MARYLAND GEOLOGICAL SURVEY
REPORT OF INVESTIGATIONS NO.11

KENNETH N. WEAVER, DIRECTOR

PETROLOGY AND ORIGIN OF POTOMAC AND MAGOTHY (CRETACEOUS) SEDIMENTS, MIDDLE ATLANTIC COASTAL PLAIN

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ABSTRACT

The Potomac Group and Magothy Formation (Early-Late Cretaceous), the basal sediments of the Altantic Coastal Plain in Delaware, Maryland, and Virginia, were studied to determine the means of sediment dispersal, provenance, and character of the depositional environments. Thickness variations, cross-bedding, pebble counts, textural analyses, and petrography with special regard to heavy minerals were employed to achieve these objectives.

The Early Cretaceous Potomac Group appears in outcrop as a variable sequence of gravel, sand, silt, and clay, divisible by paleontologic and petrographic criteria into four formations - Patuxent, Arundel, Patapsco, and Raritan - in ascending order. The Potomac Group is unconformably overlain in Maryland and Delaware by sand, silt, clay, and subordinate gravel of the Magothy Formation.

The Cretaceous sediments form a southeasterly-expanding wedge of clastics which are the main fill of the Chesapeake-Delaware Embayment - a broad, shallow basin in the crystalline basement. The lower unit (Patuxent Formation) of the Potomac Group is predominantly sand and gravel, coarsest along the basin margin to the west and fining to the east. Deposition took place in the channels of northeasterly to southeasterly flowing, probably braided rivers. Sand mineralogy, pebble lithologies, and cross-bedding direction define two dispersal systems: one emerging from a southern, mainly granitic source area transporting *low staurolite-kyanite-tourmaline, high-feldspar* sands and petromict gravels eastward to northeastward into the basin, and the second draining a northern source area of mostly high-grade schists and bringing *high staurolite-kyanite-tourmaline, low-feldspar* sands and quartzose gravels eastward to southeastward into the basin. Both source areas were located in the adjacent Piedmont region.

The overlying Arundel Formation, restricted to Maryland, consists of thick lenses of dark, massive lignitic clay accumulated as floodbasin deposits. The upper Potomac Group (Patapsco and Raritan Formations), distributed mainly across the northern flank of the basin, consists primarily of variegated silt-clay and mostly fine to medium sands deposited on the floodplains of sluggish, southeasterly-flowing rivers. The prevalence of stable minerals (zircon, tourmaline, and rutile) as mixed rounded and angular grains in the sands points to derivation from both a highly weathered Piedmont terrain and from Appalachian sandstones to the west.

The Magothy Formation is a thin clastic sheet, widespread in the northern part of the basin, which grades eastward from fluvial sands and gravels to estuarine-marginal deltaic sands and clays. The fluvial facies was deposited by easterly-flowing streams, and was derived from a high-grade schist terrain in the adjacent Piedmont.

Both the Potomac and Magothy grade basinward into marine sediments which are time transgressive eastward.

The Cretaceous sediments of the Chesapeake-Delaware Embayment constitute, in terms of basin geometry, sediment fill, dispersal pattern, and tectonic setting, a depositional model which may be applicable to other areas of the Atlantic Coastal Plain.

INTRODUCTION

The Chesapeake-Delaware Embayment (Murray, 1961) (see Fig. 1), spanning the Coastal Plain province in Virginia, Maryland, Delaware, and New Jersey, contains Cretaceous, Tertiary, and Quaternary sediments. Lower and in part Upper Cretaceous clastics, mostly nonmarine, comprise the bulk of the basin fill and are widely exposed along the Embayment margin. These rocks have been the object of considerable paleontologic and stratigraphic study, in part because they occupy a key position with regard to the introduction of angiosperms into the geologic record. Yet, in spite of these efforts, an acceptable regional stratigraphy has not been developed. Further, with the exception of a few local investigations, these rocks remain unstudied from a sedimentological point of view. Thus a twofold purpose was envisioned for this study: firstly, a clarification at least of the existing stratigraphic problems, and secondly and more importantly, the formulation of a paleogeographic reconstruction for a portion of Cretaceous time in the region of the Embayment. The latter objective is tripartite and includes: (1) the position and character of the source areas of the sediments, (2) the means and pattern of sediment dispersal, and (3) the character of the environments of deposition.

To this end, the Potomac Group and the Magothy Formation were examined in Delaware, Maryland, and Virginia (Fig. 2). Northeastern Delaware marks the northern terminus in outcrop of the Lower Cretaceous portion of the Potomac Group. The Upper Cretaceous portion (Raritan Formation) and the overlying Magothy Formation continue in outcrop northeastward across New Jersey to Raritan Bay and perhaps to Block Island. Southwest of the Delaware River, Potomac and Magothy rocks are exposed in a dissected arcuate band which follows the Fall Zone through northeastern Maryland to Baltimore. The most extensive exposure of these two units is found between Baltimore and Washington where the outcrop belt is broadest. To the south of Washington, the belt is narrowed considerably, and in fact, Upper Cretaceous strata disappear from the surface a few miles beyond the District. In Virginia, more or less continuous exposure of the Potomac Group extends from Arlington to Fredericksburg. Further south, however, exposures are limited to small isolated outcrops in major river valleys such as the James at Richmond, the Appomattox near Petersburg, and perhaps the North Anna at Doswell and Nottoway near Stony Creek.

METHODS

Inasmuch as exposures of Cretaceous rocks in the study area are generally poor and by no means uniformly distributed, a predesigned sampling grid was not deemed feasible, and virtually all available outcrops (Fig. 3) were visited for data collection. Most such outcrops are highway cuts, construction excavations, or in sand, gravel or clay pits; railway cuts, riverbanks, and natural gullies also provided exposure. Data collected at each sampling locality included measurements of cross-bedding direction and either a generalized or detailed stratigraphic section. In addition, one or more samples for mineralogic and textural analysis were taken at each outcrop. In most instances, this procedure entailed the sampling of at least one sand unit as well as the coarsest unit exposed. No attempt was made to systematically sample silt-clay beds.

In the laboratory, samples were sieved, weighed, and cumulative curves of each size distribution constructed; measures of median size, sorting, and skewness were computed from the curves. Pebble counts (lithology and roundness) were made for each sample with a gravel fraction whereas heavy and light mineral analyses were carried out for a number of selected samples.

ACKNOWLEDGEMENTS

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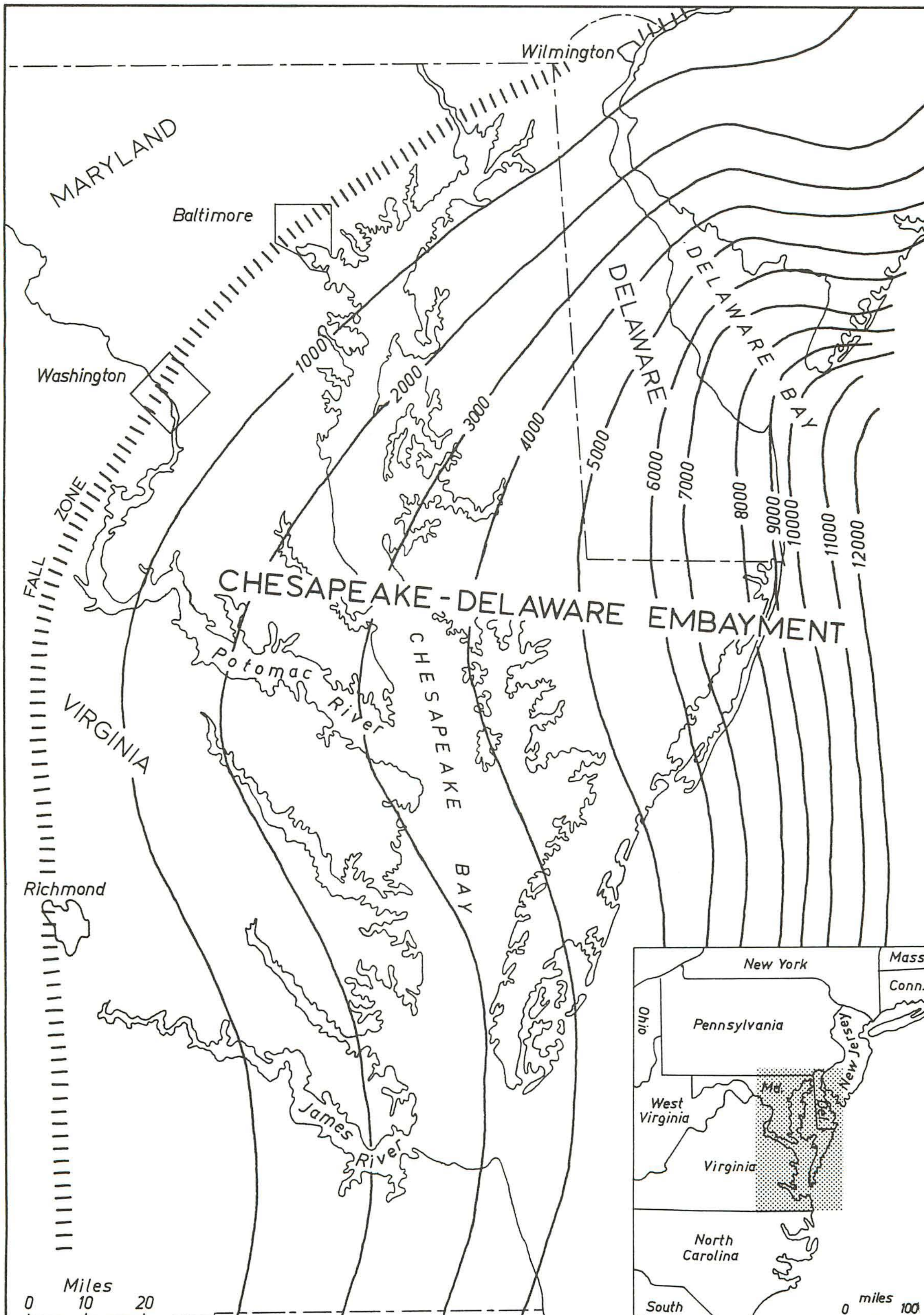


Figure 1. Chesapeake-Delaware Embayment. Structural contours are drawn on the surface of the crystalline basement.

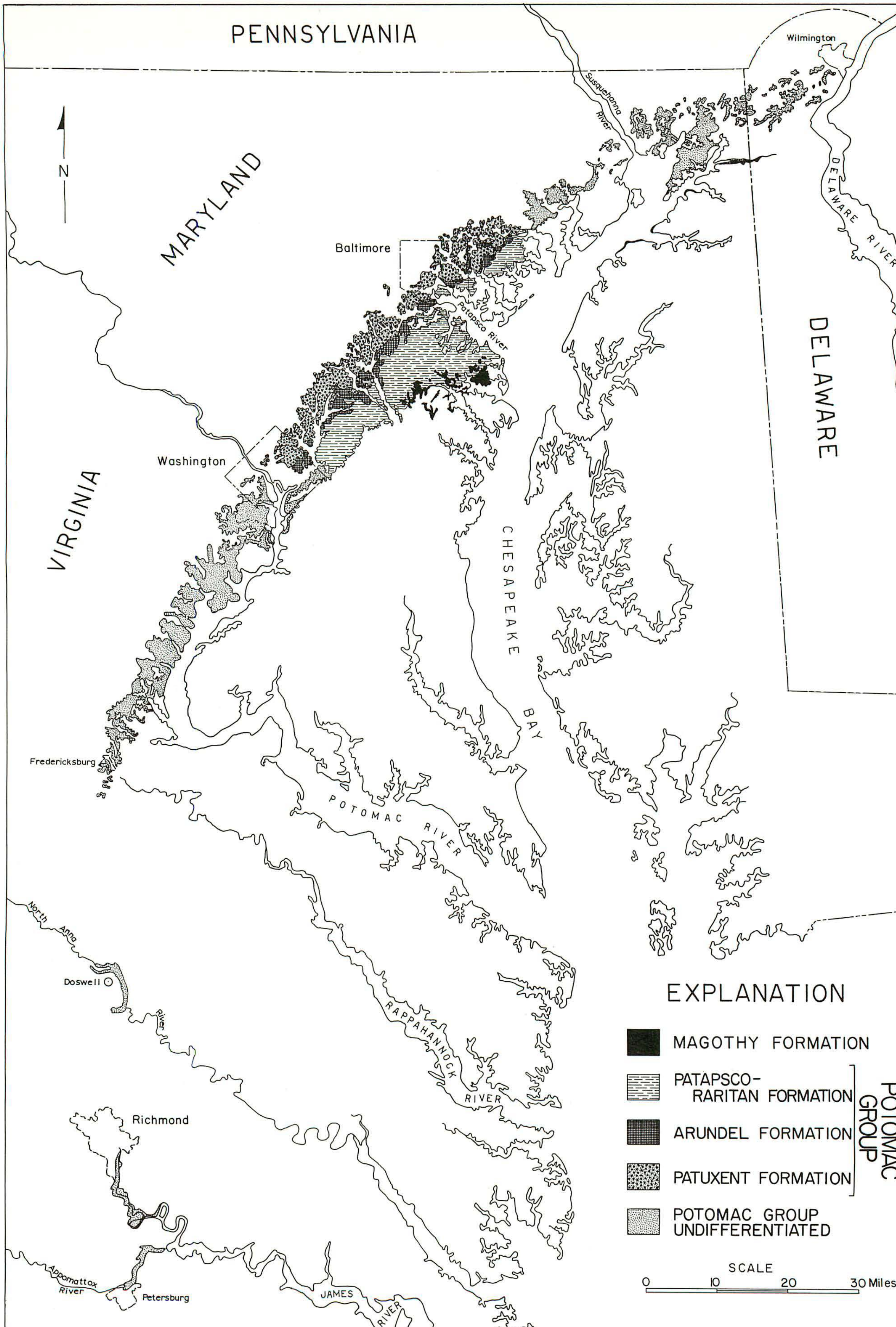


Figure 2. Outcrop belt of the Potomac Group and the Magothy Formation.

STRATIGRAPHY

GENERAL GEOLOGIC RELATIONS

Cretaceous sedimentary rocks crop out along the inner margin of the Atlantic Coastal Plain from Marthas Vineyard, Massachusetts, southward to Georgia. The outcrop belt is continuous with the exception of a 170 mile gap in southern Virginia and northern North Carolina where Cretaceous rocks are overlapped by those of Tertiary age. In the Chesapeake-Delaware Embayment the outcropping Cretaceous sediments are the proximal portion of an eastward-thickening clastic wedge which makes up the bulk of the Embayment fill. Both Lower and Upper Cretaceous rocks (Neocomian to Campanian) are represented in outcrop and are exposed in an arcuate band ranging in width from a maximum 20 miles in central Maryland to 5 miles or less at the distal ends of the belt. The strata are inclined basinward (east to southeast) at very low angles, dipping 25 to 65 feet per mile. The outcrop belt is bounded on the west by the contact between the basal sediments and Piedmont Precambrian or early Paleozoic matamorphic rocks. The contact itself corresponds to the Fall Zone of the Eastern Seaboard. The eastern boundary of the belt is the contact with overlapping Tertiary sediments.

The outcropping Cretaceous sediments can be viewed in terms of 2 broad lithologic groups: a lower, heterogenous sequence of gravels, sands, and clays of mostly continental or fluvio-marine origin, and an upper, much thinner sequence of dark, silty marine clays and greensands. The lower continental sequence, the object of this investigation, is comprised of 5 recognized stratigraphic units where maximally developed. These are, in ascending order, the Patuxent, Arundel, Patapsco, and Raritan Formations, making up the Potomac Group, and the Magothy Formation.

PREVIOUS WORK

Potomac Group

The rocks presently included in the Potomac Group have been under stratigraphic scrutiny for the better part of 170 years. Early names such as "Rappahannoc Freestone" (Latrobe, 1799), "Upper Secondary Sandstone" (Rogers, 1841), and Tyson's (1860) "Formations No. 21 and No. 22" are of historic interest, but the present designation was not applied until 1885 when McGee established a bipartite Potomac Formation along the north shore of the Potomac River in the Washington area. McGee's subunits were a basal sand-gravel and an overlying variegated clay. Three years later, Uhler (1888), working in the Baltimore area 40 miles northeastward along the strike, erected the Baltimorean and Albirupean Formations for the same rocks. Ward's (1895) monographic treatment of the Potomac added considerably to the nomenclatural confusion by further dismemberment of these rocks into 6 stratigraphic "series": James River, Rappahannock, Mt. Vernon, Aquia Creek, Iron Ores, and Albirupean, in ascending order. Each of these was presumed to bear a flora distinct from that of the others, and all were regarded as Early Cretaceous.

The present stratigraphic nomenclature was introduced by Clark and Bibbins (1897). The Potomac Formation of Maryland, elevated to group rank, was divided into 4 formations: Patuxent, Arundel, Patapsco, and Raritan. The predominantly sandy Patuxent, lowermost of the 4 units, and the overlying drab clays of the Arundel were referred to the Upper Jurassic based on Marsh's (1888, 1896) diagnosis of the Arundel dinosaurs. Variegated clay and interbedded sand, presumed unconformable on the Arundel, were assigned to the Patapsco Formation and regarded as Early Cretaceous. Definition of the uppermost formation, the Raritan, predates the Group nomenclature by several years. Originally introduced by Clark (1893) for interbedded sands and plant-bearing clays in northern New Jersey, the name Raritan was extended to similar strata overlying the Patapsco Formation in Maryland and Delaware in 1897. Although it was subsequently removed from the Potomac Group by Clark (1910) upon demonstration of its late Cretaceous age, current practice in Maryland (Weaver et al, 1968; Hansen, 1968; Glaser, 1968) has been the reinclusion of the Raritan as the uppermost formation of the Group, largely because it is lithologically indistinguishable from the underlying Patapsco Formation.

The Group nomenclature of Clark and Bibbins proved unacceptable to Ward for the Potomac strata of Virginia. His contention was that "the terms Patuxent, Arundel, and Patapsco.... must be regarded as merely local synonyms and cannot be applied to beds outside of Maryland" (Ward, 1905). Nevertheless, Berry (1910) successfully traced the distinctive floras of the Patuxent and Patapsco Formations across the Potomac River into Virginia, thus extending Clark's nomenclature and laying permanently to rest Ward's sixfold division of the Potomac Group.

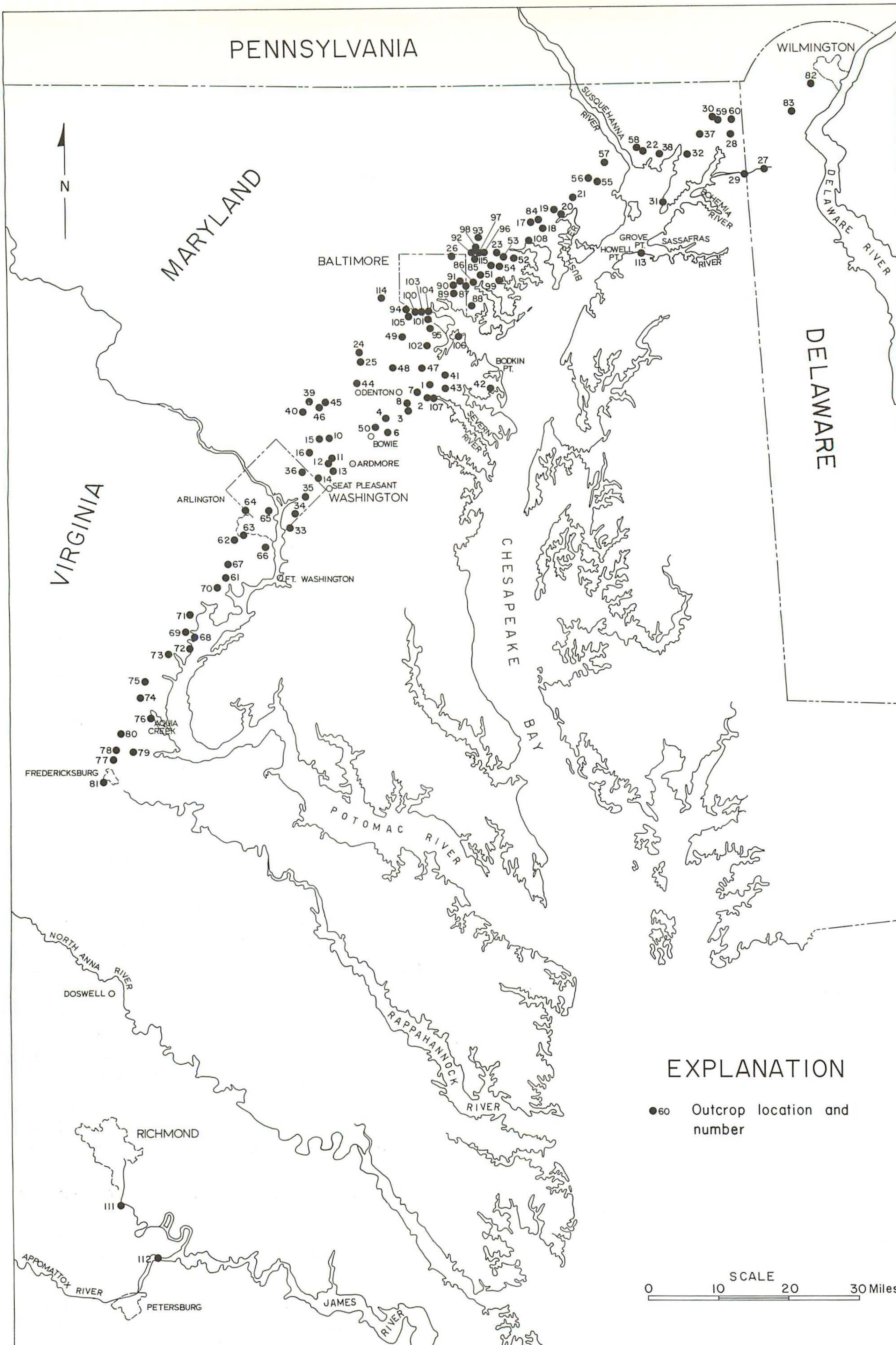


Figure 3. Sampling localities. Numbers refer to outcrops tabulated in Appendix A.

Magothy Formation

The Magothy Formation was named by Darton (1893) for exposures along the Magothy River in Anne Arundel County, Maryland. Prior to 1892, these rocks were included in the Potomac Formation. However Uhler, in that year, removed from the top of the Potomac "thin layers of clay and fine white sand with a thick stratum of fine argillaceous marl near the top" and termed the new unit the Alternate Clay Sands. The Alternate Clay Sands was evidently composite in character, including a portion of the late Cretaceous Matawan Formation as well as the underlying Magothy. Darton's description of the Magothy in the year following restricted it to a thin sequence of loose white to buff lignitic sands and dark carbonaceous clays unconformably overlying the Potomac Formation. Further, he called attention to the presence of gravel and ferruginous conglomerate in the Magothy Formation near the southwestern terminus of the outcrop belt near the Patuxent River in central Maryland. Although the outcrop was traced northeastward only to the Maryland-Delaware line, Clark (1904) subsequently suggested that similar white lignitic sands and carbonaceous clays beneath the Matawan Formation in the banks of the Chesapeake and Delaware Canal were doubtless the equivalent of Darton's Magothy Formation. Clark further speculated that laminated clays in the bluffs on the south side of Raritan Bay in northern New Jersey long known as the Cliffwood Clays and grouped with the Matawan Formation, as well as the underlying "laminated sands" heretofore assigned to the Raritan, would very likely prove correlative with the Magothy. Berry's (1906) work in tracing the distinctive Magothy flora northeastward through Delaware and New Jersey to Long Island proved Clark's speculations correct.

STRATIGRAPHIC ANALYSIS

General Statement

The evolution of the stratigraphic nomenclature (see Table 1) presently employed for the outcropping nonmarine Cretaceous sediments of the Chesapeake-Delaware Embayment has been traced in the preceding section. The following discussion of the stratigraphy is based on my own observations in the field, examination of published and unpublished drill-hole data, and the observations of other workers as presented in the recent literature.

Potomac Group

Introduction – The Potomac Group is the basal unit in the Coastal Plain of Virginia, Maryland, Delaware, and southern New Jersey, and overlies with angular unconformity a basement of beveled and largely saprolitized Precambrian and early Paleozoic metamorphic and igneous rocks over the greater part of the Embayment area. Exceptionally, Potomac sediments rest on Triassic rocks of the Newark Group, as in a small area near Doswell, Virginia (Fontaine, 1896) and possibly in the subsurface of Caroline County, Virginia (Cederstrom, 1945b), and in Charles and Prince Georges (Ball Associates, 1959) as well as Wicomico and Worcester Counties, Maryland (Anderson, 1948). In contrast, rocks overlying the Potomac Group vary widely in age with geography, including late Cretaceous sediments of Magothy and Monmouth age, as well as Eocene, Miocene, and Quaternary deposits.

Gross lithology – Large and abrupt variations in lithology, both laterally over short distances and vertically, are wholly typical of the Potomac Group. Consequently, an outcrop description or a drill-hole log taken at a given point may very well not be applicable to sediments at the same stratigraphic level a few hundred feet in either direction. Variable combinations of gravel, sand, silt, and clay are characteristic. Gravels and ferruginous conglomerates, commonly very coarse, are most abundant within the lowest hundred feet of the Potomac Group, but are also present at higher stratigraphic levels. Estimates made at 86 exposures of these rocks disclose an average 11 percent gravel for the entire unit. Potomac gravels are typically composed of partly-rounded to rounded quartzose pebbles averaging 8-16 mm in diameter, and interstitial sand. About 60 percent of the outcropping sediments are sands, present as discontinuous lenticular bodies interbedded with clays, silty clays, and gravels. The sands are generally trough cross-bedded, white to buff in color, and almost always have considerable silt-clay matrix. Individual grains are mostly angular quartz, although feldspar may make up as much as 48 percent of the sand. Medium sand is the most abundant textural class.

Clay-silt beds in the Potomac Group are generally developed as irregular or lenticular, internally massive bodies with little lateral continuity which are interbedded with sands and gravels at all stratigraphic levels. Pale-gray to buff is the most common clay-silt color in the lower and uppermost portions of the unit. Coloration by ferric iron is widespread, however, particularly in

Table 1. Evolution of stratigraphic nomenclature and chronology of the Cretaceous rocks of Delaware, Maryland, and Virginia

SERIES	EUROPEAN STAGES	Rogers 1841 (Va.)	Tyson 1862 (Md.)	McGee 1885 (Md., Va.)	Uhler 1888 (Md.)	Darton 1891 (Md., Del.)	Uhler 1892 (Md.)	Darton 1893 (Md.)	Ward 1895 (Md., Va.)
UPPER CRETACEOUS	Maestrichtian				GREENSAND CRETACEOUS	SEVERN FM.	GREENSAND CRETACEOUS	SEVERN FM.	SEVERN FM.
	Campanian			UPPER CRETACEOUS GREENSANDS					
	Santonian								
	Coniacian				ALBIRUPEAN FM.		ALTERNATE CLAY SANDS		
	Turonian								
	Cenomanian								POTOMAC FM.: ALBIRUPEAN SERIES
LOWER CRETACEOUS	Albian					POTOMAC FM.	ALBIRUPEAN FM.	MAGOTHY FM.	IRON ORE SERIES; AQUIA CREEK SERIES
	Aptian							POTOMAC FM.	
	Neocomian								MT. VERNON SERIES; RAPPAHANNOCK SERIES; JAMES RIVER SERIES
UPPER JURASSIC		UPPER SECONDARY SANDSTONE	FORMATION 22 (IRON ORE CLAYS); FORMATION 21 (SAND AND CLAY)	POTOMAC FM.: CLAY MEMBER; SANDSTONE MEMBER	BALTIMOREAN FM.		BALTIMOREAN FM.		

SERIES	EUROPEAN STAGES	Clark 1897 (Md., Del.)	Ward 1905 (Va.)	Clark 1910 (Md., Del.)	Carter 1937 (C. & D. Canal)	Anderson 1948 (Md.)	Spangler & Peterson 1950 (Md., Del.)
UPPER CRETACEOUS	Maestrichtian	RANCOCAS FM.		RANCOCAS FM.	MT. LAUREL SAND; MARSHALLTOWN FM.	MONMOUTH FM.	MONMOUTH FM.
	Campanian	MONMOUTH FM.; MATAWAN FM.		MONMOUTH FM.	ENGLISHTOWN SAND	MATAWAN FM.	MATAWAN FM.
	Santonian				CROSSWICKS CLAY		MAGOTHY FM.
	Coniacian				MAGOTHY FM.	MAGOTHY FM.	
	Turonian			MATAWAN FM.			
	Cenomanian			MAGOTHY FM.; RARITAN FM.	RARITAN FM.	RARITAN FM.	RARITAN FM.
LOWER CRETACEOUS	Albian	POTOMAC GP.: RARITAN FM.		POTOMAC GROUP: PATAPSCO FM.		POTOMAC GROUP: PATAPSCO–ARUNDEL FMS.	POTOMAC GROUP: PATAPSCO–ARUNDEL FMS.; PATUXENT FM.
	Aptian	PATAPSCO FM.	POTOMAC FM.: BROOKE SERIES				
	Neocomian	ARUNDEL FM.[1]; PATUXENT FM.	MT. VERNON SERIES; RAPPAHANNOCK SERIES; JAMES RIVER SERIES	ARUNDEL FM.[1]; PATUXENT FM.		PATUXENT FM.	

SERIES	EUROPEAN STAGES	Dorf 1952 (Md., Del.)	Cederstrom 1957 (Va.)	Jordan 1962 (Del.)	Brenner 1963 (Md.)	Present study (Md., Del.)	Present study (Va.)
UPPER CRETACEOUS	Maestrichtian	MONMOUTH FM.		MONMOUTH GROUP: REDBANK FM.		MONMOUTH FM.	MATTAPONI FM.[2]
	Campanian	MATAWAN FM.	MATTAPONI FM.[2]	MT. LAUREL-NAVESINK FM.; MATAWAN GROUP: WENONAH FM.		MATAWAN FM.	
	Santonian			MERCHANTVILLE FM.			
	Coniacian	MAGOTHY FM.				MAGOTHY FM.	
	Turonian	RARITAN FM.		MAGOTHY FM.			
	Cenomanian		POTOMAC GROUP: PATAPSCO FM.	POTOMAC FM.		POTOMAC GROUP: RARITAN FM.	
LOWER CRETACEOUS	Albian	POTOMAC GROUP: PATAPSCO FM.	PATUXENT FM.		POTOMAC GROUP: PATAPSCO FM.	PATAPSCO FM.	POTOMAC GROUP: PATAPSCO FM.
	Aptian	ARUNDEL FM.[1]			ARUNDEL FM.; PATUXENT FM.	ARUNDEL FM.[1]; PATUXENT FM.	PATUXENT FM.
	Neocomian	PATUXENT FM.					

1 MARYLAND ONLY
2 SUBSURFACE ONLY

Patapsco clays, and produces strikingly variegated or mottled hues of maroon, yellow, purple, and brown. Dark-gray to nearly black, lignitic clays are most characteristic of Arundel sediments but also occur at other stratigraphic levels.

The practical definition of the component formations of the Potomac Group has historically been based largely on mass lithologic properties such as color, gross texture, and proportions of gravel, sand, and clay-silt. Sediments assigned to the Patuxent Formation are usually medium to coarse sands or pebbly sands and gravels interbedded with relatively thin, pale-gray clays. The Arundel lithology is essentially a tough, dark-gray to maroon massive clay containing abundant lignite and sideritic concretions. Massive or laminated silt-clay, mottled in shades of red, gray, brown, and purple, and interstratified with yellowish fine to medium clayey sands are generally regarded as indicative of the Patapsco Formation. The Raritan lithology, as seen in the type area in northern New Jersey, typically consists of interbedded white to yellow, cross-bedded micaceous sands, subordinate amounts of gravel, and multicolored, commonly lignitic clays. Sediments in Maryland and Delaware which have historically been assigned to the Raritan can be described in much the same terms, and as such are not lithologically differentiated from the Patapsco Formation. For this reason, much of the recent literature dealing with these rocks, e.g. Otton (1955), Slaughter and Otton (1968), Hansen (1968), employs the Patapsco-Raritan undivided as an operational unit.

Although valid as regional generalizations, the utility of the broad lithologic contrasts outlined above is open to serious question at the outcrop or drill-hole level. Tough gray lignitic clays, for example, occur not only in the Arundel Formation but also in sediments mapped as Patuxent or Patapsco. Variegated clay, admittedly most abundant in the Patapsco, is nonetheless encountered at many stratigraphic levels. Moreover, although gravels are concentrated in the Patuxent Formation, they are certainly not limited to that unit. One final point may be emphasized – the Arundel clays where present, as in central Maryland, are distinct and serve as a useful marker bed; however, the Arundel is absent over better than half of the outcrop belt of the Potomac Group. Here, differentiation of the Patuxent and Patapsco Formations on the basis of mass lithology is difficult at best and commonly impossible.

Areal distribution, thickness, and contacts – The Potomac Group in the area studied is exposed in a much-dissected arcuate band extending from Wilmington, Delaware, southwestward paralleling the Fall Zone to Fredericksburg, Virginia – a distance of about 150 miles. The outcrop belt is broadest in the region between Baltimore and Washington, reaching 15 miles in width, but it narrows at either end to less than a mile wide. Northeast of Wilmington, the Raritan Formation overlaps the whole of the subjacent Potomac Group and directly overlies basement rocks along the Delaware River in southern New Jersey. To the south of Fredericksburg, on the other hand, Eocene and ultimately Miocene beds transgress the Potomac and rest on basement crystallines in the Fall Zone. This Tertiary cover has been breached, however, exposing lower Potomac rocks in several deep river valleys in central and southern Virginia. The largest of such areas follows a 12 mile reach of the James River from Richmond to Deep Bottom in Henrico County. A second narrow band borders the Appomattox River from Petersburg northeast for 10 miles to the Appomattox-James confluence. Small areas of Potomac lithology along the Nottoway River in Sussex County and at Doswell in Hanover County have been described by Fontaine (1896), but outcrops were not identified during fieldwork in these locales.

The initial phase of the Potomac Group, the Patuxent Formation, is exposed along the western margin of the outcrop belt throughout its length, and paleontologic evidence suggests that it is the only unit present in outcrop south of Fredericksburg, Virginia (Cedarstrom, 1945a). In the Fall Zone region, the outcrop is much dissected, sediment having been eroded from the stream valleys but left as a capping on the upland divides. Such cappings commonly form western outliers isolated from the main outcrop belt. The maximum width of Patuxent exposure is about 7 miles in central Maryland.

The basal contact of the Potomac Group is rarely seen in natural exposures but has been observed in excavations and highway cuts. The contact is almost invariably underlain by saprolite, and although generally sharp, it may appear transitional due to incorporation of abundant saprolitic clay clasts into the basal few feet of sediment. Numerous borings in the Baltimore area indicate a maximum local relief of about 100-150 feet on the basement surface which slopes seaward at 60 to 150 feet per mile (Bennett and Meyer, 1952).

The Patuxent-Arundel contact is less commonly encountered and difficult to identify with

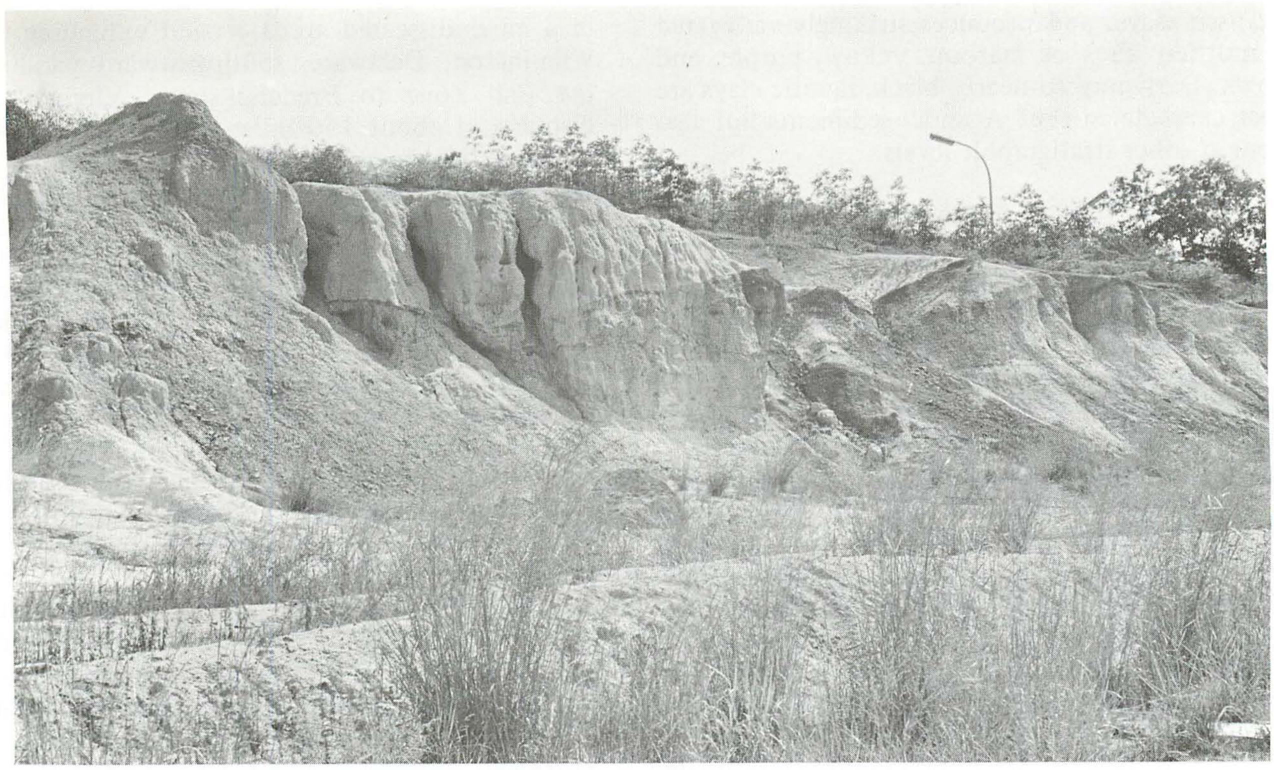


Figure 4. Patuxent-Arundel contact exposed in abandoned sand pit (Loc. 89), Baltimore City. Massive dark-gray lignitic clay of the Arundel Formation rests unconformably on the channeled surface of the Patuxent Formation. The Patuxent lithology (white cross-bedded sand) is obscured by rainwashed clay from above.

certainty, even with the aid of paleontologic criteria (Brenner, 1963). In drill-holes, the contact is usually drawn at the base of the first appreciable thickness above the basement of gray or red clay lacking sand interbeds. Such a sand-clay interface, observed in several outcrops in the Baltimore area (Fig. 4), is in all likelihood the Patuxent-Arundel contact. The lithologic relations are nearly identical in all of these exposures, i.e. dense, massive, gray clay overlying an irregular channeled sand surface. The upper few inches of sand is limonite-cemented in many instances and the subjacent sand stained red or purple.

The Arundel Clay is mapped discontinuously from Washington, D.C., northeast to the Bush River in Harford County, Maryland – a linear distance of about 50 miles (Clark et al, 1911). The greatest thickness of section, and consequently the maximum width of outcrop, occurs in the southwestern portion of the outcrop belt in Anne Arundel and Prince Georges Counties.

The Arundel-Patapsco contact is reportedly unconformable and marked in the type area, notably in northern Anne Arundel County, Maryland, by a "ferruginous ledge" separating gray clay below from overlying variegated clay and argillaceous sand (Clark et al, 1911).

Several good exposures in southern Baltimore City show just such a lithologic succession and probably mark the Arundel-Patapsco contact, although ferruginous cementation or other indications of apparent unconformity are lacking. In northeastern Maryland and Delaware, where the Arundel is absent, and similarly in Virginia, the Patapsco presumably succeeds the Patuxent unconformably (Clark et al, 1911; Berry, 1912; Bascom and Miller, 1920). The latter unconformity, however, apparently lacks precise identity and has not been recognized by later workers (Spangler and Peterson, 1950; Groot, 1955) nor was it identified during my own fieldwork. The differentiation of the Patuxent and Patapsco Formations in these areas has always rested on floral evidence. Such evidence indicates that the Patapsco outcrops in a narrow broken belt extending southeast from Wilmington, Delaware to Baltimore City. Between Baltimore and Washington, the belt is continuous and reaches its maximum width – about 10 miles. Beyond Washington, the outcrop is considerably narrowed by Tertiary overlap and ultimately reduced to discontinuous exposures on either side of the Potomac River south to the vicinity of Aquia Creek.

Sediment thicknesses within the Potomac Group are difficult if not impossible to determine from exposures. The latter usually show a few vertical feet only of section, and aside from the basal unconformity, contacts are rarely exposed. Data from drill-holes is of far greater value in estimating thicknesses. Within the Richmond-Petersburg outcrop area, a maximum 300 feet of sediment, presumably wholly Patuxent Formation, is indicated by borings. The Fredericksburg area is underlain by a similar thickness, but 16 miles northeast at Quantico where both Patuxent and Patapsco Formations are present, sediment thickness increases to 500 feet. Uniformly increasing thicknesses are encountered northeastward along the strike, due in part to an expanding Patapsco Formation but also to the insertion of the Arundel Clay north of Washington. Very nearly 1000 feet of sediments underlie the eastern margin of the outcrop belt in northern Prince Georges County, Maryland. This is the maximum thickness attained in outcrop, and beyond this point progressive reductions occur, i.e. 400 feet between Baltimore and the Susquehanna River, decreasing to 250-300 feet in northeastern Maryland and Delaware.

Clark (1916) described what he presumed to be the Patapsco-Raritan contact as "a clearly defined erosional unconformity . . . . . at some points marked by a line of broken and redeposited iron crusts". Such an unconformity, perhaps that seen by Clark, was encountered at a single locality only – Hawkins Point in southernmost Baltimore City (Fig. 5). Here, clean cross-bedded sand sharply overlies dense variegated clay along a broadly undulatory surface marked by a thin ironstone crust. Elsewhere, no such contact was observed during fieldwork. It is reasonable to assume, then, that the Hawkins Point unconformity is a local feature only. Furthermore, there is no really convincing evidence to support the presence of Upper Cretaceous beds (i.e. Raritan) west of Chesapeake Bay. Rocks heretofore assigned to the Raritan are not, as earlier noted, lithologically distinct from the Patapsco Formation, nor is the floral evidence presented by Berry (1916) compelling. Moreover, recent palynological studies (Brenner *in* Hansen, 1968; Brenner, pers. comm.) show that the uppermost Potomac strata in the subsurface of central and southern Maryland are correlative with the outcropping Patapsco Formation rather than the Raritan of New Jersey. Thus it is clear that the proven occurrence of the Raritan Formation within the area studied is limited to

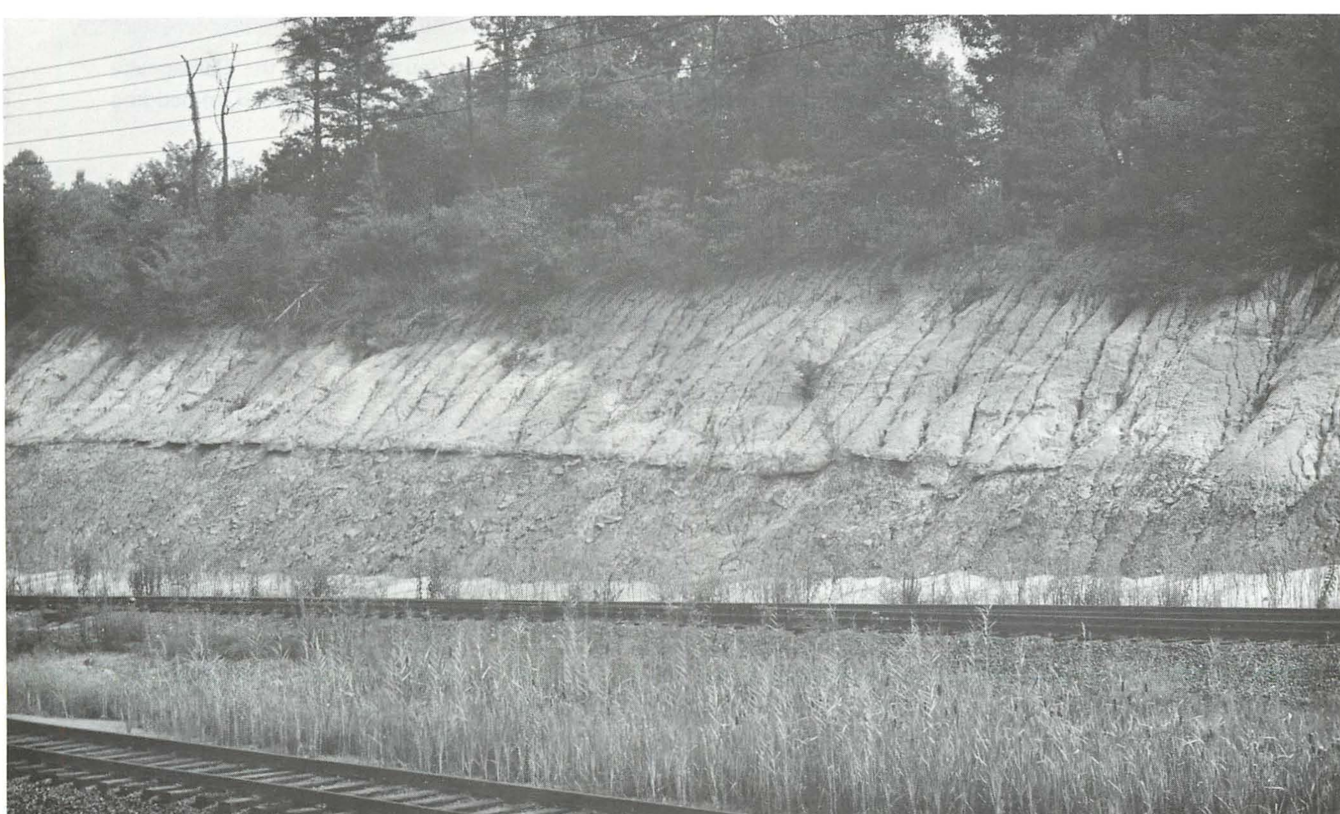


Figure 5. Exposure in Baltimore and Ohio Railway cut (Loc. 106), Hawkins Point, Baltimore City. Buff cross-bedded orthoquartzitic sand in sharp contact with massive red and yellow variegated clay. The contact is broadly undulatory and marked by a thin limonite-cemented zone.

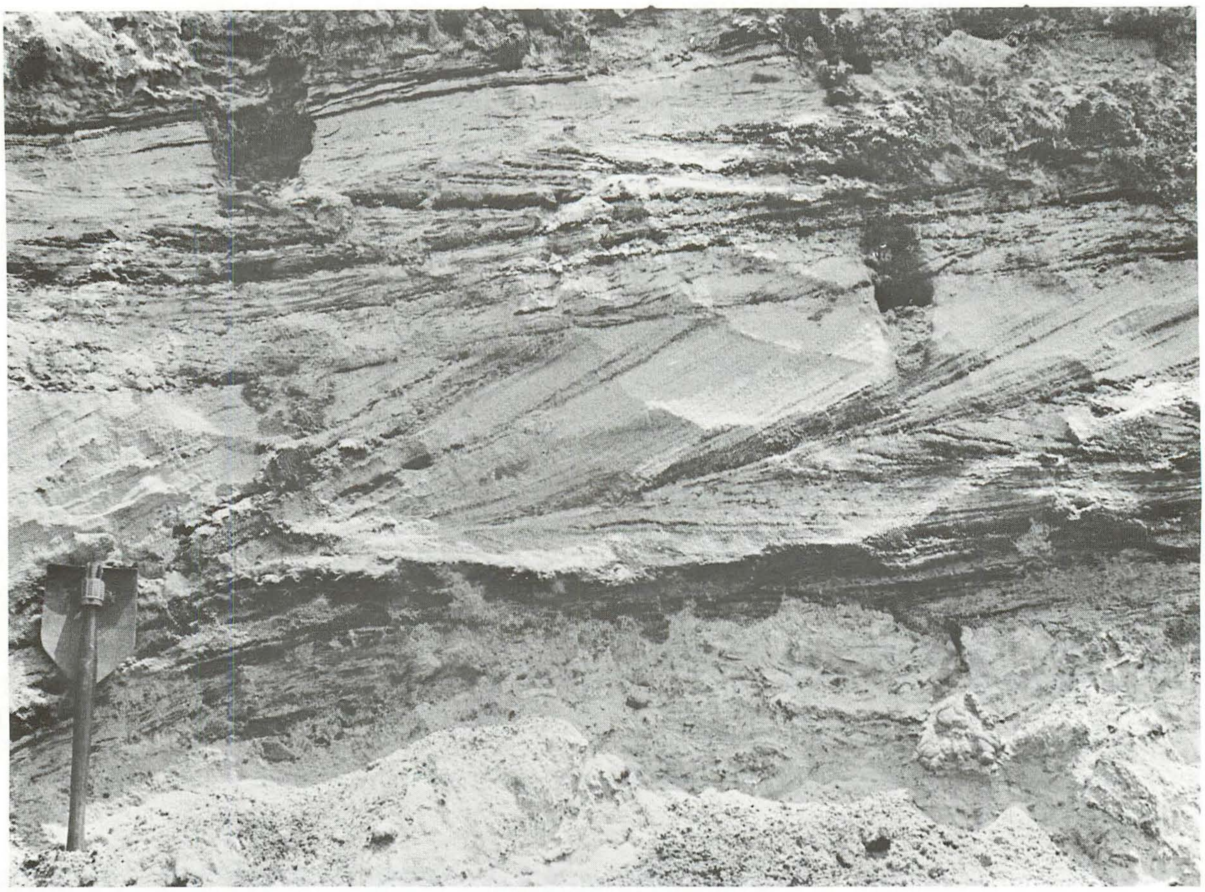


Figure 6. Cross-bedded "sugary" sand of the Magothy Formation in the south bank of the Chesapeake and Delaware Canal (Loc. 27) near Summit Bridge, Delaware. Abundant lignite concentrated on bedding and foreset planes is conspicuous.

far-northeastern Maryland and Delaware where the flora of the uppermost Potomac beds is indeed late Cretaceous. Good outcrops of these upper beds are few and scattered. They are largely limited to the western end of the Chesapeake and Delaware Canal, Shannon Hill, the southern portion of Elk Neck in Cecil County; and Howell and Worton Points in Kent County, all in Maryland.

