

Hydrochemical Facies and Ground-Water Flow Patterns in Northern Part of Atlantic Coastal Plain

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By WILLIAM BACK

HYDROLOGY OF AQUIFER SYSTEMS

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HYDROLOGY OF AQUIFER SYSTEMS

HYDROCHEMICAL FACIES AND GROUND-WATER FLOW PATTERNS IN NORTHERN PART OF ATLANTIC COASTAL PLAIN

By WILLIAM BACK

ABSTRACT

The part of the Atlantic Coastal Plain that extends from New Jersey through Virginia was selected as a suitable field model in which to study the relationships between geology, hydrology, and chemical character of ground water. The ground-water flow pattern is the principal hydrologic control on the chemical character of the water. Within the Coastal Plain sediments, the proportions of clay, glauconitic sand, and calcareous material are the principal lithologic controls over the chemistry of the water.

A subsurface body of salt water extends from southern New Jersey through southern Virginia and occupies the deposits deeper than about 500 feet below land surface in the eastern part of the Coastal Plain. The position of its top is determined by the relative head, which in turn is influenced by topography, drainage density, and the thickness and permeability of the Coastal Plain sediments.

Hydrochemical facies is a term used in this paper to denote the diagnostic chemical aspect of ground-water solutions occurring in hydrologic systems. The facies reflect the response of chemical processes operating within the lithologic framework and also the pattern of flow of the water. The distribution of these facies is shown in trilinear diagrams and isometric fence diagrams and on maps showing isopleths of chemical constituents within certain formations. The occurrence of the various facies within one formation or within a group of formations of uniform mineralogy indicates that the ground-water flow through the aquifer system modifies the distribution of the facies.

Flow patterns of fresh ground water shown on maps and in cross sections have been deduced from available water-level data. These patterns are controlled by the distribution of the higher landmasses and by the depth to either bedrock or to the salt-water interface. The mapping of hydrochemical facies shows that at shallow depths within the Coastal Plain (less than about 200 ft) the calcium-magnesium cation facies generally predominates. The bicarbonate anion facies occurs within more of the shallow Coastal Plain sediments than does the sulfate or the chloride facies. In deeper formations, the sodium chloride character predominates. The lower dissolved-solids content of the ground water in New Jersey indicates less upward vertical leakage than in Maryland and Virginia, where the shallow formations contain solutions of higher concentration.

INTRODUCTION

The science of chemical geohydrology in the United States has for many years received little attention, not only in comparison with the general field of ground-water hydrology, but also in comparison with the broad field of geochemistry. Of the geochemical cycle of the elements the part that has been studied least is that in which the circulation of ground water modifies the concentration and distribution of chemical constituents within particular environments of the earth's crust. Most of the interpretative reports prepared in this country that pertain to the hydrosphere has been restricted to the fields of oceanography, potamology, and limnology.

Although the amount of water stored in and circulating through the rocks is but a small percentage of the total water of the earth, it is this water that is largely responsible for both the chemical character and quantity of dissolved solids carried to the oceans by streams. This paper and certain succeeding papers in this series are concerned with this part of the geochemical cycle.

Interest in the geochemistry of ground water has been gradually increasing during the past several years. One factor that has contributed to this renewed and increased interest is the realization of the significance of ground-water circulation in the occurrence of uranium minerals in the Colorado Plateau. Another significant factor has been the realization that hydrochemical features of a basin may reflect the hydrodynamics of petroleum accumulation.

The primary purpose of the study reported here is to relate the chemical character of ground water to the geologic and hydrologic environment. The identification and emphasis of these interrelations should provide a firm basis for future study, which will be useful in improving data-collection programs and enabling more effective utilization of our water supplies. This

report is largely a description and presentation of the chemistry of ground water in the Coastal Plain portions of Virginia, Maryland, Delaware, and New Jersey. The Atlantic Coastal Plain was selected for study because of its diverse geology and the large amount of information available from previous ground-water investigations. The geology and hydrology are known in broad general terms but not in detail, whereas the chemistry of the water is known in detail for some areas but its regional setting is not well understood. The major stratigraphic units and their gross lithology are known, but detailed knowledge of their mineralogy is usually lacking. Generalized piezometric maps are available for some areas, but the movement of ground water in many areas is only poorly understood.

In any area the main factors that control the chemical character of ground water are the climate and vegetative cover, the mineral composition and physical properties of the rocks and soil through which the water circulates, and the relief of the land surface. Humid climate (precipitation about 45 in. per yr) is characteristic throughout this part of the Coastal Plain and is not discussed in this paper. Other factors that affect the chemistry of the water are physical and chemical character of the soils through which the water percolates and the activity of microorganisms.

The controls on the chemistry of the water considered in this paper are the physical properties and mineralogic composition of the sediments and the movement of ground water. The biochemical effect of microorganisms is not sufficiently understood to be considered in this type of study. The influence of the soils on the chemistry of the water is also beyond the scope of the present study.

The area of the Coastal Plain reported herein extends from southern Virginia northward through New Jersey as shown in figure 1. It is approximately 300 miles long and ranges in width from about 30 to 110 miles.

More than 3,000 chemical analyses were studied during this investigation; however, only about 200 are shown on the fence diagrams. Among the analyses generally not used were partial analyses and analyses in which sodium and potassium were determined by difference. Where replicate analyses were available, the most nearly representative analysis is shown on the fence diagram. Where the location of the source of the sample was unknown, the analysis could not be used.

The data used for this study were obtained from published reports of the U.S. Geological Survey in cooperation with State water agencies, and from the unpublished-data files in the district offices in each State.

I am grateful to E. G. Otton, P. M. Brown, Allen Sinnott, H. C. Barksdale, and W. C. Rasmussen for making these data available and particularly to R. R. Bennett for his many helpful discussions.

GEOLOGY

The Coastal Plain is underlain by a wedge of sediments ranging in age from Cretaceous to Recent and consisting primarily of sand, silt, and clay, with minor amounts of gravel overlying the pre-Cretaceous bedrock. Several studies of the geology of Coastal Plain were used in the preparation of this paper for information on stratigraphic correlation and lithologic character of sediments. Although the stratigraphic relationships are fairly well understood, little detailed information is available on the mineralogy of the Coastal Plain sediments. The major stratigraphic units are summarized in table 1 from the extensive literature of the geology of the Coastal Plain (among which are Anderson and others, 1948; Bennett and Meyer, 1952; Cederstrom 1943b; Groot, 1955; Johnson and Richards, 1952; Owens and Minard, 1960; Richards, 1945, 1948; Spangler and Peterson, 1950).

The lithologic properties that most greatly affect the chemistry of the water are shown on plate 1A. The sediments are divided into those deposits predominantly of continental origin and those deposits predominantly of marine origin. A fourfold subdivision of these two major units is made on the basis of the percentage of clay within each sequence. The units are further differentiated as to the presence of greensand (glauconitic sand) or calcareous material. The percentage of clay and the presence or absence of greensand and calcareous sediments are believed to be the dominant controls on the chemistry of the water. Although the percentages of clay as shown in this illustration are approximate, the general relationships and the relative amounts of clay, greensand, and calcareous sediments are representative of the regional variations.

RELATION OF SALT WATER TO FRESH WATER

FACTORS AFFECTING POSITION OF THE SALT-WATER BODY

Figure 2 shows the generalized topography of the Coastal Plain. The highest parts of the Coastal Plain are near the Fall Zone. However, two landmasses not connected with the Fall Zone are in southern Maryland and in northern New Jersey, where the altitude is about 300 feet. As can be seen in figure 2 the altitude of most of the eastern part of the Coastal Plain, including the Eastern Shore of Maryland and most of Delaware, is less than 100 feet and is generally less than 50 feet.

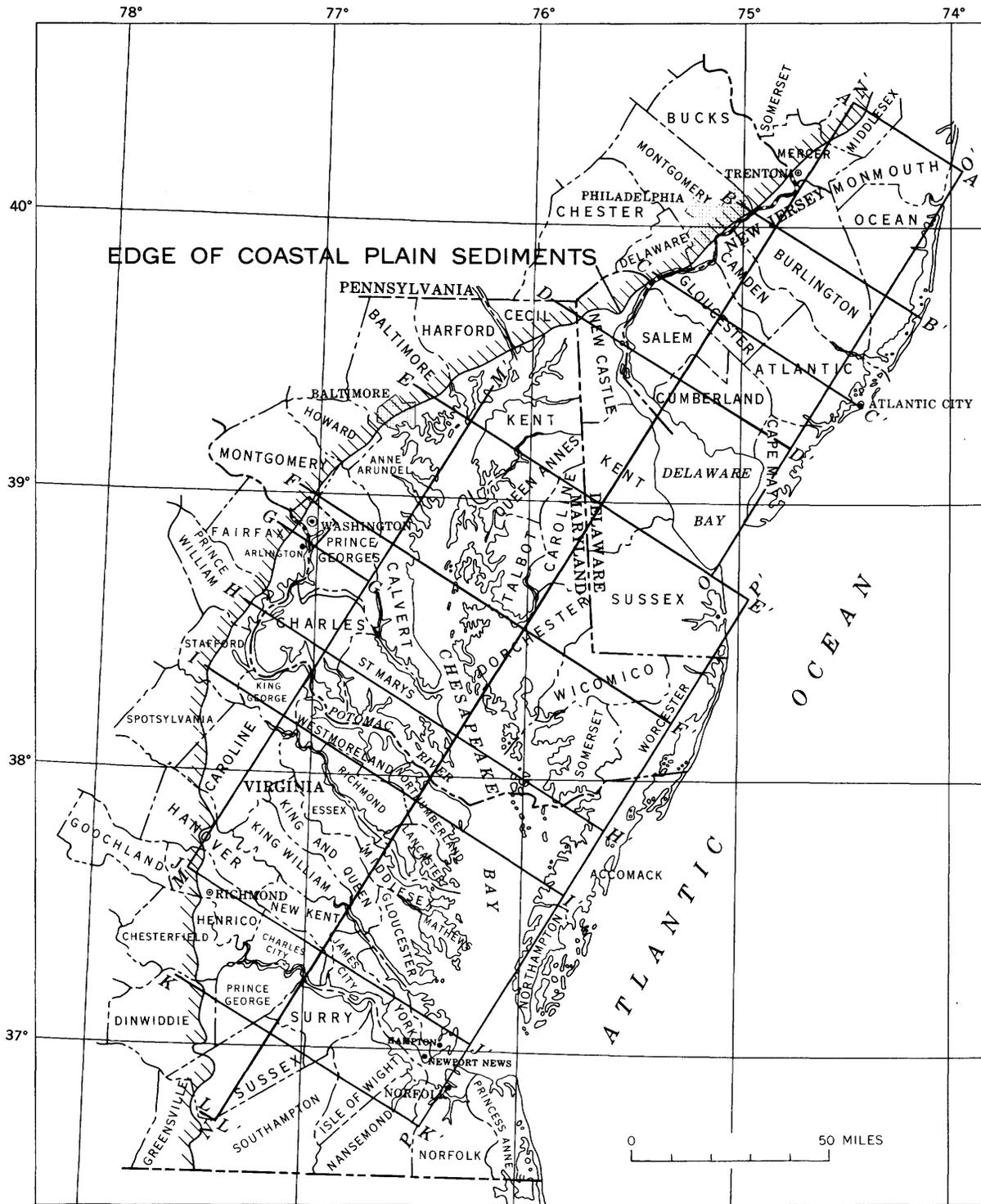


FIGURE 1.—Part of the northern Atlantic Coastal Plain: location of cross sections in the fence diagrams.

TABLE 1.—Stratigraphic units of the northern part of the Coastal Plain

Virginia	Southern Maryland	Delmar Peninsula	New Jersey
Alluvium, Qal, sand and gravel, chiefly beach deposits (of wind and wave origin) and channel deposits (of fluvial origin) and smaller amounts of marsh and lagoon deposits, dunes, bay-mount bars and spits.			
Columbia group, Qdu, 0-60 ft, clay and sand; fluvial and marine; the higher, westerly terraces are of continental origin; the lower, easterly terraces are of marine origin.	Lowland deposits, Qdu, 0-150 ft, sand, gravel, sandy clay, and clay; fluvial and marine.	Columbia Group, Qdu, 0-150 ft, unconsolidated lenticular deposits of buff sand and silt, and small amounts of gravel and clay; fluvial and marine; deposits occur as stratified drift containing a few erratic boulders, stabilized dunes, marsh mud, crossbedded channel fill, well-sorted beach sand. Disconformable lower boundary.	Cape May Formation, Qcm, 0-200 ft, buff to brown poorly to well-sorted unconsolidated gravel, sand, silt, and clay in filled valleys and broad alluvial terraces; fluvial and marine (Pleistocene).
	Upland deposits, 0-55 ft, irregularly stratified cobbles, gravel, sand, and clay lenses; fluvial and marine (Pliocene and Pleistocene).	Brandywine, Bryn Mawr, and Beacon Hill Gravels, 0-70 ft, slightly cemented red, orange, and brown gravelly sand. Locally in hard ledges a few inches to 2 ft thick, usually at the base of the formation. Chiefly channel fill. Disconformable lower boundary (Pliocene and Pleistocene).	Beacon Hill and Bryn Mawr Gravels, 0-20 ft, iron-stained gravel and sand composed of residually weathered quartz, chert, and quartzite; caps a few hills as remnants of a once extensive alluvial plain. Semiconsolidated permeable deposits chiefly above the water table. Transmits water to underlying aquifers (Pliocene and Pleistocene).
Chesapeake Group, Tc, 0-600 ft, snell marl, dark-blue or gray clay and some sand; marine (Miocene).	Yorktown Formation, Ty, sandy and very fossiliferous.	Yorktown Formation Ty, and Cohansey Sand, Tch, 0-150 ft, gray sand and gray or blue clayey silt; the sands are predominantly fine to medium grained; coarse sand, grit, or fine gravel present in minor amounts. Black sand, green sand, and shell beds are reported locally. The clayey silt is occasionally brown or green. Estuarine and marine. Disconformable lower boundary.	Cohansey Sand, Tch, 0-270 ft, coarse to fine quartz sand and lenses of silt and clay; estuarine and deltaic; possibly marine down-dip toward the ocean; loosely consolidated thick permeable aquifer. Chiefly unconfined; receives direct recharge. Locally artesian (Miocene? and Pliocene?).
	St. Marys Formation, Tsm, consists largely of tough, blue or gray clay.	St. Marys Formation, Tsm, 0-50 ft, sand, clayey sand, and blue clay; marine (Miocene).	Kirkwood Formation, Tkw, 0-600 ft, gray and brown clay, silt and fine micaceous quartz sand; estuarine and marine (Miocene).
	Choptank Formation, Tck, 20-105 ft, fine sand, sandy clay, and sand containing fossiliferous layers; marine (Miocene).	Choptank Formation, Tck, 0-260 ft, gray and brown sand and clay containing shell marl and Foraminifera; marine; conformable lower boundary (Miocene).	
	Calvert Formation, Tcv, diatomaceous and sandy but less fossiliferous than the Yorktown Formation.	Calvert Formation, Tcv, 20-180 ft, sandy clay and fine sand, fossiliferous, contains diatomaceous earth; marine (Miocene).	Calvert Formation, Tcv, 15-680 ft, gray diatomaceous silt and clay containing lenses and thin sheets of gray sand, shell beds, and Foraminifera; marine (Miocene).
Chickahominy Formation, Tcy, 0-80 ft, consists of gray marl beds containing subordinate glauconite and pyrite. Highly foraminiferal; marine; known from well cuttings only (Eocene).	Piney Point Formation, Tpp, 0-60 ft, sand, slightly glauconitic, containing intercalated "rock" layers (Miocene).	Chickahominy Formation, Tcy, 80-170 ft, brown glauconitic clay. Aquiclude (Eocene).	Piney Point Formation, Tpp 0-60 ft, coarse to fine glauconitic sand and greenish clay; marine; contains fossils of Jackson age (Eocene).
		Piney Point Formation, Tpp, 0-220 ft, a white quartz sand and glauconitic green-sand grading into brown shales; marine; contains foraminifera. Conformable lower boundary (Eocene).	
Nanjemoy Formation, Tn, gray marl, glauconite and quartz sand, and thin limestone beds. Includes pink Marlboro Clay Member at base (Eocene).	Nanjemoy Formation, Tn, 40-240 ft, glauconitic sand containing clay layers. Basal part is red or gray clay (Eocene).	Nanjemoy Formation, Tn, 0-295 ft, blackish-green highly glauconitic sand, silt, and clay. Conformable lower boundary; marine (Eocene).	Snark River Marl, Tsr, 0-25 ft, fine glauconite and light-colored clay; marine (Eocene).
			Manasquan Formation, Tmq, 0-25 ft, fine glauconitic sand interbedded with greenish-white clay; marine; a leaky aquiclude (Eocene).

TABLE 1.—Stratigraphic units of the northern part of the Coastal Plain—Continued

Virginia	Southern Maryland	Delmar Peninsula	New Jersey
Aquia Formation, Ta, 0-125 ft, glauconitic marl and basal quartz sand beds. No unconformity with underlying Mattaponi Formation (Eocene).	Aquia Greensand, Ta, 30-203 ft, glauconitic greenish to brown sand, containing indurated ("rock") layers in middle and basal parts (Eocene).	Aquia Formation, Ta, 0-230 ft, green glauconitic quartz sand containing a few lenses of clay, shell fragments, Foraminifera, and hard beds; marine (Eocene).	Vincetown Formation, Tvt, 0-100 ft, calcareous fossiliferous sand and glauconitic quartz sand. Semiconsolidated; marine (Paleocene).
Mattaponi Formation, Tkm, 0-600 ft, mottled clay, glauconitic sand and marl, and thick basal quartz sand. Deposited in estuaries and bays.	Brightseat Formation, Tb, 0-40 ft, gray to dark-gray micaceous silty and sandy clay (Paleocene).	Brightseat Formation, Tb, 0-300 ft, alternating hard and soft beds of gray clay and sparsely glauconitic sand containing Foraminifera and shells; marine; regional unconformity (Paleocene).	Hornerstown Sand, Tht, 0-30 ft, glauconite, clay, and quartz sand; fossiliferous; marine (Paleocene).
Upper Cretaceous, undifferentiated, 0-200 ft, red, brown, gray and blue clay, gray sand, and slightly glauconitic sand containing indurated layers. Deposited in near-shore marine waters. Sediments have a continental aspect, although they contain marine fossils, are highly variable in composition, and contain bright-colored strata.	Monmouth, Kmo, and Matawan Kma, Formations, 20-135 ft, dark-gray to black sandy clay and sand containing some glauconite. Basal part is lighter in color and less glauconitic.	Monmouth Formation, Kmo, 0-230 ft, dark-green and brown glauconitic sand and gray clay containing shells and Foraminifera; marine; lower boundary conformable.	Red Bank Sand, Krb, 0-20 ft, discontinuous bodies of reddish-brown fairly coarse sand. Littoral marine.
		Matawan Formation, Kma, 0-220 ft, white silty chalk, glauconitic sand and clay, and gray micaceous fine sand and conglomerate; marine.	Navesink Formation, Kns, 0-40 ft, glauconitic green marl, lenses of sand and clay, and a basal bed of shells; marine.
			Mount Laurel Sand, Kml, 0-60 ft, salt-and-pepper-colored glauconitic quartz sand; marine.
			Wenonah Formation, Kw, 0-50 ft, brown fine to medium quartz sand, slightly glauconitic; marine.
			Marshalltown Formation, Kmt, 0-40 ft, black sandy clay and lenses of glauconitic sand; marine; confines the Englishtown Formation.
			Englishtown Formation, Ket, 0-140 ft, yellow fine to pebbly quartz sand, slightly micaceous and glauconitic. Slightly consolidated; contains ledges of hard sandstone; lagoonal and marine.
			Woodbury Clay, Kwb, 0-50 ft, bluish-black tough micaceous clay, not glauconitic; marine.
			Merchantville Formation, Kmv, 0-60 ft greenish-black micaceous clay and sandy clay, glauconitic; marine; in conjunction with the Woodbury Clay and the Marshalltown Formation, forms an effective, extensive confining bed.
	Magothy Formation, Km, 0-140 ft, light-gray to white sand and fine gravel, containing interbedded clay layers; contains pyrite and lignite; nonmarine.	Magothy Formation, Km, 30-140 ft, white yellow and gray sand interlaminated with gray and brown shale, containing lignite and carbonaceous matter, but no animal fossils; nonmarine in the south but estuarine and littoral marine in the north; unconformable lower boundary.	Magothy Formation, Km, 0-50 ft, alternating beds of gray clay and gray to brown sand, commonly lignitic. Estuarine, marsh, and littoral marine.
	Raritan Formation, Kr, 0-100 ft, interbedded sand and clay containing ironstone nodules; locally contains indurated layers; nonmarine.	Raritan Formation, Kr, 0-1,700 ft, intercalated thin sand and shale. The sand is lenticular, crossbedded, generally gray, fine grained, micaceous, and lignitic. The shale is mottled pale gray, brown, and red in the upper section and gray brown in the lower. A few beds that contain Foraminifera and macrofossils with glauconite are marine tongues; the formation is predominantly nonmarine but downdip becomes deltaic and estuarine. The lower boundary is unconformable.	Raritan Formation, Kr, 0-900 ft, varicolored red, gray, and yellow tough clay and yellow silty fine to medium quartz sand. Contains a few thin beds of shells and lignitic sand. Predominantly fluvial and deltaic; contains a few thin marine beds.

