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Sedimentary Geology 108 (1997) 3–18

Sedimentary Geology

Correlation of Miocene sequences and hydrogeologic units, New Jersey Coastal Plain

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Received 3 August 1995; accepted 31 January 1996

Abstract

We have developed a Miocene sequence stratigraphic framework using data from recently drilled boreholes in the New Jersey Coastal Plain. Sequences are shallowing upward, unconformity-bounded units; fine-grained shelf and prodelta sediments grade upward to delta front and shallow-marine sands, corresponding to confining bed–aquifer couplets. By dating Miocene sequences using Sr-isotope stratigraphy, and mapping with borehole data and geophysical logs, we can predict the continuity and effectiveness of the confining beds and aquifers. The following are illustrated on a 90-km basinward dip section: (1) the composite confining bed is comprised of the Kw0 and lower Kw1a (ca. 23.8–20.5 Ma) sequences downdip at Atlantic City, and the Kw1b, Kw1a and older sequences updip (ca. 69.3–20.6 Ma), and is continuous throughout most of the coastal plain; (2) the major confined aquifer, the Atlantic City 800-foot sand, is comprised of the upper Kw1a and Kw1b sequences (ca. 20.5–20.2 Ma) and is an areally continuous sand that is interconnected with the Kirkwood–Cohansey aquifer system updip of Mays Landing; (3) the confining bed above the Atlantic City 800-foot sand is comprised of the Kw2a, Kw2b, and Kw3 sequences (18.1–13.3 Ma) and is an extensive confining bed that pinches out updip. These sequences and aquifer-confining bed couplets are linked to global sea-level changes evinced by the $\delta^{18}O$ record. We conclude that sequence stratigraphy is a powerful tool when applied to regional hydrogeologic problems, although basinal tectonic differences and localized variations in sediment supply can affect aquifer thickness and permeability.

Keywords: Sequences; Miocene; Hydrogeology; Facies; Atlantic Coastal Plain; Strontium isotopes

1. Introduction

Production of ground-water and remediation of contaminated sites has focused attention on aquifer sands and confining-bed silts and clays in the New Jersey Coastal Plain. Although aquifer-confining bed couplets have been recognized in the subsurface of the New Jersey Coastal Plain using well cuttings (e.g., Woolman, 1895) and geophysical logs (Zapecza, 1989), their regional distributions were not predictable and their continuities could only be evaluated by drilling. The development of sequence stratigraphy, or the study of unconformably bounded units and facies variations therein (Vail et al., 1977; Posamentier et al., 1988), has provided a means of predicting the regional distribution of porous sands and semi-permeable silt and clay. We

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PII S0037-0738(96)00046-2

apply sequence stratigraphic principles to Miocene strata obtained from recently-drilled boreholes in the New Jersey Coastal Plain (Owens et al., 1988; Sugarman et al., 1993; Miller et al., 1994a,b, 1996a; Miller and Sugarman, 1995) to address ground-water and remediation issues.

During the past decade, extensive geologic studies in the New Jersey Coastal Plain were undertaken to produce a new geologic map of New Jersey under the Cooperative Geologic Mapping Program (COGEOMAP) between the New Jersey and the United States Geological Surveys. In addition, geologic studies have been conducted as part of local initiatives directly related to ground-water supply (Leahy et al., 1987). A major emphasis of these efforts was to develop a subsurface stratigraphic framework and ground-water models. These studies are needed to address problems including overproduction of ground-water that results in declining ground-water levels, degradation of ground-water quality primarily due to migration of saltwater into cones of depression, and shallow ground-water contamination from inorganic and organic chemicals (Leahy et al., 1987).

Of importance to this paper were ground-water and stratigraphic studies undertaken in Atlantic City and vicinity. These studies were precipitated by the population expansion that resulted from legalized gambling and led to a large increase in pumpage from the Atlantic City 800-foot sand, which is the primary confined aquifer providing water supply for the barrier beach communities in southern New Jersey (Zapecza, 1989). Stratigraphic studies included the drilling of the continuously cored ACGS-4 borehole at Mays Landing 25 km updip of Atlantic City (Fig. 1; Owens et al., 1988).

Following drilling of the ACGS-4 borehole, the National Science Foundation (Continental Dynamics and Ocean Drilling Program (ODP)) funded drilling of three continuously cored downdip boreholes at Island Beach, Atlantic City, and Cape May as part of ODP Leg 150X that targeted Miocene strata (Miller et al., 1994a,b, 1996a). Recent drilling at these sites onshore and offshore on the New Jersey continental slope (Mountain et al., 1994) was designed to test the relationship between stratigraphic sequences and global sea-level change.

Sequences provide an objective means of subdividing the stratigraphic record. While Vail et al. (1977) and Haq et al. (1988) suggested that sequences are genetically related to global sea-level change, this relationship has only recently begun to be tested by the academic community. Recent studies have documented that New Jersey Oligocene to middle Miocene sequences, both onshore (Miller and Sugarman, 1995) and offshore (Miller et al., 1996b), correlate with the oxygen isotope proxy for global sea-level change. The relationship between global sea-level change and sequences may provide predictions useful in ground-water studies. Aquifer-confining bed couplets in the Miocene strata of New Jersey are bracketed by unconformities which represent sequence boundaries; these hydrogeologic couplets can be correlated throughout the coastal plain (Miller et al., 1994a,b). By placing the local stratigraphic section into a regional (and global) sequence stratigraphic framework, the continuity and effectiveness of aquifers and confining beds can be predicted. This is particularly critical in regions of contamination where continuity of confining beds is of primary concern.

In this paper, lower to middle Miocene stratigraphic sequences mapped using data from continuously and partially cored boreholes and geophysical logs are integrated with identified hydrogeologic units (Zapecza, 1989) to develop a modern, detailed geologic and hydrogeologic framework. Understanding this framework can help to address fundamental questions which have arisen over the past century of ground-water usage and investigation of the Miocene hydrogeologic units in New Jersey. Such questions include delineating the lateral extent of major confining beds, and the updip delineation and separation of major aquifers.

2. Methods

We integrated published (Owens et al., 1988, 1995a,b; Sugarman et al., 1993; Miller et al., 1994a,b, 1996a; Miller and Sugarman, 1995) lithostratigraphic, biostratigraphic, Sr-isotopic, and well log data (primarily gamma-ray logs) to develop a subsurface sequence stratigraphic framework for geologic and hydrogeologic studies. Unconformities were recognized by reworked and bioturbated intervals, phosphatic buildups and associated positive

