outcrop belt on the west side of Chesapeake Bay, where the age of the basal Potomac Group is generally early Aptian, possibly Barremian in places (Brenner, 1963; Doyle & Robbins, 1977; Hickey & Doyle, 1977; Upchurch & Doyle, 1981). Palynofloras from so close to the base of the Cretaceous have not been previously recognized from the exposed portion of the Atlantic continental margin, although they are reported from the offshore Baltimore Canyon Trough (Bebout, 1981) and offshore eastern Canada (Barss et al., 1979).

It is convenient to discuss samples from the Crisfield well in two groups. The Berriasian samples (4148'-4121') are discussed together in

greater detail than the younger samples and are documented photographically, both because of the greater intrinsic interest of the flora to other workers and because more effort seems desirable in order to justify adequately the conclusions reached. Palynological studies on sediments near the Jurassic-Cretaceous boundary have varied greatly in their relative emphasis on different groups, level of stratigraphic resolution, and taxonomic philosophy. Despite some attempts at synthesis of previous zonations (Dörhöfer & Norris, 1977a,b; Hughes, 1981), dating of the Crisfield samples has required much critical evaluation of the conflicting taxonomic and stratigraphic concepts of different authors. On the other hand, samples from 3430'-3450' and higher in the section can be related to the standard Potomac Group zonations of Brenner (1963) and Doyle & Robbins (1977) in a more or less routine fashion, and they are discussed in their own section.

Data on occurrences of taxa, presented in Tables 1 and 2, are based on a complete scan of at least one slide from each sample. Percentages are based on a count of 200 grains, except in the case of the poor sample from 4138'. In addition, 166 single grain preparations were made from sample 4148' (technique described by Doyle et al., 1975) in order to clarify the morphology and taxonomic placement of certain key spore groups which were difficult to interpret or photograph in the slides because of unfavorable orientation or obscuring debris.

SAMPLES 4148'-4121': MID-BERRIASIAN

One of the most useful reference sections for correlation of the basal Crisfield samples is in southern England (Anglo-Paris Basin). Here Upper Jurassic marine sediments are overlain by the Purbeck Beds, which are lagoonal and evaporite-bearing below but become largely freshwater and lacustrine above (Norris, 1969). The Purbeck is in turn overlain by the freshwater-deltaic Wealden Beds, which extend up to the Barremian and are overlain by marine Aptian strata (Lower Greensand). Preliminary palynological data on the Purbeck interval, most relevant for the present purposes, were presented by Couper (1958), but the first detailed account of the Purbeck palynoflora was that of Norris (1969), who recognized three palynological assemblages in the Late Jurassic-Purbeck sequence, Suites A, B, and C. Although the Purbeck was formerly assumed to be the uppermost unit of the English Jurassic, ostracode and palynological correlations with other European sections (Dörhöfer & Norris, 1977a,b) indicate that the Tithonian-Berriasian boundary (the Jurassic-Cretaceous boundary if the Tethyan scale is adopted) coincides closely with the boundary between Suites A and B, near the base of the Purbeck, while the Suite B-C boundary falls near the middle of the Berriasian (see Fig. 1). Norris (1969) did not attempt to define the upper limit of Suite C; an invaluable source of evidence for this purpose and for still finer subdivision of the Purbeck is the detailed work of Hughes and coworkers (Hughes & Moody-Stuart, 1967, 1969; Hughes & Croxton, 1973; Hughes, 1981) on striate schizaeaceous spores, mostly from the Warlingham Borehole, one of the sections studied by Norris (1969).

Other useful reference sections have been described from the Lower Saxonian Basin of northern Germany and the Netherlands. In the northwest German portion of the basin, as in England, marine Upper Jurassic rocks are overlain by an evaporite-bearing unit (Münder Formation), which straddles the

<table>
<tr><th></th><th>Stage</th><th colspan="2">S England</th><th>Crisfield</th><th colspan="2">NW Germany</th><th>NE Germany</th></tr>
<tr><td rowspan="6">LK</td><td rowspan="2">Valanginian</td><td colspan="2" rowspan="2">Wealden</td><td rowspan="4"></td><td colspan="2">marine</td><td>marine</td></tr>
<tr><td rowspan="3">Bückeberg Formation</td><td>Hils 4</td><td>Wealden F-G</td></tr>
<tr><td rowspan="4">Berriasian</td><td rowspan="4">Purbeck</td><td rowspan="3">Suite C</td><td>Hils 3</td><td rowspan="3">Wealden A-B</td></tr>
<tr><td>Hils 2</td></tr>
<tr><td>4148'-21'</td><td>Hils 1</td><td rowspan="4">Ober-Malm</td></tr>
<tr><td>B</td><td colspan="2">Münder Formation</td></tr>
<tr><td rowspan="3">UJ</td><td rowspan="2">Tithonian</td><td rowspan="3">marine</td><td rowspan="2">A</td><td colspan="2">etc.</td><td>etc.</td></tr>
<tr><td rowspan="2">Kimmeridgian</td></tr>
<tr><td></td></tr>
</table>

Figure 1. Proposed correlation of Crisfield samples 4148'-4121' with reference sections in England (Norris, 1969; Hughes, 1981) and Germany (Döring, 1965; Dörhöfer, 1977). Correlations among European sections follow Dörhöfer & Norris (1977a,b), with modifications discussed in text.

Jurassic-Cretaceous boundary, and this is overlain by a lacustrine-deltaic unit, the Bückeberg Formation, which was formerly called "Wealden" (Dörhöfer & Norris, 1977a,b). In contrast to the English section, however, marine sedimentation here resumed in the late Valanginian. Dörhöfer (1977) recognizes four palynological assemblages within the Bückeberg Formation, designated Hils 1 to Hils 4. As is discussed by Dörhöfer & Norris (1977a,b), the Hils 1 through Hils 3 assemblages, dated on ostracodes as late Berriasian, correlate palynologically with Suite C, whereas the Hils 4 assemblage, dated as early Valanginian, appears to be largely or wholly younger than Suite C. Comparable floras have also been described from the Netherlands (Burger, 1966). In a study of the "Wealden" of northeastern Germany, Döring (1964, 1965) recognized seven palynological assemblages, designated Wealden A to Wealden G. Dörhöfer (1977) concludes that these assemblages cover roughly the same interval as Hils 1 through 4, but comparisons made by Hughes & Moody-Stuart (1969) and below suggest that the Wealden A is slightly younger than the base of Suite C, and, by similar reasoning, than Hils 1, as shown in Fig. 1.

Dörhöfer & Norris (1977b) point out that there are important quantitative differences between the English and German floras, presumably for environmental reasons (cf. below), as well as qualitative similarities: Purbeck assemblages are dominated by conifer pollen (Classopollis, Inaperturopollenites), while the German assemblages are dominated by fern spores. These differences and the perceived greater stratigraphic utility of spores are probably both responsible for the tendency of the German authors to devote more attention to spores and less to gymnosperm pollen than does Norris (1969).

Published data on latest Jurassic-earliest Cretaceous palynofloras from the Baltimore Canyon Trough and offshore eastern Canada are less useful for correlation of the Crisfield samples than the English and German data, since the zones of Bebout (1981) are rather broadly defined on "tops" of species ranges, and those of Barss et al. (1979) are based largely on dinoflagellates. Bebout's data have been useful, however, in correlation of ditch samples from higher in the section.

Occurrences and frequencies of taxa recognized in the core samples from 4148', 4138', and 4121' are summarized in Table 1. Taxonomic treatment most commonly follows Norris (1969), but with many exceptions. As is often the case in palynology, the literature on Jurassic-Cretaceous boundary floras suffers from insufficiently critical identification of forms with species described from elsewhere in the geologic column, resulting in long-ranging, ill-defined "balloon taxa" of little stratigraphic value (Hughes, 1970). Since the primary aim of this report is stratigraphic, I have not attempted to resolve such taxonomic problems, but I have tried to minimize their effects by basing comparisons as much as possible on published illustrations of specimens from near the Jurassic-Cretaceous boundary rather than on figures or descriptions of the original authors of names used, and I have signaled cases where species concepts of original and later authors appear to differ by indicating in which author's sense the name is used. In some cases, where intrageneric taxonomy is particularly confused and there is insufficient evidence on the stratigraphic distribution of types to make attempts at species identification worthwhile, I have preferred to identify forms to genus only in Table 1. However, some remarks on morphological variation and possible species

relationships within such problem groups are presented in the correlations discussion.

Correlation: lower Suite C (mid-Berriasian: Fig. 1).

Despite important differences in relative frequencies of elements, discussed further below in the section on paleoecology, palynofloras from 4148', 4138', and 4121' are fairly similar in qualitative composition. The most important qualitative difference is the greater number of stratigraphically useful spore taxa in 4148', which allows this sample to be correlated most precisely with the English and German sections. However, the less diverse floras of the other samples allow them too to be assigned to Suite C of Norris (1969) and tend to point toward correlation with the same lower interval within Suite C, though less securely because of the smaller number of species and lesser confidence in the significance of absences. Hence all three samples may be discussed together, with greatest emphasis on 4148'.

All but a few rare pollen and spore groups recognized in the Crisfield samples have been figured from Berriasian floras elsewhere, but most of them represent relatively undiagnostic, long-ranging complexes which enter at various points in the Triassic or Jurassic and continue well into the Cretaceous or beyond. These include most of the dominant gymnosperms (Classopollis, Exesipollenites, Inaperturopollenites/Spheripollenites, Perinopollenites elatoides, Araucariacites, Callialasporites, Cerebropollenites, Podocarpidites, Alisporites, Abietineaepollenites, Vitreisporites, Eucommiidites, Monosulcites/Cycadopites) and many of the more common spore groups (Cyathidites, Dictyophyllidites, Gleicheniidites, Osmundacidites/Baculatisporites, Klukisporites, Lycopodiumsporites austroclavatidites, Marattisporites scabratus). However, the fact that Perinopollenites elatoides, Callialasporites, Cerebropollenites, Vitreisporites, Klukisporites, and Marattisporites scabratus are more abundant and/or morphologically diverse than in the outcrop Potomac Group is suggestive of an earlier Cretaceous age, since these are groups that are most prominent in the Jurassic and decline during the Early Cretaceous. Also suggestive are the relatively low abundance and diversity of bisaccate conifers (Alisporites, Abietineaepollenites, Parvisaccites, Podocarpidites) and gleicheniaceous ferns (Gleicheniidites), both of which undergo important radiations in the Early Cretaceous, and the absence of angiosperms, which appear in the Barremian.