TABLE 1.—Stratigraphic units of the northern part of the Coastal Plain—Continued

Virginia	Southern Maryland	Delmar Peninsula	New Jersey
Potomac Group, Kp, 0-1,000 ft, interbedded clean arkosic, white to gray quartz sand and light-colored clay containing few lenses of gravel. Deltaic sediments deposited in fresh to slightly brackish waters.	Patapsco Formation, Kpt, 100-650 ft, interbedded sand, clay, and sandy clay; color variegated but chiefly hues of red and yellow; nonmarine.	Patapsco Formation, Kpt, and Arundel Clay, Ka, 130-2,100 ft, medium- to fine-grained white sand in the upper part, but coarse and gravelly in the lower 600 ft. Clay shales and sandy shales are gray and brown in the upper part, variegated gray, red, brown and green in the middle part, and olive green and gray in the lower part. Generally nonfossiliferous. Nonmarine and deltaic. Lower boundary not conformable.	
	Arundel Clay, Ka, 25-200 ft, red, brown, and gray clay; nonmarine; in places contains ironstone nodules and plant remains.		
	Patuxent Formation, Kpx, 100-450 ft, chiefly gray and yellow sand containing interbedded clay; kaolinized feldspar and lignite common; nonmarine, locally clay layers predominate.	Patuxent Formation, Kpx, 125-2,300 ft, poorly sorted fine to very coarse sand and gravel, lenticular and crossbedded. Varicolored shales. Fluvial and alluvial-fan deposits. Lower boundary not conformable.	
Rocks of pre-Cretaceous age, pk, undifferentiated complex of gneiss, schist, gabbro, granodiorite, serpentine, and marble containing pegmatitic dikes of form platform upon which the sediments of the Coastal Plain were deposited.			

The positions of the salt-water interfaces are shown in figure 2. They represent the westward extension of ground water containing about 350 ppm (parts per million) or more chloride and referred to as "saline or salt water" in this report. No analyses are available which indicate that any of the saline ground water has chlorine concentrations as great as that of sea water.

For the regional discussion and the illustrations presented here, salt-water intrusions that result from artificial ground-water withdrawal are considered to be local details that do not appreciably alter the original natural relationship between fresh water and salt water. In addition, the shallow Pleistocene deposits contain salt water in some areas. This occurrence is neither discussed nor illustrated here.

In southern Virginia and in Maryland, the position of the interface represents the landward limit of salty water in the Cretaceous and Tertiary sediments. Fresh water can be obtained from aquifers at depths of more than 1,000 feet in the area west of this line. Except for local salt-water encroachment into some shallow sediments, the water in these deposits is fresh. East of the interface in Virginia and Maryland, fresh water cannot be obtained from depths much greater than about 500 feet. In Virginia, south of the York River, the limiting depth of fresh water is less than 500 feet (Cederstrom, 1943a, pl. 3); but near the coast in Delaware, fresh water locally extends as deep as 700 feet (Sanford, 1911, p. 78).

In New Jersey two salt-water interfaces are shown. The northern line indicates the interface in the Magothy and Raritan Formations and is based on theoretical

considerations (Barksdale and others, 1958, p. 109-111). The probable position of the salt-water interface in the Raritan and Magothy Formations was determined by consideration of the head of the fresh water in the outcrop area and the relative density of the fresh and salt water. All available chemical data verify the general position. This interface has been used in the construction of the flow diagram (fig. 3) for the Cretaceous sediments, and its theoretical position is indicated on the fence diagrams (section *B-B'*).

The southern line, in New Jersey (fig. 2), is a possible position of the salt-water interface in the Miocene sediments. (See section *O-A'*, pl. 1B.) Fresh water is obtained from a depth of about 800 feet at Atlantic City. In Cape May County, salt water is obtained at less than 500 feet (Gill, 1959, fig. 7).

In New Jersey, the southern line, which represents the interface in the Miocene sediments, is more comparable to the line drawn for Maryland and Virginia. There is no known occurrence of salt water in the deep Tertiary sediments northwest of this line. Those sediments in which the bulk of the water is fresh and those sediments in which the water is mostly saline are indicated on plate 1B. The distribution of pre-Cretaceous bedrock and the thickness of the Coastal Plain deposits also is shown. The thickness of the Cretaceous deposits is many times greater than that of the overlying Tertiary deposits. The bedrock surface was compiled from the tectonic map of the United States (1960).

The shape of the salt-water interface is schematic; however, it is patterned after the shape observed in

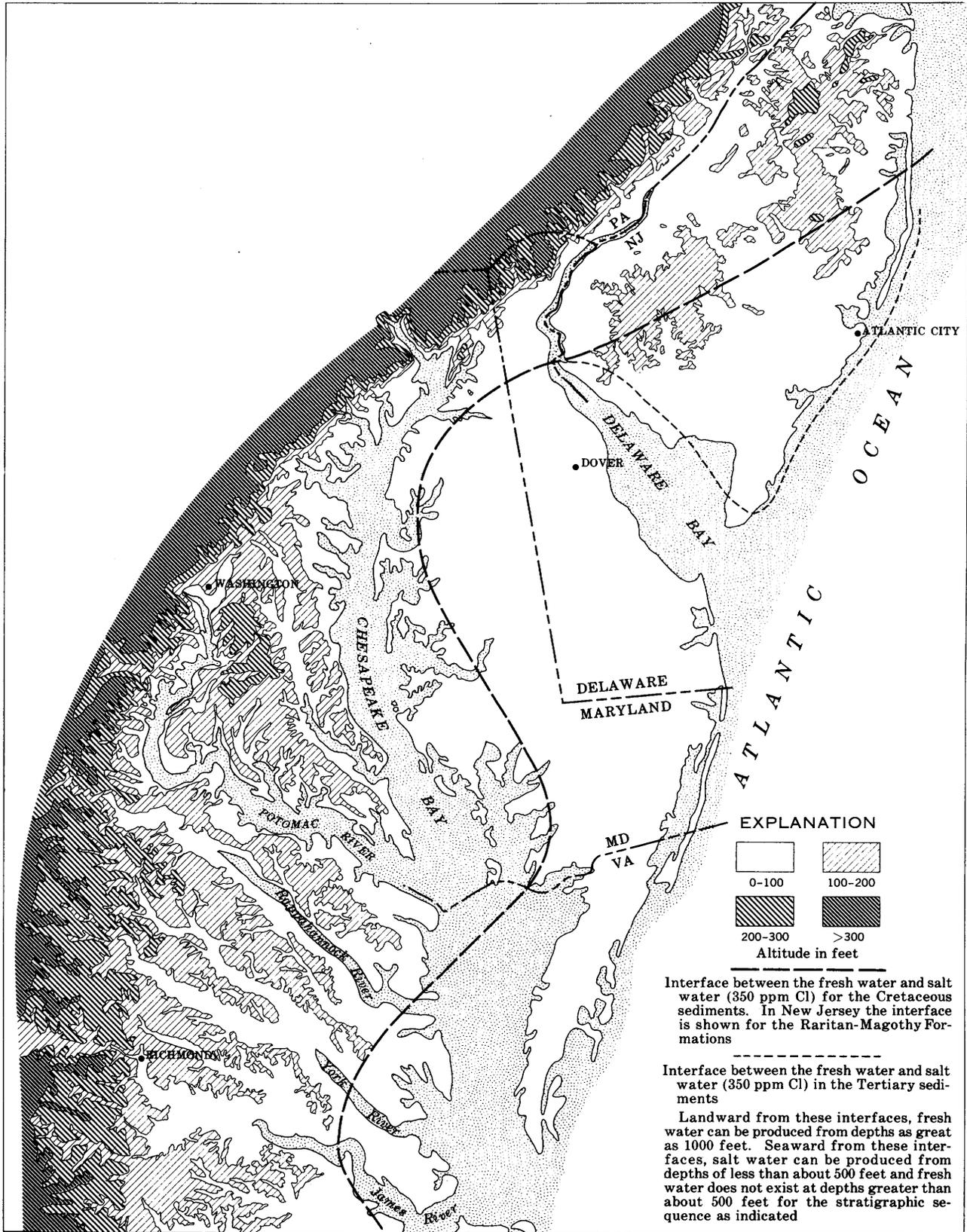


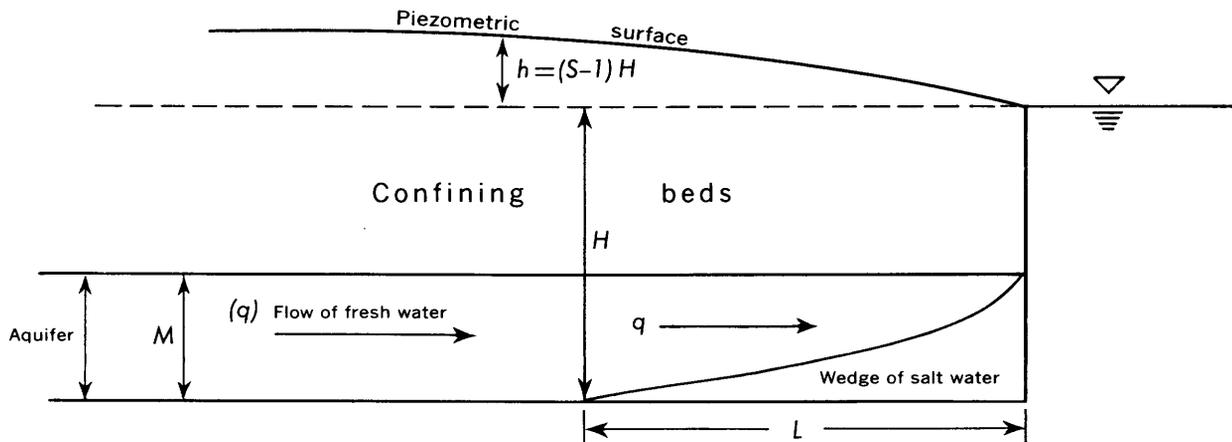
FIGURE 2.—Map showing the relation of topography to landward extent of salt- and fresh-water interfaces in the Cretaceous and Tertiary deposits.

areas of salt-water encroachment into aquifers (Kohout, 1960, fig. 3) or after the shape identified in tidal estuaries. From plate 1B it is seen that probably 80 percent of the Cretaceous and Tertiary section of the Coastal Plain contains saline ground water. This constitutes a large potential source of supply in case fresh ground-water supplies may not be adequate for future demands (Krieger and others, 1957, p. 34).

Several factors determine the positions of salt-water-fresh-water interfaces in coastal areas. A major control is the distribution of fresh-water head in the recharge and discharge areas. The fresh-water head is influenced by topography, thickness of sediments, amount of recharge and discharge, and vertical and horizontal changes in permeability.

The relationship of several factors that determine the position of fresh-water-salt-water interfaces in coastal aquifers can be seen from a statement of Darcy's law:

$$q = P \frac{\partial h}{\partial D} \quad (1)$$



Equation 4 expresses the length of the salt-water wedge as a function of permeability, flow of fresh water, relative densities of the two fluids, thickness of sediments, and fresh-water head, assuming the following conditions:

1. Steady-state flow.
2. A horizontal confined aquifer discharging only at the submarine outcrop.
3. Absence of tidal fluctuations.
4. No salt-water circulation due to dispersion or diffusion.

From equation 4 and the diagram it can be seen that the length of the salt-water wedge is directly proportional to the permeability and thickness of the sediments and that it varies inversely with fresh-water head and quantity of flow. By the integration steps of the derivation the terms related to head have been combined with

where

q = rate of flow of water through a unit cross-sectional area of porous material
 P = permeability of porous material
 $\partial h / \partial D$ = rate of head change along the flow path;

and from the Ghyben-Herzberg principle:

$$h = (S-1)H \quad (2)$$

where

h = head of fresh water above sea level
 S = density of salt water
 H = depth of salt water below sea level.

On the basis of the two preceding statements and certain idealized conditions, Harder and others (1953, p. 44) derived the following equations to express the relation of these factors to the length (L) of the salt-water wedge:

$$q = \frac{P}{2} (S-1) \frac{M^2}{L} \quad (3)$$

$$L = \frac{P}{2} (S-1) \frac{M^2}{q} \quad (4)$$

Where M is the thickness of the aquifer. The terminology is illustrated in the accompanying diagram (after Harder and others, 1953 p. 7).

the density and thickness terms. However, it is obvious from the diagram that a decrease in fresh-water head (h) will cause a corresponding decrease in depth of salt water below sea level (H), which has the effect of increasing the length of salt-water wedge.

These general relationships are shown on plate 1B and in figure 2. For example, the salt-water interface in the Miocene sediments in New Jersey is farther seaward than the interface in the Cretaceous formations because the head in the recharge area of the Miocene sediments is higher than in the recharge area of the Cretaceous formation at low altitudes along the Fall Zone. The interface in the sediments of Miocene age is farther seaward than the extent of most of the fences shown on plate 1B; however, the relative position of the two interfaces is shown in section $O-A$.

In Delaware and in northern Maryland (section

E-E') the salt-water interface is close to the Fall Zone primarily because of the absence of highlands near the outcrop area and the lower heads in the aquifers. One of the highest outcrop areas (alt, 175 ft) of the Cretaceous formations is northeast of Washington. The Cretaceous sediments and the overlying sediments also receive recharge in a highland area southeast of Washington. The existence of these high land masses and of the highland region along the northern neck of Virginia, between the Rappahannock and Potomac Rivers, allows the fresh-water head to become high enough to maintain the salt-water interface at a distance from the Fall Zone (section *G-G'*) greater than that to the north (section *F-F'*, pl. 1B).

In the central part of Virginia along the Fall Zone, the altitude on the surface of the Coastal Plain sediments is approximately 175 feet, which is about the same as that of the recharge area in Maryland. However, the streams have much wider flood plains and the uplands are more deeply dissected. This advanced stage of erosion facilitates the discharge of ground water locally and prevents formation of high fresh-water heads under the Coastal Plain. Because of these fresh-water heads fresh water and salt water are balanced in an area closer to the Fall Zone (section *I-I'*, pl. 1B).

Because of the mutually interrelated effects of permeability and thickness of sediments on the distribution of head and quantity of water flow, generalization concerning their relative significance in determining the position of the salt-water wedge cannot be made within the scope of this study.

In view of the preceding relationships, an obvious conclusion is that in a region of uniform rainfall the position of the salt-water-fresh-water interface is controlled primarily by the topography of the region, the extent of erosion, relative thickness of sediments, and the permeability of material in the beds within the area of ground-water flow.

FACTORS AFFECTING OCCURRENCE OF SALT WATER

Saline water may accumulate in geologic formations by any of the following processes: Retention of ions from salt water trapped at the time of deposition; intrusion of salt water after deposition due to change in sea level or in discharge; solution of minerals and concentration of the constituents by filtration by the clays; and recharge by atmospheric precipitation containing ions.

An objection to the hypothesis that the deep salt water is the original water in which the sediments were deposited is that salt water occurs in the Potomac group of fresh-water origin, as at Chestertown, Md., and at

Salem, N.J. Salt water in some of the marine formations may be in part residual water or ions that have not been completely flushed by fresh water. However, owing to postdepositional chemical reactions, the original chemical character of the water or its source in time or space cannot be determined from the present chemistry of the water (Chaves, 1960, p. 369).

The presence of salt water may also be partly due to entrance of sea water during the Tertiary and Pleistocene submergence of the Coastal Plain. Sanford (1911, p. 82-83) stated this idea as follows:

In periods of elevation underground circulation has been quickened and fresh water has gradually leached marine deposits and forced out any original sea water. In periods of depression the outcrops of fresh-water bearing beds have been saturated by sea water and blanketed by marine deposits. Another period of elevation has started fresh water down the dip, displacing sea water, leaching marine deposits, and forcing the salt but freshening solutions into the underlying beds. Thus, a bed that originally was a fresh-water deposit may have been repeatedly invaded by salt water from above and the present salinity of the water in a particular area is to be regarded as connected with the last invasion of salt water rather than with any sea water imprisoned in the beds at the time of deposition.

Some of the deep salt water may also be due to solution of minerals and to the concentration of ions by filtration by the clays. Although no analyses are available for this part of the Coastal Plain, on the basis of work done in other areas (Spangler, 1950, p. 106; Meents and others, 1952, figs. 4-13) the deeper water (below 1,500-2,000 ft), certainly is more concentrated than sea water. The specific processes involved are not sufficiently understood to satisfactorily explain the origin of brines. The dominant controls thus far identified are the relative solubilities of minerals in concentrated solutions and the effect of clays undergoing compaction and ion exchange. The membrane properties of clays may, as has been postulated by several workers (de Sitter, 1947; Bredehoeft and others, 1963), lead to the exclusion of ions from water flowing across a membrane. That is, where the clays act as semipermeable membranes the water moves through and is discharged while the ions remain behind and are concentrated.

GROUND-WATER FLOW PATTERNS

A generalized ground-water flow pattern for the Cretaceous sediments of the Coastal Plain is shown in figure 3. The western boundary of the flow patterns was established along the outcrop of the sediments near the Fall Zone and the eastern boundary along the salt-water interface in the Cretaceous deposits. The numbers along these boundaries represent head values. They were obtained in the outcrop area by measurement of water levels; along the salt-water interface they were

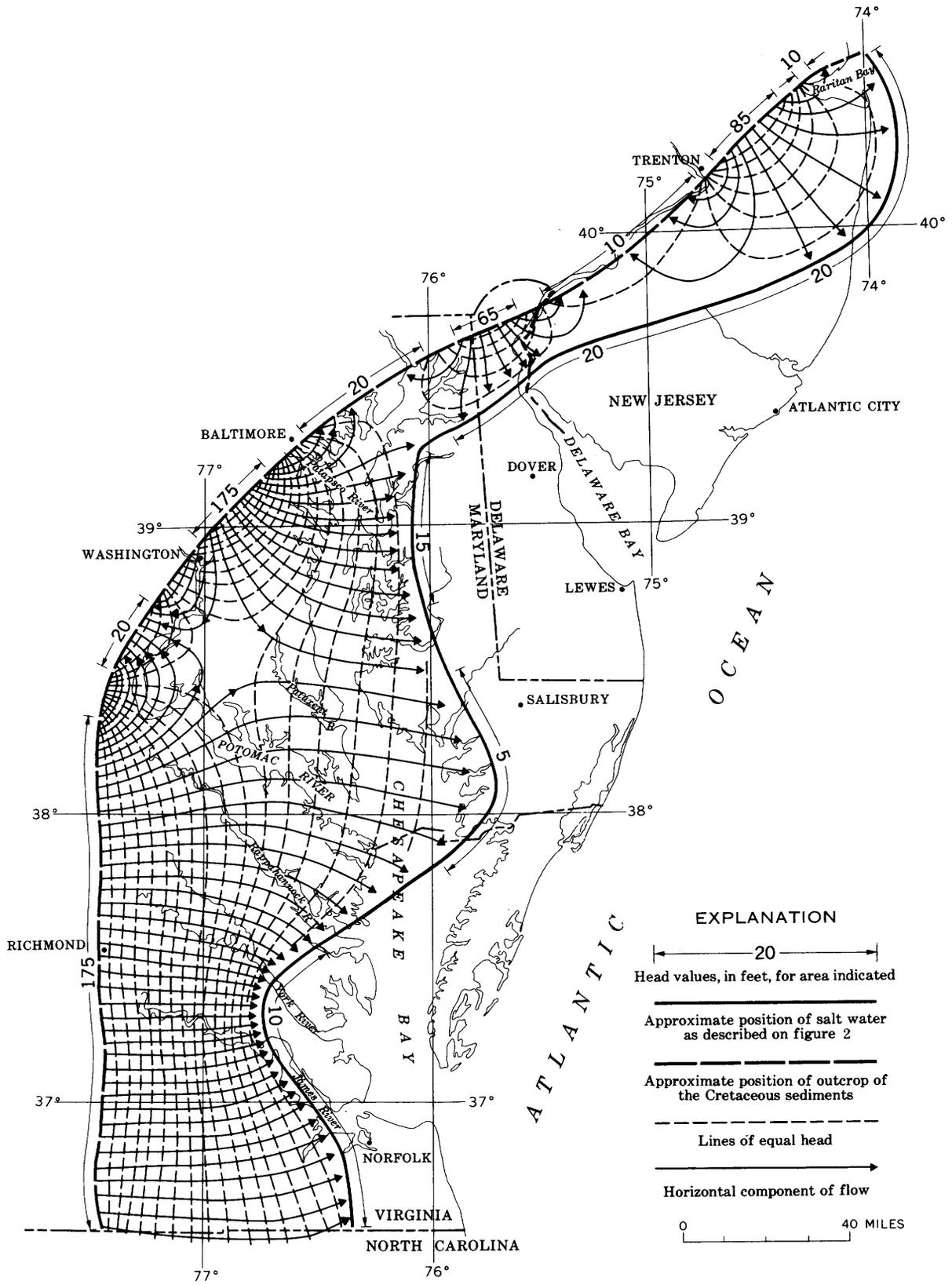


FIGURE 3.—General pattern of ground-water flow in the Cretaceous sediments.

obtained from historic records that indicate the approximate altitudes of the piezometric surface as defined by flowing wells in those areas. Because the maximum height to which the water would rise was not measured, these are minimum head values for defining the original natural conditions.

In drawing and in analyzing the pattern of ground-water flow, the salt-water interface was treated as an impermeable boundary—that is, as a limiting flow line. By definition no fresh water can cross this boundary. If fresh water could move into the salt water, the effects would be dilution of the salt water and migration of its boundary. Therefore, in effect the salt-water interface marks the limit of horizontal flow of the fresh water.