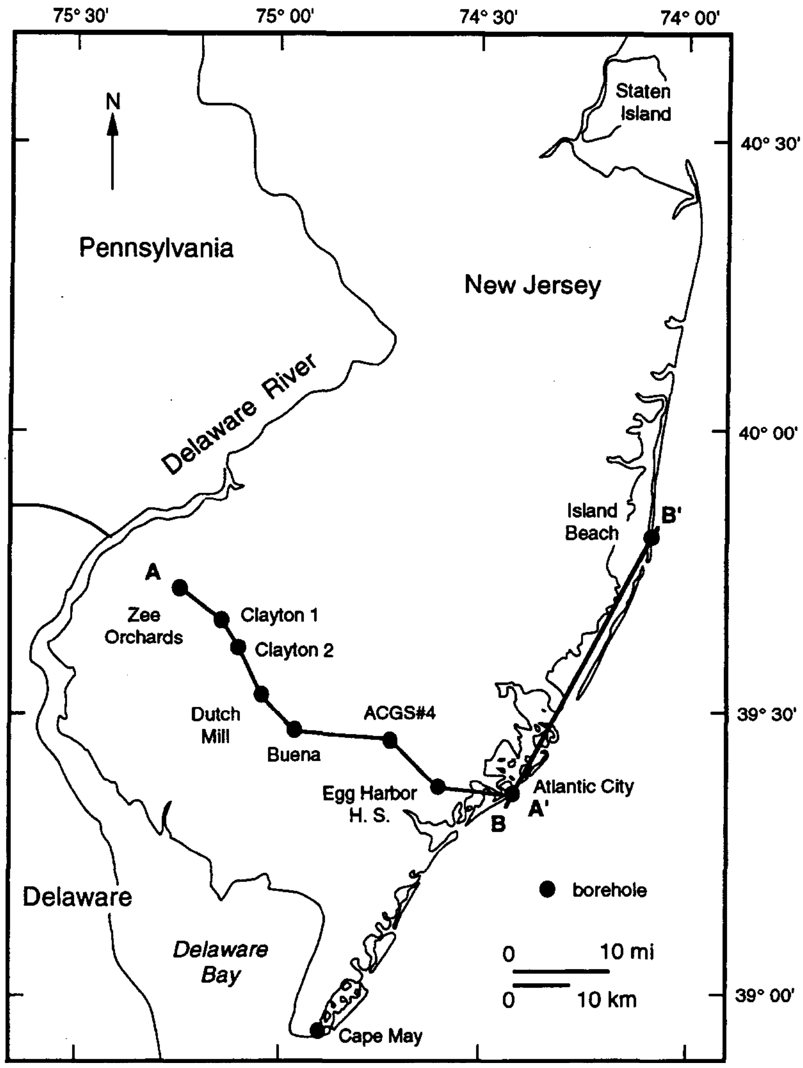

Fig. 1. Location of boreholes used in this study. Also shown are lines of cross-sections *A–A′* (Fig. 5) and *B–B′* (Fig. 6).

gamma-ray spikes, major changes in depositional environments, biostratigraphic evidence, and Sr-isotope age estimates.

Chronostratigraphic correlations of New Jersey Miocene sequences depend heavily on Sr-isotope stratigraphy. Previous to Sr-isotopic studies (Sugarman et al., 1993; Miller et al., 1994b, 1996a; Miller and Sugarman, 1995), chronostratigraphic control of the Miocene of New Jersey relied primarily on diatom zonation (the East Coast Diatom Zonation (ECDZ) of Andrews (1988)) because calcareous microfossil zonal markers are generally absent in these strata. However, diatoms are not well calibrated to the global time scale and Sr-isotopic studies allow the placement of the New Jersey Miocene into a global framework. Sr-isotope analyses used here were made on calcareous mollusk shells as reported in Miller et al. (1994a,b) and Miller and Sugarman (1995). We obtain ages using the regression equations of Oslick et al. (1994) for the Miller et al. (1988) for the Oligocene. Early Miocene age estimates have a resolution of ±0.4 m.y. for replicate analyses (Oslick et al., 1994). Age resolution for the middle Miocene decreases to about ±0.9 m.y. because of a corresponding lower $^{87}Sr/^{86}Sr$ rate of change, but still provides excellent chronostratigraphic potential (Oslick et al., 1994). The Geomagnetic Polarity Time Scale (GPTS) of Berggren et al. (1985) is used throughout.

The Atlantic City borehole provides the best reference for comparing Miocene sequences and previously published hydrogeologic units (Zapecza, 1989). We choose Atlantic City as the reference section for Miocene subsurface sequences and hydrogeologic units because of its continuity and location near classic subsurface sections (Woolman, 1895). The Cape May borehole (Miller et al., 1996a) contains some Miocene sequences that may be restricted to the Cape May Peninsula and are not represented at Atlantic City.

We provide detailed lithofacies and paleoenvironmental interpretations of Miocene strata at the Atlantic City borehole here for the first time. These interpretations are based on original descriptions (Miller et al., 1994b) and subsequent evaluation of the lithology (this study) and on benthic foraminifera (Gwynn, 1995). Facies interpretations follow principles outlined by Owens and Sohl (1969), Owens and Gohn (1985), and Owens et al. (1988).

We tied the Atlantic City results to other boreholes on dip and oblique strike cross-sections using previously published (ACGS-4, Owens et al., 1988; Clayton 1 and 2, Owens et al., 1995b; Zee Orchards, Zapecza, 1989; Fig. 1) interpretations and new (Egg Harbor H. S., Buena, Dutch Mill; Fig. 1) gamma-ray logs. Continuous cores at the ACGS-4 and Clayton sites provided ground truth for the geophysical-log interpretations.

2.1. New Jersey sequences

Miocene sequences in New Jersey commonly are shallowing-upward siliciclastic sequences, typically with a thin lower glauconite sand (transgressive), a middle clay–silt (regressive), and an upper coarse quartz sand (regressive) as shown in Fig. 2. Sequence stratigraphic models contain the following three major facies groups or 'systems tracts' within sequences: the lowstand (bounded at its base by an unconformity), transgressive, and highstand (bounded at its base by the maximum flooding surface, and at its top by an unconformity). Lowstand systems tracts are not represented in the New Jersey Coastal Plain and transgressive systems tracts are generally thin; therefore, unconformities may merge with the maximum flooding surface. Thus, the sequences can be

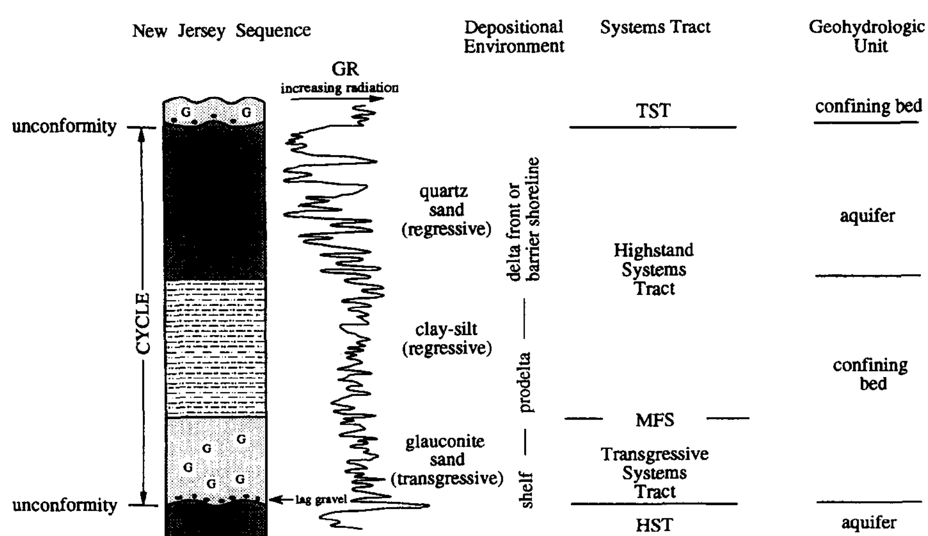

Fig. 2. Schematic of New Jersey sequence, corresponding systems tract interpretations and hydrogeologic units. *GR* = gamma-ray log; *G* = glauconite sand; *HST* = highstand systems tract; *TST* = transgressive systems tract; *MFS* = maximum flooding surface.

equivalent to the parasequence concept of shoaling-upward cycles bounded by flooding surfaces (Van Wagoner et al., 1988). In the New Jersey Miocene sequences, shoaling upward is reflected in the transition from marine-shelf facies to near-shore marine and nonmarine facies (Sugarman et al., 1993).

