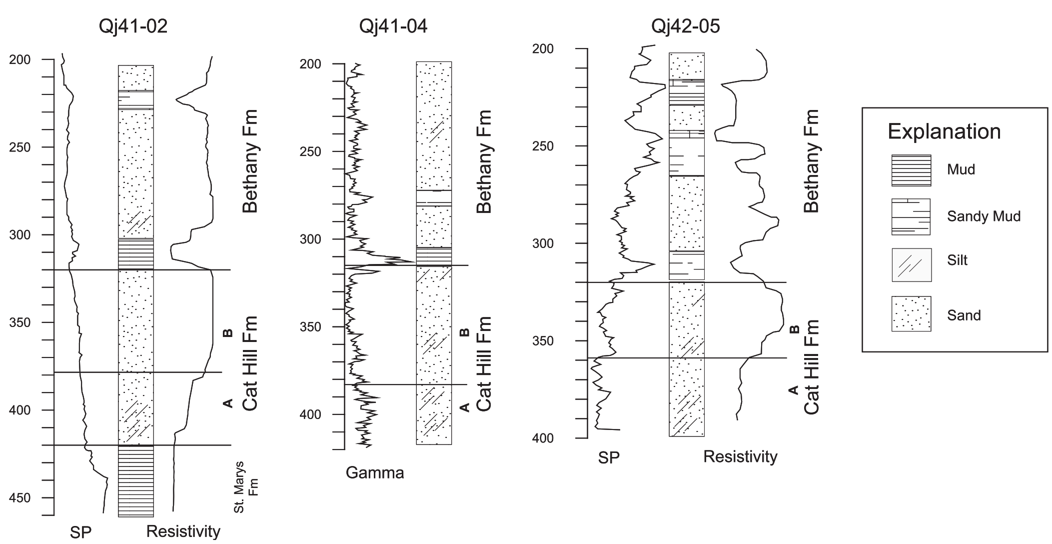
State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 67

THE CAT HILL FORMATION AND BETHANY FORMATION OF DELAWARE

By

A. Scott Andres



University of Delaware
Newark, Delaware
2004

State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 67

THE CAT HILL FORMATION AND BETHANY FORMATION OF DELAWARE

By

A. Scott Andres

University of Delaware
Newark, Delaware
2004

CONTENTS

ILLUSTRATIONS

TABLE

THE CAT HILL FORMATION AND BETHANY FORMATION OF DELAWARE

A. Scott Andres

ABSTRACT

Because of the rapid development occurring in coastal Delaware and the importance of ground water to the economy of the area, definition of formal lithostratigraphic units hosting aquifers and confining beds serves a useful purpose for resource managers, researchers, and consultants working in the area. The Pocomoke and Manokin are artesian aquifers pumped by hundreds of domestic and dozens of public wells along the Atlantic coast in Delaware and Maryland. These aquifers are being increasingly used for public water supply.

Two formal lithostratigraphic units, the Cat Hill Formation and Bethany Formation, are established to supercede the Manokin formation and Bethany formation, respectively. In Delaware, these lithostratigraphic units host important aquifers—the Manokin, which occurs in the Cat Hill Formation, and the Pocomoke, which occurs in the Bethany Formation. Composite stratotypes of these units are identified in five drillholes located near Bethany Beach, Delaware.

INTRODUCTION

Ground water is the source of all fresh water used for potable, industrial, commercial, and irrigation purposes in eastern Sussex County, Delaware and adjacent Maryland (Fig. 1). Identification and description of the geologic units hosting these aquifers are important to predicting the distribution and water-bearing characteristics of the aquifers and in managing the use of the water.

The Pocomoke and Manokin are artesian aquifers pumped by hundreds of domestic and dozens of public wells along the Atlantic coast in Delaware and adjacent Maryland (Sundstrom and Pickett, 1969; Hodges, 1983; Andres, 1986a; Talley, 1987; Achmad and Wilson, 1993). These aquifers are being increasingly used for public water supply as the area is developed and contamination limits use of the shallower Columbia aquifer. The significant complexity of the geologic framework has resulted in confusing and contradictory correlations of aquifers and confining beds; hence, formal identification of the lithostratigraphic units containing the Pocomoke and Manokin aquifers will be helpful for characterizing and managing the ground-water resources of the area.

Purpose and Scope

Two formal lithostratigraphic names are proposed for late Miocene to Pliocene sedimentary deposits in Delaware. The Cat Hill Formation and Bethany Formation supercede the Manokin formation and Bethany formation, respectively. The Manokin aquifer occurs in the Cat Hill Formation and the Pocomoke aquifer occurs in the Bethany Formation. Composite stratotypes of these units are identified in five drillholes (Qj41-02, Qj41-04, and Qj42-05 (Cat Hill) and Qj32-27 and Qj32-14 (Bethany) located near Bethany Beach, Delaware (Fig. 2).

Andres (1986b) introduced for use in Delaware the informal lithostratigraphic names "Bethany formation" and "Manokin formation" for the sediments between the Miocene St. Marys Formation and Pliocene Beaverdam Formation. Using borehole and seismic reflection data, Andres (1986b) interpreted these units to have been deposited in inner neritic, near shore, and marginal marine environ-