Magothy Formation

Gross lithology – The association of loose white "sugary" sand, commonly lignitic, and dark laminated silt-clay is typical of much of the Magothy Formation and serves to distinguish it from contiguous units. Magothy sands and clays tend to be relatively homogeneous bodies which unlike similar beds in the Potomac Group are laterally traceable for many hundreds of feet. Carter (1937) recognized 3 such units in the banks of the Chesapeake and Delaware Canal, each from 15 to 25 feet thick – a lower sand, a middle interbedded sand-black clay unit, and an upper homogeneous black lignitic clay. Equally characteristic of the Magothy is closely-interbedded fine white sand and laminated bluish-gray silt-clay in beds of an inch or less in thickness, a mode of bedding which gave rise to Uhler's term Alternate Clay Sands.

Magothy sand beds are generally cross-bedded, commonly with conspicuous lignite concentrations along bedding and foreset planes and to a lesser extent disseminated through the sand (Fig. 6). Interbedded clays can be equally lignitic and in isolated cases crowded with lignite logs. Abundant sideritic and pyritic concretions are also characteristic.

A notably coarser facies of the Magothy is encountered near the southwestern termination of the outcrop belt in Anne Arundel County, Maryland. Here coarse to very coarse sand interbedded with ferruginous quartzose gravel becomes important. Ledges of hard rock resulting from limonite cementation of these sediments are common in this area.

Areal distribution, thickness, and contacts – The Magothy-Potomac contact is poorly exposed in the area studied. In the upper Severn River region of Anne Arundel County, it is marked by a basal gravel sharply overlying fine clayey sand or variegated clay. The same disconformable relations hold for eastern Maryland where the contact is exposed for a considerable distance in the bluffs along the south shore of the Bohemia River. Magothy sands here succeed what is probably the Raritan Formation along an eastward-dipping, undulatory surface cut in variegated clay.

Good exposures of the Magothy are decidedly few in the Maryland-Delaware area. Those in Delaware are virtually limited to a 2 mile stretch of the Chesapeake and Delaware Canal. In northeastern Maryland, the Magothy is exposed along the Canal near Bethel, at Thackery Point on the Bohemia River, and at Grove and Howell Points on the Sassafras. The western shore outcrop is limited to a southwest-trending series of disjunct exposures extending from Bodkin Point to Odenton in Anne Arundel County. Clark (1916) and Darton (1947, 1951) mapped as Magothy a narrow band paralleling the Potomac Group from the Patuxent to the Potomac Rivers. Cooke (1948), however, failed to recognize such rocks in that area, a finding with which I agree. In fact, the Magothy as well as the Matawan Formations are wholly overlapped southwest of the Patuxent River by the Monmouth Formation. Exposures of dark Monmouth sand unconformably overlying mottled clay or clayey sand of the Patapsco Formation in Prince Georges County are many and can be seen near Bowie, High Bridge, Ardmore, Seat Pleasant, and Fort Washington.

Within its outcrop belt, the Magothy is thin, only rarely exceeding 50 feet thick and generally averaging much less.

Subsurface

Introduction – The distribution and thickness variation basinward of the Cretaceous units is poorly known due in large measure to too widely-spaced deep drill-hole data but also due to facies change. Units such as the Arundel Clay and the Magothy Formation, relatively distinct in outcrop, can be identified in drill-holes for several miles downdip through lithologic character alone. However, in the deeper portions of the Embayment, this lithologic identity is lost through facies change, and identification of these units as well as the others involved is uncertain at best. The ultimate resolution of these problems no doubt lies in careful and detailed paleontologic study of serial drill-hole samples supplemented by equally careful petrographic work. Too little of this has been done thus far to give more than a broad, generalized picture of the subsurface stratigraphy.

Potomac Group – The Potomac Group, present in the subsurface throughout the Embayment, comprises a wedge-shaped sheet which is thickest along the structural axis of the basin and thins to both north and south (Fig. 7).

Although surface exposure of the Potomac along the southern flank of the Embayment is virtually nil, the thin edge of the sediment sheet is nevertheless present in southeastern Virginia beneath probable late Cretaceous rocks and thickens eastward in 60 miles from about 200 feet near Branchville to nearly 1000 feet at Newport News (Cedarstrom, 1945b, 1957). Just 30 miles south of Branchville, interbedded Cretaceous sand and clay overlies the basement in the vicinity of Weldon, North Carolina. Long assigned *in toto* to the late Cretaceous Tuscaloosa Formation (Richards, 1950), recent work (Swain and Brown, 1963) has demonstrated that the lower 100 feet or more of the Weldon rocks is of Albian age and thus correlative with the upper Potomac Group. The available subsurface data is at present inadequate to prove physical continuity with the Branchville Potomac; consequently, the precise relationship between these rocks remains moot.

North and east of Richmond, Potomac beds reach westward beneath the Tertiary cover to within a few miles of the Fall Zone. About 300 feet of these sediments in eastern Caroline and Hanover Counties thicken downdip to 800 feet beneath Mathews in Mathews County. The maximum thickness values for the Potomac Group occur along the structural axis of the Embayment, i.e. between the general area of Washington, D. C., and eastern Maryland. A few miles southeast of Washington in Prince Georges County, Maryland, 1100 to 1300 feet of Potomac sediments have been encountered by drill-holes, whereas near Ocean City, a little over 100 miles eastward along the axis, the section has expanded to nearly 5000 feet (Anderson, 1948). The Potomac Group thins across the northern flank of the basin; about 1400 feet were logged at Chestertown, Maryland (Overbeck and Slaughter, 1958) and only 950 feet in a drill-hole at Salem, New Jersey (Richards, 1945).

The decrease northward in total thickness is paralleled by systematic changes in the strati-

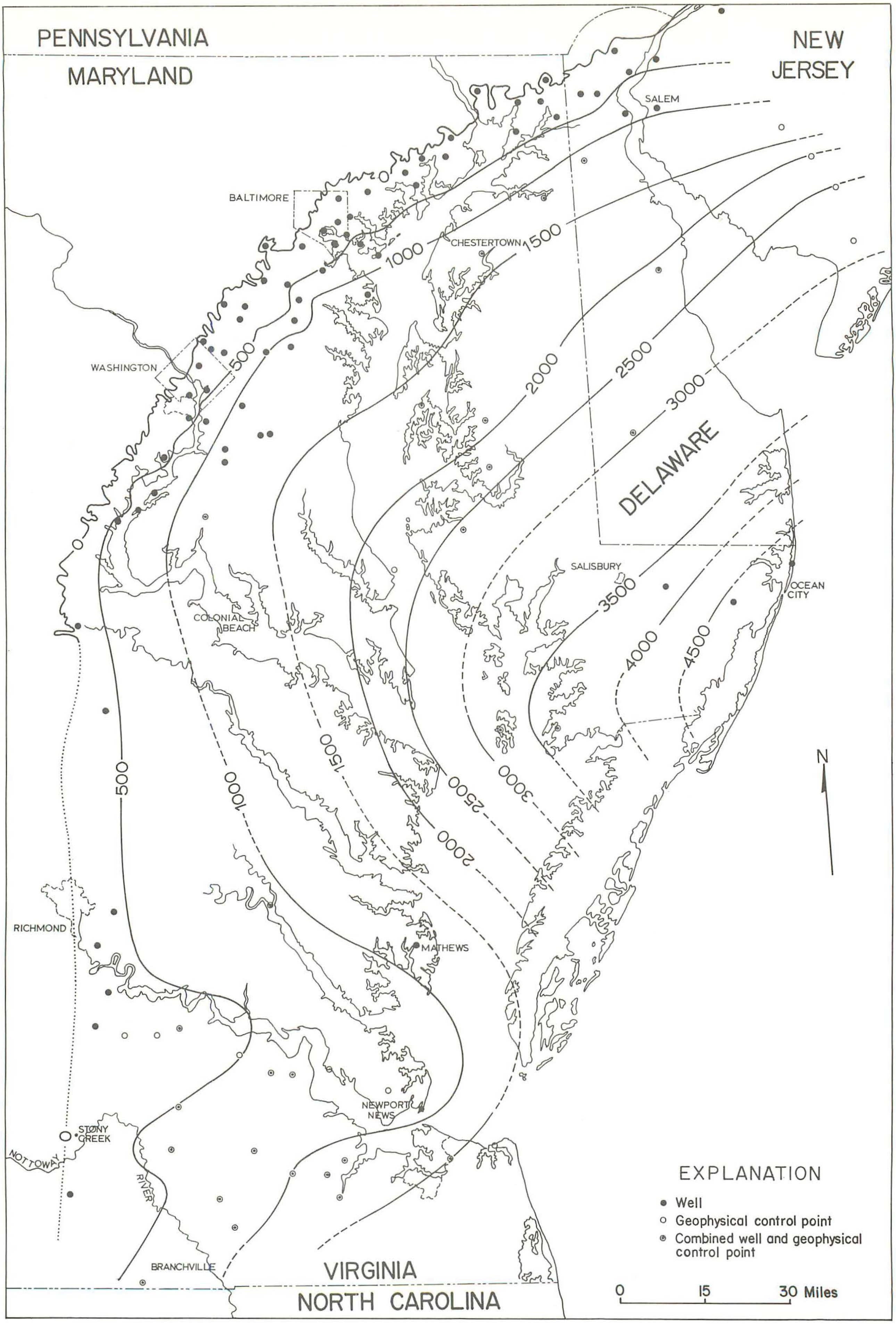


Figure 7. Isopach map of the Potomac Group (sources of data given in Appendix B).

graphic composition of the Potomac Group. The lowermost 300 feet only of Potomac rocks in the Salem borehole has been assigned to the Patuxent through Patapsco Formations with the remaining 650 feet presumably belonging to the Raritan. At Island Beach State Park, 75 miles further northeast, test drilling has disclosed 1728 feet of pre-Magothy sediments (Gill et al, 1963), all of which is thought to be Raritan Formation. It must be concluded, then, that the early Cretaceous portion of the Potomac Group, i.e. Patuxent through Patapsco, thins and ultimately pinches out on the northern flank of the Embayment. Conversely, the late Cretaceous Raritan Formation is maximally thick on the northern flank and thins southward. Anderson (1948), in outlining the stratigraphy in the Hammond Oil Test Well in Wicomico County, Maryland, drilled about 120 miles south of Island Beach and nearly on the Embayment axis, concluded that the upper 700 feet only of the 3800 feet of Potomac Group belonged to the Raritan Formation. Although considerable doubt has been raised regarding the validity of Anderson's stratigraphic assignments, it is apparent that 700 feet of Raritan, even if only a correct order of magnitude, represents a significant southward thinning of that unit. Moreover, rocks of Raritan age (i.e. Cenomanian) are apparently absent over the southern flank of the Embayment.

The gross lithology of the Potomac Group in the subsurface of Virginia is not significantly different from that seen in outcrop; interbedded sand and clay bodies, 30 to 50 feet thick, and subordinate local gravels are wholly typical. Clays, mostly gray to dark-green in color, increase in abundance downdip or basinward (Cedarstrom, 1945b). For example, in the vicinity of Branchville near the Fall Zone of southeastern Virginia, sand and gravel make up the bulk of the Potomac sediments encountered in drill-holes, whereas at Lake Prince, 40 miles downdip to the northeast, nearly half of the Potomac Group is drab clay. The thick Potomac section logged in borings along the Embayment axis in southern Maryland is largely clay. Several drill-holes to basement completed by the Washington Gas Light Co. (Ball Associates, 1959) disclosed from 55 to 76% clay in the total section, mostly variegated in brown and green. Downdip along the Embayment axis in extreme eastern Maryland, the thickest Potomac Group thus far penetrated in the basin is essentially a fining-upward succession of interbedded white to olive-green, sporadically glauconitic sands, and brown, gray, or variegated clays (Anderson, 1948). Coarse, commonly pebbly sands are concentrated in the lower one-fourth of the section. In contrast, the upper portion is mostly laminated clay and subordinate very fine sand.

Magothy Formation – The Magothy Formation is extensive as a thin sheet through the subsurface of most of the northern half of the Embayment. The characteristic Magothy lithology can be traced downdip from the outcrop for a number of miles with reasonable accuracy; further basinward, however, convergence in lithologic character between the Magothy and the upper Potomac Group as well as with the overlying Matawan make recognition of the upper and lower contacts increasingly difficult.

The thickness of the Magothy Formation within the Maryland-Delaware portion of the basin ranges from a feather edge of several feet to slightly better than 150 feet (Fig. 8). The maximum thickness apparently occupies a relatively small area beneath Chesapeake Bay and eastern Talbot County in Maryland. The area of relatively thick Magothy, i.e. 100 feet or more, seemingly continues nearly due eastward along a rather narrow zone axial to the Embayment but the drill-hole data supporting this trend are sparse indeed.

The subsurface lithology of the Magothy is similar to that seen in outcrop but with some more or less systematic downdip changes. Gravel, coarse sand, and much-subordinate pale silt-clay, prevalent in the shallow subsurface of central Anne Arundel County, diminish basinward in importance. The predominant downdip lithologic association is interbedded lignitic sand and dark-gray laminated silt-clay. Thick beds of gray lignitic silt enter the section in southern Delaware and eastern Maryland.

Mattaponi Formation – Cederstrom (1957) proposed the name Mattaponi Formation for interbedded brightly-mottled clays and glauconitic sands known only in the sub-surface of eastern Virginia between the Potomac and James Rivers. These rocks, formerly assigned to Eocene units or "Upper Cretaceous undifferentiated", were found by Cederstrom to contain Late Cretaceous to Paleocene foraminifera, and in his view required a new name. As thus constituted, the Mattaponi is heterogeneous, from the standpoint of both age and lithology. The upper part of the unit, presumably the Paleocene portion, is a variable thickness of gray to dark-green glauconitic sand and clay, lithologically identical and doubtless correlative with the lower Aquia Formation of Maryland. Beneath these strata, red, gray, and brown mottled clays, in part glauconitic, appear in the section, and still lower, medium to coarse pale-colored sands. The lower Mattaponi is reminiscent of the Potomac Group and probably

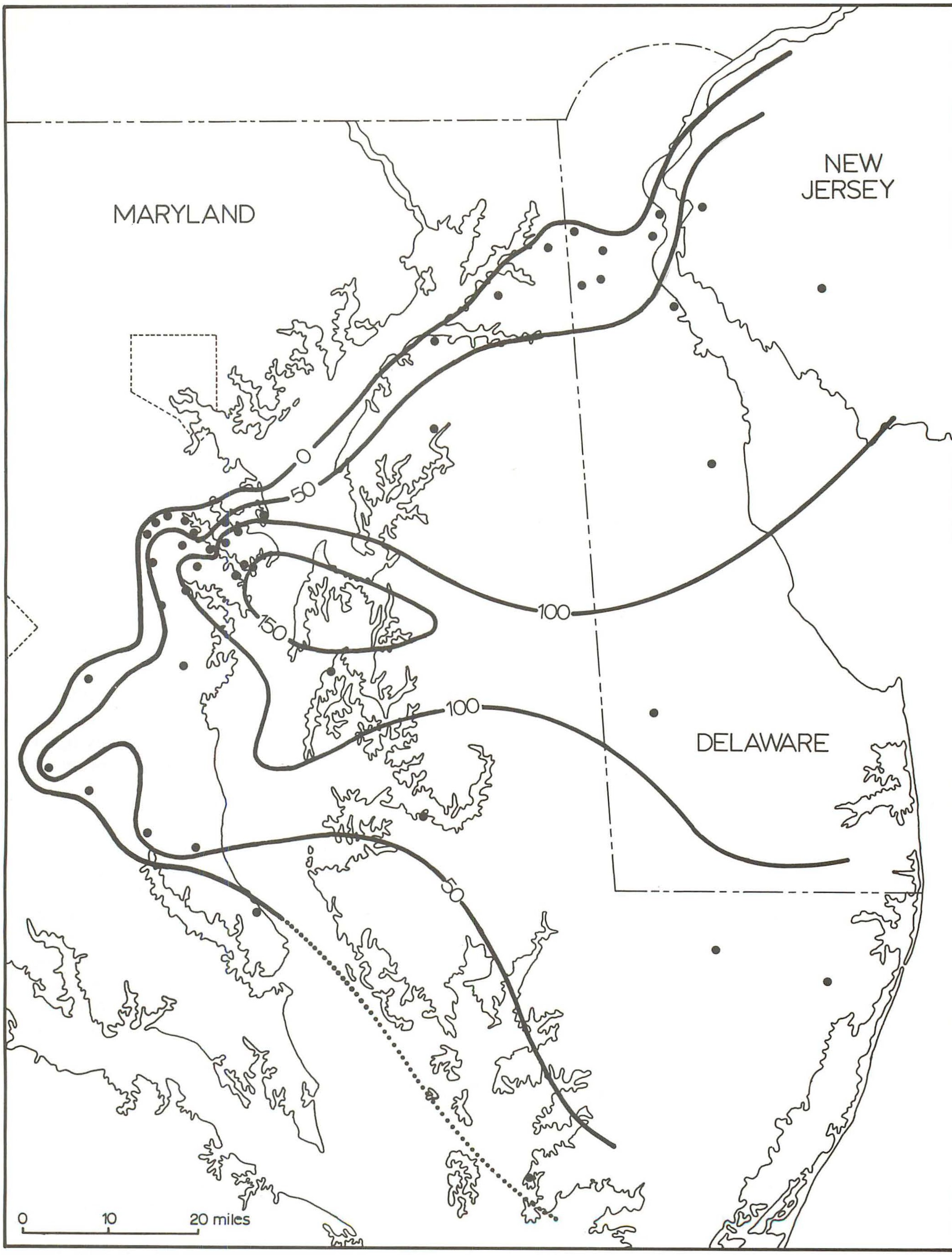


Figure 8. Isopach map of the Magothy Formation (sources of data given in Appendix B).

correlates with the upper portion. Cederstrom reports a maximum thickness for the Mattaponi of 429 feet at Colonial Beach, Virginia.

Several deep drill-holes in the region below the James River in southeastern Virginia encountered a thin sequence (max. 55 feet) of gray to blue clays overlying the Potomac Group. Characteristic late Cretaceous mollusks including *Exogyra* and *Gryphaea* were recovered from these beds (Cederstrom, 1945b). In other borings in the same general area, bright-red to brown unfossiliferous clays up to 120 feet thick occupy the same stratigraphic position. All of these clays may be Mattaponi equivalents. However, the subsurface data available at present is just not adequate to prove or disprove correlation.

Conclusions

It should be evident from the foregoing analysis that the stratigraphic nomenclature presently employed for the pre-Magothy Cretaceous rocks is not really satisfactory. Poor exposure, lithologic similarity, and pronounced lateral variation all contribute to the considerable difficulty encountered in field identification of the various formations. The maximum lithologic differentiation within the Potomac Group is obtained in the type area of central Maryland where relatively good exposure, the presence of the Arundel clays, and the consistently coarse nature of the Patuxent clastics combine to permit discrimination of three formations with a minimum of difficulty. Elsewhere, however, the Patuxent, Patapsco, and Raritan Formations are not lithologically distinct and cannot be mapped without recourse to paleontologic evidence. Sundstrom et al (1967), working in the Delaware subsurface, have been able to subdivide the Potomac into 3 broad hydrologic zones – 2 sandy ones separated by a more clayey one – but correlation with the conventional surface units has not been attempted.

Dissatisfaction with the existing nomenclature is not new. Spangler and Peterson (1950), in reviewing the geology of the Middle Atlantic Coastal Plain, concluded:

> "After a careful study of the evidence the writers have come to the opinion that there are no well-defined units from the base of the Magothy to the top of the crystalline basement."

A similar conclusion was reached by Groot (1955) with respect to the Delaware Cretaceous:

> "These formations (Patuxent, Patapsco, Raritan) are so similar in lithology and so devoid of recognizable fossils in this area, that it is not clear on what basis Miller (Bascom and Miller, 1920) differentiated them. In fact, the question arises whether they deserve to be called formations at all."

Virtually all of the paleobotanists who have dealt with the problem agree that three distinct floral assemblages, corresponding to strata mapped as Patuxent-Arundel, Patapsco, and Raritan, are represented within the Potomac Group. Moreover, it is evident from examination of the older literature that the paleontologic identity of these pre-Magothy units has played no small role in their definition as formations. While the value of fossils as stratigraphic aids cannot be questioned, identifiable plant fossils are not sufficiently common in these beds to be of material value in stratigraphic assignment. Furthermore, it must be kept in mind that the definition of rock-stratigraphic units, e.g. formations, should properly be independent of paleontologic sequence (ACSN, 1961). If a formation is to be regarded as a "body of rock characterized by lithologic homogeneity . . . . mappable at the earth's surface or traceable in the subsurface", then it is reasonably clear that the component formations of the Potomac Group do not qualify as such throughout the greater part of their distributional area. This unsatisfactory situation might be remedied by treating Patuxent, Arundel, Patapsco, and Raritan as stratigraphic facies, thus removing from such names any connotation of mappability, or alternatively, by redesignating them as members of a resurrected Potomac *Formation*. The latter course of action is probably the best choice and has much to recommend it. In fact, Jordan (1962) has referred the Delaware section to an undifferentiated Potomac Formation. However, until some such formal change in Cretaceous nomenclature is adopted in Maryland and Virginia, it seems least confusing to retain the Group terminology for the present report. Accordingly, Patuxent, Arundel, and Patapsco-Raritan *Formations* are employed wherever paleontologic or petrologic criteria permit the discrimination of these subdivisions. Where subdivision is not practical, Potomac Group is employed as an undifferentiated unit.

PALEONTOLOGY

INTRODUCTION

Paleontologic study was not undertaken as a part of this investigation. Nevertheless, I think it justifiable to include the following summary of the known flora and fauna of the nonmarine Cretaceous rocks chiefly because of its direct bearing on the interpretation of depositional environment. Thorough reviews of Cretaceous paleontology in the study area may be had in Clark et al (1911, 1916) and in Dorf (1952).

FAUNA

Animal fossils are notably rare in the Potomac Group and the Magothy Formation. A single fresh water *Unio* and a fish comprise the known fauna of the Patuxent (Little, 1917), whereas the Arundel clays have yielded the fragmentary remains of 8 species of dinosaur, both carnivores and herbivores included. Most of these were found in clay pits in northern Prince Georges County, Maryland. A crocodile, a turtle, a garfish, three gastropods, and a single pelecypod complete the Arundel faunal list (Clark et al, 1911). Patapsco-Raritan animals are considerably more scarce – a few poorly-preserved *Unios* and a single dinosaur bone (Cooke, 1952). Raritan clays in northern New Jersey, however, contain a small shallow-water or brackish molluscan assemblage. Overlying Magothy beds in the same area are at least in part marine with a molluscan fauna of 40 or more species (Dorf and Fox, 1957). These marine elements are absent in the Magothy Formation of Delaware and Maryland. Impressions of pelecypods, found some years ago in the Washington area and purported to be Magothy in age, later proved to be Miocene (Cooke, 1952). Fossiliferous marine tongues are of sporadic occurrence in the upper Potomac Group basinward in the subsurface. Raritan shale and limestone at 1648-1710 feet in 2 drill-holes in southern New Jersey yielded an assemblage of 35 marine molluscan species, this about 30 miles downdip from the outcrop (Richards, 1961). Further, marine foraminifera of late Early Cretaceous age (Comanchean) were recovered from cuttings of a 7 foot thick glauconitic sand bed in a Port Penn, Delaware, test well, presumably well within the upper Potomac Group (Richards et al, 1957). Additional evidence of marine conditions is afforded by molluscan assemblages contained in cores from 3 deep oil tests drilled through the Cretaceous section in eastern Maryland. Intervals 1588-1603 feet and 2250-2257 feet in the Hammond Well near Salisbury, Maryland, held small poorly-preserved faunas which Stephenson (1948) tentatively correlated with outcropping Raritan beds in northern New Jersey. A similar correlation was suggested for mollusks recovered from 1894-1896 feet in the Bethards Well, 11 miles southeast of the Hammond Well. A third brackish or marine molluscan fauna from considerable depth (4875-4885 feet) in the Esso Well at Ocean City was unfortunately wholly new and thus cannot be unequivically correlated, or dated for that matter. Vokes (1948) suggested a Cenomanian age (Raritan) and assigned the fossiliferous section to the Arundel-Patapsco but this assignment has been seriously questioned (Dorf, 1952; Doyle, 1969). Although these questions remain unsettled,

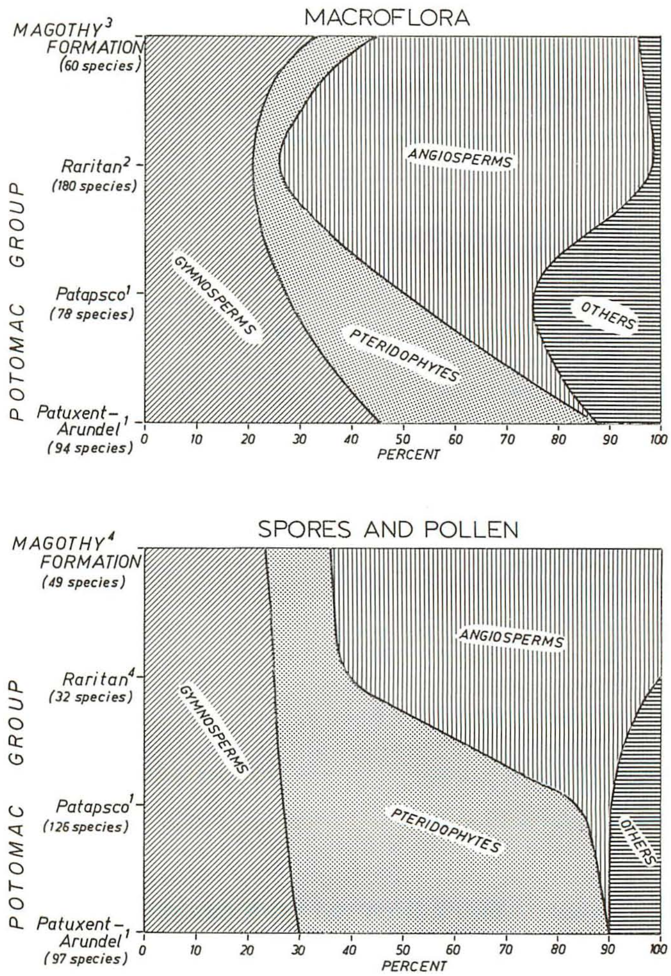


Figure 9. Stratigraphic variations in major floral groups, Patuxent through Magothy Formations. Sources of data: (1) Brenner (1963), (2) Dorf (1952), (3) Clark (1916), (4) Groot, Penny, and Groot (1961).

the important point is the occurrence of brackish-water or marine fauna in the upper portion of the Potomac Formation in eastern Maryland.

FLORA

Flora, rather than fauna, is the significant fossil element in the nonmarine Cretaceous rocks. The plants of the Potomac and Magothy sediments have been intensively studied for nearly 100 years, certainly in large part because of the introduction into the geologic record of the first undoubted angiosperms during Patapsco time. The age and composition of the extensive macroflora has been carefully reviewed by Dorf (1952), and the palynology discussed by Groot, Penny, and Groot (1961), Brenner (1963), and Doyle (1969).

The Patuxent and Arundel floras are strikingly similar with ferns and various conifers dominant and cycads, horsetails, and ginkgos as lesser elements. According to Brenner (1963), the Patuxent and Arundel Formations are palynologically inseparable, thus minimizing any hiatus between the 2 units. The Patapsco flora is marked by the introduction of a number of new ferns and allied forms, but most of the Gymnosperm and Pteridophyte genera are identical with those of the underlying beds. The significant change is the first appearance of angiosperms which increase in abundance as higher Patapsco beds are attained. The Raritan plant community is strikingly more modern in aspect with an abundance of new angiosperm genera (Fig. 9). Flowering plants, for the first time, are the dominant element of the flora. This advance is palynologically marked by the abundance of tricolpate and tricolporate pollen and the introduction of triporate forms in the upper beds of the Raritan. The succeeding Magothy flora, like most modern floras, is characterized by highly-diversified angiosperms including a number of living genera. The abundance of triporate pollen is markedly greater in the Magothy.

Berry (1911) found notable similarities in composition between the flora of the Potomac Group and some modern temperate rain forests. Similar conclusions were reached by Brenner (1963) who characterized the Potomac forests as "similar in character to the warm-temperate gymnosperm and fern forests of New Zealand" but perhaps somewhat more tropical. As regards the Magothy floral association, Berry (1916) found few if any differences from the Potomac; Groot et al (1961), however, suggested the prevalence of subtropical or tropical conditions during Magothy time.

SEDIMENTARY STRUCTURES

INTRODUCTION

Sedimentary structures are the macrofeatures of a rock which commonly give important clues concerning depositional processes and environment as well as events in the history of the rock. Such structures are generally classed as primary or mechanical, as bedding, cross-bedding, ripple marks etc.; or secondary or chemical, such as concretions, diffusion banding etc. Moreover, some primary structures, most importantly cross-bedding, are directional in nature and reveal direction of flow of the sediment-bearing currents, and indirectly, location of source area. Such structures are widespread and abundant in the nonmarine Cretaceous sediments and are treated in detail below.

BEDDING

Bedding, generally defined by the plane of contact between contrasting lithologies or textures, may be observed in virtually all fresh exposures. Exceptions are thick clay bodies in the Arundel and to a lesser extent the Patapsco which are seemingly devoid of any trace of internal stratification. Such clays, however, commonly display pseudo-bedding in the form of extensive diffusion banding or cross-cutting ironstone layers.

Bedding planes in the rocks under scrutiny are in most instances either curved or irregularly formed. Planar parallel bedding is relatively rare. Curved planes define lenticular sedimentation

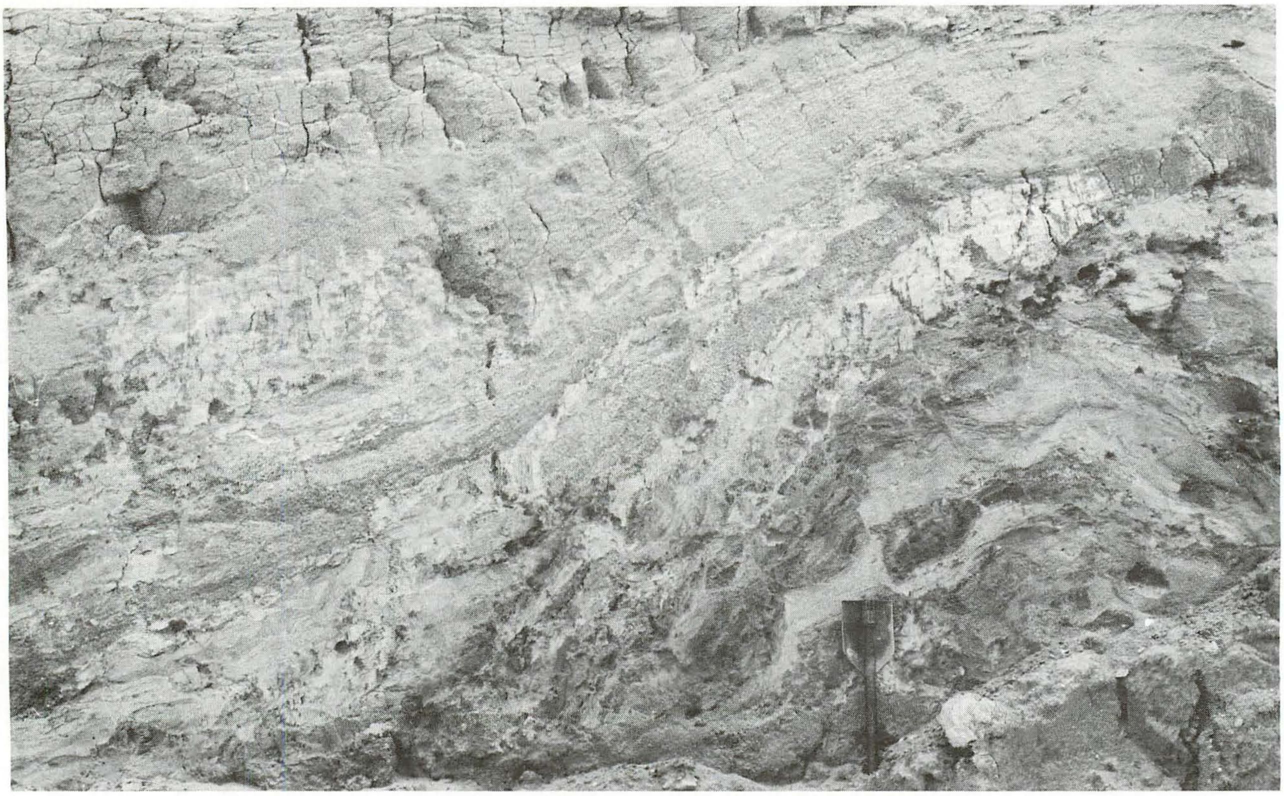


Figure 10. Steeply-inclined, disrupted bedding in interstratified sand (dark) and silt-clay (light) of the upper Potomac Group. Road cut (Loc. 60) near Iron Hill, Cecil County, Maryland.

units, most common in gravels and cross-bedded sands. Irregular undulatory bedding, on the other hand, is generally associated with fine sand or silt-clay. This latter type, commonly met with in the Potomac Group, is no doubt primary to some extent and merely reflects sediment accumulation on irregular surfaces. On the other hand, the common occurrence of all gradations between hummocky irregular bedding and much contorted as well as disrupted bedding suggest that penecontemporaneous slumping and compaction effects are almost certainly responsible for much of the irregularity. The role of differential compaction in producing anomalously steep bedding may be significant. For example, the oversteepened, partly-disrupted clays and fine clayey sands shown in Fig. 10 might best be explained as the result of compaction over the relatively unyielding hummock of coarse sand immediately below.

Beds variously inclined[1] at from one to as much as 15 degrees are common and characteristic, notably in the Patuxent Formation and in the Magothy Formation (Fig. 11). Such beds may be transitional from inclined to horizontal within a given outcrop through lensing out of units updip or through truncation. Large-scale inclined bedding wherein the surfaces of thick gravel or sand bodies are inclined as is the internal stratification is particularly evident in the coarser Patuxent clastics (Fig. 12). The dip direction is generally crudely subparallel to the mean current direction as indicated by cross-bedding.

Inclined bedding, exclusive of cross-bedding, is typically present in several types of sedimentary associations among which beaches, talus deposits, and bars are perhaps the best documented examples. In the first case, the foreshore or backshore laminations of beach sands may slope respectively seaward or landward, yet an interpretation of Potomac or Magothy clastics as beach deposits does not accord with the evidence supplied by texture, fossils, or associated sedimentary structures. On the other hand, little similarity between these Cretaceous rocks and characteristically unsorted, unbedded talus materials can be found. Bar-bedding, then, would seem the best explanation. Further, the occurrence of inclined bedding in interstratified coarse sands and gravels suggests river channel or point bars. Inclined bedding in fluvial clastics is well-

1/ Exclusive of cross-bedding, which although also a type of inclined bedding consists of inclined foreset bedding internal to a single sedimentation unit.

documented, as for example strata in the Lafayette gravel of Kentucky and in Pleistocene outwash deposits in Illinois (Pettijohn and Potter, 1964). Doeglas (1962) concluded that steeply-dipping beds in the Holocene deposits of the River Durance were associated with the downstream, convex sides of channel and point bars where they were actively building channelward or with cobble layers paralleling the sloping channel sides. In either case, such inclined strata do not necessarily dip in the current direction, but may be transverse to the current, dipping instead toward the channel axis.

CROSS-BEDDING

Cross-bedding is doubtless the most common sedimentary structure excepting bedding proper in the Potomac Group and Magothy Formation and can be seen in virtually every exposure of sand as well as in many gravels.

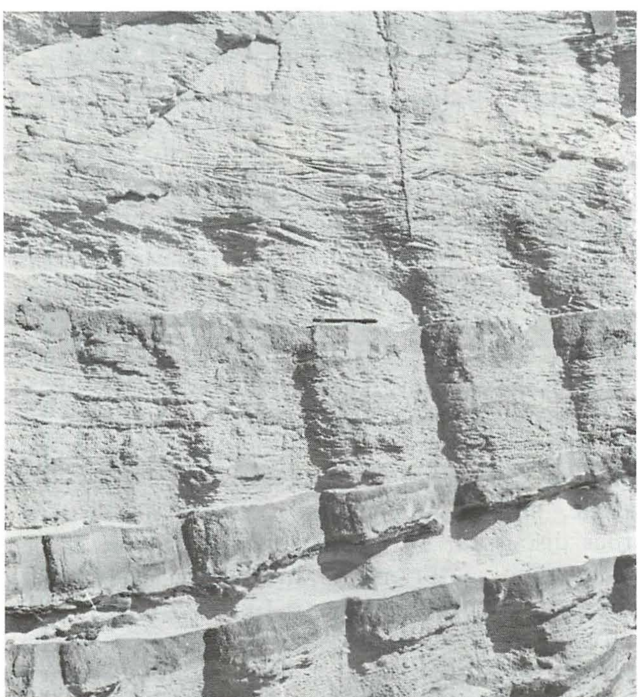


Figure 11. Inclined bedding planes in sand of the Magothy Formation (pen for scale), Dorrs Corner (Loc. 107), Anne Arundel County, Maryland.

Cross-bedded sand or gravel units are generally lenticular in form and of relatively limited lateral extent. The number of such units observed in any given exposure varied from one to 47 but the latter number is exceptional, the average being about 10 per exposure. The arrangement of cross-bedded units is most commonly in unbroken vertical successions of 2 to 15 or more beds, and only rarely are flat-bedded or massive sands inserted into the sequence. Clay or gravel beds generally separate vertical sets.

Trough cross-bedding – lensoid in cross-section with curved basal contacts – is by far the most abundant type in the Cretaceous formations. Tabular units, characterized by planar upper and lower contacts, are infrequent, as are units with straight foresets (Fig. 13). Those tabular units seen were mostly fine to medium gravels. Several sand beds of exceptional lateral extent, initially thought to be tabular in form, proved to have convergent contacts when traced out. Such beds, one of which was followed for nearly 100 feet in outcrop, might be viewed as gradational in character between trough and planar types.

Foreset thickness within cross-bedded units ranges from a fraction of an inch to 6 inches or more; however, the average thickness is rather less than one inch. Individual foresets are defined for the most part by textural contrast, and secondarily by heavy mineral, pebble, or flat clay gall concentrates on the foreset planes. Much less commonly, thin clay laminae or lignite bands bound foresets.

Measurements of foreset inclination within the Potomac Group show values of from 8 to 37 degrees, and an average inclination of 20 degrees (Fig. 14). Based on a thorough review of the literature, Potter and Pettijohn (1963) concluded that the average angle of inclination of foresets in undeformed rocks is usually within the span 18 to 25 degrees. Dips of less than 10 degrees are rather uncommon (2 percent of the total) and tend to characterize units of minor thickness, mostly less than 6 inches. The low dips probably represent erosional remnants of originally thicker units with concave foresets such that the dips actually reflect the flattening out of the foresets near the unit base.

The range of foreset inclination in the Magothy is entirely similar; average inclination is 23 degrees.

Cross-bed thickness ranges widely in both the Potomac and the Magothy; values of from 2 to 96

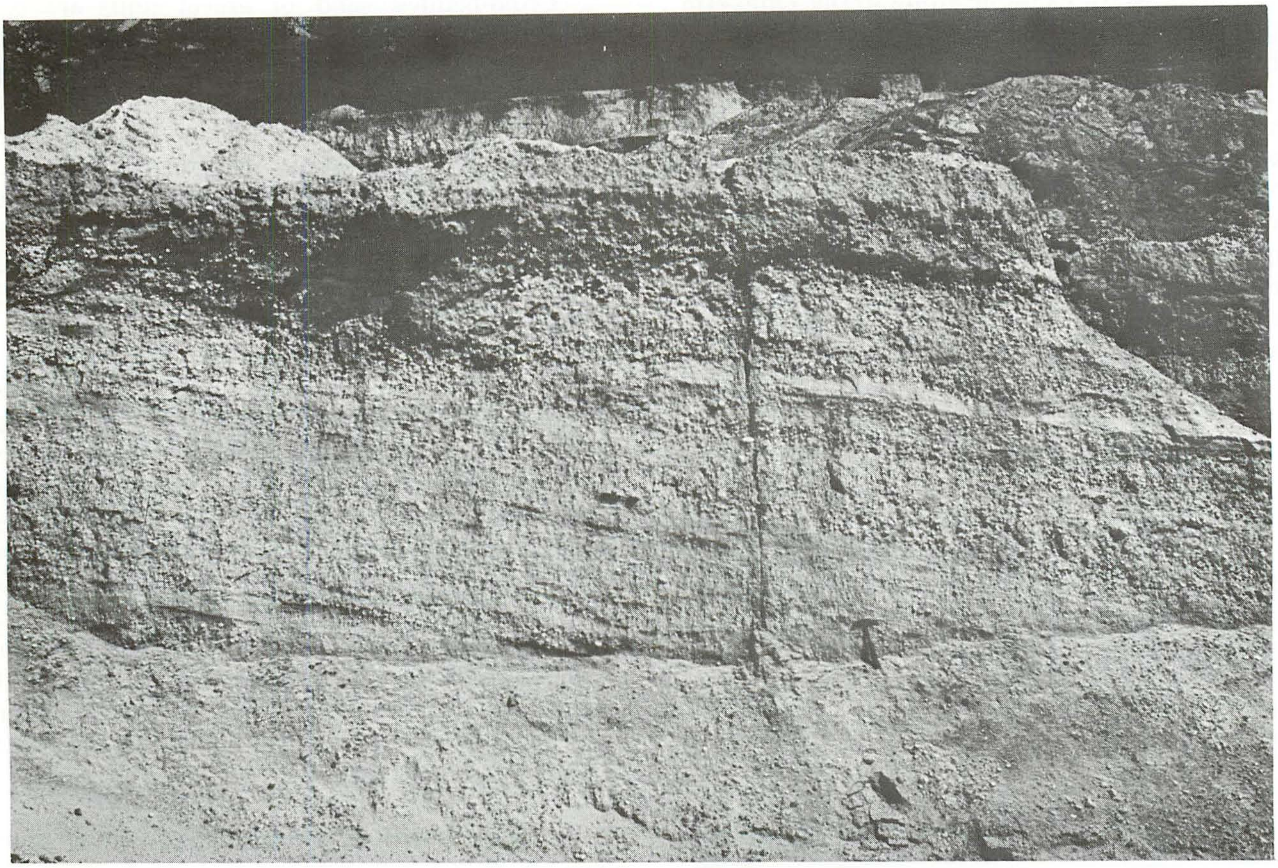


Figure 12. Uniformly inclined gravel beds in the Patuxent Formation, Washington Brick Co. pit, Muirkirk, Maryland.

inches were noted. Some differences among the Patuxent, Patapsco-Raritan, and Magothy rocks are apparent. The greatest thickness range occurs in the case of the Patuxent. A significant percentage of Patuxent units exceed 40 inches (Fig. 14), reflecting the relative abundance of cross-bedded gravel and coarse pebbly sand beds. Such lithologies generally form thicker beds than do the associated medium to fine-grained sands. It follows, then, that in Patapsco-Raritan rocks where gravels and coarse sands are considerably less abundant, the percentage of sedimentation units exceeding 40 inches is notably less.

The direction of foreset dip is doubtless the most significant parameter associated with cross-bedding. Systematic measurement and plotting of such data reveals the direction of flow of the sediment-bearing currents, and in the case of fluvial-deltaic sediments, the paleoslope and source rock location.

Viewed as a single unit, the Potomac Group yields a mean transport direction of 121 degrees, but with considerable dispersion about the mean. The nearly 800 current azimuths measured concentrate in the sector between 40 and 200 degrees with no clear mode indicated. An attempt was made to resolve the cross-bedding dispersion into separate components by plotting the data individually for the Patuxent and Patapsco-Raritan Formations. The results are depicted in the maps of Figure 15. The formational assignment of outcrops rests on a combination of criteria including petrographic, paleontologic, and geographic, and although subject to the limitations earlier discussed, it is believed in the main to be correct. The vector means and vector magnitudes were computed according to Curray (1956). The vector mean or resultant vector is a measure of the mean current direction at a given locality, whereas the vector magnitude, with a range from 0 to 100 percent, reflects the degree of dispersion about the mean such that high values indicate low dispersion and vice versa. The vector means have been plotted with length proportional to vector magnitude to indicate degree of dispersion and have also been assigned arbitrary significance levels denoted by solid, dashed, and dotted lines (Adams, 1964). The latter procedure has the distinct advantage of taking into consideration the number of observations; thus the resulting plot clearly reflects the actual level of significance of the various vector means.

Although the vast majority of the outcrop vector means are significant at the 10 percent probability level, variable transport directions are nonetheless apparent. Moreover, the distribution of Patuxent outcrop means is weakly bimodal with maxima in the northeast and southeast quadrants in contrast to that of the Patapsco-Raritan which indicates more or less uniform southeasterly transport. Perhaps a more meaningful way of depicting the paleocurrent pattern is presented in Figure 16 – a moving average of outcrop means which generalizes the data along an arbitrary grid superposed on the outcrop belt. Each arrow on the grid presents a current direction which is the average of all outcrop vectors in 3 contiguous grid segments; in this manner, local variations are smoothed out and the visual effect of clustered or scattered data is eliminated. Shown are separate moving averages for the Patuxent Formation and the Patapsco-Raritan as well as the transport scheme for the Potomac Group *in toto*. Although considerable outcrop to outcrop variability is evident, it can readily be seen that the overall Patuxent transport pattern is directed eastward to slightly southeastward. However, a significant northeasterly component is also apparent and is responsible for the bimodal character of the Patuxent vector mean composite. This latter component is most evident in the Virginia exposures. The pattern suggests the convergence of 2 dispersal systems in the Potomac River region, a conclusion supported by petrologic evidence presented later in the text. In the case of the Patapsco-Raritan, where nearly all of the cross-bedding observations were made in the Maryland-Delaware area, dispersal was more uniformly southeastward.

Conclusions with regard to sediment transport in the Magothy Formation are of necessity tentative. The outcrop belt is much restricted relative to that of the Potomac Formation, and consequently observations are few. The 43 measurements obtained indicate eastward transport (Fig. 17) with a grand mean of 110 degrees.

Figure 13. Straight foresets in cross-bedded sand of the Magothy Formation, Dorrs Corner (Loc. 107), Anne Arundel County, Maryland.

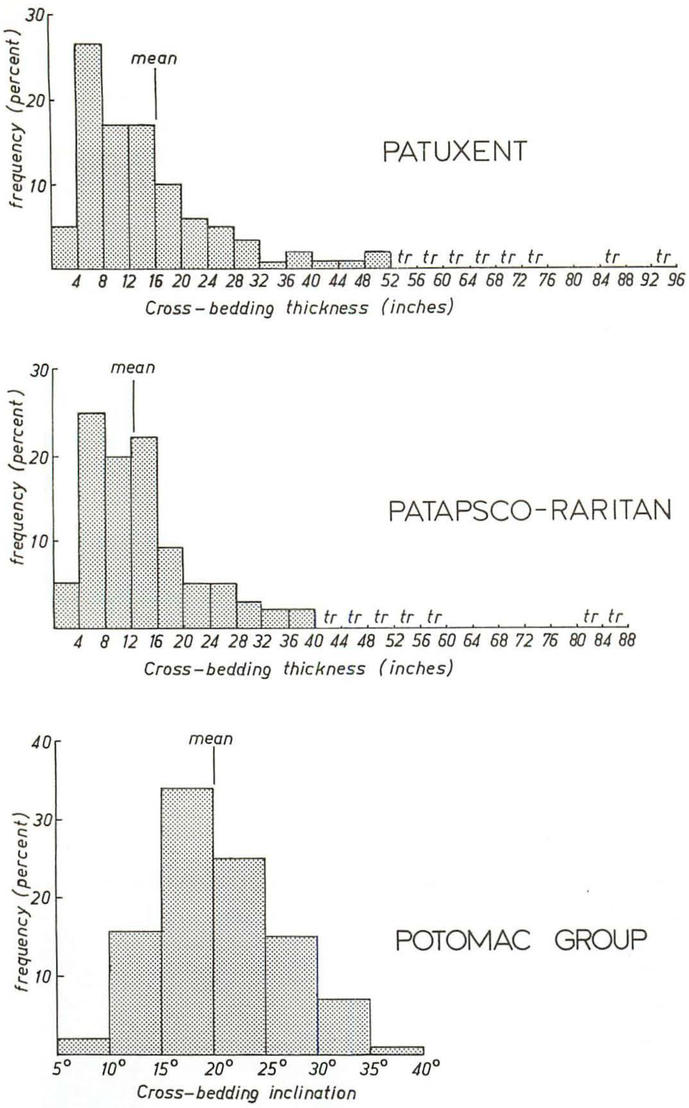


Figure 14. Histograms showing distribution of cross-bed thicknesses and inclinations in the Potomac Group.

The consideration of cross-bedding variability can give valuable clues respecting both constancy of the transporting currents with time and environment of deposition. However, it is important to first determine the source of the variability, i.e. whether actual shifts in current direction are involved, or whether sampling methods are responsible for the dispersion. Once this factor has been evaluated, cross-bedding variability can be considered at 2 levels, namely, within the individual exposure and from the standpoint of regional variance.

The role of sampling in cross-bedding variability has been carefully considered by Yeakel (1959), McIver (1961), and Meckel (1964) among others. The consensus is that sampling methods have little if any effect on the mean current direction as established by cross-bedding. Although measurements concentrated on the limbs of troughs may give a bimodal distribution in which the modal classes are 30 degrees apart, the mean current direction in such cases is very much the same as that indicated by trough axes.