The flow pattern was drawn by using an electric analog model in which head values are simulated by electrical potentials (voltage) applied to a sheet of graphite-coated paper having uniform resistance. After building the model the electrical potential was contoured between the boundaries to describe the configuration of the piezometric surface. Flow lines were sketched in orthogonally to the equipotential contours to form rough squares, according to standard procedures for constructing flow nets (Casagrande, 1937). However, owing to the lack of data, primarily values for natural discharge of ground water, this illustration is not a rigorous flow net and cannot be used for quantitative studies of aquifer transmissibility and rates of water movement. In constructing the model it was not possible to take into account the amount of upward vertical leakage. Hence, this flow pattern shows the direction of ground-water movement in the Coastal Plain as if there were no upward vertical leakage. This is not to imply that the major ground-water discharge of the Coastal Plain sediments is not upward into the overlying sediments but only that the flow pattern is shown for two dimensions. The vertical movement of ground water is shown in figure 4.

This method of construction, however, is adequate to demonstrate important general features of ground-water movement. The recharge areas of the Cretaceous sediments are evidently in New Jersey, Delaware, the area between Washington and Baltimore, the high area of southern Maryland, and along the Fall Zone in Virginia. The areas of discharge in the outcrop area are indicated by the flow lines and by the low-head values.

In New Jersey this flow pattern is quite similar to that for the Magothy and Raritan Formations. The errors introduced into the flow pattern owing to lack of modeling for upward vertical discharge are small for the New Jersey area. Upward vertical leakage is not a major factor in New Jersey owing to the high

head in the overlying Tertiary sediments. The water is discharged into the Raritan Bay area, along the Delaware River, and perhaps eastward from the coast through submarine springs.

It is evident that the outcrop area of artesian aquifers can function either as a discharge area or as a recharge area. This, of course, demonstrates that the water moves updip (that is, to the west or northwest) in many parts of the Coastal Plain.

Figure 4 shows relation of topography to the generalized flow pattern in four selected cross sections. The direction of movement is based on the interpretation of piezometric surface shown in figure 3 and other water-level maps and measurements made for local areas. Some of the water that is shown in section *E-E'* as being discharged updip has moved laterally southward from the recharge areas in New Jersey and northern Delaware. Some of it has been recharged through the Tertiary sediments of the central part of Delaware. The cross section *H-H'* shows that much more of the water is discharged updip to the west and some flows upward to the east over the salt-water interface. In southern Virginia the ground-water flow is restricted by the shallow bedrock and by the proximity of the salt water.

Throughout much of the eastern part of the Coastal Plain the recharge is from the local rainfall. The major movement of ground water during wet periods is primarily downward to the water table; during dry periods it is upward. Of course, the ground water is discharged locally into many streams and estuaries. The water that is locally recharged and discharged has little effect on the overall chemistry of the water with the possible exception of dilution in the upper beds.

HYDROCHEMICAL FACIES

DEFINITION

The concept of hydrochemical facies has been used (Seaber, 1962; Morgan and Winner, 1962; and Back, 1960) to denote the diagnostic chemical character of water solutions in hydrologic systems. The facies reflect the effects of chemical processes occurring between the minerals within the lithologic framework and the ground water. The flow patterns modify the facies and control their distribution. This definition of hydrochemical facies is a paraphrase of the definition of sedimentary facies given by Moore (1949, p. 8): "sedimentary facies are areally segregated parts of differing nature belonging to any genetically related body of sedimentary deposits."

The term "geochemical facies" has been used by Teodorovich (1949) and Pustalov (1933, 1954) to define different sedimentary environments by means of

HYDROLOGY OF AQUIFER SYSTEMS

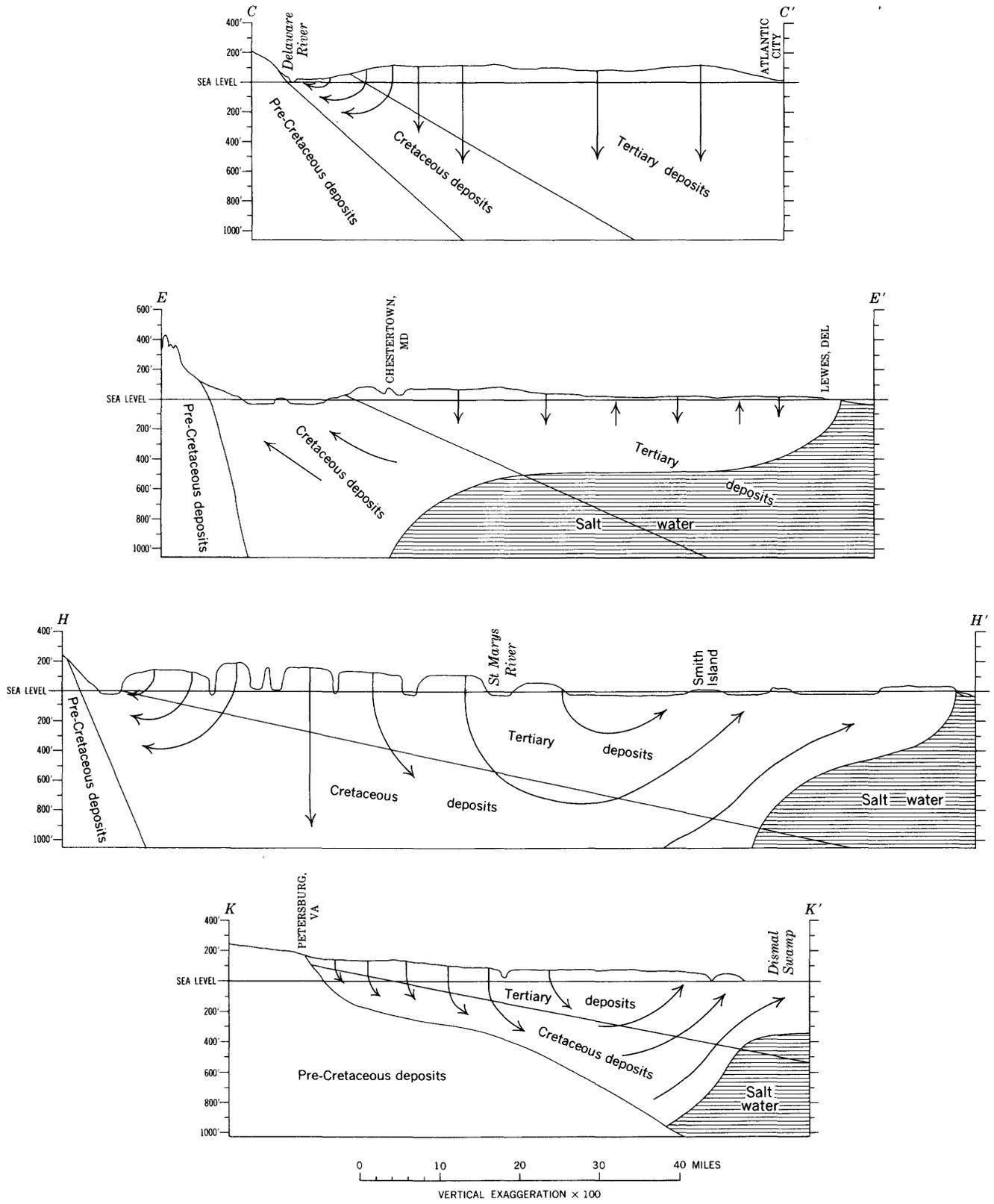


FIGURE 4.—Sections showing the vertical component of the major ground-water flow. Location of sections shown in figure 1.

specific mineral indicators of oxidation-reduction potentials and pH. Adams and Weaver (1958) proposed that "geochemical facies" of sedimentary rocks be defined in terms of the thorium-uranium ratio. Keith and Degens (1959, p. 40) used the term "chemofacies" to designate all the chemical elements that are collected, precipitated, or adsorbed from the aqueous environment, or fixed by chemical reactions in the bottom muds, as a basis for differentiating between marine and freshwater sediments.

The term "hydrochemical facies" was used previously by Chebotarev (1955, p. 199) for a column heading in a table; however, he did not define the term and used it only to indicate concentration of dissolved solids—that is, low-saline facies, transitional-saline facies, and high-saline facies.

Many Russian scientists have contributed to formulation of the "principle of hydrochemical zones." The concept of hydrochemical facies, as used in this report, is a refinement of this approach and can be considered, in part, as subdivision of major zones. According to the usage by some Russians, hydrochemical zones cover large regions and are segregated according to the predominant anion. For instance, the European part of the Soviet Union is segregated into five hydrochemical zones (Garmonov, 1958). The zone (1) of hydrocarbonate (bicarbonate)-siliceous water coincides with the soil-tundra zone, where the average yearly temperature is 0°C. This water is low in dissolved solids. The zone (2) of hydrocarbonate (bicarbonate)-calcium water covers an extensive area in which there are many different geologic deposits, most of which contain calcareous materials. Sulfate and chloride occur in the southern part. Cation exchange also results in the creation of hydrocarbonate-sodium water in this zone. The zone (3) of sulfate and chloride-sulfate water roughly coincides with the central and southern parts of the steppes and is characterized by a predominance of evaporation over precipitation. Calcium is the dominant cation. The zone (4) of chloride water occurs in the area of the Black Sea lowland and in the northern part of the Crimean peninsula; a second area is the Caspian lowland. The first area contains saliferous soils, salt licks, and salt marshes. The Caspian lowland is an area of desert and semidesert in which the water is the chloride-magnesium-sodium type. Zone (5), in which the water has a low content of dissolved solids of the hydrocarbonate-calcium type, is in the mountainous regions of the Crimea and the Caucasus.

In addition to the geographic hydrochemical zones, several scientists (Kamensky, 1958, p. 285; (Chebotarev, 1955, p. 200) have discussed three vertical hydrodynamic zones that are characterized by certain chemi-

cal types of water. The uppermost zone is characterized by a high degree of water circulation and well-leached rocks and sediments. The water is of the bicarbonate type and has a low dissolved-solids content. In the intermediate zone water circulates less, the dissolved-solids content is higher, and the water is of the sulfate type. The lowermost hydrodynamic zone is a "stagnant" regime in which rocks are unleached and the water is highly mineralized and primarily of the chloride-sodium type.

The hydrodynamic zones have been subdivided within the hydrochemical zones by the Russians to produce hydrogeochemical zones. The following vertical succession of hydrogeochemical zones was established by Kravtsov in the coal-bearing measures of the Donetz basin (Kamensky, 1958, p. 285): Hydrocarbonate (bicarbonate)-calcium water, hydrocarbonate-sulfate-sodium mixed water, sulfate-sodium water hydrocarbonate-sodium water, hydrocarbonate-chloride-sodium water, and possibly a zone of highly mineralized chloride-sodium water. The term "hydrogeochemical zones" is used to emphasize the relationship between the chemistry and movement of water.

The term "hydrochemical facies" includes all the concepts signified by hydrochemical zones, hydrochemical microzones, hydrodynamic zones, and hydrogeochemical zones. Accordingly, one term can be used instead of four.

The terminology used to designate the hydrochemical facies of the Atlantic Coastal Plain (Back, 1961b) is shown in figure 5 and in table 2. A further refinement is used here to subdivide a particular facies into a chemical type of water on the basis of the dominant ion within the facies. For example, water showing the calcium-magnesium facies may be of either the calcium type or the magnesium type. On the other hand, either the facies or the type may be combined to designate the overall chemical character of the water (for example,

TABLE 2.—Classification of hydrochemical facies of the Atlantic Coastal Plain^a

	Percentage of constituents, in equivalents per million			
	Ca+Mg	Na+K	HCO ₃ +CO ₃	Cl+SO ₄ ^b
Cation facies:				
Calcium-magnesium.....	90-100	0<10	-----	-----
Calcium-sodium.....	50-90	10<50	-----	-----
Sodium-calcium.....	10-50	50<90	-----	-----
Sodium-potassium.....	0-10	90-100	-----	-----
Anion facies:				
Bicarbonate.....	-----	-----	90-100	0<10
Bicarbonate-chloride sulfate.....	-----	-----	50-90	10<50
Chloride-sulfate-bicarbonate.....	-----	-----	10-50	50<90
Chloride-sulfate.....	-----	-----	0-10	90-100

^a Modified from Back (1961b, p. D-381).

^b May include some NO₃ and F.

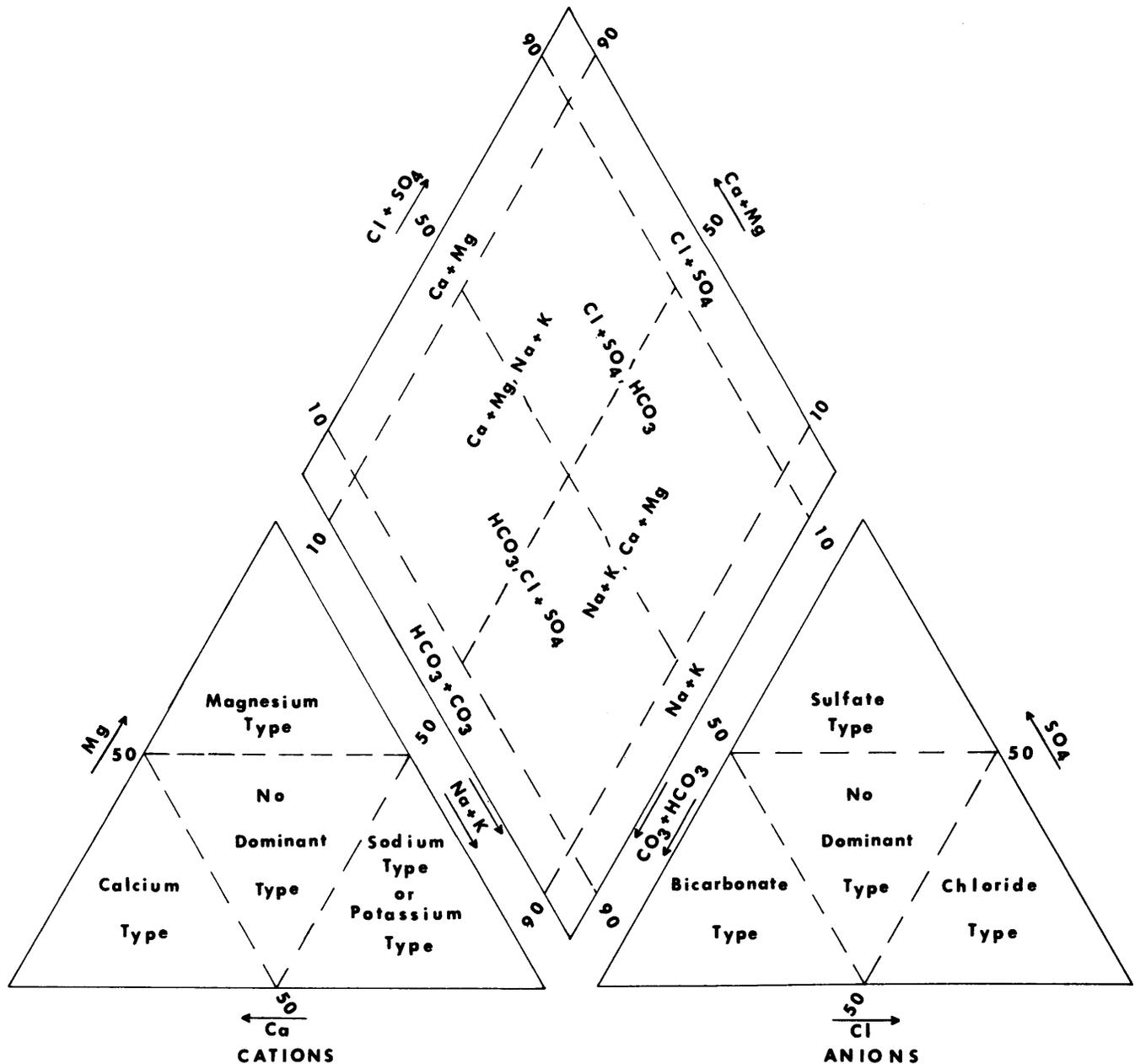


FIGURE 5.—Water-analysis diagram showing hydrochemical facies, in percent of total equivalents per million.

water of the sodium type and chloride type would be classified as sodium chloride character).

PROCEDURES AND MAPPING TECHNIQUES

Significant characteristics of hydrochemical facies can be illustrated by methods similar to those used in lithofacies studies trilinear diagrams that show the facies present in an area or in formations, fence diagrams that show the facies distribution, and maps that

show isopleths of chemical constituents within certain formations.

Trilinear and similar diagrams have long been used to study the chemistry of water. Emmons and Harrington (1913) used two triangles, one for cations and one for anions, with each vertex representing 100 percent of a particular ion or groups of ions, as is often used in petrographic studies. Hill (1940; 1942, p. 1517) published a trilinear diagram which added to the origi-

nal two triangles a diamond-shaped area in which the two points plotted in the triangles are projected into the diamond and are plotted as a single point. Piper (1944) independently developed a similar diagram that has undergone minor changes and is used in this and other recent papers.

Trilinear diagrams were used in this study as the first step in the classification of the hydrochemical facies present. They were used to determine in which stratigraphic units waters were sufficiently close in composition to assume hydrologic connection between stratigraphic units to permit study as a hydrochemical unit. Therefore, the analyses were converted from parts per million to equivalents per million, and the percentages of equivalents were computed and were plotted. Because only a limited number of analyses can be plotted on any one diagram, the analyses were divided: first by States, second by formation or groups of age-related formations, and third by county boundaries.

Isometric fence diagrams (Back, 1961b) were selected as the most effective means of illustrating the geographic and stratigraphic distribution of the hydrochemical facies. A base-fence diagram was prepared to show the topography in cross section and the stratigraphic units from land surface to 1,000 feet below sea level. Twelve parallel cross sections trending nearly perpendicular to the strike of formations were arbitrarily selected. Then, 3 northwest-trending longitudinal sections perpendicular to the 12 lateral sections were prepared. The location of wells from which water analyses were used in this study is shown on the fence diagrams. Most of these wells are within 5 miles of the particular cross section to which they are projected. The true altitude of the well top was plotted; hence, on the fence diagrams the well top may not coincide with the land surface shown.

The concentrations or percentages of the constituents selected as being most informative were: Sodium and potassium as percentage of total cations, in equivalents per million (cation facies); bicarbonate and carbonate (where present) as percentage of total anions, in equivalents per million (anion facies), sum of determined constituents, in equivalents per million; concentration of the chloride ion, in parts per million; and concentration of the bicarbonate ion, in parts per million.

OCCURRENCE OF HYDROCHEMICAL FACIES WITHIN STRATIGRAPHIC UNITS

CRETACEOUS SEDIMENTS

The hydrochemical facies of the undifferentiated Cretaceous formations in Virginia, as plotted in figure

6, show that the sodium and bicarbonate facies are dominant in most of the area. The water from the counties along the Fall Zone is of a mixed character. Two analyses from Nansemond County (53, 54) show the presence of saline water. Typical analyses of water from the Cretaceous formations are shown in table 3. The index numbers in all the tables refer the analyses to the corresponding trilinear water-analyses diagrams. The well numbers given in the tables refer the analyses to the fence diagrams.

The hydrochemical facies of the Mattaponi Formation of Cretaceous and Paleocene age in Virginia are shown in figure 7. As in the Cretaceous formations, the sodium and bicarbonate are the major cation and anion facies. The one analysis reflecting the calcium-sodium facies is of water near the Fall Zone. The samples from York County indicate the saline character of the water in the Mattaponi Formation in that area.

Typical analyses are given in table 4.

The hydrochemical facies of Cretaceous formations in Maryland, as plotted in figure 8, shows that the water from these formations represents all major types. Some individual formations within the Cretaceous System contain the full range of facies. Selected analyses of water (table 5) show the range of concentration of ions in the areas where the Cretaceous formations are used extensively as aquifers. The trilinear diagram (fig. 8) shows that most of the water from Anne Arundel and Prince Georges Counties, in the higher piezometric area, is primarily of the calcium type. The availability of calcareous material determines whether the anion facies is of the sulfate or bicarbonate type. On the Eastern Shore, downgradient, the water has the sodium bicarbonate character.

The wide variability of the hydrochemical facies in the Raritan and Magothy Formations in New Jersey is shown in figure 9. Representative analyses are given in table 6. In the area of the piezometric high of Mercer and Middlesex Counties, the water is primarily of the calcium-magnesium and chloride-sulfate facies. Downgradient in the general discharge area along the Delaware River in Camden and Gloucester Counties the bicarbonate facies is dominant. The increase in bicarbonate may be due to the solution of calcareous material in the Tertiary sediments underlying the piezometric high to the east. The water from Salem County and parts of Gloucester County is of the sodium type primarily owing to the ion-exchange process and to presence of salt water from the river and from the extensive body of saline ground water.