For relatively complete sequences, hydrogeologic facies can be easy to correlate (Fig. 2). Confining beds are composed of the glauconite sand and clay–silt at the base of a sequence, and aquifers consist of the more permeable upper quartz sands. Aquifers are also simple to trace in the subsurface with geophysical logs, especially gamma-ray logs, because of the contrast between the high gamma-ray values of glauconite sands and clay–silt and the low values of aquifer sands. Sequence boundaries also can be mapped with gamma-ray logs because of a high gamma-ray response at the base of each sequence.

If the upper quartz sand is not present due to nondeposition (e.g., facies change) or nonpreservation (e.g., erosional truncation), then mapping of sequences becomes more difficult due to the juxtaposition of similar fine-grained shelf and prodelta lithologies. While continuous coring preserves sedimentary structures, thus making facies analysis and sequence differentiation possible, gamma-ray logs cannot be used to distinguish between these fine-grained facies in truncated sequences. Typically, some method of chronostratigraphic resolution is necessary to distinguish between stacked partial sequences.

3. Previous geologic and hydrogeologic studies

The Miocene Kirkwood Formation had been drilled more than a century ago for water supply at Atlantic City and southward on the beaches, and was described by Woolman (1892) as a series of permeable sands, separated by impervious diatom-rich clays (Fig. 3). Four water-bearing horizons were encountered in artesian wells along the coast; at Atlantic City, the lower three horizons include: (1) an upper zone at 168 m (550 ft) situated in the middle of a 'diatomaceous clay bed' between 122 and 213 m (400–700 ft); (2) a water horizon at 213–220 m (700–720 ft, immediately below the 'diatomaceous clay bed'); and (3) the deepest horizon at 290 m (950 ft; Woolman, 1892). Correlations from New Jersey to Maryland, based on diatoms and mollusks, were shown by Woolman (1895), who subdivided the Kirkwood Formation at Wildwood into an upper St. Mary's bed, a thick middle 'Great Diatom Bed' (~120 m thick; previously termed the 'diatomaceous clay bed') and correlative with the Chesapeake Group, and ~90 m of lower Miocene clays and sands (including a major water-bearing horizon) infrequently containing rare *Actinophytcus heliopelta* (a diatom).

Woolman (1898) revised his terminology for the coastal plain water-bearing horizons to reflect only major water-bearing zones. Six horizons (the higher numbers are younger) were identified, with the No. 6 Horizon, named the '700-foot Atlantic City horizon', occurring just below the base of the Great Diatom Bed, and the No. 5 Horizon, occurring 38 m below the Great Diatom Bed, named the '800-foot Atlantic City horizon.' The No. 4 Horizon, believed to be part Eocene and part Miocene, was termed the 'Atlantic City 950-foot horizon.'

Richards and Harbison (1942) reviewed geologic and paleontologic studies of the Kirkwood Formation, reexamined the Miocene invertebrate fauna, and suggested a subdivision of the Kirkwood Formation similar to that of Woolman (Fig. 3), in part based on correlations with the Chesapeake Group of Maryland and Virginia. They subdivided the Kirkwood Formation into a thin upper St. Mary's Phase, and a thick lower Calvert Phase, which consisted of (from top to bottom): the Great Diatom Bed, the 800-foot Sand, the Lesser Diatom Bed, and a Basal Greensand Marl. Richards and Harbison (1942) combined the 700 and 800 foot sand horizons of Woolman (1892) into a single water-bearing zone (shown as the '800 ft' sand on Fig. 3).

Isphording (1970) reexamined the outcropping relationships of the Kirkwood, and subdivided it into three members: (1) Asbury Park; (2) Grenloch; and (3) Alloway Clay. These members are distinct facies interpreted predominantly as nearshore deposits, but cannot be recognized or subdivided downdip.

Beginning in the 1980s, modern hydrogeologic and geologic frameworks were developed for the New Jersey Coastal Plain, including the Miocene Kirkwood and Cohansey Formations. Zapecza (1989) developed a hydrogeologic framework of the New Jersey Coastal Plain based on over 1000 geophysical logs. Zapecza (1989) mapped the fol-