A correlation between cross-bedding variability and the number of observations at any given locality is apparent because dispersion becomes greater as the number of observations increase. Histograms were constructed for those localities with 15 or more observations (Fig. 18). Several of these, e.g. localities 15, 102, and 31, exhibit dual modes separated by one or two 30 degree sectors. Such distributions may be a function of sampling procedure insofar as the sampling plan used did not emphasize axes in favor of the limbs of troughs. However, a number of the remaining histograms are polymodal with modal classes in widely separated sectors, e.g. localities 98, 105, and 91. Here an explanation based on sampling procedure will not suffice. The question of current variability through time in fluvial sandstones was examined by Pelletier (1957) and Yeakel (1959), and their conclusions indicated that directions varied little through as much as 1500 feet of vertical section. Pelletier, for example, found that sub-means calculated for 200 foot intervals of 1000 to 1200 foot sections of Pocono Sandstone did not generally deviate from the locality means by more than 20 degrees. Meckel's (1964) findings in basal Pennsylvanian sandstones were similar although a greater degree of non-systematic variability was exhibited over much less extensive vertical sections (40 feet or less). Several unusually thick sand sections in the Potomac Group were examined for this purpose, i.e. to test for current variability through time. The results in the case of the two most extensive profiles, both in the Patuxent facies, are shown in Figure 19. Both profiles are characterized by successive sand-gravel intervals, each exhibiting relatively homogeneous transport directions within themselves, but which differ from one another by as much as 180 degrees. The intervals are bounded by basal gravels or clay clast conglomerates, commonly with erosional bases, or by clay beds, suggesting discrete depositional pulses. No systematic variation is apparent in the vertical distribution of cross-bed thicknesses which are plotted alongside each azimuth profile; Meckel (1964) found examples of both non-systematic variation and of upward-decrease in bed thickness in profiles of Pennsylvanian sandstones. Similar, though less significant current shifts between successive sand bodies can be demonstrated as well in the Patapsco-Raritan Formation. There is, then, some evidence to suggest that changes in current

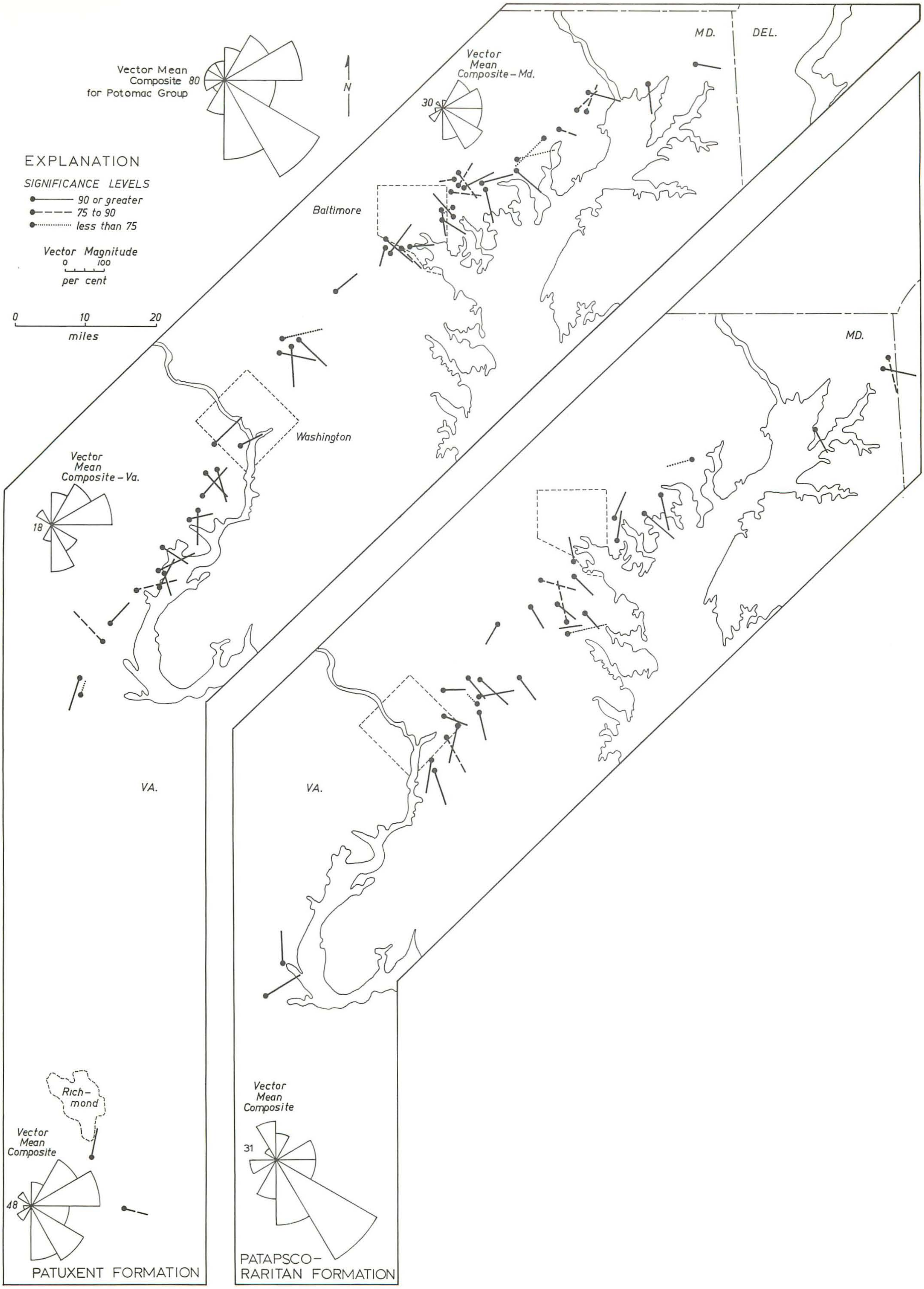


Figure 15. Outcrop vector means of Potomac Group cross-bedding dip azimuths.

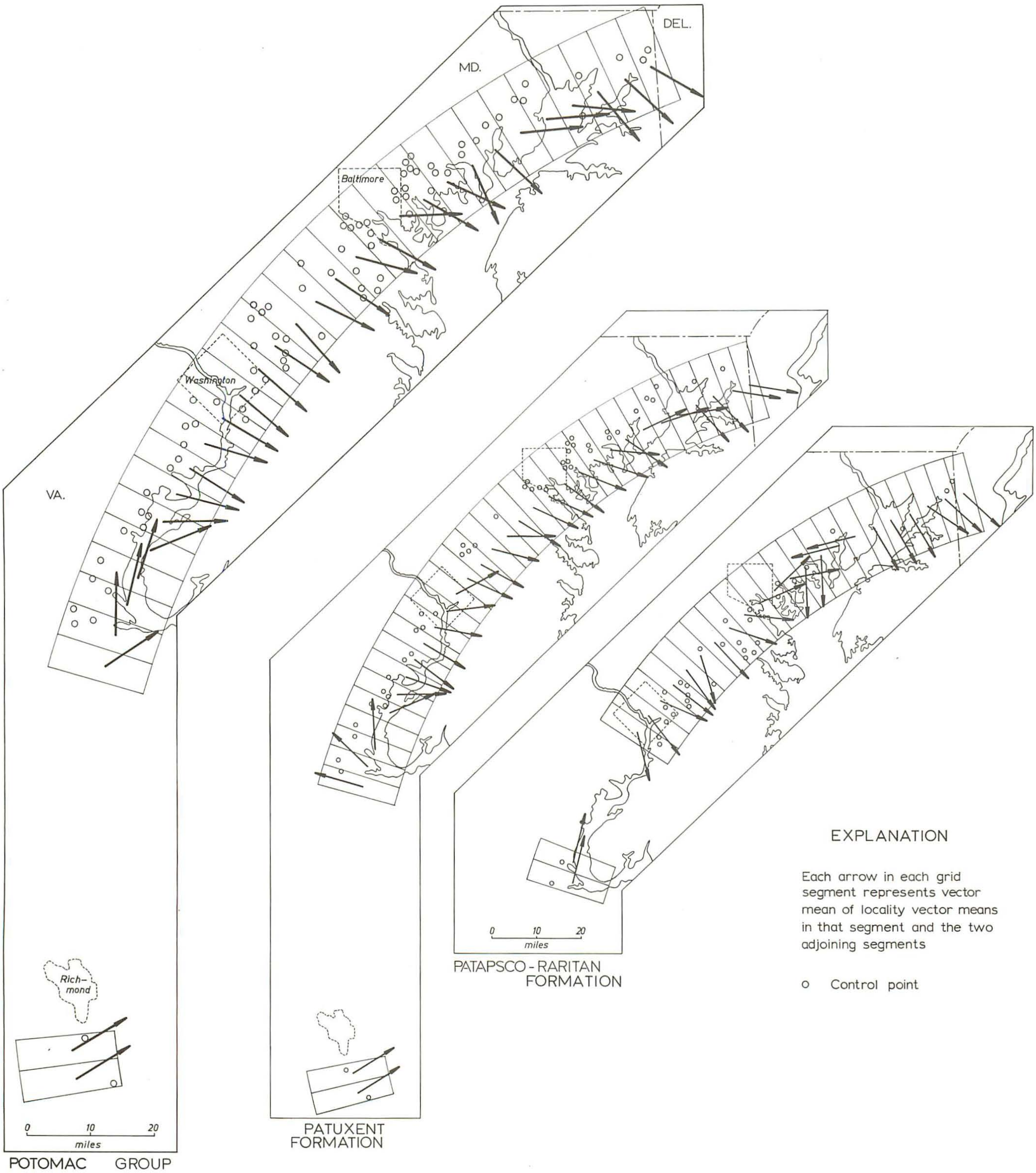


Figure 16. Moving average of Potomac Group cross-bedding vector means.

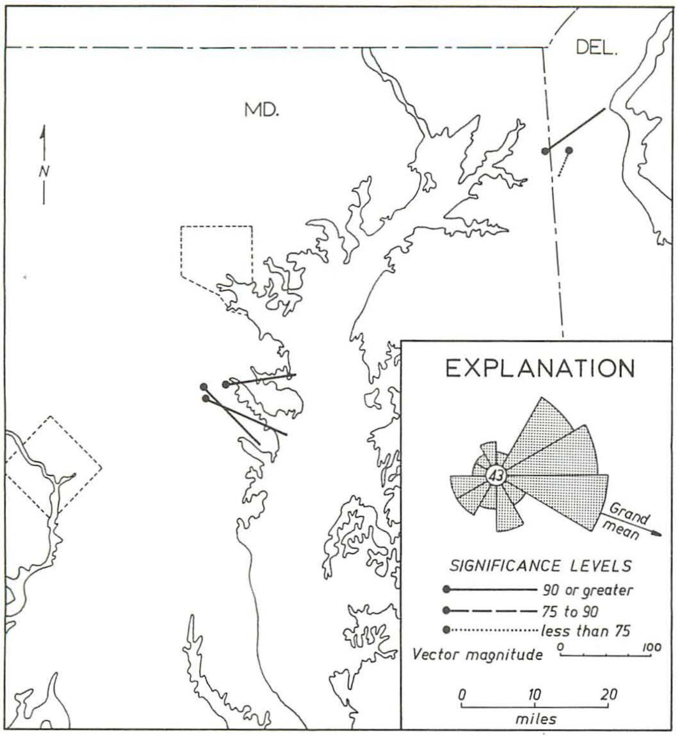


Figure 17. Outcrop vector means of Magothy Formation cross-bedding dip azimuths.

direction between successive depositional pulses may be an important factor in explaining the polymodal character of some Potomac cross-bedding distributions. On the other hand, vertical cross-bedding profiles of relatively homogeneous sand bodies generally exhibit little variation and plot as unimodal distributions. An important exception to this generalization can be seen, however, in some Magothy cross-bedded sands. Excellent exposures along the Chesapeake and Delaware Canal clearly show that the foresets of successive cross-bedded units, commonly separated by thin flat-bedded sands, may dip in opposing directions. The resulting histograms are polymodal with modes in opposite sectors (as locality 27, Fig. 18). Bimodal cross-bedding distributions with opposed modal classes are characteristic of tidal sands in the North Sea (Brinkman and Hulseman, 1955). As here interpreted, the Magothy Formation is environmentally transitional between the Potomac Group (mostly nonmarine) and the Matawan-Monmouth (marine shelf deposits); thus, tidal sands might be expected to occur in such a transitional unit.

The variance (square of the standard deviation) of regional cross-bedding distributions has been considered environmentally significant (Potter and Pettijohn, 1963). Viewed as such, variances in the range 4000 to 6000 are typical of fluvial-deltaic rocks whereas marine rocks, generally with more variable cross-bedding, show higher values from 6000 to 8000. Considerable overlap does occur, however, in that variances as low as 2482 have been recorded in marine units, and conversely, as high as 7778 in fluvial-deltaic sands (Potter and Pettijohn, 1963). The regional variances of both the Potomac Group and Magothy Formation have been determined, and further are compared with those of a number of other units, both marine and nonmarine, to test environmental significance (Fig. 20). Unfortunately, however, the comparison is more or less inconclusive. Both Cretaceous units, at 6300 to 6800, rank in the region of variance overlap between marine and nonmarine sandstones. In view of the fact that nearly all of the evidence points to a fluvial environment for most of the Potomac and much of the Magothy, an explanation of the relatively high variances of these units must be considered. At least 2 and possibly 3 factors have almost certainly contributed to the cross-bedding variability as measured by the variance. Firstly, the inclusion of contrasting cross-bedding directions, i.e. predominant easterly to southeasterly transport in Maryland and Delaware versus a significant component of northeasterly transport in Virginia, has unquestionably increased the variance. The second factor is current shifts which are apparently important at the outcrop level. The possibility of inclusion of spurious bimodal distributions stemming from sampling procedure is in all probability minor yet cannot be wholly discounted as a third factor.

The observations of a substantial number of workers have amply documented the origin of cross-bedding in recent environments as the sediment record left by migrating sand waves or megaripples, or by the infilling of scour troughs. With particular regard to the fluvial environment, sand waves of varying size and wave length have been observed as bed forms in a number of modern rivers including the Mississippi (Carey and Keller, 1957), the Klaralven (Sundborg, 1956), and the Columbia (Jordan, 1962). The downstream migration of such sand waves is probably the dominant mode of bed load transport and is directly or indirectly responsible for the production of the foresets of most cross-bedding (Potter and Pettijohn, 1963). Trough cross-bedding, perhaps the most important sedimentary structure in modern river sands, is apparently the result of the infilling by migrating dunes or sand waves of relatively deep elongate depressions produced by localized scour within the dune field (Harms and Kahnestock, 1965).

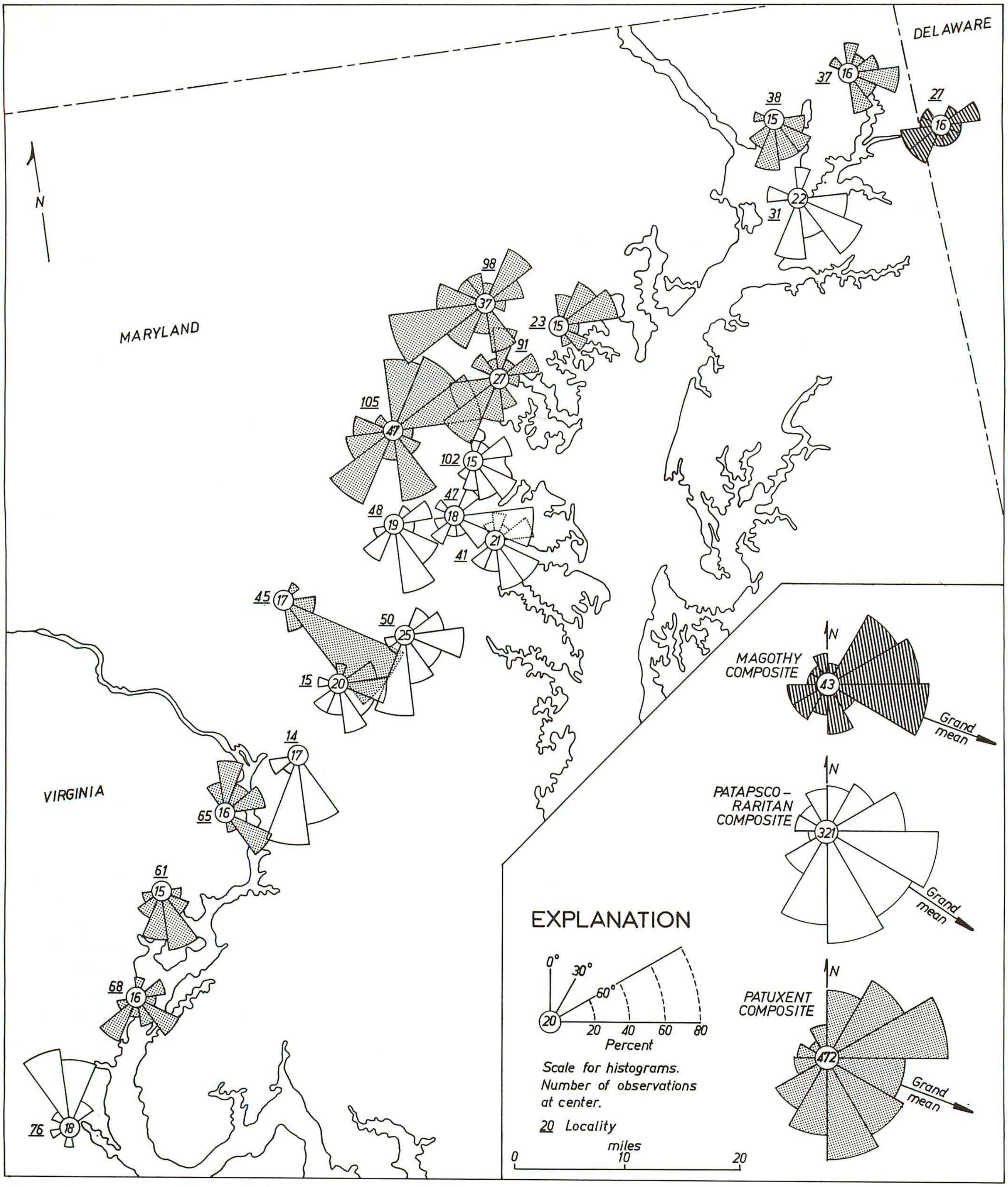


Figure 18. Locality histograms for Potomac and Magothy exposures at which 15 or more cross-bed dip azimuths were recorded.

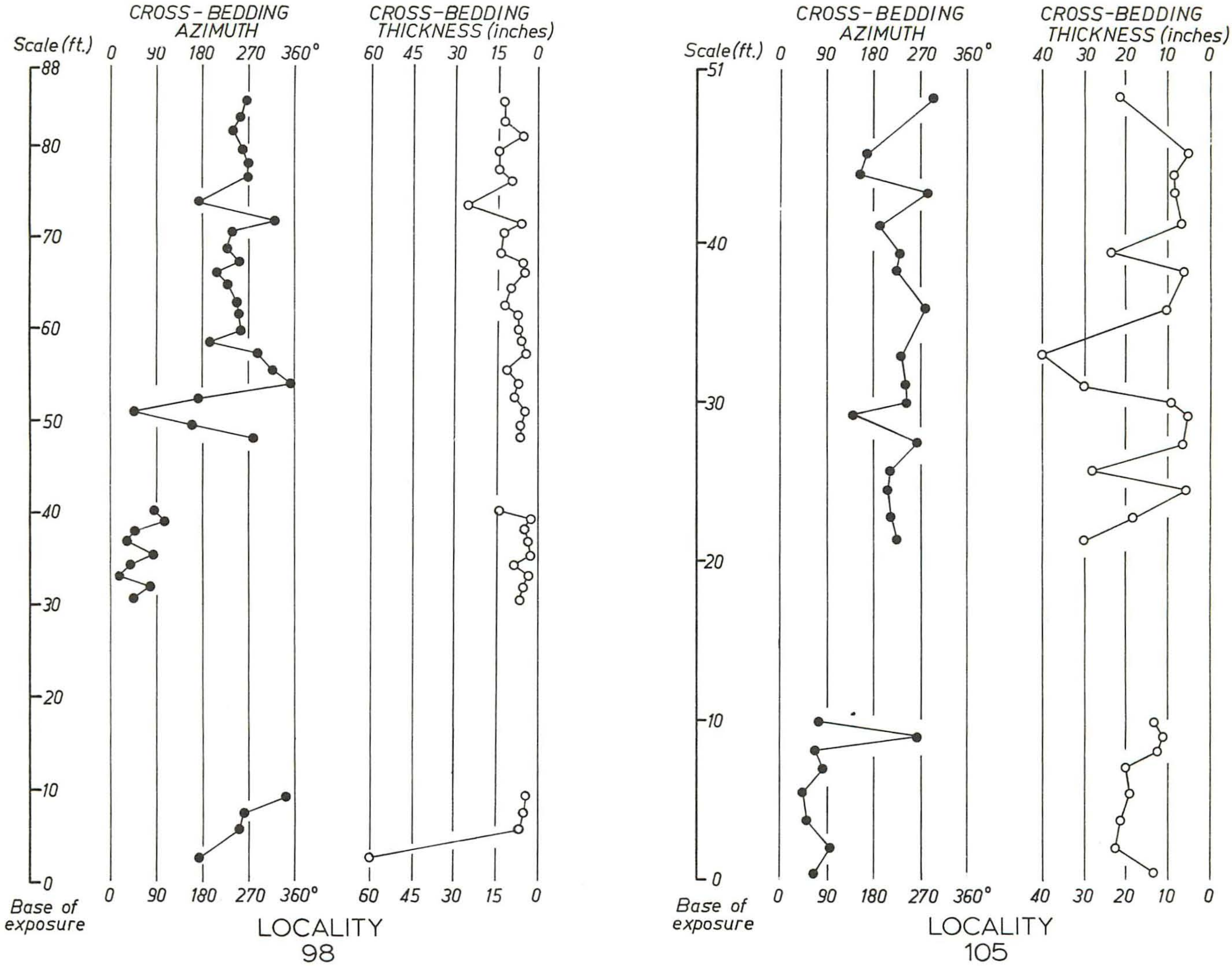


Figure 19. Vertical profiles of cross-bedding variability and thickness changes at 2 Patuxent Formation exposures.

CLAY CLAST CONGLOMERATES

Sand or gravel units in which clay clasts are important constituents are very common in the Potomac Group and particularly so in the Patuxent Formation. Rounded or angular, usually somewhat flattened clay fragments occur in virtually all gravels, comprising one to 90 percent or more of the framework elements. Moreover, most Potomac sands bear clay clasts (Fig. 21), commonly as scattered chips, but in other cases concentrated along bedding planes or in the basal portions of beds.

Clay clast shape may take the form of roughly equidimensional balls rather then flattened chips, particularly as size increases. The latter range is large – from granules to lumps 30 inches in diameter; Fontaine (1896) reports clay clasts as large as 5 feet in diameter in the Patuxent Formation of central Virginia. Large clasts are virtually restricted to the basal few feet of thick gravel beds (Fig. 22) or sand bodies (Fig. 23). In most cases, discernible internal structure is lacking within the balls. However, in others a concentric banding of thin limonitic laminae can be detected in the otherwise massive clay (Fig. 23), but this is doubtless secondary, probably a diffusion banding phenomenon.

An uncommon feature of some Patuxent sands is the inclusion of armored clay balls – rounded, generally elliptical clasts studded with pebbles. The size range of the armored balls observed spans one to 6 inches in diameter. Many such balls occur in isolated fashion, embedded in fine to medium sands with no apparent proximity to pebbly beds or gravels.

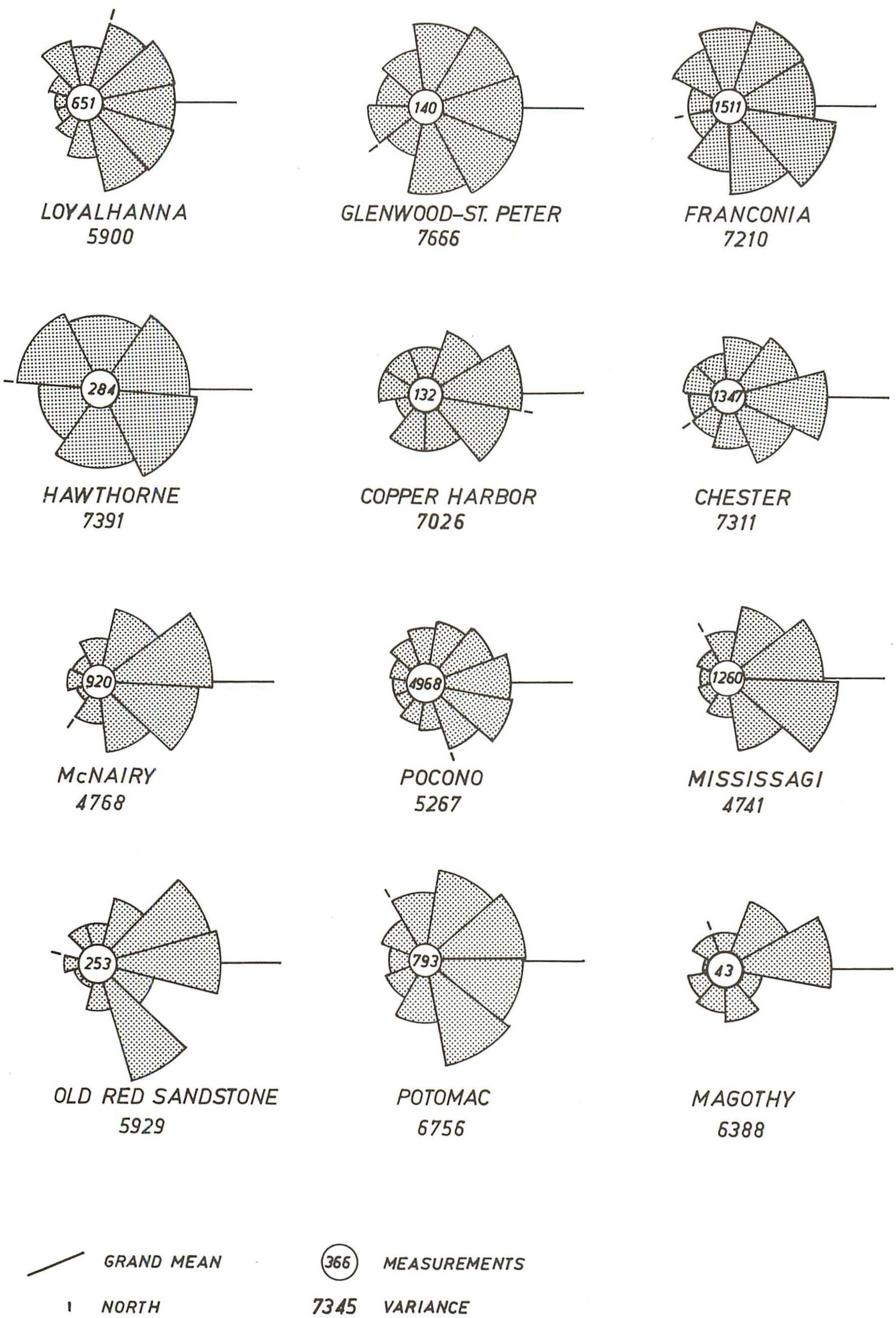


Figure 20. Comparison of cross-bedding dip azimuth distributions and regional variances of sandstones from various environments. Loyalhanna, Glenwood-St. Peter, Franconia, and Hawthorne are marine units; others fluvial-deltaic.

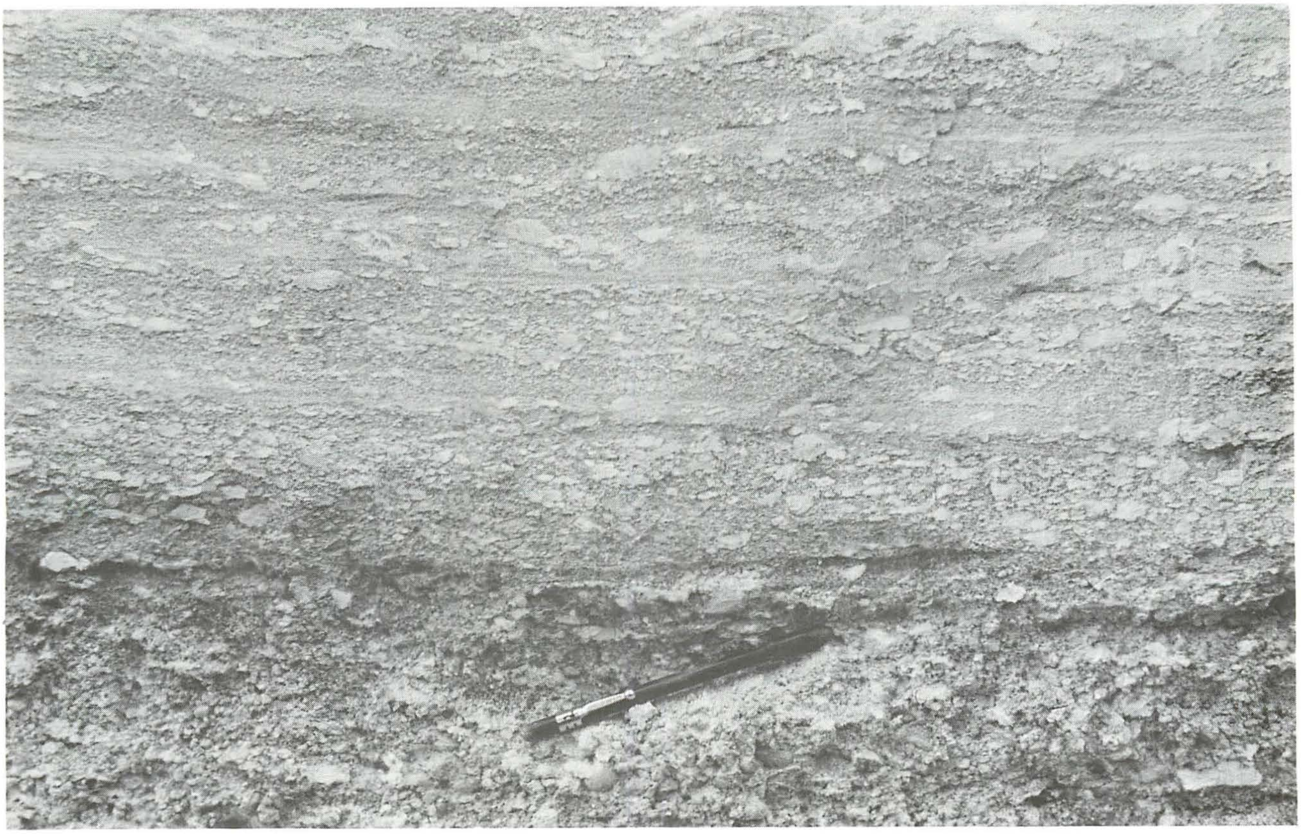


Figure 21. Flat-bedded sands of the Patuxent Formation crowded with angular clay clasts and interstratified with laminated silt-clay. Faint banding which dips to right in center of photograph is limonitic diffusion banding. Abandoned sand pit (Loc. 105), Baltimore City.

Figure 22. Exposure of the Patuxent Formation in an abandoned sand pit (Loc. 73) at Triangle, Virginia. Large, rounded, dark clay clasts are conspicuous in the basal portion of the coarse petromict gravel bed shown in the photograph. Most of the pebbles in the gravel are highly-weathered metamorphic rock types.

Clay balls are relatively uncommon components of sediments, and the reported occurrences are mostly associated with continental deposition. Bell's (1940) conclusions, based on a thorough study of clay ball genesis in a California ravine subject to strong flooding, are applicable in part to clay clasts in the Potomac Formation. The clasts are formed from blocks of clay cast into the channel through bank undercutting and subsequent collapse, or by tearing up of mud-cracked layers in the river bed. The latter process is apt to yield tabular fragments of relatively small size whereas bank caving may be the source of larger equidimensional clasts. In either case, the fragments may then be carried or rolled downstream, or buried by sediment near the site of derivation. The distance and velocity of transport to which clay balls may be subjected is a function of several variables, namely the structural strength of the ball, the transporting ability of the current, and initial size. Such balls rapidly round during transport; consequently, it may be assumed that highly angular clasts, common in Potomac sands, are of very local derivation. In the case of armored clay balls, the characteristic pebbly rind is acquired by rolling across gravelly portions of the stream bed.

A relatively uncommon yet significant lithologic association in the Potomac is the occurrence of clay lenses or masses of irregular form which contain dispersed pebbles and sand pockets. Equally significant are isolated, laterally truncated clay layers of irregular thickness, commonly disrupted into several parts with variable orientations in the enclosing sediment. Such clay "beds" are apparently not primary lenses but rather re-sedimented clays. The chaotic bedding, marginal truncation, and lack of continuity suggest redeposition of brokenup clay lenses in much the same manner as that proposed for clay clast conglomerates. Further, the irregularly-shaped, pebbly clay masses are perhaps best explained as the result of compaction and welding of local concentrations of transported clay clasts mixed with pebbles and in many cases interstitial sand. Intermediate stages of

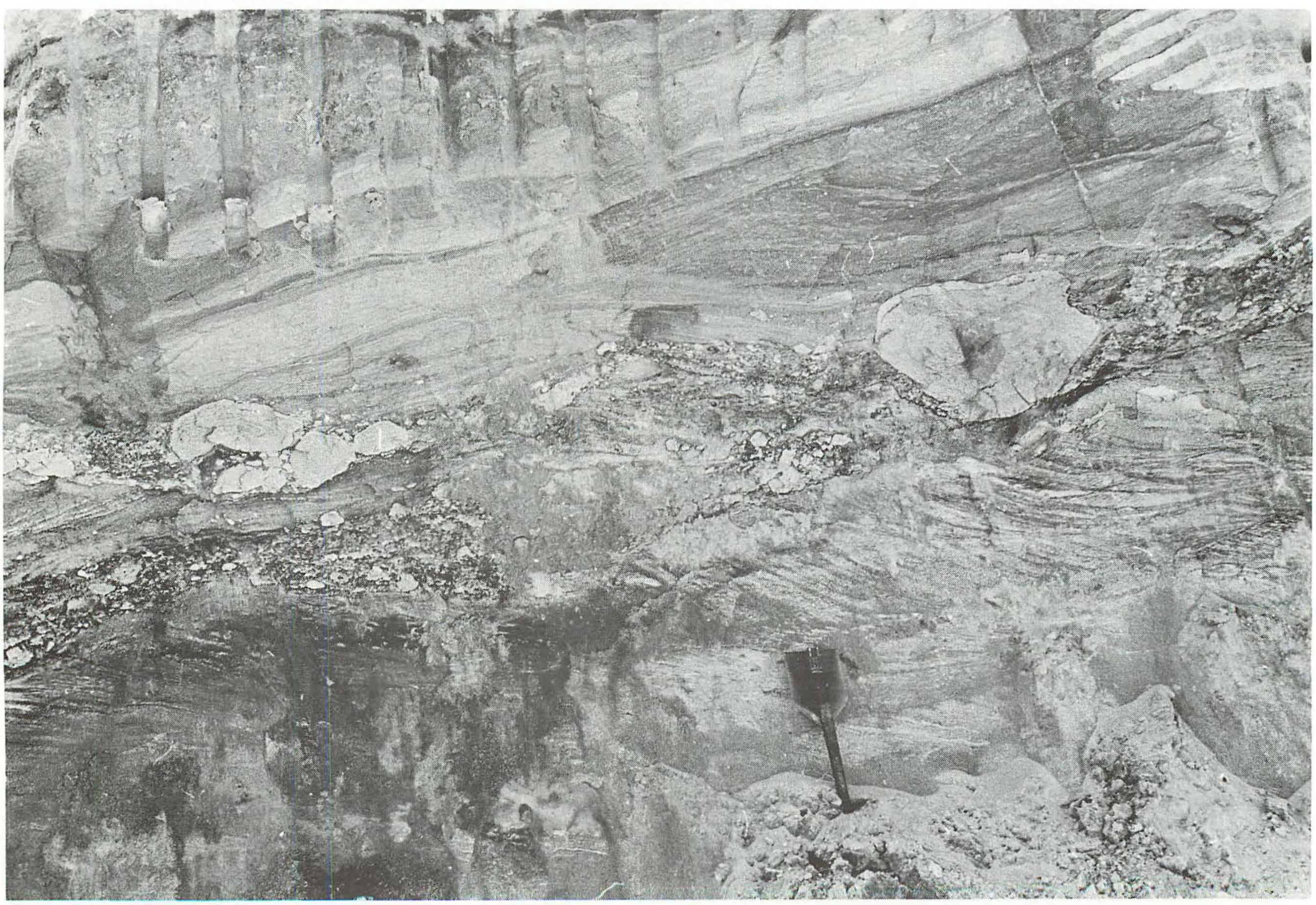


Figure 23. Pale clay clasts of diverse sizes in the basal portion of the sand fill of a broad, shallow channel. Sand pit (Loc. 98), Carney, Baltimore County, Maryland.

development seen in some exposures strengthen the case. The large clay mass in the center of the photograph of Figure 24 illustrates the point; the outlines of individual clasts can be clearly distinguished near the margin but the mass tends toward homogeneity in the interior. A like origin for thoroughly-welded, seemingly massive bodies is revealed by the included pebbles and sand pockets, and most decisively, by the thin anastomosing sand films which outline relict clasts.

RIPPLE MARKS

Ripple marks are rarely seen in the Cretaceous rocks studied. It is probable however, that they are more abundant than observation indicates, and that their apparent rarity is a function of the lack of bedding plane exposures. Internally cross-laminated current ripples of small amplitude were noted in a few Potomac exposures and in several outcrops of Magothy rocks. In the latter unit, ripples are virtually confined to intervals of interlaminated clays and flat-bedded sands.

Megaripples or sand waves are rarely preserved in the rock record, yet most cross-bedding in fluvial sediments is considered to be the result of downstream megaripple migration. Shown is Figure 25 is a succession of four such sand waves in the basal Patuxent Formation. The average amplitude in this case is 8 inches, and the average wavelength 6 feet. The dip azimuths of the internal cross-bedding, measured in each successive wave, do not vary from one another by more than 5 degrees.

CUT AND FILL

Channeling features such as cut and fill are abundantly represented in the Potomac Group and to a lesser extent in the Magothy Formation. Trough cross-bedded units are properly considered the product of a scour and fill mechanism whereby some portion of the underlying unit is removed by current erosion and the resulting scour trough filled by successive increments of sand.

Small-scale channels with cross-sections measured in inches to several feet are particularly

Figure 24. Concentration of clay clasts welded by compaction into a large irregular mass. Exposure in sand pit (Loc. 94), Baltimore City.

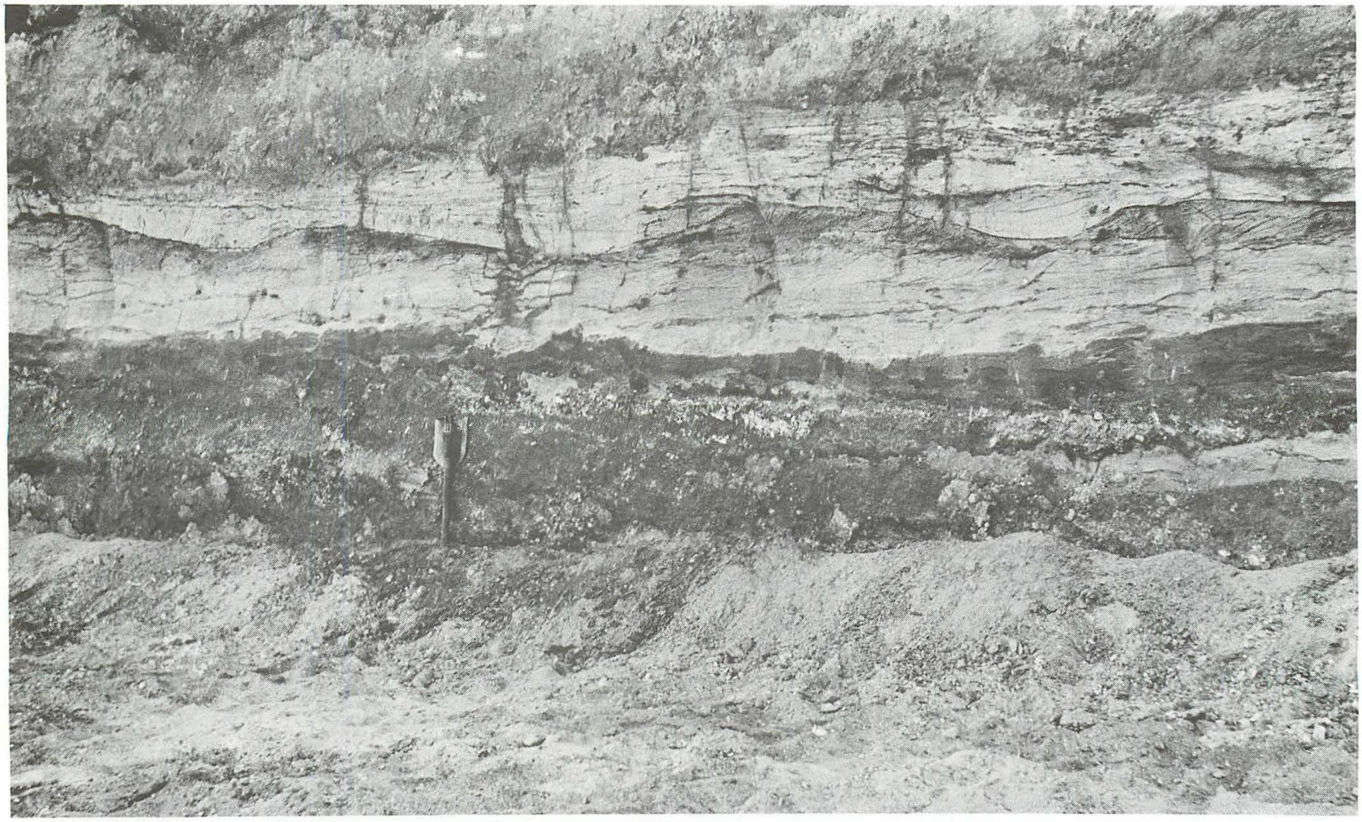


Figure 25. Exposure in sand pit (Loc. 96) showing succession of four internally cross-laminated magaripples.

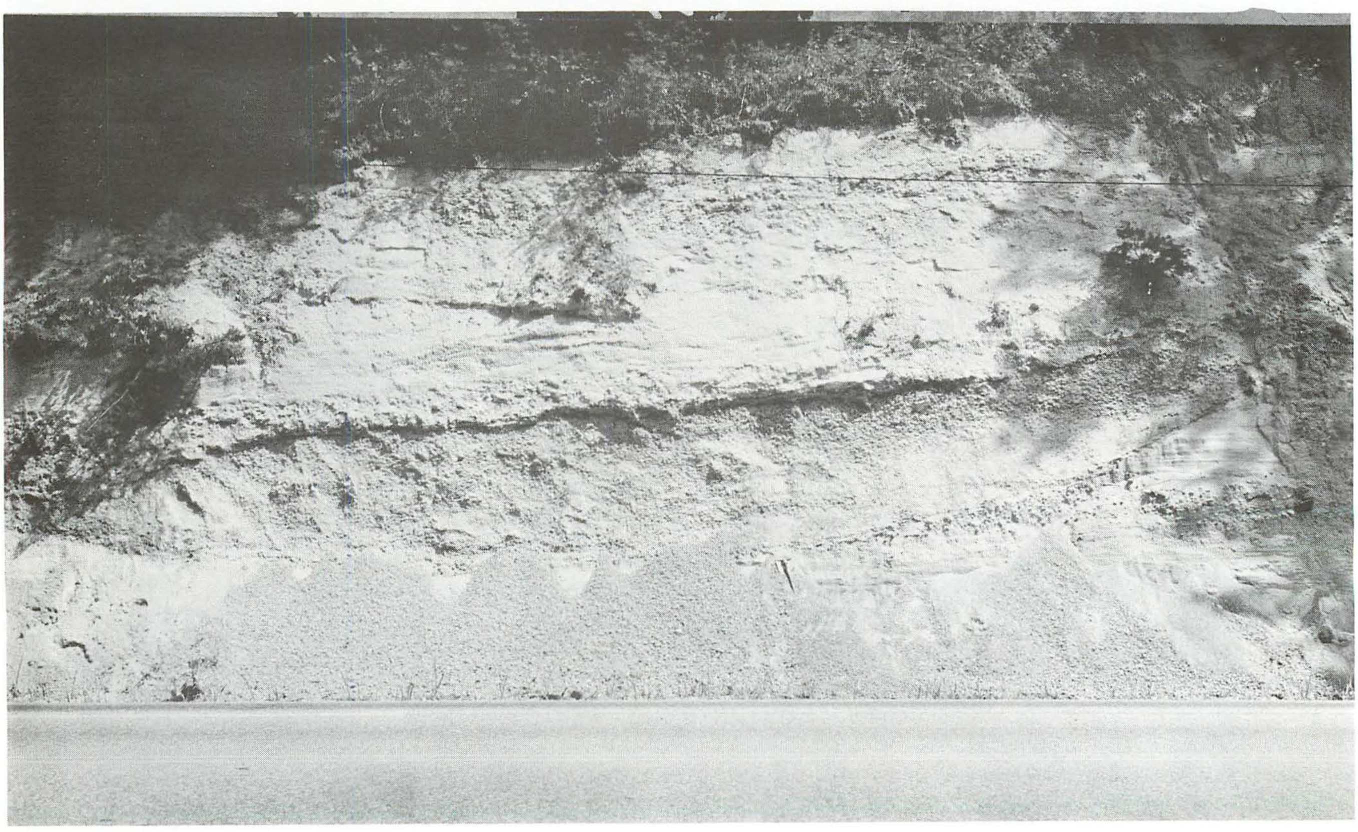


Figure 26. Clay plug in the Patuxent Formation (Loc. 75), Stafford County, Virginia. A broad shallow channel cut in coarse pebbly sand has been filled with massive silt-clay (shovel for scale).

prevalent in the Patuxent Formation. The majority of these are smoothly concave upward and more or less symmetric in form, but all gradations to steep-walled, flat bottomed scours do occur. Channel fill is commonly coarse to pebbly sand, in many cases with a concentration of pebbles, cobbles, or clay clasts at the base. Clay-silt fill is much less common; the example in Figure 26 is cut in coarse pebbly sand of the Patuxent and filled with massive silty clay. Fisk (1944) described numerous such clay plugs within the Pleistocene alluvial fill of the Lower Mississippi Valley. Clay plugs result when channels are cut off from the active river and abandoned, thereafter receiving only fine silt and clay during flood stages.

OPEN-WORK GRAVEL

Open-work gravel, i.e. gravel with unfilled voids, is a common feature of the basal Patuxent coarse clastics where it almost invariably occurs as individual foreset layers in thick planar-cross-bedded units. Such open-work foresets are a minor element in any given gravel unit, the proportions of normal layers with sand-filled voids always being considerably greater. Hematite precipitation as pebble coatings is commonly localized in open-work gravels. Many such layers are graded from coarse to fine. The thickness range of open-work foresets extends from 2 to 10 inches.

Whereas sand-filled gravel interstices are the normal case in which packing considerations suggest that the sand and gravel fractions are simultaneously deposited, it would seem that open-work gravels demand special hydraulic conditions. Cary (1950) noted that open-work gravels are found most commonly in torrentially (planar) cross-bedded gravels at the downstream ends of bars or deltas. His observations indicate that vortices, prevalent on the lee sides of projections into a stream, may well lower the hydraulic pressure on the bar face, thereby causing water to flow outward from within the gravel interstices. Sand might then be prevented from coming to rest in the gravel interstices yet the outward flow would presumably not be of sufficient strength to prevent pebble deposition on the bar face. Thus open-work gravel would result. Moreover, graded open-work gravel might be explained, granted the validity of Cary's hypothesis, by waning currents and consequently weakened vortices which would permit deposition of successively smaller pebbles but still exclude sand. The establishment of conditions favorable to open-work gravel deposition may be primarily a function of current velocity and bottom topography.

WOOD PETRIFACTIONS

In addition to abundant lignite, numerous examples of mineral pseudomorphs after wood are contained in the Cretaceous rocks studied. Such pseudomorphs are, for the most part, hematite, limonite, pyrite, marcasite, or silica replacements of woody matter ranging from twigs to logs. Cellular structure is preserved in great detail in many of the petrifactions.

The host sediments of most of these structures are silt-clay, as is commonly the case elsewhere, but they can also be seen in the sands and even the gravels of the Potomac Group. A consistent relationship apparently exists between the permeability of the host sediment and the kind of replacing mineral matter. Wood petrifactions in sands and gravels are mostly silica or hematite whereas those preserved in fine clastics tend to be some form of iron oxide, iron sulphide, or lignite. Ward (1893) cites a case in which a log embedded half in sand and half in clay in the Patuxent facies of Virginia was silicified only to the sand-clay contact, the half in clay remaining lignite.

WOOD FRAGMENT ORIENTATIONS

Plant matter, mostly lignitized coniferous wood, is very abundant in gray to nearly black clays and less so in the fine to medium sands of both units studied. The range in dimensions of such wood fragments is immense – from tiny splinters to logs 2 feet in diameter and 40 feet in length. Some degree of sub-parallel alignment, although relatively uncommon, may characterize an assemblage of elongate fragments in a given bed. Measurements taken at several exposures demonstrate that wood fragment alignment, if present, is usually transverse to the current direction indicated by the associated cross-bedding, or less commonly, crudely subparallel to the current. Potter and Pettijohn (1963) concluded, based on a literature survey, that parallel and perpendicular alignment of wood fragments are equally common.

SOFT-SEDIMENT DEFORMATION

Penecontemporaneously disturbed bedding, seen at a number of exposures, occurs at various stratigraphic levels in the Cretaceous section. Disordered crumpling of sand beds on a relatively minor scale is most common, and although generally confined to a single sedimentation unit, deformation of this type may involve several feet of section or several beds. The disturbed beds are nearly always inclined. In detail, cross-bedding foresets are broadly crumpled, oversteepened, or irregularly and more closely buckled.

