Hydrostratigraphy of the New Jersey Coastal Plain: Sequences and facies predict continuity of aquifers and confining units

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ABSTRACT: The regional extent and connectivity of Cretaceous to Miocene aquifer sands in the New Jersey Coastal Plain are evaluated using detailed facies analysis within a sequence stratigraphic framework. We correlate sequences from continuous coreholes using well logs to trace strike and dip sections throughout this region, allowing us to predict the continuity of confining units and aquifer sands. Marine sequences follow a predictable shallowing upward pattern: fine-grained shelf and prodelta sediments grade upward into delta front and shallow-marine sands, corresponding to confining unit-aquifer couplets. Aquifer sands deposited in marine shelf environments tend to be continuous on the 10+ km (6.2 mi) scale and are traceable for >60 km (37.3 mi) along strike and >25 km (15.5 mi) along dip. Confining units for these marine sequences are typically shelf or prodelta silty clays that are even more laterally continuous than their associated aquifer sands. Marginal marine to non-marine sequences are more difficult to predict due to a lack of continuous marine marker beds, difficulty in interpreting paleoenvironments of thick sand beds, and lack of fossil material except pollen for biostratigraphy. Marginal to non-marine sequences are generally less continuous, though some show surprising lateral continuity along strike (>60 km [37.3 mi]), reflecting the widespread extent of delta front environments. We conclude that sequence stratigraphy provides a predictive framework for aquifers and confining units, but that regional and local differences in sediment supply and tectonics affect the development of the hydrostratigraphic framework.

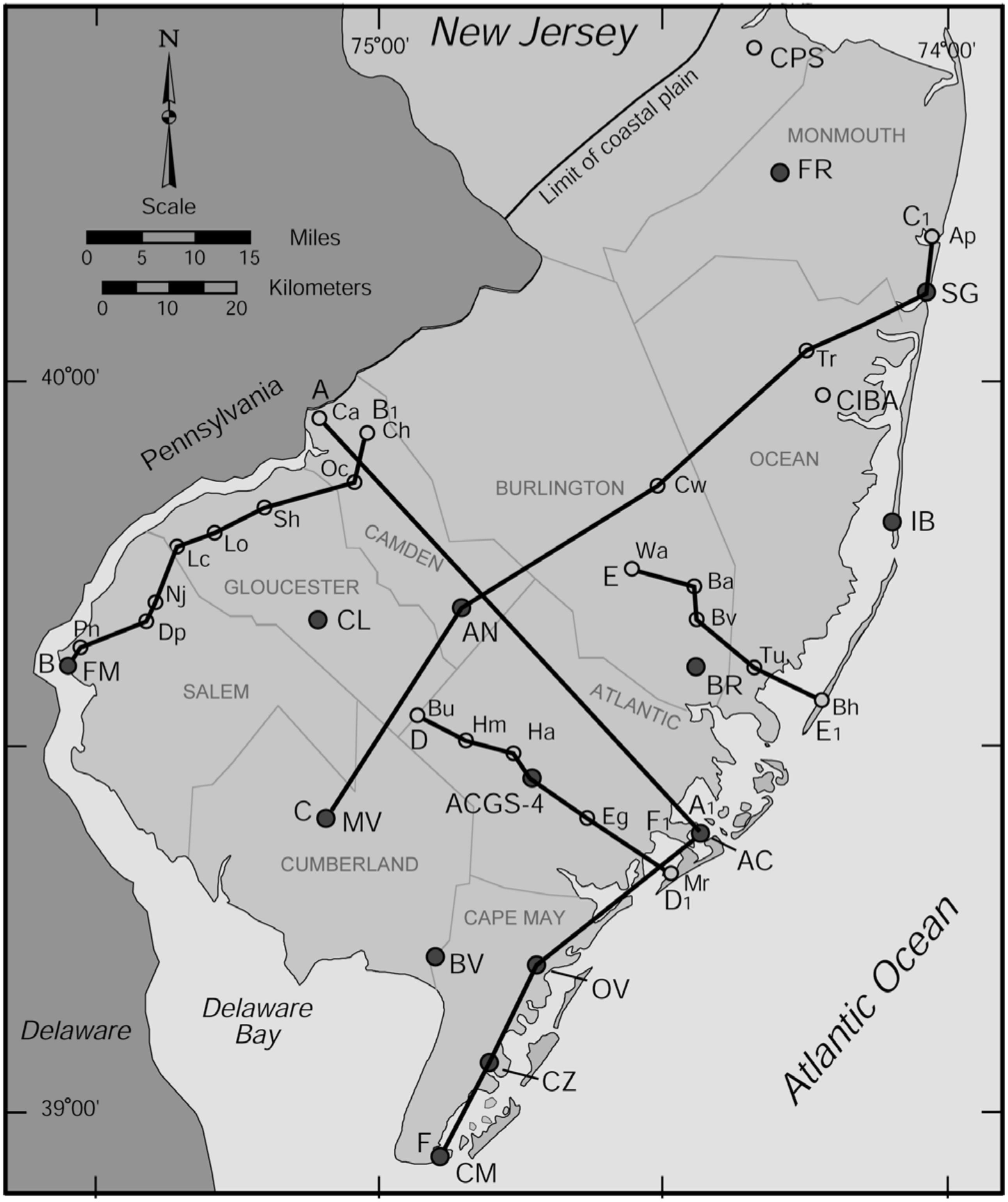
INTRODUCTION

The Atlantic Coastal Plain (Long Island through Florida) consists predominantly of Cretaceous-Holocene sands, silts, clays and occasional gravels that contain an essential source of groundwater for millions of people. The water-bearing unconsolidated sands (aquifers) are heavily utilized due to population growth, yet are easily contaminated in the shallow subsurface. Many coastal plain confined aquifers communicate over large distances (km-10's km scale), especially those deposited in marine environments, though some are locally restricted (e.g., non-marine sands). Confining units may be regionally continuous or very discontinuous depending on the environment of deposition. Any attempt to predict the distribution of aquifers and confining units in the coastal plain must consider the facies and environments of deposition.

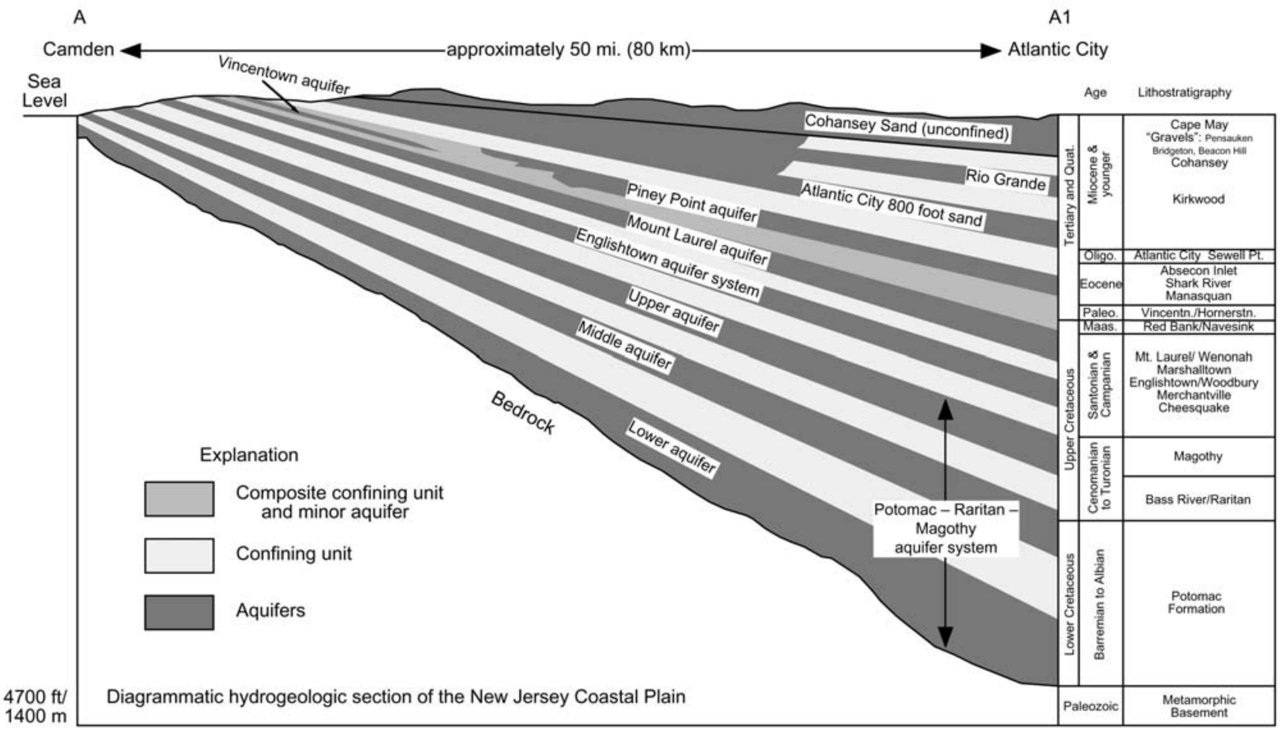
Previous hydrostratigraphic investigations in the New Jersey Coastal Plain (text-figs. 1, 2) have delineated aquifers and confining units primarily from outcrops and subsurface geophysical logs. Zapecza (1989) developed a hydrogeologic framework using downhole geophysical logs to map major aquifers and confining units (text-fig. 2). Geophysical logs must be groundtruthed by comparison with geological samples, especially core samples. Lithologic units are initially identified and named in updip, thin, deeply-weathered outcrops; these formational names are then applied downdip to lithologic and hydrologic units by logs. However, hydrogeologic units named after thin, weathered outcrop sections often lead to mistaken and forced correlations in thicker, more fossiliferous downdip sections. Equivalency of units based on geophysical characteristics assumes that correlations made in wells deep in the basin are equivalents of units named in outcrop areas (text-fig. 2), often without any supporting geologic criteria. Problems can arise with these correlations; for example, downdip units may have no outcropping equivalent. Downdip and along strike facies changes can also create erroneous correlations and flawed hydrogeologic frameworks.

Sequences are unconformity-bounded units that comprise the building blocks of the stratigraphic record and provide a means of predicting facies changes (Mitchum et al. 1977; Vail et al. 1977). Sequence stratigraphy has long provided predictions about petroleum reservoirs and impermeable caps (Vail et al. 1977) and has potential for similar applications in groundwater predictions. Since the advent of its use for basin-scale petroleum exploration in the 1970s, sequence stratigraphy has evolved into an important tool for finer-scale stratigraphic problems in industry such as reservoir geology. Hydrogeologic investigations face many of the same challenges as petroleum geology, chief among them delineating the fine-scale stratigraphy of aquifers (analogous to reservoirs) and confining units (analogous to traps).