It may be useful to point out some cases where morphological variation within complexes identified to genus only seems greater than that described in the literature on Berriasian floras, or where proposed distinctions between taxa are difficult to apply to Crisfield forms. Some of these inconsistencies may of course reflect real differences between the Maryland and European floras, but most are probably only apparent. Many of the Crisfield bisaccate conifers can be related to the four Purbeck species recognized by Norris (1969) (Alisporites bilateralis, Abietineaepollenites minimus, Podocarpidites sp. cf. P. ellipticus, Parvisaccites radiatus), but the Alisporites and Abietineaepollenites groups are so variable in size and sac morphology that a generic distinction would be arbitrary at present, and there are grains with reduced sacs, as in Parvisaccites radiatus, but a thinner exine, recalling later Cretaceous forms assigned to Phyllocladidites. Some Callialasporites

grains fit fairly well into Norris species such as C. obrutus or C. dampieri, but most are less distinctive types which resemble C. sp. 4 of Norris in having an unconstricted sac and often a trilete mark, but which are larger and smoother, converging on Araucariacites (Pl. 2, fig. 9). In Cerebropollenites, the surface vesicles vary from prominent, as in typical C. mesozoicus, to much more reduced. Norris (1969) assigned Purbeck members of the monoporoidate genus Exesipollenites to the new species E. scabrosus rather than E. tumulus, the species recognized by Brenner (1963) in the Potomac Group, but Crisfield Exesipollenites is highly variable and includes specimens that could be matched with both Norris's and Brenner's figures. The small, thin-walled inaperturates designated Inaperturopollenites/Spheripollenites spp. exhibit great but difficult-to-assess variation in size and sculpture of the exine; in some, the exine is clearly two-layered, suggesting relationships with Perinopollenites elatoides. Smooth monosulcates (Monosulcites/Cycadopites spp.) vary greatly in size, length:width ratio, shape of the ends of the grain and the sulcus, and thickness of the exine. Some, like the Potomac forms described by Brenner (1963) as Monosulcites glottus, have apparent subsidiary furrows, suggesting a relationship with Eucommiidites, which also seems to be represented by several species. Among the smooth-walled trilete spores, it is difficult to recognize discontinuities between large, thin-walled forms (Cyathidites australis) and thick-walled forms which approach Concavissimisporites in all but sculpture (Dictyophyllidites equiexinus/Cardioangulina spp.: Pl. 5, fig. 1), or in the morphological series consisting of Cyathidites minor, Dictyophyllidites harrisii, and Gleicheniidites. The round, baculate to irregularly sculptured spores designated Osmundacidites/Baculatisporites spp. are another group where the great range of size and sculpture suggests several species are present, but where too many intermediate types occur to allow simple distinctions. Future detailed revision of these groups may yield refinements of interest for both stratigraphic and botanical purposes.

Other members of the Crisfield flora, mostly spores, are more significant stratigraphically, since they belong to species that enter at various points in the Late Jurassic-Purbeck sequence of Norris (1969), including some restricted to his Suite C. Species believed to separate Suite A (late Kimmeridgian-Tithonian) from older Jurassic assemblages include Cicatricosisporites australiensis (Pl. 3, figs. 7-12; cf. below), Coronatispora valdensis (Pl. 1, figs. 1, 2), Klukisporites pseudoreticulatus (Pl. 1, figs. 8, 9), and Reticulisporites semireticulatus (Pl. 1, figs. 4, 5). Norris (1969) lists several other species with probable representatives in the Crisfield samples as appearing in Suite A (Exesipollenites scabrosus, Inaperturopollenites sp., Podocarpidites sp. cf. P. ellipticus, Callialasporites dampieri, C. obrutus, C. sp. 4, and Cycadopites sp. cf. C. nitidus), but it is not certain that all of these are distinct from forms that occur in the earlier Jurassic of either Europe (e.g., Inaperturopollenites vs. Spheripollenites) or other areas (e.g., Exesipollenites scabrosus vs. E. tumulus from the Early Jurassic of Australia: Balme, 1957). Species present which appear in Suite B are Acanthotriletes varispinosus (Pl. 1, fig. 3), Cicatricosisporites purbeckensis (Pl. 3, figs. 1-6; cf. below), Couperisporites complexus (Pl. 1, figs. 6, 7), Leptolepidites psarosus (Pl. 1, fig. 10), Microreticulatisporites diatretus, and Parvisaccites radiatus (Pl. 1, figs. 11, 12); these forms establish the Cretaceous rather than Jurassic age of the samples. Most important, several groups are present which first appear in Suite C and thus serve to raise the Crisfield

samples securely above the base of the Berriasian: Concavisporites juriensis (Pl. 1, fig. 13), Densoisporites perinatus (Pl. 1, fig. 14), Foraminisporis wonthaggiensis (Pl. 2, fig. 1), Leptolepidites epacrornatus (Pl. 2, fig. 2), Pilosisporites delicatulus (Pl. 2, fig. 3), P. trichopapillosus (Pl. 2, fig. 4; more than one species may be represented, as noted by Dörhöfer, 1977), and Trilobosporites spp. (Pl. 6, figs. 1, 2; cf. below). Several other Crisfield forms were not reported from Suite C by Norris (1969) but do occur in the supposedly correlative Hils 1-3 interval of Dörhöfer (1977), and may hence indirectly support a Suite C age: Aequitriradites spinulosus (sensu Dörhöfer, not Norris: Pl. 2, figs. 5, 6), Contignisporites hilsei (Pl. 2, fig. 7), and large, finely sculptured Densoisporites closer to D. microrugulatus than D. perinatus (Pl. 2, fig. 8); the Concavissimisporites-Tuberositriletes complex discussed further below may also be placed in this category.

The arguments presented so far clearly favor correlation of the 4148'-4121' interval with Suite C rather than older units of Norris (1969), but they do not rule out a younger age, since ranges of the groups cited are either uncontrolled above or known to extend into Valanginian or younger strata. The two most useful groups for more precise age determination are striate spores of the fern family Schizaeaceae (Cicatricosisporites s. lat.), which first appeared in the Late Jurassic (C. australiensis in the Kimmeridgian of England and other areas: Norris, 1969) and underwent an explosive radiation in the Early Cretaceous, and a complex of large spores with verrucate sculpture, assigned to Concavissimisporites, Trilobosporites, and several less consistently used genera, whose botanical affinities are less certain but may also be schizaeaceous (near Lygodium?). Despite much taxonomic confusion in the literature, analysis of these groups in the Crisfield samples (especially 4148') yields consistent correlations with the lower part of the Suite C interval of Norris (1969) and the lower Bückeberg Formation of northwestern Germany (Hils 1 assemblage of Dörhöfer, 1977), significantly below the Berriasian-Valanginian boundary. Similar arguments indicate that the Crisfield interval is near but probably slightly older than the basal "Wealden" of northeastern Germany (Wealden A of Döring, 1965).

The most detailed and reliable morphological and stratigraphic data on the Cicatricosisporites complex near the base of the Cretaceous are those of Hughes and coworkers (Hughes & Moody-Stuart, 1967, 1969; Hughes & Croxton, 1973; Hughes, 1981), based largely on samples from the Warlingham Borehole of southern England (WM), one of the sections studied by Norris (1969) in his work on the Purbeck. Hughes's material is treated in terms of a system of informal "biorecords" rather than formally named species, but morphological variation within these entities is so well described and illustrated that they serve as a better frame of reference for comparisons than the formally named species of other authors. The base of the Purbeck in the Warlingham Borehole is placed at 2150' and the Purbeck-Wealden boundary at 1892' (Norris, 1969). Norris placed all samples from 2004' to 1900', the highest he studied, in Suite C, and recognized Suite B only in a few samples between 2022' and 2027'. He did not subdivide Suite C in this well or define its upper limit, but Hughes & Moody-Stuart (1969) and Hughes (1981) document significant changes in the Cicatricosisporites group within this interval and going into the overlying Wealden. Taxonomic interpretation and documentation of Cicatricosisporites assemblages from correlative strata in Germany are less satisfactory, but

the data of Döring (1965) and Dörhöfer (1977) are valuable in confirming and extending the arguments used for correlation with the English section.

As in the mid-Berriasian floras cited, the Cicatricosisporites complex from 4148'-4121' shows a much narrower total range of morphological variation than in younger floras (cf. Hughes & Croxton, 1973) and an almost continuous spectrum of morphotypes within this range, making recognition of species boundaries highly problematical. Both phenomena undoubtedly reflect the fact that striate schizaeaceous ferns were near the beginning of their evolutionary radiation at this time.

The most distinctive and abundant Cicatricosisporites group in sample 4148' has relatively narrow and well-spaced muri (positive sculpture of Hughes & Moody-Stuart, 1969) which are generally somewhat irregular and sinuous in shape and run parallel to the sides of the spore (Pl. 3, figs. 1-6). This group corresponds to C. purbeckensis of Norris (1969) and biorecord 3 AR of Hughes & Moody-Stuart (1969), which Hughes (1981) indicates first appears in the Warlingham interval (2027'-2000') assigned to Suite B by Norris (1969).

Other members of Cicatricosisporites from 4148'-4121' have muri which are more closely spaced than in C. purbeckensis (negative or positive/negative sculpture of Hughes & Moody-Stuart, 1969) but which again run parallel to the sides and do not cross the equator except at the apices--apparently a primitive feature in Cicatricosisporites. Except for a few individuals with better analogs in German floras (cf. below), most specimens fall within the patterns of variation of the biorecords reported from the lower part of Suite C in the Warlingham section (1987'-1957'). Many specimens have relatively narrow muri which converge but do not fuse completely at the apices, leaving a radial lumen (Pl. 3, figs. 7-12), as in biorecord 1 AT of Hughes & Moody-Stuart (1969). Hughes (1981) points out that 1 AT corresponds fairly well to C. australiensis of Norris (1969), which extends down into the Upper Jurassic (Suite A). More diagnostic stratigraphically are forms with a radial lumen but wider muri than in 1 AT (Pl. 4, figs. 1-4), characters used by Hughes & Moody-Stuart (1969) to define biorecord 4 AW, which appears at WM 1987', the lowest sample that Norris (1969) assigned to Suite C. As Hughes (1981) notes, Norris identified such spores as Plicatella abaca (Burger), probably better retained in Cicatricosisporites as C. abacus, although he apparently distinguished this species primarily on thickening of the exine at the apices, a common but not constant character in 4 AW, rather than on width of the muri. Norris (1969) reports C. abacus from Suite B as well as Suite C, but Hughes (1981) suggests that the Suite B specimens in question actually represent biorecord 2 AF of Hughes & Moody-Stuart (1969), present in both upper Suite B (WM 2027'-2000') and lower Suite C (WM 1987'-1941'), which like 4 AW has wide muri and a tendency for thickened apices, but in which the sculpture fuses apically into a radial murus rather than leaving a radial lumen. For present purposes, the important point is that specimens with wide muri and the apical configuration of 4 AW rather than 2 AF are present in sample 4148', confirming a post-Suite B age. The fact that 2 AF has not been recognized in the Maryland samples may seem somewhat anomalous if they correlate with lower Suite C, but it would probably be premature to take this absence as stratigraphically significant: Hughes & Moody-Stuart (1969) record 2 AF as consistently less abundant than 1 AT, 3 AR, and 4 AW, and in view of the relatively low frequency of Cicatricosisporites in the Maryland samples and the difficulty of

determining apical configuration in poorly oriented specimens, it is possible that it has been overlooked.

Although the Cicatricosisporites groups discussed so far continue into Valanginian or even younger horizons in England (Hughes & Moody-Stuart, 1969; Hughes & Croxton, 1973), it seems unlikely that the Crisfield samples are younger than lower Suite C (mid-Berriasian), since intensive search has failed to reveal any of the Cicatricosisporites groups of Hughes & Moody-Stuart (1969) that appear above this part of the English section. These include: cfB. 5 A2, which enters at WM 1945'; cfB. 7 C1 (= C. lucifer Hughes & Moody-Stuart, 1967), also appearing at WM 1945', which Norris (1969) identified as Appendicisporites potomacensis (Hughes, 1981); and cfB. 6 B5, entering at WM 1924', which was apparently identified by Norris (1969) as C. angicanalis (Hughes, 1981).