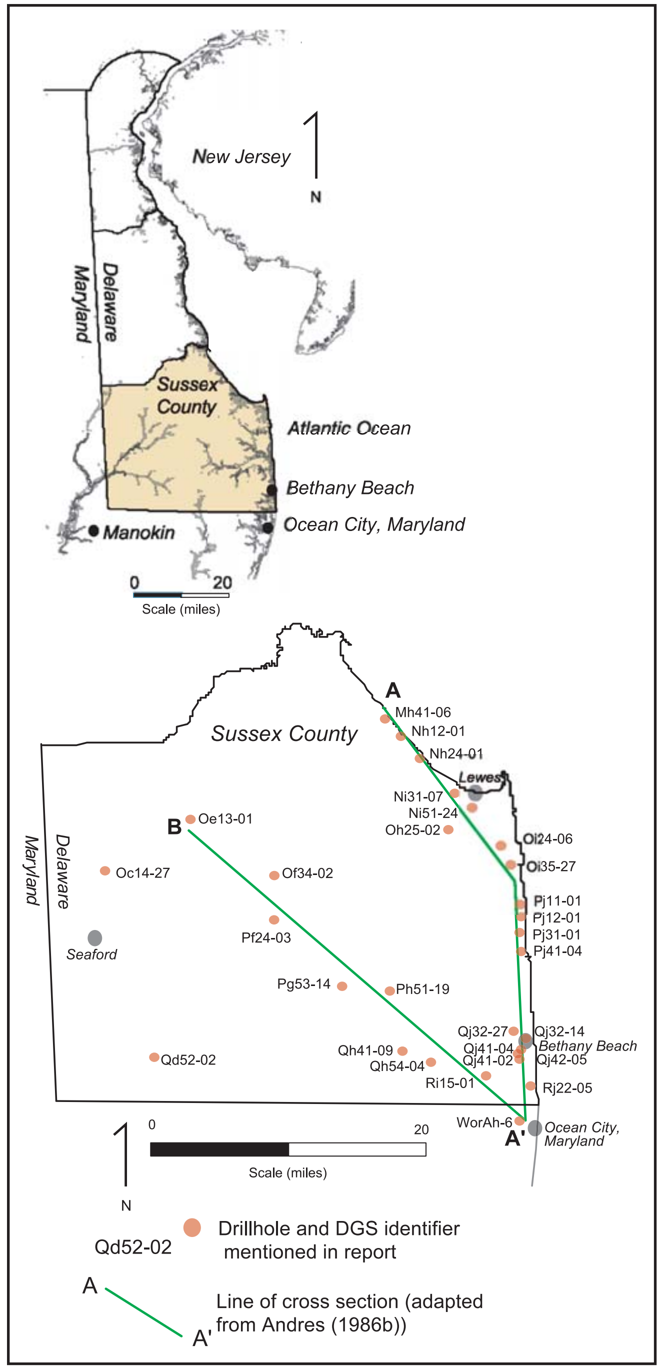


Figure 1. Map showing location of study area and place names mentioned in text. Detailed map of Bethany Beach area shown in Figure 2. Cross sections shown in Figure 5.

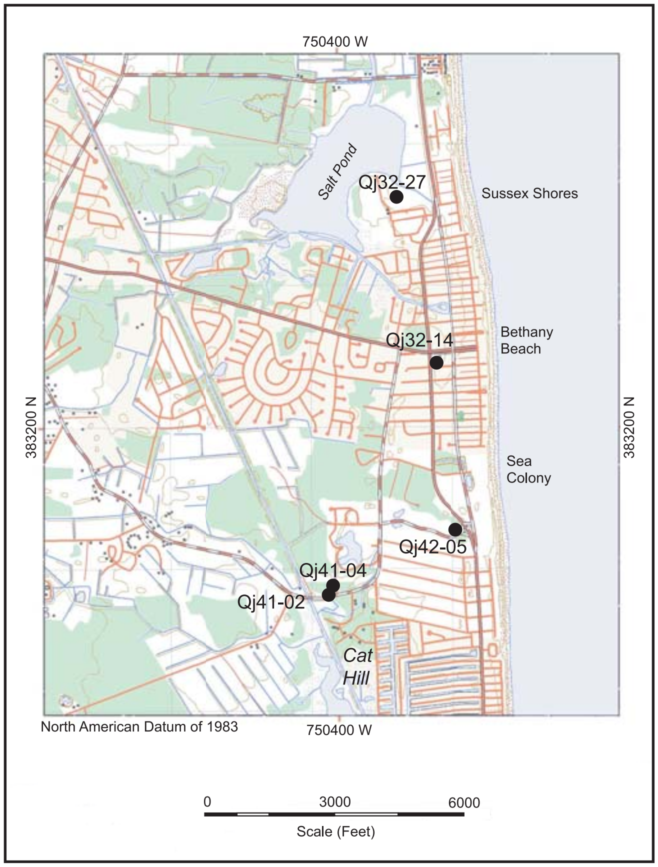


Figure 2. Map showing area of type locations of Cat Hill Formation and Bethany Formation. Base map U. S. Geological Survey (1992).

ments. The distribution of sandier sections and the seismic data indicate that these units were deposited in a prograding delta complex with the loci of sandy deposits changing during basin infilling. Formal names for the units were not established at that time because available samples and descriptive data were not sufficient to meet the requirements of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983).

Since that time, additional works (Benson, 1990; Groot et al., 1990; Ramsey and Schenck, 1990; Achmad and Wilson, 1993; Andres and Ramsey, 1995, 1996; Ramsey, 2001, 2003; Miller et al., 2003) have amplified descriptions of the composition and distribution of the Bethany formation and Manokin formation to the point that formalization of lithostratigraphic names is warranted. Further, the difficulties and confusion expressed by researchers, resource managers, and consultants attempting to use a combination of formal and informal names in reports and publications makes formalizing the lithostratigraphic names a useful service.

This report completes the information needed to establish formal lithostratigraphic names for the Cat Hill Formation and Bethany Formation. Published maps and reports and descriptions are the primary data sources used to define the distributions and compositions of the units. These data were supplemented with descriptions of cutting samples and interpretations of geophysical logs from drillholes Qj41-02 and Qj42-05. No new drillhole data were collected for this study. The content of this report is not exhaustive in order to make the report more accessible for its most frequent use—applications in hydrogeologic and water supply issues. Additional detailed discussions of the sedimentology, ages, fossils, sequence stratigraphy, depositional architecture, and environments of deposition of these units are beyond the scope of this report and are the subject of published (Andres, 1986b; Achmad and Wilson, 1993; Miller et al., 2003) and future Delaware Geological Survey reports (Peter P. McLaughlin, oral communication).

The procedures for establishing formal names of lithostratigraphic units (North American Commission on Stratigraphic Nomenclature, 1983) are the guide used in this investigation. The National Geologic Map database GEOLEX (U. S. Geological Survey, http://ngmdb.usgs.gov/Geolex/) was consulted in October 2003 to avoid conflicts with previous uses of the proposed names.