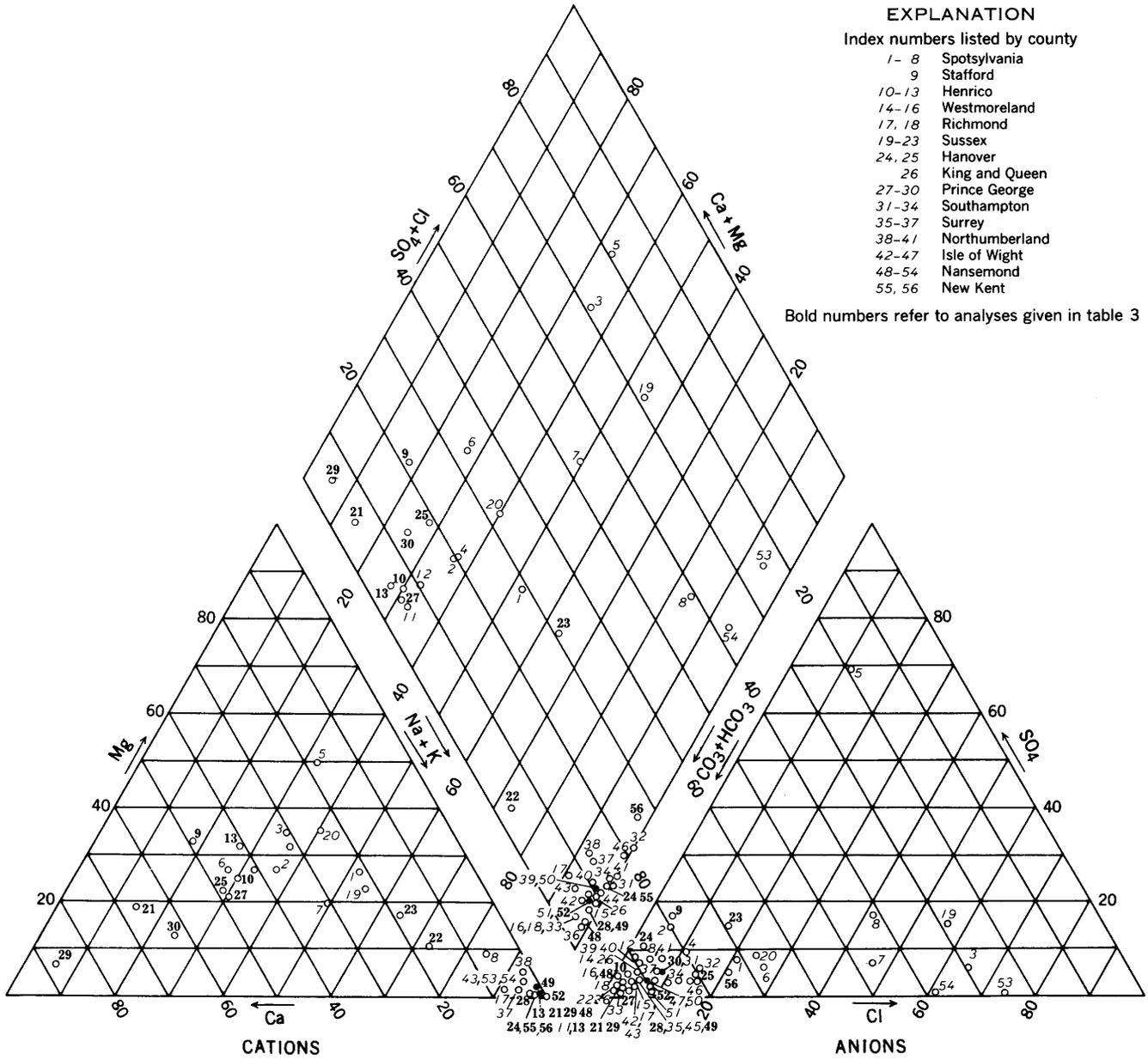


FIGURE 6.—Water-analysis diagram for the Cretaceous formations in Virginia.

TABLE 3.—Analyses of water from the undifferentiated Cretaceous formations in Virginia
 [Temperature: In wells 4, 6, and 87—89°, 65°, and 49°F, respectively; no data for other wells]

Location	Index No.	Well No.	Depth of well (ft. below land surface)	Date of collection	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)
										Upper figure in ppm; lower, epm									
Hanover County: Hanover Court House	25	19	154	Dec. 31, 1943	7.9	-----	224	8.0	2.6	41 2.05	12 .96	28 1.22		210 3.44	0 .00	7.0 .16	23 .65	0.1 .01	0.0 .00
Eastern View Farm	24	34	366	June 26, 1945	8.2	214	532	-----	.64	7 .04	2 .02	76 3.30		169 2.77	3.9 .13	16 .33	2.8 .08	.6 .03	.2 .00
Henrico County: Oak Hill Development	13	12	291	Nov. 6, 1947	-----	-----	173	26	.11	25 1.25	12 .96	19 .83		175 2.87	0 .00	5.5 .11	2.0 .06	.3 .02	.2 .00
Sandston	10	29	272	Dec. 30, 1943	7.7	-----	200	44	.03	29 1.45	10 .80	22 .96		183 3.00	0 .00	7.9 .16	2.4 .07	.0 .00	.1 .00
Nansemond County: Chuckatuck	48	1	580	Aug. 4, 1939	-----	-----	439	17	.05	1.2 .06	.7 .06	174 7.57	6.4	406 6.66	20 .67	3.8 .08	8.2 .23	3.5 .18	.58 -----
Cypress	49	115	420	do	-----	-----	782	9.9	.07	2.3 .12	3.3 .27	311 13.53	12 .31	707 11.59	34 1.13	16 .33	26 .73	6.4 .34	2.5 .04
Suffolk City	52	4	673	July 28, 1954	8.3	783	484	16	.09	.8 .04	.0 .00	190 8.26	6.8 .17	468 7.67	0 .00	7.5 .16	12 .34	5.0 .26	.5 .01
Prince George County: Brandon	28	40	405	Oct. 3, 1939	-----	-----	240	38	.03	1.9 .09	.5 .04	83 3.61	4.6 .12	221 3.62	0 .00	5.2 .11	5.8 .16	.7 .04	.15 .00
Burrowsville	27	48	126	do	-----	-----	219	31	.25	38 1.90	10 .82	15 .65	19 .49	222 3.65	0 .00	3.3 .07	3.0 .08	.4 .02	1.1 .02
Hopewell	30	23	156	June 29, 1939	-----	-----	213	37	.09	44 2.20	5.1 .42	17 .74	4.5 .12	180 2.96	0 .00	8.4 .18	9.5 .27	.4 .02	.10 .00
Prince George Court House	29	53	129	July 14, 1939	-----	-----	225	26	2.37	69 3.44	3.1 .26	3.7 .16	2.0 .05	225 3.70	0 .00	6.0 .13	2.2 .06	.0 .00	.0 .00
New Kent County: Walkers	55	3	440-445	Mar. 14, 1955	8.1	802	541	35	.44	3.6 .18	0 .00	210 9.13	5.8 .15	479 7.85	0 .00	13 .27	33 .93	2.4 .13	.1 .00
Do	56	4	615-625	do	8.1	1,270	800	35	.49	4.8 .24	0 .00	310 13.48	5.0 .13	588 9.64	0 .00	31 .65	118 3.33	2.8 .15	.1 .00
Stafford County: Fredericksburg	9	11	1,102	Sept. 23, 1953	6.8	132	-----	-----	15	13 .65	5.5 .45	5.4 .24		64 1.05	0 .00	11 .23	.8 .05	.1 .01	.2 .00
Sussex County: Wakefield	22	87	230	Nov. 26, 1937	-----	-----	209	18	.08	12 .60	4.8 .39	61 2.65		210 3.44	0 .00	3.0 .06	2.2 .06	.0 .00	1.9 .03
Waverly	21	79	240	do	-----	-----	245	37	.03	58 2.89	10 .82	14 .61		244 4.00	0 .00	6.0 .13	2.9 .08	.2 .01	2.0 .03
Jarratt	23	132	98	Apr. 19, 1938	-----	-----	120	30	8.9	8.4 .24	2.7 .22	9.8 .43	14 .36	60 .98	0 .00	9.6 .20	8.1 .23	.0 .00	.98 .02
Westmoreland County: Montross	15	6	648	May 20, 1953	8.5	529	328	19	.04	1.6 .08	.4 .03	130 5.65	3.9 .10	299 4.90	14 .47	7.5 .16	2.6 .07	2.4 .13	2.3 .04

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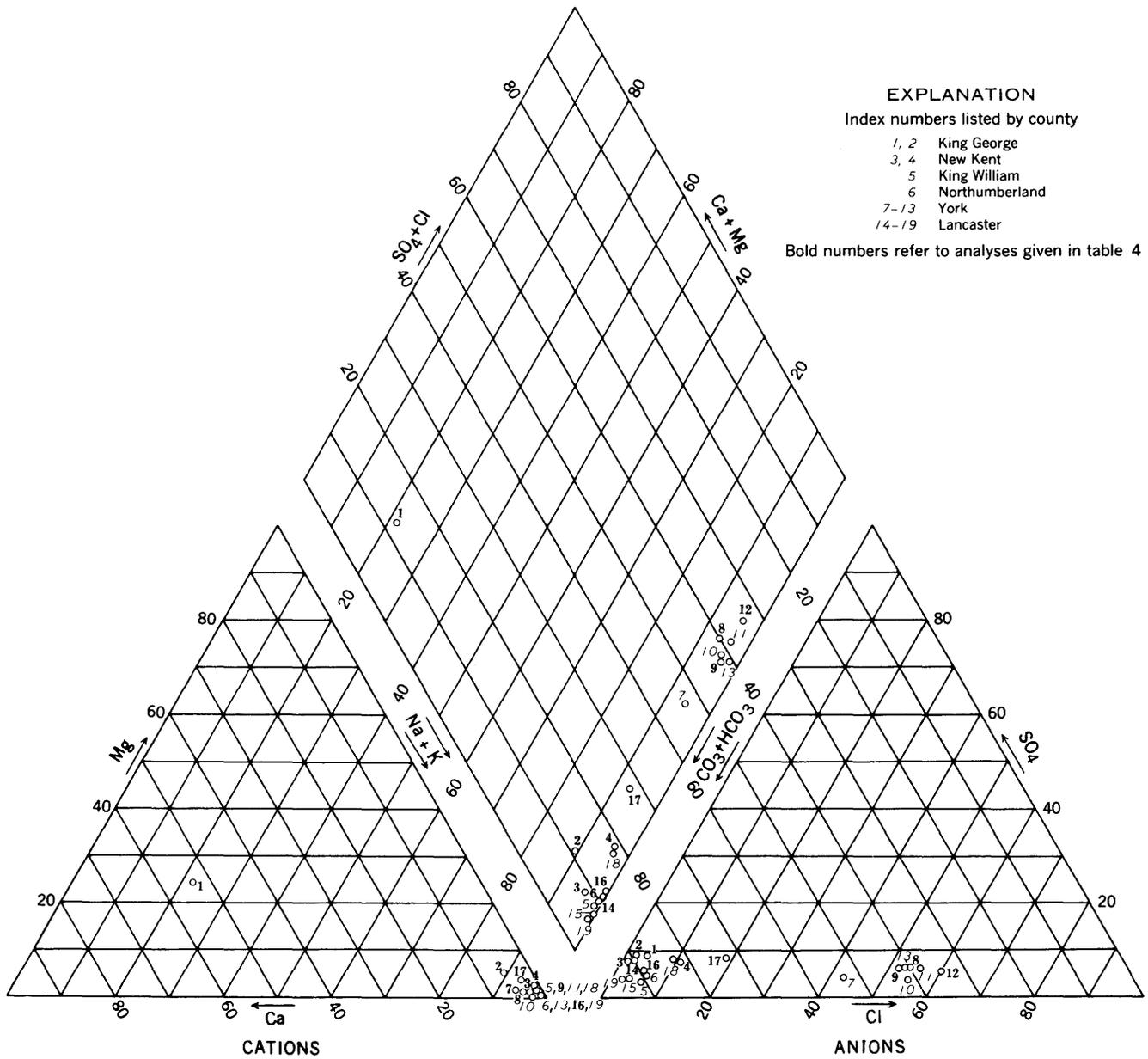


FIGURE 7.—Water-analysis diagram for the Mattaponi Formation in Virginia.

TABLE 4.—Analyses of water from the Mattaponi Formation in Virginia

[Temperature: 65°F in well 13; no data for other wells]

Location	Index No.	Well No.	Depth of well (ft below land surface)	Date of collection	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)
										Upper figure in ppm; lower, epm									
King George County: King George Court House	2	13	400	May 14, 1953	8.3	370	230	19	0.04	3.8 .19	2.5 .21	78 3.39	8.4 3.44	210 3.44	0 .00	18 .37	1.0 .03	0.4 .02	0.9 .01
Sealston	1	4	201	June 16, 1949	6.8	238	154	30	5.0	26 1.30	7.4 .61	12 .52	129 2.12	0 .00	11 .23	2.8 .08	.3 .02	.2 .00	
New Kent County: Providence Forge	3	41	286	Dec. 30, 1943	8.1	-----	279	33	.02	2.0 .10	1.0 .08	101 4.39	247 4.05	3.0 .10	15 .31	1.9 .05	1.1 .06	.0 .00	
Walkers	4	2	340-345	Mar. 14, 1955	8.2	681	473	34	.23	3.2 .16	0 .00	171 7.44	6.0 .15	435 7.13	0 .00	11 .23	15 .42	2.4 .13	.1 .00
Northumberland County: Avalon	6	37a	605	June 8, 1948	8.3	608	366	14	.16	1.4 .07	.8 .07	146 6.36	356 5.83	4.9 .16	17 .35	2.8 .08	1.0 .05	.6 .01	
Fleeton	-----	75	711	do	8.3	742	455	15	.05	.7 .03	.4 .03	185 8.05	415 6.80	3.9 .13	32 .67	13 .37	2.4 .13	.5 .01	
Richmond County: Downing	-----	6	622	June 9, 1948	8.5	501	309	16	.38	7.6 .38	.9 .07	114 4.96	281 4.61	14 4.7	8.6 .18	2.8 .08	1.8 .10	.2 .00	
Westmoreland County: Leedstown	-----	72	500	Oct. 14, 1944	8.4	-----	444	11	.03	2.2 .11	1.8 .15	171 7.44	9.0 .23	422 6.92	25 .83	11 .23	2.0 .06	1.7 .09	.0 .00
York County: Camp Peary	8	11	472	Sept. 23, 1946	8.5	-----	1,010	18	.06	16 .80	4.2 .35	365 15.88	8.6 .22	390 6.40	14 .47	49 1.02	328 9.25	1.8 .09	.1 .00
Grove	9	25	485	Oct. 17, 1918	-----	-----	1,356	-----	.14	8.0 .40	3.5 .29	478 20.79	393 6.45	76 2.53	63 1.31	404 11.39	-----	1.02 .02	
Do	12	29	554	do	-----	-----	1,474	-----	1.2	8.8 .44	5.8 .48	526 22.88	14 .36	439 7.20	33 1.1	61 1.27	524 14.78	-----	1.1 .02
Lancaster County: White Stone	14	18	634	May 15, 1956	8.7	817	499	13	.29	1.9 .10	.7 .06	193 8.39	4.9 .12	412 6.75	31 1.03	33 .69	8.3 .24	2.8 .15	.6 .01
Irvington	16	32	750	June 9, 1948	8.7	951	587	12	.04	1.4 .07	.6 .05	241 10.47	547 8.96	15 .60	29 .60	12 .34	3.4 .18	.6 .01	
White Stone	17	25	580	July 5, 1918	-----	-----	872	-----	-----	8.0 .40	6.8 .56	280 12.18	364 5.97	108 3.60	53 1.10	86 2.42	-----	2.0 .04	

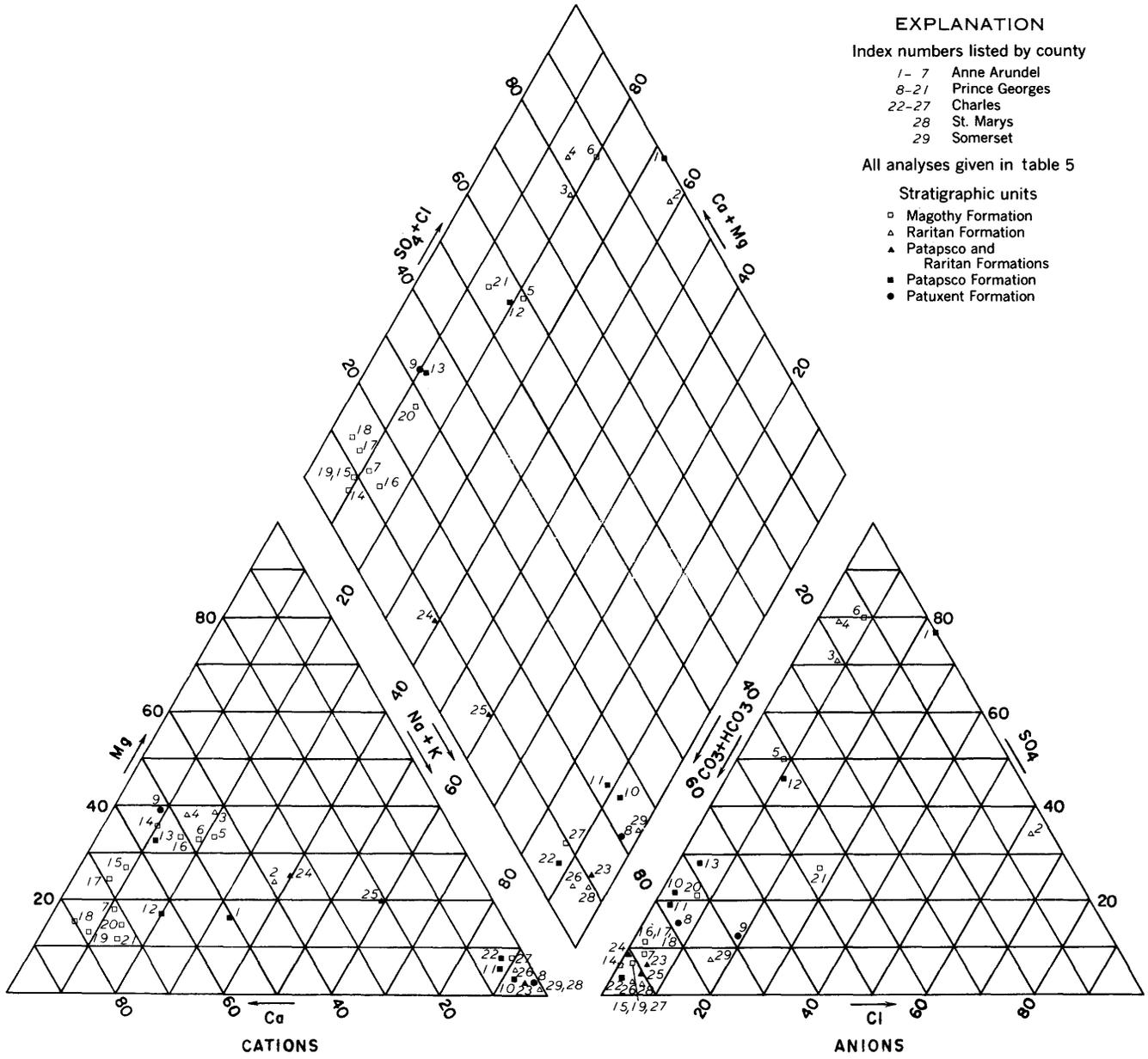


FIGURE 8.—Water-analysis diagram for the Cretaceous formations in Maryland.