Data on Cicatricosisporites distributions in northern Germany (Döring, 1965; Dörhöfer, 1977) are valuable both in confirming the validity of the sequence of types observed in the English reference section and in allowing independent correlations of the Crisfield interval with two other sections dated as Berriasian. The German flora which is closest to the Crisfield and lower Suite C floras is the Hils 1 assemblage of Dörhöfer (1977), dated on ostracodes as earliest late Berriasian. Although more species are recognized in this unit than in lower Suite C, and some of them are questionably identified with younger Cretaceous taxa, most of the figured specimens, as in the Crisfield assemblage, can be fairly readily related to biorecords 1 AT, 3 AR, and 4 AW of Hughes & Moody-Stuart (1969). Correlation with lower Suite C and the Crisfield flora is strengthened by the fact that the overlying unit, Hils 2, contains two new species which are not known from Crisfield but which are close to groups that appear in upper Suite C: C. hannoverana, which resembles 5 A2, and Plicatella pseudomacrorhyza, which resembles 7 C1. The Wealden A assemblage of Döring (1965), also dated on ostracodes as late Berriasian, also contains elements comparable with lower Suite C and Crisfield species (e.g., C. recticicatricosus, compared with 1 AT by Hughes & Moody-Stuart, 1969), but in addition forms close to the younger biorecords 5 A2 (C. perforatus) and 6 B5 (C. angicanalis), suggesting it is younger than the lower part of Suite C, as noted by Hughes & Moody-Stuart (1969, p. 109), and the 4148'-4121' interval in the Crisfield well.

The German floras are of further interest in containing analogs of the few Maryland specimens which, while still clearly related to the C. australiensis/C. abacus complex, fall near or outside the limits of morphological variation of the lower Suite C biorecords of Hughes & Moody-Stuart (1969). For example, the specimen in Pl. 4, figs. 5, 6 resembles 1 AT in general configuration of the muri, but it is larger and the muri are coarser, as in C. sprumonti of Döring (1965) from the Wealden A. Hughes & Moody-Stuart (1969) and Hughes (1981) also compare C. sprumonti with 1 AT and suggest that the differences are due to preparation procedure, but the fact that the same variation is seen in the Maryland samples suggests they may be genuine. The specimens in Pl. 4, figs. 7-9 resemble forms figured as C. sternum by Burger (1966) from the basal Cretaceous of the Netherlands and by Dörhöfer (1977) from Hils 1 in their even greater size and coarse, often perforated muri, several of which pass over the apices in parallel. Hughes & Moody-Stuart (1969) compare Burger's material with 4 AW, but again both the Maryland and

European specimens lie near or above the upper size limit cited for 4 AW. Even if these specimens represent extreme variants of 1 AT and 4 AW, the fact that they converge so closely in width and character of the muri suggests that some revision of characters used to define species limits in this complex may be in order. On the other hand, even if they fall outside the range of variation of the lower Suite C flora, they are consistent with correlation with lower Suite C, since the German horizons where they occur are either correlative with lower Suite C on other grounds or only slightly younger, and they cannot be related to groups that appear higher in the English section.

In contrast to Cicatricosisporites, detailed morphological and stratigraphic data on the verrucate Concavissimisporites-Trilobosporites complex in England are lacking, but stratigraphically significant changes in this complex during the Berriasian-Valanginian interval have been documented in Germany (Döring, 1964, 1965; Dörhöfer, 1977, Dörhöfer & Norris, 1977a,b). Existing taxonomic schemes unfortunately split the verrucate complex into what appears to be an excessive number of genera and along lines which sometimes seem to break up natural groups while associating unrelated ones. Most of the representatives figured by Döring (1964, 1965) are from either the Wealden A or the Wealden F and G rather than intervening zones, but enough specimens are figured from both intervals to be confident that the Crisfield assemblage has closer affinities with the Wealden A. The assemblages of Dörhöfer (1977) are harder to compare with the Maryland material, since several members of the complex in the lower part of his sequence are not illustrated but only identified with younger Cretaceous species of other authors, making it difficult to evaluate critically the range of morphology present. However, closest affinities seem again to be with the Hils 1 interval. In addition, Dörhöfer (1977) and Dörhöfer & Norris (1977b) recognize broad morphological trends within the complex as a whole during the Berriasian-Valanginian which support the correlations based on species comparisons.

The verrucate complex in Crisfield samples 4148'-4121' shows an almost continuous spectrum of sculpture variation, from obscurely sculptured forms barely distinguishable from large psilate spores in the same samples (Dictyophyllidites equiexinus/Cardioangulina spp.: Pl. 5, fig. 1) to forms with verrucae up to 10 µm in diameter, again suggesting a group in the midst of rapid diversification. The same spectrum apparently occurs in the Wealden A and Hils 1 floras. The most finely sculptured extreme (Pl. 5, figs. 2, 3) recalls Maculatisporites undulatus and M. microverrucatus of Döring (1964, 1965), both not found above the Wealden A, which tend to be smaller than M. granulatus from the Wealden F and G (synonymized with Concavissimisporites punctatus by Dörhöfer, 1977). Somewhat coarser forms (Pl. 5, fig. 4) are more comparable to Concavissimisporites pulcher Dörhöfer (1977), which ranges from Hils 1 to 4 but is most common in Hils 1. One of the most common groups consists of still more coarsely verrucate and usually larger spores with a tendency for coalescence of verrucae near the apices (Pl. 5, fig. 5), as in a specimen figured by Dörhöfer (1977) from Hils 1 as Tuberositriletes sp. A few specimens have similar sculpture but a noticeably thicker exine (Pl. 5, figs. 6, 7), suggesting C. robustus Dörhöfer (1977) from Hils 1 and 2. Another common group, which has more widely spaced verrucae and tends to be still larger (Pl. 5, fig. 9), seems to correspond to Tuberositriletes montuosus of Döring (1964, 1965), which ranges from the Wealden A to G but is most common in the Wealden A, and T. grossetuberculatus of Dörhöfer (1977)

from Hils 1 to 4. Other Crisfield forms have even sparser verrucae, mostly near the apices (Pl. 5, fig. 8), as in Varirugosisporites mutabilis Döring (1965), another Wealden A species.

Curiously, verrucate spores with thicker exine at the apices (Trilobosporites in the strict sense of recent authors) appear to be much rarer and less diverse in the Crisfield samples than in any of the German assemblages. The best examples are spores with one or two prominent apical verrucae and finer verrucae elsewhere (Pl. 6, fig. 1), as in T. rarigranulatus Döring from the Wealden A, and more obscurely sculptured forms (Pl. 6, fig. 2), possibly related to T. weylandi from the Wealden A (Döring, 1965).

Forms as extreme as the most coarsely verrucate spores in the Crisfield samples are not well illustrated in the German sections, but the data available suggest that they occur throughout the late Berriasian-early Valanginian interval. All these forms have large sculptural elements which rise above an irregular, more finely verrucate surface. In some, the large elements are smooth and often constricted basally into gemmae (Pl. 6, fig. 3), suggesting Rubinella major of Dörhöfer (1977), which is recorded from Hils 1 to 3. In others the large verrucae are more irregular in shape and often sculptured themselves, suggesting they were formed by coalescence of smaller round elements (Pl. 6, fig. 4). Similar sculpture is seen in a specimen figured by Dörhöfer (1977) as Impardecispora fsp. A, recorded from Hils 1 to 4, and one of the Wealden specimens figured by Couper (1958, Pl. 21, fig. 12) as Trilobosporites apiverrucatus, which however is larger and more lobate than the Crisfield specimens. These spores are connected with less extreme members of the Concavissimisporites-Tuberositriletes complex by their lobate shape and the existence of specimens showing intermediate degrees of coarseness (e.g., Pl. 6, fig. 5, or Tuberositriletes major of Döring, 1964).

A Berriasian rather than Valanginian age for the Crisfield samples is further supported by the fact that they have failed to yield any of the large spores with both extremely concave sides and large, discrete apical verrucae which appear in the Hils 3-4 and Wealden F-G assemblages (e.g., Concavissimisporites apiverrucatus, C. informis, etc. of Döring, 1965; C. verrucosus, C. multituberculatus, and Impardecispora spp. of Dörhöfer, 1977). Such forms represent the culmination of the Berriasian-Valanginian trends in size, shape, and sculpture noted by Dörhöfer & Norris (1977b). The Crisfield specimen in Pl. 6, fig. 6 has rather concave sides and coarser apices, but it is fairly small and the apical verrucae are low and coalescent, suggesting that it may be an extreme member of the Concavissimisporites pulcher group. Another specimen (Pl. 6, fig. 7) has large, discrete apical verrucae but nearly straight to convex sides, suggesting the coarsest specimens of Trilobosporites ivanovae Batten (1973b) from the Wealden, a species identified by Dörhöfer (1977) without illustration from Hils 1-4.

A few other groups seen in the Crisfield samples are reported to show temporal trends or restricted ranges within Berriasian-Valanginian sections elsewhere, but their stratigraphic significance is problematical. The low abundance and diversity of Gleicheniidites in the Crisfield samples perhaps support a Berriasian age, since Dörhöfer & Norris (1977b) note that gleicheniaceous types proliferate in Hils 4, and a similar phenomenon can be discerned in Döring's (1965) data. However, further study is desirable in order to

determine whether this is a valid evolutionary effect rather than a result of environmental changes within the Lower Saxonian Basin. On the other hand, the Maryland samples contain Aequitriradites (Pl. 2, figs. 5, 6), listed by Dörhöfer (1977) and Dörhöfer & Norris (1977a,b) as restricted to Hils 2 and the upper part of Suite C, which would conflict with other evidence for an earlier age. The Crisfield material appears to be different from the specimen figured as A. spinulosus by Norris (1969), but it is close to A. spinulosus of Dörhöfer (1977) from Hils 2. However, the fact that Dörhöfer (1977) records A. spinulosus as disappearing above Hils 2, although similar forms are widespread in younger Cretaceous deposits, suggests that its distribution in the German section may be facies-sensitive and unreliable for long-distance correlation. Similarly, the Crisfield samples contain Pilosisporites delicatulus (Pl. 2, fig. 3), also listed by Dörhöfer & Norris (1977a,b) as restricted to upper Suite C. However, they note that this species has not been observed in Germany, raising the possibility that its distribution too may be sensitive to environmental effects.

An interesting anomaly in Crisfield sample 4121' is the presence of a single small, finely striate grain of Ephedripites (Gnetales; Pl. 2, fig. 12), since this genus is said to appear first in the Barremian of England (Hughes, 1976). However, Ephedripites occurs down to the base of the Cretaceous in Africa and Brazil (Jardiné et al., 1974; Regali et al., 1974), in the Middle Jurassic and "Tithonian" of Argentina (Volkheimer, 1972; Volkheimer & Quattrochio, 1975), and the supposedly Upper Jurassic Morrison Formation of Colorado (Hotton & Doyle, unpubl.). In light of these data, this isolated occurrence is better interpreted as a range extension for the Southern Laurasian belt than as evidence against a Berriasian age. Another Crisfield element which has not been reported from the Purbeck or equivalent German floras but which is abundant in younger Cretaceous deposits is Taurocusporites cf. segmentatus (Pl. 2, figs. 10, 11). However, Taurocusporites is known from the "Tithonian" of Argentina (Volkheimer & Quattrochio, 1975) and from the Fairlight Clay of England, which immediately overlies the Purbeck (Batten, 1973a).

Crisfield sample 4121' contains a few grains of Classopollis and Alisporites whose unusually dark color suggests they may be reworked from older strata; both genera are abundant in the Newark Group (Cornet & Traverse, 1975).

These results indirectly contradict previous dating of the "red beds" below typical Potomac Group sediments in the Bethards well as Early Cretaceous (Doyle & Robbins, 1977), based on a slide from 7040'-7058' lent by Exxon Company. As was noted by Doyle & Robbins, this sample was obviously contaminated with younger pollen, but the bulk of the palynoflora seemed suggestive of a Hauterivian or younger age (several species of Cicatricosisporites and Appendicisporites, Concavissimisporites, Pilosisporites trichopapillosus, Apiculatisporis asymmetricus, Trilobosporites, Klukisporites, Ephedripites, and post-Jurassic dinoflagellates identified by F. May, pers. comm. to Robbins). Although one of the arguments used for this dating, the presence of Ephedripites, no longer seems valid (cf. above), the rest of the association, if indigenous, would still indicate a Cretaceous age. However, since the geophysical correlations of Hansen (1982) indicate that the Bethards "red beds" are almost surely older than the Waste Gate Formation in the Crisfield well,

it is perhaps most likely that the whole 7040'-7058' flora represents contamination from higher in the section.