Acknowledgments

Delaware Geological Survey staff, Richard N. Benson, Kelvin W. Ramsey, and Peter P. McLaughlin provided the motivation to complete work begun nearly 20 years ago. Discussions over the years with David Powars, Gerry Johnson, John M. Wilson, and the late James P. Owens helped my understanding of the problems and possible solutions to naming these units. David W. Bolton, Peter P. McLaughlin, and Kelvin W. Ramsey are thanked for reviewing the draft manuscript.

CAT HILL FORMATION (*herein named*)

Much of the early work on the section of sediments identified as the Cat Hill Formation was completed while investigating ground-water resources; therefore, naming and mapping of the sediments were tied to identification of aquifers and confining beds derived from observations of geophysical logs and drill-cutting samples. Rasmussen and Slaughter (1955) used the name "Manokin aquifer" for the first sandy interval above the St. Marys Formation in a water supply well located in Manokin, Maryland (Fig. 1). Owens and Denny (1979) and Hansen (1981) identified this section as the "Manokin beds" and "Manokin aquifer," respectively.

Rasmussen et al. (1960) extended the use of the name Manokin aquifer into Sussex County, Delaware. Sundstrom and Pickett (1969, 1970) identified, described, and mapped the Manokin aquifer in more detail in Sussex County. Although generally in agreement with later work, their interpretations of the lateral and vertical extent of the Manokin aquifer were somewhat inaccurate because of the limited data from deep drillholes available to them. Further confusion regarding the distribution and composition of the Manokin aquifer in Delaware resulted from hydrostratigraphic interpretations by Hodges (1983). Many of the problems with interpretations by Rasmussen et al. (1960), Sundstrom and Pickett (1969, 1970), and Hodges (1983) are the result of correlating by counting the vertical succession of major sand beds downward from land surface at a limited number of sites.

I propose the name Cat Hill Formation to replace the Manokin formation, in part to avoid confusing the lithostratigraphic unit with the aquifer unit. More importantly, the composition of the Cat Hill Formation varies spatially and includes fine-grained beds that do not function as part of the

Manokin aquifer. The type locality of the Cat Hill Formation is a composite stratotype (Fig. 3) defined in three drillholes Qj41-02, Qj41-04, and Qj42-05 (Table 1), located near Cat Hill (U.S. Geological Survey, 1992) in eastern Sussex County near the town of Bethany Beach, Delaware (Fig. 2). Formal definition of the Cat Hill Formation requires a composite stratotype because each of the individual drillholes does not contain the minimum data needed to satisfy the requirements of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983).

In the composite stratotype (Fig. 3), the Cat Hill Formation has an apparent thickness of 100 to 105 ft. It is dominantly composed of sand with minor beds of mud (mixtures of silt and clay) and is informally subdivided into two subunits. The lower subunit (A) is a coarsening upward fine to medium silty quartzose sand and clayey fine sand; the upper subunit (B) is a medium to coarse gray quartzose sand with beds of gravelly coarse sand. Mica, lignite, phosphatic grains, and glauconite are rare accessory components.

Throughout its known extent, gamma (Figs. 3, 4, and 5) and descriptive logs indicate that the Cat Hill Formation is generally sandy with minor beds of mud (mixtures of silt and clay), and the two informal subunits present in the composite stratotype are commonly observed (Andres and Ramsey, 1996; Ramsey, 2003). Macrofossils, typically described as shells or shell hash on drillers' logs, are reported in scattered locations. In some locations, subunit A is not present (Oc14-27, Pg53-14, Fig. 4). All available data show that the Cat Hill Formation occurs only in the subsurface. As a result, precise identification of lateral boundaries (Fig. 6) is problematic. Variations in thickness reflect spatial changes in depositional environments during filling of the sedimentary basin and post-depositional erosional truncation (Andres, 1986b).

Available data on the composition of the Cat Hill Formation varies with location. In the Seaford area, Andres and Ramsey (1996) describe the Cat Hill Formation as consisting of a coarsening-upward sequence that can be informally subdivided into two subunits. The upper unit consists of light to medium gray or yellow-orange to red-orange (where weathered) medium to fine and coarse sand with common beds of gravelly sand and rare beds of clayey to silty sand. The lower unit consists of gray, blue-gray, and brown-gray silty clayey sand and silty sand. It is expected that where the lower unit has been exposed to oxidizing conditions it would weather and contain yellow to red hues. In some locations, the lower subunit is not present. In the Lewes area, Ramsey (2003) also describes the Cat Hill Formation as having two subunits, an upper unit (B) consisting of well-sorted, clean, white to reddish brown, fine to medium sand. Some beds of medium to coarse sand and gray to white clayey silt are also present. The lower unit (A) consists of gray, very fine silty sand to silty clay with rare to common pieces of lignite. Miller et al. (2003) report that in Qj32-27 the Cat Hill Formation consists of silty fine to medium sand; silty fine sand; medium sand with thin interbeds of silty organic-rich clay; and shelly, glauconitic, granule-bearing fine to medium sand. Laminations of lignite and heavy minerals are common.