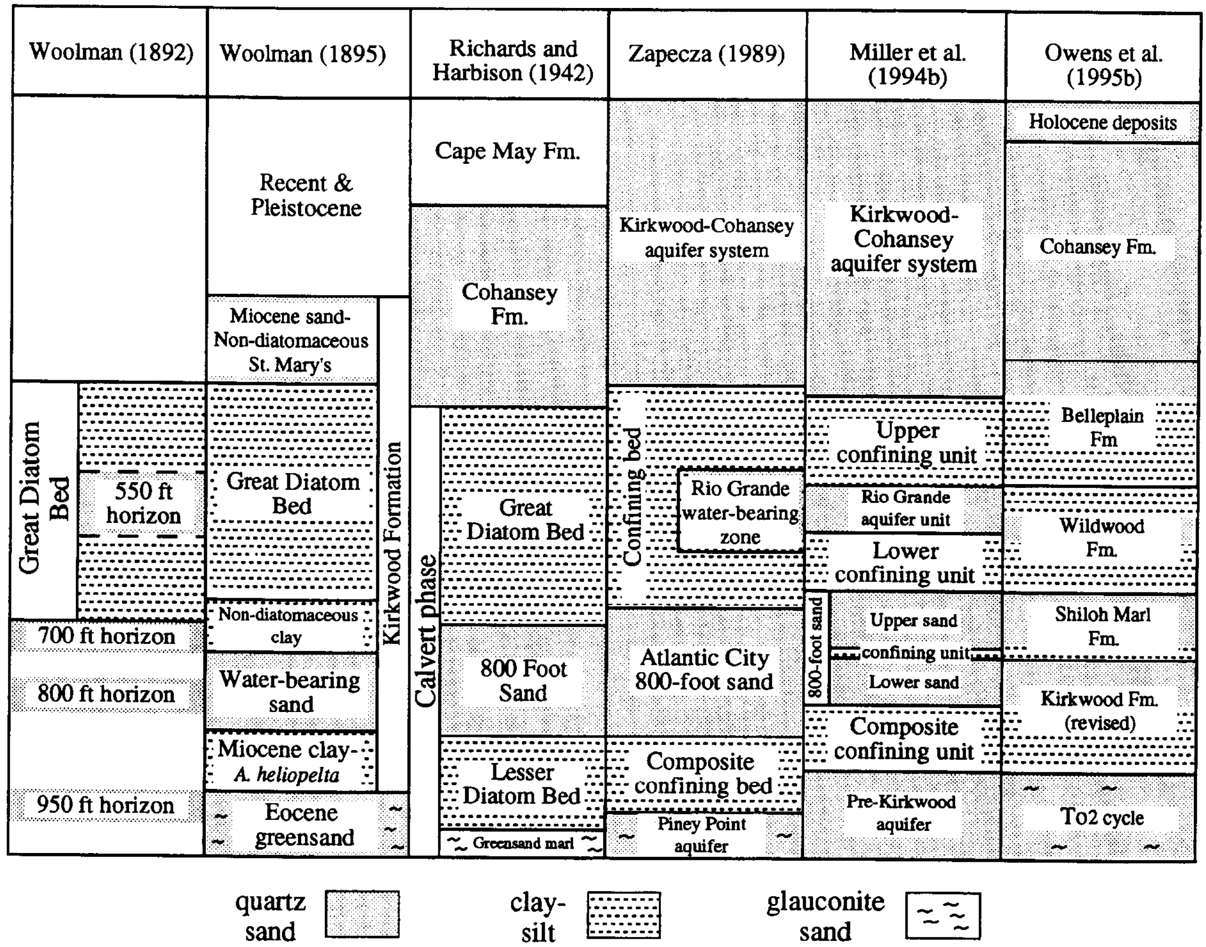

Fig. 3. Correlation chart of nomenclature of hydrogeologic and geologic units developed in the Atlantic City area over the past century. Also shown is dominant lithology of the units. *Fm.* = formation.

lowing two major aquifers and two major confining beds (Fig. 3): (1) the Kirkwood–Cohansey aquifer system, which is a water-table aquifer that includes the upper Kirkwood Formation, the Cohansey Formation, and parts of surficial sand and gravel units including the Bridgeton and Cape May Formations; (2) a major confining bed that underlies the Kirkwood–Cohansey aquifer system and overlies the Atlantic City 800-foot sand, that consists of a massive clay bed whose thickness varies between 30 and 137 m and is correlative with the 'Great Diatom Bed' of Woolman (1895); (3) the Atlantic City 800-foot sand, a major water-bearing unit near the base of the Kirkwood Formation, whose thickness varies from 12 to 46 m, and contains a thin (3–9 m) clay bed in the middle of the aquifer; and (4) the composite confining bed, a complex unit containing geologic strata ranging in age from Maestrichtian through lower Miocene. In the middle of the confining bed separating the Atlantic City 800-foot sand from the Kirkwood–Cohansey aquifer system is a thin (~12 m thick), confined water-bearing zone termed the Rio Grande water-bearing zone (the Atlantic City 550 ft horizon of Woolman, 1892).

Zapecza (1989) outlined two major unresolved hydrogeologic relationships within the Kirkwood Formation. First, identification of the Atlantic City 800-foot sand requires the recognition of its upper confining bed (and its associated positive gamma-ray response). In areas to the northwest where this confining bed is absent, the distinction between the Atlantic City 800-foot sand and the Kirkwood–Cohansey aquifer system is extremely difficult because of their similar lithologies. This information is essential because if the two aquifers are connected, most of the recharge for the Atlantic City 800-foot sand would be from the unconfined aquifer system to the west. Second, the updip extent of the confining bed overlying the Atlantic City 800-foot sand is only approximated. This clay defines the extent of the separation of the Kirkwood–Cohansey aquifer system and the Atlantic City 800-foot sand. It is unclear whether this confining bed is erosionally truncated updip, or if there are facies changes that result in gradational changes from clay to silt to sand.

The drilling of the ACGS-4 borehole (Fig. 1; Owens et al., 1988) marked the beginning of modern integrated stratigraphic studies of the Kirkwood Formation. By incorporating subsurface geologic data including lithology, geophysical logs and biostratigraphy, depositional facies were determined and a sequence stratigraphy was developed for the Kirkwood Formation. In the subsurface of New Jersey, three unconformity-bounded stratigraphic sequences were mapped correlative with ECDZ 1 (estimated age range of 19.1–18.9 Ma), ECDZ 2 (17.4–15.6 Ma), and ECDZ 6 (13.8–12.8 Ma) (Owens et al., 1988; Andrews, 1988). However, these age estimates were uncertain because of poor calibration of the diatom ranges to the geologic time scale.

Sr-isotope stratigraphy was used to correlate sequences in the Kirkwood Formation to the Geomagnetic Polarity Time Scale (Sugarman et al., 1993), and thus provide a better chronostratigraphic framework for measuring sequence timing and duration. Three unconformity bounded Kirkwood sequences were confirmed, and a fourth sequence inferred. Maps of the three sequences, including structure-contour and isopach maps, were generated from borehole data. The lowermost sequence (Kw1) has Sr-isotope age estimates of 22.6–19.2 Ma $\pm$ 0.6 m.y; the middle sequence (Kw2) has Sr-isotope age estimates of 17.4–15.5 Ma $\pm$ 0.6 m.y., with an inferred hiatus separating it into two sequences; and the youngest sequence (Kw3) has age ranges of 13.6–12.2 Ma $\pm$ 0.9 m.y. The ages of these lower to middle Miocene sequences compare well with other indicators of sea-level change, including the global sea-level record of Haq et al. (1988) and oxygen isotopes, suggesting that eustatic sea-level changes had a major influence on the depositional history of the New Jersey continental margin (Sugarman et al., 1993).

During 1993 to 1994, three continuously cored boreholes were drilled at Island Beach, Atlantic City, and Cape May (Fig. 1; Miller et al., 1994a,b, 1996a). Sequences, lithologic units, and hydrogeologic units were identified at the Atlantic City site, along with corresponding Sr-isotope age estimates (Miller et al., 1994b). The upper Oligocene and Miocene sections of the Atlantic City borehole were correlated with those of the Cape May borehole (Miller et al., 1996a) and with those of the Calvert Cliffs of Maryland (Miller and Sugarman, 1995). Data from these boreholes, particularly the one at Atlantic City, provides material for establishing a geologic and hydrogeologic reference section.

4. Results

4.1. Atlantic City reference section

The continuous corehole drilled at Atlantic City as part of Ocean Drilling Program Leg 150X (Fig. 1) serves as an excellent reference section for Miocene sequences and aquifers (Fig. 4) in New Jersey for the following reasons.

(1) The lower and lower middle Miocene sequences are relatively thick and well preserved (Miller and Sugarman, 1995).

(2) The location has been used historically as a reference site for aquifer nomenclature (Fig. 3), allowing for easy comparison with previous stratigraphic and hydrogeologic nomenclature.

(3) A detailed Sr-isotope chronology was developed at this site (Miller et al., 1994b; Miller and Sugarman, 1995) resulting in excellent chronostratigraphic resolution of Miocene sequences.

(4) The Kirkwood sequences at Atlantic City (Fig. 4) provide excellent examples of Miocene sequences in New Jersey, and this study provides detailed facies interpretations at this site.