Paleoecology. The Crisfield samples from 4148', 4138', and 4121' exhibit marked differences in quantitative composition (Table 1) which, considering the qualitative similarities among the floras, are presumably the result of local, short-term environmental shifts. On the one hand, sample 4148' is dominated by spores (23.5%, mostly smooth cyatheaceous/dicksoniaceous and gleicheniaceous types) and non-coniferous gymnosperm pollen, including 9.5% smooth monosulcates (mostly Bennettitales?), 3% Eucommiidites and the possibly related species "Monosulcites" glottus (Gnetales?: Hughes, 1961; Doyle et al., 1975; Trevisan, 1980), and a remarkably high frequency (28%) of Vitreisporites pallidus, pollen of the Mesozoic seed fern family Caytoniaceae. Except for the ubiquitous small, thin-walled inaperturates (20.5%; mostly Taxodiaceae?), conifer pollen is relatively subordinate, with only 7.5% bisaccates (Pinaceae and/or Podocarpaceae) and 3% Classopollis (the extinct family Cheirolepidiaceae). Sample 4121', on the other hand, contains only 10.5% spores and 0.5% Vitreisporites and is dominated by conifer pollen, including 26% small inaperturates, 13.5% bisaccates, 8.5% Classopollis, and 2.5% Araucariacites (Araucariaceae); it is unclear whether one of the most conspicuous elements, Exesipollenites (19.5%), is a conifer or a cycadophyte (Bennettitales?: Hughes, 1976). Sample 4138' is unfortunately dominated by wood fragments and very poor in pollen and spores, but the palynoflora present differs from that in both 4148' and 4121' in consisting largely of smooth spores (26%), Classopollis (25.3%), and apparent thin-walled inaperturates (20.7%, possibly including some degraded spores), and in lacking bisaccate conifers. Similar variations, though never as much Vitreisporites, are common in the much younger outcrop Potomac Group (cf. Brenner, 1963; Upchurch & Doyle, 1981). None of the samples have yielded any of the dinoflagellates, foraminifer chamber linings, or diverse acritarchs considered evidence of marine influence in the outcrop Potomac Group and other Jurassic-Cretaceous deposits (cf. Dörhöfer & Norris, 1977b; Upchurch & Doyle, 1981).

Some insight into the significance of these variations can be gained by comparison with coeval floras in England and Germany and consideration of their sedimentary context. Although only a few quantitative data are available (Norris, 1973), the English and German floras appear to be both very different from each other and less locally variable than the Crisfield samples in gross composition. Purbeck assemblages are dominated by the conifers Classopollis and Inaperturopollenites, which together usually make up at least 70%, sometimes more than 90%, of the flora (Norris, 1969)--much higher percentages than in even the relatively conifer-dominated Crisfield samples 4138' and 4121'. There is a general trend for decline of Classopollis and increase of Inaperturopollenites within the sequence (Norris, 1973). According to Döring (1965), the Purbeck-type lower Berriasian beds in Germany are also dominated by Classopollis (40-80%) and other gymnosperms, but the Bückeberg and "Wealden" assemblages differ from their English equivalents in being dominated by pteridophyte spores (Döring, 1965; Dörhöfer & Norris, 1977b); this cannot be said of any of the Crisfield samples.

Since the Purbeck Beds are interpreted as lagoonal (often evaporitic) below, becoming freshwater-lacustrine above, whereas the Bückeberg Formation is interpreted as lacustrine with extensive marginal deltas, the differences

in their palynofloras may be a special case of a widely noted phenomenon in the Mesozoic (Chaloner & Muir, 1968): dominance of fern spores in coals and other continental swamp sediments, dominance of conifer pollen in equivalent marine strata. Chaloner & Muir argue that this pattern would result if ferns were most abundant in swampy (e.g., delta-top) habitats, where pollen and spore deposition should be dominated by local plants, whereas conifers made up most of the vegetation of the regionally more extensive, better-drained "upland" areas and hence contributed most of the allochthonous pollen carried out into marine (and presumably lacustrine) environments. The latter part of this interpretation has been questioned by Hughes (1976), who argues that near-shore marine sediments should be dominated by pollen from coastal (e.g., mangrove) communities. There is evidence that some Classopollis-producing conifers were coastal halophytes (see reviews in Upchurch & Doyle, 1981; Alvin, 1982): cheirolepidiaceous megafossils have highly reduced leaves and apparently fleshy stems and are often abundant in lagoonal and other marine-influenced sediments. However, there is also evidence that they were not restricted to such habitats: cheirolepidiaceous megafossils are also known from deposits showing no evidence of marine influence, and their morphological features are as consistent with adaptation to aridity as to salinity. Classopollis is regionally dominant throughout the Southern Laurasian belt in the Late Jurassic and in Northern Gondwana in the Early Cretaceous, associated with evidence for hot and dry climates, and its decline near the Jurassic-Cretaceous boundary in Laurasian sections is also a regional phenomenon (Vakhrameev, 1970; Norris, 1973; Brenner, 1976). Hence, under one interpretation, the decline of Classopollis in the Purbeck could be a direct result of a shift from saline to freshwater coastal conditions, or, under the other, the two phenomena could be independent results of a shift from dry to wetter climate (cf. Dörhöfer & Norris, 1977b), or both factors could be involved. In any case, the relative homogeneity of the English and German floras can be interpreted as a result of relatively stable, laterally extensive sedimentary environments: lacustrine in England, paludal in Germany.

Compared with the European sections, the more variable and mixed character of the Crisfield assemblages and the lack of marine indicators are suggestive of a fluvial floodplain sequence. This fits Hansen's (1982) interpretation of the Waste Gate Formation as of fluvial origin, although differing from the younger outcrop Potomac Group in predominance of braided rather than meandering stream deposition. In such a depositional system, one would expect local sites to be dominated by pollen and spores derived throughout the year from the immediately surrounding vegetation, as in a deltaic swamp environment, but more variation in dominants due to greater spatial and temporal heterogeneity in habitats and vegetation, and generally greater degrees of dilution of local pollen by allochthonous pollen and spores transported in with clastic material during floods. These suppositions are supported by observations on megafossil localities in the outcrop Potomac Group, where palynofloras tend to contain higher-than-average frequencies of groups also represented in the associated megafossil flora (which should generally reflect local vegetation better than the palynoflora), but also a large admixture of groups not represented by megafossils at the locality (Hickey & Doyle, 1977; Upchurch & Doyle, 1981; unpubl. obs.). Assuming that the variations among the Crisfield assemblages roughly reflect differences in the character of local source vegetation, 4121' suggests a mixed conifer forest, while 4148' suggests lower, more scrubby vegetation, perhaps an example of

the "cycadophyte shrublands" reconstructed by Krassilov (1981) from megafossil data. 4138' is somewhat reminiscent of later Potomac Classopollis-dominated samples which sedimentary evidence and associated plankton suggest were derived from cheirolepidiaceous vegetation of marine-influenced habitats (Upchurch & Doyle, 1981), but considering the very poor quality of the sample, the lack of recognizable marine indicators, and the evidence for ecological heterogeneity of Cheirolepidiaceae (Upchurch & Doyle, 1981; Alvin, 1982), any environmental inferences would probably be premature.

The Crisfield palynofloras are also of paleoclimatological interest. Like correlative mid-Berriasian floras of England and Germany and the younger floras of the outcrop Potomac Group, they can be readily assigned to the fern- and gymnosperm-rich Southern Laurasian province of Brenner (1976), intermediate between the high latitude, presumably temperate floras of Siberia and Canada (Northern Laurasian province), which were dominated by bisaccate and inaperturate conifers and poor in ferns and Classopollis, and low latitude, tropical floras of Africa and South America (Northern Gondwana province), which were dominated by Classopollis, ephedroids, Araucariaceae, and monosulcates, with ferns low in diversity and bisaccates usually absent (Brenner, 1976). Also like mid-Berriasian floras of Europe, they contrast with the Classopollis-dominated floras of the Late Jurassic of Southern Laurasia, indicating that the relatively wet subtropical conditions that prevailed in Maryland through the rest of the Cretaceous were established by this time (cf. Brenner, 1963; Vakhrameev, 1970; Dörhöfer & Norris, 1977b).

SAMPLES 3430'-1113': BARREMIAN-APTIAN TO EARLY CENOMANIAN

Occurrences and frequencies of taxa identified in the ditch samples from 3430'-3450', 2550'-2570', and 2200'-2220' (hereafter abbreviated 3430', 2550', and 2200') and the core samples from 1143', 1127', and 1113' are presented in Table 2. In order to facilitate comparisons with the existing zonation, taxonomic treatment of spores and gymnosperm pollen generally follows Brenner (1963), except for taxa not recognized by him. In some cases, however, where Brenner's species have been subsequently transferred to more appropriate genera, the revised names are indicated in parentheses. Treatment of the angiosperm pollen generally follows Doyle & Robbins (1977), with some simplifications.

3430'

Correlation: Zone I (Barremian-Aptian, probably Aptian).

This ditch sample contains several Zone II (Albian) elements (the tricolpates and Cicatricosisporites patapscoensis, a Subzone II-B index species), but the Zone I character of the bulk of the flora suggests that these are contaminants from higher in the section. This supposition is supported by the presence of occasional Quaternary or Recent pollen (Quercus, Carya, Compositae) and the stratigraphic position of the sample, so far below assured Zone II samples. Most taxa identified are known from both Zone I and Zone II, but many of the most conspicuous elements are among those listed by Brenner (1963) as more abundant in Zone I (Cicatricosisporites, the Concavissimisporites-"Trilobosporites" complex, Classopollis). The most common spores are large, verrucate triletes similar to a form figured by

Bebout (1981) as Concavissimisporites crassatus, a species which Bebout records as restricted to Aptian and older (hence pre-Zone II) horizons in the Outer Continental Shelf. Precisely comparable spores are not figured by Brenner (1963), but they do occur in Zone I of the outcrop belt (pers. obs.); perhaps Brenner included them in C. punctatus or C. variverrucatus. On the other hand, several groups which are common in the basal Crisfield samples and in Jurassic and basal Cretaceous sediments elsewhere but rare or absent in the outcrop Potomac Group have not been seen, such as Marattisporites scabratus, Callialasporites, and Trilobosporites s. str. (with apical valvae, as opposed to "T." marylandensis and other Potomac species, which are probably better referred to Impardecispora). According to Bebout (1981), typical members of the last group (T. bernissartensis, T. domitus) disappear above the Hauterivian in the Outer Continental Shelf. These considerations, plus the presence of rare reticulate angiospermous monosulcates (cf. Clavatipollenites hughesii, Retimonocolpites peroreticulatus), indicate a Barremian or Aptian age, as for Zone I at the outcrop belt. Forms close to C. hughesii occur in both Barremian and Aptian sediments, but R. peroreticulatus, a species present to the base of Zone I in Delaware City well D12 of Doyle & Robbins (1977) and in all but a few basal Potomac Group samples at the outcrop, appears at the base of the Aptian in England (Hughes et al., 1979). The presence of Decussosporites microreticulatus, which enters somewhat above the base of Zone I (Hickey & Doyle, 1977), also suggests an Aptian rather than Barremian age. However, since only one grain of each of the last two species was seen, it is hard to exclude the possibility that they are up-hole contaminants. Detailed study of the abundant striate Schizaeaceae, which are much more diverse morphologically here than in the Berriasian samples from 4148'-4121', might allow more precise correlation with the English section.