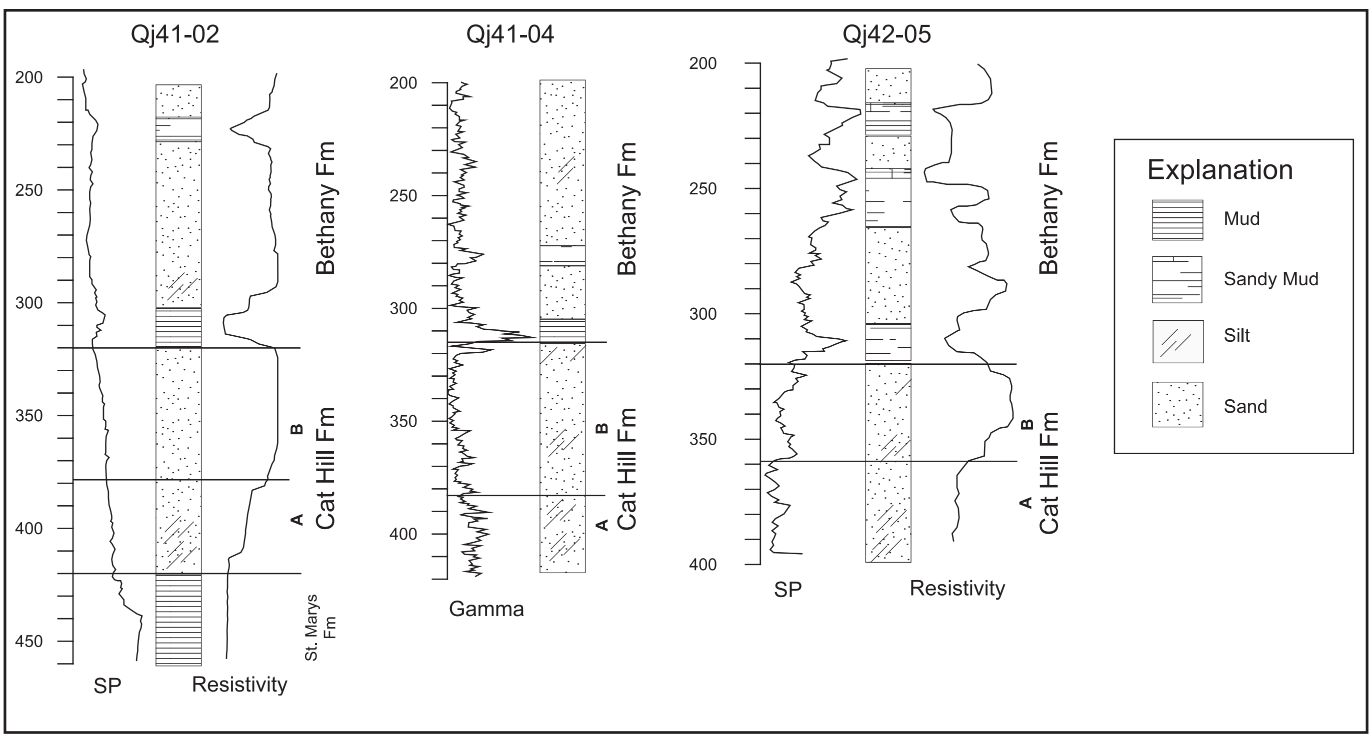


Figure 3. Composite stratotype of the Cat Hill Formation. Logs are arranged from southernmost (Qj41-02) to northernmost (Qj42-05). Depths shown are in feet below land surface. "A" and "B" denote informal subunits of the Cat Hill Formation. Land surface elevations for all log locations are approximately 5 ft NGVD 1988. Gamma denotes natural gamma radiation; resistivity denotes short normal resistivity; SP denotes spontaneous potential.

					Cat Hill Formation		Bethany Formation	
DGS ID	Latitude (ddmmss)	Longitude (ddmmss)	LSE (ft)	Type of Information	Top (ft bls)	Bottom (ft bls)	Top (ft bls)	Bottom (ft bls)
					Stratotypes			
Qj41-02	383125	750403	5	D,G	320	420	---	---
Qj41-04	383122	750405	5	D,G	315	420	---	---
Qj42-05	383137	750326	6	G,L	320	>400	---	---
Qj32-14	383215	750317	5	D,G	---	---	125	320
Qj32-27	383253	750345	5	C,G,L	---	---	118	313
					Reference Sections			
Oc14-27	384413	753611	46	D,G,L	65	95	---	---
Oh25-02	384350	751014	20	G,L	173	310	119	173
Pg53-14	383524	751742	23	D,G,L	180	255	95	180
Qd52-02	383040	753316	43	D,G,C,L	90	180	---	---
Qj32-14	383215	750317	5	D,G	---	---	125	320
Qj32-27	383253	750345	5	C,G,L	---	---	---	---
Qj41-04	383122	750405	5	D,G	---	---	130	315

Table 1. Locations and depths of type and reference sections of the Cat Hill Formation and Bethany Formation. Latitude and longitude are reported as degrees (dd), minutes (mm), seconds (ss) in North American Datum of 1983. Land surface elevation (LSE) reported in ft North American Vertical Datum of 1988. Top and bottom are reported in ft below land surface (bls). Type of information D= driller log, C= geologist core description, G=geophysical log, L=geologist cutting sample description. Formation picks for borehole Qj32-27 are from Miller et al. (2003) and McLaughlin (written communication), Oh25-02 is from Benson (1990), Pg53-14, Qd52-02, Qj41-04, and Qj32-14 are from Andres (1986b), Oc14-27 is from Andres and Ramsey (1995), and Qj41-02 and Qj42-05 are from this study.