All of this disturbed bedding can probably be attributed to small-scale down-slope movement in response to gravity, in most cases prior to deposition of the overlying bed. The slopes involved were very likely the inclined faces of channel or point bars.

CONCRETIONS

Concretions are particularly common in the clays of the Potomac Group and Magothy Formation and include a number of diverse types. Siderite concretions, oxidized in varying degree to limonite, are most characteristic of the Arundel facies but occur as well in some dark lignitic Patapsco and Magothy clays. These vary in size from a few inches to 6 feet or more in diameter, and in shape from ovoid flattened bodies to irregular knobby forms. Although the concretions are in isolated cases concentrated in roughly horizontal layers, presumably parallel to bedding, most are randomly distributed through the clay. Because internal bedding is hardly ever distinct in Arundel clays, no direct evidence is available to indicate whether concretionary growth was static or whether bedding was displaced by the growing concretions. In thin section, the concretions disclose a mosaic of tiny siderite crystals with scattered quartz silt.

Almost all of the siderite concretions exhibit a network of cracks which may be confined to the surface and open, or more commonly, extend into the interior of the concretion and show fillings of siderite or limonite. Open cracks and irregular cavities are in many instances lined with drusy siderite. Moreover, oxidation has affected the majority of the concretions examined to the extent that many consist of numerous thin concentric shells of limonite enclosing a small unaltered core of siderite or sideritic clay. None of the concretions contain identifiable nuclei.

The occurrence of sideritic concretions in dark lignitic clays or shales is a rather common phenomenon of sedimentary rocks. Decaying plant materials, generally abundant in such clays, account for the reducing conditions necessary for siderite precipitation. The only additional requirement is the initiation of nuclei around which iron carbonate, having migrated to the collecting point from the surrounding host rock, can precipitate. Volume changes, either during or after the formation of the concretion, may initiate the network of cracks so commonly associated with such structures. Kauffman (1965) reports that shells in siderite concretions are in many instances fractured into small equidimensional polygons. These are doubtless shrinkage phenomena, perhaps formed during drying of water-saturated siderite and host clay. On the other hand, the possibility that cracks were formed in the presence of abundant water cannot be discounted; recent work (Burst, 1965) suggests that shrinkage cranks can form subaqueously if a swelling clay is present during conditions of increasing salinity.

Limonite and less commonly hematite concretions are conspicuous in many of the Cretaceous sands and show great variety of form; botryoidal, cylindrical, and spheroidal shapes, however, predominate. Some are hollow and partly filled with highly ferruginous sand or clay. Voidal concretions, such as these, have been attributed to oxidation of originally sideritic bodies wherein siderite is removed leaving insoluble quartz sand or clay enclosed in a limonitic shell (Pettijohn, 1957). Most if not all iron oxide concretions are essentially weathering phenomena, generated above the water table in the zone of oxidation.

A third concretion type is composed of pyrite or marcasite and is common only in the dark lignitic clays of the Magothy Formation. Most of these are crudely cylindrical in form and have precipitated around a nucleus of lignite, in many instances a twig. The chemical conditions required for iron sulphide precipitation are much the same as those specified for siderite, and in fact, siderite is a common associate.

DIFFUSION BANDING

Parallel and closely-spaced pseudo-laminations of limonite-permeated sediment are widespread in the outcropping Potomac rocks and are no doubt attributable to diffusion banding, also known as Liesegang banding. Striking patterns of yellow, brown, and purple banding which may be either subparallel to or transect bedding are common. In the absence of well-defined textural definition of stratification, such banding may be mistaken for cross-bedding, primary laminations, or contorted laminations unless closely examined. Diffusion banding is a common secondary structure in sandstones, manifested as yellowish-brown oxidation bands of finely-divided limonite which are more or less independant of the textural features of the rock. Bastin (1950) points out:

> "Oxidation (diffusion) banding cannot be the product of a single episode of diffusion but represents the composite effects of many episodes of wetting and drying, solution and deposition, during prolonged periods."

Experimental Liesegang bands have been developed in a potassium dichromate-sand-geletin block by suspending the block in silver nitrate solution (Carl and Amstutz, 1958). The same authors suggest that diffusion banding in rocks may develop in parallel fashion, i.e. alternate diffusion and precipitation in a colloidal matrix of intergranular film.

PETROLOGY

LITHOFACIES

Potomac Group

The Potomac Group is made up of a number of lithofacies, the proportions of each varying widely from outcrop to outcrop and regionally.

Gravels – Fine to very coarse gravels composed of mostly subrounded pebbles and cobbles of vein quartz, metaquartzite, sandstone, and subordinate chert, held in an interstitial sand matrix, are an important rock type in the Patuxent Formation and are sporadically distributed through the upper portion of the Group. A minor but nearly ubiquitous component of Potomac gravels is angular to rounded clasts of pale-gray clay, generally of the same or somewhat larger size than the associated pebbles. The gravel units range from a few inches to 5 feet in thickness, are generally lenticular in form, and are interbedded with sands and thin lenses of pale-gray clay. Internal bedding is well-defined to absent and includes cross-bedding, horizontal bedding, and uncommonly, graded bedding.

Such orthoquartzitic gravels (Fig. 27) in the Patuxent facies are excellently exposed in numerous sand-gravel pits distributed along the western outcrop margin as well as in outliers on the Piedmont from Washington, D.C., northeast to the Maryland-Delaware line. Petromict gravels (Fig. 28), made up of varying proportions of quartzose pebbles, dark-green to brown clay clasts, and highly-weathered fragments of igneous and metamorphic rocks, are both uncommon and geographically restricted within the Potomac Group. Such gravels are interbedded with arkosic sands in the lower portion of the unit in Virginia only. Typically, they are massive and show erosional basal contacts; moreover, they can be notably coarse, with occasional boulders of 18 to 24 inch diameter.

Clay clast conglomerates – Pebble gravels in the Potomac pass gradationally into conglomeratic beds in which as much as 90 percent of the framework is made up of clay clasts. Clast color defines two geographically restricted kinds of such conglomerates. North of the Potomac River, the clasts are invariably white to pale-gray, whereas in Virginia, dark-green to brown is the predominant color.

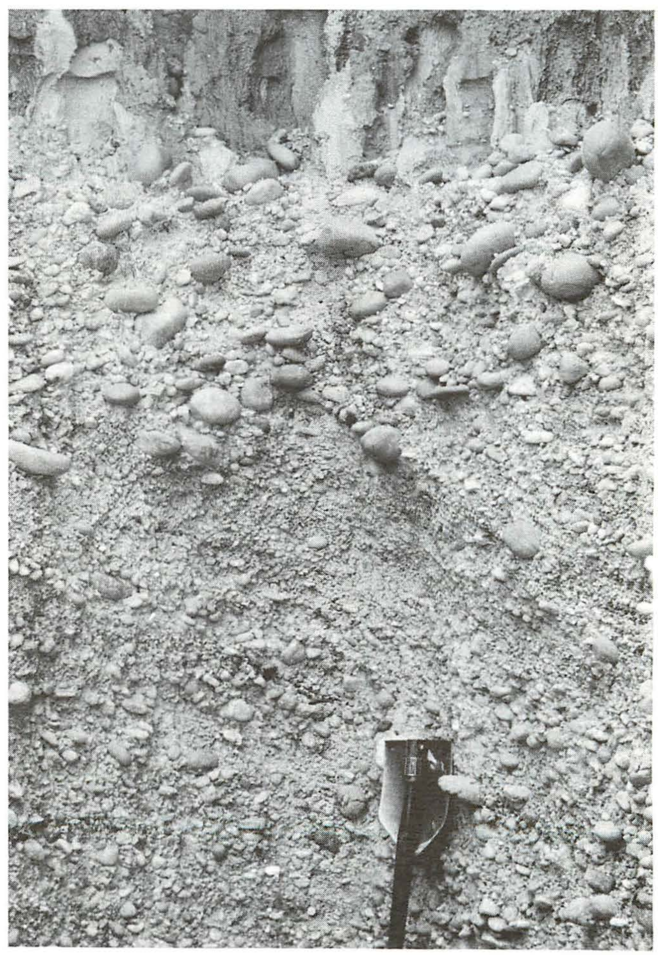


Figure 27. Massive, very coarse gravel near the base of the Patuxent Formation. Exposure in Contee sand and gravel pit (Loc. 40), Montgomery County, Maryland.

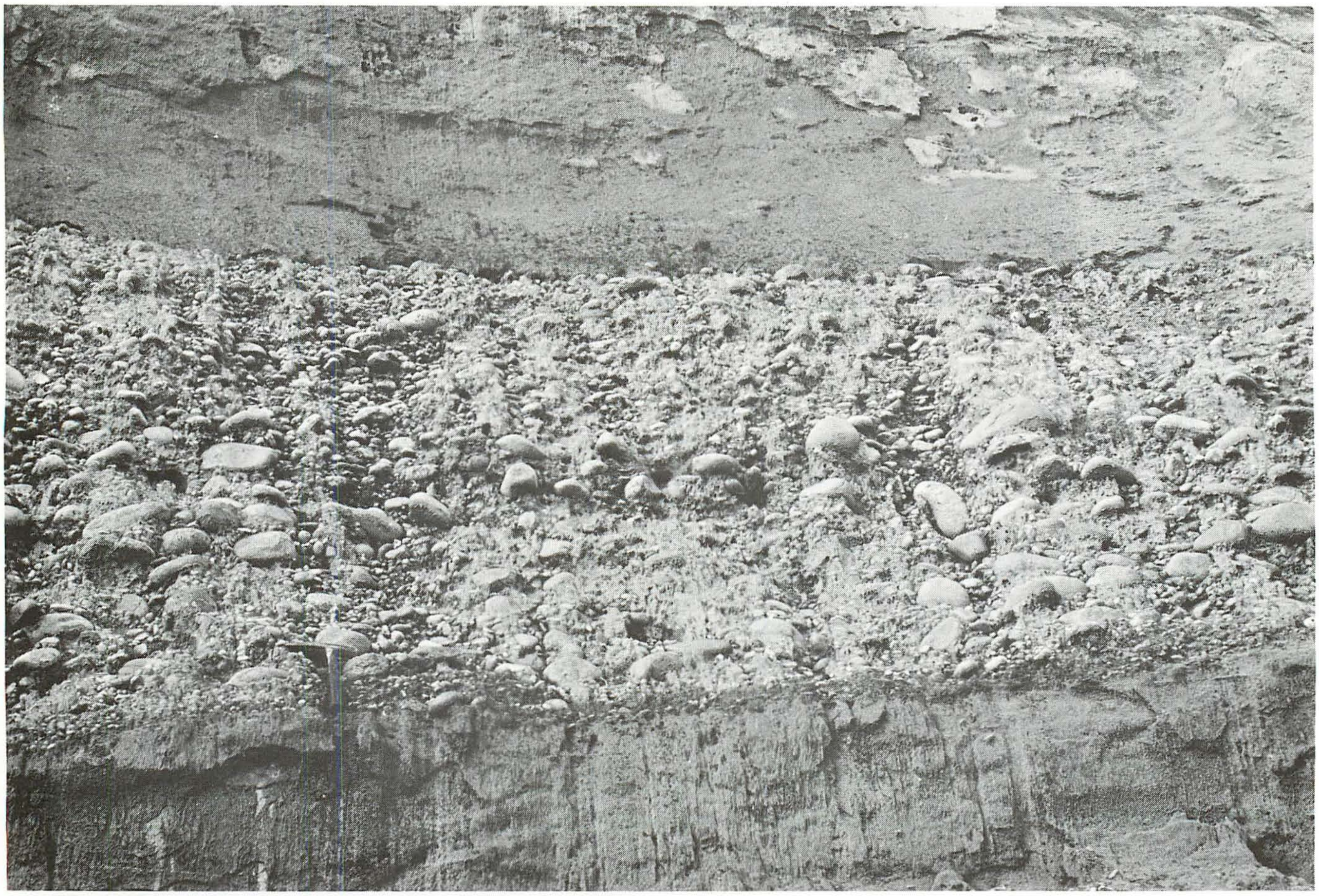


Figure 28. Very coarse, petromict gravel bed interstratified with argillaceous feldspathic sand. Exposure in west bank of James River (Loc. 111), Chesterfield County, Virginia.

Ferruginous conglomerate – Gravels are in many instances thoroughly lithified by hematite or limonite cement resulting in conspicuous ledges of ferruginous conglomerate as well as large irregular masses strewn over the outcrop. Such cementation is a phenomenon of the zone of weathering; thus the occurrence of ferruginous conglomerate is virtually restricted to the near-surface.

Sand and sandstone – White to gray, variably clayey, fine to coarse-grained sand is a dominant lithology in the Potomac Group. Sand beds or lenses, a few inches to 4 feet or more thick, are generally arranged in laterally restricted bodies ranging up to 60 feet in thickness. Sand is most abundant in the Patuxent Formation where it makes up from 25 to as much as 70 percent of the unit, and in the upper Patapsco-Raritan which contains extensive bodies of clean sand in central Maryland. Potomac sands are commonly distinctly pebbly; thin pebble layers along bedding and foreset planes can be seen in nearly every sandy outcrop as can scattered pebbles and cobbles (Fig. 29). Potomac sands, like the gravels, exhibit geographically restricted compositional types. Unconsolidated, highly quartzose sands are associated with orthoquartzitic gravels from the Potomac River northward, whereas sands in the Potomac Group of Virginia are generally gray in color, coarse-grained, and are marked by an abundance of clay aggregates and chalky feldspar grains. These latter two components impart a mealy character to the Virginia sands. Moreover, they are typically semi-lithified to lithified resulting in a friable sandstone which breaks around the clastic grains.

A far less common yet widely-distributed sandstone type, distinguished by iron oxide or iron carbonate cement, generally occurs as isolated beds or zones which transect bedding and are interstratified with uncemented sands.

In a number of Patuxent exposures, particularly those with relatively great vertical extent, sandy sections characterized by systematic upward textural and bedform changes were observed. Such sequences, when complete, share the following features: (1) upward textural succession from gravel or coarse pebbly sand at the base to fine sand or silt at the top, and (2) cross-bedding of medium to large scale in pebbly sand or massive bedding in gravel in the basal portion, trough cross-bedded medium sand in the central part, and small-scale cross-bedding in the fine-grained sediment of the upper portion. In addition, the coarse basal bed generally overlies an irregularly scoured surface. An excellent example of such a fining-upward sequence is shown in Fig. 30. Far more commonly, what are apparently truncated remnants only of fining-upward sequences are preserved. In the latter case, gravel or pebbly sand grading up into medium sand is succeeded with local unconformity by the same cycle, the fine-grained uppermost portion having been removed by erosion. Cyclic fining-upward sequences are well-documented in modern fluvial environments (Jahns, 1947; Frazier and Osanik, 1961; Stricklin, 1961; Bernard and Major, 1963), and each one, in all probability, records a single episode of lateral channel migration during which a point bar offlap sequence, graded from coarse to fine, is deposited in the channel. The thickness of sediment deposited during each cycle may well correspond to the maximum river depth during flood stage.

Variegated clay – Silt-clay, variously mottled in red, brown, purple, gray, white, and yellow, is a volumetrically important lithology throughout the Potomac Group but is particularly abundant and characteristic of the Patapsco-Raritan Formation in Maryland and Delaware. As much as 75 percent of the latter unit in parts of central Maryland may consist of mottled or variegated silt-clay with individual bodies reaching 100 feet or more in thickness. Stratification is commonly very difficult to recognize within such clays; in fact, they are for the most part internally massive, excepting a pervasive mottling and irregular textural variations from clay to silty or sandy clay. In some cases, mottling patterns are obviously related to joints and cracks suggesting control by weathering processes.

Carbonaceous clay – Typically dark-gray to nearly black massive silty clay containing an abundance of lignitized wood is the major Arundel lithology and a much subordinate but widespread lithology throughout the remainder of the Potomac Group. Such carbonaceous clays, like the mottled clays, generally lack internal stratification excepting horizontal bands of concentrated lignite.

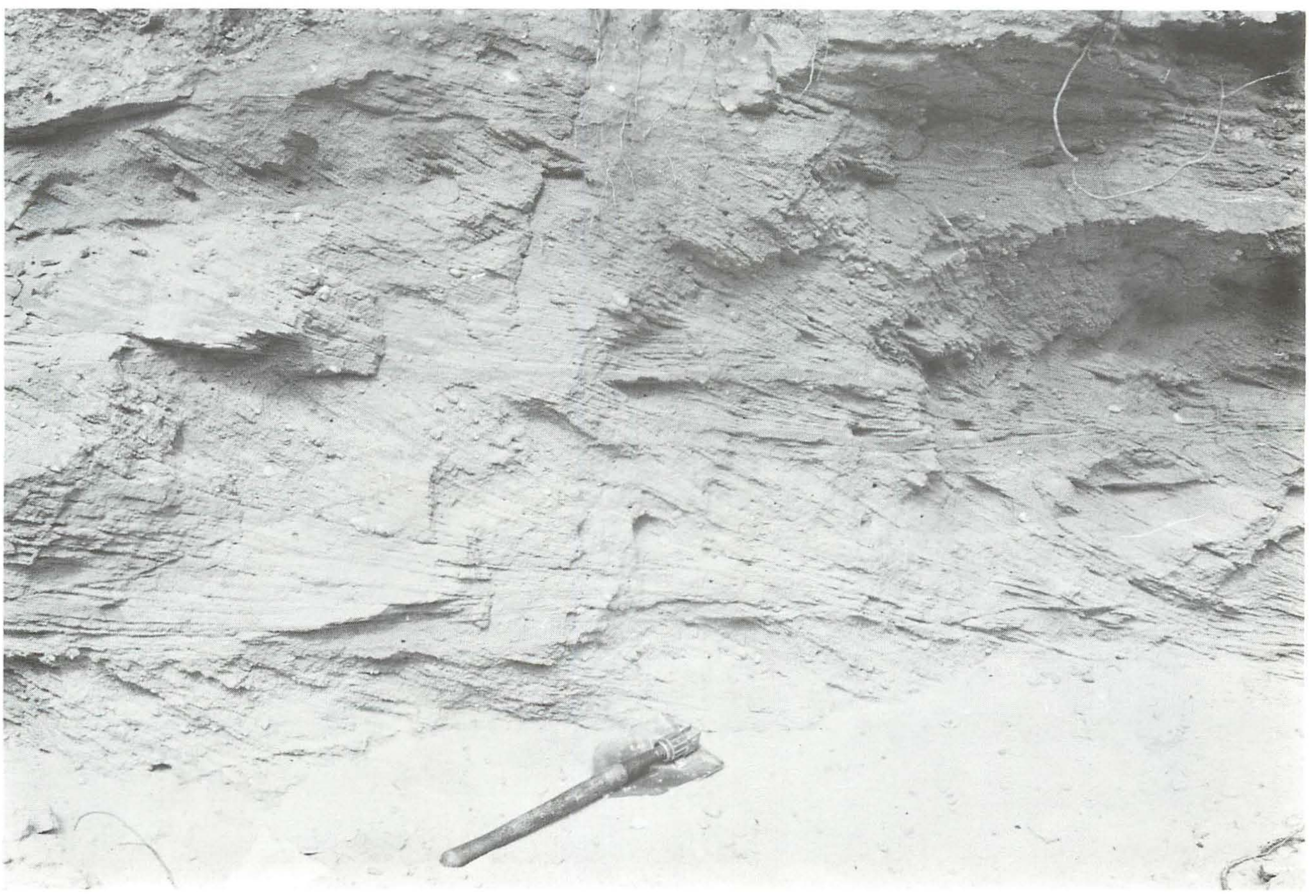


Figure 29. Cross-bedded coarse sand of the Patuxent Formation with conspicuous scattered pebbles. Exposure in sand pit (Loc. 105), Baltimore City.

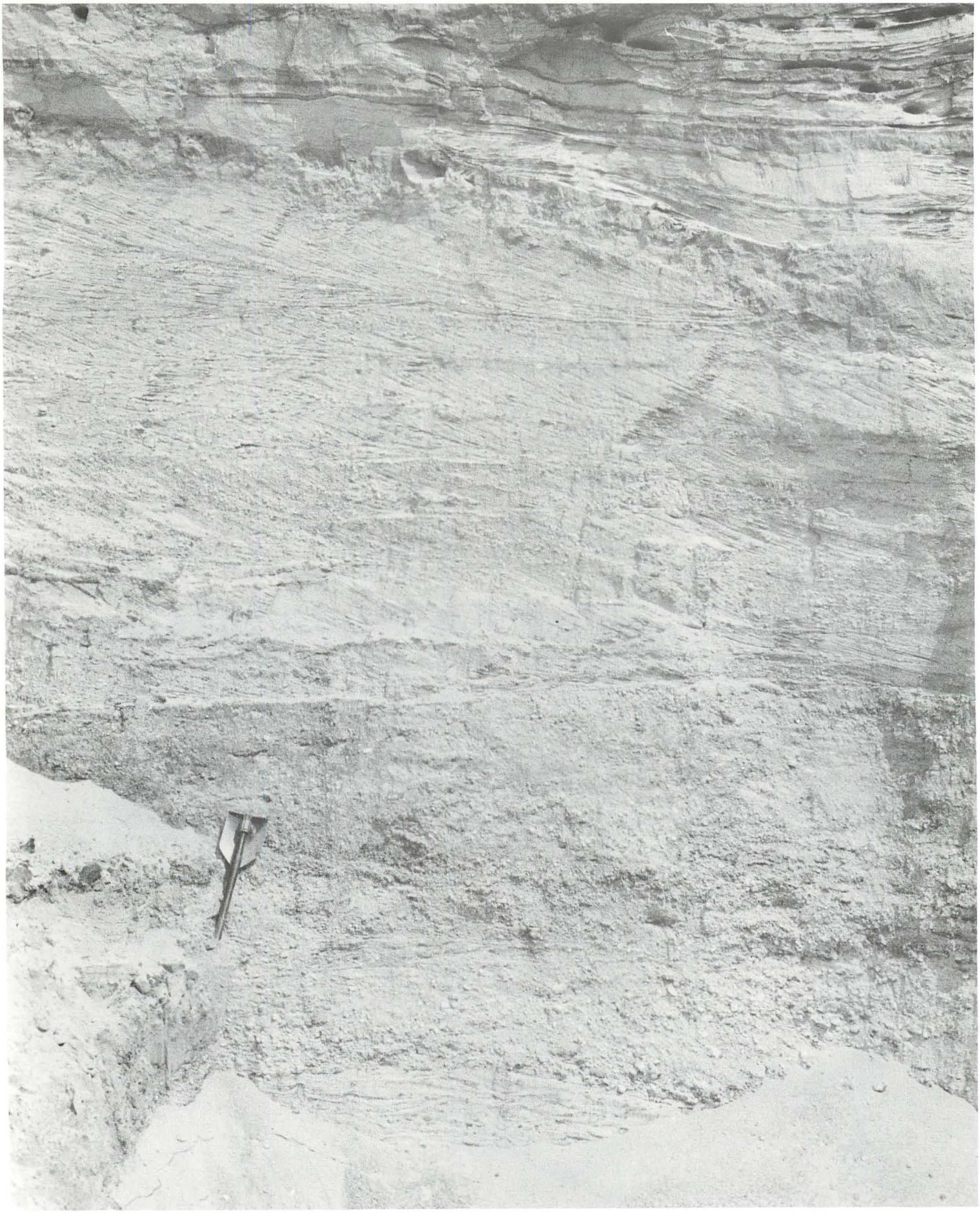


Figure 30. Fining-upward sequence in the Patuxent Formation, Mechanic Valley (Loc. 37), Cecil County, Maryland. Basal gravel resting on scoured surface is succeeded by intermediate unit of cross-bedded pebbly sand. Uppermost unit is flat-bedded fine sand and silt.

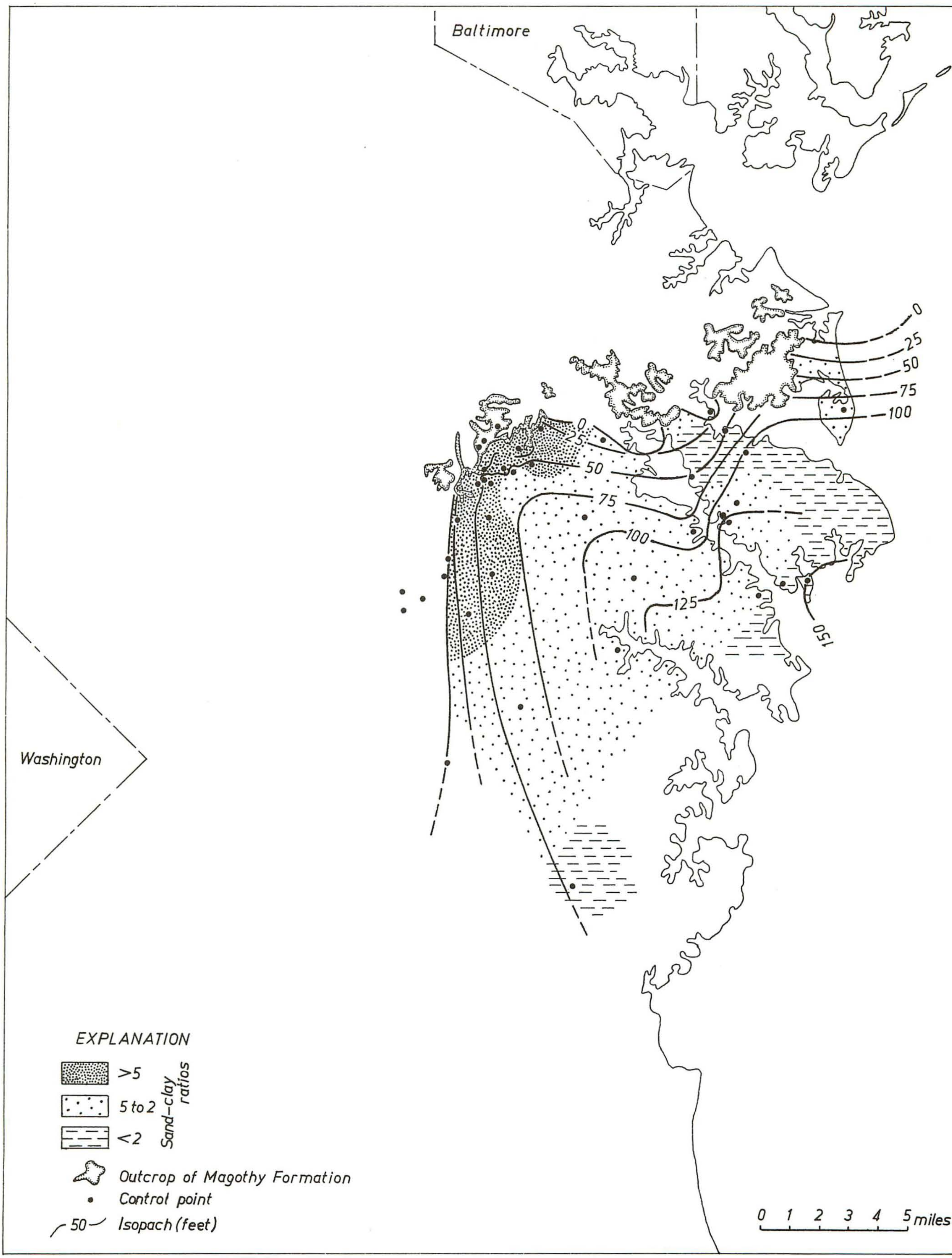


Figure 31. Sand-clay ratio and isopach map of the Magothy Formation in Anne Arundel and Prince Georges Counties, Maryland (sources of data given in Appendix B).

Conspicuous, however, in such clays are discontinuous networks of fractures, many with slickensided surfaces.

White clay – Thin lenses of nearly pure white chalky kaolinite, interbedded with colored clays, are an uncommon but conspicuous lithologic association in the Patapsco-Raritan Formation.

Dark-green to brown clay – Coarser Potomac clastics in Virginia contain interbedded lenses of massive silty clay of a relatively homogeneous olive-green to olive-brown color which are of identical lithology to the clay clasts in the associated sand and gravel. These somber clays are the dominant fine-grained lithology in Virginia; mottled and pale-gray clay, so prevalent in the Potomac Formation of the Maryland-Delaware area, is rare to absent south of the Potomac River.

Pale-gray clay – Thin lenses of pale-gray massive clay are a constant associate of sand-gravel bodies in the Maryland-Delaware Potomac; the ubiquitous clay clasts in the interbedded sand-gravel are lithologically identical to the clay in such lenses.

Magothy Formation

The Magothy Formation exhibits considerably less lithologic complexity than the underlying Potomac; on the other hand, however, lateral lithofacies variation is perhaps more pronounced. The latter is illustrated by a plot of sand-clay ratio and isopach (Fig. 31) constructed from drill-hole data in the Magothy Formation in the western shore of Chesapeake Bay. Within this area, a generalized decrease in sand-gravel abundance is accompanied by increasing sediment thickness from northwest to southeast. These trends are in good accord with the limited cross-bedding data indicating southeastward transport. Thus, the interpretation given to the combined data points to a southeasterly thickening sediment wedge, coarsest in the west proximal to the basin margin and fining down the dip away from the source area.

Magothy lithofacies fall into three broad groupings:

Gravel – Fine to medium quartzose gravel and ferruginous conglomerate, made up of mostly subrounded vein quartz pebbles and interstitial sand, comprise a significant portion of the outcropping Magothy Formation along the western basin margin. The gravel is either cross-bedded or flat-bedded in thin lenticular units interbedded with similarly thin, coarse-grained, commonly ferruginous sands. This coarse phase of the Magothy is poorly exposed, but blocks of ferruginous conglomerate, residual from the Magothy, are conspicuous on low hills and valley slopes between the upper Severn and Patuxent Rivers in Anne Arundel County, Maryland.

Sand – Loosely-bedded, clean white cross-bedded sand is volumetrically the most important lithology in the Magothy within the outcrop belt. The predominance of sharply-angular quartz grains and paucity of interstitial silt-clay lend a sugary aspect to much of this sand. Moreover, the accompanying presence of abundant sand-size lignite particles, particularly in eastern Maryland and Delaware, imparts a salt and pepper appearance to the sand. Sands associated with gravels in the Magothy are prevailingly coarse although fine to medium textures are more abundant in the formation as a whole. To the east and southeast of the gravel-coarse sand facies of the Magothy, an increasing proportion of fine to very-fine-grained laminated or ripple-bedded sand and micaceous silt enters the section.

Table 2. Textural classification of aggregate samples

		POTOMAC FORMATION		MAGOTHY FORMATION
		Patuxent Formation	Patapsco-Raritan Formation	
Gravel		7	–	–
Sandy gravel		17	–	2
Gravelly sand		23	12	–
Sand	Coarse	8	4	3
	Medium	26	29	4
	Fine	8	21	2
Silty sand		–	–	1

Clay – Dark-brown to black, carbonaceous silty clay is typical of the Magothy Formation beyond the coarse basin-margin facies where the little clay present is pale-gray to buff in color. The model occurrence of carbonaceous clay is in relatively homogeneous beds up to 20 feet thick. Dark clay is also common as laminations in close sequence with fine micaceous sand and silt. Lignitized and pyritized wood, siderite, and pyrite or marcasite concretions are common associates in such clays; beds in some instances are crowded with logs up to 2 feet in diameter.

TEXTURE

Introduction

Textural analyses of 170 samples of Cretaceous sands and gravels were plotted as cumulative frequency curves on log probability paper, and statistical measures of median grain size, sorting, and skewness computed according to the method of Inman (1952). The object of developing this data is twofold: (1) determination of the extent of regional and stratigraphic textural variation, and (2) as a contribution to environmental reconstruction.

Median size

The distribution amoung the various textural groupings of the samples analysed[2] is shown in Table 2. As can be readily seen, sands are the most abundant group, making up 84 percent of the total samples. The modal grouping is medium sand. Gravels are important only in the Patuxent Formation where they comprise 27 percent of the samples. The sample distribution reflects a gross fining upward of the Potomac Group; the coarsest clastics are clearly concentrated in the lower portion whereas fine sands comprise a much higher percentage of the total sands in the upper or Patapsco-Raritan portion.

Stratigraphic textural variation may also be considered in terms of median grain size. The latter parameter in the Patuxent Formation exhibits a wide range from very coarse (-5.91ϕ) to very fine (3.47ϕ). In contrast, the range in median diameter within the succeeding Patapsco-Raritan is much smaller (-0.35ϕ to 2.90ϕ) – from coarse to fine sand. The median diameters of the coarsest bed exposed at each sampling point in the two portions of the Potomac Group are graphically plotted in Fig. 32. It is evident that significantly coarser medians are characteristic of Patuxent clastics throughout the area, and further, that the greatest concentration of large values occurs in central Maryland between the Potomac and Susquehanna Rivers.

Variations in median diameter can reflect singly or in combination: (1) differences in the size range of the materials available for transport, (2) variation in current velocity between the source area and the depositional site, and (3) varying distance of transport. As will be subsequently shown, the location and essential composition of the source area, factors controlling (1) and (3), did not change substantially during Potomac time, and thus could not have had major influence on median diameter. Rather, a significant decrease in current velocity through Potomac time is suggested. Similarly, the concentration of relatively coarse diameters within the Patuxent facies of central Maryland probably marks areas of locally higher current velocities.

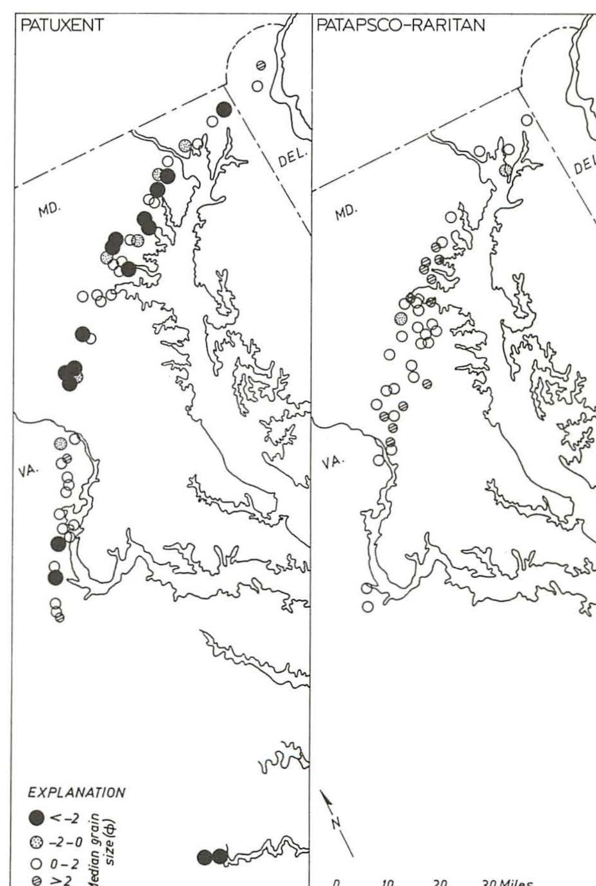


Figure 32. Median grain sizes of coarsest sedimentation units exposed at Potomac Group sampling localities.

2/ See discussion of sampling procedure under Methods.

The distribution of median diameters in the Magothy Formation parallels in a general way that of the Patuxent Formation. The range (-3.03ϕ to 3.89ϕ) is nearly as broad indicating variable current velocities, but the available samples are too few to suggest any meaningful regional pattern. Nevertheless, it should be noted that maximum median diameters at sampling points west of Chesapeake Bay show a general increase from east to west, a trend in good agreement the sand-clay ratio and thickness data presented earlier.

Sorting coefficient

The sorting coefficient ($\sigma\phi$) approximates the standard deviation and constitutes a measure of the size spread of the sample, such that with perfect sorting, $\sigma\phi$ equals zero. Sorting is essentially a measure of the competency of the transporting medium. In the Patuxent Formation, $\sigma\phi$ ranges from .41 (well-sorted) to 4.71 (very poorly sorted); in comparison, Patapsco-Raritan sands are somewhat better sorted, the spread being .31 to 3.40. Values in the Magothy Formation range from .66 to 2.60. Although theoretically independent of median diameter, sorting has in practice been shown to be correlated with size by several workers, e.g. Inman (1949, 1952) and Griffiths (1951). On the other hand, Plumley (1948) found no such relationship in the Black Hills terrace gravels. A plot (Fig. 33) of median size versus sorting for all of the Cretaceous samples analyzed (median size 3.89 to -5.91) exhibits a very general trend toward poorer sorting with increasing median size, particularly so in the case of median size greater than 1ϕ. However, the data do show considerable scatter. The best sorting is apparently achieved in sands with median diameters of 1.5 to 2.5ϕ. The present data generally support Inman's (1952) findings that fine sands (2 to 3ϕ) tend to show the best sorting whereas sediments coarser or finer are progressively less well-sorted, although in this case samples with median less than 3ϕ are too few to establish a clear trend.

Skewness

Skewness, as a measure of the asymmetry of the size frequency distribution, is like sorting theoretically independent of the other curve parameters. In fact, it is neither independent of sorting nor of median size. In practice, the best sorted samples are the least skewed. Moreover, in the case of bimodal size distributions, skewness as well as median size is a measure of the relative magnitude of the two modes (Plumley, 1948). In Fig. 34, a plot of skewness versus percent silt-clay in each sample, practically all Patapsco-Raritan and most Patuxent bimodal samples exhibit negative skewness, reflecting a primary mode in the sand fraction and a tail of gravel. However, a significant number of Patuxent samples have a primary gravel mode and are consequently positively skewed. The plots also show a general correlation between the magnitude of positive skewness and the percent silt-clay in unimodal samples, or simply that large values of positive skewness are commonly associated with a higher than normal percentage of

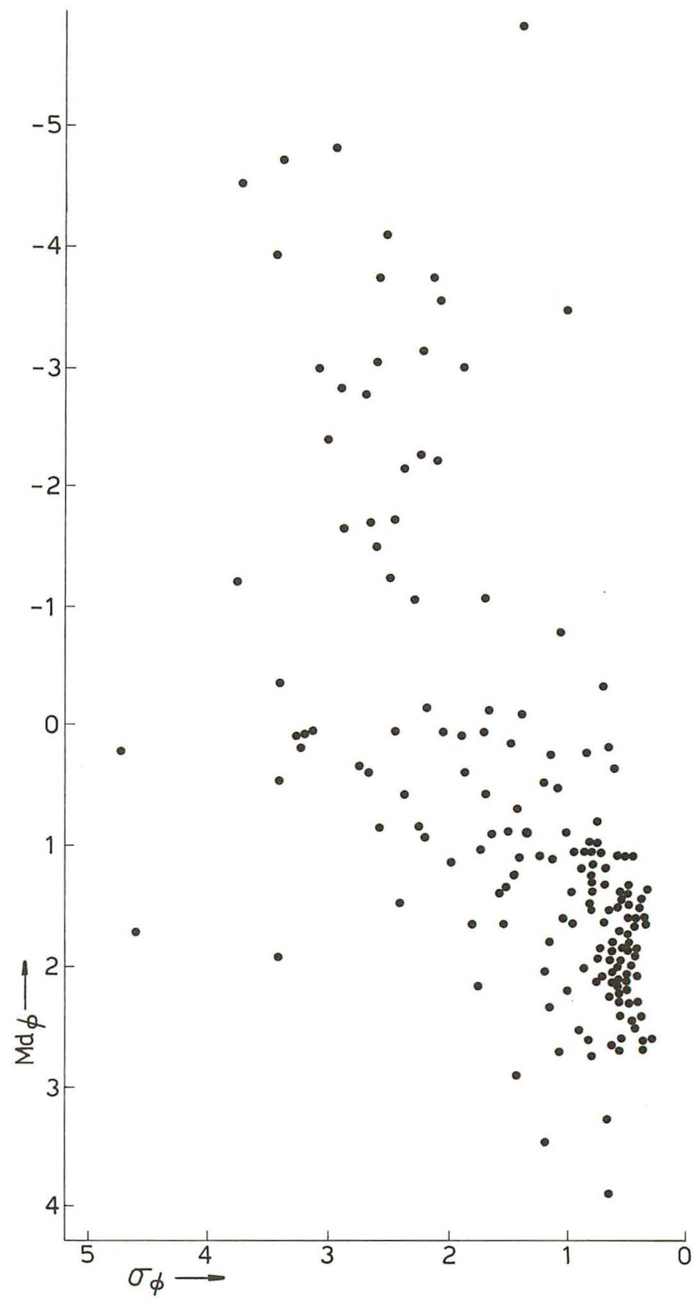


Figure 33. Plot of median size versus sorting coefficient for all Potomac and Magothy samples.

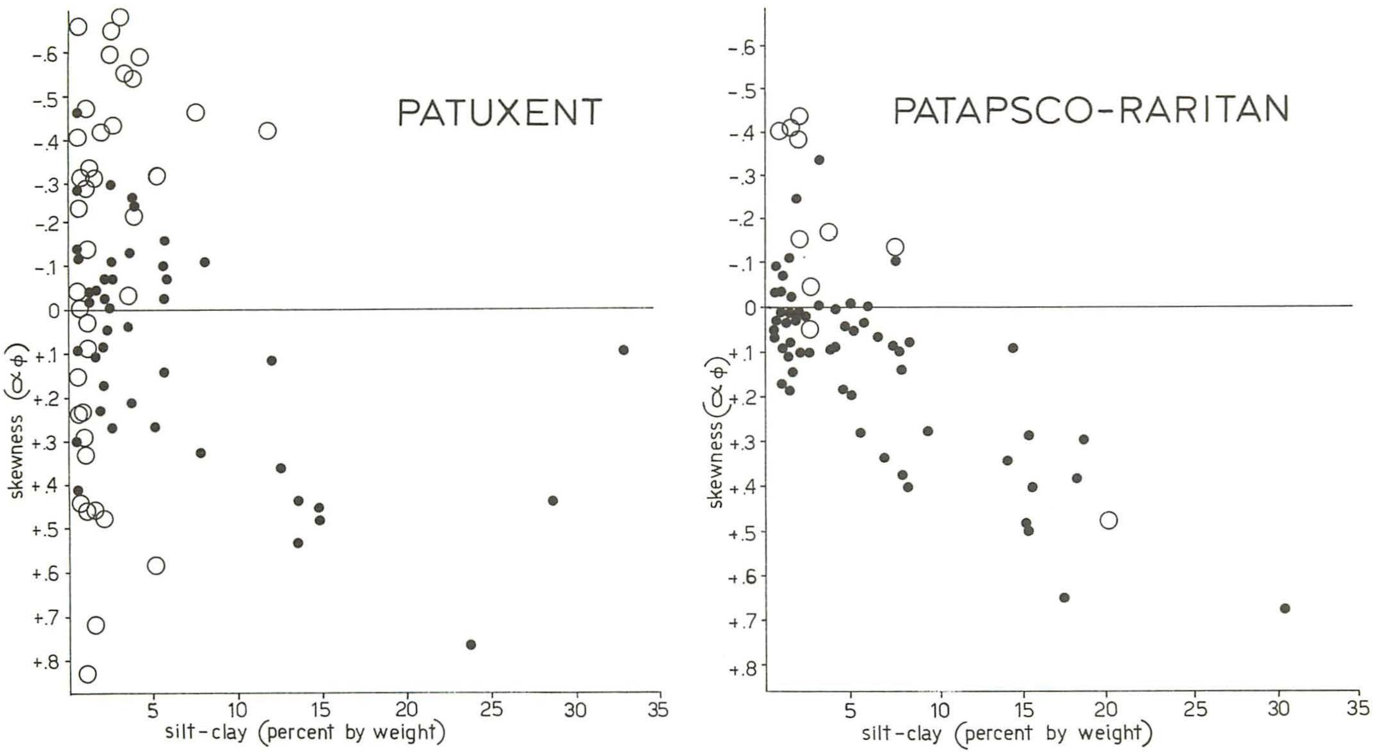


Figure 34. Plots of skewness versus percent silt-clay for Patuxent and Patapsco-Raritan samples (open circles are bimodal samples).

fines. On the other hand, Patuxent unimodal samples with a normal percentage of fines (0 to 10%) exhibit a greater spread of skewness values than similar Patapsco-Raritan samples, a relationship also noted with respect to sorting coefficients. The greater Patuxent spread reflects the abundance of sands with gravel tails (pebbly sands) in the case of large negative skewness values, or in the case of large positive values unimodal gravels with sand tails.

Bimodal distributions

Slightly more than a third of the size analyses are bimodal, and of these three-quarters are Patuxent samples. The collective positions of the primary and secondary modes are plotted in the histogram of Figure 35; most bimodal sediments with a gravel and a sand mode are deficient in materials of the 1 to 4 mm size range, and these analyses are no exception. Among the various explanations offered for this deficiency, that of Sundborg (1956) is perhaps the best. Sundborg noted that particles in the size range 1 to 6 mm are hydrodynamically unstable and are the materials most easily dislodged by the current and entrained when bed load transport commences. Thus they are prevented from coming to permanent rest until reduced by abrasion to a size of 1-2 mm or less.

A second troublesome aspect of bimodal distributions is the question of time of deposition of the gravel and sand fractions. Udden (1914) and Krumbein (1940) among others have advocated the simultaneous deposition of traction and suspension loads as the consequence of an abrupt velocity decrease. Another point of view, however, as expressed by Fraser (1935), contends that such a

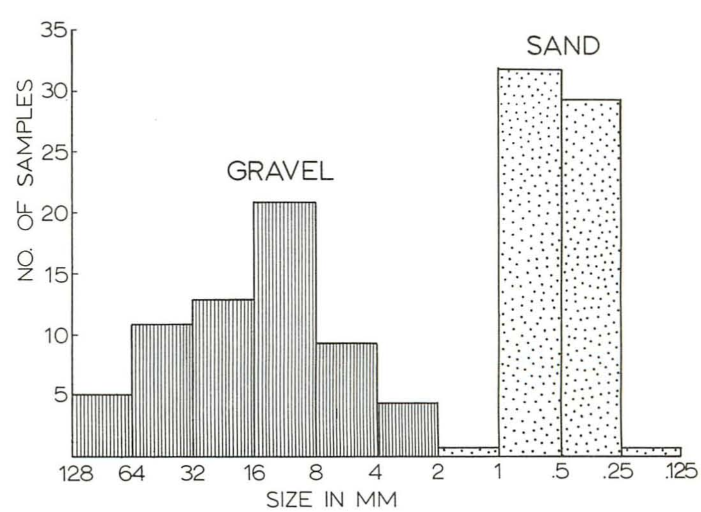


Figure 35. Histogram showing modal class position for sand and gravel fractions of 63 Potomac and Magothy bimodal samples.

mechanism is improbable considering the repeated violent current velocity changes demanded, and that later infiltration of fines into gravels is a more plausible explanation. Plumley (1948) examined the problem from another standpoint. He calculated that for the loosest packing of identical spheres, the weight percent of much smaller spheres of the same density filling the interstices would be 32 percent, and similarly 22 percent for the tightest packing of the larger spheres. Plumley reasoned then that the 20 percent average weight percent of sand in bimodal Black Hills terrace gravels argued for later infiltration of fines. Potter (1955) and Schlee (1956), however, applied the same test to Quaternary gravels in the Mississippi Valley and in Maryland respectively and concluded that simultaneous deposition of sand and gravel was in fact the case. The average percent of interstitial sand in these cases ranged from 29 to 32.

Bimodal Cretaceous gravels were examined from this point of view, considering only analyses of single sedimentation units with the primary mode in the gravel fraction. The average weight percent of the sand fraction in these samples is 29 percent. It would seem then that both the sand and gravel fractions of the Cretaceous samples were simultaneously deposited, almost certainly so in the case of nearly half of the gravels in which the sand fraction exceeds 35 percent.

Interpretation

The close dependence of median size and skewness on the relative magnitudes of the primary and secondary modes of bimodal sediments limits the value of these parameters in stratigraphic comparison, particularly so in that the bimodal samples are concentrated in the Patuxent Formation. A more useful comparison is that of median size, sorting, and skewness of *sands* only; these data are summarized in Figure 36. The average median size of Potomac and Magothy sands falls between 1 and 2ϕ – medium sand. Further, Patuxent Formation sands tend to be somewhat coarser than those of the Patapsco-Raritan. Average sorting values are closely similar for all of the sands although the spread is large, particularly within the Potomac Group. Average values for Patuxent, Patapsco-Raritan, and Magothy sands are .86, .81, .86 respectively – moderately sorted; the modal group in the case of each of these units is .50 to .80 – moderately well-sorted sand. Skewness does not appear to be significantly different among the three. However, within the Potomac, the prevalence of sands in the Patuxent with tails of coarse material is responsible for the slightly negative modal Patuxent skewness as compared with the positive Patapsco-Raritan mode.

Friedman (1962) proposed after examining large numbers of recent sands from known environments that sorting and skewness are environmentally sensitive parameters. His data indicate that most natural sands do not exhibit normal distributions but rather are skewed. Moreover, the great majority of river sands are positively skewed while beach sands are mostly negatively skewed. With respect to sorting, most river sands possess standard deviations of .50 to .80, many fall into the interval .80 to 1.40, and some are well-sorted, ranging down to .35. Because Inman's sorting coefficient ($\sigma\phi$) approximates the standard deviation, sorting and skewness characteristics of Cretaceous sands can be examined in the light of Friedman's data. The distribution of sorting values (Fig. 36) agrees well with the values for river sands; 75 percent of the samples fall within his empirically determined limits for such sands. Moreover, the majority of the Cretaceous sands exhibit positive skewness as do most of Friedman's samples.