Paleoecology. No dinoflagellates, diverse acritarchs, or other plankton believed to indicate marine influence have been observed, nor any of the psilate and very fine-spined acritarchs believed to extend into freshwater environments (Upchurch & Doyle, 1981). As in the Berriasian sample from 4121' and much of the outcrop Potomac Group, the flora is dominated by inaperturate conifer pollen of probable taxodiaceous affinities (Inaperturopollenites, 43%), but there is a large component of cheirolepidiaceous conifers (Classopollis, 15%) and fern spores (26.5%). This suggests that the main source of pollen was a wet, conifer-dominated, floodplain forest, perhaps analogous to the Taxodium swamp forests of today, with either a large number of subdominants in the forest itself or significant influx of pollen and spores from other communities.

2550'

Correlation: lower Subzone II-B (middle Albian?).

This ditch sample too is slightly contaminated with Quaternary or Recent pollen (Quercus, Carya, Chenopodiaceae/Amaranthaceae, Gramineae), but unlike 3430' it contains no anomalous mixtures of Cretaceous elements indicating contamination from higher in the Potomac Group; all taxa identified are highly consistent with derivation from near the base of Subzone II-B. The flora contains several Zone II index species of Brenner (1963), which enter in Subzone II-A and continue into younger horizons ("Monosulcites" chaloneri, Lycopodiacidites irregularis, Perotriletes pannuceus, Reticulatisporites

arcuatus), plus one Subzone II-B index species ("Taurocusporites" spackmani, = Acritosporites sibiricus Obonitzkaja and Scopusporis spackmani Wingate). The angiosperms allow more precise localization within Subzone II-B, to near the 660'-640' interval in Delaware City well D13 (Doyle & Robbins, 1977). Many of the tricolpates belong to groups that enter in Subzone II-A (cf. Tricolpites micromunus, cf. T. albiensis, aff. T. georgensis, cf. "Tricolpopollenites" parvulus), while cf. Tricolpites crassimurus and several of the angiospermous monosulcates extend down into at least upper Zone I (aff. "Clavatipollenites" minutus, cf. C. tenellis, cf. Retimonocolpites dividuus, R. peroreticulatus). However, there are several other angiosperm types which enter at the base of Subzone II-B (Tricolpites sp. B, aff. "Retitricolpites" fragosus, aff. Stellatopollis barghoornii, Stephanocolpites fredericksburgensis, and possibly aff. Liliacidites sp. E), and one specimen of cf. Tricolpites micromunus shows slight differentiation of ora in the colpi (tricolporoidate condition), a tendency not seen until the base of Subzone II-B. A lower Subzone II-B age is supported by the rarity of tricolporoidates and Subzone II-B index spores and the absence of any of the distinctive angiospermous monosulcates and tricolpates that appear in middle and upper Subzone II-B; in addition, the grains identified as aff. "Clavatipollenites" minutus are of a loosely reticulate variety most common below middle Subzone II-B. The quantitative character of the flora also supports this dating: it is rich in several hilate, zonate, and related spore types of probable hepatic and lycopsid affinities which are long-ranging but especially conspicuous near the Subzone II-A/II-B boundary in the Delaware City wells and at the outcrop belt (Apiculatisporis asymmetricus, Cingulatisporites distaverrucosus, C. reticingulus, Lycopodiacidites irregularis, L. triangularis, Taurocusporites segmentatus, Triporoletes radiatus), while Pilosisporites, Concavissimisporites, and to a lesser extent Cicatricosisporites are on the decline.

Paleoecology. Unlike 3430', this sample does contain a few psilate and very fine-spined acritarchs, but none of the more diverse acritarchs or dinoflagellates typical of marine sediments. Evidence that such depauperate acritarch assemblages are consistent with freshwater conditions is adduced by Upchurch & Doyle (1981). Once more, the pollen and spore flora is dominated by probable taxodiaceous pollen (Inaperturopollenites, 63%), with Cheirolepidiaceae next most abundant (Classopollis, 17%), suggesting a wet floodplain conifer forest, with abundant bryophytes and lycopsids but less contribution from fern-dominated communities than in 3430'.

2200'

Correlation: upper Subzone II-B (middle-late Albian?).

Like 2550', this ditch sample contains some Quaternary or Recent contaminants (Quercus, Ambrosia, Chenopodiaceae/Amaranthaceae), but no clear evidence of contamination from higher in the Potomac Group. A Subzone II-B age is indicated by the presence of several of Brenner's (1963) index spores for Zone II ("Monosulcites" chaloneri, Lycopodiacidites irregularis, Perotriletes pannuceus, Reticulatisporites arcuatus) and Subzone II-B (Cicatricosisporites subrotundus, Neoraistrickia robusta, "Taurocusporites" spackmani). Many of the angiosperms belong to groups already noted in 2550' or known from lower Subzone II-B in the Delaware City wells (Asteropollis asteroides, cf. "Retitricolpites" prosimilis), but a significantly younger

age is indicated by both the greater abundance of angiosperms and several specific occurrences: typical Stellatopollis barghoornii and "Retitricolpites" fragosus, which have relatives in 2550' and other lower Subzone II-B horizons but attain their typical morphology in the middle of the subzone; Tricolpites minutus, possible relatives of "Retitricolpites" magnificus, and abundant tricolporoidate variants of the T. micromunus and T. albiensis groups, all typical of middle and upper Subzone II-B; and typical Liliacidites sp. E, which appears in upper Subzone II-B. On the other hand, the presence of the Asteropollis asteroides-Stephanocolpites fredericksburgensis group, which disappears in the uppermost part of Subzone II-B (but persists into the late Albian of the Gulf Coast: Wingate, 1980) helps place the sample below the Subzone II-B/II-C boundary, as does the absence of characteristic new Subzone II-C forms such as Rugubivesiculites rugosus and Tricolporoidites subtilis. The absence of "Retitricolpites" vermimurus, one of the distinctive elements of upper Subzone II-B, is somewhat anomalous, but it could be due to local environmental factors.

Paleoecology. A few psilate acritarchs were observed, but no diagnostic marine plankton, suggesting freshwater conditions. This is another Inaperturopollenites-dominated sample (50.5%), suggesting a floodplain conifer forest. It may be contrasted with certain angiosperm-dominated outcrop and subsurface samples of similar age, which have been interpreted as representing early successional vegetation of stream margins and other disturbed habitats rather than mature conifer forests (Hickey & Doyle, 1977). A curious feature is the abundance of the hepatic spore Triporoletes reticulatus; since a large clump of these spores was observed, their high frequency may be the result of fortuitous inclusion of sporangium-bearing megafossils in the sample prepared rather than exceptional local abundance of the parent plants.

1143', 1127', 1113'

Correlation: middle Zone III (early Cenomanian?).

Of these core samples, 1143' differs markedly from the other two in frequencies of elements, but all three are similar enough in qualitative composition, including most of the same stratigraphically significant forms, to be discussed together.

Most of the spores and gymnosperm pollen and many of the angiosperms represent groups present since Subzone II-B or earlier. A Subzone II-C or younger age is indicated by the presence of the conifers Rugubivesiculites reductus and R. rugosus and the abundance of very small, psilate, tricolporoidate angiosperms, many difficult to identify to species but some definitely assignable to Tricolporoidites subtilis, which appears at the base of Subzone II-C, and "Tricolporopollenites" distinctus, which appears in its upper part. Many of the other angiosperms belong to groups that enter in basal Zone III: cf. Tricolpites vulgaris, aff. T. nemejci, aff. Tricolporoidites bohemicus, T. sp. A, T. sp. B, aff. Tricolporopollenites sp. A, T. sp. B, typical Ajatipollis sp. A, and tricolporoidate relatives of "Retitricolpites" prosimilis. Correlation with the middle half of Zone III (post-330', pre-220' in Delaware City well D13 of Doyle & Robbins, 1977), unfortunately one of the most poorly known parts of the Potomac sequence, is supported by several lines of evidence: presence of Striatopollis sp. B, known from middle and upper

Zone III; rarity of triangular tricolporoidates ("Tricolporopollenites" triangulus, T. sp. B), which peak in lower Zone III; presence of Stellatopollis barghoornii, not known above middle Zone III; and lack of forms which appear in upper Zone III, such as typical Tricolpites nemejci, T. barrandei, Stephanocolpites tectorius, or "Foveotricolporites" rhombohedralis.

Several species in these samples are of problematical stratigraphic significance. A conspicuous element in 1143' is a medium-sized, very coarsely reticulate, columellar monosulcate with tall muri and a peculiar elliptical sulcus, listed in Table 2 under Retimonocolpites spp., which appears to represent a new species. Sample 1127' contains a fairly common form, identified as aff. Clavatipollenites tenellis, which differs from typical C. tenellis of lower Zone III and older horizons in its smaller size and often irregular aperture, approaching Asteropollis sp. A of upper Zone III. Rare specimens of Liliacidites in 1127' and 1113' are somewhat suggestive of L. sp. D and L. sp. F of Doyle & Robbins (1977), both of which disappear above basal Zone III, but since they do not correspond precisely to either species, their stratigraphic significance is unclear. Many of the spores in all three samples are not identifiable with taxa described by Brenner (1963); some of them may eventually prove to be index species for Zone III.

Paleoecology. No acritarchs or other plankton have been observed in 1143' or 1113', while 1127' contains only a few psilate acritarchs believed to be consistent with freshwater conditions. Sample 1143' differs from all previously discussed samples in being dominated by angiosperms (65.5%) and poor in Inaperturopollenites (3%). This is in part a function of the worldwide increase in angiosperms during the Albian-Cenomanian, but it probably also reflects local ecological factors, since angiosperms are less abundant (28.5%, 39%) and Inaperturopollenites is more abundant (49%, 33.5%) in the overlying samples from 1127' and 1113'. This could be an example of the postulated contrast between angiosperm-dominated secondary vegetation of disturbed habitats and conifer-dominated climax forests of floodplain swamps mentioned above (Hickey & Doyle, 1977). Interestingly, 1143' also differs from 1127' and 1113' in the pale appearance of most of the pollen, perhaps as a result of somewhat more oxidizing conditions after deposition.

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Table 1. Spores and pollen identified in Crisfield (Som-Dd 47) samples 4148', 4138', and 4121' (Berriasian). Percentages based on count of 200 specimens in 4148' and 4121', 150 specimens in 4138'. X = present but not encountered during count.