Sequence stratigraphic studies of the New Jersey Coastal Plain have provided new insights into fundamental controls on the stratigraphic record, demonstrating that sequence boundaries are causally related to sea-level lowerings (Miller et al. 1998, 2004). Facies changes within these sequences generally follow predictable patterns. Tectonics and sediment supply affect the distribution of sequences and the type of facies found within individual sections (Browning et al., in press), though the repeti-



TEXT-FIGURE 1
New Jersey location map showing counties, United States Geological Survey coreholes, Leg 150X and 174AX coreholes, and various water wells used to construct reference sections and cross sections shown on text-figs. 3, 4, 7, 8, 10, and 11. County boundaries (Salem, Cumberland, etc.) are shown as thin gray lines. Coreholes (closed circles): AC - 150X Atlantic City; ACGS 4 - Atlantic County Girl Scout Camp #4; AN - 174AX Ancora; BR - 174AX Bass River; BV - Belleplain; CIBA - Ciba-Geigy; CL - Clayton; CM - 150X Cape May; CPS - CPS/Madison Industries; CZ - 174AX Cape May Zoo; FM - 174AX Fort Mott; FR - Freehold; IB - 150X Island Beach; MV - 174AX Millville; OV - 174AX Ocean View; SG - 174AX Sea Girt. Geophysical logs (open circles): Ap - Asbury Park; Ba - Oswego Lake; Bh - Beach Haven; Bu - Buena; Bv- Bass River Township; Ca - Camden; Ch - Cherry Hill; Cw - Chatsworth; Dp - Dupont; Eg - Egg Harbor; Ha - Hamilton; Hm - Hamilton 2; Lc - Landtect Corp; Lo - Lopes; Mr - Margate; Nj - NJ Turnpike; Oc - Owens Corning; Pn - Pennsville; Sh - Shell; Tr - Toms River; Tu - Tuckerton; Wa - Washington Township.



TEXT-FIGURE 2
Generalized hydrostratigraphic dip section (modified after Martin 1998) and corresponding lithostratigraphic units from Camden to Atlantic City.

tive and predictable facies successions that are found regionally can only be explained by a repetitive process such as sea-level change (Miller et al. 1998, 2004). Sugarman and Miller (1997) used available Miocene continuous coreholes to develop a sequence stratigraphy and improved hydrogeologic framework for New Jersey Coastal Plain Miocene strata.

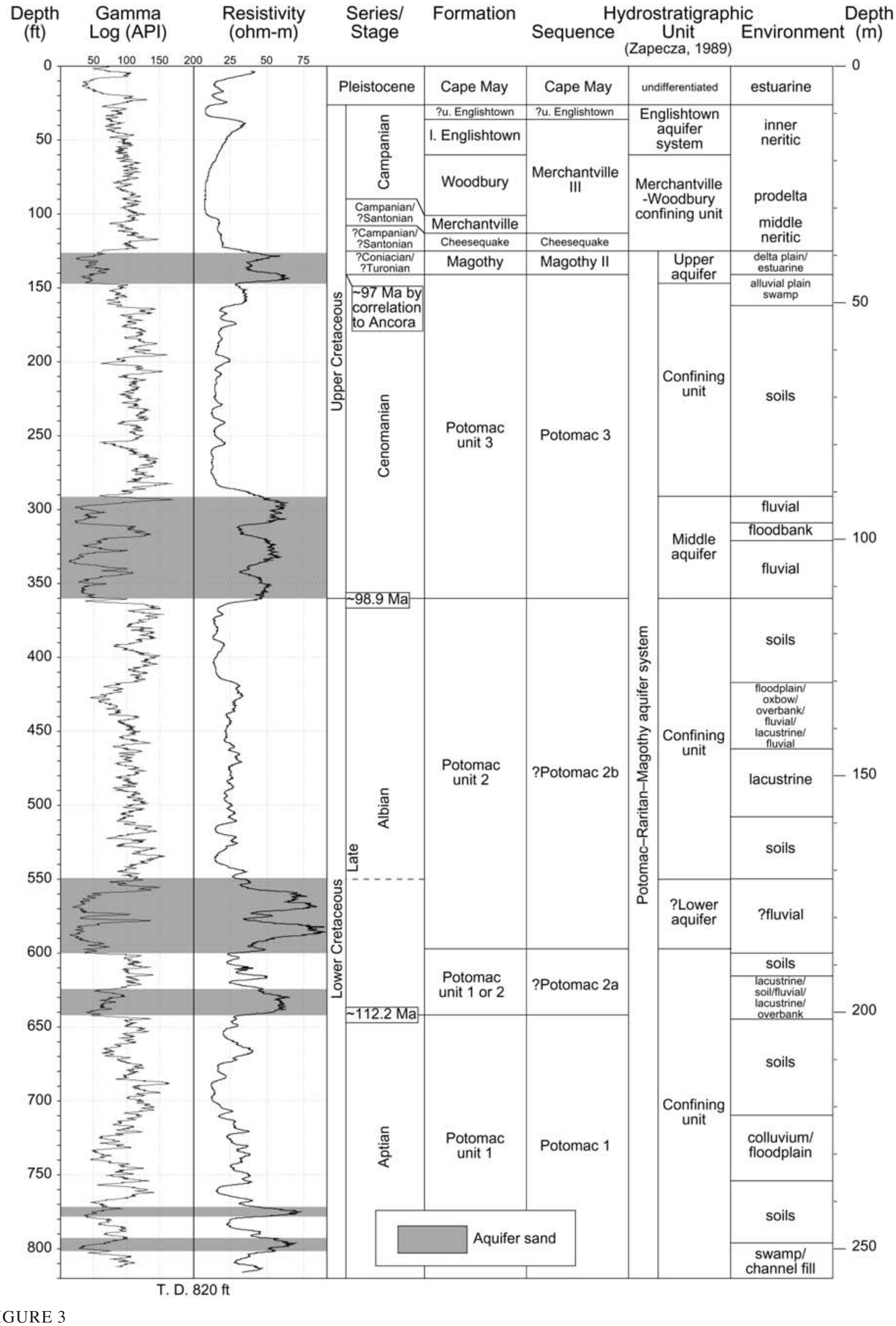
Recent drilling in New Jersey has provided continuous core records (text-fig. 1) that allow us to develop an integrated sequence and hydrogeologic framework for the coastal plain from the oldest sediments (mid-Cretaceous Potomac Formation) through the Miocene. Continuous coring and logging provide a registry of sediments and logs that allows regional correlation to sections with only well logs or cuttings. Continuous coring was very rare in the coastal plain until 1984, when the USGS began a campaign of shallow (305m [1000 ft] or less) boreholes with the ACGS-4 (Mays Landing), Freehold, Clayton, and Belleplain coreholes (Owens et al. 1998). Subsequently, drilling onshore by ODP Legs 150X (Island Beach, Atlantic City, and Cape May coreholes) and 174AX (Bass River, Ancora, Ocean View, Bethany Beach (DE), Fort Mott, Millville, Sea Girt, and Cape May Zoo) has continuously cored and geophysically logged over 4267 m (14,000 ft) of sediment from deeper (365 to 596 m [1200 to 1956 ft] total depth) downdip locations for stratigraphic and hydrogeologic investigations (text-fig. 1) (Miller et al. 1998, 2002).

We combine results from continuous coreholes with wireline logs from intervening water wells (text-fig. 1) to develop a sequence stratigraphic framework, place hydrogeologic units into this framework, and reinterpret the distribution and connectivity of aquifers using sequence stratigraphic concepts from the base of the coastal plain (the mid-Cretaceous Potomac Formation) through the Miocene. We restrict this study to well-characterized aquifers for which new data are available, focusing on sequences and aquifers within the Potomac (Berriasian-lowermost Cenomanian), Magothy (upper Turonian-lower Santonian), Englishtown (mid-Campanian), Mount Laurel (upper Campanian), and Kirkwood (lower-middle Miocene) Formations.

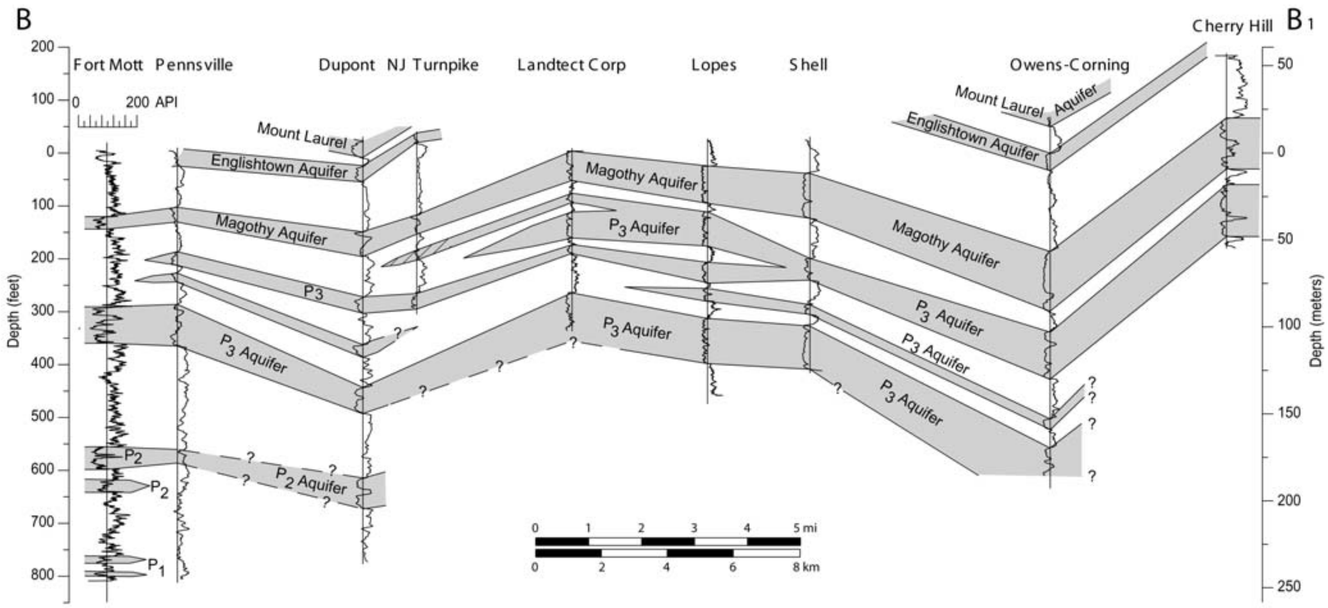
METHODS

Continuous coreholes were drilled in specific areas of the New Jersey Coastal Plain (text-fig. 1) to evaluate and improve the hydrogeologic framework of Zapecza (1989), including the delineation of aquifers and confining units. Geophysical logs were obtained from each corehole. We integrated published (Owens et al. 1988, 1998; Sugarman et al. 1993, 2004, 2005; Miller et al. 1994, 1998; 2005; Miller and Snyder 1997) lithostratigraphic, biostratigraphic, Sr-isotopic, and well log data to develop a subsurface sequence stratigraphic framework to guide mapping of the geometry of aquifers and confining units. An essential element of sequence stratigraphic mapping was the identification of unconformities using reworked and bioturbated intervals, phosphatic buildups and associated high gamma-ray spikes, major changes in depositional environments, biostratigraphic evidence, and Sr-isotope age estimates.