TABLE 5.—Analyses of water from the Cretaceous formations in Maryland

[Location: The last well listed here is at Crisfield; the location of all the others is indicated on pl. 15 of Otton, E. G. (1955). Geologic formation: Kpt, Patapsco Formation; Kr, Raritan Formation; Km, Magothy Formation; Kpx, Patuxent Formation]

Index No.	Well No.	Depth of well (feet below land surface)	Geologic formation	Date of collection	Temperature (°F)	pH	Specific conductance (micromhos at 25 °C)	Dissolved solids (residue at 180 °C)	Silica (SiO ₂)	Total iron (Fe)	Upper figure in ppm; lower, epm												
											Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)			
Anne Arundel County.	1	AA-Bf2...	318	Kpt	May 1, 1951	58	4.1	54	34	9	2.5	1.8	0.6	1.3	1.6	0	9	2	0	0.2			
	2	AA-Be45...	67	Kpt-Kr	Apr. 16, 1946	56	4.7	114	75	2.8	.35	6.2	2.3	6.1	1.4	2	14	7	.06	.00			
	3	AA-Ce1...	213	Kpt-Kr	Apr. 1, 1946	---	5.3	86	53	6.2	30	6	3.6	2.2	1.4	10	26	.29	.20	.01			
	4	AA-Df12...	600	Kpt-Kr	Mar. 20, 1945	---	5.2	---	66	7.6	19	7.9	3.8	1.5	1.7	9	32	.64	.05	.02			
	5	AA-Ce46...	96	Km	May 8, 1946	57	5.6	95	62	13	11	7.8	3.5	2.1	2.7	21	20	.67	.03	.01			
	6	AA-Cf11...	95	Km	Apr. 16, 1946	---	4.9	83	55	9.1	21	6.2	2.5	1.8	1.8	5	25	.42	.06	.02			
	7	AA-Ed8...	265	Km	June 28, 1946	---	7.2	342	209	17	1.2	50	7.7	4.2	7.2	190	15	.52	0.4	.02			
Charles County.	22	Ch-Ce5...	274	Kpt	Apr. 2, 1952	---	7.9	411	265	19	1.9	5.9	3.5	88	7.6	265	7.5	.5	.9	.8			
	23	Ch-Dd10...	414	Kpt-Kr	Mar. 7, 1951	---	8.2	365	245	19	.98	1.4	1.2	85	4.0	216	16	2.4	.7	.4			
	24	Ch-Cf9...	679	Kpt-Kr	Apr. 17, 1952	---	7.5	268	158	11	.73	21	8.3	20	11	165	11	.33	.07	.04			
	25	Ch-Da1...	210	Kpt-Kr	Mar. 20, 1951	---	7.4	371	244	32	1.8	15	9.4	54	7.6	229	9	.23	.03	.02			
	26	Ch-Ee18...	300	Kr	Jan. 27, 1947	---	8.6	327	204	13	.96	3.4	1.6	68	5.7	188	19	6.8	.19	.01			
	27	Ch-Be12...	234	Km	Mar. 28, 1950	---	7.8	357	224	16	.48	5.9	2.4	70	8.6	210	13	1.2	.06	.02			
	8	PG-Eb1...	603	Kpx	Mar. 28, 1949	52	8.0	255	180	24	.19	1.2	1	60	.8	132	20	4.5	.1	1.6			
Prince Georges County.	9	PG-Dd17...	214	Kpx	Apr. 18, 1951	---	6.6	95	58	10	10	8.8	3.9	1.5	1.9	39	5.9	3.8	.0	.5			
	10	PG-Fb7...	263	Kpt	Mar. 31, 1949	60	8.1	265	209	32	.59	2.8	1	6	.6	130	28	1.5	.3	.1			
	11	PG-Ec26...	324	Kpt	Mar. 31, 1952	---	7.8	246	157	13	.95	3.4	1.6	60	4.8	123	24	1.5	.1	.8			
	12	PG-Cf25...	398	Kpt	Apr. 17, 1952	---	5.9	69	60	22	10	7.6	1.2	1.6	1.8	17	14	.50	.04	.01			
	13	PG-Ce18...	464	Kpt	Nov. 4, 1949	58	6.5	177	99	7.6	1.8	20	6.8	3.5	2.6	73	22	2.9	.06	.01			
	14	PG-Fd32...	490	Km	Apr. 17, 1952	---	7.8	320	184	12	.83	39	15	4.9	5.5	203	9.2	1.4	.1	.5			
	15	PG-Fd10...	366	Km	Apr. 14, 1952	---	7.9	254	149	16	.28	35	8.6	2.7	4.8	153	9.6	1.8	.2	.3			
	16	PG-Fc14...	150	Km	Apr. 13, 1950	54	7.7	263	149	13	1.8	29	11	4.2	9.2	147	13	2.0	.05	.01			
	17	PG-Fd6...	404	Km	Mar. 25, 1949	60	7.7	285	169	13	.21	37	7.9	3.4	1.2	158	13	.27	.03	.02			
	18	PG-Ef5...	226	Km	Apr. 15, 1946	---	7.5	33	210	25	.31	60	6.7	3.1	1.7	192	18	2	.3	.2			
	19	PG-Ef3...	366	Km	June 6, 1949	---	6.9	307	183	15	14	50	5.2	5	1.9	178	10	3.7	.06	.02			
	St. Marys County. Somerset County.	20	PG-Cf2...	171	Km	Mar. 22, 1949	57	6.5	132	128	45	12.7	17	2	3.1	1	58	13	2.5	.1	.8		
21		PG-Ce17...	118	Km	Nov. 4, 1949	59	7.5	149	108	4.4	.32	21	2	3.4	2.1	40	18	.27	.07	.01			
28		STM-Ef4...	661	Kr	Jan. 16, 1947	67	8.4	308	192	13	.31	1	1.05	.16	.05	66	38	12	.34	.00			
29		Som-Ec3...	1,076	Km	Oct. 19, 1951	79	8.5	1,160	732	14	.12	1	.5	1.2	294	3	586	51	70	.08	.03		

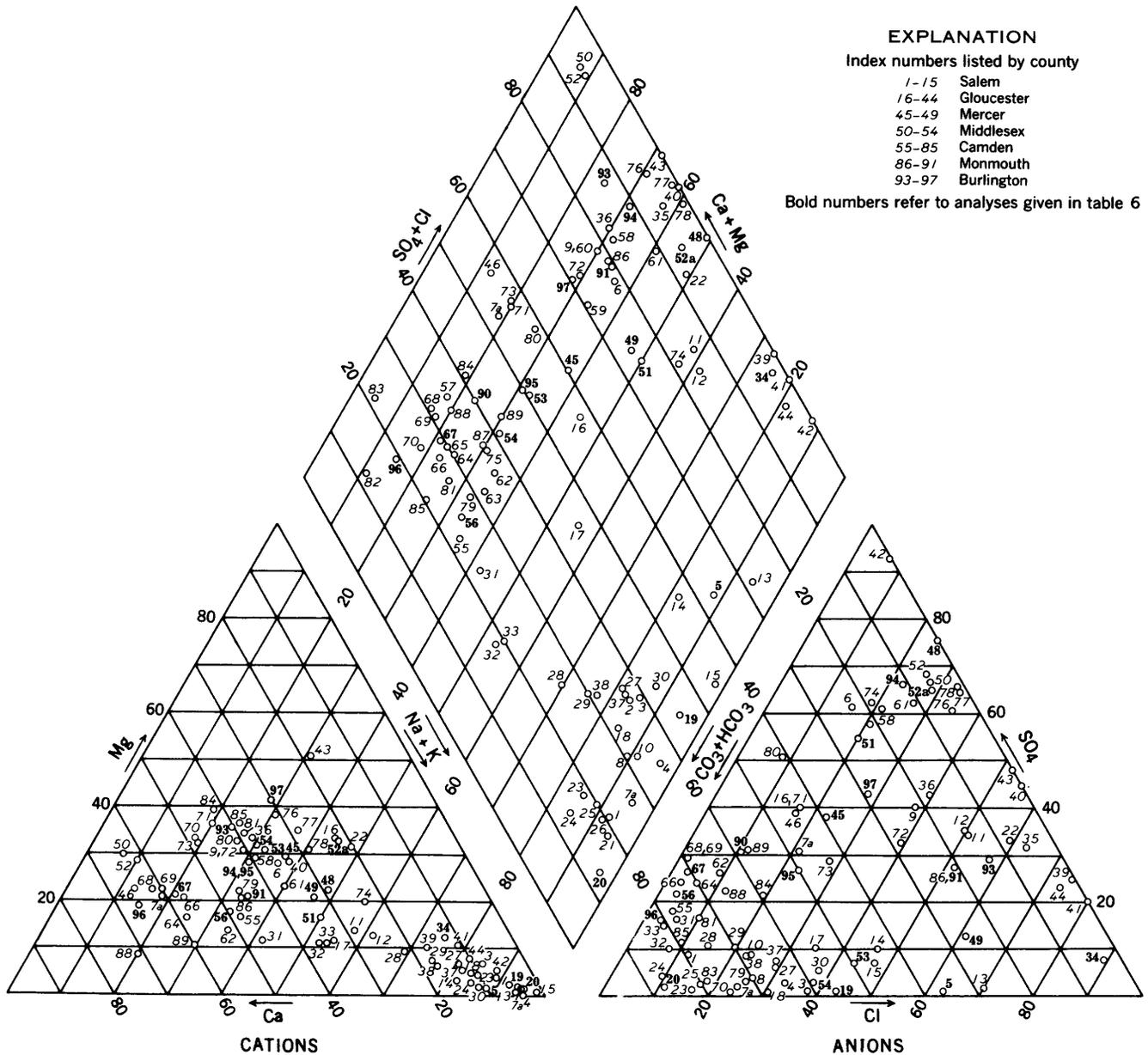


FIGURE 9.—Water-analysis diagram for the Magothy and Raritan Formations in New Jersey.

Although the sulfate and chloride contents of the water in the Raritan and Magothy Formations of New Jersey are not appreciably different from those in the formations farther to the south, the extremely low content of the bicarbonate ion permits the development of the chloride-bicarbonate and the bicarbonate-chloride facies.

Figure 10 shows that water from the Red Bank Sand, Mount Laurel Sand, and Wenonah Formation is primarily of the calcium bicarbonate character. Typical analyses are given in table 7.

Hydrochemical facies of the Englishtown and Vincentown Formations of Paleocene age, shown in figure 11 and table 8, are similar to those of the Mount Laurel

Formation and Wenonah Sand. Seaber (1962) has done detailed mapping of the hydrochemical facies in the Englishtown Formation.

EOCENE FORMATIONS

The water from the Eocene formations in Virginia, as shown in figure 12 and table 9, is almost entirely of the sodium bicarbonate character. A few analyses show the sodium-calcium bicarbonate character.

The hydrochemical facies of the Aquia Greensand (fig. 13) and the other aquifers of Eocene age (fig. 14) in Maryland are predominantly bicarbonate. Tables 10 and 11 show the decrease in calcium and magnesium with the corresponding increase in sodium in the water

TABLE 6.—Analyses of water from the Magothy and Raritan Formations in New Jersey

Location	Index No.	Well No.	Depth of well (ft below land surface)	Date of collection	Temperature (°F)	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total Iron (Fe)	Upper figure in ppm; lower, epm										
											Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	
Burlington County: Beverly	97	B9	57	July 3, 1953	6.9	216	145	9.4	0.00	12	10	10	3.6	34	0	40	12	0.0	13		
Burlington	95	B4	86	May 24, 1951	55	7.2	318	203	10	2.0	23	10	14	10	88	38	20	2	5.9		
Florence	93	B1	120	May 3, 1951	55	7.1	112	84	12	.03	1.15	4.4	4.8	1.4	8	14	8.0	0	21		
Mt. Holly	96	B6	385	May 24, 1951	58	7.9	190	113	9.8	.68	8.0	4.6	3.2	6.3	98	15	1.2	0	.34		
Stevens Station	94	B2	150	May 3, 1951	55	5.6	49.1	41	12	.71	3.6	1.5	2.8	3	0	14	3.2	0	.6		
Camden County: Haddon Heights	67	C2	267	Dec. 23, 1949	7.4	228	131	9.6	.64	.27	1.35	6.1	6.2	8.0	98	29	1.6	0	.01		
Runnemede	56	C3	318	do.	7.5	186	109	8.8	.16	19	4.2	11	6.6	87	20	1.6	0	0			
Gloucester County: Gibbstown	34	G3	105	Aug. 20, 1951	56	5.8	373	208	10	.15	7.8	5.0	54	2.9	5	12	96	0	6.2		
Glassboro	20	G1	630	May 7, 1951	65	8.1	515	315	12	.11	3.9	1.0	18	4.6	0	6.2	19	1.6	.10		
Mullica Hill	19	G2	263	Dec. 21, 1950	58	8.2	967	538	9.7	1.4	9.2	2.4	196	8.1	323	13	140	1.4	.01		
Mercer County: Bordentown	48	M2	85	Sept. 26, 1949	54	4.5	53.2	27	7.7	.28	1.6	.8	2.7	.9	0	11	2.5	0	.01		
Hamilton Square	49	M4	228	May 4, 1950	5.4	34.3	28	6.5	.15	.18	.08	.07	1.2	.02	0	23	.07	0	.00		
Hightstown	45	M1	205	Sept. 26, 1949	5.6	38.3	27	9.3	4.1	.2	2.2	1.1	2.3	1.0	8	6.2	.4	1	.12		
Middlesex County: Browntown	53	Mx3		Apr. 18, 1933			27	2.0	34		2.9	1.5	2.8	.4	12	1.4	6.0	.01	.00		
Do.	54	Mx4	117	June 6, 1941			50	1.1	106.9		6.2	3.3	3.0	5.1	30	.03	4.2	4	11		
Old Bridge	52a	Mx2		Nov. 13, 1942	4.8		22	7.1	3.2		1.0	.9	1.9	.8	0	8.1	2.6	0	.00		
Runyon	51	Mx1	260	July 18, 1923			38	8.0	4.4		2.9	.9	5.0	.2	6.1	11	3.0	0	.00		
Monmouth County: Asbury Park	90	Mo1	1,135	Nov. 13, 1924			66	5.5	8.1		1.4	.07	6.2	.22	37	15	23	4.0	.00		
Fort Hancock	91	Mo2	481	Mar. 20, 1948	5.5	115	66	8.2	22		8.9	2.5	7.5	.33	12	13	18	0	.00		
Salem County: Salem	5	S1	320	Apr. 26, 1956	53	7.6	654	346	5.4	2.1	12	1.4	116	4.9	129	1.8	131	3	.00		

TABLE 7.—Analyses of water from selected Cretaceous formations in New Jersey

(Geologic formation: Kmw, Wenonah Formation and Mount Laurel Sand; Krb, Red Bank Sand)

Location	Index No.	Well No.	Depth of well (ft below land surface)	Geologic formation	Date of collection	Temperature (°F)	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total Iron (Fe)	Upper figure in ppm; lower, epm										
												Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	
Burlington County: Browns Mills	5	B17	279	Kmw	June 4, 1951	59	7.7	187	109	11	0.30	21	5.4	3.3	8.4	107	0	4.5	2.2	0.0		
Vincentown	4	B18	150	Kmw	June 21, 1951	57	8.1	192	115	13	.28	1.05	5.7	5.3	8.5	111	0	5.0	2.0	.14		
Camden County: Clementon	14	C1	280	Kmw	Apr. 24, 1951	60	7.9	163	103	15	.11	1.10	2.7	.23	.22	1.82	0	.10	.06	.00		
Monmouth County: Belmar	9a	Mo6	452	Kmw	Aug. 8, 1951	54	7.8	210	130	14	.15	24	6.1	2.4	3.5	86	0	9.0	1.8	.3		
Eatontown	9	Mo7		Krb	Mar. 20, 1947	54	7.4	229	131	10	.47	1.19	2.2	.10	.09	1.41	.19	.05	.01	.01		
Salem County: Salem	10	S6	135	Kmw	Dec. 21, 1950	48	7.4	217	30	10	2.2	28	1.40	2.8	9.0	116	0	12	5.5	.6		
Do.	13	S7		Kmw	Sept. 15, 1952		7.9	305			.71	36	1.80	2.3	.39	1.90	.25	.16	.01	.00		
												23	3.8	9.7	3.0	56	0	40	6.6	.7		
												1.15	.31	.42	.08	159	0	.83	.19	.01		
												58		12		0	.28	7.7	.3	.00		
												2.87		54	2.61		.58	.32		.01		

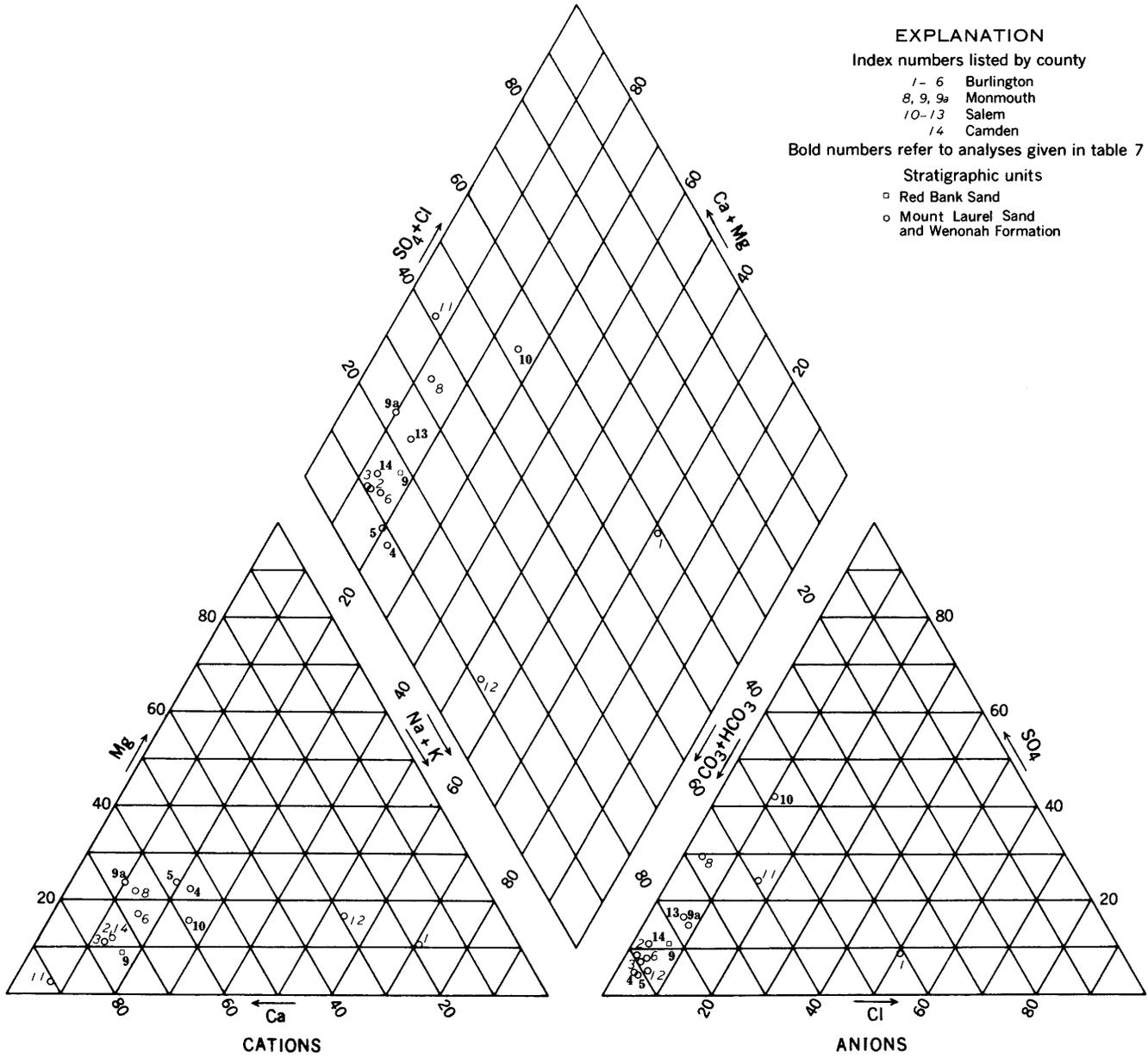


FIGURE 10.—Water-analysis diagram for selected Cretaceous formations in New Jersey.

TABLE 8.—Analyses of water from the Englishtown and Vincentown Formations in New Jersey

(Geologic formation: Ket, Englishtown Formation; Tvt, Vincentown Formation)

Location	Index No.	Well No.	Depth of well (ft below land surface)	Geologic formation	Date of collection	Temperature (°F)	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	
																						Upper figure in ppm; lower, epm
Burlington County:																						
Marlton.....	1	B16	260	Ket	Mar. 22, 1951	56	8.2	251	166	27	0.45	{ 43 2.14	{ 4.0 .33	{ 2.2 .10	{ 5.7 .15	{ 149 2.44	{ 0 -----	{ 7.0 .15	{ 2.6 .07	{ 0.4 .00	{ 0.3 .01	
Pemberton.....	5	B13	300	Ket	May 28, 1951	56	7.8	253	166	16	.16	{ 44 2.20	{ 3.0 .25	{ 2.2 .10	{ 4.3 .11	{ 153 2.51	{ 0 0	{ 5.0 .10	{ 3.4 .09	{ .1 .01	{ .3 .01	
Do.....	10	B14	392	Ket	Apr. 23, 1956	58	8.0	196	118	9.7	{ .02 .00	{ 27 1.35	{ 4.6 .38	{ 2.7 .12	{ 7.4 .19	{ 112 1.84	{ 0 0	{ 6.4 .13	{ 2.2 .06	{ .1 .01	{ .9 .02	
Smithville.....	4	B15	110	Ket	June 4, 1951	61	7.4	134	101	27	3.0	{ 20 1.00	{ 1.6 .13	{ 1.8 .08	{ 4.3 .11	{ 67 1.10	{ 0 0	{ 7.2 .15	{ 2.2 .06	{ .2 .00	{ .2 .00	
Monmouth County:																						
Asbury Park.....	17a	Mo3	600	Ket	Nov. 13, 1924	-----	-----	-----	124	9.5	1.7	{ 26 1.30	{ 5.4 .44	{ 8.3 .36	{ 85 1.39	{ 0 0	{ 25 .52	{ 2.0 .06	-----	-----	-----	-----
Avon by the Sea.....	17b	Mo4	-----	Ket	Nov. 12, 1924	-----	-----	-----	138	11	.10	{ 32 1.60	{ 7.2 .59	{ 9.4 .41	{ 100 1.64	{ 0 0	{ 32 .67	{ 4.0 .11	-----	-----	-----	-----
Fort Monmouth.....	15	Mo5	325	Ket	Apr. 9, 1953	58	7.3	228	-----	-----	1.5	{ 38 1.90	{ 3.0 .25	{ 4.9 -----	{ 121 1.98	{ 0 0	{ 8.6 .18	{ 6.8 .19	-----	-----	.1	.00
Ocean County:																						
Mantoloking.....	18a	O1	-----	Ket	Sept. 1, 1955	69	7.7	250	-----	-----	.39	-----	-----	{ 39 1.69	{ 140 2.29	{ 0 0	{ 14 .29	{ 1.5 .04	-----	-----	1.5	.02
Salem County:																						
Alloway.....	24	S5	156	Tvt	Apr. 26, 1956	53	8.0	327	200	12	.15	{ 36 1.80	{ 12 .99	{ 9.0 .39	{ 6.9 .17	{ 170 2.79	{ 0 0	{ 30 .63	{ 3.0 .09	{ .3 .02	{ .0 .00	
Quinton.....	23	S4	133	Tvt	Dec. 21, 1950	-----	7.6	390	254	36	1.9	{ 60 2.99	{ 8.7 .72	{ 7.4 .32	{ 4.9 .13	{ 212 3.47	{ 0 0	{ 24 .50	{ 5.6 .16	{ .4 .02	{ .7 .01	

TABLE 9.—Analyses of water from the Eocene formations in Virginia

(Geologic formation: Ta, Aquia Formation; Tn, Nanjemoy Formation; Tcy, Chickahominy Formation)