We summarize here the Miocene sequences and facies at Atlantic City (Fig. 4). Four sequences are recognized in the lower Miocene: Kw0, Kw1a, Kw1b, and Kw2a. Together, the Kw0 and lower

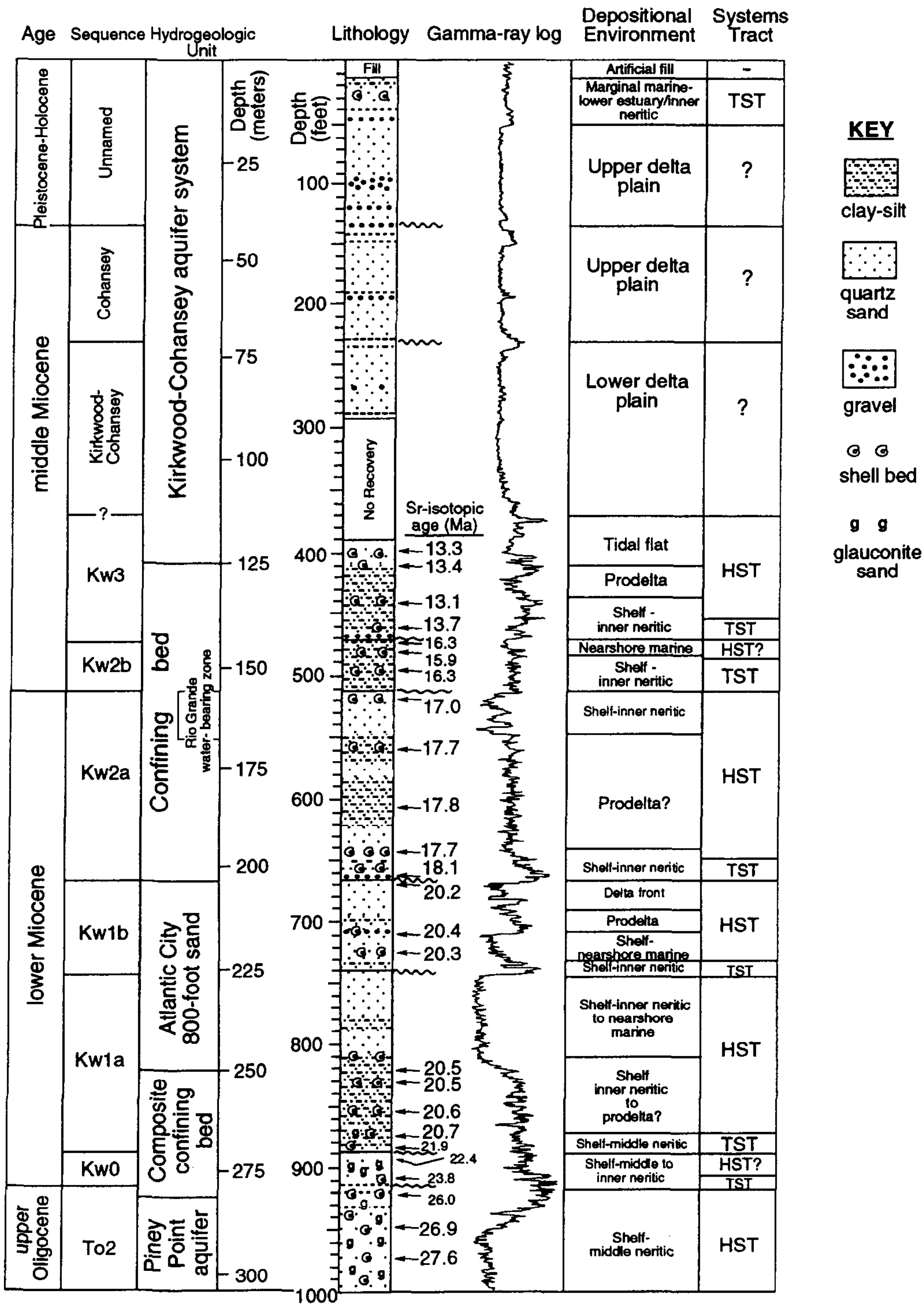

Fig. 4. Correlation of hydrogeologic units with sequences and systems tracts at the Atlantic City borehole. Sr-isotope age estimates from Miller and Sugarman (1995). *HST* = highstand systems tract; *TST* = transgressive systems tract. We assume a maximum flooding surface between the boundary of the TST and HST.

Kw1a sequences constitute a confining bed at Atlantic City equivalent to the composite confining bed of Zapecza (1989).

The Kw0 sequence is thin (7.6 m, ~25 ft) at Atlantic City (Fig. 4). Glauconite sand and a shell bed mark the base of the Kw0 sequence at 278.3 m (913 ft). Sr-isotope ages for the sequence are 23.8–22.4 Ma ± 0.4 m.y. and probably represent the temporal equivalent of the Kw0 sequence defined at Cape May (Miller et al., 1996a; Miller and Sugarman, 1995). Benthic foraminifera (*Bulimina gracilis*, *Cibicides primulus*; Gwynn, 1995) indicate inner to middle neritic paleodepths. The thinness and poor recovery prevent documenting details of this sequence, although the upper quartz sands present at the top of sequences elsewhere (Fig. 2) are absent, perhaps due to erosional truncation. Hence, this sequence at Atlantic City contains no aquifer sands.

The Kw1a sequence is approx. 45 m thick at Atlantic City, with neritic shelf and prodelta facies grading upward into shallower inner neritic and nearshore facies (Fig. 4). The Kw1a sequence has a glauconitic shell bed at the base that contains reworked shells (e.g., the 21.9 Ma age; Fig. 4). This bed grades upward into a thick (~21 m) section of burrowed clay–silt to silty sand and laminated clay–silt, typically containing thin dispersed shell hash. These marine sediments are characteristic of inner to middle neritic shelf deposits, with possible minor interfingering of prodelta deposits. This is supported by benthic foraminifera that indicate a maximum flooding surface at 268.2 m (880 ft; dominated by *Uvigerina*) and shallowing upsection from middle (30–100 m) to inner (0–30 m) neritic paleodepths (Gwynn, 1995). Thus, the section from 270.7 to 268.2 m (888–880 ft) corresponds to the transgressive systems tract of Posamentier et al. (1988), while the section above the flooding surface (from 268.2 to 225.9 m; 880 to 741 ft) consists of the highstand systems tract (Fig. 4). Sr-isotope age estimates for this interval are between 20.7 and 20.5 Ma ± 0.4 m.y, indicating a relatively rapid sedimentation rate of 61 m/m.y. Miller and Sugarman (1995) indicate a hiatus of 1.2–1.7 m.y. between the Kw0 and Kw1a sequences at the burrowed unconformity surface (270 m; 886 ft).

The upper facies of the Kw1a sequence consists of a 21 m-thick sand (Fig. 4). The laminated, fine- to medium-grained sand grades upward into a massive coarse quartz sand. Interbedded clays are uncommon. Weathered carbonate is present in several intervals, indicating that shells were present during deposition; sparse diatoms are also present in this interval (Miller et al., 1994b). While some evidence of deltaic facies is present, the overall lack of carbonaceous material and mica indicates that deltaic deposition was minimal at best, with sands being deposited mainly in nearshore to inner neritic environments.