Sequences bracketed by unconformities were subdivided into facies. The New Jersey Coastal Plain contains facies deposited in a variety of marine, marginal marine, and nonmarine settings. The marine environments include clastic shelf and prodelta deposits. Marginal marine deposits include delta front, wave-dominated shoreline, and estuarine sediments, while the nonmarine settings include upper and lower delta plain/fluvial deposits. We developed facies models based on studies of modern depositional environments (e.g. deltas) and their various



TEXT-FIGURE 3
Correlation of formations, sequences, hydrostratigraphic units, and depositional environments at the Fort Mott State Park 174 AX corehole. Aquifer sands are highlighted in gray. Modified after Sugarman et al. (2005).



TEXT-FIGURE 4
Oblique strike hydrostratigraphic cross-section for the major aquifers in the southwestern New Jersey Coastal Plain from Fort Mott in the southwest to Cherry Hill in the northeast based on gamma logs. Well locations are shown on text-figure 1.

subenvironments (e.g. prodelta, delta front, delta plain). Typically, a facies has a distinct lithologic, physical and biological component allowing it to be distinguished from adjacent genetically related facies. In our coreholes, facies are stacked in a vertical succession, and changes in subenvironments are mapped by their corresponding changes in lithology, bedding, fossils, and bioturbation. For example, in our deltaic model (initially developed by Sugarman et al. (1993), Sugarman and Miller (1997), and Miller et al. (2005) after modification of Allen's (1970) modern study) open shelf marine facies are overlain by prodelta, delta-front, and lower delta-plain facies (see text-fig. 4 in Miller et al. (2005) for Cretaceous example and text-fig. 2 in Browning et al. (in press) for a Miocene example). These facies successions can be further subdivided into smaller scale subenvironments (e.g., Owens and Gohn 1985) such as we do here with the Magothy Formation and sequences (see below). We use a wave-dominated shoreline facies model developed by Browning et al. (in press; their text-fig. 3) from modern studies by Harms et al. (1975, 1982) and McCubbin (1982). In this facies model, a typical facies succession involves the upward shallowing from offshore to lower shoreface and finally foreshore facies. Finally, we present here several fluvial models to help explain the origin of the Potomac Formation and sequences. Sugarman et al. (2005) and this study compare similarities in the Potomac facies found at the Fort Mott corehole with anastomosing river systems as outlined by Smith and Smith (1980) and Makaske (2001), whereas facies from the Potomac and Magothy Formations and sequences also display aspects of meandering and delta front environments as summarized by Allen (1970).

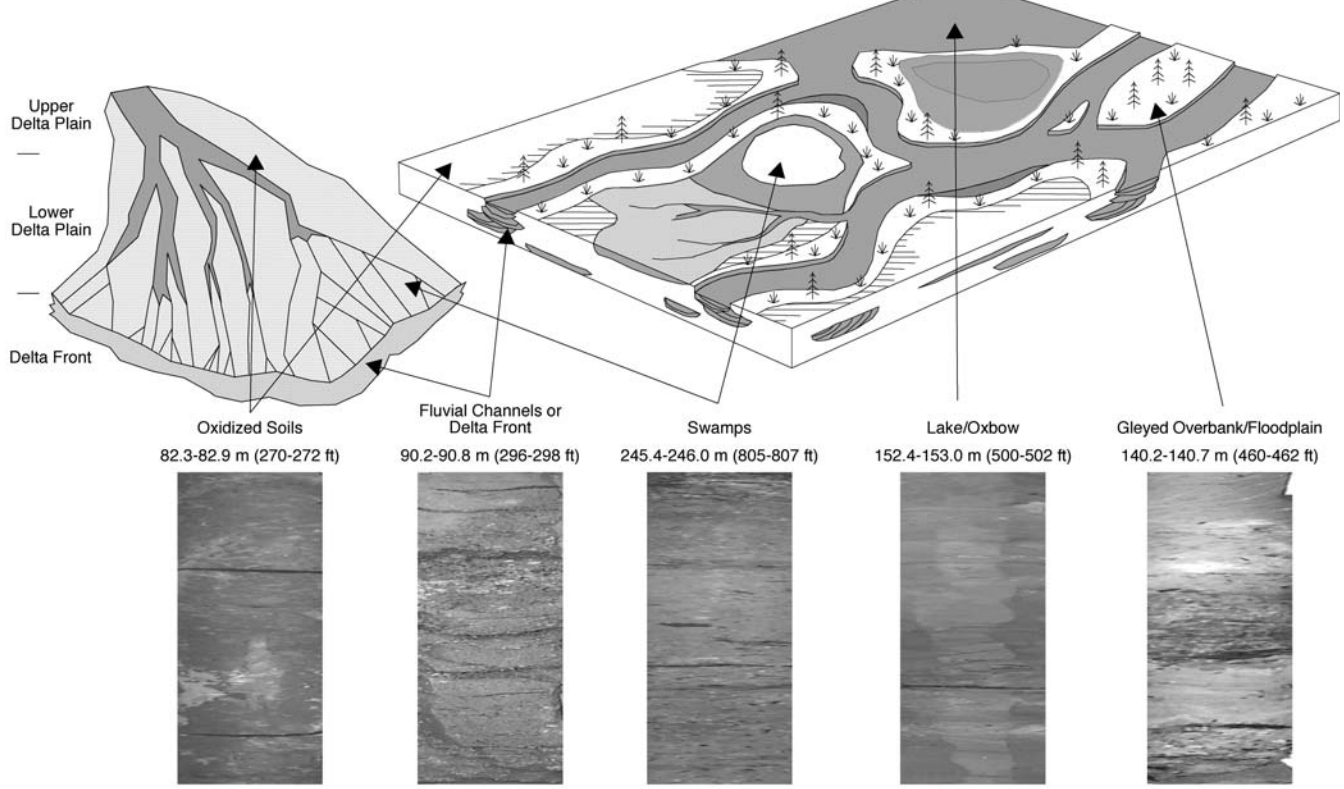
Sequences can be divided into systems tracts of Posamentier et al. (1988) based on facies and intrasequence surfaces. Lowstand deposits are rare in the coastal plain, with preservation of Late Cretaceous Lowstand Systems Tracts only in a few Cretaceous sequences (Miller et al. 2005). Transgressive ravinement surfaces of the lower Transgressive Systems Tract (TST) are rarely preserved (for an exception see fig. 3a in Miller et al. 2005). TSTs are generally thin and lithofacies show deeper water paleoenvironments upsection. TSTs of Cretaceous to Paleogene sequences are generally comprised of *in situ* glauconite sands or glauconitic clays deposited in middle neritic environments; Miocene TSTs are generally comprised of deepening upward shelly quartz sands also deposited in middle neritic environments (Sugarman et al. 1993; Miller et al. 1997). Maximum flooding surfaces cap the TSTs and separate them from the regressive Highstand Systems Tracts (HST). The lower part of the HSTs is often prodelta or shelfal silty clays and the upper HSTs are thick, sandy delta front or inner shelf deposits.

Sequences and systems tracts were then used to interpret regionally significant aquifers and confining units. We prepared strike and dip sections (text-fig. 1) for major aquifers using continuous coreholes and intervening well logs. We primarily used gamma-ray logs for correlation, though electric logs were used when possible (e.g., text-fig. 3) to identify sands and used exclusively when gamma log quality was inadequate.

The depositional setting of major aquifer systems must be considered when evaluating the geometry of aquifers and confining units, the connection between various permeable zones, and the regional extent of aquifer sands and confining beds. The depositional styles of the major aquifers: Potomac, Magothy, Englishtown, Mount Laurel, and Kirkwood, are discussed below to illustrate the effects that the different depositional styles have on regional hydrostratigraphic frameworks.

POTOMAC FORMATION AND AQUIFERS: FLUVIAL-DELTAIC INFLUENCES

The Potomac Formation crops out along the Delaware River Valley, and includes the Lower and Middle Poto-