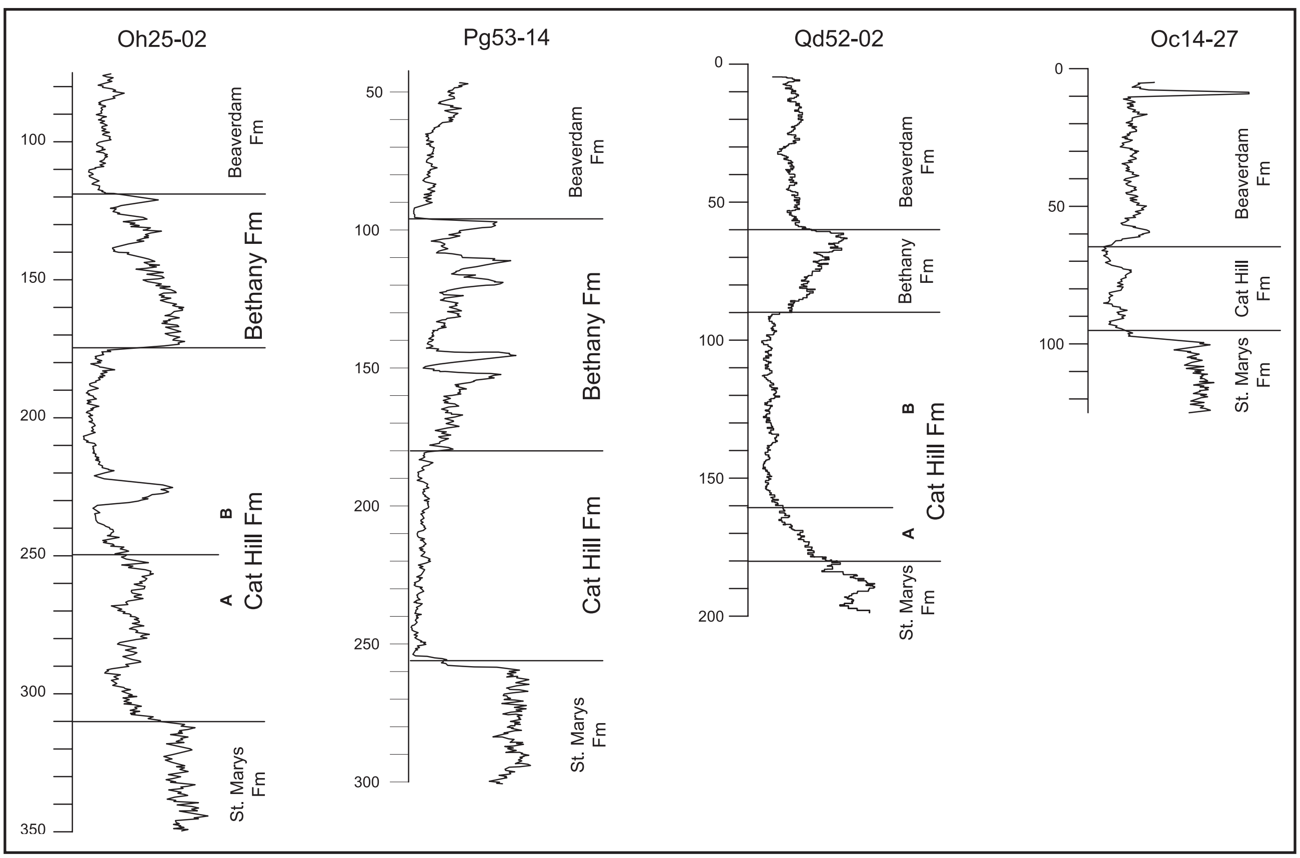


Figure 4. Geophysical logs showing reference sections of the Cat Hill Formation and Bethany Formation. Depths shown in feet below land surface. "A" and "B" denote informal subunits of the Cat Hill Formation. Logs shown are natural gamma radiation logs.

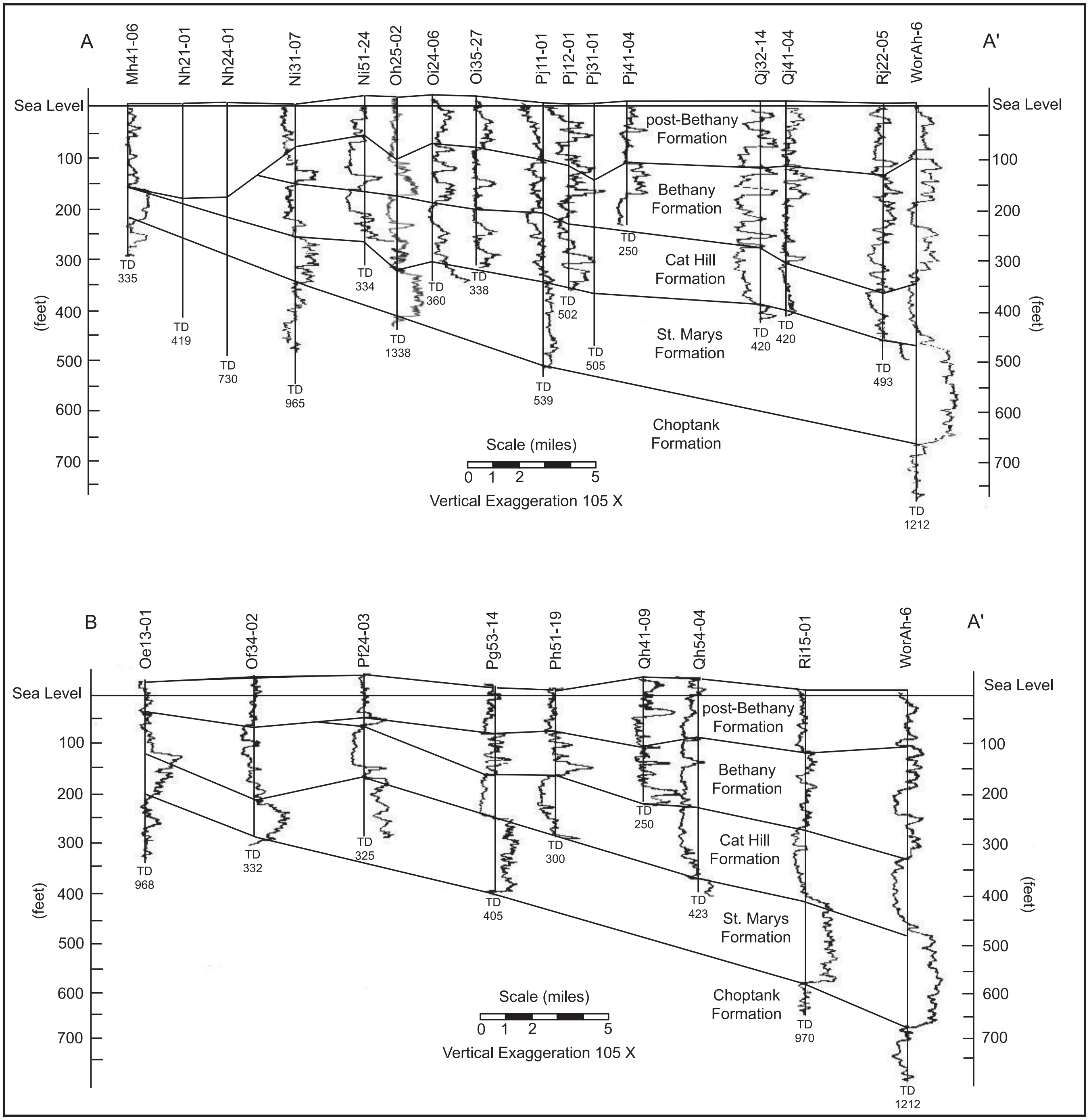


Figure 5. Regional cross sections showing variations in depths and thicknesses of the Cat Hill Formation and Bethany Formation (adapted from Andres, 1986b). Logs shown are natural gamma radiation logs. Locations of cross sections are shown in Figure 1.