The positive skewness of fluvial sands may well be a function of unidirectional flow in the sense that the upper size limit of materials transported by rivers is governed by the competency of the currents, but no such limit is imposed on the lower limit of the fines (Friedman, 1962). Consequently, a coarse tail is commonly lacking while a tail of fines is present, the result being positive skewness. Beach sands, on the other hand, are subjected to opposing forces in the form of waves and backswash which operating repeatedly winnow out the fines, thus eliminating the fine tail. Negative skewness is the result. However, at least one limitation on the utility of skewness as an environmental parameter is imposed by the common postdepositional introduction of interstitial fines, e.g. clays and iron oxides, the net effect of which is to shift skewness toward the positive end. Friedman found that the majority of ancient sandstones were, regardless of presumed depositional environment, positively skewed. Postdepositional introduction of fines was adjusted the culprit. This situation imposes obvious limitations on the value of skewness and indirectly sorting in environmental reconstruction. Indeed, it is clear from the limited number of indurated Cretaceous beds examined in thin section that authigenic clays have grown interstitially in many cases, and further that additional fines represent disintegrated rock fragments and crushed intraformational clay

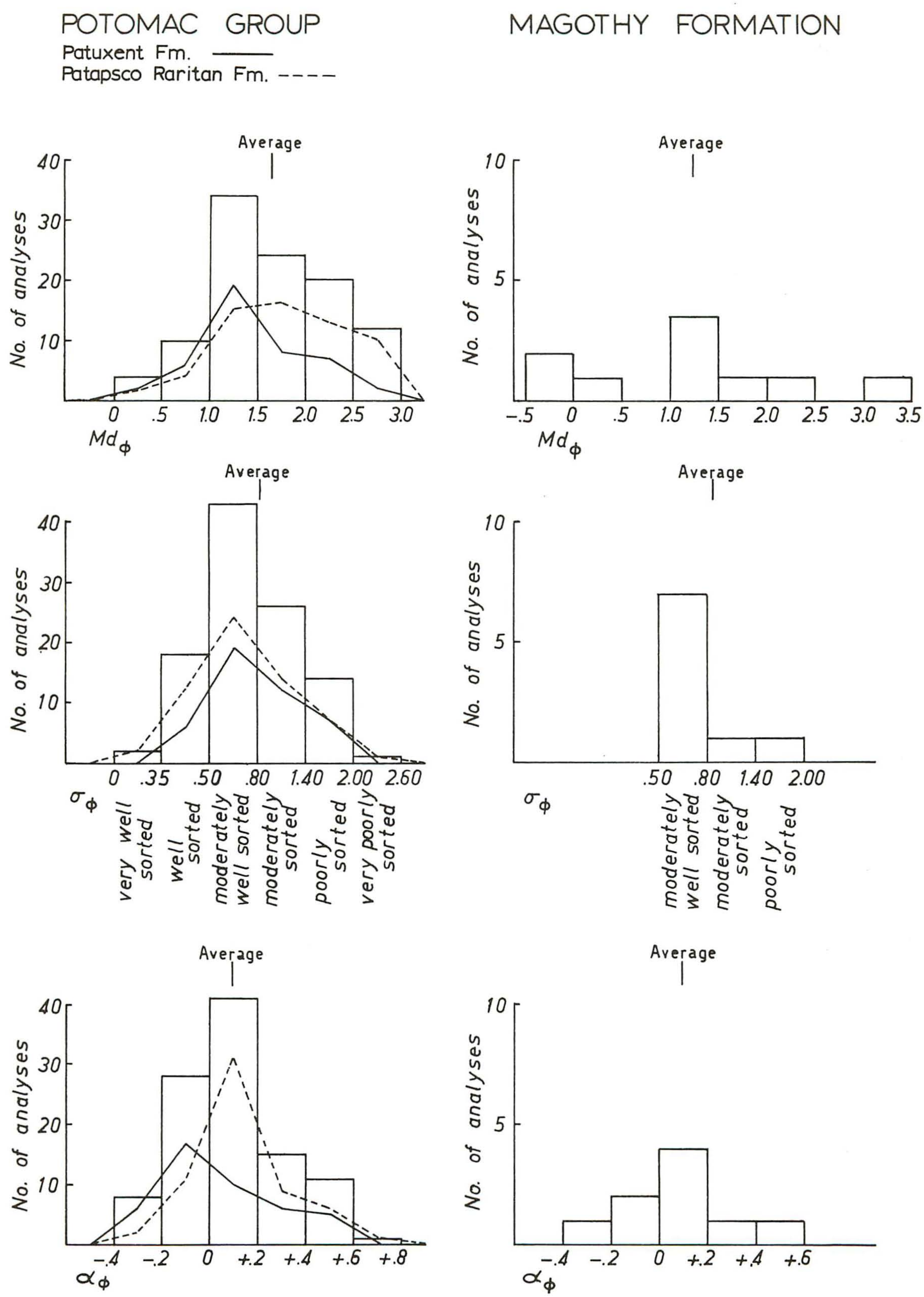


Figure 36. Histograms comparing median size, sorting, and skewness of sands in the Potomac Group and Magothy Formation.

pellets. It seems a fair conclusion then that the positive skewness exhibited by most of the samples at hand, although doubtless due in largest part to a primary tail of fines, has been augmented to some degree by secondary fines.

Size Frequency Curve Classification

Thus far, texture has been examined in terms of statistical parameters derived from critical portions of the size frequency curve. An alternative approach to interpreting grain size is examination of the shape of the curve itself. Doeglas (1946) proposed that the shape of the size frequency curve is a function of mixing of a limited number of principal grain size types, and that groups of such curves are characteristic of specific environments. This approach was adopted and expanded by Van Andel and Postma (1954) for textural studies of recent sediments in the Gulf of Paria. They were able to distinguish three principal sand types - designated *F*, *M*, and *B* - based on curve shape, and two clay types - *C* and *S*. Zone diagrams, defined by the entire set of grain size curves of each type, are reproduced for the *F* and *M* sands in Figure 37. Included as well is the zone representing the *F* + *S* sands - mixtures of *F* sands and *S* clays. The third group of sands – *B* – comprises unsorted coarse materials of very limited distribution adjacent to rock outcrops.

Figure 37 also depicts analogous zone diagrams constructed from composite plots of size frequency curves of 45 Patuxent sands and 60 Patapsco-Raritan sands. The zone of concentration of the majority of the curves in each case is indicated by close hatchuring. It can be seen through comparison that Patuxent sands resemble most closely the *F* type of Van Andel and Postma. Grain size curves of Patapsco-Raritan sands occupy a broader zone, and while largely similar to Patuxent sands or *F* types, are apparently in part intermediate between *F* and *F* + *S* sands. Magothy sands are mostly *F* types with some intermediates;

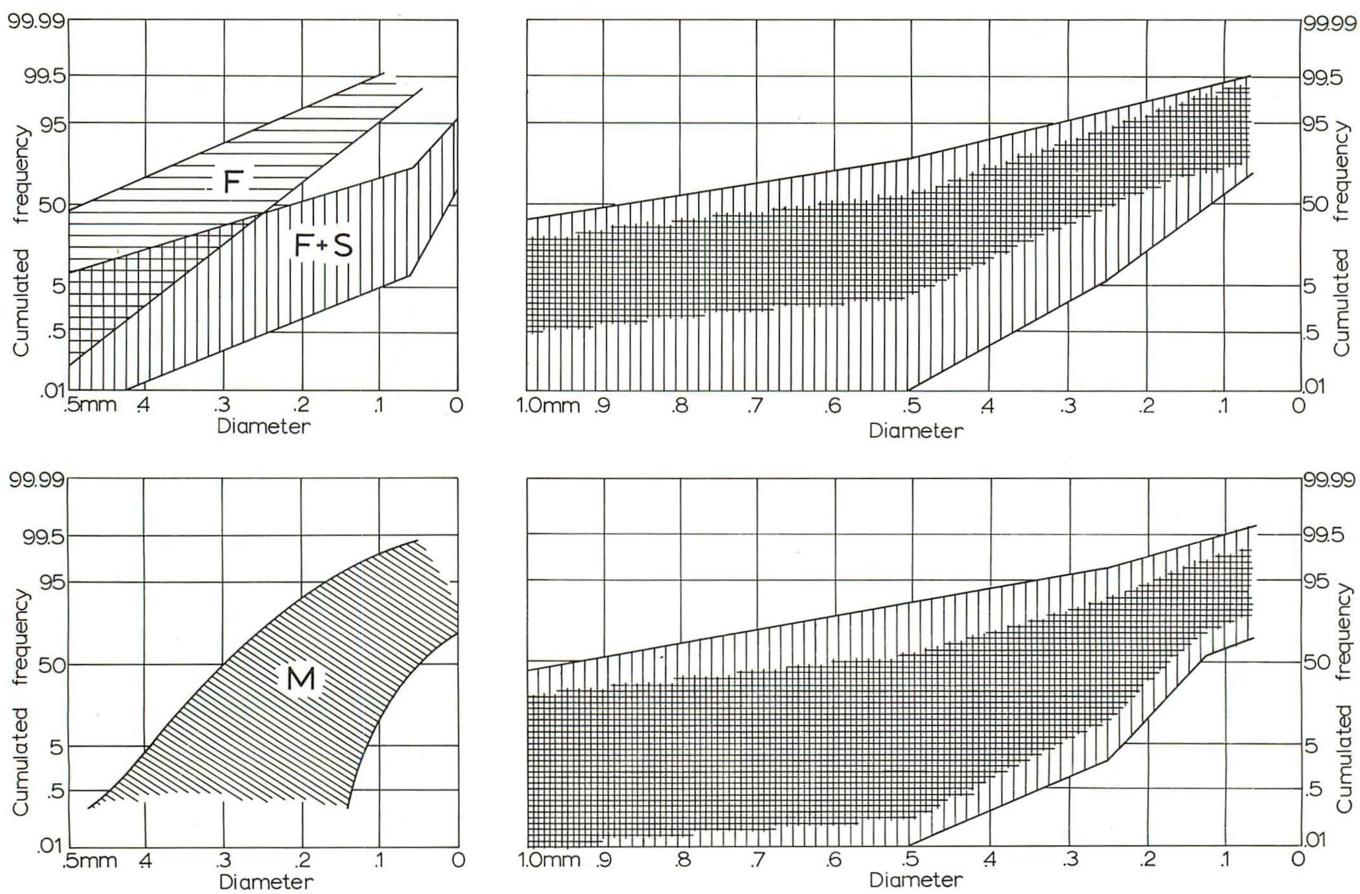


Figure 37. Zone diagrams showing sand types in recent sediments of the Gulf of Paria (modified from Van Andel and Postma, 1954) and in the Potomac Group. Upper left: *F* and *F+S* types, Gulf of Paria; Lower left: *M* type, Gulf of Paria; Upper right: Patuxent Formation sands; Lower right: Patapsco-Raritan Formation sands (darker shading in Potomac Group zones shows predominant curve type).

however, too few samples are available to draw positive conclusions. In the Gulf of Paria area, *F* sands are characteristic of the Upper Orinoco delta region where a normal river regime predominates. *S* clays occur in the lower delta and in adjacent estuaries, and *F* + *S* mixtures are found in environments intermediate between the upper and lower delta. *M* type sands, included for contrast, are beach sands within the wave zone. The similarity between the shapes of size frequency curves of Patuxent facies sands and the *F* sand type of Van Andel and Postma suggests, then, the prevalence of a normal river regime above tidal influence during Patuxent time. Patapsco - Raritan grain size curves are, for the most part, also *F* types, and indicate the persistance of essentially similar environments. However, the occurrence of possible *F* + *S* mixtures suggests deposition in part in environments nearer to the shoreline in which mixed fluvial sands and clays of the lower deltaic type were introduced.

GRAVELS

Introduction

Roundness and lithology of pebbles from three size grades (8-16, 32-64, and 64-128 mm) were studied for all sampling localities at which gravel-sized materials were exposed. Pebble counts to a maximum of 50 per size grade were tabulated for 42 sampling localities. Gravels are abundant only in the Patuxent Formation; consequently, a disproportionate number of samples are from this unit.

Composition

Vein quartz, comprising 79 percent of the pebbles examined, is by far the most abundant pebble lithology in the Cretaceous gravels. Quartz sandstone and metaquartzite make up 17 percent of the pebbles and include sandstones (clearly visible clastic grains, cross-bedding, or lamination) and metamorphic quartzites (interlocking elongate grains) as well as intermediate types. Lithologies other than vein quartz, sandstone, and metaquartzite are quantitatively unimportant. White to dark-gray chert, generally with a chalky weathered rind, makes up less than 1 percent of the pebbles. Fragments of igneous and metamorphic rocks (other than metaquartzite) are decidedly uncommon, and further, are restricted to the Patuxent Formation. With few exceptions, these are thoroughly weathered and readily disintegrate upon removal from the outcrop. The weathered character of most of these pebbles makes certain identification of rock type difficult at best;

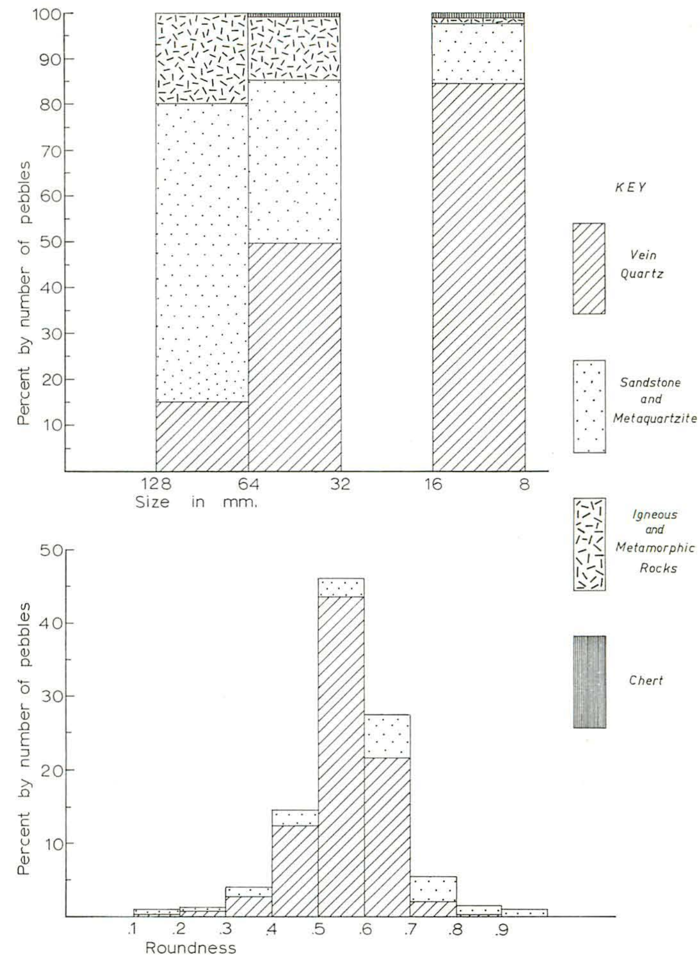


Figure 38. Pebble roundness and lithology in Cretaceous gravels. Top: distribution of lithologies by size grade; Bottom: roundness distribution among vein quartz and sandstone-metaquartzite pebbles.

however, a crude classification of lithologies discloses that quartzo-feldspathic gneissic or granitic rock is the most abundant grouping at 47 percent of the lithic pebbles. The remainder include a variety of rock types such as metarhyolite and other indeterminate metavolcanics, phyllite, mica schist, and several fine-grained quartz-clay-mica lithologies which are probably low-grade metamorphic rocks.

Roundness

Although both highly angular and well-rounded pebbles do occur in the Cretaceous gravels at hand, the bulk of the vein quartz (78 percent) is subrounded and falls into the range .5 to .6 on the Krumbein scale. On the other hand, sandstone-metaquartzite pebbles show better rounding (Fig. 38) – more than 50 percent have values of .6 or higher. Moreover, sandstone pebbles are generally better rounded (average .68) than metaquartzite in the same size grade (average .56). The small percentages of chert and lithic pebbles are mostly subrounded, the latter slightly better rounded than vein quartz.

The greater degree of rounding of sandstone-metaquartzite and lithic pebbles is in part a consequence of concentration in the coarser size grades. Generally speaking, larger gravel sizes are better rounded than smaller (Pettijohn, 1957). However, the greater sandstone rounding as contrasted with vein quartz and metaquartzite in the same size grade may be significant. Schlee's (1956) explanation of a similar phenomenon in the Brandywine gravels of southern Maryland is that quartzite may abrade more rapidly than vein quartz. While this may be so, it does not explain the greater sandstone rounding as compared with both vein quartz and metaquartzite. Rather, the possibility should be considered that the better sandstone rounding was acquired through longer distance of travel. The nearest sandstone source ledges are about 25 miles distant to the west from the present limit of Potomac outcrop; these are the Weverton and Antietam sandstones. Pebbles of cross-bedded hard bluish sandstone closely resembling the Weverton are not rare in Potomac gravels. Other possible sandstone sources are the Tuscarora and Oriskany sandstones, 60 miles distant, and the Pocono, outcropping 85 miles to the west. In contrast, major sources of metaquartzite, e.g. Setters, Chickies, Wissahickon, are concentrated in the metamorphic rocks of the nearby Piedmont region, the latter spanning much of the area between the site of deposition and the nearest sandstone ledges. The greater sandstone roundness may thus be a function of distance traveled rather than a consequence of lesser durability.

Size

The proportions of the various lithologies among the size grades examined vary systematically (Fig. 38). Vein quartz, the dominant rock type in the finest grade (84%), declines to 15 percent of the coarsest grade whereas the proportions of sandstone-metaquartzite increase sympathetically from 13 percent in the finest to 65 percent in the coarsest.

The largest clasts seen at any given Potomac exposure were almost invariably sandstone. Sandstone boulders up to 12 inches in long diameter are not uncommon, and Fontaine (1896) reports 24 inch sandstone clasts as well as lithic boulders up to 18 inches in Potomac outcrops in Virginia. The concentration of sandstone and metaquartzite in the coarser size grades is a general phenomenon in gravels and has been noted, for example, by Schlee (1956) and Jordan (1964). In the case of the Potomac Group, three possible explanations can be suggested: (1) vein quartz abrades more rapidly than sandstone or metaquartzite and is rapidly eliminated from the coarser grades, (2) vein quartz pebbles are farther traveled than sandstone or metaquartzite and have thus been subjected to more prolonged abrasion with attendant greater size reduction, and (3) sandstone and metaquartzite are produced in fragments of larger initial size than vein quartz at the source ledges. The first explanation fails for lack of evidence to suggest that vein quartz is in any way less durable than sandstone or metaquartzite; in fact, the converse might be expected in view of the particulate nature of the latter two rocks. Indeed Wentworth (1922) determined experimentally that vein quartz is 3 times more durable than sedimentary quartzite. On the other hand, all provenance indicators imply that vein quartz in the Cretaceous units was derived from source rocks nearer the depositional site than the probable source ledges of the sandstone clasts. It follows then that any valid explanation must involve initial size differences. However, direct observations of such differences at modern source ledges are lacking.

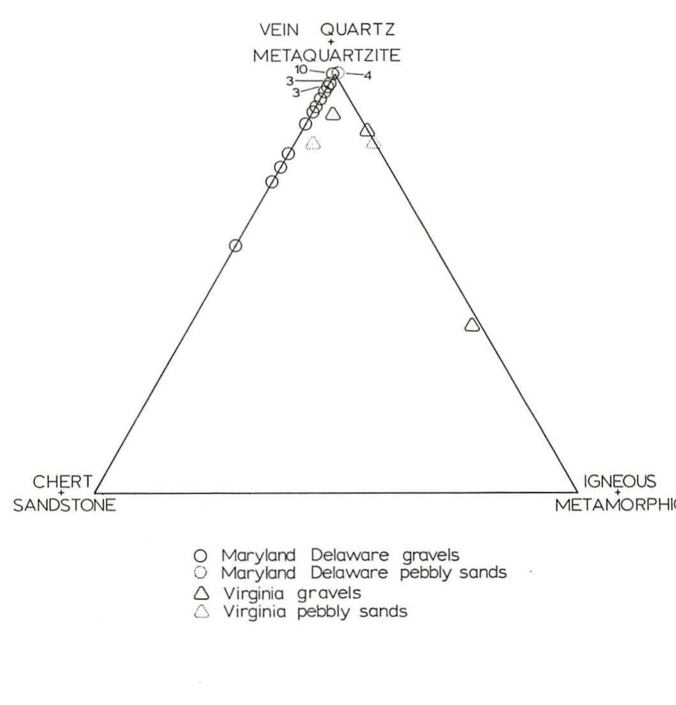


Figure 39. Triangular diagram showing geographic variation in the composition of gravels in the Potomac Group (numbers indicate number of samples if more than one).

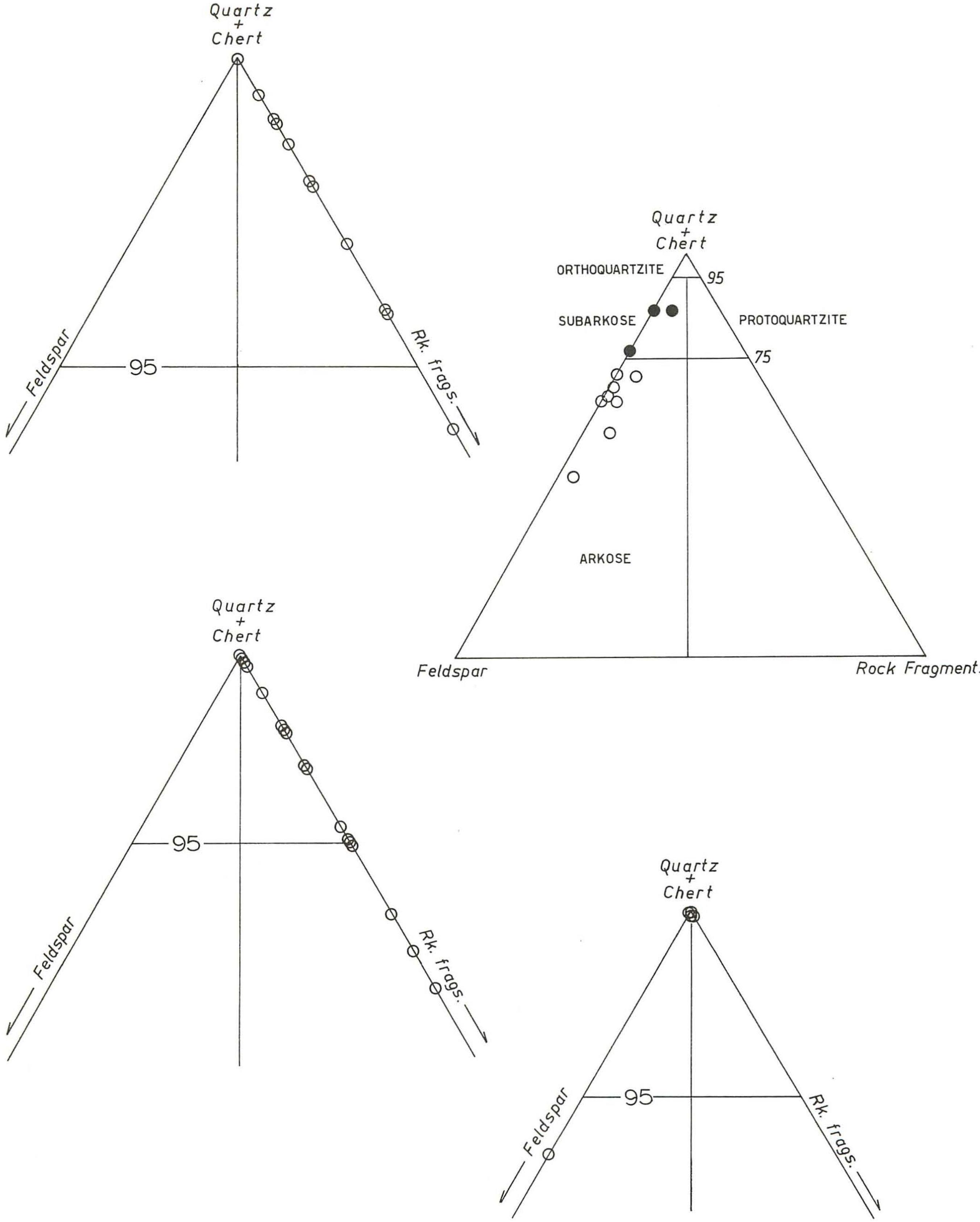


Figure 40. Petrographic classification of Potomac and Magothy sands. Upper left: Patuxent Formation of Maryland-Delaware; Upper right: Potomac Group of Virginia (open circles — Patuxent Formation, closed circles — Patapsco Formation); Lower left: Patapsco-Raritan Formation of Maryland-Delaware; Lower right: Magothy Formation.

Spatial variations

Lithic pebbles in the Potomac Group are virtually restricted to Virginia with the exception of rare occurrences in the Patuxent Formation of the Maryland-Delaware area. These latter occurrences, moreover, are restricted to the lowermost few feet of sediment and comprise lithic clasts which are essentially within a stones throw of the source ledges from whence they came. In Virginia, lithic pebbles make up a significant proportion of gravels relatively high in the section (Fig. 39). It is difficult to envision transport and abrasion over any appreciable distance of saprolite clasts so thoroughly decomposed as the ones observed. It is far more likely that these lithic pebbles were deposited as unaltered or slightly weathered clasts and saprolitized in place by groundwater.

The pebble counts also demonstrate the lesser importance of sandstone in the source area of the Virginia Potomac than farther north. Sandstone makes up only 5 percent of the two coarser size grades in Virginia as contrasted with 34 percent of the same grades in Maryland-Delaware gravels.

SANDS

Light mineral composition

The light mineral composition of the 1-2ϕ size grade was determined in 38 well-spaced samples from the Potomac Group and 5 from the Magothy. Standard methods of preparation and point-counting were employed to tabulate 150 grains per slide and the results summarized in Table 3.

Quartz, predictably the most abundant constituent, ranges from 35 to 100 percent of individual samples and averages 86 percent of all of the samples. Most of the grains are milky white with abundant inclusions of zircon, tourmaline, and rutile in tiny crystals, or more commonly opaque amorphous materials. Glassy transparent grains are much subordinate. A third quartz type, absent from most of the sands but present in the remainder in amounts of 1 to 10 percent of the total quartz, is translucent blue-gray to pale-violet.

Quartz grains were grouped as 3 varietal types: (1) unstrained (all parts of grain extinguishing simultaneously), (2) strained (marked undulatory extinction), and (3) polycrystalline (grains with 2 or more crystal units of differing optical orientation). The order of abundance of these varieties in the Cretaceous sands is unstrained (38-88 percent), strained (7-44 percent), and polycrystalline (1-30 percent); varietal quartz is summarized in Table 3.

Quartz was also categorized as angular, subangular, or round by visual comparison with the diagrams of Rittenhouse (1948); these data are also tabulated in Table 3 as grain angularity. The sands studied are predominantly angular (70 to 100 percent angularity) with most of the grains exhibiting low sphericity.

The abundance of feldspar ranges from 1 percent or less in the majority of sands to as much as 48 percent. Microcline is by far the most abundant species, averaging 72 percent of the total feldspar. The remainder is untwinned alkali feldspar. Nearly all of the feldspar is highly weathered, appearing chalky and opaque under reflected light.

Angular to subrounded white to dark-gray chert occurs in very small quantities in most of the samples, the amounts ranging from nil to 6 percent. Muscovite, the only mica seen, is absent from about half of the samples but comprises as much as 9 percent of others. The deficiency of micas in so many of the sands is doubtless a function of sorting rather than source rocks. Sorby (1908) first demonstrated that the hydraulic behavior of micas in contrast with quartz commonly results in the segregation of the two minerals in spite of closely similar grain size, this a consequence of widely-differing settling velocities. Thus micas tend to accumulate separately in thin layers or in fine sand or silt beds. Thin laminae containing mostly muscovite were seen at several Potomac outcrops.

Angular to subangular rock fragments[3] are a subordinate component (0-8.6 percent) of Potomac Group sands but are lacking in the Magothy Formation. Certain identification of many rock fragments was not really possible due to their highly-weathered state; however, those identified include phyllite, granite or gneiss, and ferruginous siltstone.

Glauconite, as pale-green, smooth, lobate or botryoidal aggregates, is decidedly rare in the Potomac and Magothy and in fact has been counted in other than trace amounts in one Potomac sand only - an atypical marine lense in Virginia.

3/ All of the slides of Potomac Group sands from the Virginia area contain abundant, sand-sized, variably coherent clay aggregates. Thin sections of lithified equivalents reveal that whereas some of the aggregates are highly-weathered rock fragments, most are either clay clasts of probable intraformational origin or purely authigenic aggregates of kaolinite. Those grains recognizable with certainty as rock fragments were so classified; the remainder were excluded from the light mineral counts because their abundance in the size fraction examined was more a function of durability during sieving than absolute abundance in that size fraction.

Table 3. Light mineral composition, varietal quartz, and quartz angularity

Unit	Sample No.	Light Minerals (percent) Quartz	Feldspar	Chert	Mica	Rock fragments	Silt-Clay[1]	Varietal Quartz Unstrained	Strained	Polycrystalline	Quartz angularity
POTOMAC GROUP, Patuxent Formation	20	95	–	2	2	1	2	71	24	5	86
	24	89	–	5	1	5	5	69	23	8	78
	38	92	Tr	–	4	5	Tr	65	27	8	98
	46	90	Tr	2	1	7	4	65	30	5	86
	53	93	Tr	4	1	1	2	56	34	10	93
	56	96	–	3	–	1	2	69	22	9	70
	59	98	–	1	1	–	1	61	23	16	99
	82	92	Tr	3	3	2	1	79	16	5	88
	90	95	–	5	–	1	1	46	44	10	91
	98	93	–	2	3	2	2	60	25	15	96
	105	91	–	5	–	3	8	58	34	8	98
	61	56	37	2	–	5	4	48	35	17	96
	62	65	31	–	–	3	4	63	17	20	91
	64	71	25	–	–	5	1	68	15	17	96
	73	45	48	1	1	5	2	68	16	16	93
	74	65	35	–	–	1	3	38	32	30	100
	80	62	32	2	–	4	12	54	29	17	96
	112	66	28	3	1	3	15	56	19	25	99
POTOMAC GROUP, Patapsco-Raritan Formation	13	95	–	3	–	1	1	74	20	6	92
	14	90	–	6	–	5	30	69	25	6	90
	18	96	–	2	–	2	1	68	24	8	91
	28	94	–	3	Tr	2	Tr	72	21	7	91
	33	91	–	4	1	4	2	81	18	1	95
	44	92	–	5	–	3	1	80	13	7	95
	49	91	–	1	–	8	7	66	28	6	93
	50	91	–	1	–	7	1	72	21	7	82
	58	100	–	–	–	–	7	77	22	1	99
	86	94	–	1	–	5	4	62	26	12	89
	99	91	–	3	–	5	1	62	31	7	93
	104	88	–	3	–	9	18	80	9	11	75
	66	69	22	3	3	4	7	46	28	26	92
	76	56	37	–	2	6	3	40	30	30	100
	79[2]	36	8	2	–	3	7	63	25	12	92
	7	99	–	1	–	–	1	82	16	2	83
	31	99	–	1	–	1	1	75	22	3	78
	43	99	–	1	–	–	3	86	13	1	84
	47	93	–	4	–	3	1	88	7	5	80
	106	95	–	3	–	2	2	80	13	7	88
MAGOTHY FM.	8	100	–	–	–	–	2	64	31	5	100
	29	100	–	–	–	–	1	82	17	1	100
	42	100	–	–	–	–	1	87	12	1	88
	107	100	–	–	–	–	Tr	83	15	2	92

1. Percent by weight; all others number percent
2. 51 percent glauconite

Silt and clay, summed as matrix, were determined by sieving and are expressed as weight percent. Matrix amounts range widely (.3-30.3 percent) and average 4.4 percent for all samples.

Sand classification

The sandstone classification proposed by Pettijohn (1957) is convenient for describing the composition of Potomac and Magothy sands. Sand compositions have been plotted on ternary diagrams (Fig. 40) with end members quartz plus chert, feldspar, and rock fragments, and compositional fields delineated for the relevant sandstone groups.

Potomac sands north of the Potomac River are chiefly orthoquartzites and less commonly protoquartzites, in contrast with arkoses and subarkoses in Virginia. Magothy sands are wholly orthoquartzitic.

Heavy mineral composition

Heavy minerals were separated in bromoform and mounted for each of 61 well-spaced Potomac sands and 6 from the Magothy. Two-hundred non-opaque grains were identified and tabulated in each of 2 separate grades (2-3 and 3-4ϕ) for each sample, and further, zircon, tourmaline, and staurolite were classified as angular, subangular, or

Table 4. Descriptions of important heavy mineral species in the Potomac Group and Magothy Formation

ZIRCON:	colorless to pale-pink included grains predominant; mauve, pale-brown, and pale-yellow varieties less common; most abundant are sharply euhedral to slightly rounded grains but a variable percentage of rounded to well-rounded pitted grains in each sample.
TOURMALINE:	very pale-brown to deep pinkish-brown grains, very dark to nearly opaque at maximum absorption and deep grayish-green in basal section, vastly predominant; euhedral, angular, or subangular grains most common, subrounded to well-rounded grains much less so; minor subangular to angular blue grains.
STAUROLITE:	pale-yellow to deep orange-brown, much included grains; large angular unaltered equant grains most abundant; much less common are smaller dark altered grains with ragged margins; rounded to well-rounded grains in minor proportions.
KYANITE:	colorless to very pale-blue, most grains with inclusions; sharply angular to subangular rectilinear bladed grains most common, rounded grains rare.
SILLIMANITE:	colorless; commonly angular to subangular elongate fragments with distinctly fibrous aspect.
RUTILE:	deep red, reddish-brown, and yellow; predominantly angular to subangular, rarely rounded to well-rounded.
CHLORITOID:	slate-blue to green, pleochroic; mostly angular platy fragments varying from fresh to highly-altered with ragged margins.
BROOKITE:	yellow, less commonly orange-brown; most grains display prominent striations and anomalous blue interference colors.
ANATASE:	pale-yellow; euhedral prisms or less commonly parallel groups of prisms; probably authigenic.
GARNET:	colorless to pink; angular and irregularly etched; rare.

round. An additional 200 grains were counted to determine the relative percentage of opaque and non-opaque species. The opaques were not systematically counted for species; however, it was noted that magnetite, ilmenite, leucoxene, and pyrite are the major species present. The characteristics of the non-opaque assemblage is summarized in Table 4 and the frequency and roundness data tabulated in Table 5.

Spatial variations

Relative abundances within both the light and heavy mineral assemblages of the Potomac Group vary geographically in systematic fashion. The Patuxent Formation of Maryland and Delaware contains significantly high proportions of staurolite and kyanite, the combined percentage of these two species reaching as high as 76 percent and averaging 33 percent. In sharp contrast, correlative strata in northern Virginia are notably deficient in staurolite-kyanite. Here the combined percentage does not exceed 6 percent in any of the 8 samples examined. Similar contrasts in abundance extend to tourmaline and rutile. On the other hand, the few samples from isolated Patuxent exposures in Southern Virginia again contain high staurolite-kyanite. These variations are diagrammatically depicted in Figure 41. Significant changes in light mineral composition parallel those among the heavy assemblage and are similarly diagramed in Figure 41. Feldspar, rare to absent in Maryland and Delaware, is abundant in Patuxent sands throughout Virginia. These Virginia sands are arkoses, averaging 34 percent feldspar, in contrast to orthoquartzites and protoquartzites north of the Potomac River. Patuxent sands in Maryland and Delaware have historically been termed "arkosic". Clark and Bibbins (1897) in naming the Patuxent, characterized the sands as "containing a considerable amount of kaolinized feldspar", and subsequent statements referring to such sands as "arkosic" are common in the literature of the Maryland-Delaware Coastal Plain. However, quantitative data to support this contention has been lacking. In fact, feldspar has been found, in this study, to be rare indeed in these sands. A number of size grades were carefully examined, and thin sections of lithified beds in both the Maryland and Virginia Patuxent were studied. In many Patuxent sands, sand-sized aggregates of irregular shape and composed of sericite and white clay are common; some such grains are clearly foliated, suggesting highly-weathered and bleached fragments of schist or phyllite. The majority, however, display no apparent structure. The resemblance between such grains and kaolinized feldspar might well have led early workers to describe the host sands as arkosic in the Maryland-Delaware region as well as in Virginia. The fact remains that widely differing abundances of undoubted feldspar exist between the two portions of the outcrop belt, differences which are probably related to source area more than to any other factor.

Varietal quartz likewise shows geographic variation such that polycrystalline grains are more abundant in Virginia sands than in those to the north. This quartz variety averages slightly more than 20 percent of the total quartz in Virginia compared to only 9 percent in Maryland-Delaware. The distribution of blue-gray to pale-violet quartz, henceforth termed blue quartz, is also regionally controlled. Minor but persistent amounts of blue quartz are present in virtually all of the Virginia sands and in many of those in the Baltimore-Washington area, but are absent northeast of Baltimore.

Thus, two petrographic provinces can be distinguished within the basal portion of the Potomac Group – a northern province of highly quartzose sands, orthoquartzitic gravels, and a heavy mineral assemblage containing abundant staurolite, kyanite, tourmaline, and persistent rutile; and a southern province of feldspathic sands, petromict gravels, and little else besides zircon in the heavy mineral assemblage.

The same provinces are probably valid for the upper portion of the Potomac as well, although Patapsco Formation samples from Virginia are too few for firm conclusions. The major trends (Fig. 42) in staurolite, tourmaline, and feldspar abundance, however, parallel those demonstrated in the Patuxent.

In addition to regional variation, well-defined stratigraphic differences in relative mineral abundance and grain angularity can be established within the Cretaceous section. The first recognition of this fact must be attributed to Anderson (1948) who pointed out that staurolite was much more abundant in the Patuxent than in the succeeding Patapsco Formation. A more extensive investigation by Groot (1955) recognized two mineral zones within the Potomac Group of northern Delaware – a lower staurolite-kyanite-zircon tourmaline zone characterizing the Patuxent rocks, and an upper zircon-tourmaline-rutile zone corresponding to the Patapsco-Raritan. Similarly, Groot found a staurolite-tourmaline suite typical of the Magothy Formation.

Table 5. Heavy mineral composition of Potomac and Magothy sands

Unit	Sample No.	Heavy Minerals (percent)																		Percentage Angular		
		Weight Percent Heavy Minerals	Opaque	Zircon	Tourmaline	Staurolite	Kyanite	Sillimanite	Rutile	Chlorotoid	Brookite	Anatase	Garnet	Epidote	Sphene	Hornblende	Andalusite	Monazite	Altered	Zircon	Tourmaline	Staurolite
POTOMAC GROUP – PATUXENT FORMATION – Maryland – Delaware	17	3.7	80	23	24	27	10	–	2	–	1	–	–	–	–	Tr	–	–	13	63	98	99
	19	2.7	77	16	34	39	6	–	Tr	–	Tr	1	–	–	–	–	–	–	3	71	99	100
	21	2.2	79	29	22	34	9	1	Tr	–	Tr	Tr	–	–	–	–	–	–	3	94	100	100
	22	6.6	79	51	27	13	3	–	2	Tr	–	Tr	–	–	–	–	–	Tr	3	87	94	100
	23	4.2	70	11	11	54	18	2	Tr	–	–	–	–	–	–	–	–	–	3	70	98	100
	24	2.8	82	56	15	12	3	1	2	–	–	–	–	–	–	–	–	–	11	58	92	100
	37	2.4	81	34	27	33	1	Tr	2	–	–	–	–	Tr	–	–	–	–	2	68	99	99
	38	2.6	80	23	12	48	8	Tr	Tr	–	Tr	–	–	–	–	–	–	–	5	59	94	100
	40	1.7	86	45	23	16	3	Tr	3	Tr	Tr	Tr	–	–	–	–	–	–	8	62	93	100
	46	2.9	83	37	14	28	8	2	3	Tr	–	–	–	–	1	–	–	–	6	57	89	100
	53	4.1	70	9	15	51	20	–	1	–	2	–	–	–	–	–	–	–	2	50	100	100
	56	3.5	74	10	8	60	16	–	Tr	1	1	–	–	–	–	–	–	–	2	57	97	100
	57	9.3	90	31	27	27	5	Tr	2	Tr	Tr	Tr	Tr	–	–	–	–	Tr	5	90	92	99
	59	5.0	80	46	19	27	1	–	1	1	Tr	–	–	–	–	–	–	1	3	52	93	92
	60	4.5	77	29	45	16	1	5	–	–	–	Tr	–	–	–	–	–	–	2	88	97	97
	82	1.8	59	25	9	62	1	–	1	–	–	–	–	–	–	–	–	–	2	88	92	100
	83	5.4	56	27	12	55	3	–	Tr	–	–	Tr	–	–	–	–	–	–	2	81	100	99
	89	3.0	87	46	30	5	2	–	2	Tr	2	Tr	–	–	–	–	–	–	12	71	91	57
	94	.8	81	30	27	15	14	–	3	–	3	–	–	–	–	–	–	–	8	72	92	92
	98	6.8	71	27	18	35	13	–	2	–	1	–	–	–	–	–	–	–	4	69	97	100
	08	2.0	71	10	9	55	14	–	1	–	Tr	Tr	–	–	–	–	–	–	10	70	100	100
POTOMAC GROUP – PATUXENT FORMATION – Virginia	61	3.9	77	92	2	5	–	–	–	–	–	–	–	–	–	–	–	–	1	99	83	100
	63	.9	81	91	3	1	–	–	–	–	–	–	–	–	–	–	–	–	5	98	100	100
	64	2.4	79	85	1	5	1	Tr	1	–	–	–	1	–	Tr	–	–	–	5	89	100	100
	71	1.6	81	94	1	Tr	–	–	–	Tr	–	–	–	–	–	–	–	–	4	93	100	100
	72	5.8	86	97	Tr	Tr	–	Tr	–	–	–	–	–	–	–	–	–	–	2	95	100	–
	73	2.7	87	91	1	3	–	–	–	–	–	–	–	–	–	–	–	–	5	92	80	100
	74	5.3	84	96	1	1	–	–	–	–	–	–	–	–	–	–	–	–	2	95	100	100
	78	6.2	89	84	3	2	Tr	–	–	2	–	–	–	–	–	–	Tr	–	8	91	82	100
	111	2.2	70	32	8	25	9	Tr	Tr	6	Tr	Tr	7	Tr	Tr	Tr	Tr	Tr	8	91	95	99
	112	3.8	51	6	Tr	73	17	Tr	–	–	Tr	–	–	–	–	–	–	Tr	2	88	100	100
POTOMAC GROUP – PATAPSCO-RARITAN FORMATION – Maryland – Delaware	13	.3	80	44	28	8	2	–	2	Tr	2	Tr	–	–	Tr	–	–	–	12	81	84	82
	14	.3	83	64	11	18	Tr	–	Tr	–	Tr	Tr	–	Tr	–	–	–	–	5	90	94	99
	15	.5	91	38	28	10	3	–	1	2	1	Tr	–	–	–	–	–	–	16	51	91	90
	16	6.6	87	84	6	1	–	–	Tr	3	–	Tr	–	–	–	–	–	–	5	84	95	100
	18	2.5	79	35	25	18	3	2	2	Tr	2	–	–	–	Tr	–	–	–	11	72	96	99
	28	2.4	75	49	24	16	Tr	–	3	–	–	–	–	–	–	–	–	–	7	62	97	97
	32	3.0	79	48	28	7	1	Tr	2	–	1	–	–	–	–	–	–	–	12	42	86	90
	33	1.1	82	55	21	6	Tr	Tr	2	–	–	–	–	–	–	–	–	–	15	63	81	85
	36	3.2	86	46	35	5	1	Tr	2	Tr	1	Tr	–	–	–	–	–	–	8	71	86	35
	49	2.6	88	39	40	9	3	Tr	1	Tr	2	1	–	Tr	–	–	–	–	3	73	87	86
	50	.3	84	63	21	2	1	Tr	2	–	–	–	–	–	–	–	–	–	10	78	88	100
	51	1.2	84	28	46	7	1	–	1	–	2	–	–	–	–	–	–	–	14	55	94	83
	58	6.3	82	25	51	9	2	Tr	Tr	–	Tr	–	–	–	–	–	–	–	11	95	96	100
	86	.6	83	26	61	3	Tr	–	Tr	–	2	Tr	–	–	–	–	–	–	6	86	88	75
	88	1.0	84	30	43	9	1	–	1	Tr	2	Tr	–	–	–	–	–	–	13	80	86	74
	95	.9	87	45	27	6	2	–	2	–	1	Tr	–	–	–	–	–	–	16	83	89	92
	104	1.8	79	10	24	4	Tr	–	Tr	47	1	–	–	–	–	–	–	–	13	48	78	60
	105	6.3	86	35	24	2	5	–	1	1	5	1	Tr	–	–	–	–	–	25	78	97	89
	1	2.8	65	73	5	11	2	1	5	–	–	–	–	–	–	–	–	–	2	39	70	47
	2	1.8	79	67	16	2	Tr	–	2	–	Tr	–	–	Tr	1	–	–	–	10	68	76	56
	7	3.3	79	41	18	21	3	–	3	1	–	–	–	–	–	–	–	–	13	41	57	69
	31	4.2	81	40	41	1	–	–	2	Tr	4	2	–	–	Tr	–	–	–	9	61	100	80
	41	.4	86	60	18	9	1	–	2	–	Tr	Tr	–	–	–	–	–	–	9	67	85	98
	43	.4	86	70	9	5	Tr	–	6	–	–	–	–	–	1	–	–	–	8	51	76	100
	48	.9	85	57	25	5	Tr	Tr	3	Tr	Tr	–	Tr	–	Tr	–	–	–	7	53	81	87
	106	1.1	75	51	28	8	–	–	2	Tr	–	2	Tr	–	–	–	–	–	7	72	79	61
	6	3.3	83	50	27	9	–	–	3	–	–	–	–	–	–	–	–	–	11	31	54	38
POTOMAC GROUP – PATAPSCO-RARITAN FORMATION – Va.	66	7.0	86	95	1	–	–	–	Tr	Tr	–	–	Tr	–	–	–	–	–	3	94	100	–
	76	6.8	77	94	1	4	–	–	–	–	–	–	–	–	–	–	–	–	1	95	100	100
	79	7.1	84	89	Tr	2	–	–	–	–	–	–	–	–	–	–	–	–	8	92	100	100
MAGOTHY FORMATION	3	4.2	47	20	7	55	12	–	1	–	1	Tr	–	–	1	–	–	–	2	70	100	100
	27	1.0	37	12	19	65	2	Tr	Tr	–	–	–	–	–	Tr	–	–	–	–	90	99	100
	29	12.6	32	22	9	65	1	–	1	–	–	–	–	–	–	–	–	Tr	1	86	100	100
	42	.8	62	18	12	44	12	3	2	7	Tr	–	–	–	–	–	–	–	1	47	80	92
	107	1.3	39	13	13	57	17	Tr	–	–	Tr	–	–	–	–	–	–	–	–	65	100	100

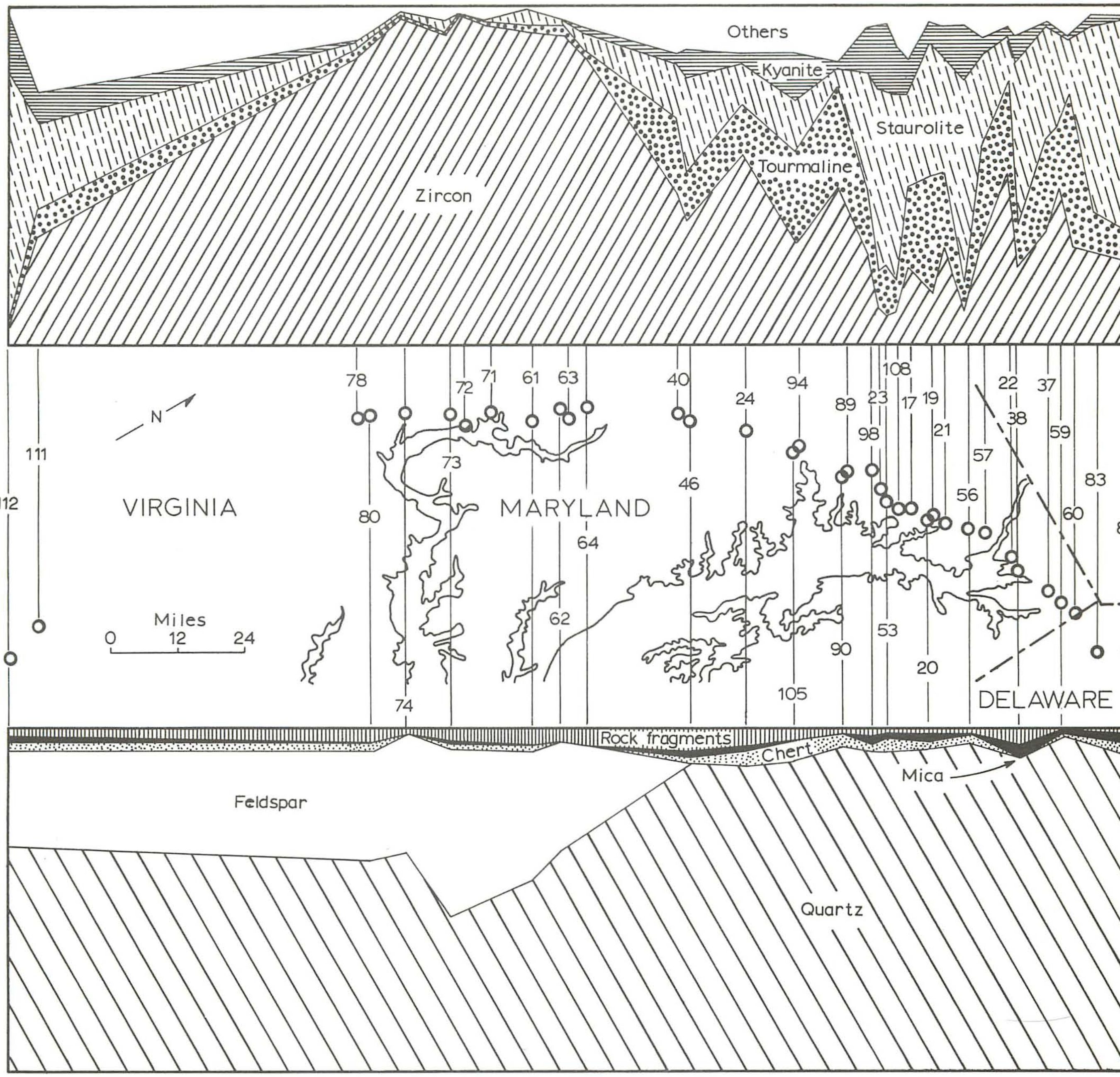


Figure 41. Regional variation in the composition of Patuxent Formation sands. Upper diagram: abundance of major heavy mineral species; Lower diagram: abundance of light mineral species.