Location	Index No.	Well No.	Depth of well (ft below land surface)	Geologic formation	Date of collection	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	
																					Upper figure in ppm; lower, epm
Hanover County:																					
Ellerson.....	3	24	142	Ta	Nov. 7, 1947	7.3	-----	222	17	0.11	{ 30 1.50	{ 14 1.12	{ 36 1.57	{ 230 3.77	{ 0 0.00	{ 14 .29	{ 4 .11	{ 0.2 .01	{ 0.7 .01		
Henrico County:																					
Bottoms Bridge.....	5	35	268	Ta	Oct. 28, 1947	8.1	-----	167	16	18	{ 6.7 .33	{ 2.3 .18	{ 57 2.48	{ 136 2.23	{ 14 .47	{ 8.1 .17	{ 4 .11	{ 4 .02	{ .5 .01		
San Rafael Court.....	4	22	181	Ta	Dec. 1943	7.9	-----	183	26	.03	{ 26 .30	{ 11 .88	{ 24 1.04	{ 177 2.90	{ 0 0.00	{ 13 .27	{ 2.1 .06	{ .0 .00	{ .0 .00		
King and Queen County:																					
Shackelfords Fork.....	7	45a	320	Tn	May 18, 1948	8.4	429	267	23	.19	{ 4.8 .24	{ 1.4 .12	{ 94 4.09	{ 241 3.95	{ 5.9 .20	{ 7.6 .16	{ 2.5 .07	{ 1.0 .05	{ 1.0 .05		
Lancaster County:																					
Lively.....	19	3	365	Tcy	June 9, 1948	8.4	634	400	25	.83	{ 5.2 .26	{ 2.4 .20	{ 148 6.45	{ 374 6.13	{ 9.8 .33	{ 11 .23	{ 4.0 .11	{ 1.8 .10	{ .6 .01		
Northumberland County:																					
Lewisetta.....	15	16a	325	-----	July 5, 1918	-----	-----	-----	31	.67	{ 5.0 .25	{ 6.7 .55	{ 107 4.65	{ 180 2.95	{ 60 2.00	{ 3.5 .16	-----	-----	-----	-----	-----
Westmoreland County:																					
Kinsale.....	9	65	280	-----	May 1946	7.8	-----	212	45	.05	{ 14 .70	{ 5.8 .48	{ 49 2.13	{ 182 2.98	{ 0 0.00	{ 11 .23	{ 1.8 .05	{ .5 .03	{ .1 .01		

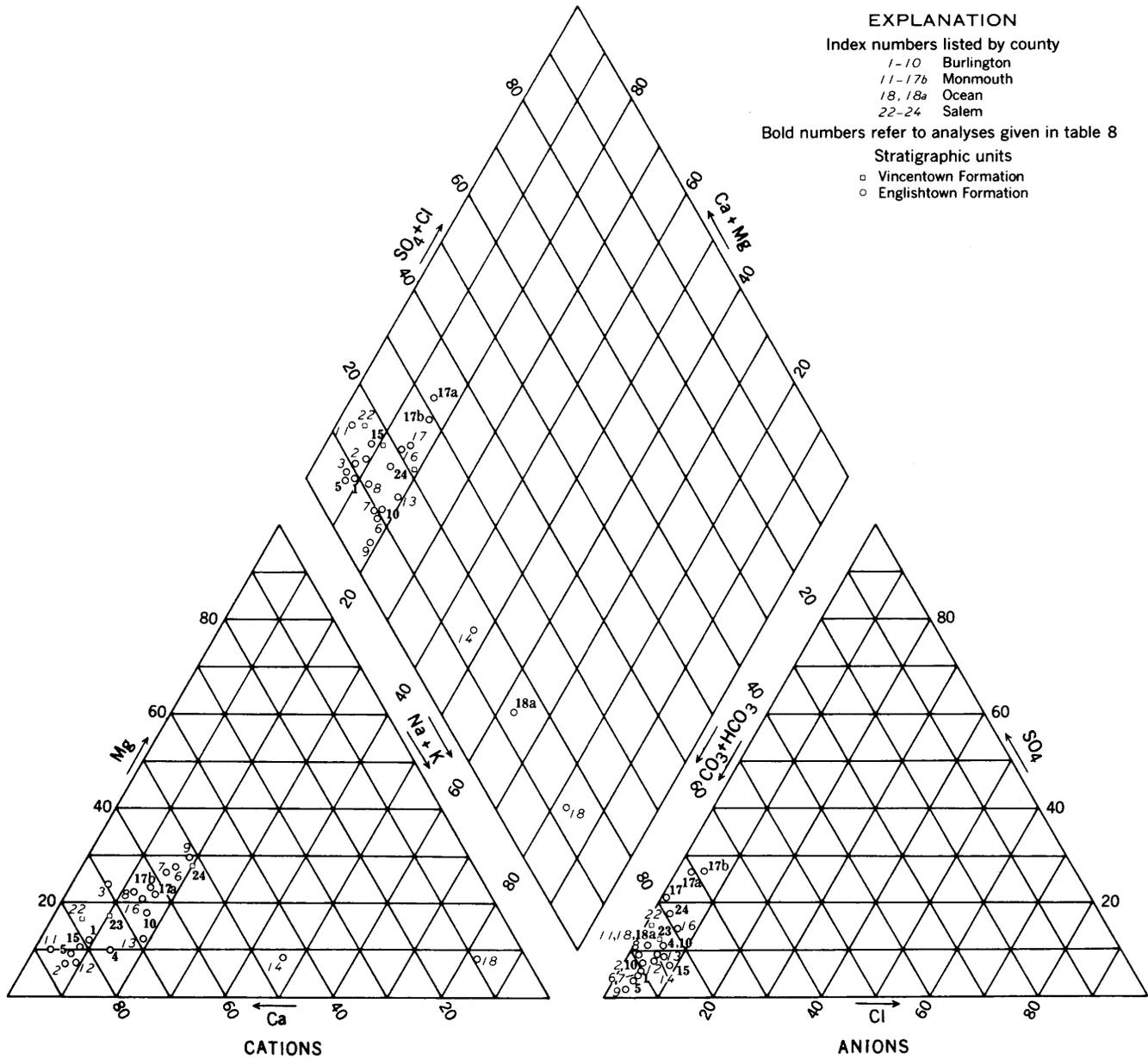


FIGURE 11.—Water-analysis diagram for the Englishtown and Vincenttown Formations in New Jersey.

TABLE 10.—Analyses of water from the Aquia Greensand in Maryland

[Location: Wells for which only county is listed are shown on pl. 15 of Otton, E. G. (1955). Temperature: 56°F in wells AA-De35 and Dor-Bc5; no data for other wells]

Location	Index No.	Well No.	Depth of well (ft below land surface)	Date of collection	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)
										Upper figure in ppm; lower, epm									
Anne Arundel County.	3	AA-De35	81	June 25, 1946	7.8	365	238	33	1.4	67 3.34	5.4 .44	2.6 .11	5.0 .13	220 2.61	-----	12 .25	2.2 .06	0.1 .01	0.2 .00
	10	AA-Fe30	150	Mar. 27, 1950	8.2	280	164	11	1.4	40 2.00	.83 .68	4.4 .19	5.7 .15	140 2.29	0.20	23 .48	1.2 .03	.3 .02	.5 .01
Charles County	23	Ch-Dd5	218	Jan. 22, 1947	8.5	332	206	16	1.4	2.9 .15	1.7 .14	69 3.00	4.8 .12	184 3.02	-----	11 .23	2.5 .07	.4 .02	.3 .01
	24	Ch-Df9	374	Mar. 21, 1951	8.1	252	168	32	.2	17 .85	6.1 .50	21 .91	12 .31	143 2.35	-----	8.0 .17	1.6 .06	.3 .2	1.1 .02
	25	Ch-Ee43	236	Apr. 10, 1950	8.6	330	208	12	.08	4.1 .21	2.1 .17	69 3.00	5.7 .15	180 2.95	-----	9.4 .20	1.6 .05	.5 .03	.1 .00
Dorchester County: Cornersville	53	Dor-Bc5	560	Feb. 18, 1954	8.5	411	-----	0	-----	-----	-----	100 4.35	-----	224 3.67	16 .53	8.4 .18	3.0 .09	-----	.4 .01
Kent County: Lees Corner	40	Ken-Cd15	140	Dec. 21, 1954	7.8	197	131	28	5.6	34 1.70	1.0 .08	2.6 .11	2.6 .07	102 1.67	-----	7.5 .16	2.8 .08	.0 .00	.1 .00
Prince Georges County.	12	PG-Df5	90	Mar. 26, 1950	7.8	320	212	33	5.2	59 2.94	3.8 .31	2.5 .11	4.1 .11	198 3.11	-----	9.7 .20	2.1 .06	.1 .01	.2 .00
	13	PG-Cf11	23	Apr. 17, 1950	6.1	80	67	20	16	6.0 30	1.5 .12	5.1 .09	3.5 .09	18 .30	-----	4.1 .09	11 .31	.0 .00	3.7 .06
Queen Annes County: Church Hill	42	QA-Cf2	170	Sept. 29, 1954	7.4	319	-----	1.7	-----	-----	-----	8.7	-----	199 3.26	-----	6.8 .14	2.6 .07	-----	.2 .00
Kingston	45	QA-Be4	86	Dec. 21, 1954	6.7	92.0	77	20	.6	11 .55	.4 .03	2.9 .13	1.1 .03	38 .62	-----	.1 .00	2.5 .07	.1 .01	8.4 .14
St. Marys County	30	STM-Cb1	350	Jan. 17, 1947	8.4	258	155	14	.05	11 .55	4.4 .36	34 1.48	12 .31	140 2.29	-----	9.9 .21	1.1 .03	.1 .01	.0 .00
	31	STM-Dc12	326	Mar. 28, 1950	7.9	304	212	50	.08	17 .85	7.7 .63	31 1.35	13 .33	171 2.80	-----	7.9 .16	2.5 .07	.4 .02	.4 .01
	33	STM-Dd1	494	Mar. 9, 1949	8.5	236	148	10	.17	3.6 .18	1.1 .09	49 2.13	1.9 .49	136 2.23	-----	8.9 .19	2.5 .46	-----	.6 .10

TABLE 11.—Analyses of water from selected Eocene formations in Maryland

[Location: Wells in St. Marys County are shown on pl. 15 of Otton, E. G. (1955). Geologic formation: Tpp, Piney Point Formation; Tr, Nanjemoy Formation]

Location	Index No.	Well No.	Depth of well (ft below land surface)	Geologic formation	Date of collection	Temperature (°F)	pH	Specific conductance (micromhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)
												Upper figure in ppm; lower, epm									
Caroline County: Denton	20	Car-Dd2	402	Tpp	Nov. 24, 1953	63.5	8.5	809	517	23	0.04	4.4 .22	3.6 .30	190 8.26	8.0 .21	512 8.39	18 .60	7.4 .15	3.5 .10	1.6 .08	0.7 .01
Dorchester County: Cambridge	24a	Dor-Ce6	420	Tpp	Sept. 8, 1951	64	8.5	809	505	22	.10	6.0 .30	4.5 .27	180 7.83	8.4 .21	486 7.96	12 .40	9.2 .19	14 .40	1.0 .05	.6 .01
Church Creek	24	Dor-Cd28	370	Tpp	Feb. 18, 1954	53	8.5	720	-----	-----	.00	-----	72	167	412	20	4.6 .10	17 .48	-----	.2 .06	
St. Marys County.	10	STM-Dd5	263	Tpp	Mar. 9, 1949	-----	8.0	282	183	32	.33	22 1.10	9.8 .81	14 .61	6.9 .18	182 2.66	-----	9.2 .19	3.5 .10	.2 .01	.4 .01
	11	STM-Dd12	200	T _n and T _{pp}	Mar. 28, 1950	-----	8.3	278	185	31	.07	8.5 .42	3.3 .27	46 2.00	9.9 .25	152 2.49	-----	9.7 .20	2.5 .07	.2 .01	.3 .01
	16	STM-Fg4	420	T _{pp}	Mar. 7, 1950	-----	8.3	712	439	24	.79	4.5 .23	2.4 .20	159 6.91	10 .26	405 6.64	-----	3.6 .08	9.8 .28	1.4 .07	.8 .01
	19a	STM-Ee4	325	T _n and T _{pp}	Mar. 28, 1950	-----	7.8	293	210	56	.39	25 1.25	12 .99	11 .48	16 .41	169 2.77	-----	9.1 .19	.6 .02	.4 .12	.8 .01

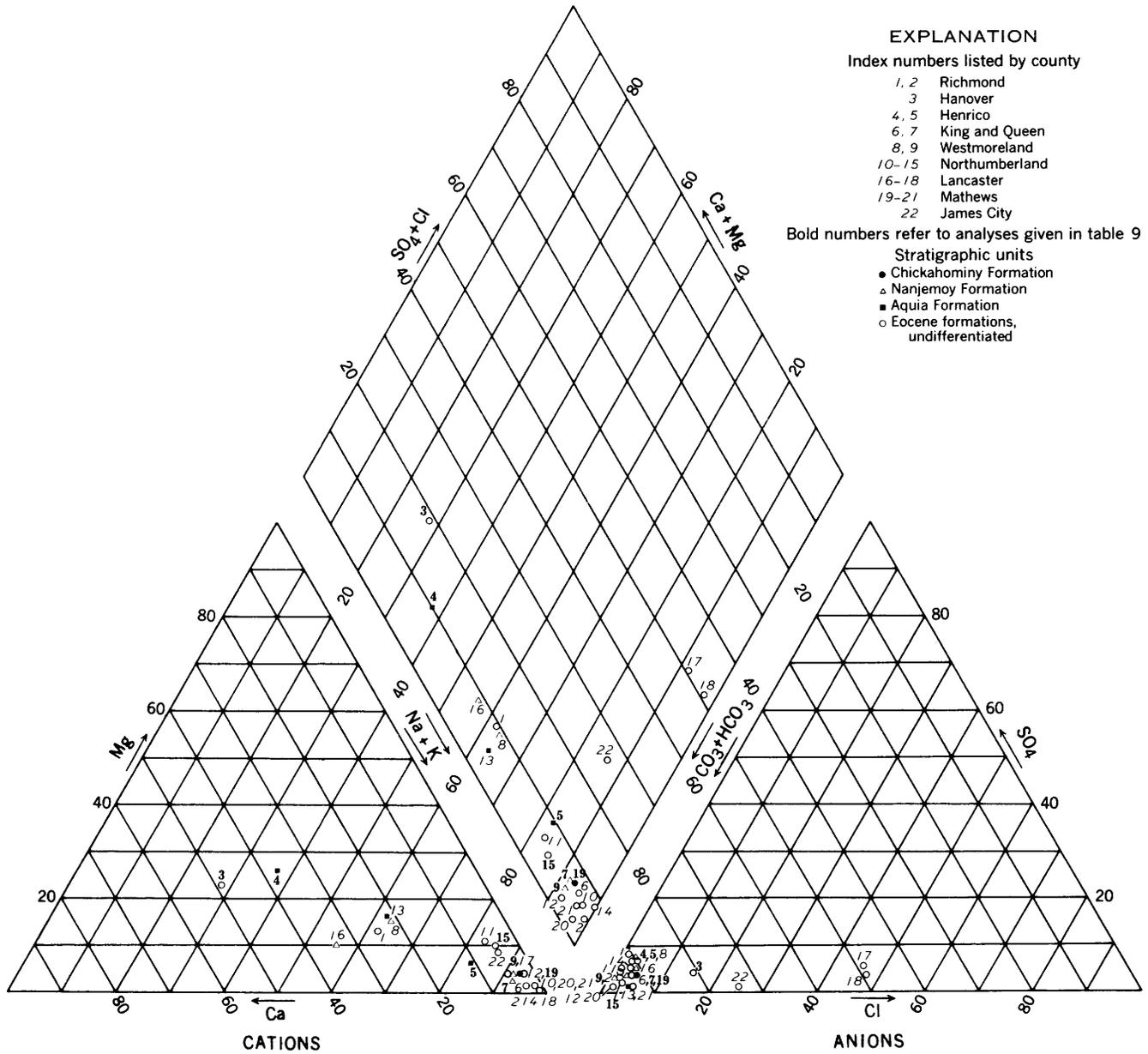
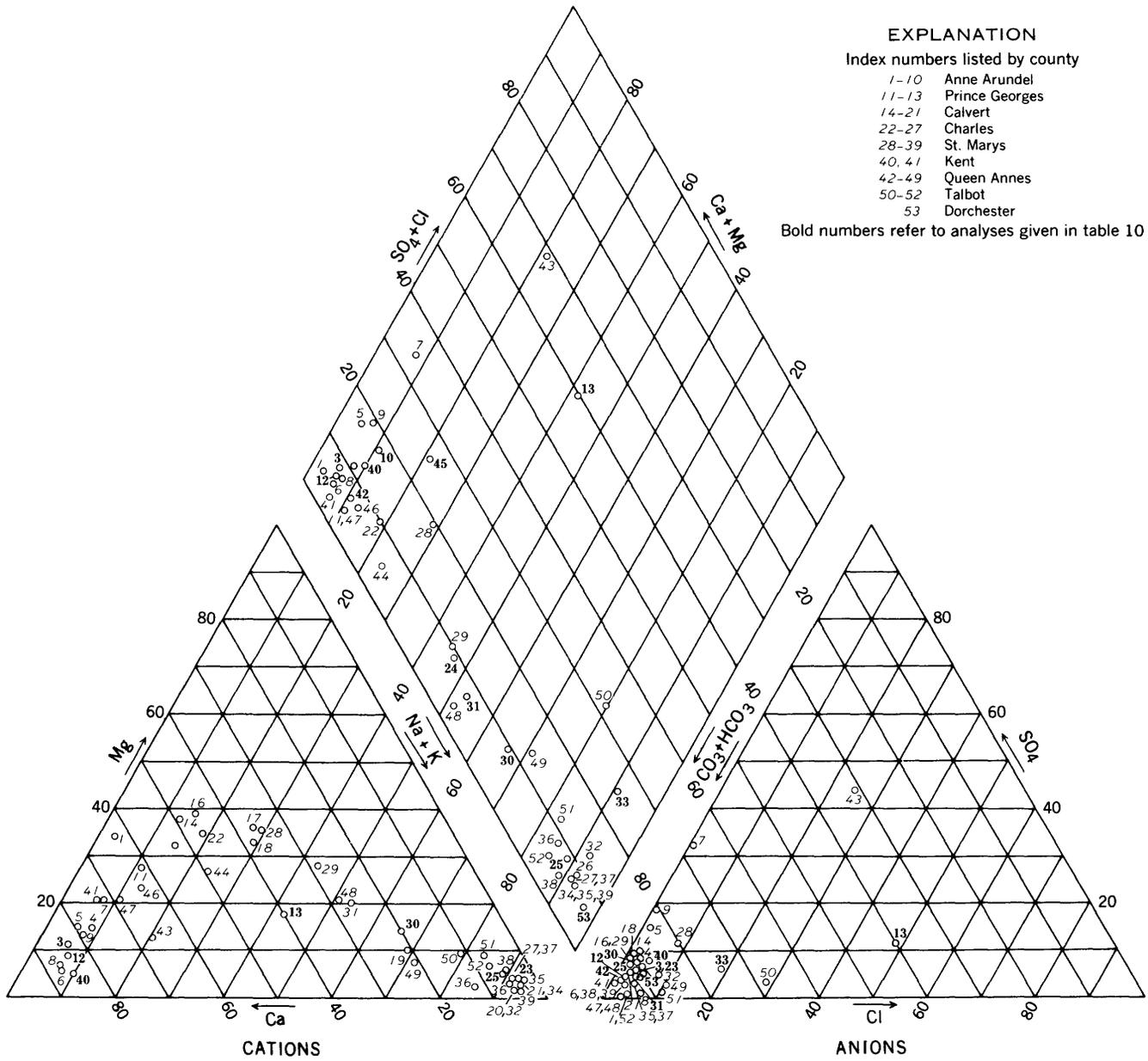


FIGURE 12.—Water-analysis diagram for the Eocene formations in Virginia.



EXPLANATION
Index numbers listed by county

- 1-10 Anne Arundel
- 11-13 Prince Georges
- 14-21 Calvert
- 22-27 Charles
- 28-39 St. Marys
- 40, 41 Kent
- 42-49 Queen Annes
- 50-52 Talbot
- 53 Dorchester

Bold numbers refer to analyses given in table 10

FIGURE 13.—Water-analysis diagram for the Aquia Greensand of Eocene age in Maryland.