The Kw1a sequence is overlain by the Kw1b sequence. At Atlantic City, the Kw1b sequence is 23 m thick with Sr-isotope age estimates of 20.4–20.2 Ma (Fig. 4). The Kw1b sequence is dark gray and contains two coarsening-upward parasequences. Clayey shelly sands and laminated sands and silts grade upward into massive clayey sands with shells, interbedded sands and lignitic silts, and pebbly sands. The sands in the Kw1b sequence at Atlantic City have characteristics of delta front, inner neritic, and nearshore marine facies. The lower parasequence in Kw1b contains shells and is interpreted as inner neritic to nearshore, while the absence of shells, foraminifera, and diatoms in the upper parasequence is interpreted to represent delta front conditions (Fig. 4).

At Atlantic City, the composite confining bed is composed of the Kw0 sequence and the lower part of the Kw1a sequence. This confining bed overlies the Piney Point aquifer, an upper Oligocene glauconitic quartz sand. The Atlantic City 800-foot sand is correlative with the sands of the upper Kw1a and Kw1b sequences; the thin lower clay–silt at the base of the Kw1b sequence may act as a leaky confining bed in certain locations (Zapecza, 1989). The consolidation of the 700 ft and 800 ft horizons into the 'water-bearing sand' of Woolman (1895) or the Atlantic City 800-foot sand of Zapecza (1989) is based in part on: (1) the fact that the Kw1a sand is much thicker, and is the sand in which the majority of wells are screened in the Atlantic City area; and (2) the relatively thin (~3 m at Atlantic City; 9 m thick maximum) clay–silt at the base of the Kw1b sequence is mainly a leaky confining bed (Zapecza, 1989). This clay–silt has minimal hydrologic effect compared with the confining properties and thickness of the clay–silt within the Kw2a, Kw2b, and lower Kw3 sequences.

The Kw1b sequence is overlain by the Kw2a sequence; a hiatus of ~2 m.y. is present at the unconformity between Kw1b and Kw2a (20.2–18.1 Ma). The Kw2a and Kw2b sequences are 60 m thick at Atlantic City. Together, these sequences constitute a predominantly fine-grained unit consisting of laminated clay–silt to fine sand that is frequently micaceous and shelly, with thin interbeds of clay and sand. Less typical is a massive, burrowed silt facies. Sr-isotope age estimates for the Kw2a and Kw2b sequences are 18.1–16.3 Ma; a 0.7 m.y. hiatus (17.0–16.3 Ma) separates them (Miller and Sugarman, 1995). The base of the Kw2a sequence consists of shelly, silty sands (203–201.2 m; 666–660 ft) with inner neritic benthic foraminifera (*Nonionella* dominate; Miller et al., 1994b). From 202.4 to 167.6 m (664 to 550 ft), silty clays dominate; occasional shell beds suggest prodelta to inner neritic environments. An upper quartz sand, interbedded with carbonaceous silts, is present in the upper Kw2a sequence. This sand is the upper part of the highstand systems tract, and is the Rio Grande water-bearing zone of Zapecza (1989). It is a thinner sand and a less important aquifer, compared to the Atlantic City 800-foot sand.

The Kw2b sequence is thin (13 m) at Atlantic City (Fig. 4). Shelly silty clays deposited in inner neritic environments dominate this sequence. No upper sands are present and only the transgressive systems tract predominates. The absence or thinness of the highstand systems tract sands indicate that they may be truncated. The Kw2a and Kw2b sequences contain characteristic prodelta facies, and less typically, delta front facies. Where the sand bed at the top of the Kw2a sequence is absent, it is extremely difficult to separate the Kw2a and Kw2b sequences. The Kw2a and Kw2b sequences form the major part of the confining bed overlying the Atlantic City 800-foot sand. The lower part of the Kw3 sequence forms the upper part of this confining bed.

The Kw2b sequence is overlain by the Kw3 sequence. A major hiatus of 2.6 Ma at Atlantic City separates them; typically, a thin gravel layer primarily composed of quartz with phosphatized bone material is present at the contact (Owens et al., 1995b). The Kw3 sequence has a limited distribution compared with that of the older Kw sequences (Sugarman et al., 1993). The Kw3 is ~30 m thick at Atlantic City; the upper contact is inferred from the gamma-ray log because core was not recovered in this interval. Sr-isotope age estimates are 13.7–13.1 Ma at Atlantic City.

Where it is well preserved, the Kw3 sequence is a shallowing upward-sequence. Inner neritic (dominated by *Nonionella* and *Buliminella*) sediments consisting of burrowed silty clay and micaceous fine sand, both with occasional shell hash, grade upwards into laminated clay–silt and fine sand, shelly in places, which commonly contain mica and carbonaceous material. The latter sediments are interpreted as prodelta deposits. The clay–silt and fine sand laminae grade upward into interbedded fine sand and silt, indicating marine deposition more proximal to the main delta. While the Kw3 section typically shoals upward, in places, the sequence grades upward into a laminated silt–clay sequence containing some interbeds of sand; the environment of deposition for this facies has been interpreted as tidal flat. However, while the upper sands (from 124.4 to 118.9 m; 408 to 390 ft) can be recognized on gamma-ray logs, they commonly are associated with interbedded clays and laminated beds, and form the lower part of the Kirkwood–Cohansey aquifer system.

The contact of the Kw3 sequence and the Cohansey Formation is not certain at the Atlantic City borehole. Miller et al. (1994b) placed it at 70.4 m (231 ft), while Owens et al. (1995b) placed it in the interval of no recovery between 89 and 118.9 m. The Cohansey typically consists of medium to coarse sands with gravel, containing clay or carbonaceous material as a matrix in places, and with minor clay layers. This formation contains fluvial sediments that were possibly deposited in an upper delta plain environment. In this study the entire section upward from 124.4 m is placed in the Kirkwood–Cohansey aquifer system.

4.2. Hydrogeologic cross-sections

Cross-sections *A–A′* (Fig. 5; dip section) and *B–B′* (Fig. 6; oblique strike section) illustrate how a detailed sequence stratigraphic framework allows for resolution of hydrogeologic relationships. In section *A–A′*, these relationships include the extent of the composite confining bed, and the confining bed that overlies the Atlantic City 800-foot sand, and the lo-