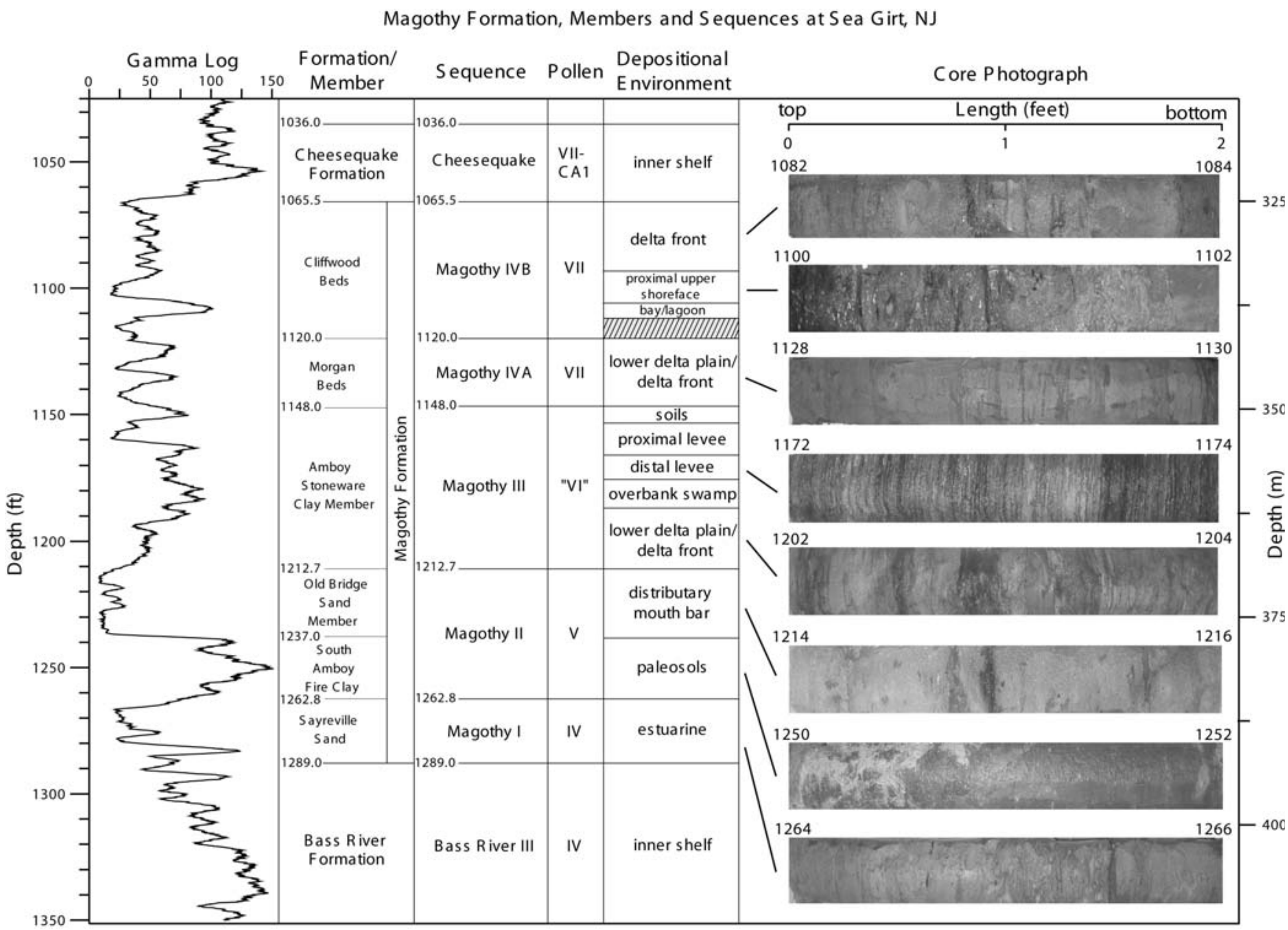
TEXT-FIGURE 5
Facies model for an anastomosing river and for an abandoned delta lobe (after Fisher et al. 1969) showing examples from the Fort Mott State Park corehole.

mac-Raritan-Magothy (PRM) aquifers (text-fig. 3) of Zapecza (1989), part of the most productive aquifer system in the state. It is composed of Lower to Upper Cretaceous massive to finely laminated clay (frequently mottled) interstratified with fine to very coarse-grained sand with occasional gravel. Potomac sediments were deposited in predominantly fluvial or fluvial-deltaic settings, with occasional marginal marine (delta front, prodelta, and limited chenier or strandplain) facies. Glaser (1969) interpreted depositional environments of the Potomac Formation as predominantly fluvial (meandering and braided). Owens et al. (1970) applied a slightly different interpretation to the facies of the Potomac Formation as being deposited in a delta plain and delta front. Their facies model for the Potomac Formation interpreted sand facies as fluvial-dominated delta front deposits. Recent drilling at Fort Mott, NJ (Sugarman et al. 2005, Figs. 1, 3) has prompted us to revisit depositional models for the Potomac Formation.

Potomac Formation sediments in the Fort Mott borehole are predominantly fine-grained (clays, silty clays, and clayey silts), with a few critical sand bodies (text-figs. 3, 4). The finer-grained units are heavily overprinted by soil forming processes, with light blue and gray gleyed soils indicating soil formation in reduced conditions and dark red (lateritic?) soils indicating oxidized conditions deposited as heavily vegetated overbank deposits (Sugarman et al. 2005).

We interpret the dominant depositional environment of the Potomac Formation as an anastomosed fluvial system (text-fig. 5) (McLaughlin and Benson 2001; Sugarman et al. 2005). Anastomosing rivers combine features of meandering and braided systems with multiple, meandering channels (e.g., the modern Amazon River). Anastomosed systems are streams that are divided into multiple coexistent channels that have stable islands or bars separating the channels (Smith and Smith 1980). Bar stability is provided by either vegetation, fine-grained sediments, or by both working together (Makaske 2001). Anastomosed systems differ from braided systems in that the channel and bar stability in the anastomosed system prevents the river from reworking sediments and organic-rich sediments. As a result, fine floodplain deposits and organic-rich sediments or coals dominate anastomosed systems. Channel sands in the anastomosed system are generally more confined and tend to aggrade (Makaske 2001). Anastomosing rivers are believed to form by avulsion splitting the primary flow into two or more channels. Avulsion is facilitated by a low-gradient floodplain and by rapidly elevating baselevel control downstream (Smith and Smith 1980).

We interpret the depositional environment of much of the Potomac Formation as an anastomosed system based on several observations. The predominance of fine, overbank deposits are more typical of anastomosed versus braided or meandering systems. Lakes are a common subenvironment of such systems and we interpret numerous organic-rich fine-grained sections at Fort Mott as fluvial-lacustrine deposits. These lacustrine sediments include not only oxbow lakes, but also more regionally pervasive lakes with a distinct cyclicity. Though lakes are important, the dominant subenvironment appears to be either overbank/levee soils or subaqueous swamps. Variations in color and



TEXT-FIGURE 6
Subdivisions of the Magothy Formation and sequences with depositional environments and pollen zones showing examples from the Sea Girt 174AX core photographs.

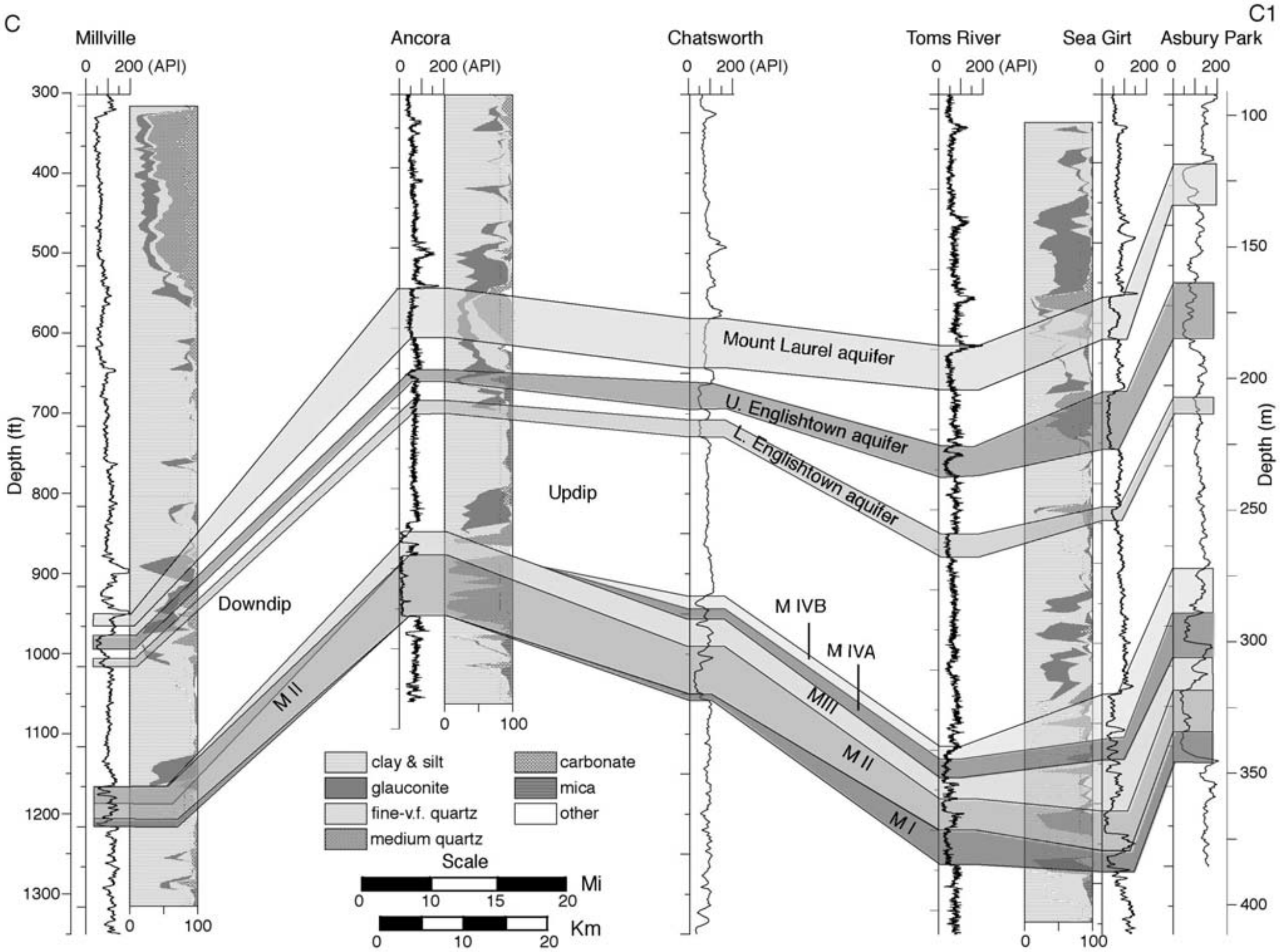
downhole logs occur on the 60-90 cm (2-3 ft) and 3 m (10 ft) scales; these cycles appear to reflect differences in evaporation and precipitation with red, oxidized (high gamma log values) alternating with gray or gleyed reduced sediments (low gamma log values). This cyclicity not only reflects regional climate changes, its regularity implies a global imprint on climate and precipitation.

Anastomosed systems develop in regions experiencing rapid sea-level rise such as the Holocene transgression (Makaske 2001). The Potomac Formation was deposited during the first stages of thermo-flexural subsidence in the coastal plain when accommodation rates were highest (Watts and Steckler 1979). This is consistent with our interpretation of the Potomac as an anastomosing river.

We follow the classification of major environments and sedimentary facies for anastomosing river systems described by Smith and Smith (1980; text-fig. 5). Two major environments are found in an anastomosed system. Fined-grained overbank deposits comprise the majority of the sediments (text-fig. 5). Subordinate channel facies consist of gravel and coarse sand (text-fig. 5). Levees flanking the rivers consist of sandy silt and silty sand containing roots. Low areas between levees have lakes and peat bogs or back swamps; they are differentiated based upon the frequency with which they receive water and their connection to the main channels. Lakes are intermittently supplied with fine sediment including laminated clay and silty clay with sparse organic matter. Peat bogs and back swamps have no direct connection to the main channels and may receive clastic sediments only during times of flood. Sediments are organic-rich silty clay and clayey silt. Finally, crevasse splays are recognized as thin layers of sand and fine gravel rarely more than 40 cm (15.8 in) thick (Smith and Smith 1980).