	4148'	4138'	4121'
PTERIDOPHYTE AND BRYOPHYTE SPORES			
Acanthotriletes varispinosus	X		X
Aequitriradites spinulosus sensu Dorhofer	X		X
Chomotriletes minor		0.7	X
Cicatricosisporites australiensis/C. abacus	0.5	1.3	X
Cicatricosisporites purbeckensis	0.5	0.7	
Concavisporites juriensis sensu Norris	0.5		X
Concavissimisporites/Maculatisporites spp.	X	0.7	X
Contignisporites hilsei	X		
Coronatispora valdensis	X		X
Couperisporites complexus sensu Norris	X		X
Cyathidites australis	2.5	6.7	1.0
Cyathidites minor/Dictyophyllidites harrisii	12.5	17.3	5.0
Densoisporites microrugulatus	X		
Densoisporites perinatus	X		
Dictyophyllidites equiexinus/Cardioangulina spp.	4.5	1.3	X
Foraminisporis wonthaggiensis	X		X
Gleicheniidites spp.	0.5	0.7	X
Klukisporites pseudoreticulatus	X		X
Klukisporites variegatus	X		
Leptolepidites epacrornatus	X	2.0	1.0
Leptolepidites psarosus	X	1.3	X
Lycopodiumsporites austroclavatidites	X		X
Marattisporites scabratus	1.0	1.3	2.5
Microreticulatisporites diatretus	X		
Osmundacidites/Baculatisporites spp.	1.0	3.3	0.5
Peromonolites fragilis	X		
Pilosisporites delicatulus	X		0.5
Pilosisporites trichopapillosus	X		X
Reticulisporites semireticulatus	X		X
Taurocusporites cf. segmentatus	X		X
Trilobosporites rarigranulatus	X		
Trilobosporites aff. weylandi	X		
Tuberositriletes montuosus/T. grossetuberculatus	X	0.7	
Tuberositriletes/Rubinella spp. (coarse)	X		X
GYMNOSPERM POLLEN			
Abietineaepollenites/Alisporites spp.	5.0		11.0
Araucariacites australis	0.5	0.7	2.5
Callialasporites spp.	1.0		1.0
Cerebropollenites spp.	1.5		2.0
Classopollis sp.	3.0	25.3	8.5
Ephedripites sp.			X
Eucommiidites spp.	1.5	4.7	1.5
Exesipollenites sp.	X	3.3	19.5
Inaperturopollenites/Spheripollenites spp.	20.5	20.7	26.0
Monosulcites/Cycadopites spp.	9.5	2.7	8.0
"Monosulcites" glottus	1.5		1.5
Parvisaccites radiatus/P. sp.	2.5		2.5
Perinopollenites elatoides	2.0		5.0
Podocarpidites sp.	X		X
Vitreisporites pallidus	28.0	4.7	0.5

Table 2. Spores and pollen (excluding Quaternary or Recent contaminants) identified in Crisfield (Som-Dd 47) samples 3430' through 1113'. Percentages based on count of 200 specimens. X = present but not encountered during count.

	3430'	2550'	2200'	1143'	1127'	1113'
PTERIDOPHYTE AND BRYOPHYTE SPORES						
Apiculatisporis (Foraminisp.) asymmetricus		X				X
Appendicisporites spp.	1.0	X	0.5	1.0	2.0	X
Ceratosporites parvus				0.5	0.5	
Chomotriletes minor			0.5			
Cicatricosisporites patapscoensis	X					
Cicatricosisporites subrotundus			X			
Cicatricosisporites spp.	7.5	7.0	3.5	0.5	X	4.0
Cingulatisporites distaverrucosus	X	X	X		X	0.5
Cingulatisporites reticingulus		X			X	
Cingulatisporites sp. (psilate)			X		3.0	0.5
Cirratriradites (Aequitrirad.) spinulosus	0.5		2.0	X		
Concavissimisporites crassatus	9.0					
Concavissimisporites punctatus		X				
Aff. Concavissimisporites sp. (psilate)	X	0.5	1.0	1.0	0.5	X
Converrucosisporites sp.		1.0	X	X		
Cyathidites australis	0.5	0.5	X	X	0.5	1.5
Cyathidites minor	4.5	2.0	3.5	5.0	3.0	7.5
Densoisporites microrugulatus			0.5			
Foraminisporis spp.	X				1.0	
Gleicheniidites spp.				X	X	0.5
Granulatisporites dailyi		X	X	0.5		
Inaperturopollenites pseudoreticulatus	0.5		X			
Klukisporites spp. (inc. Ischyosporites)	X		X			0.5
Laevigatosporites gracilis	X	X	1.0	0.5	X	
Lycopodiacidites ambifoveolatus			X			X
L. cerniidites (Camarozonosporites)				0.5		
Lycopodiacidites irregularis		X	X		X	
Lycopodiacidites triangularis		X		X	1.0	0.5
Lycopodiumsporites dentimuratus			X			
Matonisporites (Acritosporites) excavatus						1.0
Monosulcites (Verrucatosporites) chaloneri		X	X			
Neoraistrickia robusta			X			
Osmundacidites sp.	0.5					
Peromonolites spp.	X	0.5	X		1.0	X
Perotriletes pannuceus		X	X		X	0.5
Pilosisporites trichopapillosus & aff.	1.5	X	X	X	0.5	
Psilatriletes circumundulatus				X	1.0	0.5
Reticulatisporites arcuatus		X	X	0.5		
Taurocusporites reduncus	X		0.5	0.5	0.5	X
Taurocusporites segmentatus		0.5	X			
T. spackmani (Acritosporites sibiricus)		X	X			X
Trilobosporites marylandensis	1.0					
Triporoletes spp.	X	1.0	5.5		0.5	
Undetermined spores	X	0.5	0.5	1.0	2.5	1.0
GYMNOSPERM POLLEN						
Abietineaepollenites/Alisporites spp.	4.5	0.5	1.0	9.0	X	X
Araucariacites australis	0.5	X	0.5	X	X	X
Zonalapollenites (Callialasporites) sp.			X			
Classopollis spp.	15.0	17.0	13.5	9.5	1.5	5.5
Decussosporites microreticulatus	X	X				

Table 2, Cont.	3430'	2550'	2200'	1143'	1127'	1113'
Ephedripites spp.	1.5	X	X	X	2.0	2.5
Eucommiidites sp.	0.5					X
Exesipollenites tumulus	2.5	3.5	6.5		0.5	0.5
Inaperturopollenites spp.	43.0	63.0	50.5	3.0	49.0	33.5
Laricoidites spp.	0.5	X	0.5		0.5	
Monosulcites/Cycadopites spp.		1.0	1.0		X	X
"Monosulcites" glottus	X	0.5	0.5	X	0.5	X
Monosulcites scabrus					X	
Perinopollenites elatoides	0.5	X				
Phyllocladidites sp.				1.0		X
Podocarpidites sp.			X			
Rugubivesiculites reductus				0.5	X	0.5
Rugubivesiculites rugosus				X		
MONOSULCATE AND RELATED ANGIOSPERM POLLEN						
Asteropollis asteroides			X			
Clavatipollenites hughesii & aff.	X		X	X		
"Clavatipollenites" minutus & aff.		X	0.5	X		0.5
Cf. Clavatipollenites tenellis		X	1.5			
Aff. Clavatipollenites tenellis					X	
Liliacidites aff. sp. D or F					X	X
Liliacidites sp. E (trichotomosulcate)			X			
Aff. Liliacidites sp. E (monosulcate)		X				
Cf. Retimonocolpites dividuus		X		0.5		
Retimonocolpites peroreticulatus	0.5	X	0.5			
Retimonocolpites spp.			X	8.0		X
Stellatopollis barghoornii			X	X	X	
Aff. Stellatopollis barghoornii (fine)		0.5				
Stephanocolpites fredericksburgensis		X	X			
TRICOLPATE AND RELATED ANGIOSPERM POLLEN						
Ajatipollis sp. A				X	1.0	
"Retitricolpites" fragosus			1.0			
Aff. "Retitricolpites" fragosus		0.5				
"Retitricolpites" geranioides				0.5		
Aff. "Retitricolpites" magnificus	X		X			
"Retitricolpites" prosimilis & aff.			0.5	0.5	1.0	0.5
Striatopollis sp. B				X		
Cf. Tricolpites albiensis		X	0.5			
Cf. Tricolpites crassimurus	1.0	X	X	X		
Tricolpites georgensis & aff.		X		0.5	X	
Tricolpites micromunus & aff.	2.0	X	2.0	2.5	5.0	4.0
Tricolpites minutus & aff.			X	3.0	5.0	2.5
Aff. Tricolpites nemejci				1.0	1.5	2.0
Cf. Tricolpites vulgaris				3.5	0.5	1.5
Tricolpites sp. B & aff.	0.5	X		5.0		X
Cf. "Tricolpopollenites" parvulus	X	X		7.5	3.0	6.0
Undetermined tricolpates			0.5	0.5	0.5	
Aff. Tricolporoidites bohemicus				X	1.5	2.0
Tricolporoidites subtilis & aff.				22.5	5.5	8.0
Tricolporoidites sp. A				0.5	X	3.5
Tricolporoidites sp. B				7.0	X	X
"Tricolporopollenites" distinctus & aff.				2.5	3.5	5.5
"Tricolporopollenites" triangulus				X		
Aff. Tricolporopollenites sp. A				X	X	1.5
Tricolporopollenites sp. B						0.5
Undetermined tricolpor(oid)ates					0.5	1.0

PLATES

PLATE 1

All figures 750X

1, 2: Coronatispora valdensis, SGP CF 4148-43;

3: Acanthotriletes varispinosus, CF 4148-1b, 15.0 X 91.7;

4, 5: Reticulisporites semireticulatus, CF 4148-1b, 3.9 X 105.6;

6, 7: Couperisporites complexus sensu Norris, SGP CF 4148-39;

8, 9: Klukisporites pseudoreticulatus, CF 4148-1b, 4.3 X 95.8;

10: Leptolepidites psarosus, CF 4121-1b, 1.1 X 112.6;

11: Parvisaccites radiatus, CF 4148-1b, 10.5 X 89.6;

12: P. radiatus, CF 4148-1b, 12.1 X 103.1;

13: Concavisporites juriensis sensu Norris, CF 4121-1b, 8.0 X 114.3;

14: Densoisporites perinatus, CF 4121-1b, 19.9 X 95.6.

CF = Crisfield well, Som-Dd 47; SGP = single grain preparation.

Coordinates: UCD Zeiss microscope UC 78 30 05524.

PLATE 1

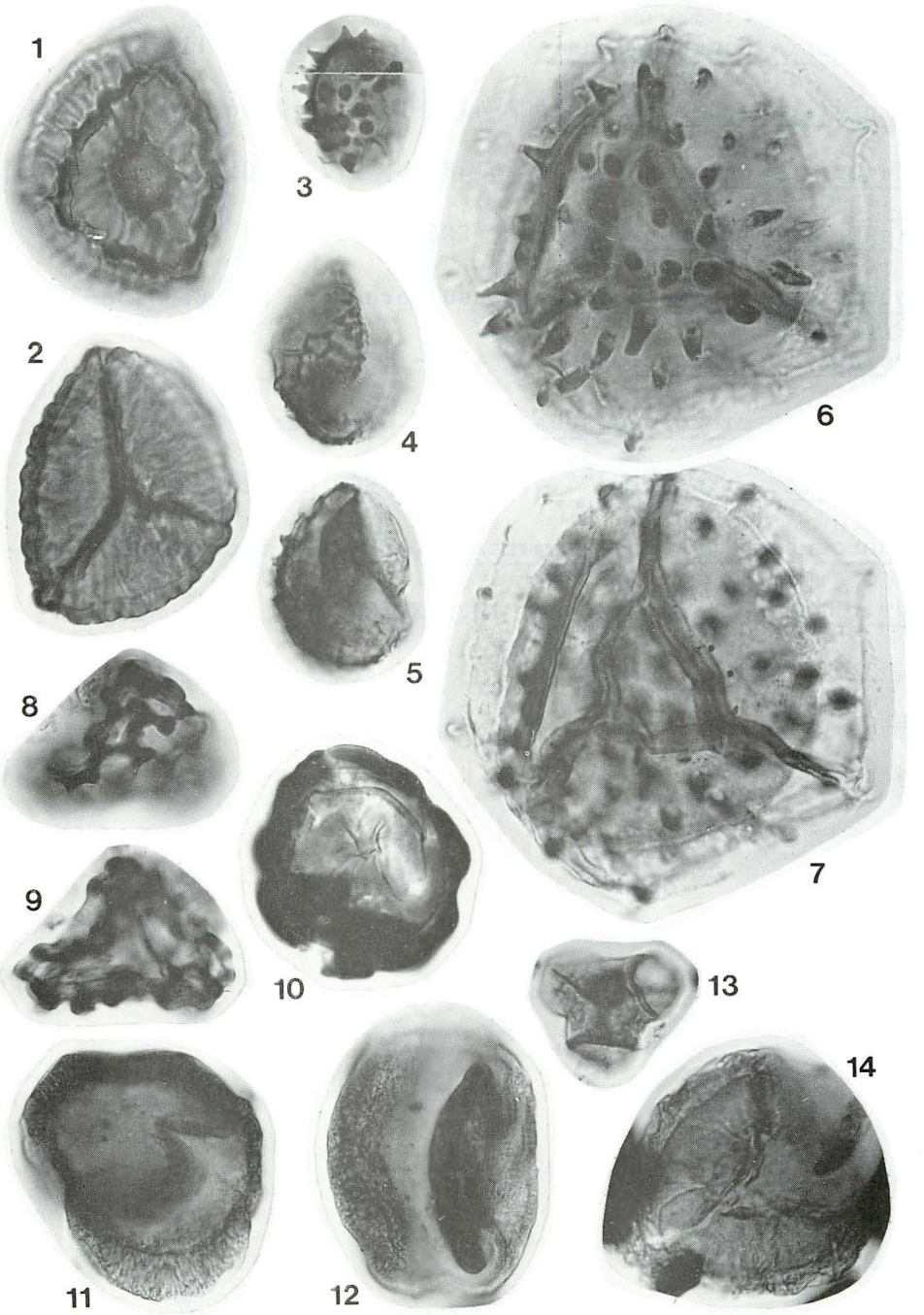

PLATE 2

All figures 750X

1: Foraminisporis wonthaggiensis, CF 4121-1b, 20.3 X 111.0;