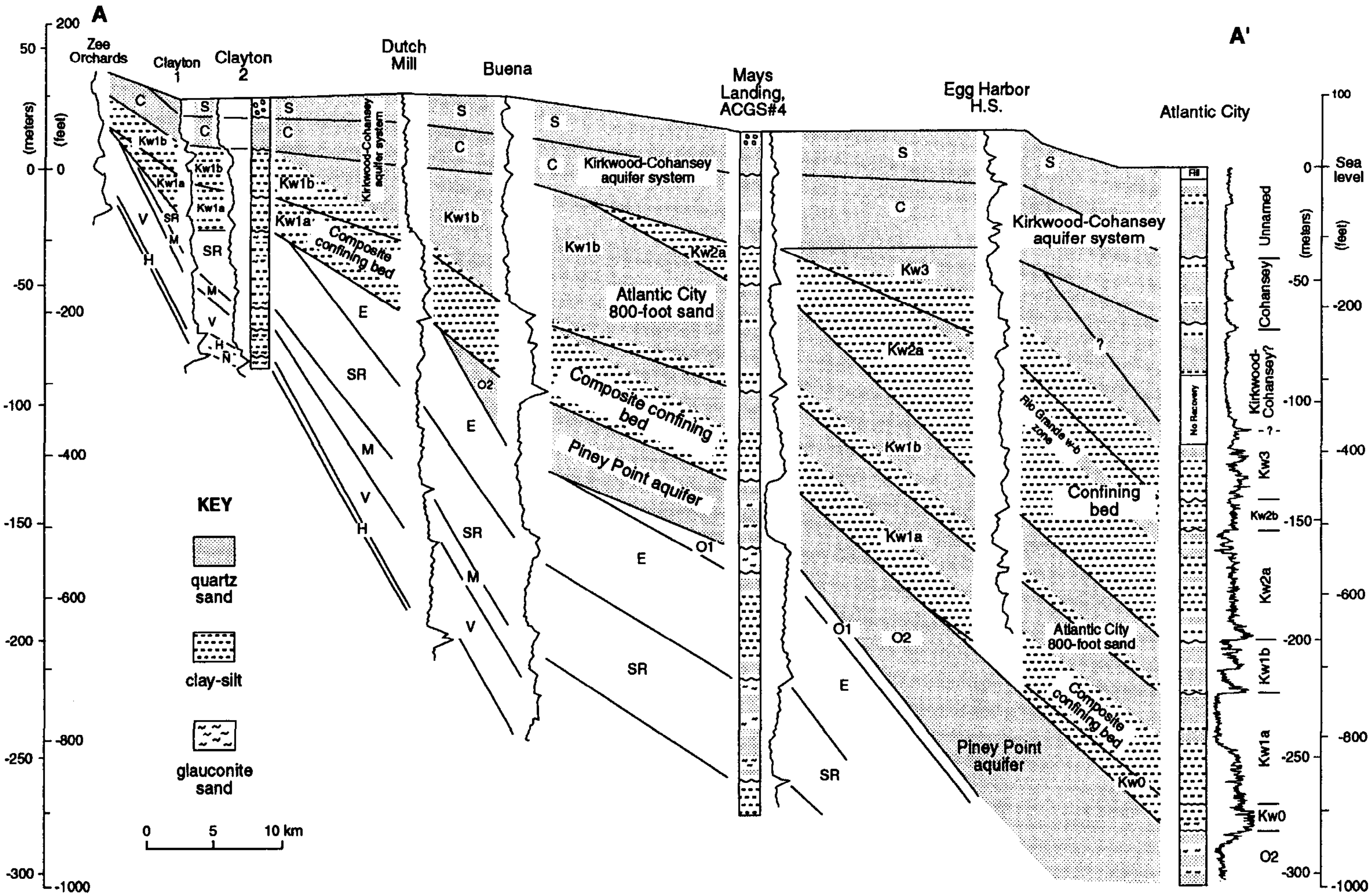

Fig. 5. Cross-section A–A' correlating sequences, generalized lithologies, and hydrogeologic units using the Clayton 2, ACGS-4, and 150X-AC coreholes, and gamma-ray logs from the Zee Orchards, Clayton 1, Dutch Mill, Buena, and Egg Harbor H. S. boreholes. S = surficial deposits; C = Cohansey Formation; *Kw3*, *Kw2b*, *Kw2a*, *Kw1b*, *Kw1a*, *Kw0* = numbered Kirkwood sequences; *Rio Grande w-b zone* = Rio Grande water-bearing zone; *O2*, *O1* = numbered Oligocene sequences; E = unnamed upper Eocene sequence; SR = Shark River Fm.; M = Ma nasquan Fm.; V = Vincentown Fm.; H = Hornerstown Fm.; N = Navesink Fm. Scale is not exact. Modified from Owens et al. (1995b).

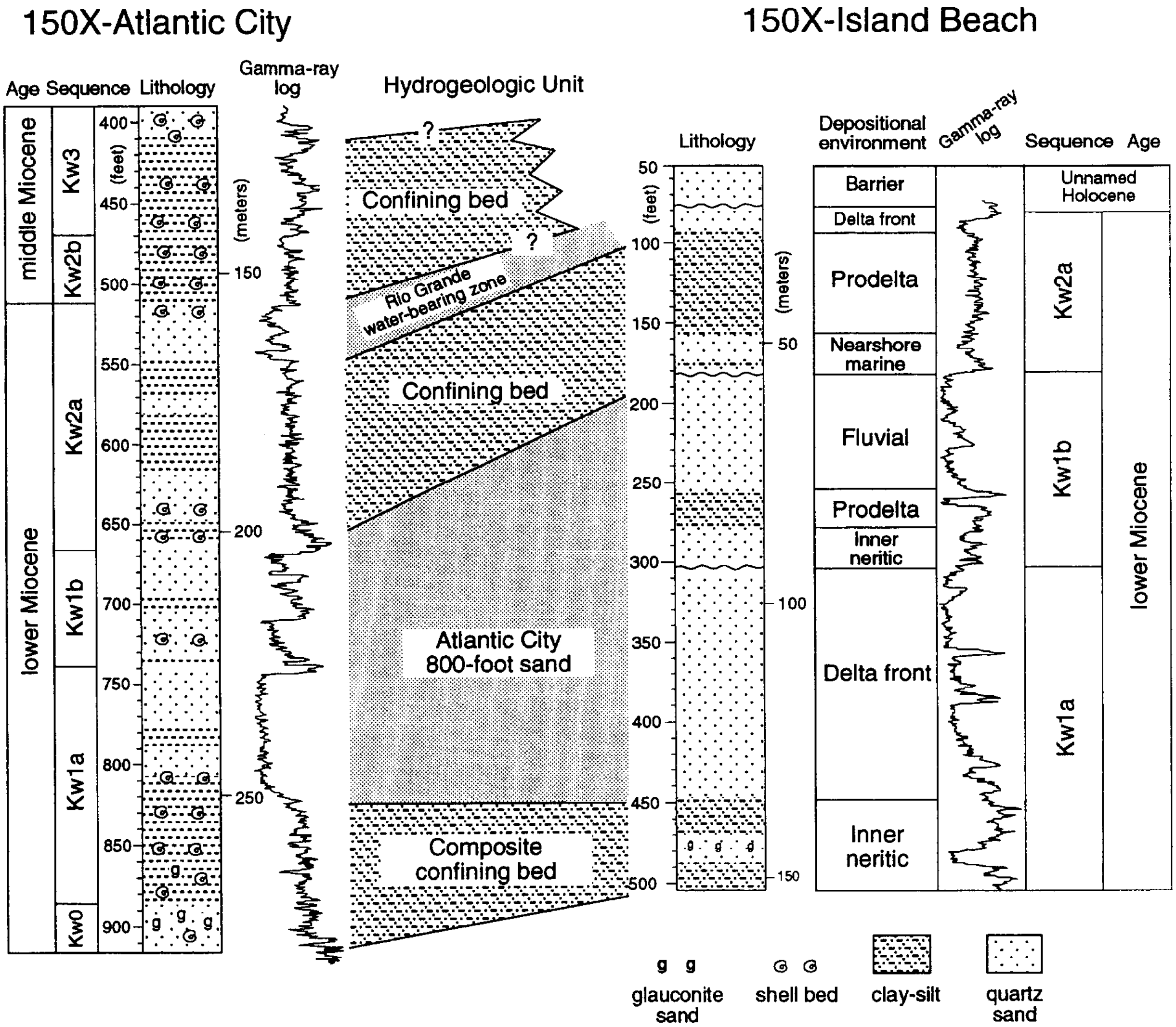

Fig. 6. Cross-section B–B' showing the correlation of hydrogeologic units and sequences between the Atlantic City and Island Beach boreholes, and thickening of the Atlantic City 800-foot sand to the north towards Island Beach.

cation of hydrologic connection between the Atlantic City 800-foot sand and the Kirkwood–Cohansey aquifer system in updip areas of the Coastal Plain. In section B–B' (Fig. 6), the relationships are illustrated along the oblique strike of the Atlantic City 800-foot sand and the confining beds above and below this aquifer.