An outstanding question is the extent to which the anastomosing environment includes the upper delta plain environments. Many modern workers now consider the channels in a deltaic environment to be fundamentally similar to anastomosing channels in a continental setting (see Makaske 2001 for a discussion). Thus, the contrast with the deltaic model for the Potomac Formation outlined by Owens et al. (1970) is minor except for the interpretation of the thick sand bodies at the base of Potomac Formation units 3 and 2.

The anastomosing model (text-fig. 5) may not adequately explain the thick sand bodies at the base of the Potomac Formation units 3 and 2 at Fort Mott (text-fig. 4; 88.6-110.8m [290.7-363.5 ft] and 169.2-182.8m [555.1-599.7 ft], respectively). These sand bodies appear to be laterally continuous (text-fig. 4) and



TEXT-FIGURE 7
Well log correlation of the Magothy and upper Englishtown sequences, and the lower Englishtown and Mount Laurel aquifers . This strike section (see text-figure 1 for corehole and gamma log locations) covers almost the entire New Jersey Coastal Plain.

may extend from New Jersey into Delaware. They can be traced on gamma logs within New Jersey a distance of 40km (24 miles; text-fig. 4). Such widespread sand sheets are difficult to explain using the anastomosing stream model. The thick, widespread nature of the sand body at the base of the Potomac unit 3 (text-fig. 3, the upper P_3 aquifer on text-fig. 4) has the geometry of a delta front shoreline sand (text-fig. 5), although no direct marine evidence (e.g., marine fossils) has been uncovered within them. If this interpretation of a delta front environment is correct, then at least for Potomac unit 3, the sediments may represent a transgressive regressive cycle, with delta-front sands (Fig. 5) being prograded over by an anastomosed river system or delta-plain deposits, including lower delta plain interdistributary lakes, marshes and swamps, and upper delta plain deeply weathered soils.

The alternate interpretation to delta front is that these sand bodies are sand ridges contained within the lower delta chenier plain similar to the modern Orinoco (Wells and Coleman 1981). However, the lateral extent of the Potomac 3 sands (text-fig. 4) is more consistent with a delta front origin. We have less data to trace the Potomac 2 sands; they can be shown to extend 6 km (3.7 mi) along an oblique dip profile and 8km (5mi) along an oblique strike profile (text-fig. 4), and could be interpreted as either delta front or alluvial plain deposits.

THE MAGOTHY FORMATION AND AQUIFERS: DELTAIC INFLUENCES

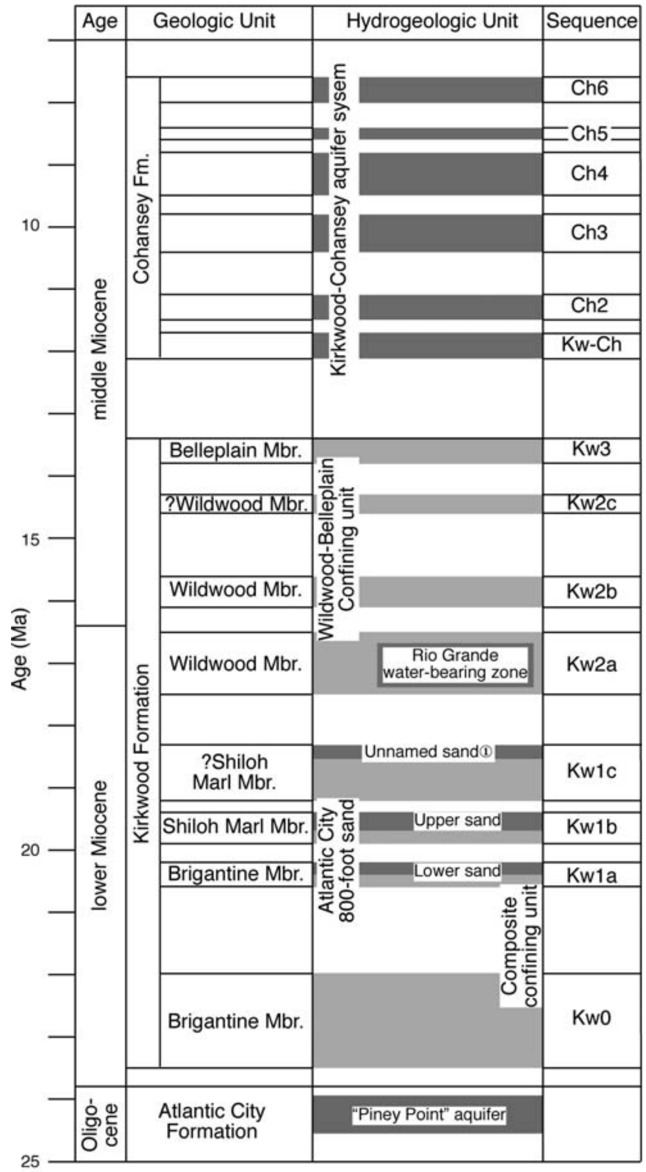
The Upper Cretaceous (upper Turonian to lower Santonian) Magothy Formation crops out along the Raritan River and sporadically along the Cretaceous outcrop belt extending through New Jersey, with the type section in Maryland (Darton 1893). It comprises the Upper PRM aquifer of Zapecza (1989)(text-figs. 2, 3), part of the most productive aquifer system in the state. It is composed of relatively thick fine-coarse grained quartz sands intercalated with thin bedded, carbonaceous clays and silts. The Magothy Formation was deposited in fluvial to marginal marine environments interpreted as lower delta plain to delta front (Owens et al. 1998). Large sheet sands characterize the aquifers and these are interpreted as being deposited in delta-front, marginal marine environments (Owens et al. 1998). To the southwest towards Delaware, the Magothy dramatically thins (e.g., Fort Mott, text-fig. 4), with the sediments preserved primarily in incised valleys (McLaughlin and Benson 2005).

The Magothy Formation is best represented in the northern New Jersey coastal plain near the Raritan Bay outcrops, though it thickens out of New Jersey toward Long Island (Perry et al. 1975). Continuous coring at Sea Girt, NJ (text-figs. 1, 6) provides a thick (70.9m, 232.5ft) Magothy Formation that represents at least 4 sequences (I through IV), with a possible subdivision into sequences IVA and IVB (Kulpecz 2005). Sequence(s) IVA/IVB pinch out south of Chatsworth, NJ (text-fig. 7) and are not represented at other continuous coreholes. We describe the sequences and facies of the Magothy Formation using the Sea Girt corehole (text-fig. 6) and extend these correlations with well logs to Ancora and Millville (text-fig. 7).

The Magothy I sequence fines upsection from a lignitic, pyritic gravelly coarse sand, to a granule-rich clayey sand, to a muddy coarse to medium sand. These sands and clays are bioturbated and cross-bedded with coarse material and have contrasts in grain size from granules to clay, all of which suggest an estuarine environment. The Magothy I sequence appears to correlate to the coarse Sayreville Sand Member in outcrop which comprises a very minor aquifer. The Magothy I is assigned to pollen Zone IV and is found from the Bass River corehole and to the north (text-fig. 7)

The Magothy II sequence consists of a local confining clay and a major aquifer. At Sea Girt, a distinct sequence boundary associated with a major gamma ray spike at 384.7m (1262.1ft) separates the Magothy I sequence from mottled clays and paleosols of the overlying Magothy II sequence. These clays represent paleosols deposited in upper delta plain environments. The upper part of the Magothy II sequence at Sea Girt consists of a granuliferous medium to very coarse sand with organic-rich laminae that occur as several fining upward packages ~30-90 cm (1-3ft) thick. Though this section could be a fluvial channel deposit, the wide lateral extent argues for it being a distributary mouth bar in the delta front (text-fig. 7). The lower Magothy II sequence appears to correlate to the South Amboy Fire Clay Member in outcrop, which is locally confining, but pinches out to the south (text-fig. 7). The upper part of the Magothy II sequence appears to correlate to the Old Bridge Sand Member, which comprises a major aquifer. The Magothy II is assigned to pollen Zone V and is found throughout the coastal plain, although it is apparently cut out at the Bass River corehole.

The Magothy III sequence is largely fine-grained and comprises a confining unit. At Sea Girt, the Magothy III section consists of a complex series of deltaic subenvironments from swamp, overbank, levee, and soil (text-fig. 6). The section generally fines upsection above the basal sequence boundary (text-fig. 6) from sands with organic-rich interlaminated clays to organic-rich clays with interlaminated sands. The lack of clear bioturbation, thin laminations, common rip-up clasts, common organic matter indicative of swamps, and the lack of coarsening upward sections argues against a subaqueous delta front interpretation and in favor of a lower delta plain overbank deposit. This section is overlain by: 1) a sandy lignite with pyrite concretions interpreted as a near-levee swamp; 2) an interlaminated dark gray organic-rich, slightly silty clay, and thin fine sand interpreted as a distal levee deposit; 3) lignitic, cross bedded, micaceous and fine-grained sand and laminated, silty, sandy clays interpreted as a proximal levee; and 4) tan clays with micaceous, very fine sand beds and laminae, with evidence of rooting and sphaerosiderite, deposited in an interfluvial overbank subenvironment.



TEXT-FIGURE 8
Correlation chart of Miocene formations, hydrogeologic units, and sequences.

The Magothy III apparently correlates with the Amboy Stoneware Clay Member in outcrop. It is assigned to pollen Zone VI (G. Brenner, written communication, 2004), a transitional zone between V (Turonian) and VII (Santonian). It is found throughout the coastal plain except possibly in the far southern regions around Millville.

The Magothy IV is well expressed in outcrops in Monmouth County, but is restricted in distribution to the northern part of the coastal plain. The lower Magothy IVA consists of interbedded, laminated sands and clays in outcrops (the Morgan Beds) that were deposited in lagoonal/intertidal environments. The upper Cliffwood Beds (Magothy IV) in outcrop consists of cross-bedded sand and woody clays deposited on a shallow shelf (it contains marine fossils) influenced by a delta.

The Magothy IVA/Morgan Beds may be a separate sequence based on interpretations of the Sea Girt corehole (text-fig. 6;

Kulpecz 2005). At Sea Girt, the sequence is a generally cross-bedded sand with intermittent mud beds that was deposited in a delta front environment. This facies succession upsection is: 1) very lignitic, micaceous medium-fine sand deposited in tidal channel/bay subenvironments; 2) an organic-rich, micaceous, sandy silty clay deposited in a marsh subenvironment; 3) trough cross bedded, micaceous, lignitic, silty, fine-to-very fine sand with abundant mud laminae/drapes deposited in tidal channel subenvironments.