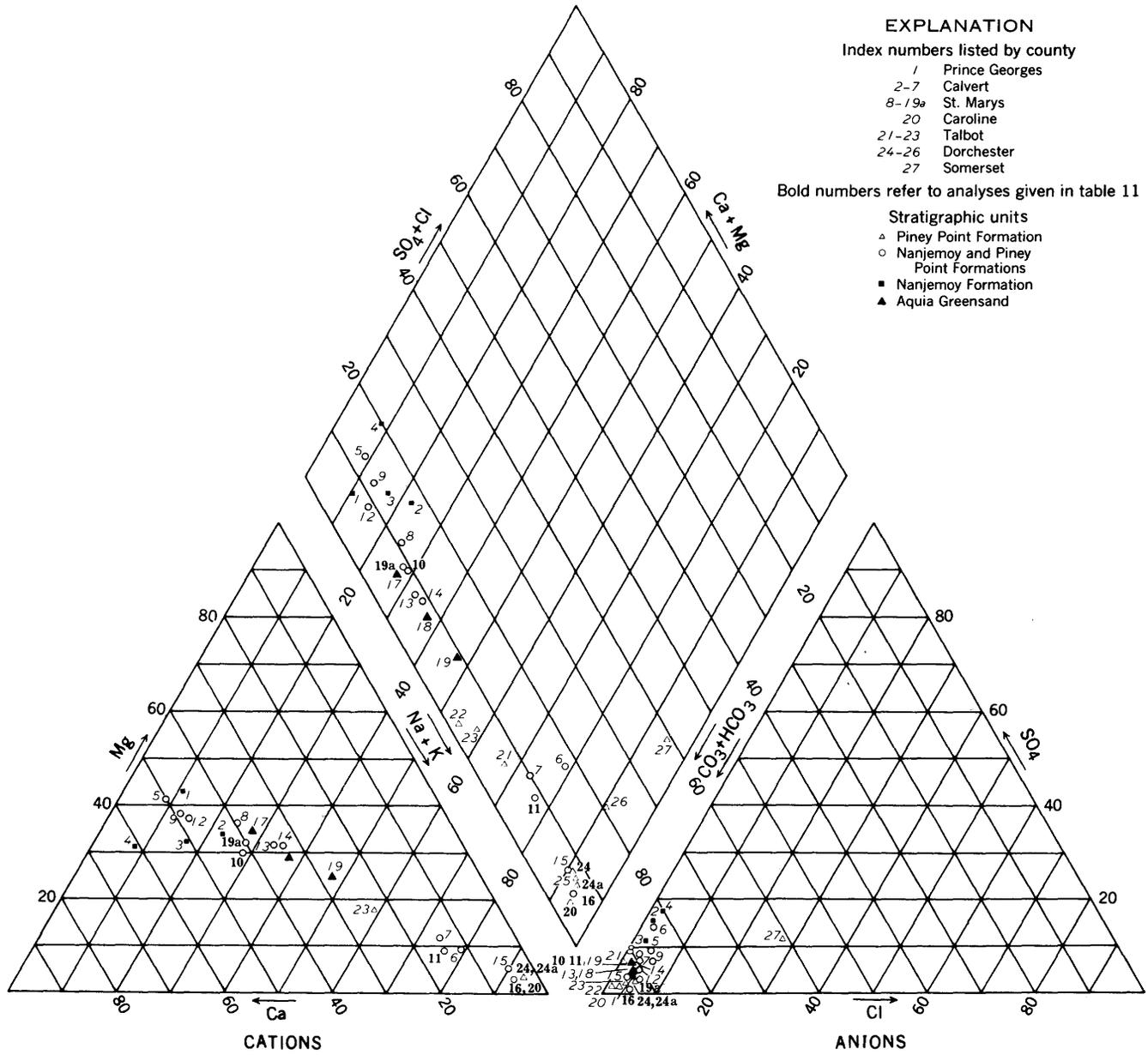


FIGURE 14.—Water-analysis diagram for selected Eocene formations in Maryland.

from the piezometric high. These aquifers provide an excellent example of natural softening of water by ion exchange.

MIOCENE FORMATIONS

As would be expected from the abundance of calcareous material in the Miocene sediments in Virginia, the water is primarily of the calcium bicarbonate character (fig. 15). For some areas the sodium content has increased owing to ion exchange. Selective chemical analyses of water are given in table 12.

The diversity of the chemical character of water from the Miocene formations of Maryland is shown in figure 16 and in table 13. These analyses are from the Eastern Shore, where the recharge and discharge of the water in these shallow aquifers is of a local nature. Slight changes in the hydrologic environment cause pronounced changes in the chemical character. Some of the samples show the effect of nearby salt-water bodies.

The Kirkwood Formation of New Jersey contains

water of the bicarbonate-chloride-sulfate anion facies and the calcium-sodium and sodium-calcium cation facies (fig. 17). The low dissolved-solids content of the water is shown in table 14.

The hydrochemical facies of the Cohansey Sand in New Jersey are shown in figure 18. The chloride-sulfate facies is present to a much greater degree in this formation than in any other group of formations of the Coastal Plain. The sodium-calcium, the chloride-sulfate, and the chloride-sulfate-bicarbonate facies are dominant in the Cohansey Sand.

The primary difference between the water from the Cohansey Sand and the water from the Kirkwood Formation, as shown in table 15, is a decrease in the chloride and sulfate content in the Kirkwood Formation that permits the development of the bicarbonate-chloride facies. The dissolved-solids content of water from the Kirkwood is among the lowest for any formation in the Coastal Plain.

TABLE 12.—Analyses of water from the Miocene formations in Virginia

[Geologic formation: Tsm, St. Marys Formation, Ty, Yorktown Formation; Und, Miocene formations undifferentiated]

Location	Index No.	Well No.	Depth of well (ft below land surface)	Geologic formation	Date of collection	Temperature (°F)	pH	Specific conductance (microhms at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total iron (Fe)	Upper figure in ppm; lower, epm									
												Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)
Accomack County:																					
Hallwood.....	12	47a	160	Ty	Apr. 6, 1955	59	8.1	199	129	31	0.44	{ 25 1.25	{ 5.5 .45	{ 8.0 .35	{ 2.1 .05	{ 112 1.84	{ 0 0.00	{ 0.5 .01	{ 7.8 .22	{ 0.1 .01	{ 0.2 .00
Do.....	13	47b	250	Tsm	do.....	61	8.3	275	154	16	.06	{ 23 1.15	{ 9.5 .78	{ 18 .78	{ 7.0 .18	{ 142 2.33	{ 0 0.00	{ 1.0 .02	{ 17 .48	{ .1 .00	{ .7 .01
New Church....	11	6a	259	Tsm	May 30, 1955	59.5	8.0	567	345	28	.64	{ 28 1.40	{ 13 1.07	{ 64 2.78	{ 14 .36	{ 229 3.75	{ 0 0.00	{ 6.7 .14	{ 66 1.86	{ .2 .01	{ .9 .01
Pungoteague....	14	52	210	Tsm	1906			358	250	45	.1	{ 25 1.25	{ 11 .90	{ 32 1.39	{ 14 .36	{ 218 3.58	{ 0 0.00	{ 1.6 .03	{ 12 .34	{ .2 .06	{ .9 .06
Wachapreague..	9	56	385	Und	Sept. 7, 1948	61	8.1	482	482	14	.14	{ 5.5 .27	{ 3.8 .31	{ 180 7.83	{ 346 5.67	{ 0 0.00	{ 4.0 .08	{ 93 2.62	{ .7 .04	{ .8 .01	
Onancock.....	10	42	210	Und	Sept. 4, 1948		7.9	290	203	24	.07	{ 24 1.20	{ 8.5 .70	{ 34 1.48	{ 168 2.76	{ 0 0.00	{ 6.5 .14	{ 15 .42	{ .1 .01	{ 2.9 .05	
Elizabeth City County:																					
Hampton.....	22	7c	178	Ty	Nov. 5, 1944		7.9			14	.09	{ 58 2.89	{ 21 1.73	{ 804 34.97	{ 625 10.25	{ 0 0.00	{ 119 2.48	{ 950 26.79	{ .6 .03	{ 1.6 .03	
Wythe Theater..	21	12	138	Ty	Aug. 6, 1940				308	42	19	{ 26 1.30	{ 9.0 .74	{ 61 2.65	{ 4.3 .11	{ 163 2.67	{ 0 0.00	{ 24 .50	{ 54 1.52	{ .1 .01	{ .6 .01
James City County:																					
Norge.....	23	59	88	Ty	June 15, 1946		7.3		108	11	8.1	{ 32 1.60	{ .8 .07	{ .16 .09	{ 3.7 .09	{ 93 1.52	{ 0 0.00	{ 9.9 .21	{ 3.1 .09	{ .1 .01	{ .1 .00
Williamsburg...	24	52	68	Ty	do.....		7.3		122	18	.12	{ 34 1.70	{ .9 .07	{ .3 .16	{ 3.6 1.57	{ 96 1.57	{ 0 0.00	{ 10 .21	{ 5.0 .14	{ .1 .01	{ .1 .00
Nansemond County:																					
Drivers.....	5	40	46	Und	Aug. 1, 1939				464	11	7.7	{ 15 6.24	{ 9.0 .74	{ 10 .44	{ 3.7 .10	{ 247 4.05	{ 0 0.00	{ 105 2.18	{ 22 .62	{ .0 .00	{ 38 .61
New Kent County:																					
Providence Forge.	1	39	110	Und	Dec. 31, 1943		7.9		144	26	.03	{ 33 1.65	{ 4.4 .36	{ .8 .38	{ 131 2.15	{ 0 0.00	{ 7.0 .15	{ 2.9 .08	{ .2 .01	{ .0 .00	
Northampton County:																					
Nassowadox....	17	44b	304	Tsm	Apr. 5, 1955		8.0	316	176	17	.00	{ 28 1.38	{ 9.2 .76	{ 16 .70	{ 2.5 .06	{ 131 2.15	{ 0 0.00	{ 3.5 .07	{ 29 .82	{ .1 .01	{ 2.0 .03
Eastville.....	16	25	165	Und	Sept. 12, 1948		8.0	207	145	39	.04	{ 26 1.30	{ 3.7 .30	{ .11 .48	{ .96 1.57	{ 0 0.00	{ 1.2 .03	{ 17 .48	{ .1 .01	{ .2 .03	
Oyster.....	19	81	182	Ty	Mar. 5, 1946		7.3		177	32	.04	{ 29 1.45	{ 10 .82	{ .16 .70	{ 144 2.36	{ 0 0.00	{ .8 .02	{ 18 .51	{ .2 .01	{ .6 .01	
Cape Charles....	20	204	74	Ty	Sept. 27, 1955		7.9	402	230	18	.34	{ 41 2.05	{ 7.0 .58	{ 28 1.22	{ .70 .05	{ 120 2.97	{ 0 0.00	{ 24 .50	{ 54 1.52	{ .0 .00	{ .2 .00
Norfolk County:																					
Great Bridge....	4	59		Und	Aug. 28, 1939	62			325	27	.67	{ 68 3.39	{ 4.9 .40	{ 41 1.78	{ 2.6 .07	{ 243 3.98	{ 0 0.00	{ 5.0 .10	{ 54 1.52	{ .6 .03	{ .0 .00

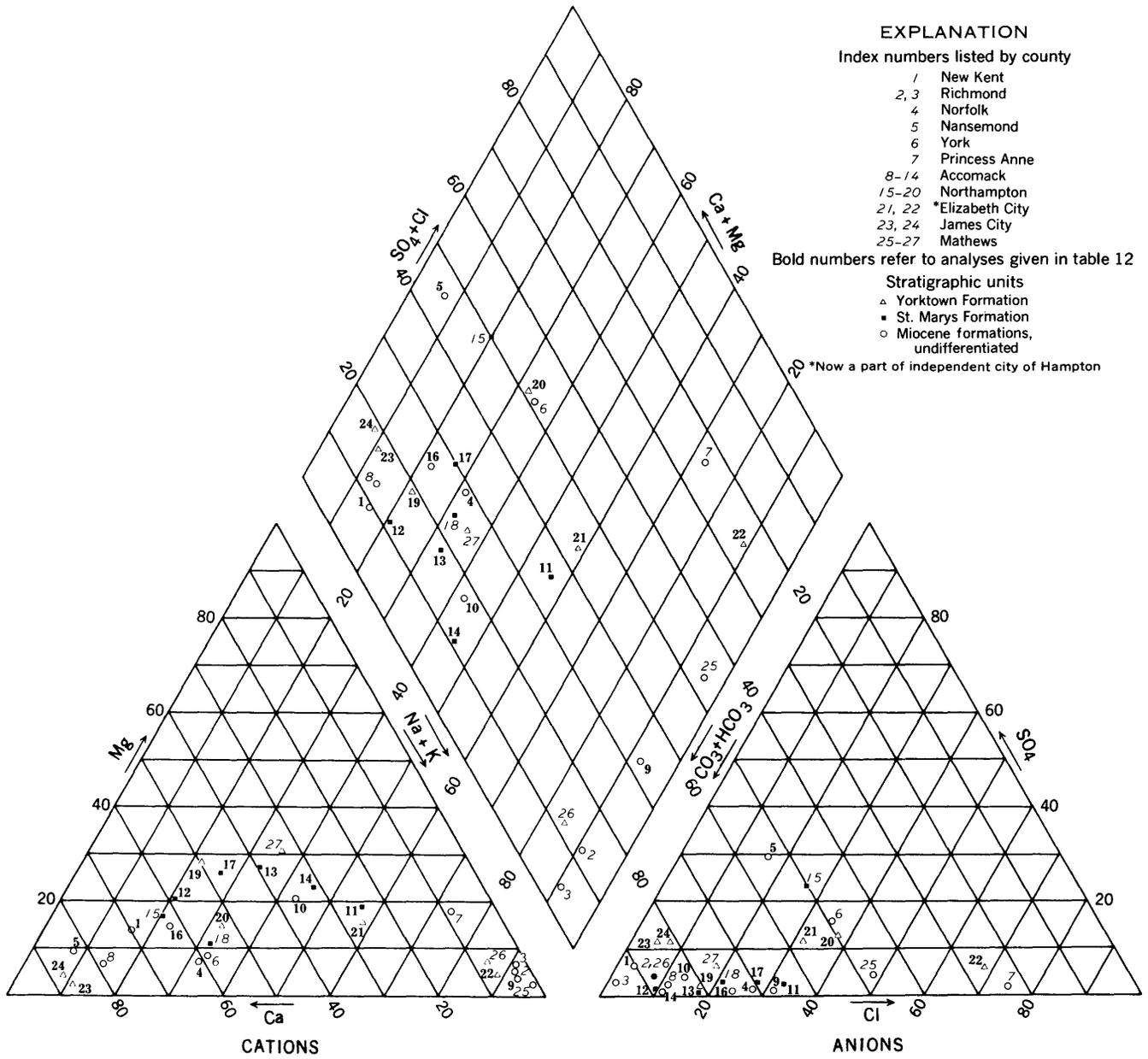


FIGURE 15.—Water-analysis diagram for the Miocene formations in Virginia.

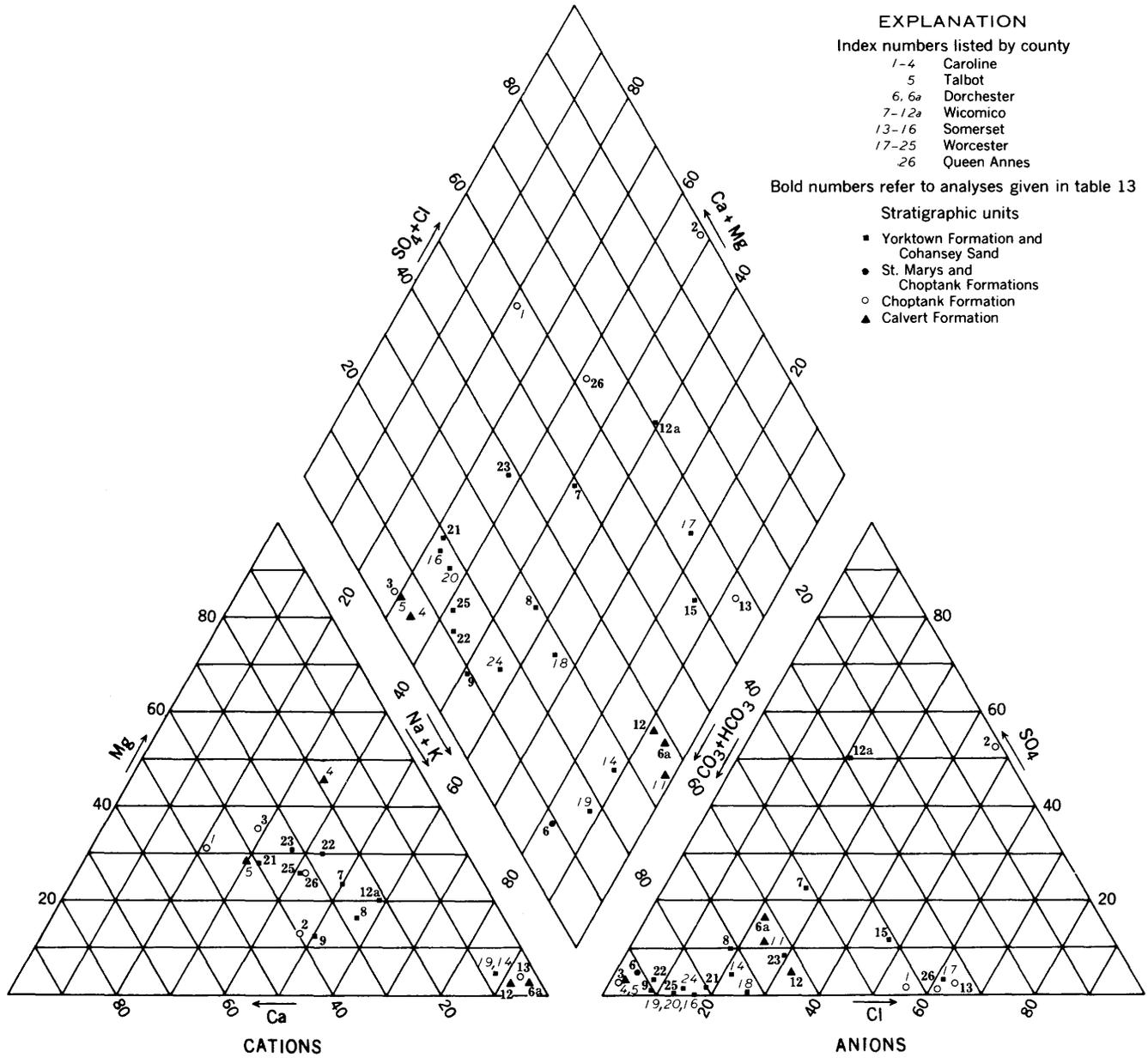


FIGURE 16.—Water-analysis diagram for the Miocene formations in Maryland.

EXPLANATION

Index numbers listed by county

- 2, 3 Burlington
- 4 Salem
- 5-15a Atlantic
- 16, 17 Cape May

Bold numbers refer to analyses given in table 14

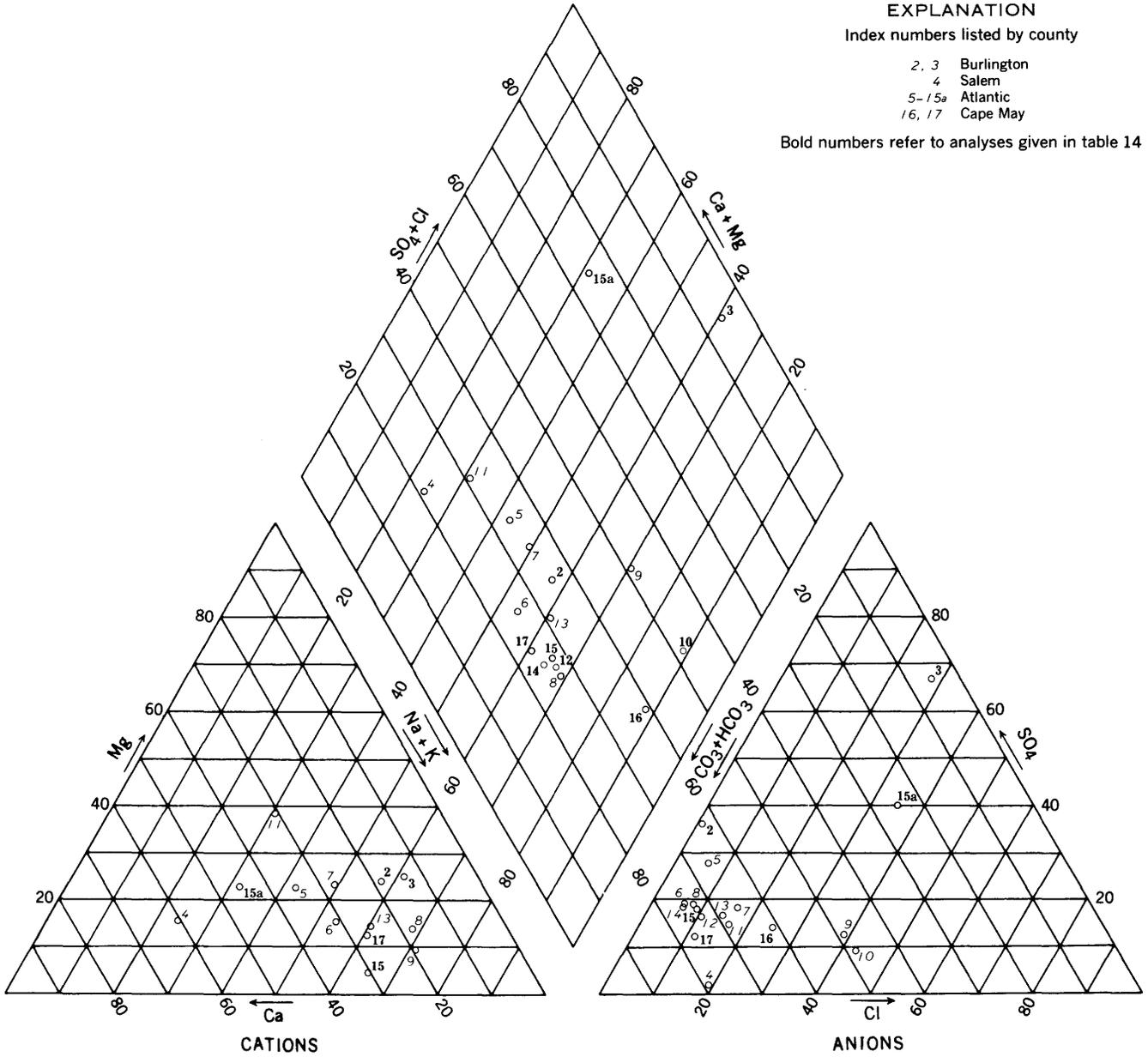


FIGURE 17.—Water-analysis diagram for the Kirkwood Formation in New Jersey.