2: Leptolepidites epacrornatus, CF 4121-1b, 3.4 X 96.2;

3: Pilosisporites delicatulus, CF 4148-1b, 3.2 X 105.3;

4: Pilosisporites trichopapillosus, SGP CF 4148-44;

5, 6: Aequitriradites spinulosus sensu Dorhofer, SGP CF 4148-38;

7: Contignisporites hilsei, SGP CF 4148-1;

8: Densoisporites microrugulatus, SGP CF 4148-42;

9: Aff. Callialasporites sp. 4 of Norris, SGP CF 4148-41;

10, 11: Taurocusporites cf. segmentatus, CF 4121-1b, 21.8 X 95.7;

12: Ephedripites sp., CF 4121-1b, 10.9 X 104.9.

PLATE 2

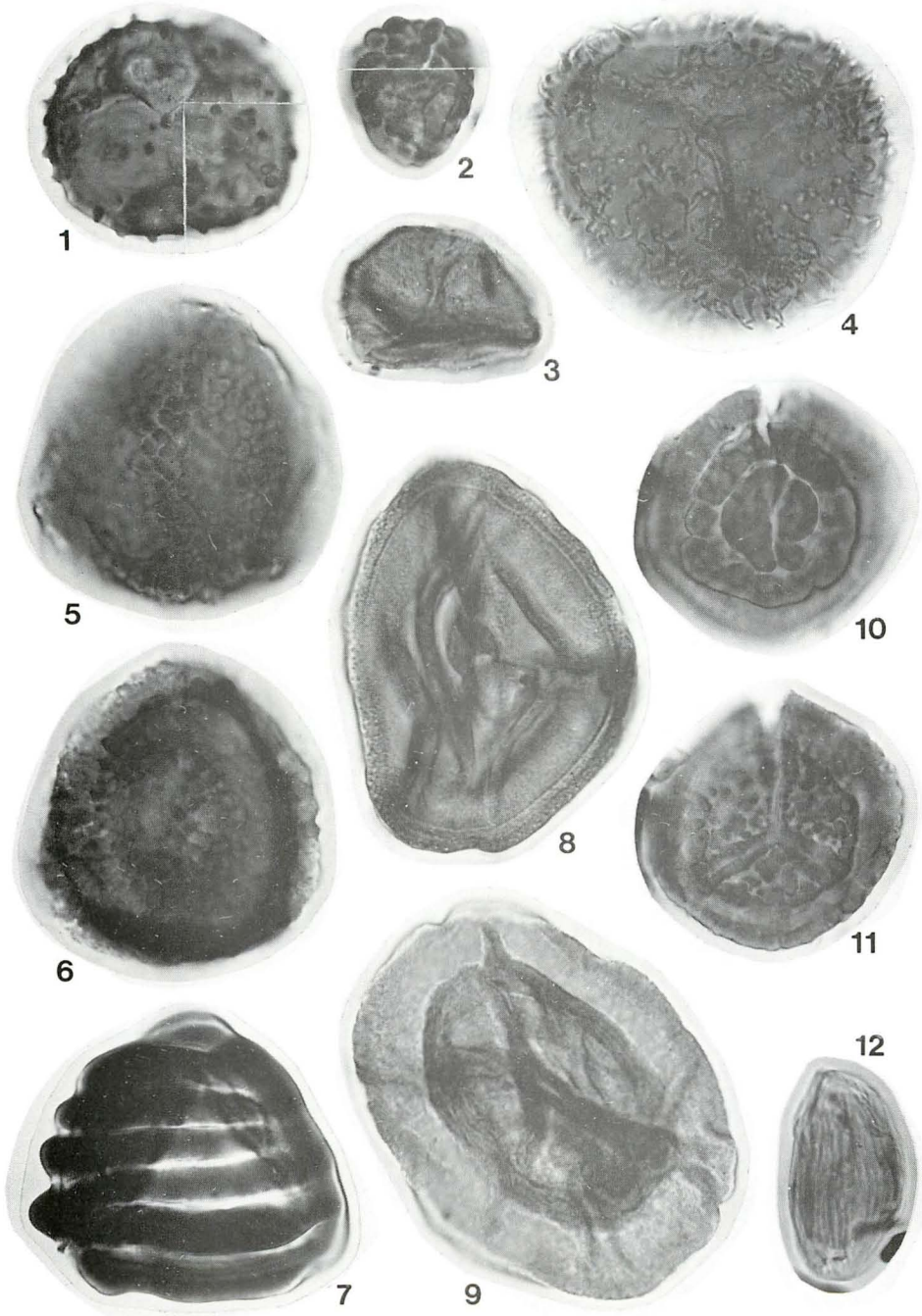

PLATE 3

All figures 750X

1, 2: Cicatricosisporites purbeckensis (biorecord 3 CICATR AR), SGP CF 4148-33;

3, 4: C. purbeckensis, SGP CF 4148-34;

5, 6: C. purbeckensis, SGP CF 4148-35;

7, 8: Cicatricosisporites australiensis (biorecord 1 CICATR AT), SGP CF 4148-13;

9, 10: C. australiensis, SGP CF 4148-12;

11, 12: C. australiensis, SGP CF 4148-6.

PLATE 3

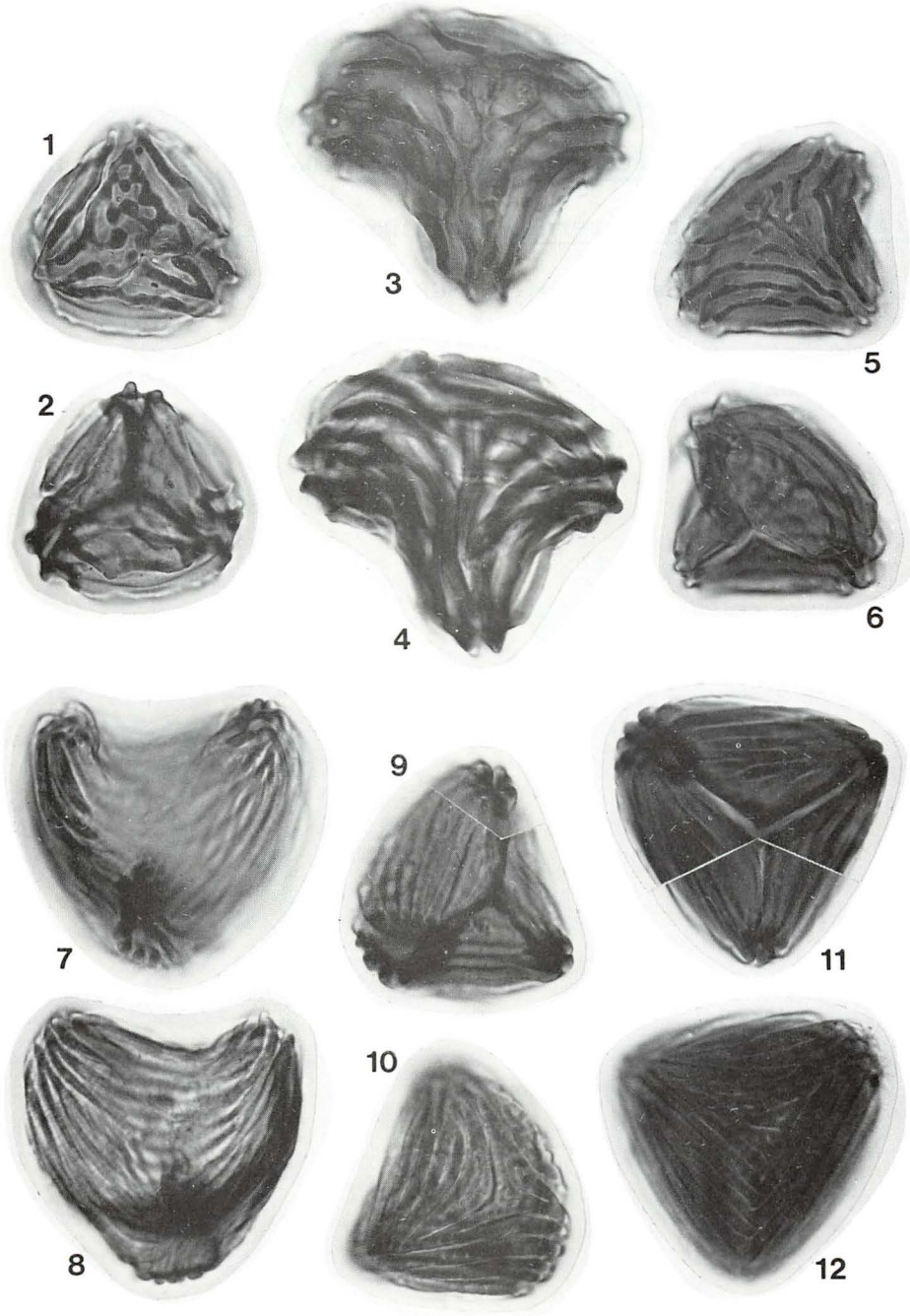

PLATE 4

All figures 750X

1, 2: Cicatricosisporites abacus (biorecord 4 CICATR AW), SGP CF 4148-2;

3, 4: C. abacus, SGP CF 4148-3;

5, 6: Cf. Cicatricosisporites sprumonti sensu Doring, SGP CF 4148-5;

7: Cf. Cicatricosisporites sternum sensu Dorhofer, SGP CF 4148-8;

8, 9: Cf. C. sternum sensu Dorhofer, SGP CF 4148-9.