Vertical variation in the average abundance of some of the important heavy mineral species is diagramed in Figure 43; included as well is the accompanying variation in tourmaline and staurolite angularity. Several trends in mineral abundance are apparent. Staurolite, dominant in most of the outcropping Patuxent Formation, falls off sharply in the Patapsco-Raritan, and again becomes abundant in the Magothy Formation. The proportions of kyanite parallel those of staurolite. Rutile, while never more than 6 percent in any of the sands, increases steadily to maximum abundance in the upper Potomac and then declines in the Magothy. Parallel vertical trends in tourmaline and staurolite angularity can also be demonstrated. Subrounded to rounded grains are increasingly abundant in stratigraphically higher beds of the Potomac Group but decreases notably in the overlying Magothy.

Within the light mineral fraction of the sands, some vertical trends are apparent but these are not really well defined. In general, the sands tend to become more quartzose upward in the section (Fig.

43), chiefly as a consequence of the decline in rock fragments, chert, and mica. Viewed from the standpoint of average composition alone, the decline in non-quartz components can also be expanded to include feldspar, although its limited regional distribution lends a certain ambiguity to any such inclusion. Less significance can be attached to variation in the abundance of mica and silt-clay matrix. Whereas the other light components are largely source area parameters, mica and matrix proportions are a function not only of source but of sorting at the depositional site as well. With respect to grain angularity, it can be shown that the proportions of angular quartz grains decline slightly in the upper Potomac Group but show an increase in the Magothy. Further, the varietal quartz data (Fig. 43) establish a uniform upward decrease in the proportions of polycrystalline quartz which is paralleled, at least in the Potomac, by a similar decrease in strained quartz

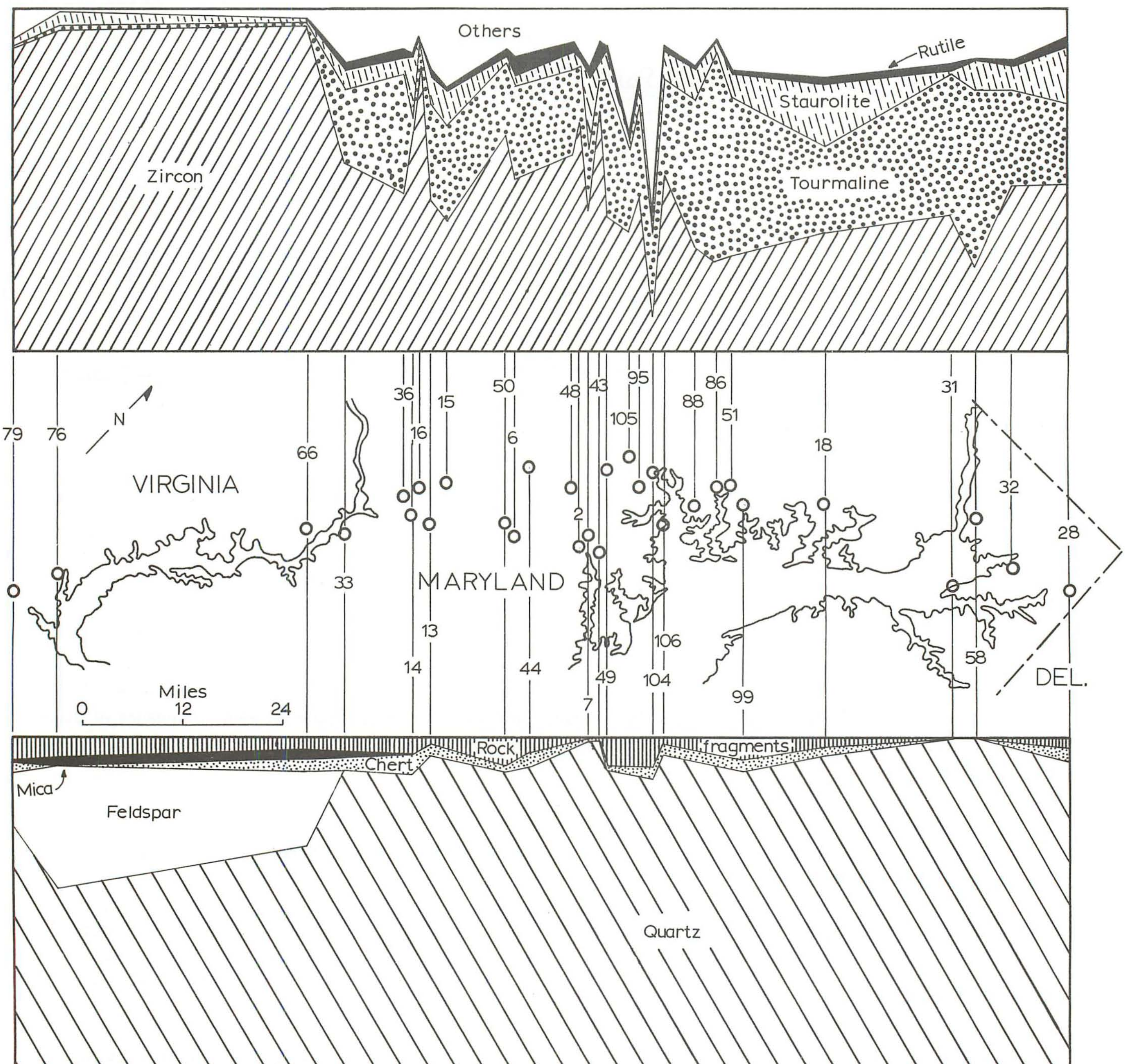


Figure 42. Regional variation in the composition of Patapsco-Raritan sands. Upper diagram: abundance of major heavy mineral species; Lower diagram: abundance of light mineral species.

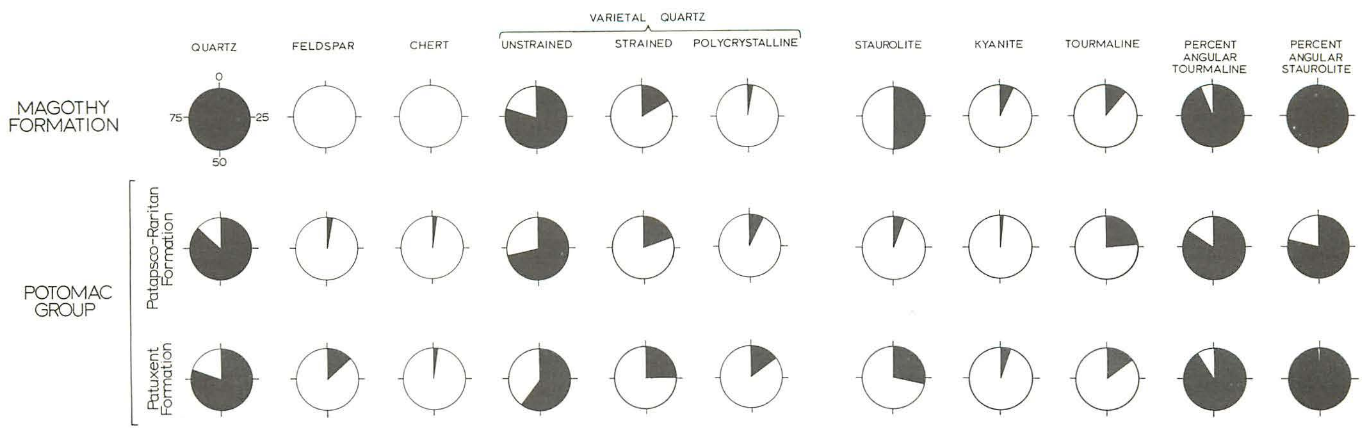


Figure 43. Vertical variations in abundance and angularity of selected components of Potomac and Magothy sands.

Maturity

From a synthesis of the textural and compositional data thus far developed, it is fairly clear that successively higher beds in the Potomac Group are increasingly mature. The textural aspects of this trend are threefold: (1) decreasing average median size, (2) increasing average degree of sorting, and (3) increasing abundance of subangular and rounded grains. Compositionally, increasing maturity is reflected by: (1) decreasing abundance of feldspar, rock fragments, and chert, (2) decreasing staurolite and kyanite proportions, and (3) decreasing percentage of polycrystalline and strained quartz. Thus, the basal Potomac clastics (Patuxent) are immature, spanning feldspathic matrix-rich sands and lithic gravels in the south to more quartzose yet immature sands and gravels in the Maryland-Delaware region. In contrast, submature sands with better sorting and small but significant proportions of subrounded and rounded grains begin to appear in the upper Potomac, and gravels become much subordinate. The heavy mineral suite of the Patuxent Formation to the north is dominated by fresh highly-angular grains of moderately-stable metamorphic minerals (staurolite and kyanite) as well as equally angular tourmaline and zircon. The Patapsco-Raritan suite, on the other hand, is mostly tourmaline, zircon, and rutile with only small admixtures of staurolite – a basically stable impoverished assemblage. Moreover, this upper Potomac suite is further characterized by the initial appearance of small proportions of abraded grains of staurolite and tourmaline. Subangular to rounded grains of these two species increase noticeably in abundance in uppermost Patapsco-Raritan sands as do rounded zircons. An additional index of heightened maturity is the upward decrease in the proportions of polycrystalline and undulatory quartz.

The actual significance of these systematic maturity changes is the obvious next question to be explored. It is clear that textural maturity may be either inherited from the source rocks or acquired during transport or at the site of deposition. The rounding of sand is a very slow process under normal circumstances and is seldom achieved during one cycle of transport (Pettijohn, 1957). In fact, first-cycle sands can probably acquire appreciable rounding at the depositional site only under rather special conditions, such as an extremely potent beach or dune environment (Folk, 1960). There is no evidence to suggest that either of these environments was important during Potomac deposition. It is a fair conclusion, then, that the rounded quartz as well as rounded zircon, tourmaline, and staurolite which occur with vertically increasing frequency in the upper Potomac Group are second-cycle from pre-existing sediments and thus exhibit inherited roundness. The remaining components of textural maturity in the upper Potomac, i.e. decreasing median size, better sorting, and less matrix, reflect processes operating during transport and at the site of deposition. The reduced proportions of gravel and coarse sand points to decreasing current competency and is also responsible, at least in part, for the smaller sorting range in that median size and sorting are not independent parameters.

Any evaluation of the comparatively weak upward trend of decreasing matrix must take into consideration secondary as well as primary causal factors. Some portion of the interstitial clay in lower Potomac sands is doubtless secondary in origin, whereas secondary matrix decreases considerably in the upper Potomac, notably in sands of the uppermost Potomac of central Maryland. A second consideration is that the observed trend does not reflect a systematic bed-to-bed vertical decrease in matrix proportions but rather the intercalation of clean, well-sorted sands with greater frequency in the uppermost Potomac. This greater frequency of better-sorted, matrix-poor sands, in combination with the evidence of upward decreasing competency offered by median size, suggests a decelerating subsidence of the Potomac basin or essentially a flattening-out of the depositional slope.

The upward stratigraphic increase in compositional maturity within the Potomac Group is probably more significant than the accompanying textural changes. The general paucity in the upper Potomac of any but chemically stable mineralogic components, i.e. quartz, zircon, tourmaline, and rutile, contrasts sharply with the abundance of relatively unstable minerals such as staurolite, kyanite, feldspar etc. in the Patuxent Formation. This sharp decline in the proportions of unstable species could reflect either a change in the location of the primary source area or a change in the relative importance of multiple sources. A third possibility is a significant alteration in the chemical or lithologic character of the same source area from which the Patuxent clastics were derived. Although the paleocurrent data indicate small shifts in current direction between the Patuxent and Patapsco-Raritan Formations, the overall transport pattern is essentially similar and reveals no major variation in source area direction. Rather the evidence points to the persistence of the same source areas through the entirety of Potomac time but with progressive modifications grouped as follows:

(1) Heightened chemical weathering accompanying peneplanation during late Potomac time in the primary source area acted to decrease the availability of unstable components.

(2) An increasing but small contribution of second-cycle abraded grains, mostly stable species such as quartz, zircon, tourmaline, and rutile, derived from pre-existing sedimentary rocks outside of the primary source area, served to further dilute the resulting mineral assemblages.

The coarser clastics of the Magothy Formation present a reversion to more immature sediments, duplicating to a large degree the conditions extant during Patuxent time. Textural immaturity is marked in the Magothy by abundant gravels, almost wholly angular quartz and heavy mineral grains, and relatively poor sorting; however, abundant matrix, a salient Patuxent characteristic, is lacking. Mineralogic immaturity is manifested by abundant staurolite and kyanite. Other unstable constituents, however, such as feldspar, rock fragments, chert, and polycrystalline quartz, are uncommon or lacking.

LITHIFICATION AND DIAGENESIS

Introduction

The Cretaceous sediments in the area studied are mostly unconsolidated to semi-consolidated. However, well-lithified beds were seen at a number of exposures, particularly in the southern half of the outcrop belt, and samples were secured for thin-sectioning. Point-count percentages of the constituents in 8 thin sections were determined. Several modes of lithification, including clay authigenesis in mudstones and the matrix of sandstones as well as cementation by iron oxides, siderite, and silica, were examined.

Ferruginous cement

The most common and widespread type of induration is hematite or limonite cementation. Individual beds or lenses, undulatory zones, and irregular pods, ranging from merely stained to firmly-cemented by iron oxide, occur in all parts of the Potomac Group and in the Magothy Formation. The abundance of iron oxide cements is correlated in part with permeability. For example, partial to complete cementation of gravel and coarse sand is a much more common phenomenon than cementation of medium and fine sand. Further, open-work foresets in gravels are preferentially cemented while adjacent foresets with sand-filled interstices remain uncemented. Iron oxide cements are relatively rare in Virginia, where sand interstices are with few exceptions silt-clay filled. The geometry of ferruginous zones as well as the extent of cementation is widely variable. The most simple case is staining as irregular mottling or banding, commonly in anastomosing fashion, or undulatory banding which in a general way parallels bedding. At the other end of the spectrum are isolated pods or discontinuous layers firmly indurated by limonite cement, in many cases forming concretionary bodies ranging to several feet in diameter. Deposition of iron oxides as staining or cementing agents is in some instances primary and in others penecontemporaneous, but in the vast majority of cases clearly postdepositional. Silt-clay in the Potomac Group is commonly variegated in red, brown, purple, and yellow; in these cases, irregular mottling rather than bedding control is the rule. Much of the pigmentation is unquestionably postdepositional, having been introduced by groundwater; examples are coloring localized along bedding planes, fractures, slickensides, etc. Yet in other cases, red clays of primary origin seem indicated. The most compelling examples of primary pigmentation are bright-red clay lenses wholly enclosed in white oxide-free sands, seen at several exposures. Evidence of penecontemporaneous cementation is provided by irregularly scoured surfaces on weakly-cemented limonitic sands, the whole overlain by texturally-similar clean white sand. Further evidence is the inclusion of angular and broken fragments of limonite-cemented siltstone as clasts in quartz gravels clearly implying erosion and redeposition of penecontemporaneously-cemented sediments. However, the vast majority of zones of ferruginous cement or staining transect bedding and are thus of post-depositional origin.

Unconformities of greater or lesser magnitude in the Potomac Group are commonly marked by ferruginous layers ranging from thin crusts to zones several inches in thickness. Such ironstones may be iron oxide pans developed by weathering during the hiatus represented by the unconformity and as such penecontemporaneous in origin. Alternatively, in that many of the unconformities are spring zones, post-depositional iron oxide deposition from groundwater along these boundaries might be favored. In other cases, however, ironstones localized along sedimentary contacts in some portions of an outcrop cross-cut (Fig. 44) overlying or underlying sedimentation units in other portions of the same outcrop, revealing their post-depositional character.

Siderite cement

Cementation of sand beds in the Potomac Group by siderite, although uncommon, is widespread. Most such siderite-cemented beds share the following features: pyrite-bearing, abundantly lignitic, lacking silt-clay matrix, and interbedding with drab lignitic clays. The precipitation of siderite requires a strongly reducing microenvironment. That such conditions prevailed locally is indicated by the abundance of wood fragments and the carbonaceous clay association. Increased permeability in the absence of matrix might then have allowed the free flow of iron-bearing waters, thus enhancing the likelihood of a chemical cement.

Matrix cementation

The third type of lithification encountered – matrix cementation – is restricted to the region south of the Potomac River where it is widespread. The degree of induration of these sandstones is highly variable; most Virginia exposures are semi-consolidated, indurated yet friable sandstones less common, and hard firmly-indurated rocks occur in a few areas only, notably near Fredericksburg and at Point of Rocks south of Richmond (Fig. 45). Degree of induration shows an apparent correlation with percentage of matrix such that lithified sands contain abundant matrix, and conversely, loose sands exhibit low matrix proportions. Lithified layers may transect sedimentation units and vary in thickness from a few inches to tens of feet.

The most significant feature of such sandstones is of course the matrix which consists of highly-weathered rock fragments, clay aggregates, and authigenic kaolinite. Undoubted rock fragments, mostly bleached and thoroughly weathered schistose or phyllitic grains, are perhaps the least abundant of the three components. Matrix patches with vague boundaries, seen in thin section to vary in composition along their diameter, are probably badly-squeezed rock fragments and were classed as such. The most abundant matrix component is clay pellets or aggregates – aggregates of randomly oriented clays mixed with variable amounts of quartz silt and marked by distinct boundaries. The apparent gradation in thin section between true rock fragments and clay pellets is complete; consequently, these components were lumped in modal analyses. The pellets themselves range from roughly spherical to tabular in form and are generally as large or slightly larger than the associated quartz and feldspar. Similar silt-clay aggregates are seemingly common in fluvial sandstones, having been reported by Potter and Glass (1958) and Allen (1962). Allen's explanation for the presence of clay pellets in the Old Red Sandstone involves flocculation of suspended clays, an idea supported by the fact that the Old Red pellets are confined to sandstones with mean diameter less than 2ϕ, i.e. suspended load materials. He reasons, probably correctly, that clay aggregates or pellents in the form of delicate floccules cannot be expected to occur in bed load sands where extreme attrition between grains would assure their rapid destruction. Clay pellets in the Potomac Group of Virginia, however, are equally abundant in sediments ranging in texture from fine sand to gravel. Furthermore, there is more or less of a continuum between sand-sized clay pellets and clay clasts several feet in diameter.

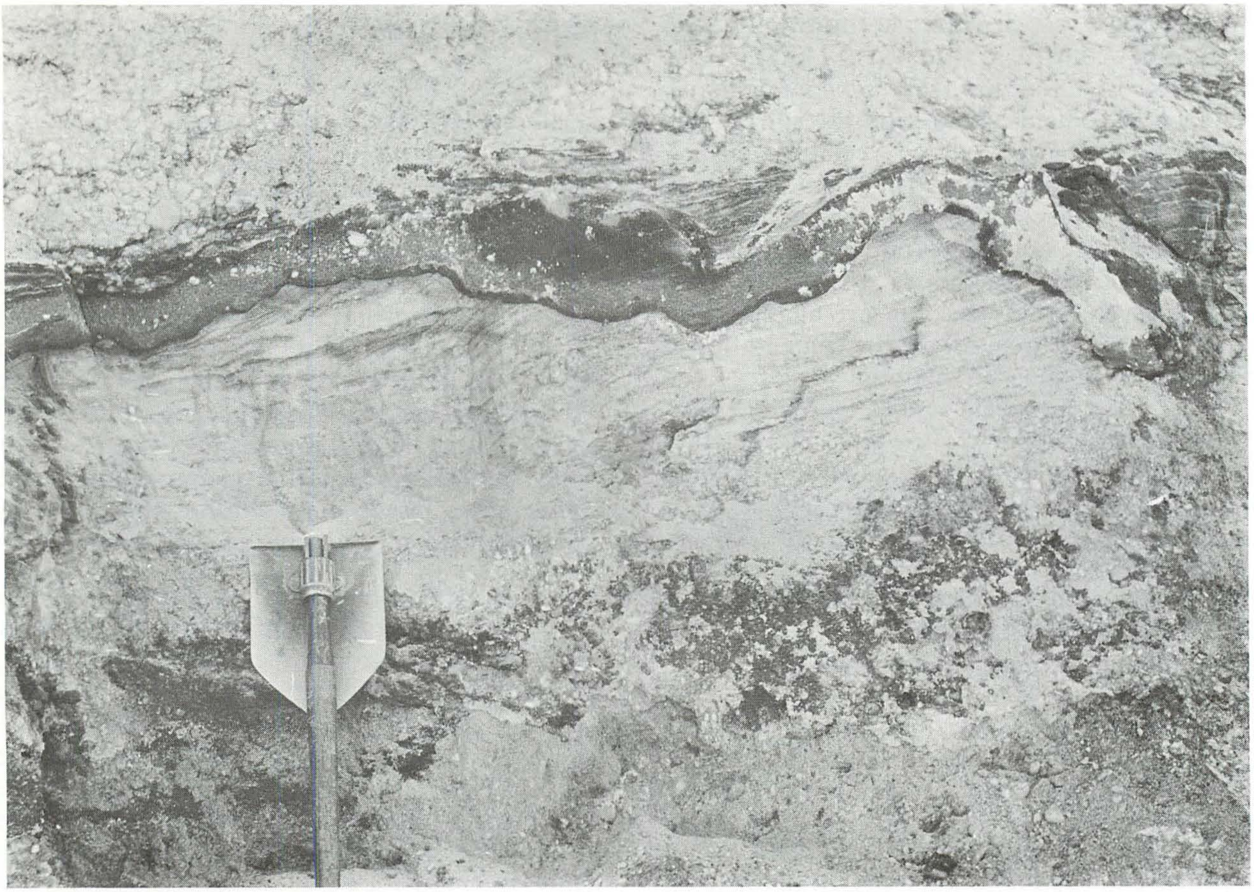


Figure 44. Undulatory band of highly ferruginous sand which transects bedding in white pebbly sand of the Patuxent Formation, Campbell sand pit, Baltimore County, Maryland.

On the whole then, pellet origin as clay floccules, at least in the Potomac sediments, does not fit the evidence; rather the break-up and redeposition of intraformational silt-clay beds as discrete clasts of varying size is a more tenable explanation. This explanation is probably valid for the majority of the pellets. However, it is likewise clear that the growth of authigenic kaolinite has modified the texture and composition of many of the pellets, and in fact aggregates of purely authigenic origin are not uncommon in the sandstones. These appear as patches made up of vermicular book-like kaolinite crystals or large sheaf or fan-shaped individuals present as matrix elements and replacing quartz grains or more commonly feldspars.

The remaining undifferentiated matrix is a more or less homogeneous silt-clay paste which cannot be further subdivided with any degree of certainty. However, the apparent gradation in definition from easily recognizable rock fragments and clay pellets through vague patches distinguished by color, texture, or quartz silt content to undifferentiated silt-clay suggests that the present paste arose in large part through crushing of the softer lithic elements of the rock. Moreover, it is evident that an undeterminate amount of matrix has been generated through authigenesis at the expense of the quartz-feldspar framework. Feldspar, in particular, is extensively kaolinized.

Residual sandstone blocks

The crests of several isolated low hills in northern Anne Arundel County, Maryland are strewn with large blocks of tough silica-cemented sandstone (Fig. 46). Similar rocks project above the waters of the Patapsco River near Ft. Smallwood in the easternmost portion of the county. These occurrences were first noted by Uhler (1888) who proposed that the Albirupean (upper Potomac) sands were a product of the "decay" of this sandstone. Clark (1916) lumped these rocks with local ferruginous sandstones as indurated portions of the Patapsco-Raritan Formation. The same general conclusions were reached by Brookhart (1949) who thought that some upper Potomac sands "become case-hardened upon exposure to form resistant rock masses", and by Otton (1955) who reported "small hills....capped by a ten to twenty foot layer of especially tough sandstone."

The true mode of occurrence of the sandstone blocks is well shown in borrow pits opened in two low hills in the area. The sandstone occurs as isolated partly-rounded tabular blocks embedded in the soil zone. Further, the blocks are distributed at various elevations on the slopes as well as the crests of hills, suggesting a residual character rather than strict association with any given stratigraphic level in the underlying Potomac Group. The blocks, ranging from 4 to over 20 feet in length and up to 10 feet in thickness, are composed of pale-gray sandstone laced with irregular purplish mottles of interstitial hematite. Most are internally massive or exceptionally faintly laminated or cross-bedded. Cementation is by authigenic silica and is variable, even within individual blocks, such that some portions are friable and easily disaggregated with the fingers, and others are firmly cemented and break across detrital grains. All of the sandstones examined are 99 to 100 percent quartzose.

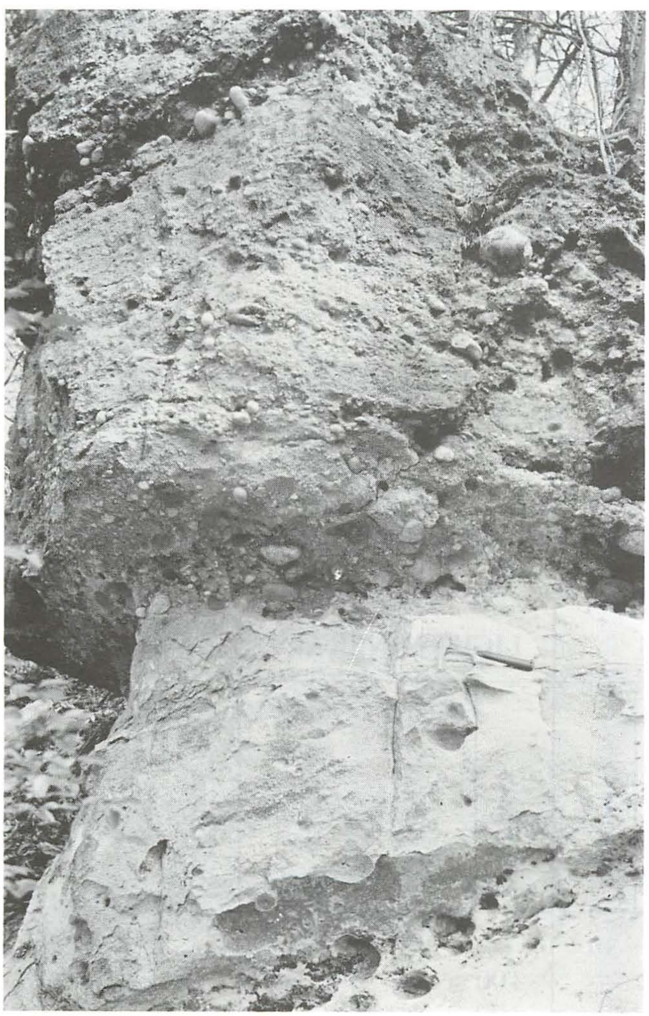


Figure 45. Semi-lithified arkosic sand overlain by well-lithified coarse conglomerate. Exposure of the Patuxent Formation at Point of Rocks, Chesterfield County, Virginia.

The mineralogic and textural parameters of the sandstone blocks, summarized in Table 6, exhibit several significant differences from those of the enclosing sands. The heavy mineral assemblage of the sandstone is dominated by angular staurolite and also contains considerable kyanite. Moreover, opaques make up only 39 percent of the suite. In contrast, the host sands show a typical Patapsco-Raritan suite with abundant zircon, a high percentage of opaques, and only minor amounts of staurolite and kyanite. Although both the blocks and underlying sands are ortho-quartzitic in composition, they differ in grain roundness. The cemented sands contain larger proportions of rounded grains and show somewhat better sorting; consequently, they are more mature.

It is readily apparent, then, that the blocks are unlike the enclosing sediment and are relict where they are now found. The association of a relatively high proportion of subangular to rounded quartz and a staurolite-dominated heavy mineral suite is not known in the outcropping Cretaceous sediments. The blocks might represent some higher Potomac bed or some portion of the Magothy Formation now unrepresented in outcrop due to removal by post-Potomac or post-Magothy erosion. McCallum (1957) reports that upper Raritan beds in northern New Jersey are characterized by a staurolite-rich assemblage; thus the residual sandstone in Maryland may be relict from equivalent strata which were eroded away before deposition of the Magothy Formation had begun.

The greater rounding and better sorting of the sandstone raises the possibility that they may be remnants of a selectively-cemented beach or dune facies of the upper Potomac Group. Such an interpretation is compatible with evidence of increasing maturity upward within the Potomac section and the westward approach of the shoreline environment. The selective cementation might well be a consequence of the greater permeability of shoreline sands, much as Alimen (1936) proposed for similarly-cemented sands in the Oligocene Fontainebleau Formation of the Paris Basin. In the latter case, parallel linear belts of silica-cemented sandstone arrayed within the unconsolidated Fontainebleau sediments are considered to represent beach ridges selectively cemented by silica-bearing phreatic waters moving upward through the dune fields. The interdune sediments are notably less porous clays and limy shales.

Figure 46. Large residual sandstone blocks on crest of low hill near Lipins Corner, Anne Arundel County, Maryland.

Table 6. Comparison of mineralogic and textural parameters of sandstone blocks and host Patapsco-Raritan sand

		HEAVY MINERALS						LIGHT MINERALS				
									Quartz angularity			
	Sample No.	Zircon	Tourmaline	Staurolite	Kyanite	Others	Opaque	% Quartz	Angular	Subangular	Round	Sorting Co-efficient (σ_ϕ)
Sandstone	41-4	15	13	59	11	2	39	—	–	–	–	–
	41-5	–	–	–	–	–	–	100	15	54	31	–
	41-6	–	–	–	–	–	–	100	21	62	17	.33
Host sand	41-1	60	18	9	1	12	86	100	25	69	6	.79
	41-2	–	–	–	–	–	–	100	53	44	3	.36
	41-3	–	–	–	–	–	–	—	–	–	–	.56

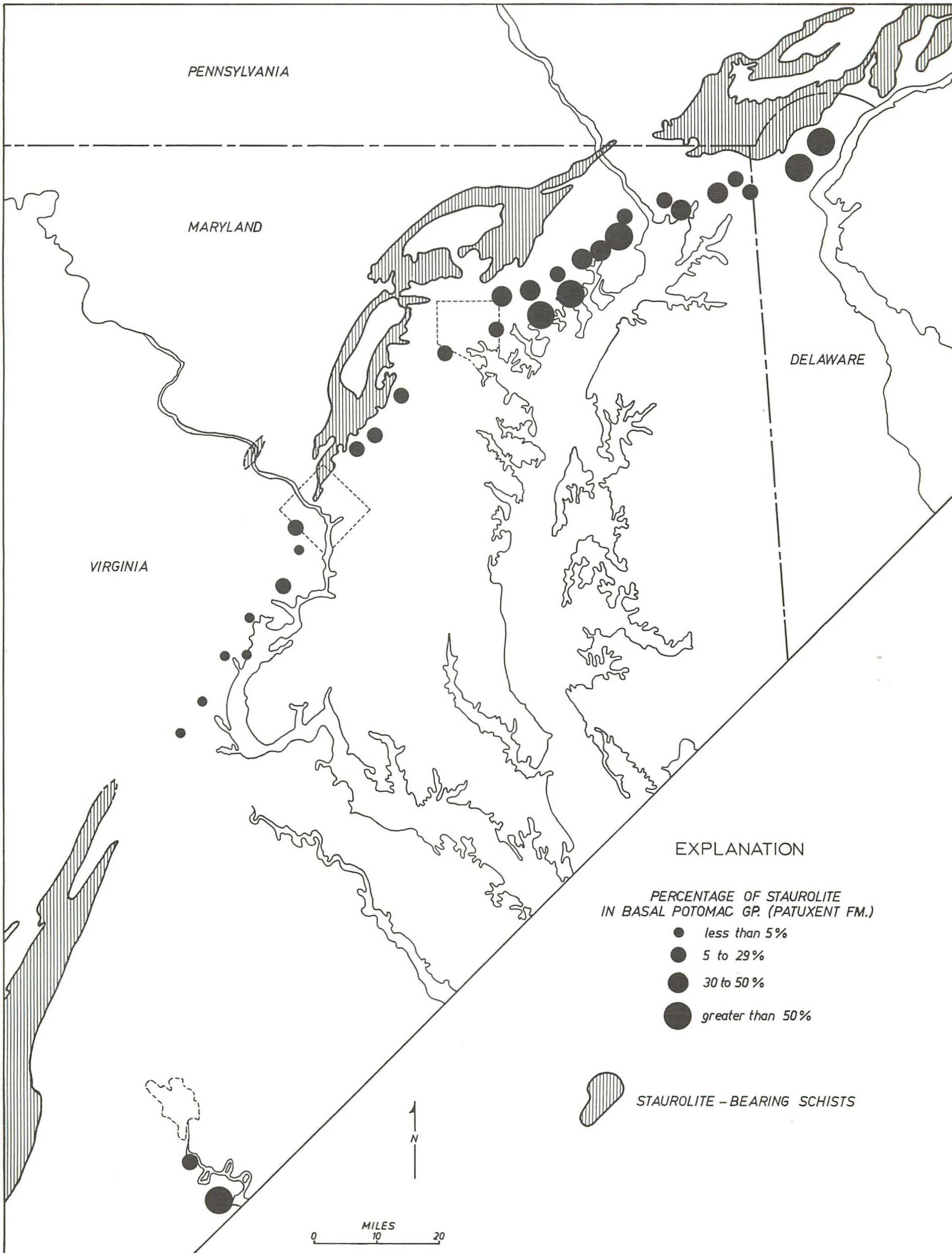


Figure 47. Map showing distribution of major outcrop bodies of staurolite-bearing schist in the Maryland through Virginia Piedmont, and the percentage of staurolite in the heavy mineral suite of the outcropping Patuxent Formation.

SOURCE AREAS

Patuxent Formation clastics were clearly derived in largest part from crystalline source rocks. Moreover, these source rocks can be separated into two geographic provinces by the character of their residues – a northern area which supplied sediment to Maryland, Delaware, and southern New Jersey, and a southern province from which the Virginia clastics were derived. That the source rocks of the southern province were primarily granitic igneous rocks and gneisses is indicated by: (1) large proportions of feldspar, mostly microcline, in the sediments, (2) a heavy mineral suite containing little else but zircon, and (3) the predominance of granitic or gneissic rock types among the lithic pebbles in the gravels. On the other hand, the northern source was largely metamorphic rocks with high-grade schists prevalent. Support for the latter conclusion is: (1) the abundance of angular staurolite, kyanite, and tourmaline in the northern Patuxent heavy mineral suite, (2) the lack of feldspar, and (3) the predominance of subrounded, probably first cycle vein quartz in the gravels coupled with the absence of granitic or gneissic pebbles.

Polycrystalline quartz is relatively abundant throughout the Patuxent Formation but occurs in particularly high proportions in the Virginia Patuxent. Historically, many authors have interpreted polycrystalline quartz as indicative of metamorphic rocks (see Blatt and Christie, 1963) but the latter authors have shown that plutonic igneous rocks as well as gneisses and metaquartzites can provide composite grains. Thus large proportions of this type of quartz point only to a source area with extensive primary rocks in contrast to sedimentary rocks. The occurrence in the Patuxent sands of small amounts of second-cycle quartz, zircon, and tourmaline reveals that some minor portion of the sediment has come from older sandstones. Moreover, these second-cycle grains are concentrated in the northern Patuxent and thus have a greater dilution effect in those sands than in Virginia where their proportions are much smaller. It is entirely possible, then, that the proportions of polycrystalline quartz in the two areas are not really significantly different, but that dilution by second-cycle, mostly monocrystalline grains has had the effect of antipathetically reducing the percentage of polycrystalline grains in the north.

The idea that much if not all of the nonmarine Cretaceous section in the Maryland-Delaware area has been derived from the adjacent Piedmont crystalline rocks has been discussed by Dryden (1946) and by Groot (1955). Dryden, in particular, points out that brownish-pink tourmaline prisms, common in the Potomac and Magothy sediments, are closely similar in all respects to accessory tourmalines in the Wissahickon Formation of the nearby Maryland-Delaware–Pennsylvania Piedmont. In order to test the hypothesis that the distribution of specific minerals in the Potomac Group is related to the distribution of accessory minerals in specific Piedmont rock bodies, the percentage of staurolite in Patuxent samples is plotted in Figure 47 opposite the present outcrop of major bodies of staurolite-bearing schist. The resulting map shows a clear correlation between the upcurrent location of staurolite source rocks and staurolite abundance in the sediments. In addition to supporting eastward sediment transport, this relationship suggests that sediment mixing parallel to the paleoslope was minimal, at least for the proximal sediments. An additional much broader implication is that the distribution of relative exposure of the various Piedmont rock types has not changed appreciably since early Cretaceous time. The present distribution of major granitic and gneissic rock bodies in the Piedmont-Blue Ridge region between Virginia and Pennsylvania, depicted in Figure 48, lends further credence to this idea because the largest areas of potential feldspathic source rocks are exposed in the southern portion of the source region, or roughly opposite the outcrop of the highly-feldspathic Potomac sediments in Virginia. Moreover, an adequate source for the small but persistent amounts of blue quartz in the Potomac Group of Virginia is probably to be found in some of the granitic and gneissic rocks of central Virginia, e.g. abundant blue quartz is an important constituent of the Lynchburg gneiss, the Old Rag granite, and the Blue Ridge granitic complex (Reed, 1954; Bloomer and Werner, 1955). Thus the conclusion that the adjacent Piedmont and Blue Ridge regions acted as the major source area during early Cretaceous time seems inescapable. Small admixtures of second-cycle materials, represented by sandstone and chert pebbles as well as abraded grains of quartz, zircon, and tourmaline, probably originated in the Paleozoic sedimentary rocks of the Appalachian region, and possibly to a lesser extent in Triassic sediments. Such preexisting sediments, however, were minor elements in the northern part of the source area, and were negligible to the south in Virginia.

If this hypothesis of derivation from the neighboring Piedmont crystalline rocks be accepted, then a comparison of the Patuxent heavy mineral suite with the mineralogy of bed load sands in a modern river draining this region should be of value, chiefly to ascertain what, if any, differences exist between the two assemblages and why. The river selected for sampling was Little Gunpowder Falls, located a few miles to the northeast of Baltimore, and draining an area wholly within the eastern Piedmont. Six samples were taken over a 17 mile reach of the river and 200 heavy mineral grains per slide counted from the sand fraction (.0625-.5 mm) of each sample. The resulting data is tabulated in Table 7.

Some similarities with the Patuxent suite are immediately apparent. The combined proportions of staurolite and kyanite plus the stable species zircon and tourmaline comprise, on the average, over half of the non-opaque constituents in the modern suite. However, here the observed similarities end. The modern suite contains significant amounts of amphibole and smaller but persistent proportions of garnet. Many grains of the latter species exhibit etched or corroded surfaces.

The relative chemical and mechanical stability of various heavy minerals has been investigated by a number of workers (see Pettijohn, 1957, and Groot, 1955), and although complete agreement is lacking as regards a rigorous stability order, there is a consensus on many points. Amphibole is considered both mechanically and chemically unstable by most investigators; thus it can be reasonably assumed that this species was destroyed in the source area by early Cretaceous chemical weathering of greater intensity than imposed at present. Garnet, on the other hand, has been assigned a relatively high stability by some (Pettijohn, 1957; Condit, 1912; Milner, 1923), but is considered unstable by others (Sindowski, 1949; Dryden and Dryden, 1946). The Drydens, in particular, have noted the rapid destruction of garnet in weathering profiles developed on the Wissahickon schist in Maryland and Pennsylvania. Further, Cazeau and Lund (1959) reported a rapid downstream decrease in garnet proportions in the bedload sands of the Chattahoochee River in Georgia following its debouchment onto the Coastal Plain. The data presented here tends to confirm the observation that garnet does not readily survive weathering and/or subsequent transport. Modal analyses of pelitic schists in the Wissahickon Formation of Maryland indicate that garnet is at least as abundant as and commonly more so than staurolite in these rocks (Hopson, 1964); yet in the case of the Little Gunpowder which drains a large area underlain by this unit, staurolite is concentrated at the expense of garnet. These observations suggest that the absence of garnet in outcropping Patuxent sands can be ascribed largely to source area weathering. If minor amounts survived the weathering process, subsequent destruction during transport or removal by ground water solution in the sediments effectively eliminated the remainder.

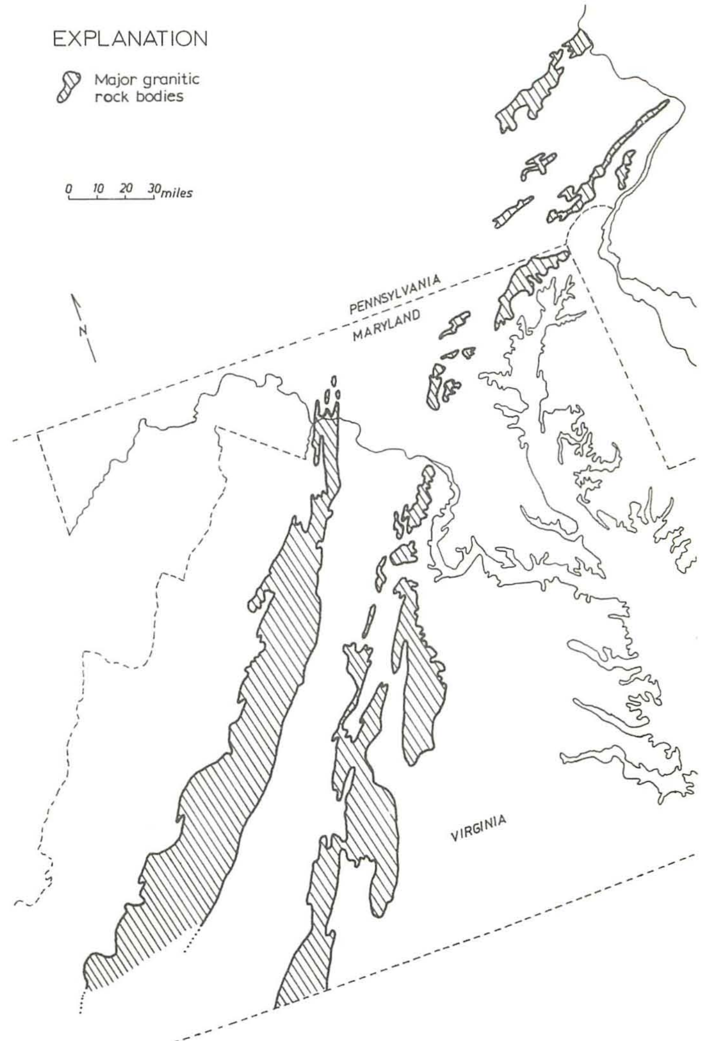
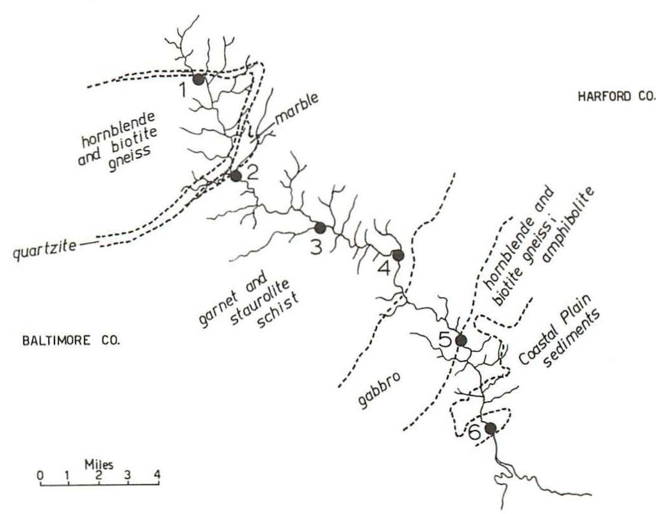


Figure 48. Distribution of major bodies of granitic rock in the Maryland through Virginia Piedmont and Blue Ridge regions.

The transition from Patuxent to Patapsco-Raritan time was apparently marked by a change in the character of the source area. The predominance of the stable association zircon-tourmaline and the general scarcity of less stable species in the northern Patapsco-Raritan Formation may be attributed to several possible causes. Groot (1955), in considering this problem with respect to the Potomac of Delaware, entertained three possibilities: (1) a change in source area from one of largely primary rocks to one of pre-existing sediments, (2) post-depositional weathering (interstratal solution), and (3) intensive source area weathering. It is clear from the paleocurrent evidence, and from the small but persistent proportions of staurolite and kyanite as well as predominantly angular quartz grains in the Patapsco-Raritan sands, that the adjacent Piedmont region remained the major source area during this time. However, the increased abundance of rounded quartz and well-rounded zircon and tourmaline indicates a larger contribution from Appalachian sandstones than was received in the underlying Patuxent. The second possibility – weathering of less stable mineral species during or after deposition – is unlikely for two reasons to have been an important factor in producing the observed assemblage. Firstly, as pointed out by Groot and borne out as well in this investigation, no significant differences in mineralogy between rapidly-deposited coarse clastics in the Patapsco and less-rapidly accumulated fine sands and silts. Had chemical weathering during transport or at the site of accumulation been important, one might expect mineralogic contrasts between coarse and fine sediments in proportion to the length of time intervening between derivation and final burial. Such is not the case. Secondly, post-depositional weathering (interstratal solution) was apparently not significant because both overlying (Magothy) and underlying (Patuxent) units contain abundant less stable species. Groot thought that the major factor operating to produce the limited Patapsco-Raritan mineral assemblage was low source area relief with accompanying intensive chemical weathering, a conclusion with which I am in essential agreement. That source area weathering was a factor of greater importance in Patapsco-Raritan as contrasted with Patuxent time is suggested by the cloudy and ragged appearance of much of the little staurolite and kyanite present, and the significantly higher percentage of altered grains (see Table 5). Moreover, it is also clear that relief and not climate was the more important influence in Patapsco-Raritan provenance. Virginia sands of Patapsco age are only slightly less feldspathic than those of the underlying Patuxent. Because it is unlikely that significant climatic differences existed between the northern and southern source areas, it must be concluded that relatively high relief persisted in the south in contrast to lower relief with a correspondingly greater weathering potential in the north.

On the other hand, it is probable that factors other than progressive relief and weathering changes through Potomac time could have contributed to the observed sediment modifications. One such factor may have been the burial beneath Patuxent sediments of some portion of the easternmost Piedmont, thus in effect removing the covered portion from availability as a potential sediment source. It can be readily seen from published geologic maps that an extension westward of the Patuxent Formation for a few miles only beyond its present western limit would bury much of the outcropping gneiss and high-grade schist which doubtless acted as an important Patuxent sediment source. Consequently, the primary availability of minerals, such as staurolite and kyanite would have been reduced, and at the same time, the major source area shifted westward. The latter shift might then account for the sporadic abundance in the Patapsco-Raritan Formation of chloritoid, a common mineral in such western Piedmont units as the Ijamsville

Table 7. Heavy mineral composition of recent sands in Little Gunpowder Falls



STATION	Zircon	Tourmaline	Staurolite	Kyanite	Garnet	Amphibole	Epidote	Sillimanite	Monazite	Apatite	Anatase	Hypersthene
1.	19	8	11	4	17	32	–	4	2	Tr	Tr	2
2.	15	3	9	2	10	51	8	1	–	Tr	–	–
3.	22	2	28	9	11	24	4	Tr	Tr	Tr	Tr	–
4.	11	7	33	17	12	17	2	–	–	–	Tr	–
5.	10	3	23	17	7	35	1	Tr	–	1	Tr	–
6.	17	4	26	10	10	29	3	Tr	–	–	–	–
AVERAGE	16	4	22	10	11	31	3	Tr	Tr	Tr	Tr	Tr

phyllite and the western portion of the Wissahickon Formation. A second factor, responsible for the first appearance in the Patapsco-Raritan of subrounded staurolite grains, was the probable reworking of underlying Patuxent sediments.

The Magothy mineralogy of almost wholly angular quartz grains and abundant fresh, angular staurolite, kyanite, and tourmaline, contrasts strongly with that of the underlying Patapsco-Raritan and points to a rejuvenation of the northern Piedmont region, approximating the conditions which produced the Patuxent clastics. Few abraded grains of any kind can be found in the mostly coarse Magothy clastics of central Maryland, indicating a preponderant source in the adjacent newly-uplifted Piedmont. However, to the east and northeast of Chesapeake Bay, Magothy sands contain varying proportions of subrounded staurolite and tourmaline (Groot, 1955) as well as sporadic chloritoid, garnet, and sillimanite. These sands belong to the probable estuarine facies of the Magothy, and have received contributions of reworked materials from the underlying Potomac Group and possibly from the Appalachians to the north. The presence of small amounts of unstable minerals reflects the first appearance of species more characteristic of the succeeding Upper Cretaceous and Tertiary marine units. The Upper Cretaceous marine units (Matawan, Monmouth, and equivalents) of New Jersey, Delaware (Groot, 1955), and Maryland consistently exhibit a much more varied heavy mineral assemblage than does the outcropping Potomac and Magothy units. Varying proportions of epidote, chloritoid, garnet, sillimanite, and andalusite are important constituents of these units in addition to characteristic Potomac and Magothy species such as staurolite, kyanite, tourmaline, and zircon. Similarly varied suites are found in the marine upper Raritan and Magothy strata of northeastern New Jersey (McCallum, 1957) and throughout most of the subsurface Cretaceous section in extreme eastern Maryland (Anderson, 1948). Dryden and Dryden (1956) have termed this assemblage the "full" suite in contrast to the "limited" suite of the outcropping nonmarine Potomac Group and Magothy Formation. The origin of the full suite and a tenable explanation for its regional and stratigraphic distribution has been a recurrent problem in Atlantic Coastal Plain geology; full discussions of the problem can be found in Dryden and Dryden (1956), and Groot and Glass (1958). The full suite is apparently restricted, within the Cretaceous section, to marine sediments. It is characteristic of the Matawan-Monmouth section, representing wholly marine deposition, and is found as well in marine beds of the Potomac and Magothy sediments in the Raritan Bay region of northeastern New Jersey and in the Delaware subsurface (Groot and Glass, 1958). Potomac-Magothy strata in the eastern Maryland subsurface also contain abundant garnet and epidote-clinozoisite as well as chloritoid, sillimanite, hornblende, kyanite, tourmaline, staurolite, and zircon, and are full suite sediments. Anderson (1948) viewed these beds as mostly fluvial-deltaic in origin; however, recent evidence presented by Groot and Glass (1958) and by Doyle (1966) suggests a more probable marine environment for these rocks. The latter conclusion is further supported by the identification in the proximal subsurface of Maryland, Delaware, and Virginia, of glauconitic, fossiliferous beds in the upper Potomac.