Differentiation of lower delta plain with marine influence versus delta front submarine is a difficult problem in facies interpretation that is illustrated by the Magothy IVB/Cliffwood Beds at Sea Girt. This sequence shallows upsection from lagoonal and shoreface to delta front environments. The possible sequence boundary separating Magothy IVA from IVB is in a coring gap overlain by a faintly laminated, organic-rich, slightly micaceous, silty clay with thin sand laminae, deposited in bay/lagoon environments (text-fig. 6). The section transgresses to a proximal upper shoreface environment consisting of burrowed, granuliferous, lignitic medium well-sorted sands and then regresses to delta front environments of heavily burrowed, micaceous, fine sand and interbedded organic-rich sands. The thin beds argue against barrier/tidal delta/lagoonal environments, heavy bioturbation indicates marine conditions, and common mica and abundant lignite indicate a fluvial influence.

The Magothy IV is assigned to pollen Zone VII (Santonian-lower Campanian). It is overlain by the Cheesequake Formation that contains mid-Santonian Zone CC15 at Bass River (Miller et al. 2004), constraining the age of the Magothy IV to early Santonian.

The Magothy sequences exhibit greater continuity than expected for primarily non-marine units, but less than that observed in marine sequences. Clays in non-marine unites can be discontinuous on the outcrop scale (e.g., the Old Bridge Sand Member). These fluvial-deltaic deposits show surprising continuity along strike (text-fig. 7), reflecting the widespread influence of delta front environments. The Magothy II and III sequences are laterally continuous for more than 60 km (37.3 mi) along strike (text-fig. 7). The surprising continuity may also reflect the reworking of delta front sands in nearshore environments (Owens and Gohn 1985). The Magothy I sequence is more localized, though it can be traced about 20 km (12 mi) along strike. As noted, the Magothy IVA/IVB are restricted to the northern coastal plain (text-fig. 7), despite the fact that these are the most marine of the Magothy sequences. We attribute this to the progressive southward thinning of the Magothy Formation, reflecting a northern source and subsidence in the north associated with the Raritan Embayment (Owens and Gohn 1985; Kulpecz 2005).

ENGLISHTOWN AQUIFERS: DELTAIC-SHELF SEQUENCES

The Englishtown Formation was named for Campanian sands outcropping in New Jersey (Kummel 1907). The Englishtown Formation is divided informally into a lower micaceous, silty fine sand and an upper coarsening/shallowing upward succession with basal glauconite sands grading upward to medial silty clays and upper sands (text-fig. 7). The lower Englishtown comprises the upper HST of the Merchantville-Woodbury-lower Englishtown depositional sequence (Miller et al. 2004) and is a moderate aquifer (Nichols 1977). The thickness of the lower Englishtown aquifer is relatively constant across the area (text-fig. 7), with a slight thinning and fining to the south.

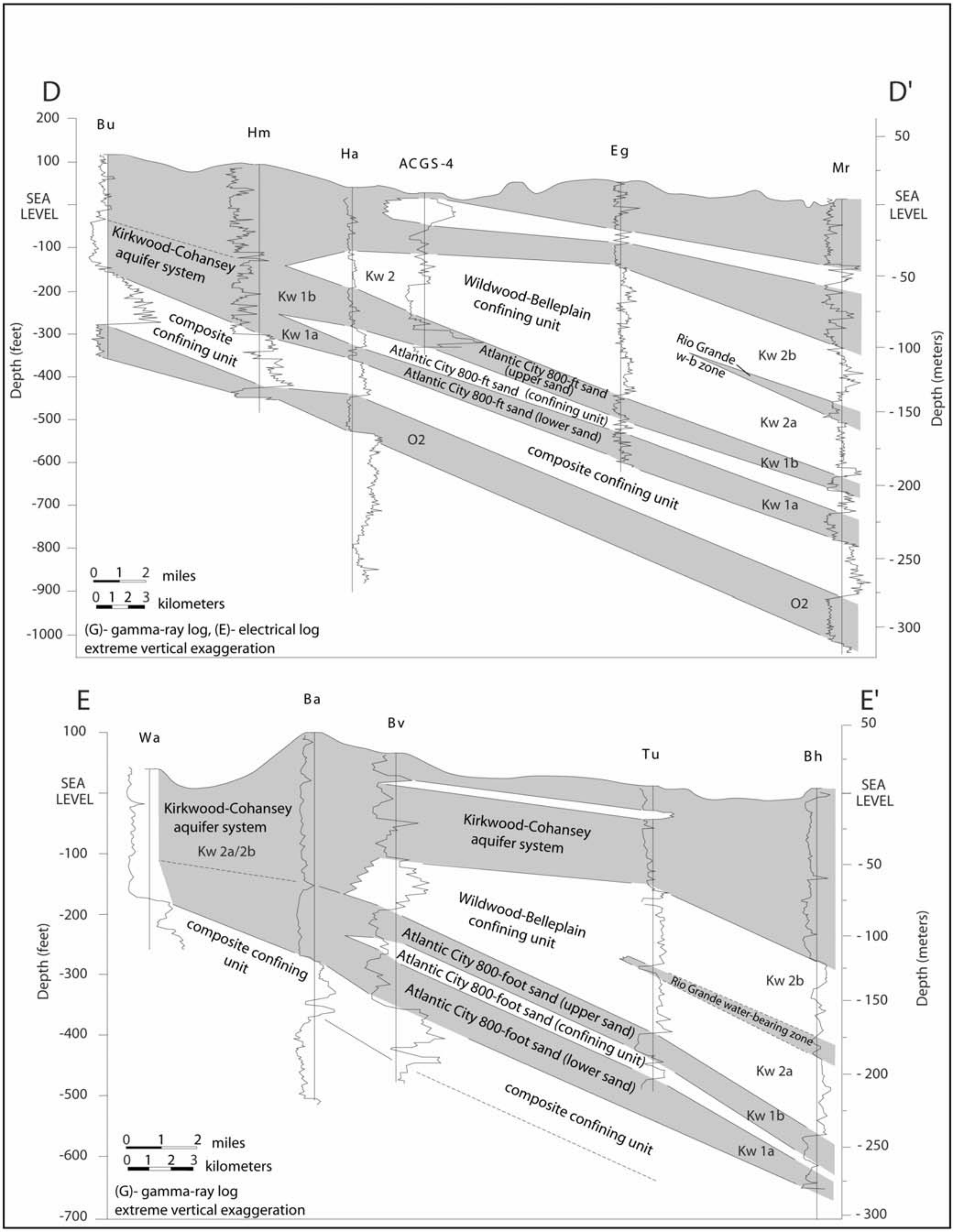
The upper Englishtown is a distinct sequence (Miller et al. 2004) and comprises an excellent aquifer in southeastern Monmouth and northeastern Ocean Counties (Nichols 1977). The expanded upper Englishtown sequence (45.8 m; 150.4 ft) was a major target of drilling at Sea Girt (text-fig. 1). Owens et al. (1998) first observed that the subsurface upper Englishtown sequence had a classic box-car log pattern in northern Ocean and southern Monmouth counties where the sequence is best developed. This log pattern reflects an upper aquifer sand and a lower confining unit both of the upper Englishtown sequence and a lower sand that is part of the lower Englishtown Formation. This is illustrated in the following upsection changes observed in the Sea Girt corehole (text-fig. 7): 1) above the basal sequence boundary, slightly glauconitic, silty, quartz sand was deposited in lower shoreface environments and represents a TST; 2) a medial shelly micaceous silty clay with occasional sand laminae was deposited in prodelta environments; and 3) an upper fine to medium-grained, micaceous sand was deposited in delta front environments.

The upper Englishtown sequence is thickest in the area of Sea Girt (Zapecza 1989; Kulpecz 2005) and thins south of Chatsworth, NJ (text-fig. 7), but can be traced throughout the coastal plain as a distinct unit (Kulpecz 2005). This thinning to the south (text-fig. 7) may partially reflect the influence of the South Jersey High as a structural feature; however, maps of the upper Englishtown shows a lobate feature of coarse deltaic sediments concentrated in northern Monmouth County (Kulpecz 2005). This suggests that the aquifer sands thicken dramatically to the north as a function of sediment supply from a source analogous to the modern Hudson River (Kulpecz 2005).

MOUNT LAUREL AQUIFER: MARINE SHELF SEQUENCES

The upper Campanian Mount Laurel Formation crops out in a broad belt from Monmouth County through Delaware and Maryland and forms a critical aquifer in southern Burlington, Camden, and Gloucester counties, all rapidly growing suburbs of Philadelphia. The Mount Laurel Formation is typically a fine to coarse-grained quartz sand that comprises the HST of the Marshalltown sequence (Sugarman et al. 1995; Miller et al. 2004). The Mount Laurel Formation was deposited on a marine shelf (e.g., Miller et al. 2004), shallowing in the upper parts to shoreface environments (Martino and Curran 1990). In the subsurface, the Mount Laurel is uniform in thickness toward the southern part of the state at Ancora (text-fig. 7). In southernmost parts of the state it thins further and loses much of its sand content. At Millville, it consists of carbonate-rich, quartzose and glauconitic sandy clay that cannot be differentiated from the underlying clays of the Wenonah Formation (Sugarman et al. 2005).

The Mount Laurel aquifer has two localized depocenters (Zapecza 1989; Kulpecz 2005). The depocenter in the north, centered near Howell, NJ, is a siltier, less productive aquifer. The southern depocenter, found in a broad swath from southern Burlington County through Gloucester County (as shown by the thickening from Chatsworth to Ancora; text-fig. 7), is composed of cleaner sand, and provides a critical aquifer for the Philadelphia suburbs.



TEXT-FIGURE 9
Well log dip correlation of Miocene Kirkwood sequences and aquifers. See text-figure 1 for location of the sections and gamma logs.