PLATE 4

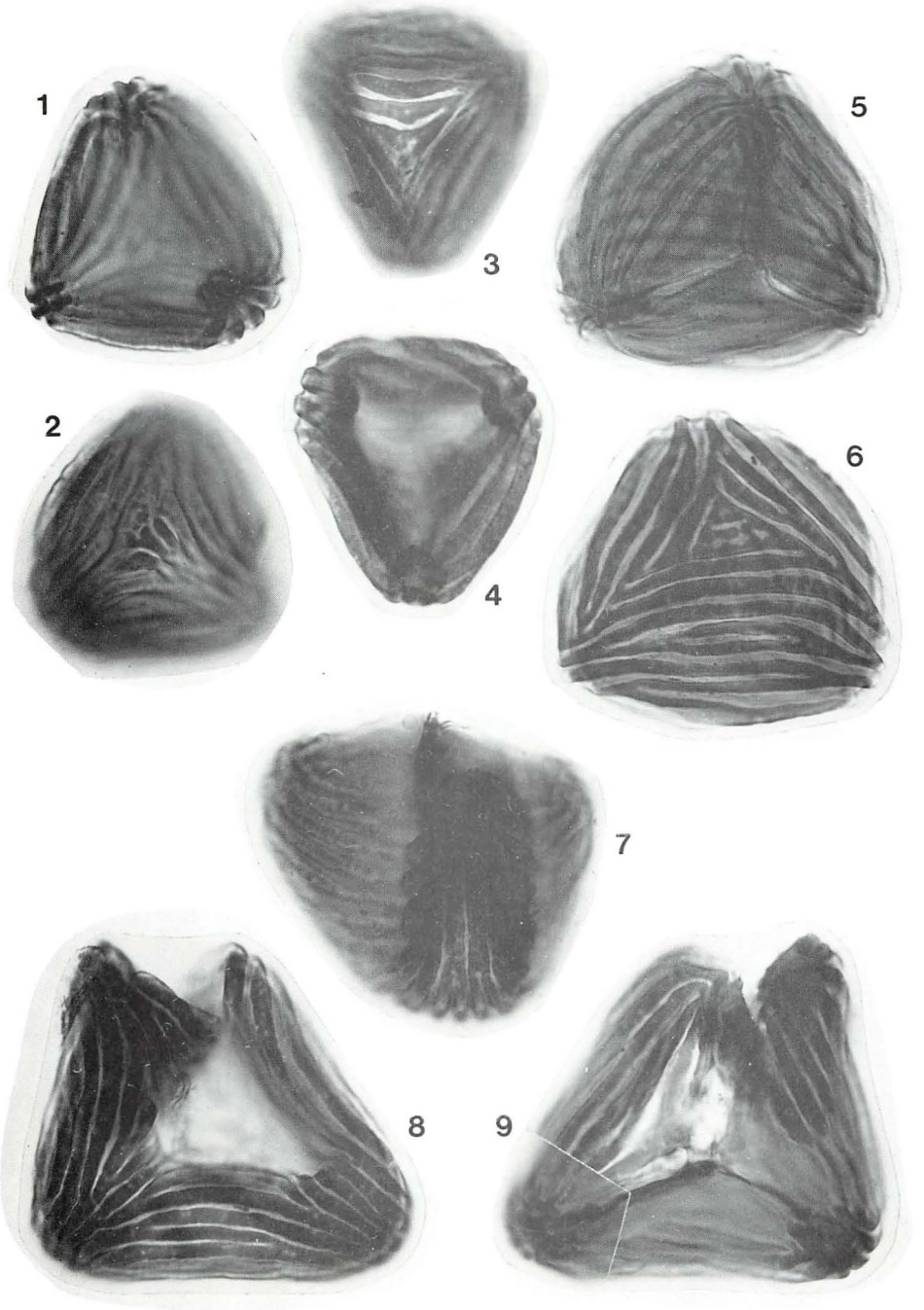

PLATE 5

All figures 750X

1: Dictyophyllidites equiexinus/Cardioangulina sp., SGP CF 4148-46;

2, 3: Cf. Maculatisporites undulatus or M. microverrucatus, SGP CF 4148-16;

4: Concavissimisporites pulcher, SGP CF 4148-19;

5: Tuberositriletes sp. of Dorhofer, SGP CF 4148-21;

6, 7: Cf. Concavissimisporites robustus, SGP CF 4148-22;

8: Cf. Varirugosisporites mutabilis, SGP CF 4148-17;

9: Tuberositriletes montuosus or T. grossetuberculatus, SGP CF 4148-27.

PLATE 5

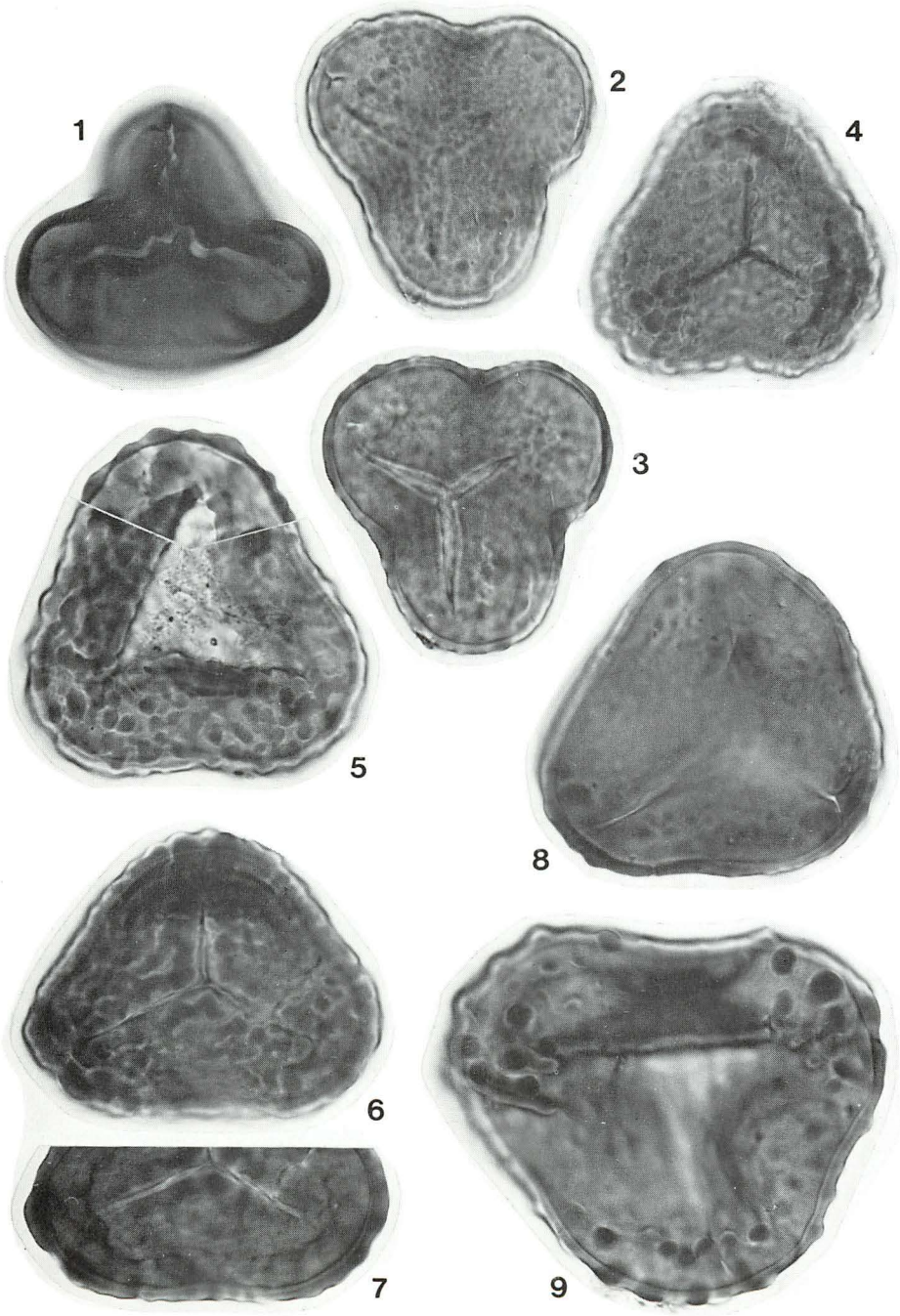

PLATE 6

All figures 750X

1: Trilobosporites rarigranulatus, CF 4148-1b, 13.0 X 103.4;

2: Trilobosporites aff. weylandi, CF 4148-1b, 10.1 X 89.4;

3: Cf. Rubinella major sensu Dorhofer, SGP CF 4148-28;

4: Tuberositriletes/Rubinella sp., SGP CF 4148-29;

5: Concavissimisporites or Tuberositriletes sp., SGP CF 4148-23;

6: Concavissimisporites sp., SGP CF 4148-20;

7: Cf. Trilobosporites ivanovae, SGP CF 4148-26.
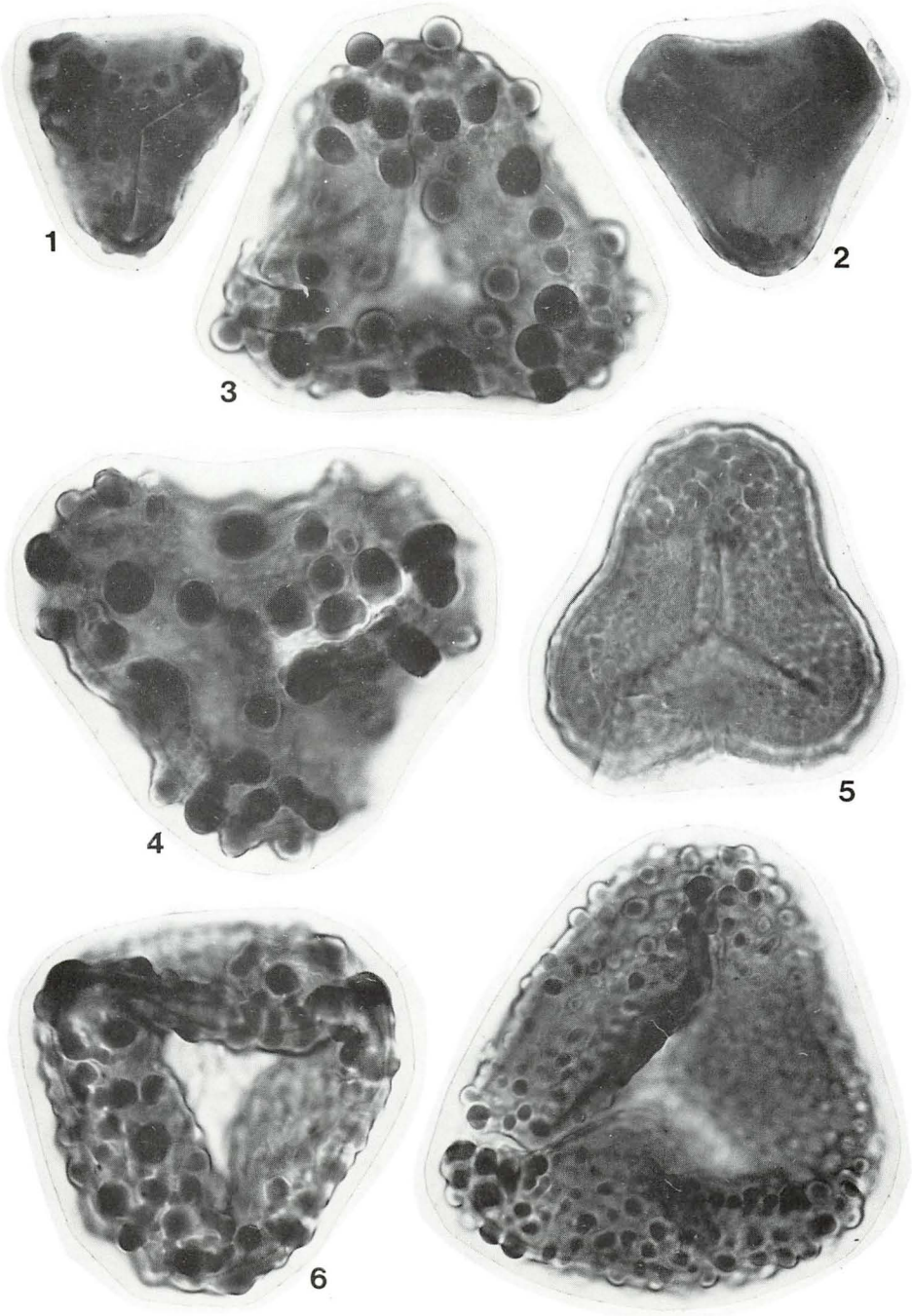
PLATE 6