Several possible explanations have been considered for the full suite-limited suite contrast in the mineralogy of the Cretaceous and Tertiary sediments. Pettijohn (1957) viewed the question as one aspect of the more general problem of interstratal solution of unstable minerals. With specific reference to the Coastal Plain sediments of Maryland, he called attention to the increasing mineralogic complexity with decreasing age evidenced by Anderson's (1948) heavy mineral work in the eastern Maryland subsurface. Pettijohn suggested that the older and more deeply buried rocks (Cretaceous) had lost their complement of unstable minerals through large-scale interstratal solution. Dryden and Dryden (1956) and Groot and Glass (1958) took exception to the latter hypothesis, maintaining that the limited suite could not be the consequence of interstratal solution. The Drydens, in summarizing their own sample studies as well as published data, proposed division of the Atlantic Coastal Plain into two geographic parts based on mineralogy – a northern part reaching from New Jersey to North Carolina, and a southern part lying to the south of an ill-defined belt of 100 mile width in northern North Carolina. The Drydens observed:

> "In the north, a limited suite is found in the (generally) older, nonmarine sediments, and a full suite in the rest of the Coastal Plain, Cretaceous to Pleistocene. In the south, a limited suite is found throughout the Coastal Plain sediments, marine and nonmarine, except for low-lying Pleistocene and certain Recent deposits."

In view of these mineralogic contrasts, they rejected a major role for interstratal solution. They concluded:

> "If solution would have produced a limited suite in all these lithologic types (gravel, sand, silt, clay) in the south, it should have been just as nonselective in the north. And if in the north, its action was restricted to the earlier part of Coastal Plain history, it seems unlikely that in the south its action would have continued to the present. Post-depositional solution may have played a role, but apparently not a major one."

Groot and Glass (1958) find support for the Drydens' viewpoint in the identification of full suite marine beds interstratified with limited suite nonmarine beds in Delaware.

An alternative hypothesis, considered as well by the Drydens, proposes the derivation of the full suite through source area diastrophism and consequent exhumation of fresher, unweathered rock. This hypothesis is inconsistent, however, with the observed interbedding of full suite marine sediments and limited suite continental beds in the upper Potomac Group – sediments here interpreted as deposited during a time of low source area relief. It also conflicts with the presence in most of the eastern Maryland subsurface Potomac sediments of a full suite mineralogy in rocks which have been demonstrated to be age equivalent (Doyle, 1966) to the outcropping limited suite Potomac sediments. It is difficult to envision a situation in which sediment streams bearing full suite minerals and originating in the same source area from which the outcrop Potomac was derived, were able to consistently bypass the latter portion of the basin in favor of eastern Maryland.

A third alternative, favored by Groot and Glass (1958), ascribes the contrasting mineral suites to differences in provenance. Thus, the occurrence of abundant unstable minerals such as epidote, garnet, sillimanite, chloritoid, and andalusite in the marine Cretaceous and early Tertiary sediments might reflect a contribution from a source area other than the adjacent Piedmont.

There is little question that interstratal solution has been effective in the removal of unstable minerals from some bodies of rock (Pettijohn, 1941; Boswell, 1933; Bramlette, 1941). However, assuming the validity of the Drydens' conclusions respecting the mineralogy of the northern and southern Coastal Plains, it is difficult to explain this situation through the operation of major interstratal solution. On the other hand, an explanation of the full suite-limited suite contrast in terms of provenance meets with lesser difficulties, but at the same time suffers from a lack of adequate supporting data. Groot (1955), in considering the abundance of epidote and associated full suite species in the subsurface upper Potomac Group of eastern Maryland, favored derivation from the Piedmont to the west and southwest of the depositional basin. However, several lines of evidence suggest that if provenance is indeed the correct explanation, a western or southern source was unlikely:

(1) Epidote as well as other full suite species are rare or absent in the outcropping Potomac Group of Virginia.

(2) If full suite species are lacking in both marine and nonmarine sediments of the southern Coastal Plain as the Drydens point out, then source rocks which did not provide these minerals to the southern Coastal Plain are unlikely to have fed them north to the Potomac basin.

(3) Additional evidence, having a direct bearing on the character of the southern Piedmont, is provided by Pryor's (1960) investigation of Upper Cretaceous sediments in the Mississippi Embayment. Pryor places the source area of these sediments in the Piedmont and Blue Ridge of the southern Appalachian area, probably centered in the Virginia region. The Cretaceous heavy mineral assemblage is dominated by staurolite, kyanite, sillimanite, and tourmaline - essentially a limited suite. Pryor's findings, then, suggest that the full suite was not available in the southern Piedmont during Late Cretaceous time.

As the remaining potential source area lies to the northeast of the Chesapeake-Delaware basin, the possibility that the full suite was derived from the New England region and transported southward into the basin by longshore currents should now be considered. Some aspects of full suite distribution offer indirect support of such a hypothesis. The regional distribution of full suite[4] minerals in the outcropping Monmouth strata may

4/ full suite is here operationally defined to include epidote, garnet, chloritoid, sillimanite, hornblende, and andalusite.

be cited as an example. Monmouth sands in New Jersey contain an average 45 percent collectively of such minerals (Groot, 1955). Southwestward along the strike in Delaware, full suite proportions decrease to 40 percent whereas still farther to the southwest in Maryland, only 25 percent of the Monmouth assemblage is comprised of such minerals. The same generalized trend is suggested by the distribution of full suite mineral species in marine beds of the upper Potomac Group. Groot and Glass (1958) report the assemblage – epidote-garnet-sillimanite-andalusite – as characterizing a glauconitic, fossiliferous Potomac stratum in the northern Delaware subsurface, but similarly glauconitic beds in the upper Potomac and Mattiponi? Formations in the Virginia subsurface, 110 miles southwestward along strike, contain largely zircon with only minor amounts of garnet, chloritoid, and epidote. These admittedly incomplete data do suggest progressively decreasing proportions of full suite components in a southwestward direction – a decrease in the direction of transport if one accepts a hypothesis of New England derivation. To sum up, it must be admitted that the evidence in support of such a hypothesis is far from conclusive; what are clearly needed are mineralogic analyses of strategically located borehole samples within the marine Potomac Group.

DEPOSITIONAL ENVIRONMENTS

POTOMAC GROUP

Previous interpretations

Sediments of the Potomac Group were early regarded by Clark and Bibbins (1897) as shallow-water deposits. Their analysis of the coarse basal Potomac rocks indicated "rapid deposition in shallow waters", followed by "marsh" sedimentation (Arundel clays). The upper Potomac was interpreted as "quieter and deeper water" sediments. The same authors, in a second paper (1902), summarized the Potomac environment as follows:

> "The distinctly estuarine character of the Potomac sediments points to the existence for a long period of an extensive area of more or less brackish water along the eastern border of the North American continent. . . . That it was either a sound, a lagoon, an embayment or an estuary, or a series of these, on a vastly greater scale than any along the Atlantic Coast today, is probable."

Most subsequent investigators have expressed essential agreement with a fluvial-deltaic interpretation. Groot (1955) concluded that the Potomac sediments of northern Delaware recorded deposition on a low-lying coastal plain in stream channels, floodplains, estuaries, and brackish lagoons.

Present interpretations

The outcropping Potomac Group was deposited in a complex of fluvial and deltaic environments.

The predominantly coarse, bimodal character of the basal Patuxent Formation, and the associated abundant plant fragments, scour and fill structures, clay-clast conglomerates, and lenticular bedding, compare well with modern river channel sediments. Analogous deposits are to be found in the basal gravel-rich section of the recent alluvial valley-fill of the Mississippi River. Complexly-interbedded, lenticular units of gravel and coarse sand containing wood fragments and clay clasts compose much of the latter succession (Fisk, 1944).

The general lack of silt-clay strata throughout much of the lower Patuxent attests to the predominance of bedload deposition over associated floodplain sediments. Large-scale inclined bedding, particularly prevalent in gravels and coarse pebbly sands in central Maryland, probably records accumulation on the downstream slipfaces of channel bars, and is analogous to similar bar-bedding in braided channels of the Rivers Durance and Ardeche (Doeglas, 1962). The ubiquitous intraformational clay clasts in Patuxent sands and gravels indicate that rapid channel shifts and accompanying erosion of cohesive clay banks was an important process, and perhaps accounts for the general lack of preservation of overbank fines. Fining-upward point- and channel-bar sequences resemble similar deposits in many modern rivers (Allen, 1965). Further evidence of rapidly shifting channels in the fact that most such cycles in the Patuxent Formation are apparently truncated remnants.

Several lines of evidence suggest braided rivers as the predominant channel pattern operative during Patuxent time, at least during deposition of the coarser portions of the unit in central Maryland and in Virginia. Allen (1965) regards a predominance of coarse materials with little associated overbank sediment as a significant characteristic of the deposits of braided river systems due to the comparative freedom with which active channels are able to comb back and forth across the floodplain. Further, he cites the prevalence of lenticular bedding as also characteristic. Doeglas (1962) similarly concluded that "large macrostructures of braided rivers hardly show any continuous horizontal bedding". The texture and bedding character of Patuxent clastics agree well with the foregoing criteria. However, Allen notes as well that the directional element variance of braided channel deposits should be relatively small because of low channel sinuosity. Patuxent cross-bedding variance is decidedly higher than might be expected if braided rivers were involved; yet it should be noted that factors other than overall channel sinuosity may combine to affect total variance – as for example, arcuation of the sedimentary strike and changes in current direction with time. Both of these variables have contributed in some degree to the lack of current direction uniformity in the present case. It was earlier observed that successive minor sediment pulses, perhaps representing periodic flood stages, exhibit internally consistent current patterns but divergent directions through successive pulses and serve in part to increase outcrop variability. Such a sedimentation plan is not incompatible with a braided river pattern in which channel shifts with successive floods are common.

An increase in the abundance of fine-grained materials – clays, silty clays, and fine sands – in the upper Patuxent Formation, particularly in northeastern Maryland and Delaware, suggests that decreasing river gradients favored the deposition and preservation of overbank sediments – floodbasin deposits, channel fills, and minor carbonaceous backswamp sediments. Groot (1955) believes that a portion of the Patuxent in Delaware was deposited in estuarine environments.

The Arundel clay was apparently laid down in quiet, shallow, fresh-water environments. The association of massive lignitic clays, logs and rooted stumps, terrestrial reptile bones, and the complete absence of marine fossils points to deposition in shallow, probably discontinuous, backswamp basins maintained by ponded drainage and slow sediment influx. Recent backswamp deposits of the Lower Mississippi Valley are analogous in most respects (Fisk, 1944). Reddish-brown to gray, highly- carbonaceous clays and silty clays, commonly without recognizable bedding, and containing logs, stumps, and lignite layers, characterize these Mississippi sediments. Fisk relates such deposits to swamp networks preserving drainage patterns inherited from the original topography.

Clays in the Arundel Formation as well as some Patapsco-Raritan clays generally exhibit a network of abundantly-slickensided fracture surfaces. This structure is common in underclays, indeed in floodbasin deposits in general, and is regarded by Allen (1965) and by Grim and Allen (1938) as a result of dessication and consequent shrinkage before burial. Schultz (1958), on the other hand, believes that the slickensides indicate "compaction of a sediment deposited in a loose, hydrous condition". It was not determined whether either of these hypotheses applies in the case of Potomac clays; however, if the latter (compaction) was important, a possible explanation is provided for the lack of bedding in the Arundel facies. Similarly massive clays were attributed by Keller (1946, p. 68) to random clay particle orientation developed in a clay-water colloidal suspension, seemingly analogous to Schultz's "loose, hydrous condition". An alternative explanation of structureless clays presumes destruction of original bedding by the churning action of plant roots (Huddle and Patterson, 1961).

Patapsco-Raritan sedimentation records the reestablishment of through drainage. Marine fossils and glauconite are absent in nearly all of the outcropping Patapsco-Raritan deposits, indicating the persistence of essentially continental environments. Many of the same features which characterize the lower Potomac are found as well in the upper Potomac. Abundant plant remains and clay clasts, as well as scoured and refilled channels, and lenticular, irregular bedding occur in all outcrop areas. However, significant differences are also apparent. Gravels and coarse sands are less common; fine to medium sands, silts, and thick clay units predominate. Carbonaceous clays containing logs and wood chips are common. Sand bodies of probable point bar origin are present throughout the section but are generally separated by clay units which vary abruptly in thickness laterally. The fine-grained units are commonly massive but also include laminated silt-clay successions, and thinly-interbedded fine sands and silty clays. All of the latter bedding types are common in modern floodbasin sediments (Allen, 1965).

The structures and textural character of the Patapsco-Raritan Formation suggest deposition on a low deltaic plain by sluggish, low-gradient, perhaps meandering rivers. Flooding accompanied by suspended load deposition in contiguous floodbasins and backswamp areas was probably a major sedimentation process and would amply account for the predominance of fine-grained sediments. Recent sediments of the Orinoco delta along the western margin of the Gulf of Paria provide a modern example of an environment similar in most respects to that here postulated. The sediments of the inner delta and adjacent estuaries are moderately-sorted to well-sorted, fine to medium, orthoquartzitic sands interbedded with dark silts and carbonaceous clays (Van Andel and Postma, 1954). *F*-type sands, *S* clays, and *FS* mixtures predominate. Deposition is by rivers and tidal streams. Faunal remains are absent with the exception of rare fresh-water invertebrates. The present surface of the delta is a low alluvial plain traversed by meandering Orinoco distributaries and backswamp rivers. The distributary beds and bars consist of sand with grain size decreasing downstream. Backswamp rivers drain the broad, swampy, clayey and peat-rich interfluve floodbasins which are wholly submerged during the Orinoco flood season and receive suspended fines. The distributaries broaden into wide estuaries in the lower delta which are marked by marginal mud flats and numerous sand bars.

That the Patapsco-Raritan shoreline lay not far to the east is demonstrated by glauconitic, probably marginal marine beds a few miles downdip in the subsurface. Rare glauconitic beds within the outcrop belt suggest a near sea-level terrain in which strand-line oscillation played some role during deposition.

MAGOTHY FORMATION

Previous interpretations

Darton (1893) thought the Magothy Formation a "product of littoral deposition" whereas Clark (1916) regarded the Magothy as a lagoonal deposit. Most modern workers (Otton, 1955; Overbeck and Slaughter, 1958; Groot, 1955) have adopted similar interpretations of deposition in largely marginal environments including deltaic, lagoonal, and estuarine.

Present interpretation

The widespread but thin Magothy sediment sheet is best interpreted as a record of environments transitional between the preceding alluvial sediments of the Potomac Group and overlying wholly-marine deposits.

The prevailing structures and textural character of the coarse Magothy clastics preserved in a narrow belt along the southwestern outcrop margin are similar in most important respects to those of the fluvial basal Potomac sediments. Bimodal gravels, trough cross-bedded coarse sands, inclined bedding, plant remains, unidirectional sediment transport, and the absence of fauna typify this facies of the Magothy Formation and point to fluvial deposition with a predominant channel phase, analogous with Patuxent sedimentation.

The more-extensive eastern to northeastern facies of the Magothy, on the other hand, exhibits a contrasting character. The major lithologic associations of this facies – i.e., interbedded lignitic, pyritic dark silts and clays and clean moderately-well-sorted sands; and closely alternating fine rippled sands and laminated dark silt-clay – suggest estuarine deposition. Sediments in the estuaries and pro-delta environments of the Orinoco delta are clean well-sorted sands, and brown to black pyritic silts and clays (Van Andel and Postma, 1954). Fauna are rare to absent. Laminated sediments, consisting of alternating thin layers of clay and pure sand, characterize some tidal channels. The resemblance between these sediments and much of the northeastern facies of the Magothy Formation is striking, and supports an estuarine-marginal deltaic environmental interpretation. Further support is gained from the current reversals observed in some Magothy sand bodies, suggesting tidal influence.

Grains of lignite are abundant in many Magothy sands as is mica in the fine sands and silts. Both of these constituents are common in lower Mississippi delta environments including the delta-front platform, delta slope, and the interdistributary bays as well as the subaerial portions, but are rare in marine sediments on the outer delta slope where glauconite first becomes apparent (Shepard, 1960).

Most of the evidence indicates, then, that the outcropping Magothy Formation accumulated in river channels in the southwest, whereas further east and northeast, transitional environments including estuaries and possibly bays and lagoons predominate.

PALEOGEOGRAPHY AND GEOLOGIC HISTORY

INTRODUCTION

Following the deposition of Triassic redbeds in a series of isolated fault troughs along the exposed crystalline axis of the Appalachians, a prolonged period of erosion commenced which lasted through the whole of Jurassic time. Jurassic sediments are not positively known from the Chesapeake-Delaware Embayment, nor from the whole of the Atlantic Coastal Plain; strata of Jurassic age may possibly be represented in the basal portions of the subsurface Mesozoic section of the Carolinas, extreme eastern Maryland, and on the adjacent continental shelf (Maher, 1965).

During this period of denudation, the Piedmont region of the Middle Atlantic states was reduced to a surface of relatively low relief, although probably not a peneplain in the classic sense of Davis (1889). The local relief of the buried crystalline surface as indicated by borings in central Maryland may be as great as 150 feet (Mathews, 1935; Cleaves, 1968). At the same time, profound argillic weathering produced a deep saprolite mantle over most if not all of the Piedmont. Present data indicate an average 40 to 50 feet of saprolite overlying unweathered crystalline rocks beneath basal Cretaceous sediments and preserved in discontinuous patches on the exhumed eastern Piedmont of central and northeastern Maryland (Cleaves, 1968). Saprolite thickness may reach 110 feet or more in some areas.

POTOMAC GROUP

Patuxent Formation

Early in Cretaceous time, the Piedmont-Blue Ridge province was uplifted, and Potomac sedimentation was initiated in a broad, subsiding basin, open-ended to the east. Deposition very likely began near or somewhat beyond the present coast line. These early-deposited sediments are poorly known, only a very few borings having reached the deeper horizons of the subsurface in this area. Fine to medium, well-sorted feldspathic sands, lead-colored clays, and subordinate green and brown mottled clays are the dominant lithologies (Anderson, 1948) which rapidly succeed each other in generally thinner beds than are present in outcrop to the west. Glauconitic and calcareous sands are of sporadic occurrence. The latter lithologies and the presence of hystrichospheres in the clays indicate at least partly marine deposition. The coarse gravels and sands, white clays, and brightly-variegated clays of the outcropping lower Potomac Group are lacking. The admittedly meagre evidence suggests deposition in a marginal environment in which both marine and continental influences were felt.

During this early period, rivers draining the newly-uplifted source region became shallowly incised along the basin margin in response to heightened gradients. The lateral spacing of such paleochannels suggests that early Cretaceous rivers in central Maryland were separated by intervals of 15 miles or so. Sites of deposition apparently migrated slowly westward toward the present outcrop belt. Anderson (1948) has suggested correlation with the outcropping Patuxent Formation of a staurolite-rich zone approximately 700 feet above the presumed base of the Potomac section in the eastern Maryland subsurface.

Deposition of the outcropping Patuxent sediments was accomplished by northeastward, eastward, and southeastward flowing rivers, heading for the most part in the adjacent Piedmont perhaps 10 to 100 miles to the west of depositional sites. Predominantly coarse clastics were deposited on an aggrading coastal plain to the east by relatively high gradient, perhaps initially braided river systems. Rapidly shifting channels, probably a response to periodic flooding, resulted in frequent truncation of earlier deposited bar sequences and prevented the preservation of overbank sediments. The abrupt relocation of channels is also the probable cause for local shifts in current direction.

Sediment carried into the basin was laid down as an alluvial wedge in which at least two petrographic provinces can be distinguished. The two provinces are petrographically distinct by virtue of deposition from river systems with contrasting drainage basin geology and relief.

Rivers draining the Maryland-Pennsylvania Piedmont region flowed mostly eastward to southeastward. The headwaters of some of the larger streams reached into the nearby Appalachians, bringing sandstone clasts, minor amounts of chert, and polycycle quartz, zircon, and tourmaline grains into the basin. However, the greater part of the sediment load carried by the rivers of Patuxent time was derived from the deeply-weathered Piedmont crystalline rocks. Metaquartzite and vein quartz clasts, angular quartz grains, and equally angular tourmaline, staurolite, kyanite, and zircon were the major contributions. Feldspar and other chemically unstable minerals were probably destroyed by intersive weathering within the deep saprolite mantling the Piedmont.

River systems emerging from the Virginia Piedmont, on the other hand, carried detritus eastward and northeastward for the most part. The Virginia Patuxent source area was apparently an upland of moderate to relatively high relief in which were exposed high proportions of granitic and gneissic rocks. High-grade schists, important in the Maryland-Pennsylvania source area, were very minor elements through most of this region but increased in importance in the extreme south. Large amounts of incompletely weathered debris, including abundant feldspar and clasts of crystalline rocks, were carried into the basin from the Virginia upland, suggesting that higher gradient streams draining the upland were able to trench through the weathered mantle, exposing fresh rock to erosion.

The character of the early Cretaceous floras in the study area support a postulated warm, wet climatic regime. Brenner (1963) finds strong similarities between the Potomac flora and modern warm temperate New Zealand rain forests in which broad-leaved conifers and abundant ferns are the dominant vegetation.

An interesting comparison may be drawn between the central Maryland Patuxent Formation and the Pliocene (?) Brandywine gravels of southern Maryland, the latter regarded by Schlee (1956) as ancestral Potomac River gravels. The Brandywine and Patuxent clastics were derived from much the same source region – the Piedmont, Blue Ridge, and Appalachian areas to the west. The gravels of both units are similar in being mineralogically mature, highly quartzose residues. However, the Brandywine reflects a larger contribution from the folded Appalachians than do the Patuxent clastics. Significantly higher proportions of chert in the Brandywine gravels, averaging 20 percent of the gravel fraction, support this conclusion. The accompanying sand fraction contains similarly high amounts of Appalachian-derived detritus. The sands average 5 percent chert, and 19 percent of the total quartz is made up of polycycle grains. Schlee suggested that the potential Piedmont contribution was considerably reduced by source area weathering, a situation analogous to that indicated for the Patuxent. Crystalline rock clasts are rare in the gravels, and feldspar constitutes only trace amounts of the sand fraction. The heavy mineral suite is dominated by zircon and tourmaline with minor amounts of hornblende, rutile, staurolite, and sphene.

The mineralogic differences between the two units can very likely be attributed to contrasting drainage basins. The ancestral Potomac River, as is the case with the modern stream, probably drained a large area wholly within the folded Appalachians as well as some portion of the adjacent Piedmont region, and thus received a proportionately large sediment contribution from the Appalachians. The rivers of Patuxent time, in contrast, headed largely within the Piedmont with only a few streams having headwaters extending into the folded Appalachians. The paucity of staurolite in the Brandywine sands, which contrasts strongly with its abundance in the Patuxent, may be explained by: (1) dilution by larger proportions of Appalachian-derived detritus, and/or (2) minimal exposure of staurolite-bearing schists within the drainage basin of the Pliocene (?) Potomac River. That the latter may have been the more important factor is suggested by the present distribution of such schists (Figure 47).

Arundel Formation

It is unlikely that the abrupt change from Patuxent sand and gravel deposition to the dark, carbonaceous clays of the Arundel in central Maryland represents an unconformity of any great magnitude. As Brenner (1963) has noted, Patuxent and Arundel sediments are palynologically inseparable. A decrease in the paleoslope to the east arising from base-leveling in the source area and/or decelerating subsidence basinward could well have resulted in considerably reduced stream gradients at the close of Patuxent time. Deposition of suspended fines might then have followed in low areas of ponded drainage, probably including marshes, swampy lakes, and abandoned channels. It is indeterminate whether comparable sediments were deposited as well in the northeastern Maryland, Delaware, and Virginia outcrop areas and subsequently removed by pre-Patapsco erosion, or alternatively, if nondeposition was truly the case. Lithologic equivalents are apparently absent in these areas; neither can they be identified basinward in the subsurface.

Patapsco-Raritan Formation

Following deposition of the Arundel clays, the source region was again subjected to mild uplift and stream gradients quickened along the basin margin, initiating a relatively brief erosional interval. Groot (1955) speculated that the amount of sediment removed from the outcrop zone was small. Brenner's analysis (1963) of the Arundel-Patapsco floral transition lends support to this supposition. The proportions of new forms introduced in the lower Patapsco were quite low, pointing to a relatively brief Arundel-Patapsco hiatus which perhaps spanned a small portion only of Aptian time.

Deposition of the outcropping Patapsco-Raritan strata took place on a low coastal plain traversed by low-gradient, probably meandering rivers. Broad flood-basins and swampy interfluves were important features of the environment. The broad drainage lines established in early Patuxent time were only slightly modified by Patapsco-Raritan paleogeography. Rivers carrying sediment into the basin from the Maryland-Pennsylvania source region were directed more generally to the southeast than were Patuxent streams. Lowered river gradients and Patapsco-Raritan mineralogic impoverishment suggest a subdued Piedmont topography in which chemical weathering was more complete than during earlier Cretaceous time. Highly quartzose sands and a stable zircon-tourmaline heavy mineral suite were the major Piedmont contribution. Increased headward erosion of larger streams into the Appalachian region resulted in a progressive dilution of Patapsco-Raritan clastics with polycyclic grains of quartz, zircon and tourmaline. Reworking of Patuxent sands and gravels provided additional second-cycle materials.

The paucity of data from the Virginia area does not permit firm conclusions regarding Patapsco-Raritan paleogeography in the southern region of the basin. The available data indicate, however, that northeastward transport of relatively unweathered detritus, only slightly lower in feldspar than underlying Patuxent clastics, continued, suggesting persistence of the granitic or gneissic upland in the Virginia Piedmont.

The progressive encroachment of the sea during Patapsco-Raritan time has been previously noted. Although fairly well-sorted, clean, sheet-form sands are intercalated within the uppermost outcrop Potomac in central Maryland, the generally excellent sorting and rounding as well as the characteristic primary structures associated with modern beach, dune, or offshore bar sands are lacking, with the exception of the fragmentary evidence offered by the residual sandstone blocks. The general absence of strandline features in the face of probable marginal marine sediments a short distance eastward suggests a vegetated, swampy shoreline along which beach and dune forming processes were largely inoperative.

Sediments in the eastern Maryland subsurface assigned by Anderson (1948) an Arundel through Raritan age, comprise a thick succession of mostly white to dark-green, well-sorted, fine to medium sands closely interbedded with dark clays. The clays increase in frequency upward within the section. As earlier indicated, much if not all of this section is probably marginal marine in character. The progressive vertical increase in clays, fine sands, and glauconite suggests increasingly marine and perhaps deepening waters.

MAGOTHY FORMATION

At the close of Potomac time, a re-elevation of the source areas bordering the basin precipitated a short erosional period which probably occupied most of the Turonian (Dorf, 1952). Sedimentation was resumed in the northern half of the Embayment with deposition of the Magothy clastics. The absence of known correlative sediments in Virginia may indicate continued uplift in the southern Embayment region during this period in which Potomac strata were involved. If so, further basinal subsidence might then have been confined to the area east and northeast of central Maryland. On the other hand, sediments correlative with the Magothy may be unrecognized in the Virginia subsurface. However, the first alternative is considered more likely correct in view of the apparent progressive shift northward within the Embayment of the axis of maximum subsidence through Cretaceous time (Glaser, 1967).

In the central Maryland region, coarse Magothy clastics were carried southeastward into the basin by one or more river systems draining the uplifted Maryland Piedmont. The similarity between these sediments and the earlier Patuxent clastics is notable, suggesting parallel conditions of sedimentation. The mineralogy of the fluvial facies of the Magothy indicates derivation almost wholly from the Piedmont crystallines with little or no Appalachian contribution in central Maryland. Localized drainage of the eastern Piedmont would seem indicated. The Magothy Formation grades eastward and northeastward into a mixed fluvial-estuarine-lagoonal facies in which polycyclic materials derived from the Appalachian region to the northwest and from reworking of Potomac sediments increase in abundance, although the Piedmont contribution remains dominant. Subsurface data respecting the Magothy eastward and southeastward within the basin is generally lacking; however, the close position of the shoreline is supported by the presence of probably nearshore marine clays and subordinate very fine sands at this horizon in the Delaware, eastern Maryland, and southern New Jersey subsurface.

FALL LINE AND SHORELINE

The early Cretaceous fall line or basin margin, here regarded as the line demarcating the source areas undergoing erosion to the west from the alluvial plain to the east, was apparently located a short distance inland from the present outcrop margin, perhaps only a few miles. Its position can be qualitatively fixed in the Maryland-Pennsylvania area between the westernmost Patuxent Formation outliers and an arcuate zone following the outcrop belt of the eastern Wissahickon Schist. The vertical variation in textural, mineralogic, and gross lithologic parameters within the Potomac Group indicates a generalized westward shift in the fall line during later Potomac time. Some direct evidence bearing on this question stems from the existence of a presumed Patapsco-Raritan outlier on the Pennsylvania Piedmont near Harmonville, some 30 miles northwest of the present outcrop limit (McCallum, 1957). Although similar outliers have not been recognized to the southwest, a westward fall line shift of like magnitude may be indicated in Maryland where the deficiency of staurolite in the Patapsco-Raritan Formation suggests the possibility of a sediment cover on the Wissahickon schist belt during late Potomac time.

The approximate position of the Magothy fall line can be inferred, at least in central and probably northeastern Maryland, from similar evidence indicating reinvolvement of the schist belt as a source rock body. An eastward shift, perhaps to a position coincident with the early Potomac fall line, is suggested.

The relative position through time of the Potomac-Magothy shoreline records a major transgression of the sea into the Embayment, punctuated by minor reversals. During earliest Cretaceous time, the shoreline was probably located somewhat beyond the present Atlantic Coast. By the close of Patuxent time, a position in easternmost Maryland is suggested by partly-marine sedimentation in the Wicomico-Worcester Counties area (Figure 49). Interbedded marine and nonmarine sediments in the Patapsco-Raritan Formation of northern Delaware and southern Maryland point to a major advance of the sea during late Potomac time, reaching nearly to the present fall zone in some areas (Figure 49). The probable presence of late Potomac equivalents in the subsurface Mattiponi formation of Virginia argues for transgression extending to the southern portion of the Embayment as well. A partial withdrawal of the sea may have accompanied the deposition of relatively coarse clastics along the basin margin during Magothy time. A concurrent reduction in the area of active sedimentation within the Embayment is also indicated. By latest Cretaceous time, the transgression begun with the initiation of deposition in the Chesapeake-Delaware Embayment was completed with wholly marine Matawan-Monmouth sedimentation.

POST-MAGOTHY SEDIMENTATION

The marine clays and greensands of the Matawan and Monmouth Groups succeed the Magothy over most of the Maryland, Delaware, and New Jersey Coastal Plain. Unconformable relations proximal to the basin margin between these marine units and progressively older underlying Potomac-Magothy strata to the southwest may point to some planation of the latter units by the advancing late Cretaceous sea. There is no evidence to suggest that similar unconformities persist basinward where deposition may have been continuous, perhaps through the whole of Cretaceous time. The shoreline may have reached inland to or perhaps beyond the present fall zone, in that the truncated margins of late Cretaceous marine sediments closely approach the crystalline border in south-central and southern Maryland.

The pregressive eastward rotation of the Matawan and Monmouth strike relative to the underlying beds in the study area persists as well into New Jersey where Minard and Owens (1960)

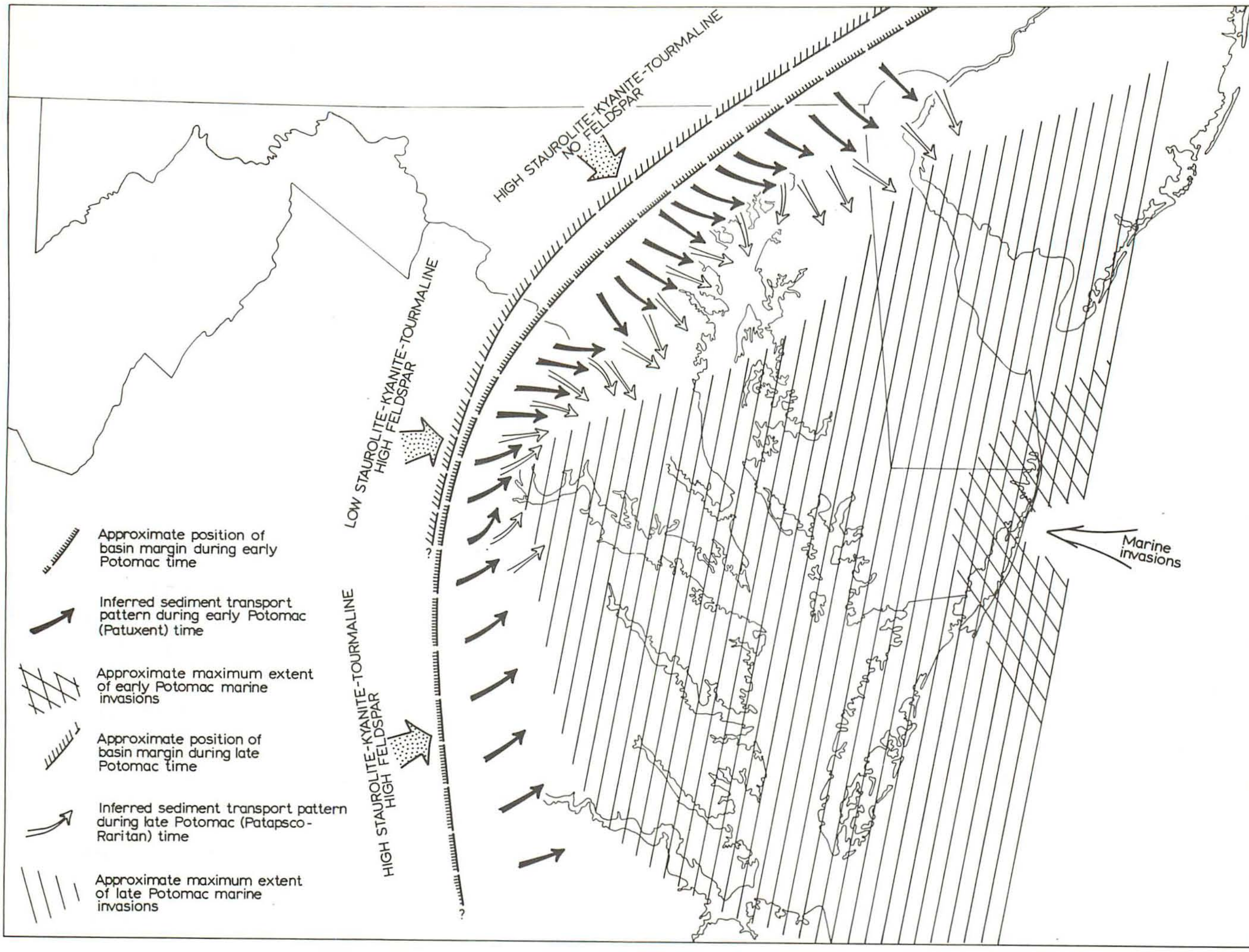


Figure 49. Depositional and paleogeographic framework of the Potomac Group.

regard this phenomenon as the result of differential uplift and consequent erosion to the north. Thus the nearshore facies of marine Cretaceous and Tertiary strata were removed in the northern New Jersey Coastal Plain, and deeper water offshore sediments exposed in an eastward-shifted outcrop belt. Although the late Cretaceous marine units in Maryland remain relatively unstudied, some observations tend to support this hypothesis, e.g. the presence of a basal gravel in the Monmouth of central and southern Maryland suggests nearshore deposition, while to the northeast, late Cretaceous marine sediments are thicker and more glauconitic, perhaps indicating a deeper water facies.

Thickness variation in the Matawan-Monmouth sequence points to a continuation of the northward shift of the axis of maximum subsidence within the Embayment during late Cretaceous time. Minard and Owens (1960) have postulated a significant downwarp in the vicinity of Delaware Bay during the latter time, a conclusion borne out by data assembled for this study.

By the close of Cretaceous time, the Embayment was nearly filled (Ewing *et al.*, 1950). However, it maintained an active influence on basal Tertiary deposition which succeeded in slowly-shoaling, inner neritic marine waters (Drobnyk, 1965).

DEPOSITIONAL MODEL

The formulation in recent years of the generalization which recognizes that the fill of a sedimentary basin is an organized and predictable response to a given pattern of dispersal has led to broad use of the model concept in sedimentology. The limited number of major dispersal patterns and basin geometries imply a relatively few sedimentary models which are recurrent in time and space (Potter and Pettijohn, 1963). The Chesapeake-Delaware Embayment can be regarded drilling, and it is likely that additional data will bring to light minor complexities in the rather simple model here proposed, particularly with regard to arrangement of lithic fill and migration of the zone of maximum subsidence in time. However, the broad similarities existing between the Chesapeake-Delaware basin and the Mississippi Embayment prototype are more striking than their dissimilarities and strongly suggest that a common sedimentary model is in fact the case.

as a somewhat modified version of Pryor's Mississippi Embayment model (Pryor, 1960). Table 8 summarizes and compares the essential features of the two basins. Many of the same similarities exist as well between the Chesapeake-Delaware Embayment and the Chesterian Illinois Basin.

Unfortunately, the more distal portions of the basin fill of the Chesapeake-Delaware Embayment are as yet poorly known due to the paucity of deep

Table 8. Comparison of Chesapeake-Delaware Embayment with Mississippi Embayment sedimentary model

	MISSISSIPPI EMBAYMENT	CHESAPEAKE-DELAWARE EMBAYMENT
BASIN GEOMETRY	Oblong basin widening and deepening down plunge to south; symmetrical transverse cross-section	Broadly oblong basin widening and deepening down plunge to east; mildly asymmetric cross-section
DIRECTIONAL STRUCTURES	Chiefly thick cross-beds which reflect a paleoslope parallel or subparallel to basin axis	Cross-beds which generally reflect paleoslope; centripetal components along southern basin margin which are normal to or greater than arcuation of sedimentary strike
LITHIC FILL	Protoquartzitic, principally nonmarine sands 30%, clay 50%, impure calcilutites and chalks 20%; minor lignites and coals	Clays greater than orthoquartzitic, protoquartzitic, and arkosic sands and gravels, principally nonmarine. Marine clays and glauconitic sands important basinward; very minor limestones and chalks; minor lignites
ARRANGEMENT	Total section expands down paleoslope. Longitudinal clastic filling. Delta pattern at updip end; carbonates and marine clays downdip	Total section expands down paleoslope. Longitudinal as well as centripetal filling. Fluvial and deltaic environments updip; marine clays, glauconitic sands, and minor carbonates downdip
TECTONIC SETTING	Mild to moderate subsidence in basin. Mild uplift of distal source area.	Mild to moderate subsidence in basin. Mild to moderate uplift of principally proximal source area

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APPENDIX A

OUTCROP LOCALITIES

The following localities were visited during the course of this investigation for the collection of crossbedding, petrologic, and stratigraphic data.

1. Md., Anne Arundel Co., POTOMAC, drainage ditch on west side of Md. Rt. 3, 1.6 miles north of Severn Run.

2. Md., Anne Arundel Co., POTOMAC, stream gully 400 ft. west of Md. Rt. 3, .2 mile south of Dorrs Corner.

3. Md., Anne Arundel Co., MAGOTHY, small gravel pit on Waugh Chapel Rd., .8 mile west of Md. Rt. 3.

4. Md., Anne Arundel Co., POTOMAC, Pennsylvania Railway cut, 100 ft. southwest of Md. Rt. 424 at Forks Church.

5. Md., Prince Georges Co., MONMOUTH, road cut on Race Track Rd., .5 mile north of U.S. Rt. 50.

6. Md., Prince Georges Co., POTOMAC, stream bank 100 ft. northeast of Race Track Rd., .4 mile north of U.S. Rt. 50.

7. Md., Anne Arundel Co., POTOMAC, road cut on Gambrills Rd., .25 mile north of Discus Mill Rd.

8. Md., Anne Arundel Co., MAGOTHY, gravel pit on south side of Dairy Farm Rd., .5 mile east of Waugh Chapel Rd.

9. Md., Prince Georges Co., MONMOUTH, construction excavation on north side of U.S. Rt. 50, 1.15 miles east of Md. Rt. 197.

10. Md., Prince Georges Co., POTOMAC, sand pit on north side of Glenn Dale Rd., .4 mile east of Baltimore-Washington Parkway.

11. Md., Prince Georges Co., POTOMAC, construction excavations at intersection of U.S. Rt. 50 and Riverdale Rd.

12. Md., Prince Georges Co., POTOMAC, road cut of the Capital Beltway at Ardmore Rd.

13. Md., Prince Georges Co., POTOMAC, road cuts at intersection Md. Rts. 704 and 202 at Dodge Park.

14. Md., Prince Georges Co., POTOMAC, abandoned sand pit on north side of Addison Rd. at Reed St.

15. Md., Prince Georges Co., POTOMAC, road cuts of the Capital Beltway at Edmonston Rd.

16. Md., Prince Georges Co., POTOMAC, abandoned sand pits on north and south sides of East-West Highway at Queens Chapel Rd.

17. Md., Harford Co., POTOMAC, B. & O. Railway cut at Md. Rt. 152, 1 mile east of Joppa.

18. Md., Harford Co., POTOMAC, sand pit on south side of U.S. Rt. 40, .6 mile southwest of Md. Rt. 408.

19. Md., Harford Co., POTOMAC, road cut of the Kennedy Expressway at Abingdon Rd.

20. Md., Harford Co., POTOMAC, B. & O. Railway cut at Abingdon Rd.

21. Md., Harford Co., POTOMAC, highway fill pit on the northwest side of Md. Rt. 7, .6 mile northeast of Md. Rt. 158.

22. Md., Cecil Co., POTOMAC, B. & O. Railway cut at Jackson, 1000 ft. southwest of Jackson-Blythedale Rd.

23. Md., Baltimore Co., POTOMAC, road cuts for Whitemarsh Interchange of Kennedy Expressway.

24. Md., Howard Co., POTOMAC, gravel pits of Arundel Corp., 1.5 miles west of Waterloo.

25. Md., Howard Co., POTOMAC, sand pit on southeast side of U.S. Rt. 1, 1000 ft. northeast of Md. Rt. 32.

26. Md., Baltimore City, POTOMAC, construction excavation at northeast corner of Northern Parkway and McClean Blvd.

27. Delaware, Newcastle Co., MAGOTHY, south bank of Chesapeake and Delaware Canal, 500 to 1000 ft. west of Summit Bridge.

28. Md., Cecil Co., POTOMAC, abandoned sand pit on west slope of Grays Hill, north side of Md. Rt. 281, 1.1 miles northeast of Elkton.

29. Md., Cecil Co., MAGOTHY, south bank of Chesapeake and Delaware Canal at Bethel.

30. Md., Cecil Co., POTOMAC, road cut of Kennedy Expressway, .7 mile west of Md. Rt. 280.

31. Md., Cecil Co., POTOMAC, bluffs along the east bank of Northeast River at Maulden Mt., Elk Neck.

32. Md., Cecil Co., POTOMAC, road cut on east side of CCC Camp Rd., .6 mile south of Md. Rt. 272.

33. Md., Prince Georges Co., POTOMAC, construction excavation at northeast corner of Livingston Rd. and Indian Head Highway.

34. Washington, D.C., POTOMAC, abandoned sand pit on west side of Wheeler Rd., 400 ft. south of Oxon Run.

35. Washington, D.C., POTOMAC, road cut on east side of Branch Ave., 1200 ft. north of Pennsylvania Ave.

36. Washington, D.C., POTOMAC, abandoned sand pit, 2400 ft. east of the intersection of Bladensburg Rd. and the Baltimore-Washington Parkway.

37. Md., Cecil Co., POTOMAC, Mason sand and gravel pits, north side of U.S. Rt. 40, 3.0 miles east of Md. Rt. 272.

38. Md., Cecil Co., POTOMAC, Mason-Dixon sand and gravel pits, intersection of U.S. Rt. 40 and Md. Rt. 7.

39. Md., Montgomery Co., POTOMAC, abandoned gravel pit, 1000 ft. south of Fairland-Beltsville Rd., .5 mile southeast of Columbia Rd.

40. Md., Montgomery Co., POTOMAC, Contee Co. gravel pit, 1.0 mile south of Columbia Rd., 1.2 miles northeast of the U.S. Naval Ordnance Laboratory.

41. Md., Anne Arundel Co., POTOMAC, highway fill pits at intersection of Mountain Rd. and Old Annapolis Rd.

42. Md., Anne Arundel Co., MAGOTHY, road cut on south side of Mountain Rd., 1800 ft. west of Forest Glen Rd.

43. Md., Anne Arundel Co., POTOMAC, Arundel Corp. sand pit, 500 ft. east of Old Annapolis Rd. at Pasadena.

44. Md., Anne Arundel Co., POTOMAC, road cut for gravel road at Mt. Zion Church, .5 mile east of Laurel Race Track.

45. Md., Prince Georges Co., POTOMAC, Contee Co. sand and gravel pits, south side of Van Dusen Rd., 2000 ft. east of Old Gunpowder Rd.

46. Md., Prince Georges Co., POTOMAC, H. & W. sand and gravel pit, 1400 ft. northeast of the intersection of Old Gunpowder Rd. and Fairland-Beltsville Rd.

47. Md., Anne Arundel Co., POTOMAC, Reagle sand pit, 1500 ft. northwest of the intersection of Quarterfield Rd. and Md. Rt. 3.

48. Md., Anne Arundel Co., POTOMAC, Link sand pit, east side of Ridge Rd., 1.0 mile north of Dorsey Rd.

49. Md., Anne Arundel Co., POTOMAC, abandoned public roads pit, east side of Ridge Rd., .5 mile southeast of Elkridge.

50. Md., Prince Georges Co., POTOMAC, Landover sand pit, north side of county road, .5 mile west of Bowie.

51. Md., Baltimore Co., POTOMAC, abandoned clay pit, west side of intersection Baltimore Beltway and Md. Rt. 7.

52. Md., Baltimore Co., POTOMAC, abandoned sand and gravel pit, south side of Md. Rt. 149, 1500 ft. west of Ebenezer Church.

53. Md., Baltimore Co., POTOMAC, road cuts for Whitemarsh Blvd. at U.S. Rt. 40.

54. Md., Baltimore Co., POTOMAC, construction excavation on southeast side of county road, 1.1 miles east of Poplar.

55. Md., Harford Co., POTOMAC, abandoned gravel pit. east side of Md. Rt. 462, .75 mile north of Md. Rt. 22.

56. Md., Harford Co., POTOMAC, road cut for Kennedy Expressway at Md. Rt. 22.

57. Md., Harford Co., POTOMAC, road cut for Kennedy Expressway, 1200 ft. east of Md. Rt. 157.

58. Md., Cecil Co., POTOMAC, road cuts for Blythedale Interchange of Kennedy Expressway.

59. Md., Cecil Co., POTOMAC, road cut for Kennedy Expressway at Md. Rt. 280.

60. Md., Cecil Co., POTOMAC, road cut for Kennedy Expressway interchange at Md. Rt. 316.

61. Va., Fairfax Co., POTOMAC, Ft. Belvoir Military Railway cut, .8 mile northwest of Accotink Rd.

62. Va., Alexandria, POTOMAC, abandoned sand pit, north side of Edsall Rd., .3 mile west of Lincolnia Rd.

63. Va., Alexandria, POTOMAC, abandoned sand pit, immediately west of U.S. Army Depot, Cameron Station.

64. Va., Arlington Co., POTOMAC, construction excavation on north side of Columbia Pike, 1500 ft. west of Fourmile Run.

65. Va., Arlington Co., POTOMAC, road cut on east side of Arlington Ridge Rd., 1500 ft. north of Glebe Rd.

66. Va., Fairfax Co., POTOMAC, construction excavation on northwest side of U.S. Rt. 1, 2000 ft. southwest of Huntington Ave.

67. Va., Fairfax Co., POTOMAC, road cut on south side of Telegraph Rd., 1200 ft. east of Beulah Rd.

68. Va., Prince William Co., POTOMAC, R. F. & P. Railway cut, 1000 ft. south of Neabsco Creek.

69. Va., Prince William Co., POTOMAC, road cut on west side of U.S. Rt. 1, .65 mile south of Neabsco Creek.

70. Va., Prince William Co., POTOMAC, road cut on south side of U.S. Rt. 1, 2000 ft. west of Pohick Church.

71. Va., Prince William Co., POTOMAC, road cuts for gravel road at intersection with U.S. Rt. 1, 1500 ft. south of Featherstone.

72. Va., Prince William Co., POTOMAC, R. F. & P. Railway cut at Cockpit Point.

73. Va., Prince William Co., POTOMAC, abandoned sand pit on east side of U.S. Rt. 1, 1000 ft. north of Triangle.

74. Va., Stafford Co., POTOMAC, road cut on east side of U.S. Rt. 1, .6 mile north of Austin Run.

75. Va., Stafford Co., POTOMAC, road cut on east side of U.S. Rt. 1, 1.2 miles north of Aquia Creek.

76. Va., Stafford Co., POTOMAC, R. F. & P. Railway cut 1 mile south of Aquia Creek.

77. Va., Stafford Co., POTOMAC, road cut on north side of Va. Rt. 17 at Falmouth.

78. Va., Stafford Co., POTOMAC, road cut on east side of U.S. Rt. 1, 1 mile north of Falmouth.

79. Va., Stafford Co., POTOMAC, R. F. & P. Railway cut 1500 ft. south of Potomac Creek.

80. Va., Stafford Co., POTOMAC, road cut on east side of U.S. Rt. 1, 3.5 miles north of Falmouth.

81. Va., Spotsylvania Co., POTOMAC, stream bank of Hazel Run at U.S. Rt. 1, .75 mile south of Fredericksburg.

82. Del., Newcastle Co., POTOMAC, abandoned sand pit, 700 ft. north of Pennsylvania Railway tracks, 1600 ft. east of Del. Rt. 41 at Newport.