Analysis of samples (Leggett, 1992; Andres and Ramsey, 1996) shows the Cat Hill Formation to be dominated by monocrystalline quartz with less than 3 percent each potassium feldspar and plagioclase. The feldspar tends to be more weathered than that observed in the Beaverdam Formation. The clay mineral suite consists of relatively similar amounts of smectite, illite, and kaolinite with lesser amounts of chlorite.

The age of the Cat Hill Formation is reported to range from late middle Miocene (Owens and Denny, 1979; Hansen, 1981; Benson, 1990) to perhaps Pliocene (Miller et al., 2003), though the age estimates are poorly constrained because of a general lack of diagnostic fossils or other materials that can be age-dated. The stratigraphic relationships between the overlying and underlying units vary with location. Hansen (1981), Andres (1986b), Achmad and Wilson (1993), Andres and Ramsey (1995), and Ramsey (2001, 2003) have noted that the contact between the Cat Hill Formation and underlying St. Marys Formation is most commonly gradational from muddy to sandy but in some updip locations is erosional, changing abruptly from the muddy St. Marys Formation to the sandy Cat Hill Formation (e.g., Pg53-14, Oc14-27, Fig. 4).

Because the contact between the Cat Hill Formation and overlying Bethany Formation occurs only in the subsurface and is typically observed on geophysical and driller's logs, it is more difficult to characterize. At the type locality, the contact with the overlying Bethany Formation is the base of a gray clay ranging in depth from 315 to 320 ft below land surface. Similarly, in many other locations the contact is marked by an abrupt change from sand in the Cat Hill Formation to mud in the Bethany Formation indicating either a disconformable erosional surface, or a change in depositional environment (Andres, 1986b; Miller et al., 2003) that represents a paraconformity. Where the Bethany Formation is absent, the Cat Hill Formation is unconformably overlain by the Beaverdam Formation. For example, in drillhole Oc14-27 (Fig. 4), coarse sands and gravels of the Beaverdam Formation exhibit higher gamma log values than the fine to medium sands of the Cat Hill Formation.

As noted by Andres (1986b), in locations where beds above and below the contact between the Cat Hill Formation and Bethany Formation are predominately sand, and in the absence of core sample, distinction between the Cat Hill Formation and Bethany Formation and interpretation of the nature of the contact is difficult (Qj32-27, Fig. 2; Qh54-04, Fig. 5). For example, although Qj32-14 (Figs. 5 and 7) and Qj32-27 (Fig. 7) are about 3,500 ft from each other, there are significant differences in lithologies and geophysical log signatures. Mud beds in the Bethany Formation appear to be better defined in logs from Qj32-14 than those from Qj32-27. Some of the difference can be directly attributed to the fact that different geophysical logging equipment was used in each drillhole, and a cuttings-based driller's log describes the Bethany Formation in Qj32-14 whereas a core-based geologist's log describes the unit in Qj32-27. As a result, Miller et al. (2003) picked the base of the Bethany Formation in Qj32-27 at an elevation of -190 ft, which is more than 100 ft higher than the contact picked in Qj32-14 (-315 ft). Reinterpretation of data from Qj32-27 (P. P. McLaughlin, written communication) places the contact at an elevation of -313 ft, between lignitic medium sand above and fine sand below.

BETHANY FORMATION (*herein named*)

As with the Cat Hill Formation, much of the early works on the section of sediments identified as the Bethany Formation were done as part of water resource investigations. As a result, naming and mapping of the unit were tied to identification of aquifers and confining beds from drillers' and geophysical logs. To avoid the confusion resulting from the misidentification and miscorrelation of aquifers and confining beds, Andres (1986b) proposed the informal name Bethany formation for the sediments containing the Ocean City and Pocomoke aquifers, and the basal, intervening, and overlying mud (confining) beds.

I propose formalizing the Bethany Formation on the bases of the original description by Andres (1986b) and additional work by Miller et al. (2003). The type location of the Bethany Formation is a composite stratotype derived from corehole Qj32-27, and drillhole Qj32-14 (Fig. 7), located near Bethany Beach, Delaware (Fig. 2). In the composite section, the apparent thickness of the Bethany Formation is about 195 ft. It is composed of a sequence of clayey and silty beds with discontinuous lenses of quartzose sand. The most common lithologies described by Miller et al. (2003) are lignitic, silty, clayey, pebbly, fine quartzose sand; sandy, silty clay; fine to medium quartzose sand; sandy, clayey silt, and medium to coarse quartzose sand with granule zones. Laminations of heavy minerals are common in the fine to medium sands, and thin layers of gravel and coarse sand are rarer (Miller et al., 2003). The differences in lithology observed in the composite stratotype reflect facies changes.

The composition, thickness, and geophysical log signature of the Bethany Formation vary with location and depth (Figs. 4, 5, and 7). In general, the Bethany Formation is a sequence of clayey and silty beds with discontinuous lenses of sand (Andres, 1986b; Ramsey, 2003). The most common lithologies are silty, clayey fine sand; sandy, silty clay; clayey, sandy silt; fine to medium sand; sandy, clayey silt, and medium to coarse sand with granule and pebble layers. Thin gravel layers occur most frequently in updip areas and are rarer in downdip areas. Sands are typically quartzose. Lignite, plant remains, and mica are common, grains of glauconite are rare. In the Lewes area, Ramsey (2003) describes the Bethany Formation as consisting of gray, olive gray, bluish-gray clay to clayey silt interbedded with fine to very coarse sand. Lignitic and gravelly beds are common.

Available data indicate that the Bethany Formation occurs only in the subsurface, and most observations and descriptions are limited to drillers' and geophysical logs and geologists' descriptions of samples of drillhole and borehole cuttings. As a result, precise identification of lateral boundaries (Fig. 6) is problematic. Variations in thickness reflect spatial changes in depositional environments during filling of the sedimentary basin and post-depositional erosional truncation (Andres, 1986b).

The age of the Bethany Formation is reported to range from late middle Miocene (Owens and Denny, 1979; Hansen, 1981; Benson, 1990) to perhaps Pliocene (Miller et al., 2003), although the age estimates are poorly constrained because of a general lack of diagnostic fossils or other materials that can be age-dated.