KIRKWOOD FORMATION AND AQUIFERS: DELTAIC-SHELF SEQUENCES

The Kirkwood Formation comprises lower and middle (partim) Miocene strata that are poorly exposed in outcrop. It is dominated by sands and silty clays that were deposited in delta and storm-dominated shelf environments. The Kirkwood Formation is differentiated from the overlying upper middle to upper Miocene Cohansey Formation by the more common silty clays (text-fig. 8) and occasional shelly beds. The Cohansey Formation is primarily a shoreface/nearshore sand (Carter 1978). In outcrop it is often difficult to differentiate the Kirkwood and Cohansey Formations though the latter generally consists of yellow, coarser sands versus more typical gray, fine "sugar" sands and silty clays of the Kirkwood Formation. The upper Kirkwood and Cohansey sands comprise the unconfined Kirkwood-Cohansey aquifer system (Zapecza 1989), a vital water table aquifer that is easily contaminated. The Atlantic City 800-foot sand is a major confined aquifer within the Kirkwood Formation (text-figs. 8, 9) that was first named for its depth in Atlantic City producing wells (Woolman 1892). A minor aquifer, the Rio Grande water-bearing zone (text-figs. 8, 9), is found between these major aquifers, though it is restricted to southernmost parts of the New Jersey coastal plain.

The Kirkwood Formation was initially divided into three units corresponding to East Coast Diatom Zone (ECDZ) 1, 2, and 6 (Owens et al. 1988). Sugarman et al. (1993) recognized that these units were unconformity-bounded sequences: Kw1, Kw2, and Kw3 based on preliminary core results from ACGS#4, Belleplain, Wildwood, and scattered split spoon samples (text-fig. 1). Continuous coring at Island Beach, Atlantic City, and Cape May led to the identification of 9 sequences within the Kirkwood Formation (text-fig. 8; Kw0, K1a-c, Kw2a-c, Kw3, Kirkwood-Cohansey; Miller et al. 1997). Sr-isotopic stratigraphy provided a means of evaluating the ages, hiatuses, and global correlations of the Kirkwood sequences (Sugarman et al. 1993; Miller et al. 1997).

Facies within the deltaically influenced Kirkwood Formation follow a predictive succession within sequences: 1) a basal unconformity, 2) a lower shelly quartz sand deposited in inner neritic environments, 3) a medial silty clay deposited in prodelta environments, 4) an upper quartz sand deposited in delta front environments; and 5) an upper unconformity (Sugarman et al. 1995). The upper sands generally comprise aquifers of the upper part of the Highstand Systems Tract whereas the silty clays are confining units of the lower part of the Highstand Systems Tract.

The Atlantic City 800-foot sand aquifer consists of a lower sand, a thin fine-grained unit with uncertain confining characteristics, and an upper sand (text-figs. 8, 9; Sugarman 2000). The lower sand is part of the HST of the Kw1a sequence (20.2-21.6 Ma), whereas the upper sand is part of the HST of the Kw1b sequence (19.9-20.2Ma) (text-figs. 9, 10). The Rio Grand water-bearing unit is part of the HST of the Kw2a sequence (text-figs. 9, 10). The Kw2b and Kw2c sequences (text-figs. 9, 10) generally lack thick HST sands, probably due to truncation.

The division of the "800-foot sand aquifer" is more complicated in the Cape May peninsula. At Cape May, there are three sand bodies that can be mapped within the "800-foot sand" (text-fig. 10). The highest of these aquifer sands is associated with the HST of the Kw1c sequence, whereas the medial and lower aquifers are associated with the Kw1b and Kw1a HST as they are at Atlantic City and Oceanview (text-fig. 10). The Kw1c sequence and associated aquifer sand clearly pinches out 15 km (9 mi) to the north at Oceanview (text-fig. 10). A corehole was recently drilled at the Cape May Zoo, halfway between Cape May and Oceanview. This corehole apparently recovered the Kw1c sequence (text-fig. 10). The preservation of this sequence and associated aquifer sands can be attributed to greater accommodation in the Cape May peninsula during the early Miocene. Browning et al. (in press) attributed greater accommodation to progradation of thick clinoformal sequences through this region in the early Miocene.

The Kw1c and Kw2c sands are extensive in Cape May County, though they are not as extensive as other marine aquifers. The presence of the Kw1c sands in the southern Cape May peninsula (i.e., from Cape May Zoo south; text-fig. 10) results in a thicker 800-foot sand aquifer. The Kw2c appears to be a separate aquifer from the 800-foot sand; it is a thin, localized lens that is only locally important.

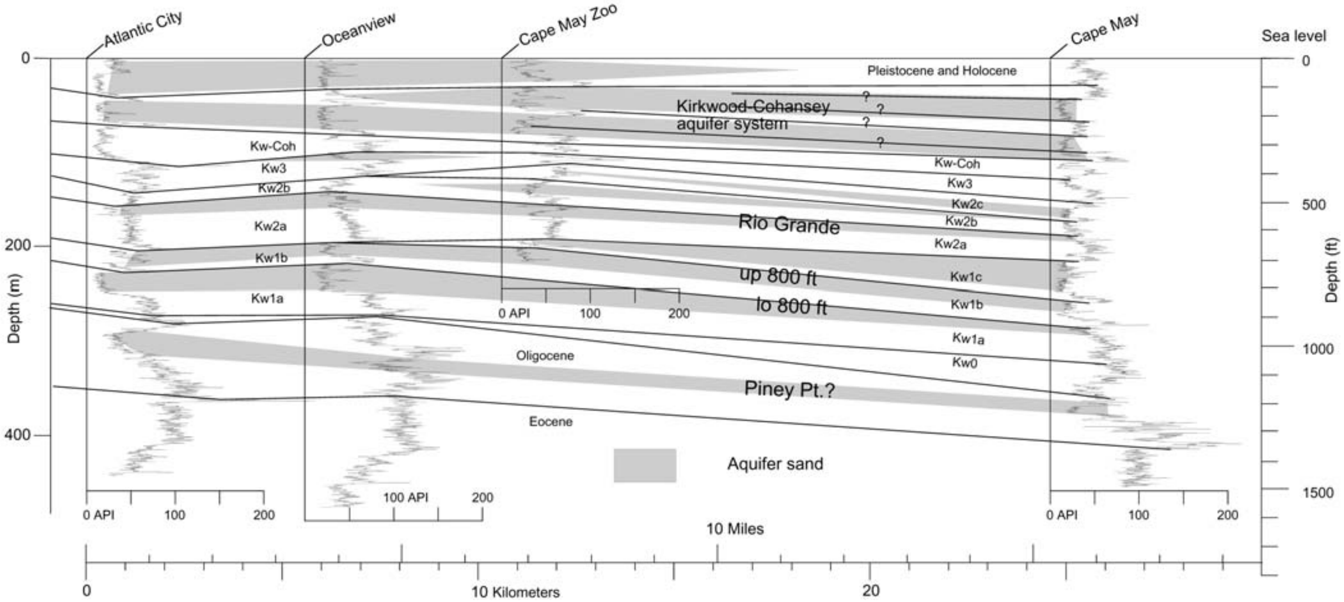
Our study shows that there are several relatively thin fine-grained beds that may serve to partially confine the "unconfined Kirkwood-Cohansey" aquifer system. These thin fine-grained beds are observed in the downdip strike section from Cape May to Atlantic City (text-fig. 10). These fine-grained beds are associated with several poorly dated upper Kirkwood to Cohansey sequences (text-fig. 9). It is unclear to what extent these fine-grained beds serve to break the unconfined Kirkwood-Cohansey aquifer into smaller, unconnected aquifers.

DISCUSSION

Predicting Continuity of Hydrostratigraphic Units

We improve the predictability of the local and regional hydrostratigraphic framework for the coastal plain by delineating stratigraphic sequences, correlating them with stratigraphic records in other parts of the Atlantic Coastal Plain, and tying them to other globally observed records and phenomena. Sugarman and Miller (1997) recognized that Miocene hydrostratigraphic units followed sequences and that these were tied to global changes in sea level. Miocene sequence boundaries can be linked to global $\delta^{18}O$ increases that are indicative of ice-volume increases and associated glacioeustatic lowerings (Miller et al. 1996, 1998). These sequence boundaries bracket hydrostratigraphic units. Miocene sequences are composed of fine-grained shelf and prodelta sediments in the base grading upward to delta-front and shoreface sands; this corresponds to confining unit-aquifer couplets. We extend this work through the coastal plain sedimentary column to the Lower Cretaceous and add numerous wells and coreholes to our hydrostratigraphic framework to test the predictability of aquifer and confining unit continuity.

The sequence stratigraphic setting and environment of deposition are critical for predicting continuity of units. Sands and overlying confining units may be continuous on various scales from tens of meters to over 100km, yet sequence stratigraphic and facies analysis provides confidence that certain aquifers and confining units are continuous on scales of 10's of km. Aquifer sands deposited in marine shelf environments (e.g., the Mount Laurel) tend to be continuous on the 10+ km scale (text-figs. 7, 9, 10) (Table 1). Confining beds for these units are typically shelf or prodelta silty clays that are even more laterally continu-



TEXT-FIGURE 10
Well log strike correlation of Miocene Kirkwood sequences and aquifers. See text-figure 1 for location of the section and gamma logs.

ous (e.g., text-fig. 7), reflecting the fact that though this is a sandy, siliciclastic margin, there is still more mud than sand.

Coastal plain units are generally more continuous along strike than dip and units deposited in marine environments are more continuous than non-marine units (Table 1). For example, Miocene aquifers between Atlantic City and Cape May are continuous for more than 67 km (40mi; text-fig. 10), the Mount Laurel can be traced on our sections for 80 km (65 mi) before it “muds out” (text-fig. 7), and the upper Englishtown aquifer can be traced for over 100km (60mi) from Asbury to Millville (text-fig. 7). Marine units can also be traced updip (Table 1), though to lesser extent than along strike because of the rapid changes in water depth and attendant facies that occur on a paleoshelf. For example, there is typically a 1m (3.3 ft) paleowater depth change over a 1000m (3280ft) distance in dip direction in the modern New Jersey shelf, and this gradient was probably higher (1:500) in the Cretaceous to Paleogene (Steckler et al. 1999). Nevertheless, for a typical shelf environment (e.g., 50m [164 ft] paleodepth), fine confining beds can be traced updip 25-33 km+ (15-20 mi+; text-fig. 9). Where the confining units pinch out is critical, because it is in these updip areas that recharge and potential contamination occur.

Continuity in shallow marine (e.g., foreshore or shallower) to non-marine units is less clear than marine shelf, prodelta, or delta front environments. Many units such as the Magothy I (estuarine at Sea Girt) are laterally continuous beneath southern Monmouth County, but pinch out to the south (~60 km, 36 mi along strike; text-fig 7). As noted above, the Magothy II and III are laterally continuous throughout much of the region examined (text-fig. 7). Although a fluvial-deltaic deposit, these sequences show surprising lateral continuity along strike, reflecting the widespread influence of delta front environments. Similarly the Potomac 3 can be traced 40km (24mi) along strike (text-fig. 4), in part reflecting a delta front depositional environment. The wide lateral extent of these facies can be explained by the fairly large influence of rivers that were about the size of the modern Rhone River (Kulpecz 2005)

In contrast to the above, delta plain, fluvial, and estuarine confining units can be remarkably localized. We provide two examples of discontinuous confining units from two remediation sites, one from the Miocene at the Ciba-Geigy Toms River, NJ remediation site, the other from the ?Coniacian at the Madison/CPS site in Old Bridge, NJ.