TABLE 13.—Analyses of water from the Miocene formations in Maryland

[Geologic formation: Tck, Choptank Formation; Tsm, St. Marys Formation; Tcv, Calvert Formation; Ty, Yorktown Formation; Tch, Cohansey Sand]

Location	Index No.	Well No.	Depth of well (ft. below land surface)	Geologic formation	Date of collection	Temperature (°F)		Specific conductance (microhmhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total iron (Fe)	Upper figure in ppm; lower, epm										
							pH					Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)	
Caroline County: Choptank	3	Car-Fb24	150	Tck	Mar. 8, 1955	57	8.0	344	244	62	0.17	28	17	19	9.4	224	0	5.2	0.6	0.5	0.9	
Williston	2	Car-Ec14	165	Tck	do	58	4.6	94.4	65	14	0.03	1.40	1.40	.83	.24	3.67	.00	.11	.02	.03	.02	
Dorchester County: Linkwood	6	Dor-cf8	189	Tsm-Tck	Feb. 19, 1954	55	8.4	530			0.05	5.2	1.0	5.2	2.6	.4	0	18	4.9	.3	11	
Vienna	6a	Dor-Dh7	305	Tcv	Dec. 9, 1952		8.5	2,030	1,270	55	3.0	1.04		111		14	13	7.0			.8	
Queen Annes County: Price	26	Qa-Cf5	50	Tck	Sept. 29, 1954		6.9	87	76	18	0.04	9.0	6.2	438	14	804	8	163	170	1.0	.5	
Somerset County: Crisfield	13	Som-Ec33	362	Tck	Dec. 8, 1952		7.6	5,780	3,550	58	0.17	2.8	2.55	19.05	.36	13.19	.27	3.39	4.79	.05	.01	
Wicomico County: Fruitland	9	Wic-De30	255	Ty-Tch	Jan. 10, 1951		7.2	302	186	21	8.3	5.7	31	7.5	1.4	20		.6	8.9	.1	18	
Mardela Spring	12	Wic-Bd11	315	Tck	Nov. 4, 1952		8.0	1,160	734	54	0.16	31	2.55	54.79	1.15	19.67	.00	62	1,360	.7	.7	
Salisbury	7	Wic-Df25	86	Ty-Tch	Sept. 15, 1950		6.3	90.3	88	39	0.19	1.55	3.1	54.79	1.15	19.67	.00	62	1,360	.7	.7	
Do	12a	Wic-Ce21	130	Ty-Tch	Mar. 4, 1948		5.3	51.3	52	23	3.6	23	3.1	54.79	1.15	19.67	.00	62	1,360	.7	.7	
(¹)	8	Wic-Bh14	122	Ty-Tch	Aug. 15, 1950		7.1	63.8	69	32	5.0	1.15	3.1	54.79	1.15	19.67	.00	62	1,360	.7	.7	
Worcester County: Girdletree	22	Wor-Ed8	181	Ty-Tch	Nov. 5, 1952		59	7.8	330	208	34	0.09	1.15	3.1	1.07	1.13	.31	2.02	0	5.2	10	.0
Ocean City	21	Wor-Bh1	285	Ty-Tch	Dec. 12, 1951		7.2	434	260	24	2.9	1.13	1.07	1.13	.31	2.02	0	5.2	10	.0	.7	
Do	25	Wor-Bh8	185	Ty-Tch	Dec. 17, 1951		7.8	413	260	28	1.3	1.13	1.07	1.13	.31	2.02	0	5.2	10	.0	.7	
Pocomoke	23	Wor-Fb9	104	Ty-Tch	Nov. 4, 1952		59	7.5	339	206	29	0.10	1.07	1.09	.11	1.23	.00	1.2	12	.99	1.2	
(¹)	15	Wor-Ce2	210	Ty-Tch	Aug. 31, 1953		6.8	241			2.4	1.07	1.09	1.09	.11	1.23	.00	1.2	12	.99	1.2	

¹ See Rasmussen and others (1957b, pl. 8).

TABLE 14.—Analyses of water from the Kirkwood Formation in New Jersey

Location	Index No.	Well No.	Depth of well (ft. below land surface)	Date of collection	Temperature (°F)		Specific conductance (microhmhos at 25°C)	Dissolved solids (residue at 180°C)	Silica (SiO ₂)	Total iron (Fe)	Upper figure in ppm; lower, epm									
						pH					Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO ₃)	Carbonate (CO ₃)	Sulfate (SO ₄)	Chloride (Cl)	Fluoride (F)	Nitrate (NO ₃)
Atlantic County: Atlantic City	15	A1	810	Apr. 17, 1956	66	7.8	140	115	34	0.16	8.2	0.8	18	2.8	65	0	12	3.4	0.1	0.5
Egg Harbor City	15a	A2	443	Aug. 18, 1925				85	40	2.0	5.0	1.6	.78	.08	7.2	0	9.4	6.0	.1	.01
Burlington County: Harrisville	3	B5	350	Aug. 14, 1951	56	4.7	48.8	49	26	.10	.8	.9	2.9	2.2	1	0	10	3.1	.0	.1
New Gretna	2	B7	232	do	56	4.7	47.1	54	32	.32	1.0	.8	2.5	2.0	2	0	7.0	3.6	.0	.2
Cape May County: Ocean City	17	CM5		May 27, 1952		7.5	245		27	.11	1.0	1.15	.11	.05	.03	0	.15	.10	.00	.00
Stone Harbor	16	CM6	966	Sept. 1, 1955		7.9	337			.20	11	3.1	29	1.26	97	0	12	8.0		.8
											.55	.26	69	2.10	128	0	23	.23		.01
																0	.48	.85		1.0

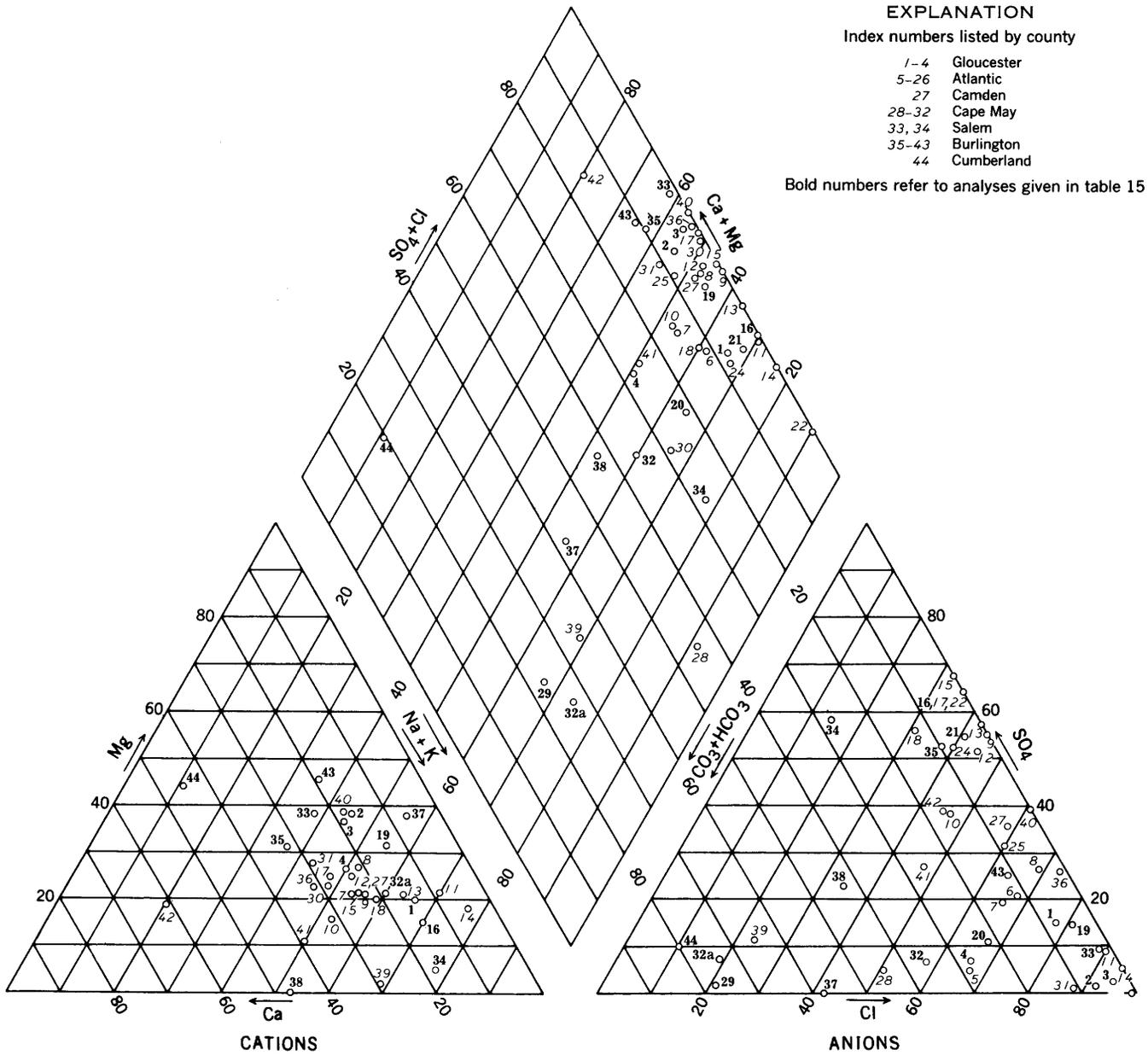


FIGURE 18.—Water-analysis diagram for the Cohansey Sand in New Jersey.

south. The presence of coarser material, which may have higher permeability, the shallow position of the bedrock that causes a shorter flow path, and the possibility of smaller amounts of soluble material will result in leaching of the sediments more rapidly than in the areas to the south where the sediments are finer grained and thicker.

The head in the Miocene formations in New Jersey is higher than the head in Cretaceous sediments, and virtually no upward leakage occurs. In Delaware and in Maryland the head in Cretaceous formations is generally higher than in the overlying Tertiary sediments. The lower head downgradient in the Tertiary sediments causes the water entering the Cretaceous sediments in the recharge area of the outcrop to move laterally and discharge vertically upward through the overlying Tertiary of the Eastern Shore. This circulation pattern provides a mechanism in which the deeper water containing more dissolved solids can move upward to cause the dissolved-solids content in the overlying sediments to be higher than it would be if the primary movement of the water were downward.

In Virginia (sections *I-I'* and *J-J'*) the Cretaceous sediments are recharged almost entirely by water that has percolated downward through the Miocene beds. Although the Miocene sediments are thin in parts of Virginia, the water has a high dissolved-solids content because the sediments contain an abundance of soluble material.

Water from the shallow Cretaceous sediments in Virginia has a higher dissolved-solids content than water from the Cretaceous sediments in Maryland and New Jersey because of solution of material from the Miocene formations overlying the recharge area of the Cretaceous formations. The water from the deeper formations in Virginia and Maryland has a higher dissolved-solids content owing to the greater amount of salt water, as shown on plate 1E.

CATION FACIES

The distribution of the cation hydrochemical facies in the Coastal Plain sediments is shown on plate 1D. The calcium-magnesium facies is in the shallow formations near the areas of recharge. This is the most restricted facies in the Coastal Plain and occurs in southern Maryland, part of New Jersey, and southern Virginia. The calcium-sodium facies also occurs in the up-gradient position and in the shallow formations. The sodium-calcium facies occurs downgradient and generally in deeper formations. The sodium-potassium facies (referred to hereafter as the sodium facies because of the small amount of potassium) occurs farther downgradient and in the deepest formations.

The New Jersey section of the Coastal Plain shows less sodium facies than the rest of the Coastal Plain. However, this does not necessarily imply that the geology and hydrology of New Jersey is significantly different but rather that all of New Jersey is much closer to the Fall Zone than is the wider part of the Coastal Plain in Maryland, Delaware, and Virginia. That is, if more of the Coastal Plain were emergent in the New Jersey area and was at greater depth and greater distance from the Fall Zone, the sodium facies no doubt would be more widespread. As it is, the sodium facies exists only in the Magothy and Raritan Formations and in the Miocene sediments at the tip of Cape May (*D'-E'*).

There are two explanations for the presence of the sodium facies in Virginia and Maryland: (1) salt water, in which sodium is the dominant cation, underlies the area and (2) ion exchange occurs between calcium in the ground water and sodium on the clays. This exchange occurs as the water moves through the exchange material, thereby creating the sodium facies. Plate 1D shows an outstanding example of ion exchange in southern Maryland (*F-F'* and *G-G'*). As the water enters the recharge area, the gradual change occurs from the calcium-magnesium facies through the calcium-sodium facies and the sodium-calcium facies to the final sodium facies. This pronounced change not only reflects a change in the composition of the ion-exchange minerals but also reflects the effect of the flow path on the chemical character of ground water. Thus, the lithology and mineralogy determine the type of facies that can possibly exist, and the ground-water flow pattern, which results from the head distribution between the recharge and discharge areas, determines the distribution of the facies. In other words, the geology controls the type of facies, and the hydrology controls the distribution.

In Maryland, the calcium-magnesium facies occurs in the Cretaceous sediments near the north-central part of southern Maryland (*F-F'* and *G-G'*). This facies is approximately coextensive with the recharge area underlying the plateau of southern Maryland. As the water enters through the Miocene beds containing calcareous clays, the calcium-magnesium facies is formed. The water continues its downward migration and lateral movement, and the exchangeable materials of the Eocene and Cretaceous formations convert the calcium-magnesium facies through the intermediate facies to the sodium facies.

The calcium-magnesium facies generally is absent in the Cretaceous sediments of Virginia. It may be that as the water enters the recharge areas of the Cretaceous formation near the Fall Zone the normal process of ion exchange converts the calcium-magnesium facies to the

sodium facies in a shorter distance than in Maryland. Another possible explanation is that there are more sodium ions from sea water near the Fall Zone (*I-I'*) in Virginia than near the Fall Zone in southern Maryland. Plate 1E shows more chloride in Virginia than in Maryland (*G-G'*), which would tend to support the last suggestion.

The calcium-sodium facies is present in the area between Washington and Baltimore (north part of section *M-M'*). It owes its existence there not to the ion-exchange process but to the lack of calcareous sediments, which, if present, would create the calcium-magnesium facies in the outcrop area of the Cretaceous formations.

ANION FACIES

The occurrence and distribution of the anion facies are determined by the relative concentration of bicarbonate, chloride, and sulfate ions. In most of the water to a depth of about 1,000 feet, the bicarbonate ion makes up more than 50 percent of the total anions, and accounts for the existence of the bicarbonate facies and the bicarbonate-chloride-sulfate facies. A few areas exist in which the chloride and the sulfate ions, as computed on a percentage basis, are the dominant anions. The distribution of the anion facies was studied by construction of fence diagrams showing the chloride- and bicarbonate-ion contents, in parts per million, and percentage of the bicarbonate plus carbonate ions. The concentration of the sulfate content was not plotted because of its low values and its rather uniform distribution.

Plate 1E is a fence diagram showing the concentration of chloride ions in ground water in the uppermost 1,000 feet of the Coastal Plain sediments. Much of the water contains less than 5 ppm chloride, and all the ground water except that associated with the deep salt water (pl. 1B) contains less than 25 ppm chloride. The salt water along the eastern part of the Coastal Plain is identified by the high chloride content. The chloride content shown for most of the Pleistocene sediments is not necessarily valid. Because the shallow sediments are contaminated by sewage effluent and by industrial wastes the distribution of chloride is erratic. Part of the chloride in the shallow sediments along the coast may be due to atmospheric precipitation of salts from the ocean.

In Maryland and Virginia (sections south of *E-E'*) the chloride content ranges from 0 to 5 ppm in the shallow sediments close to the Fall Zone. The content ranges from 5 to 25 ppm at greater depth and closer to the coast. This is due to the effect of normal solution of the minerals and to removal of residual adsorbed ions as the water enters the high topographic areas and

moves downgradient. The higher chloride content near the surface along the coast represents part of the body of salt water that extends from the deeper sediments to the present ocean.

The distribution of the bicarbonate ion in ground water of the Coastal Plain is shown on plate 1F. The values plotted are the results of bicarbonate determinations made in the laboratory. Water's bicarbonate content is controlled by its pH and temperature, the partial pressure of carbon dioxide, and the minerals it contacts. The values of pH and bicarbonate content of water obtained in laboratory measurements are known to be different from the values of these properties of the water in the aquifer, and laboratory determinations cannot be used in detailed studies. However analytical error probably does not detract from the validity of the regional relationships shown on plate 1, F and G.

In the shallow formations and in the areas of recharge, the bicarbonate content is low. As the water moves down through the calcareous sediments of the Miocene series and through some of the Eocene beds, the bicarbonate content increases. This relation is illustrated for southern Maryland in section *F-F'*, where, near Silver Spring, the bicarbonate content is less than 100 ppm because the water enters the recharge area of the Cretaceous and Eocene sediments without passing through the Miocene beds. Farther down dip, the water enters the underlying formations through the Miocene beds, and the bicarbonate content has increased. Also, as illustrated (pl. 1F, section *G-G'*), the bicarbonate content has increased to more than 100 ppm in the discharge area, where the Miocene beds crop out.

In Virginia (section *I-I'* and others to the south) where the Cretaceous formations are recharged almost entirely by water that has passed through the Miocene beds, the bicarbonate content is relatively high, more than 200 ppm. The bicarbonate content of water in all formations in New Jersey, except the Magothy and the Raritan, is the lowest for most of the rest of the Coastal Plain. The Miocene formations in New Jersey contain less calcareous material than the Miocene formations in Virginia and Delaware. The primary source of calcareous material in Miocene sediments in New Jersey is from the beds at the base of the Kirkwood Formation. The other source of calcareous material is in the Honerstown Sand of Cretaceous age.

The area in which water has the highest bicarbonate content is associated with the area in which salt water exists. This is not merely owing to mixing of the fresh water with the salt water, because sea water has a bicarbonate content of only 140 ppm. Foster (1950) studied the occurrence of bicarbonate-rich ground water

in the Atlantic and Gulf Coastal Plains by a series of laboratory experiments in which water percolated through lignite, then calcite, and finally an ion-exchange material. Analyses of the leachate closely resembled those of natural ground water; both had the sodium bicarbonate character. The water cannot attain equilibrium with the calcareous material because of the exchange of the calcium ion in solution with the sodium ion on the exchangeable material; the result is a continuous increase of bicarbonate.

Mapping of the hydrochemical facies during the present study suggests that this process may be more pronounced in the area containing salt water. The areas of high-bicarbonate water (pl. 1F) are virtually the same as the areas of high-chloride water (pl. 1E) and water containing a high percentage of sodium (pl. 1D). The correlation of high bicarbonate and high sodium is due in part to the greater solubility of calcareous material in salt water than in fresh water. The greater solubility and removal of calcium ions permits the buildup of bicarbonate ions far in excess of the concentration observed for water from limestone areas. Most water from limestone areas would have bicarbonate concentration ranging from about 150 to 300 ppm. For this part of the Coastal Plain, many analyses show more than 500 ppm; the highest show 1,200 ppm. To determine if the water containing 1,200 ppm bicarbonate was saturated with respect to calcite, the analyses (Somerset County, Md., Ec-33) were used to calculate the departure from equilibrium, as described previously (Back, 1960). The amount of bicarbonate that would be required for the water to be in equilibrium with calcite is about 4,000 ppm, as compared with the analyzed value of 1,200 ppm. Therefore, even with this high bicarbonate content the water is still capable of dissolving more calcareous material.

SUMMARY AND CONCLUSIONS

This study demonstrates a method by which the geohydrologic significance of the chemical character of water may be emphasized. The chemistry of ground water is controlled entirely by the lithology of the deposits through which the water flows and by the orientation of the flow path within the geologic framework. The flow path is determined by the permeability of the sediments and the boundaries of the hydrologic system. To establish the boundaries of the hydrologic system of this part of the Coastal Plain, a study must be made of the geomorphic controls on the creation of fresh-water head, the thickness of the sediments overlying the less permeable crystalline rocks, and the position of the fresh-water-salt-water interface.

The deep salt water that had been identified in many parts of the Coastal Plain is shown to be one continuous water body. Its position is determined by the relative head distribution in the fresh water and in the salt water. The head distribution is influenced by the topographic position of the landmasses, the thickness and the permeability of the Coastal Plain sediments, and the geomorphic development of the Coastal Plain. The genesis of the salt water is known to be due to one or more of the following processes: Retention of ions from the marine water in which the sediments were deposited; entrance of salt water after deposition; concentration of ions through common solution processes; and selective concentration, with the clays acting as semi-permeable membranes.

The three-dimensional aspect of hydrochemical facies can be illustrated effectively by fence diagrams. The calcium-magnesium facies are in the areas of higher head, and the sodium facies are in areas of lower head. The sodium facies result from an ion-exchange process with sodium-bearing exchange material and from the presence of salt water. Areal differences of chemical character of water can occur without a change in the type of aquifer material. The lithology and mineralogy determine the type of facies that can possibly exist, and the ground-water flow pattern determines the distribution of the facies.

The regional flow pattern constructed by use of available head data in the outcrop areas and along the salt-water interface was substantiated by mapping the hydrochemical data. The chemical and hydrologic data provide a convincing example of the outcrop area of an artesian aquifer functioning equally well as either a discharge or recharge area. Depending on the head, distribution of the water can move updip as readily as it can move downdip.

The existence of hydrochemical facies indicates a close relationship between the hydrologic processes and the aquifer material. More regional studies of the field relationships among ground-water movement, mineralogy of the geologic formations, and the chemical character of ground water are needed. Such studies could do the following: Test the techniques and feasibility of hydrochemical mapping, describe the field relationships as a basis for identification of the more significant chemical processes, identify areas suitable for the study of selected geochemical processes, emphasize the need for more thorough collection of valid data, and clarify the role that ground water plays in the geochemical cycle of the elements.

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