Similar to the contact between the Cat Hill Formation and the overlying Bethany Formation (discussed in previous paragraphs), the contact between the Bethany Formation and the overlying Beaverdam Formation is hindered by the fact that the contact occurs only in the subsurface, where it is typically observed only in geophysical and drillers' logs or in samples of cuttings from boreholes and drillholes. Adding to the difficulties, in some locations lithologies above and below the contact are similar, and there is a general lack of diagnostic fossils and materials in both units that can be age-dated.

At the type locality (Fig. 7) and in other locations along the coast (Fig. 5) the Bethany Formation and Beaverdam Formation can contain significant amounts of muddy sediments and multiple sand on mud contacts indicating multiple erosional contacts. In contrast, in locations to the north and west of the type locality, where the Beaverdam Formation is predominately composed of coarse sand, the contact is more clearly interpreted as an erosional surface at an abrupt change from a blue gray to olive gray mud bed to an overlying gravelly sand (e.g., Oh25-02, Pg53-14, Fig. 4). At many locations, the top few inches of the mud bed is cemented with limonitic cement suggesting the presence of a paleosol or erosional surface further supporting the interpretation of an erosional contact. Less commonly in updip areas, where the top of the Bethany Formation is a fine to medium sand,

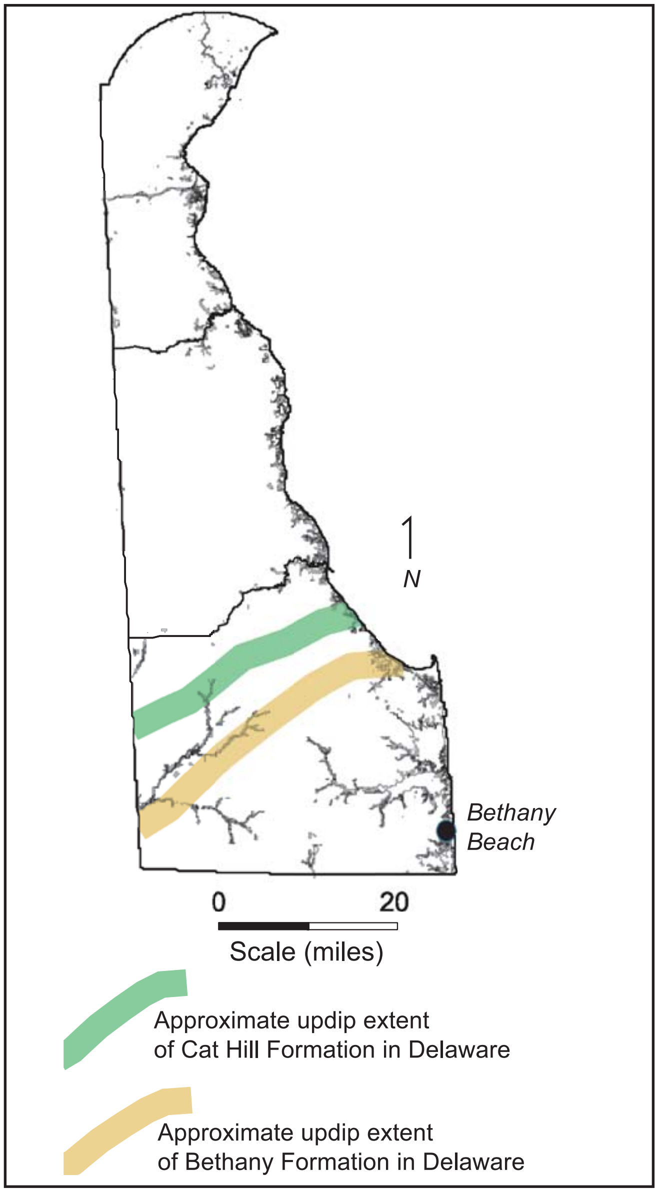


Figure 6. Map showing approximate updip limits of the Cat Hill Formation and Bethany Formation.

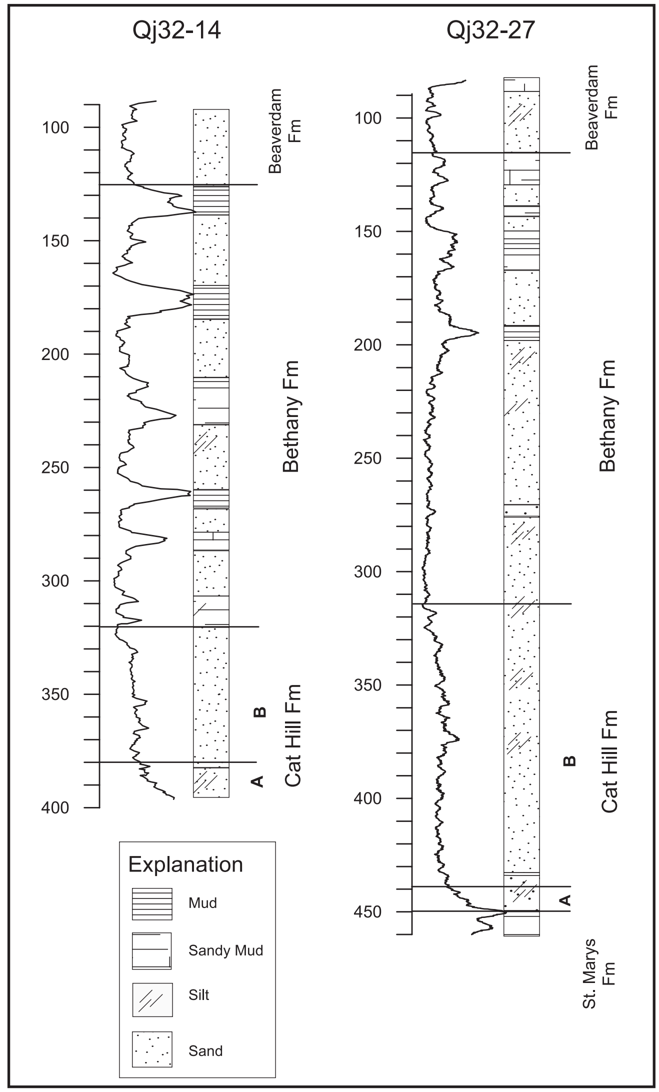


Figure 7. Composite stratotype of the Bethany Formation. Depths shown are in feet below land surface. Land surface elevations for both log locations are approximately 5 ft NGVD 1988. Logs shown are natural gamma radiation logs. Qj32-14 shows the typical character of the Bethany Formation, consisting of muds with interbedded sands. Qj32-27 shows the less common condition where the Bethany Formation is predominately sand.

or pebbly, medium to coarse sand, the contact with the overlying Beaverdam Formation may be difficult to distinguish on drillers' or geologists' logs. In the case of a sand on sand contact, the gamma log signature of the Bethany Formation typically shows lower values than the Beaverdam Formation.