83. Del., Newcastle Co., POTOMAC, construction excavation on northwest side of secondary road, 800 ft. northeast of Del Rt. 273, .75 mile west of Pleasantville.

84. Md., Harford Co., POTOMAC, road cut for Kennedy Expressway, .9 mile east of Winters Run.

85. Md., Baltimore Co., POTOMAC, Susquehanna Aqueduct trench, 1000 ft. south of Fitch Rd., .7 mile southeast of Fullerton.

86. Md., Baltimore Co., POTOMAC, B. & O. Railway cut 600 ft. northeast of Chesaco Ave., Rosedale.

87. Md., Baltimore Co., POTOMAC, abandoned sand and gravel pit, 1100 ft. east of the intersection of Md. Rt. 7 and U.S. Rt. 40.

88. Md., Baltimore Co., POTOMAC, abandoned sand pit, 1800 ft. northwest of the intersection of Holabird Ave. and Merritt Ave.

89. Md., Baltimore City, POTOMAC, abandoned sand pit, immediately southeast of Pennsylvania Railway tracks and 1700 ft. northwest of Baltimore City Hospital.

90. Md., Baltimore City, POTOMAC, abandomed sand pit, northeast side of Erdman Ave., .65 mile northwest of U.S. Rt. 40.

91. Md., Baltimore City, POTOMAC, abandoned sand and gravel pit, northeast side of Bowley's Lane, .8 mile southeast of Mannasota Ave.

92. Md., Baltimore Co., POTOMAC, abandoned sand pit, north side of intersection of U.S. Rt. 1 and Putty Hill Rd.

93. Md., Baltimore Co., POTOMAC, abandoned sand and gravel pit, south side of Magledt Rd., 1.2 miles northeast of Joppa Rd.

94. Md., Baltimore Co., POTOMAC, abandoned sand pit, northwest side of Benson Ave., .65 mile southwest of Baltimore City line.

95. Md., Anne Arundel Co., POTOMAC, sand and gravel pit, west side of Baltimore Harbor Tunnel Thruway, 2000 ft. south of Belle Grove Rd.

96. Md., Baltimore Co., POTOMAC, sand and gravel pit, south side of Whitemarsh Rd., 1.3 miles east of Ridge Rd.

97. Md., Baltimore Co., POTOMAC, sand and gravel pit, south side of Whitemarsh Rd., .65 mile east of Ridge Rd.

98. Md., Baltimore Co., POTOMAC, Nottingham Farms sand and gravel pits, south side of Joppa Rd., .75 mile east of Harford Rd.

99. Md., Baltimore Co., POTOMAC, east bank of Middle River, 800 ft. south of Eastern Ave.

100. Md., Baltimore City, POTOMAC, B. & O. Railway cut, 2000 ft. northeast of Patapsco Ave.

101. Md., Baltimore City, POTOMAC, abandoned clay pit, south side of Patapsco Ave., .6 mile southeast of the Baltimore-Washington Parkway.

102. Md., Anne Arundel Co., POTOMAC, abandoned sand pit, east side of Md. Rt. 3, 1.3 miles north of Md. Rt. 648.

103. Md., Baltimore City, POTOMAC, abandoned sand pit, east side of Cherry Hill Ave., 2000 ft. south of Waterview Ave.

104. Md., Baltimore City, POTOMAC, construction excavation on south side of Waterview Ave., 1400 ft. east of Cherry Hill Ave.

105. Md., Baltimore Co., POTOMAC, abandoned sand pits, west corner of intersection of Sulphur Spring Rd. and U.S. Rt. 1.

106. Md., Baltimore City, POTOMAC, B. & O. Railway cut, 200 ft. south of Hawkins Point Rd.

107. Md., Anne Arundel Co., MAGOTHY, sand pit at intersection of Md. Rt. 3 and Md. Rt. 178.

108. Md., Harford Co., POTOMAC, sand and gravel pit, .65 mile northwest of Pennsylvania Railway tracks, 1.4 miles southwest of Magnolia.

109. Va., Hanover Co., NEWARK GROUP (Triassic) in error, R. F. & P. Railway cut, 400 ft. south of the North Anna River.

110. Va., Hanover Co., NEWARK GROUP (Triassic) in error, R. F. & P. Railway cut, immediately east of Gum Tree.

111. Va., Chesterfield Co., POTOMAC, west bank of James River at Ft. Darling.

112. Va., Chesterfield Co., POTOMAC, north bank of the Appomattox River at Point of Rocks, 2.2 miles northwest of Hopewell.

113. Md., Kent Co., MAGOTHY, south bank of Sassafras River, 1000 ft. west of Betterton.

114. Md., Baltimore Co., POTOMAC, construction excavation, intersection of Rolling Rd. and U.S. Rt. 40.

115. Md., Baltimore Co., POTOMAC, United Clay Mines pit, southeast side of U.S. Rt. 40 at Poplar.

116. Md., Prince Georges Co., MONMOUTH, road cut on north side of John Hanson Highway at Lottsford Vista Rd.

APPENDIX B

WELL LOCATIONS

The following wells or test borings were utilized in the preparation of isopach, lithofacies, and structural contour maps presented in this report.

Potomac Group

1.	Va., Prince George Co., Well No. 1.	Cedarstrom, 1945, p. 164
2.	Va., Greensville Co., Well No. 134.	Cedarstrom, 1945, p. 194
3.	Va., Surry Co., Well No. 42a.	Cedarstrom, 1945, p. 207
4.	Va., Southampton Co., Well No. 25.	Cedarstrom, 1945, p. 255
5.	Va., Southampton Co., Well No. 207b.	Cedarstrom, 1945, p. 260
6.	Va., Isle of Wight Co., Well No. 160.	Cedarstrom, 1945, p. 276
7.	Va., Nansemond Co., Well No. 80.	Cedarstrom, 1945, p. 312
8.	Va., Norfolk Co., Well No. 20.	Cedarstrom, 1945, p. 351
9.	Va., Prince William Co., Well No. 1199.	Cady, 1938, p. 145
10.	Va., Fairfax Co., Well No. 1536.	Cady, 1938, p. 182

11.	Va., Fairfax Co., Well No. 1690.	Cady, 1938, p. 184
12.	N. J., Salem Co., Well No. 12.	Richards, 1945, p. 894
13.	Del., Sussex Co., Well No. 5.	Richards, 1945, p. 900
14.	Del., Newcastle Co., Well No. 2	Richards, 1945, p. 899
15.	Va., Matthews Co., Well No. 18.	Richards, 1945, p. 907
16.	N.J., Salem Co., Well No. 48.	Richards, 1948, p. 47
17.	Md., Kent Co., Well No. 3.	Richards, 1948, p. 101
18.	Va., Caroline Co., Well No. 23.	Cedarstrom, 1945b, p. 30
19.	Va., Spotsylvania Co., Well No. 1.	Cedarstrom, 1945b, p. 15
20.	Va., Elizabeth City Co., Well No. 8c.	Cedarstrom, 1957, p. 227
21.	Md., Harford Co., Well No. Dc-1.	Bennett and Meyer, 1952, p. 432
22.	Md., Harford Co., Well No. Dd-4.	Bennett and Meyer, 1952, p. 432
23.	Md., Harford Co., Well No. Ed-28.	Bennett and Meyer, 1952, p. 445
24.	Md., Baltimore City, Well No. 4N4E-2.	Bennett and Meyer, 1952, p. 365
25.	Md., Baltimore City, Well No. 3S1E-15.	Bennett and Meyer, 1952, p. 324
26.	Md., Baltimore City, Well No. 3S5E-31.	Bennett and Meyer, 1952, p. 332
27.	Md., Baltimore Co., Well No. Fe-14.	Bennett and Meyer, 1952, p. 384
28.	Md., Baltimore City, Well No. 1S3E-3.	Bennett and Meyer, 1952, p. 312
29.	Md., Baltimore Co., Well No. Ef-20.	Bennett and Meyer, 1952, p. 382
30.	Md., Baltimore Co., Well No. Gf-10.	Bennett and Meyer, 1952, p. 400
31.	Md., Baltimore Co., Well No. Gf-177.	Bennett and Meyer, 1952, p. 427
32.	Md., Baltimore Co., Well No. Ff-34.	Bennett and Meyer, 1952, p. 392
33.	Md., Baltimore City, Well No. 5S3E-17.	Bennett and Meyer, 1952, p. 340
34.	Md., Prince Georges Co., Well No. Ce-16.	Meyer, 1952, p. 230
35.	Md., Prince Georges Co., Well No. Cc-27.	Meyer, 1952, p. 186
36.	Md., Prince Georges Co., Well No. Bd-4.	Meyer, 1952, p. 167
37.	Md., Prince Georges Co., Well No. Bd-3.	Meyer, 1952, p. 167
38.	Md., Prince Georges Co., Well No. Ad-4.	Meyer, 1952, p. 164
39.	Md., Prince Georges Co., Well No. Bc-8.	Meyer, 1952, p. 166
40.	Md., Prince Georges Co., Well No. Bd-13.	Meyer, 1952, p. 169
41.	Md., Prince Georges Co., Well No. Cc-21.	Meyer, 1952, p. 185
42.	Md., Prince Georges Co., Well No. Cc-13.	Meyer, 1952, p. 184
43.	Md., Prince Georges Co., Well No. Be-2.	Meyer, 1952, p. 179
44.	Md., Montgomery Co., Well No. Eh-2.	Dingman and Meyer, 1954, p. 137
45.	Md., Howard Co., Well No. Cf-17.	Dingman and Meyer, 1954, p. 116
46.	Md., Howard Co., Well No. Cf-25.	Dingman and Meyer, 1954, p. 118
47.	Md., Howard Co., Well No. Df-17.	Dingman and Meyer, 1954, p. 123
48.	Md., Anne Arundel Co., Well No. Ac-10.	Brookhart, 1949, p. 86
49.	Md., Anne Arundel Co., Well No. Ad-75.	Md. Geol. Surv. unpublished well log
50.	Md., Prince Georges Co., Well No. Cf-28.	Brenner, 1963, p. 190-193 (Probe Hole No. 2)
51.	Md., Anne Arundel Co., Well No. Cc-78.	Md. Geol. Surv. unpublished well log
52.	Md., Anne Arundel Co., Well No. Bf-49.	Md. Geol. Surv. unpublished well log
53.	Md., Anne Arundel Co., Well No. Be-58.	Brookhart, 1949, p. 107-108
54.	Md., Anne Arundel Co., Well No. Ce-32.	Otton, 1955, p. 200
55.	Md., Anne Arundel Co., Well No. Bd-23.	Brookhart, 1949, p. 99
56.	Md., Anne Arundel Co., Well No. Cf-61.	Md. Geol. Surv. unpublished well log

57.	Md., Anne Arundel Co., Well No. Bc-92.	Md. Geol. Surv. unpublished well log
58.	Md., Prince Georges Co., Well No. Ed-9.	Meyer, 1952, p. 241-242
59.	Md., Prince Georges Co., Well No. Dc-4.	Meyer, 1952, p. 193
60.	Md., Prince Georges Co., Well No. Eb-2.	Meyer, 1952, p. 197
61.	Md., Cecil Co., Well No. Bb-7.	Overbeck and Slaughter, 1958, p. 249
62.	Md., Cecil Co., Well No. Bc-14.	Overbeck and Slaughter, 1958, p. 251
63.	Md., Cecil Co., Well No. Bd-6	Overbeck and Slaughter, 1958, p. 253
64.	Md., Cecil Co., Well No. Bd-12.	Overbeck and Slaughter, 1958, p. 253
65.	Md., Cecil Co., Well No. Be-1.	Overbeck and Slaughter, 1958, p. 256
66.	Md., Cecil Co., Well No. Be-46.	Overbeck and Slaughter, 1958, p. 260
67.	Md., Cecil Co., Well No. Cd-13.	Overbeck and Slaughter, 1958, p. 270
68.	Md., Cecil Co., Well No. Cf-28.	Overbeck and Slaughter, 1958, p. 278
69.	Del., Newcastle Co., Well No. Cd-46.	Marine and Rasmussen, 1955, p. 169
70.	Del., Newcastle Co., Well No. Cc-10.	Marine and Rasmussen, 1955, p. 158
71.	Del., Newcastle Co., Well No. Cb-104.	Marine and Rasmussen, 1955, p. 157
72.	Del., Newcastle Co., Well No. Cb-2.	Marine and Rasmussen, 1955, p. 156
73.	Del., Newcastle Co., Well No. Db-82.	Marine and Rasmussen, 1955, p. 174
74.	Del., Newcastle Co., Well No. Dc-15.	Marine and Rasmussen, 1955, p. 177
75.	Del., Newcastle Co., Well No. 1.	Richards, 1945, p. 899
76.	Pa., Philadelphia Co., Well No. Ph-30.	Greenman et al, 1961, p. 298
77.	Md., Anne Arundel Co., Well No. Cb-2.	Md. Geol. Surv. unpublished well log
78.	Md., Prince Georges Co., Well No. Ec-41.	Md. Geol. Surv. unpublished well log
79.	Md., Prince Georges Co., Well No. Cd-23.	Md. Geol. Surv. unpublished well log
80.	Md., Prince Georges Co., Well No. Ce-39.	Md. Geol. Surv. unpublished well log
81.	Washington, D.C., Well No. WW-Bc-3.	Md. Geol. Surv. unpublished well log
82.	Washington, D.C., Well No. AX-Ac-1.	Md. Geol. Surv. unpublished well log
83.	Va., Alexandria City, Well No. AX-Ab-2.	Md. Geol. Surv. unpublished well log
84.	Va., Fairfax Co., Well No. AN-Ac-8.	Md. Geol. Surv. unpublished well log
85.	Va., Fairfax Co., Well No. AX-Bb-8.	Md. Geol. Surv. unpublished well log
86.	Md., Charles Co., Well No. 15.	Overbeck, 1948, p. 171
87.	Md., Charles Co., Well No. Cb-9.	Md. Geol. Surv. unpublished well log
88.	Md., Charles Co., Well No. Cb-10.	Md. Geol. Surv. unpublished well log
89.	Md., Charles Co., Well No. Ce-18.	Md. Geol. Surv. unpublished well log
90.	Md., Harford Co., Well No. Ec-8.	Md. Geol. Surv. unpublished well log
91.	Md., Harford Co., Well No. De-26.	Md. Geol. Surv. unpublished well log
92.	Md., Harford Co., Well No. Cf-30.	Md. Geol. Surv. unpublished well log
93.	Va., Henrico Co., Well No. 27.	Cedarstrom, 1957, p. 72
94.	Va., Henrico Co., Well No. 42.	Cedarstrom, 1957, p. 74
95.	Md., Prince Georges Co., Well No. Ee-49.	Md. Geol. Surv. unpublished well log
96.	Md., Prince Georges Co., Well No. Ee-50.	Md. Geol. Surv. unpublished well log
97.	Md., Prince Georges Co., Well No. Fd-56.	Md. Geol. Surv. unpublished well log
98.	Md., Prince Georges Co., Well No. Fd-61.	Md. Geol. Surv. unpublished well log
99.	Md., Prince Georges Co., Well No. Fd-62	Md. Geol. Surv. unpublished well log
100.	Md., Prince Georges Co., Well No. Fd-59.	Md. Geol. Surv. unpublished well log
101.	Md., Prince Georges Co., Well No. Fc-17.	Md. Geol. Surv. unpublished well log
102.	Md., Prince Georges Co., Well No. Gc-5.	Md. Geol. Surv. unpublished well log
103.	Md., Wicomico Co., Hammond Well.	Anderson, 1948, p. 14-16
104.	Md., Worcester Co., Bethards Well.	Anderson, 1948, p. 84-85

105.	Md., Worcester Co., Ocean City Well.	Anderson, 1948, p. 92-94
106.	Va., Nansemond Co., Well No. 8.	Cedarstrom, 1945, p. 326
107.	Va., Nansemond Co., Well No. 106.	Cedarstrom, 1945, p. 328
108.	Va., Isle of Wight Co., Well No. 144b.	Cedarstrom, 1945, p. 294
109.	Va., Southampton Co., Well No. 2.	Cedarstrom, 1945, p. 254
110.	Va., Southampton Co., Well No. 337.	Cedarstrom, 1945, p. 261
111.	Va., Sussex Co., Wells No. 78, 80.	Cedarstrom, 1945, p. 190
112.	Va., Sussex Co., Well No. 96.	Cedarstrom, 1945, p. 192
113.	Va., Surry Co., Well No. 51.	Cedarstrom, 1945, p. 221
114.	Va., Prince George Co., Well No. 44.	Cedarstrom, 1945, p. 166
115.	Va., Prince George Co., Well No. 1.	Cedarstrom, 1945, p. 168
116.	Md., Baltimore, Co., Well No. Fe-16.	Bennett and Meyer, 1952, p. 384
117.	Md., Prince Georges Co., Well No. Bd-14.	Meyer, 1952, p. 169
118.	Md., Harford Co., Well No. De-3.	Bennett and Meyer, 1952, p. 433
119.	Md., Prince George Co., Well No. 63d.	Cedarstrom, 1945, p. 168
120.	Va., Fairfax Co., Well No. AX-Bb-10.	Md. Geol. Surv. unpublished well log
121.	Md., Cecil Co., Well No. Bd-23.	Overbeck and Slaughter, 1958, p. 254
122.	Md., Prince Georges Co., Well No. Ad-1.	Meyer, 1952, p. 164
123.	Md., Prince Georges Co., Well No. Ad-7.	Meyer, 1952, p. 164
124.	Md., Prince Georges Co., Well No. Bc-1.	Meyer, 1952, p. 165
125.	Md., Prince Georges Co., Well No. Bd-21.	Meyer, 1952, p. 172
126.	Md., Prince Georges Co., Well No. Bd-18.	Meyer, 1952, p. 171
127.	Md., Prince Georges Co., Well No. Ad-6.	Meyer, 1952, p. 165
128.	Md., Prince Georges Co., Well No. Bd-3.	Meyer, 1952, p. 167
129.	Md., Prince Georges Co., Well No. Bd-9.	Meyer, 1952, p. 168
130.	Md., Prince Georges Co., Well No. Bd-22.	Meyer, 1952, p. 173
131.	Md., Prince Georges Co., Well No. Bd-26.	Meyer, 1952, p. 174
132.	Md., Prince Georges Co., Well No. Bd-30.	Meyer, 1952, p. 177
133.	Md., Prince Georges Co., Well No. Bd-33.	Meyer, 1952, p. 177
134.	Md., Prince Georges Co., Well No. Bd-39.	Meyer, 1952, p. 178
135.	Md., Prince Georges Co., Well No. Be-5	Meyer, 1952, p. 179
136.	Md., Prince Georges Co., Well No. Be-6.	Meyer, 1952, p. 180
137.	Md., Prince Georges Co., Well No. Be-7.	Meyer, 1952, p. 180
138.	Md., Prince Georges Co., Well No. Cc-1.	Meyer, 1952, p. 182
139.	Md., Prince Georges Co., Well No. Cc-2.	Meyer, 1952, p. 183
140.	Md., Prince Georges Co., Well No. Cc-5.	Meyer, 1952, p. 183
141.	Md., Prince Georges Co., Well No. Cc-23.	Meyer, 1952, p. 185
142.	Md., Prince Georges Co., Well No. Cd-2.	Meyer, 1952, p. 186
143.	Md., Prince Georges Co., Well No. Ce-13.	Meyer, 1952, p. 188
144.	Md., Prince Georges Co., Well No. Eb-1.	Meyer, 1952, p. 197
145.	Md., Prince Georges Co., Well No. Eb-6.	Meyer, 1952, p. 198
146.	Md., Prince Georges Co., Well No. Ec-5.	Meyer, 1952, p. 200
147.	Md., Prince Georges Co., Well No. Ed-32.	Meyer, 1952, p. 211
148.	Md., Howard Co., Well No. Cf-7.	Dingman and Meyer, 1954, p. 116
149.	Md., Howard Co., Well No. Cg-14.	Dingman and Meyer, 1954, p. 119
150.	Md., Anne Arundel Co., Well No. Ad-29.	Brookhart, 1949, p. 89

151.	Md., Anne Arundel Co., Well No. Ad-8.	Brookhart, 1949, p. 87
152.	Md., Anne Arundel Co., Well No. Bb-20.	Brookhart, 1949, p. 95
153.	Md., Anne Arundel Co., Well No. Bb-8.	Brookhart, 1949, p. 60
154.	Md., Anne Arundel Co., Well No. Bc-7.	Brookhart, 1949, p. 60
155.	Md., Anne Arundel Co., Well No. Be-48.	Brookhart, 1949, p. 105
156.	Md., Anne Arundel Co., Well No. Bf-10.	Brookhart, 1949, p. 108
157.	Md., Anne Arundel Co., Well No. Cc-1.	Brookhart, 1949, p. 66
158.	Md., Anne Arundel Co., Well No. Cc-7.	Brookhart, 1949, p. 66
159.	Md., Anne Arundel Co., Well No. Cd-10.	Brookhart, 1949, p. 111
160.	Md., Anne Arundel Co., Well No. Ac-11.	Otton, 1955, p. 248
161.	Md., Anne Arundel Co., Well No. Ac-14.	Otton, 1955, p. 248
162.	Md., Anne Arundel Co., Well No. Ad-43.	Otton, 1955, p. 249
163.	Md., Anne Arundel Co., Well No. Ae-28.	Brookhart, 1949, p. 94
164.	Md., Anne Arundel Co., Well No. Cf-29.	Md. Geol. Surv. unpublished well log
165.	Md., Anne Arundel Co., Well No. Ad-86.	Md. Geol. Surv. unpublished well log
166.	Md., Anne Arundel Co., Well No. Ad-91.	Md. Geol. Surv. unpublished well log
167.	Md., Anne Arundel Co., Well No. Cb-3.	Md. Geol. Surv. unpublished well log
168.	Md., Baltimore City, Well No. 1S4E-19.	Bennett and Meyer, 1952, p. 316
169.	Md., Baltimore City, Well No. 2S2E-6.	Bennett and Meyer, 1952, p. 318
170.	Md., Baltimore City, Well No. 2S3E-17.	Bennett and Meyer, 1952, p. 319
171.	Md., Baltimore City, Well No. 2S4E-1.	Bennett and Meyer, 1952, p. 321
172.	Md., Baltimore City, Well No. 3S2E-1.	Bennett and Meyer, 1952, p. 325
173.	Md., Baltimore City, Well No. 3S4E-2.	Bennett and Meyer, 1952, p. 328
174.	Md., Baltimore City, Well No. 4S2E-2.	Bennett and Meyer, 1952, p. 332
175.	Md., Baltimore City, Well No. 4S3E-3	Bennett and Meyer, 1952, p. 333
176.	Md., Baltimore City, Well No. 5S2E-20.	Bennett and Meyer, 1952, p. 336
177.	Md., Baltimore City, Well No. 6S2E-3.	Bennett and Meyer, 1952, p. 348
178.	Md., Baltimore City, Well No. 1S1W-29.	Bennett and Meyer, 1952, p. 360
179.	Md., Baltimore City, Well No. 3S3W-1.	Bennett and Meyer, 1952, p. 362
180.	Md., Baltimore Co., Well No. Fe-16.	Bennett and Meyer, 1952, p. 384
181.	Md., Anne Arundel Co., Well No. Cc-85.	Md. Geol. Surv. unpublished well log
182.	Washington, D.C., Well No. WW-Ac-6.	Md. Geol. Surv. unpublished well log
183,	Washington, D.C., Well No. WE-Ba-7.	Md. Geol. Surv. unpublished well log
184.	Md., Prince Georges Co., Well No. WE-Bb-5.	Md. Geol. Surv. unpublished well log
185.	Washington, D.C., Well No. WW-Cc-3.	Md. Geol. Surv. unpublished well log
186.	Washington, D.C., Well No. WE-Ca-11.	Md. Geol. Surv. unpublished well log
187.	Washington, D.C., Well No. AC-Aa-5.	Md. Geol. Surv. unpublished well log
188.	Md., Prince Georges Co., Well No. AX-Bc-3.	Md. Geol. Surv. unpublished well log
189.	Washington, D.C., Well No. AC-Ca-1.	Md. Geol. Surv. unpublished well log
190.	Va., Arlington Co., Well No. AX-Bb-12.	Md. Geol. Surv. unpublished well log
191.	Va., Fairfax Co., Well No. AX-Cb-4.	Md. Geol. Surv. unpublished well log
192.	Va., Fairfax Co., Well No. AX-Ba-3.	Md. Geol. Surv. unpublished well log

Magothy Formation

1.	N.J. Cumberland Co., Well No. 13.	Richards, 1945, p. 895
2.	Md., Cecil Co., Well No. Cf-5.	Overbeck and Slaughter, 1958, p. 365
3.	Md., Cecil Co., Well No. Cf-16.	Overbeck and Slaughter, 1958, p. 277
4.	Md., Cecil Co., Well No. Dd-51.	Overbeck and Slaughter 1958, p. 284
5.	Md., Cecil Co., Well No. De-16.	Overbeck and Slaughter 1958, p. 287
6.	Md., Cecil Co., Well No. Ec-6.	Overbeck and Slaughter 1958, p. 289
7.	Md., Cecil Co., Well No. Ee-3.	Overbeck and Slaughter, 1958, p. 291
8.	Md., Kent Co., Well No. Ad-21.	Overbeck and Slaughter, 1958, p. 298
9.	Md., Kent Co., Well No. Cd-3.	Overbeck and Slaughter, 1958, p. 314
10.	N.J., Salem Co., Well No. 12.	Richards, 1945, p. 894
11.	Del., Newcastle Co., Well No. Eb-11.	Marine and Rasmussen, 1955, p. 183
12.	Del., Newcastle Co., Well No. Eb-8.	Marine and Rasmussen, 1955, p. 182
13.	Del., Newcastle Co., Well No. Ec-3.	Marine and Rasmussen, 1955, p. 183
14.	Del., Newcastle Co., Well No. Ec-4.	Marine and Rasmussen, 1955, p. 183
15.	Del., Newcastle Co., Well No. Ec-16.	Marine and Rasmussen, 1955, p. 183
16.	Del., Newcastle Co., Well No. Ec-31.	Marine and Rasmussen, 1955, p. 186
17.	Del., Newcastle Co., Well No. Fb-5.	Marine and Rasmussen 1955, p. 188
18.	Del., Newcastle Co., Well No. Fb-17.	Marine and Rasmussen, 1955, p. 188
19.	Del., Sussex Co., Well No. 5.	Richards, 1945, p. 900
20.	Del., Kent Co., Dover A.F.B. test well	Rasmussen et al, 1958, pp. 1-28
21.	Md., Wicomico Co., Hammond Well.	Anderson, 1948, p. 14-16
22.	Md., Worcester Co., Bethards Well.	Anderson, 1948, p. 84-85
23.	Md., Talbot Co., Well No. Cb-89.	Rasmussen and Slaughter 1957, p. 317
24.	Md., Anne Arundel Co., Well No. Cf-22.	Md. Geol. Surv. unpublished well log
25.	Md., Anne Arundel Co., Well No. Cf-64.	Md. Geol. Surv. unpublished well log
26.	Md., Anne Arundel Co., Well No. Ce-85.	Md. Geol. Surv. unpublished well log
27.	Md., Anne Arundel Co., Well No. Ce-68.	Md. Geol. Surv. unpublished well log
28.	Md., Anne Arundel Co., Well No. Df-65.	Md. Geol. Surv. unpublished well log
29.	Md., Anne Arundel Co., Well No. Df-19.	Brookhart, 1949, p. 127
30.	Md., Anne Arundel Co., Well No. Cd-44.	Md. Geol. Surv. unpublished well log
31.	Md., Anne Arundel Co., Wells No. Cd-10, 11, 12.	Brookhart, 1949, p. 111-113
32.	Md., Anne Arundel Co., Well No. De-88.	Md. Geol. Surv. unpublished well log
33.	Md., Anne Arundel Co., Wells No. Df-3, 9, 10, 11, 13.	Brookhart, 1949, p. 120-126
34.	Md., Anne Arundel Co., Well No. Cd-6.	Brookhart, 1949, p. 111
35.	Md., Anne Arundel Co., Well No. Cc-44.	Md. Geol. Surv. unpublished well log
36.	Md., Anne Arundel Co., Well No. Dd-36.	Md. Geol. Surv. unpublished well log
37.	Md., Anne Arundel Co., Well No. Fd-13.	Brookhart, 1949, p. 134
38.	Md., Prince Georges Co., Well No. Cf-26.	Meyer, 1952, p. 192
39.	Md., Anne Arundel Co., Well No. Cc-67.	Md. Geol. Surv. unpublished well log

APPENDIX C

POTOMAC AND MAGOTHY CROSS-BEDDING DATA

Loc. No.	n	$\bar{\theta}$	r	L	Loc. No.	n	$\bar{\theta}$	r	L
1	2	345	2.0	100.0	57	6	105	4.7	78.0
2	1	75	1.0	100.0	60	2	165	1.7	85.0
3	3	114	2.9	96.7	61	15	178	12.0	80.0
8	4	135	3.5	87.5	62	10	137	6.9	69.0
10	9	130	7.9	87.8	63	9	162	6.6	73.3
11	6	79	5.1	85.0	64	3	45	2.7	90.0
12	2	315	5.5	27.5	65	16	62	8.9	55.6
13	6	165	4.0	66.7	67	5	40	4.4	88.0
14	17	192	15.1	88.8	68	16	162	8.0	50.0
15	20	138	11.1	55.5	69	6	63	5.7	95.0
16	9	87	4.6	51.1	70	2	75	2.0	100.0
17	1	75	1.0	100.0	71	13	122	7.6	58.5
18	3	255	1.7	56.7	72	10	28	7.7	77.0
19	1	225	1.0	100.0	73	11	75	8.8	80.0
21	14	108	6.1	38.1	74	2	315	2.0	100.0
23	15	72	11.4	76.0	75	9	42	5.6	62.0
24	8	49	5.1	63.8	76	18	357	13.5	75.0
27	16	203	3.6	22.5	78	3	15	1.0	33.0
28	10	101	8.9	89.0	79	7	58	6.5	93.0
29	10	53	7.5	75.0	80	13	197	10.3	79.0
31	22	149	12.2	55.5	86	11	24	7.1	64.5
33	8	160	6.6	82.5	87	10	317	7.1	71.0
34	6	189	4.6	76.7	88	9	7	6.3	70.0
35	2	150	1.9	95.0	89	13	120	8.4	64.6
36	9	110	5.4	60.0	90	8	169	4.8	60.0
37	15	99	8.7	58.0	91	27	239	5.1	18.9
38	15	172	10.6	70.7	92	4	95	2.9	72.5
39	1	75	1.0	100.0	93	5	142	3.6	72.0
40	7	101	6.1	87.1	94	4	128	3.3	82.5
41	21	140	9.9	47.1	95	11	348	6.1	55.5
43	11	259	5.2	47.3	96	9	62	7.3	81.1
44	12	210	5.6	46.7	97	4	30	2.4	60.0
45	17	131	15.5	91.2	98	37	260	9.3	25.1
46	6	175	5.6	93.3	99	6	129	5.6	93.3
47	18	126	9.0	50.0	100	4	135	2.7	67.5
48	19	149	11.4	60.0	102	15	133	8.9	59.3
49	2	105	1.7	85.0	103	14	84	7.5	53.5
50	25	142	14.9	59.6	105	47	154	5.3	11.3
52	5	166	4.2	84.0	107	10	82	6.7	67.0
53	6	166	4.9	81.7	108	10	129	7.7	77.0
55	5	21	3.3	66.0	111	8	11	5.4	68.0
56	4	45	2.7	67.5	112	5	105	2.7	54.0

n – number of observations
$\bar{\theta}$ – resultant vector (degrees)
r – magnitude of resultant vector
L – magnitude of resultant vector in terms of percent

APPENDIX D

PEBBLE COUNT COMPILATION

			frequency percent				average roundness			
Locality		Size Class	Vein Quartz	Sandstone-Metaquartzite	Igneous-Metamorphic	Chert	Vein Quartz	Sandstone-Metaquartzite	Igneous-Metamorphic	Chert
1	(26)*	8-16mm	77	23	–	–	.45	.37	–	–
2	(5)	8-16mm	60	40	–	–	.43	.50	–	–
3		8-16mm	90	10	–	–	.50	.50	–	–
6		8-16mm	72	26	–	2	.67	.64	–	.60
6	(5)	32-64mm	–	100	–	–	–	.82	–	–
7	(20)	8-16mm	75	25	–	–	.47	.44	–	–
8		8-16mm	74	26	–	–	.51	.48	–	–
15		8-16mm	62	34	–	4	.51	.61	–	.50
15	(1)	32-64mm	–	100	–	–	–	.70	–	–
18	(2)	8-16mm	50	50	–	–	.40	.40	–	–
21		8-16mm	100	–	–	–	.52	–	–	–
21	(6)	32-64mm	100	–	–	–	.50	–	–	–
22		8-16mm	78	22	–	–	.50	.51	–	–
22	(5)	32-64mm	100	–	–	–	.56	–	–	–
23		8-16mm	94	6	–	–	.47	.50	–	–
24		8-16mm	82	12	–	6	.55	.63	–	.57
24	(12)	32-64mm	25	75	–	–	.60	.70	–	–
26		8-16mm	98	2	–	–	.49	.40	–	–
26	(1)	32-64mm	100	–	–	–	.50	–	–	–
37		8-16mm	56	44	–	–	.42	.41	–	–
38		8-16mm	86	14	–	–	.49	.47	–	–
39		8-16mm	86	14	–	–	.51	.66	–	–
39	(32)	32-64mm	41	59	–	–	.52	.64	–	–
40		8-16mm	78	22	–	–	.53	.65	–	–
40		32-64mm	24	76	–	–	.54	.68	–	–
40	(11)	64-128mm	9	91	–	–	.60	.65	–	–
45		8-16mm	76	12	–	12	.54	.62	–	.48
46		8-16mm	82	16	–	2	.54	.63	–	.60
46	(4)	32-64mm	25	75	–	–	.50	.63	–	–
48	(45)	8-16mm	96	4	–	–	.48	.45	–	–
48	(1)	32-64mm	100	–	–	–	.50	–	–	–
49	(5)	32-64mm	–	100	–	–	–	.70	–	–
53		8-16mm	80	18	–	2	.51	.48	–	.60
55		8-16mm	96	4	–	–	.55	.52	–	–
55	(5)	32-64mm	100	–	–	–	.50	–	–	–
56		8-16mm	72	28	–	–	.50	.51	–	–
56	(1)	32-64mm	–	100	–	–	–	.30	–	–
59		8-16mm	60	38	–	2	.35	.34	–	.30
59	(17)	32-64mm	88	12	–	–	.35	.38	–	–
61	(4)	8-16mm	75	25	–	–	.53	.60	–	–
61	(6)	32-64mm	67	33	–	–	.60	.65	–	–
62	(2)	32-64mm	100	–	–	–	.65	–	–	–
64	(4)	32-64mm	50	25	25	–	.65	.60	.60	–
64	(1)	64-128mm	100	–	–	–	.80	–	–	–
65	(3)	8-16mm	100	–	–	–	.53	–	–	–
65	(1)	32-64mm	100	–	–	–	.60	–	–	–
68	(24)	8-16mm	96	4	–	–	.48	.50	–	–
68	(6)	32-64mm	50	17	17	17	.60	.60	.60	.50
70	(2)	32-64mm	100	–	–	–	.60	–	–	–
71	(14)	8-16mm	100	–	–	–	.54	–	–	–
71	(1)	32-64mm	100	–	–	–	.70	–	–	–
73		8-16mm	48	–	52	–	.50	–	.62	–
73	(47)	32-64mm	28	6	66	–	.56	.63	.58	–
74	(4)	32-64mm	75	–	25	–	.60	–	.60	–
74	(1)	64-128mm	100	–	–	–	.60	–	–	–
75		8-16mm	88	2	10	–	.50	.60	.56	–
75	(10)	32-64mm	80	–	20	–	.61	–	.65	–
76	(1)	32-64mm	–	100	–	–	–	.70	–	–
80	(3)	32-64mm	67	–	33	–	.55	–	.70	–
80	(1)	64-128mm	–	–	100	–	–	–	.60	–
85		8-16mm	100	–	–	–	.53	–	–	–
87		8-16mm	98	2	–	–	.55	.50	–	–
87	(1)	32-64mm	100	–	–	–	.60	–	–	–
93		8-16mm	100	–	–	–	.49	–	–	–
93	(2)	32-64mm	100	–	–	–	.45	–	–	–
95		8-16mm	92	8	–	–	.53	.63	–	–
98		8-16mm	92	8	–	–	.53	.63	–	–
98	(23)	32-64mm	82	18	–	–	.50	.50	–	–
98	(1)	64-128mm	–	100	–	–	–	.40	–	–
108		8-16mm	94	6	–	–	.49	.53	–	–
111		8-16mm	72	26	–	2	.53	.51	–	.50
111	(5)	32-64mm	20	80	–	–	.50	.57	–	–
111	(2)	64-128mm	–	50	50	–	–	.70	.40	–
114		8-16mm	92	8	–	–	.44	.43	–	–
114	(4)	32-64mm	–	100	–	–	–	.40	–	–

*Number of pebbles counted; all others, 50 pebbles counted

APPENDIX E

TEXTURAL ANALYSES: STATISTICAL PARAMETERS

Sample Number	ϕ 16	ϕ 84	Md ϕ	M ϕ	$\sigma\phi$	$\alpha\phi$
1	-0.82	1.92	0.89	0.55	1.37	-0.25
2	-1.00	2.30	0.89	0.65	1.65	-0.15
3	-2.81	1.73	-1.05	-0.54	2.27	0.23
4-1	-0.33	0.89	0.35	0.28	0.61	-0.11
4-2	1.63	2.80	2.10	2.22	0.59	0.20
5	1.32	2.00	1.65	1.66	0.34	0.03
6-1	2.36	3.97	2.74	3.17	0.81	0.53
6-2	-5.18	1.00	-3.00	-2.09	3.09	0.29
7	-0.89	1.93	1.11	0.52	1.41	-0.42
8-1	-3.79	1.41	-3.03	-1.19	2.60	0.71
8-2	1.61	2.76	2.24	2.19	0.58	-0.09
9	0.75	1.80	1.35	1.28	0.53	-0.13
10	0.82	2.20	1.49	1.51	0.69	0.03
13	1.60	2.62	2.06	2.11	0.51	0.10
14-1	0.96	1.96	1.46	1.46	0.50	0.00
14-2	2.31	3.42	2.70	2.87	0.56	0.30
14-3	0.40	9.60*	1.70	5.00*	4.60*	0.72*
15-1	1.65	2.80	1.98	2.23	0.58	0.43
15-2	-3.39	1.49	0.04	-0.95	2.44	-0.41
15-3	1.59	2.73	1.93	2.16	0.57	0.40
16-1	0.65	1.58	1.09	1.12	0.47	0.06
16-2	1.54	2.32	1.87	1.90	0.42	0.07
18-1	1.80	2.80	2.29	2.30	0.50	0.02
18-2	0.32	5.11*	1.51	2.72*	2.40*	0.51*
18-3	0.41	2.44	1.60	1.43	1.02	-0.17
18-4	-0.62	3.31	1.15	1.35	1.97	0.10
19	-4.19	1.18	-2.78	-1.51	2.69	0.47
20	1.15	1.97	1.59	1.56	0.41	-0.07
21-1	-3.18	1.99	0.84	-0.60	2.59	-0.56
21-2	0.37	2.30	1.38	1.34	0.97	-0.04
21-3	-1.48	0.64	-0.79	-0.42	1.06	0.34
21-4	-4.88	-0.65	-3.74	-2.77	2.12	0.46
22-1	1.89	2.75	2.30	2.32	0.43	0.05
22-2	0.86	1.84	1.36	1.35	0.49	-0.02
22-3	-4.11	1.61	-1.65	-1.25	2.86	0.14
23-1	-1.90	1.31	0.18	-0.30	1.61	-0.29
23-2	-2.59	1.49	0.08	-0.55	2.04	-0.31
23-3	0.11	1.81	1.08	0.96	0.85	-0.14
24-1	-3.18	1.28	-2.28	-0.95	2.23	0.60
24-2	0.87	1.91	1.40	1.39	0.52	-0.02
24-3	-3.61	1.84	0.36	-0.89	2.73	-0.46
25-1	1.49	2.39	1.83	1.94	0.45	0.24
25-2	1.77	2.62	2.08	2.20	0.43	0.28
26-1	-3.42	1.50	-1.71	-0.96	2.46	0.30
26-2	0.22	1.67	1.04	0.95	0.73	-0.12
27-1	1.21	2.70	1.91	1.96	0.75	0.07
27-2	-0.88	1.90	-0.10	0.51	1.39	0.44
28	1.42	2.35	1.84	1.89	0.47	0.11
29-1	0.75	2.08	1.39	1.42	0.67	0.04
29-2	-0.97	1.99	0.16	0.51	1.48	0.24
30	2.41	4.76*	3.47	3.59*	1.18*	0.10*
31-1	-1.44	1.89	-0.11	0.23	1.67	0.20
31-2	0.64	2.26	1.52	1.45	0.81	-0.09
32	1.30	2.38	1.82	1.84	0.54	0.04
33-1	2.03	2.83	2.42	2.43	0.40	0.03
33-2	0.73	1.87	1.34	1.30	0.57	-0.07
34	2.35	3.11	2.69	2.73	0.38	0.11
35	2.07	3.71	2.59	2.89	0.82	0.37
36	2.10	3.18	2.58	2.64	0.54	0.11
37	-2.82	1.80	0.16	-0.51	1.67	-0.40
38	-2.87	1.88	0.58	-0.50	2.38	-0.46
39	-4.91	1.07	-2.39	-1.92	2.99	0.16
40	-6.12	0.61	-4.72	-2.76	3.37	0.59
41-1	0.23	1.80	0.97	1.02	0.79	0.06
41-2	2.28	3.00	2.62	2.64	0.36	0.06
41-3	1.89	3.00	2.40	2.45	0.56	0.09
42	0.60	1.99	1.32	1.30	0.70	-0.03
43	0.69	2.31	1.50	1.50	0.81	0.00
44	1.16	2.10	1.61	1.63	0.47	0.04
45-1	-4.51	1.70	0.05	-1.41	3.11	-0.47
45-2	-4.20	-2.18	-3.50	-3.19	1.01	0.31
45-3	-3.94	0.82	-2.14	-1.56	2.38	0.25
45-4	-3.40	1.91	0.40	-0.75	2.66	-0.43

*Values estimated from extended cumulative curve or computed with such estimated values

Sample Number	$\phi 16$	$\phi 84$	$Md\phi$	$M\phi$	$\sigma\phi$	$\alpha\phi$
46-1	-4.18	1.00	-1.49	-1.59	2.59	-0.04
46-2	0.03	1.68	1.06	0.86	0.83	-0.24
47-1	1.35	2.49	1.83	1.92	0.57	0.16
47-2	1.59	2.54	1.98	2.07	0.48	0.19
48-1	1.09	4.71*	1.65	2.90*	1.81*	0.69*
48-2	1.63	2.72	2.12	2.18	0.55	0.11
48-3	-2.42	1.00	0.04	-0.71	1.71	-0.44
49-1	-5.09	1.71	-0.35	-1.69	3.40	-0.39
49-2	1.60	2.82	2.03	2.21	0.61	0.30
50-1	1.08	2.06	1.58	1.57	0.49	0.02
50-2	0.63	3.79	1.39	2.21	1.58	0.52
51	1.66	3.98	2.32	2.82	1.16	0.43
52-1	1.20	2.00	1.61	1.60	0.40	-0.03
52-2	-1.69	1.69	0.58	0.00	1.69	-0.34
53-1	-3.61	1.19	-1.23	-1.21	2.40	0.01
53-2	2.10	5.00*	2.90	3.55*	1.45*	0.45*
53-3	0.98	2.26	1.55	1.62	0.64	0.11
53-4	-0.28	3.24	2.18	1.48	1.76	-0.16
54	1.69	2.94	2.26	2.32	0.63	0.10
55-1	0.31	1.86	1.17	1.09	0.78	-0.10
55-2	1.23	7.90*	1.89	4.57*	3.39*	0.79*
55-3	-5.46	-1.29	-3.56	-3.38	2.09	0.09
56-1	-3.26	1.10	-0.15	-1.08	2.18	-0.42
56-2	0.22	1.80	1.24	1.01	0.79	-0.29
57	-0.22	1.79	0.88	0.79	1.01	-0.22
58-1	1.11	3.09	2.20	2.10	0.99	-0.10
58-2	-0.83	1.48	0.23	0.33	1.16	0.09
59-1	-5.23	0.60	-4.81	-2.32	2.92	0.85
59-2	2.24	3.48	2.63	2.86	0.62	0.37
59-3	1.39	2.63	1.80	2.01	0.62	0.34
60-1	-0.61	3.76	0.90	1.58	2.19	0.31
60-2	1.20	2.94	2.00	2.07	0.87	0.08
60-3	-0.46	4.00	0.82	1.77	2.23	0.41
61-1	1.08	2.09	1.39	1.59	0.51	0.04
61-2	-5.19	1.33	0.10	-1.93	3.26	-0.62
62	-1.05	1.82	0.70	0.39	1.44	-0.22
63	1.49	2.90	2.09	2.20	0.71	0.15
64	-6.14	1.34	-1.20	-2.40	3.74	-0.32
65-1	-2.76	0.98	0.39	-0.89	1.87	-0.68
65-2	0.59	1.74	1.11	1.17	0.58	0.10
66	1.50	2.81	1.92	2.16	0.66	0.36
67	0.52	3.55	1.33	2.04	1.52	0.47
68	-5.16	1.15	0.08	-2.01	3.16	-0.66
69	0.92	2.02	1.45	1.47	0.55	0.04
70	-5.10	1.70	0.49	-1.71	3.40	-0.65
71-1	0.05	3.14	1.64	1.60	1.55	-0.03
71-2	-0.54	2.89	0.98	1.18	1.72	0.12
72	0.21	1.74	0.81	0.98	0.77	0.22
73-1	-5.65	1.19	-3.93	-2.23	3.42	0.49
73-2	-0.69	1.00	0.22	0.16	0.85	-0.07
74	-6.19	1.22	-4.53	-2.49	3.71	0.55
75	-4.96	0.32	-1.70	-2.31	2.64	-0.23
76-1	-0.60	1.55	0.52	0.48	1.08	-0.04
76-2	1.09	2.49	1.64	1.79	0.70	0.21
78-1	0.43	1.99	0.99	1.21	0.78	0.28
78-2	-0.81	1.61	0.49	0.40	1.21	-0.07
79-1	1.70	3.51	2.52	2.61	0.91	0.10
79-2	0.52	2.11	1.29	1.32	0.80	0.04
80	-6.49	2.93	0.21	-1.78	4.71	-0.42
82	1.61	2.62	2.19	2.12	0.51	-0.14
83-1	-0.01	2.25	1.11	1.12	1.13	0.01
83-2	0.02	2.93	1.27	1.48	1.46	0.15
85-1	0.09	1.82	1.20	0.96	0.87	-0.28
85-2	-4.07	-0.31	-3.00	-2.19	1.88	0.43
85-3	1.49	3.88	2.03	2.69	1.20	0.55
86	1.65	2.80	2.17	2.23	0.58	0.10
87-1	1.28	2.71	2.09	2.00	0.72	-0.13
87-2	-4.39	1.39	-2.85	-1.50	2.89	0.47
88-1	2.30	2.92	2.61	2.61	0.31	0.00
88-2	2.08	2.95	2.50	2.52	0.44	0.05
89	0.60	1.65	1.08	1.13	0.53	0.09
90	-0.50	1.98	1.11	0.74	1.24	-0.30
91	0.54	2.50	1.63	1.52	0.98	-0.11
93	-4.32	0.11	-3.15	-2.11	2.22	0.47
94	1.23	2.34	1.69	1.79	0.56	0.18
95	0.00	1.86	1.05	0.93	0.93	-0.13

***Values estimated from extended cumulative curve or computed with such estimated values**

Sample Number	ϕ 16	ϕ 84	Md ϕ	M ϕ	$\sigma\phi$	$a\phi$
98-1	1.14	2.59	1.86	1.87	0.73	0.01
98-2	-5.59	-0.45	-3.75	-3.08	2.57	0.26
99	1.71	2.83	2.28	2.27	0.56	-0.02
102	1.39	2.41	1.80	1.90	0.51	0.20
103	-2.30	1.50	0.09	-0.40	1.90	-0.26
104	1.97	4.12*	2.70	3.05*	1.08*	0.32*
105-1	0.33	1.94	1.23	1.14	0.81	-0.11
105-2	1.03	1.70	1.38	1.37	0.34	-0.03
106	2.05	2.90	2.47	2.48	0.43	0.02
107-1	-0.90	0.50	-0.33	-0.20	0.70	0.19
107-2	0.30	1.70	1.19	1.00	0.70	-0.27
108-1	0.86	1.91	1.40	1.39	0.53	-0.02
108-2	-3.76	0.43	-2.21	-1.67	2.10	0.26
111-1	-6.28	-3.48	-5.91	-4.88	1.40	0.74
111-2	1.15	3.50	1.80	2.33	1.18	0.45
112	0.14	3.15	0.89	1.65	1.51	0.50
113-1	2.64	4.00	3.28	3.32	0.68	0.06
113-2	3.23	4.54*	3.89	3.89*	0.66*	0.00*
114	-4.01	2.42	0.19	-0.80	3.22	-0.31

*Values estimated from extended cumulative curve or computed with such estimated values

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