The Ciba-Geigy Toms River remediation site illustrates the practical difference between marine and non-marine confining units. The Kw1a and Kw1b sequences occur beneath this site. These sequences are marine (as indicated by the presence of nannofossils) units deposited in delta front environments and the sequence stratigraphy is reasonably clear, with identification of the Kw1a and Kw1b sands (= the lower and upper parts of the Atlantic City 800-foot sand aquifer). This predicts that clayey confining units associated with the Kw1a and Kw1b sequence are continuous beneath the Ciba-Geigy site. Additional sequences apparently occur above the Kw1b sequence at this site. A confining clay above a sequence boundary at 9.1m (30ft) is paramount for contaminant containment (Ciba-Geigy 1994). However, the clay was deposited in an upper estuarine environment with salinities less than 20‰ (Scott et al. 1977, 1980), as evinced by the presence of thecameobians (*Difflugia*) and agglutinated foraminifers (*Reophax* and *Miliammina fusca*). This clay was mapped onsite as occurring as a laterally continuous layer over an approximately 1 km^2 area (Ciba-Geigy 1994), but in fact may be discontinuous on a 100 m scale. In this case, knowing the sequence stratigraphy and facies variations within sequences is critical to predicting the continuity, or in this case potential lack of continuity of a confining bed.

The second example is derived from the Old Bridge Sand of the Magothy Formation (the upper sands of the Magothy II; text-fig. 7). This unit lies from land surface to about 21.3m

TABLE 1
Lateral extent of aquifer sands for units discussed in text.

Aquifer Unit	Strike dimension km (mi)	Dip dimension mi (km)
Potomac I	70 (44)	20 (12)
Potomac II	60 (37)	13-26 (8-16)
Potomac III	>100 (>62)	>25 (>16)
Magothy	>60 (>37)	40 (25)
upper Engishtown	100 (62)	40 (25)
Mount Laurel	>80 (>50)	45 (28)
800-foot sand	120 (75)	30 (19)

(70ft) below the Madison/CPS site (text-fig. 1). The South Amboy Fire Clay (the lower clay of the Magothy II sequence; text-fig. 6) interfingers with the Old Bridge Sand at ~10.7m (35 ft) at this site. These clays were assumed to be continuous and a potential confining bed for contaminants (CH2M Hill 1984) until it was demonstrated that they represented small cut-off channel or oxbow lake deposits at this site (Olsson 1987). A continuous marine clay, the Woodbridge Clay of the Raritan Formation (equivalent to the Bass River III sequence in the subsurface; text-fig. 8), lies at about 21.3m (70ft) below lands surface and provides an excellent confining unit, but the patchy, discontinuous clay beds within the Old Bridge-South Amboy Fire Clay are discontinuous on the 10 m scale (Olsson 1987). In this case, the facies can be used to predict that the South Amboy Fire Clay beds are not suitable for tying in containment walls (Olsson 1987).

Miller et al. (1996, 1998, 2004) demonstrated that New Jersey Coastal Plain unconformities are inter-regional surfaces bracketing sequences and thus sequence stratigraphy and its implication to hydrostratigraphy can be exported to other regions. Global sea-level change provides a template of sequences that can be preserved in one region. However, local differences in accommodation caused by tectonics (i.e., space for sediments caused by subsidence or uplift) determine whether a given sequence is preserved in a given region. This is well illustrated by comparison of lower-middle Miocene sections in New Jersey with relatively less complete sections in Maryland (Browning et al., in press). Tectonics may remove whole portions of the section. For example, the stratigraphy of the Turonian to basal Campanian sequences is remarkably similar on the Cape Fear Arch (Self-Trail et al. 2002), but much of the Campanian to Paleogene is missing due to relative uplift of this region. Thus, the equivalents of the upper Englishtown and Mount Laurel aquifers are not found in the Cape Fear Arch region

Local differences in sediment supply also affect the development of the hydrostratigraphic framework in a particular area. This is well illustrated by the Magothy aquifer that is important in the central and northern New Jersey coastal plain. This aquifer thickens substantially from Lakewood north (text-fig. 7) toward Fire Island, NY (Long Island) (Perry et al. 1975), but thins dramatically in the southern New Jersey coastal plain (text-fig. 7), and is only preserved to the south in Delaware-North Carolina as incised valley fill (McLaughlin and Benson 2001). This is attributable to the influence of a northern source analogous to the modern Hudson River in the northern New Jersey Coastal Plain to Long Island and a central source analogous to the modern Delaware River on the central part of the coastal plain (Kulpecz 2005). The northern source influence is shown by the thickening of the Magothy sequence from their thickest in our data set at Sea Girt (text-fig. 7) toward Fire Island, NY (Perry et al. 1975). The influence of the central source can be best illustrated by the thickening of the Magothy II near Ancora (text-fig. 7; Kulpecz 2005).

Aquifers in the coastal plain vary from localized sand bodies (e.g., offshore bars of the Maastrichtian Shrewsbury Member of the Red Bank Formation) to regional sand sheets associated with the upper part of HSTs. The extent of sand vs. mud can be strongly influenced by the proximity of the sand sheets to sources. For example, the extent of the Magothy sands is linked to source (text-fig. 7), and the "mudding out" of the upper Englishtown and Mount Laurel aquifers is also related to source (text-fig. 7). As a result of the lack of a sand source, deep aquifers in the southernmost New Jersey Coastal Plain near Millville (text-fig. 7) are almost non-existent.

Extensive sand bodies (10-100+ km scale) can develop on continental shelves or in delta fronts as part of upper HST sands. The widespread nature of the upper Englishtown aquifer sands (text-fig. 7) can be attributed to their deposition in a delta front environment. Though they may be influenced by fluvial point sources (e.g., the northern and central sources), extensive sand sheets can form through reworking of sands on storm dominated continental shelves that result in regionally extensive, permeable, and connected sands. Progradation of clinoformal sequences can result in prograding sand bodies and more localized aquifers. Two examples are provided by the Oligocene of New Jersey coastal plain (Pekar et al. 2000) and the lower Miocene of the New Jersey inner continental shelf (Steckler et al. 1999). Updip continuity of the Oligocene sands is typically 10-20 km (6.2-12.4 mi; Pekar et al. 2000). Lower Miocene sequences on the shelf have been seismically imaged, but only sporadically sampled (the Integrated Ocean Drilling Program will drill three sites in this region in 2007) and the scale of these is less clear. Seismic stratigraphic studies suggest a lateral dip and strike continuity that is similar to the onshore (Monteverde et al., in prep.). This difference between Oligocene and lower Miocene shelf sequences is consistent with the greater amounts of sand in the lower Miocene as the amount of medium-coarse sand increased in this region at ca. 27 Ma (Miller et al. 1997).

We conclude that sequence stratigraphy and facies models provides a predictive framework for hydrostratigraphic units, but that regional and local differences in sediment supply, depositional environment, and tectonics affect the development of the hydrostratigraphic framework. Sequence stratigraphy allows packages of sands to be bracketed in a predictable manner by confining units. Facies analysis allows prediction of the potential scale and connectivity of sands, with a dimension of scale increasing from 10's m in fluvial environments to 100+ km in certain marine environments. Sequence stratigraphy and facies analysis provides a means of roughly predicting permeability, porosity, and hydraulic conductivity from aquifers, though precise estimates of these parameter and aquifer yields can only be done through hydraulic testing. Yet, understanding the sequence stratigraphy and depositional facies are critical for understanding scale and connectivity of aquifers and their confining units and predicting their local and regional distributions.

CONCLUSIONS

Sequence stratigraphy and facies analysis provide a powerful means of evaluating the regional extent and connectivity of Cretaceous to Miocene aquifer sands in the New Jersey Coastal Plain. We used well logs to trace sequences from continuous corehole control throughout this region. Sequences deposited in marine environments tend to be the most laterally continuous (>60km [37.3mi] along strike and >25km [15.5mi] along dip) and predictable, though marginal to non-marine sands may be similarly continuous along strike, reflecting the widespread influence of delta front environments. Facies models provide a means of predicting marine sands deposited as highstand shelf or delta front environments confined by silty clays deposited in prodelta or inner shelf environments. These observations are transportable to other mature, low-relief, siliciclastic passive margins using principles of sequence stratigraphy and facies models applied here. We evaluate the major aquifers in the coastal plain as outlined below.

1) The Potomac Formation contains aquifer sands deposited in nonmarine environments. Predictable facies patterns were not previously observed due to the rapidly shifting nature of fluvial/upper delta plain channel sands. Continuous coring at Fort Mott demonstrates that these aquifer sands are both overlain by floodplain and inter-channel clay-silts (confining beds). This coupled with an improved facies model for the confining beds of an anastomosing river and of delta front for the aquifer sands, allows for a more regionally extensive correlation of these fluvial-deltaic aquifers.

2) The Magothy Formation consists of several sands associated with at least four sequences. One of these (Magothy II/Old Bridge Sand) is a regionally useful aquifer, though two-three additional aquifer sands are present downdip. The Magothy I is a less continuous sand reflecting its estuarine depositional environments. The Magothy III is relatively continuous through much of the coastal plain reflecting its delta front origin, but these sands are generally too fine grained and silty to comprise a major aquifer in updip locations.

3) The upper Englishtown (mid-Campanian) sequence and associated aquifer sands thicken dramatically to the north as a function of sediment supply.

4) The Mount Laurel aquifer shows two localized depocenters, one in the north, which is silty, and a poorer aquifer and one in the south central that provides a critical aquifer.

5) The “800-foot sand” aquifer near Atlantic City is comprised of two sand bodies correlative with the HSTs of the Kirkwood Kw1a and Kw1b sequences. However, at Cape May, there are three sand bodies that can be mapped within the “800-foot sand.” The highest of these aquifer sands is associated with the HST of the Kw1c sequence and pinches out between Cape May and Atlantic City.

6) Our study shows that there are several relatively thin fine-grained beds that may serve to partially confine the “unconfined Kirkwood-Cohansey” aquifer. Future studies should evaluate the extent that these fine-grained beds serve to break the unconfined Kirkwood-Cohansey aquifer into smaller, unconnected aquifers.

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