SUMMARY

Two formal lithostratigraphic names, the Cat Hill Formation and Bethany Formation supercede the Manokin formation and Bethany formation, respectively. In Delaware, these lithostratigraphic units host important aquifers—the Manokin, which occurs in the Cat Hill Formation, and the Pocomoke, which occurs in the Bethany Formation. In Maryland, the Bethany Formation also contains the Ocean City aquifer. The Cat Hill Formation is defined in a composite stratotype in three drillholes Qj41-02, Qj41-04, and Qj42-05 located near Cat Hill (Bethany Beach, Delaware). The type locality of the Bethany Formation is defined in a composite stratotype in Qj32-14 and Qj32-27, located near Bethany Beach, Delaware.

REFERENCES CITED

Achmad, G. J., and Wilson, J. M., 1993, Hydrogeologic framework and the distribution and movement of brackish water in the Ocean City-Manokin aquifer system at Ocean City, Maryland: Maryland Geological Survey Report of Investigations No. 61, 125 p.

Andres, A. S., 1986a, Geohydrology of the Northern Coastal Area, Delaware, Delaware Geological Survey Hydrologic Map Series No. 5, Sheet 1, Basic Geohydrologic Data, scale 1:24,000.

___1986b, Stratigraphy and depositional history of the post-Choptank Chesapeake Group: Delaware Geological Survey Report of Investigations No. 42, 39 p.

Andres, A. S., and Ramsey, K. W., 1995, Geologic map of the Seaford area, Delaware: Delaware Geological Survey Geologic Map Series No. 9, scale 1:24,000.

___1996, Geology of the Seaford area, Delaware: Delaware Geological Survey Report of Investigations No. 53, 22 p.

Benson, R. N., ed., 1990, with contributions by A. S. Andres, R. N. Benson, K. W. Ramsey, and J. H. Talley, Geologic and hydrologic studies of Oligocene-Pleistocene section near Lewes, Delaware: Delaware Geological Survey Report of Investigations No. 48, 34 p.

Groot, J. G., Ramsey, K. W., and Wehmiller, J. F., 1990, Ages of the Bethany, Beaverdam, and Omar formations of southern Delaware: Delaware Geological Survey Report of Investigation No. 47, 19 p.

Hansen, H. J., 1981, Stratigraphic discussion in support of a major unconformity separating the Columbia Group from the underlying upper Miocene aquifer complex in eastern Maryland: Southeastern Geology, v. 22, p. 123-138.

Hodges, A. L., 1983, Hydrology of the Manokin, Ocean City, and Pocomoke aquifers of southeastern Delaware: Delaware Geological Survey Report of Investigations No. 38, 60 p.

Leggett, T. N., 1992, Sedimentary petrology of the post-early Miocene sediments on the northern Delmarva Peninsula, unpublished senior thesis, Pennsylvania State University, 41 p.

Miller, K. G., McLaughlin, P. P., Jr., Browning, J. V., Benson, R. N., Sugarman, P. J., Ramsey, K. W., Hernandez, J., Baxter, S. J., Feigenson, M. D., Monteverde, D. H., Cramer, B. S., Uptegrove, J., Katz, M. E., McKenna, T. E., Strohmeier, S. A., Pekar, S. F., Cobbs, G., Cobbs, G., III, Aubry, M.-P., and Curtin, S., 2003, Bethany Beach site report, *in* Miller, K.G., Sugarman, P. J., Browning, J.V., et al., Proc. ODP, Init. Repts., 174AX (Suppl.), 1-84 [Online]. Available at: www.odp.tamu.edu/publications/174AXSIR/VOLUME/CHAPTERS/174AXS_3.PDF.

North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin, vol. 67, no. 5, p. 841-875.

Owens, J. P. and Denny, C. S., 1979, Upper Cenozoic deposits of the central Delmarva Peninsula, Maryland and Delaware: U.S. Geological Survey Professional Paper 1067-A, 28 p.

Ramsey, K. W., 2001, Geologic map of the Ellendale and Milton quadrangles, Delaware: Delaware Geological Survey Geologic Map Series No. 11, scale 1:24,000.

___ 2003, Geologic map of the Lewes and Cape Henlopen quadrangles, Delaware: Delaware Geological Survey Geologic Map Series No. 12, scale 1:24,000.

Ramsey, K. W., and Schenck, W. S., 1990, Geologic map of southern Delaware: Delaware Geological Survey Open File Report No. 32, 1:24,000.

Rasmussen, W. C., and Slaughter, T. H., 1955, The water resources of Somerset, Wicomico, and Worcester counties: Maryland Department of Geology, Mines, and Water Resources Bulletin 16, 533 p.

Rasmussen, W. C., Wilkens, R. A., Beall, R. M., and others,1960, Water resources of Sussex County, Delaware: Delaware Geological Survey Bulletin No. 8, 228 p.

Sundstrom, R. W., and Pickett, T. E., 1969, The availability of ground water in eastern Sussex County, Delaware: University of Delaware, Water Resources Center, 136 p.

___Sundstrom, R. W., and Pickett, T. E., 1970, The availability of ground water in western Sussex County, Delaware: University of Delaware, Water Resources Center, 118 p.

Talley, J. H., 1987, Geohydrology of the Southern Coastal Area, Delaware: Delaware Geological Survey Hydrologic Map Series No. 7, Sheet 1, Basic Geohydrologic Data, scale 1:24,000.

U. S. Geological Survey, 1992, Bethany Beach 7.5-minute topographic map, scale 1:24,000.

U. S. Geological Survey, National Geologic Map database (GEOLEX), http://ngmdb.usgs.gov/Geolex/

Delaware Geological Survey
University of Delaware
Newark, Delaware 19716