The composite confining bed below the Atlantic City 800-foot sand is continuous along cross-section A–A' (Fig. 5). At the Atlantic City borehole, the composite confining bed is approx. 31 m thick, correlative with the Kw0 sequence and fine-grained strata from the base of the Kw1a sequence, and separates the Atlantic City 800-foot sand from the upper Oligocene Piney Point aquifer of Zapecza (1989). At the ACGS-4 borehole, approx. 25 km updip, the composite confining bed is 23 m thick and consists only of Miocene strata.

Gamma-ray logs from the updip Buena and Dutch Mill boreholes indicate that the composite confining bed is approx. 37 m thick. Further updip at the Clayton 2 borehole (about 30 km updip from ACGS-4), the composite confining bed is approx. 31 m thick, and the sand facies from the Kw1a and Kw1b sequences (Atlantic City 800-foot sand) are entirely absent. With no lithologic samples from the Buena and Dutch Mill boreholes, and limited fossiliferous material from the Clayton 2 borehole for biostratigraphy and Sr-isotope stratigraphy, it is difficult to reliably correlate the upper part of the composite confining bed with either the Kw1a or Kw1b sequence, and the bed may contain both sequences. A single Sr-isotope age of 20.6 Ma ± 0.5 m.y. from a depth of 52 m in the Clayton borehole apparently correlates with the base of the Kw1b sequence. At Clayton, the composite confining bed also includes the Shark River, Manasquan, Vincentown, Hornerstown, and Navesink Formations.

At Atlantic City, the Atlantic City 800-foot sand is dominantly composed of the upper sand facies from the Kw1a sequence. The upper 21 m of the Kw1a sequence is the major component of the aquifer, compared with about 12 m of sand in the Kw1b sequence (tops of two parasequences at 225–218.5 m and 209.7–203.6 m). The situation is reversed in the updip ACGS-4 borehole, with the Atlantic City 800-foot sand dominated by the Kw1b sand. The sands at the top of the Kw1a sequence at the ACGS-4 borehole are 7.6 m-thick and appear to pinch out updip near the Buena well (Fig. 5).

The confining bed above the Atlantic City 800-foot sand and below the Kirkwood–Cohansey aquifer system is composed of the Kw2a, Kw2b, and the lower part of the Kw3 sequences. This confining bed is thickest at the Atlantic City and Egg Harbor H. S. boreholes (Fig. 5) for the following reasons: (1) the Kw3 sequence, which forms the top of the confining bed, is present in the southern New Jersey Coastal Plain (Sugarman et al., 1993); and (2) the depocenters for the Kw2 sequences are also extensive in this vicinity (Sugarman et al., 1993). At Atlantic City, the confining bed overlying the Atlantic City 800-foot sand is approx. 80 m thick (Fig. 4). Within the confining bed is a thin-section of quartz sand, correlated with the Rio Grande water-bearing zone, at the top of the Kw2a sequence. Above this confining bed is a very thick section of sand correlated with the Kirkwood–Cohansey aquifer system. At ACGS-4, the confining bed above the Atlantic City 800-foot sand is 26 m thick and is correlated with the Kw2a sequence. Above the Kw2a confining bed at the ACGS-4 borehole is 49 m of the Kirkwood–Cohansey aquifer system, that extends to land surface. No Rio Grande water-bearing zone is present at the ACGS-4 borehole.

A major change takes place upsection over the 16 km distance between ACGS-4 and Buena. The Kw2 sequence and the confining bed above the Atlantic City 800-foot sand pinch out updip, allowing the Cohansey Formation to lie directly on the upper sands of the Kw1b sequence. At the Buena borehole, the sand component from the Kw1b is quite thick (~52 m). While previously assigned to the Atlantic City 800-foot sand, it is the major component of the Kirkwood–Cohansey aquifer system at Buena. At Dutch Mill, approx. 6.5 km updip, the Kw1b sand is less than 30 m thick, and provides about half of the stratigraphic thickness of the Kirkwood–Cohansey aquifer system. The Kw1b sand pinches out updip from the Dutch Mill site. At the Clayton 1 and 2 boreholes, the Kw1 sequence is entirely clay–silt, and the upper sand has either been beveled off by erosion or was never deposited. This interconnection of sands from the Kw1b sequence and sands and gravels from the Cohansey Formation and surficial deposits at Buena and Dutch Mill has important hydrologic significance because significant ground-water recharge is possible directly to the 800-foot sand from the Kirkwood–Cohansey aquifer system. Further updip at Clayton, the Kirkwood–Cohansey aquifer system lies directly on the composite confining bed.

The oblique strike section (*B–B′*; Fig. 6) between Island Beach and Atlantic City also illustrates stratigraphic thickening and thinning of units from the southerly, downdip Atlantic City borehole to the Island Beach borehole. The composite confining bed below the Atlantic City 800-foot sand is thicker at Atlantic City (22 m) than at Island Beach (19.5 m) because of the presence of thicker middle shelf strata assigned to the Kw0 sequence at Atlantic City that is absent at the Island Beach site. However, the Atlantic City 800-foot sands thicken toward Island Beach. This updip thickening toward the north reflects: (1) thickening in the Kw1a sands, probably due to closer proximity to the delta lobe in the north; and (2) thickening in the Kw1b sands because of the proximity to the delta lobe and the fluvial facies encountered at Island beach (Miller et al., 1994a;

Owens et al., 1996). This facies variation affects the hydrologic characteristics of the aquifer sands. For example, the aquifer sands at Island Beach are coarser and hence may be more permeable, although local facies variability is greater in the fluvial facies.

5. Discussion

5.1. Sequences, hydrogeologic units, and global sea-level

The New Jersey Miocene sequences can be correlated with globally-observed phenomena including oxygen-isotope data (Miller et al., 1991a,b). Boundaries between the major sequences in New Jersey (Kw0, Kw1a, Kw2a, Kw2b, and Kw3) show an excellent correspondence to global $\delta^{18}O$ increases associated with Mi1, Mi1a, Mi1b, Mi2, and Mi3 oxygen isotope zones (Miller and Sugarman, 1995). Only the Kw1b sequence lacks a corresponding $\delta^{18}O$ increase. However, as we noted above, this sequence boundary has no discernible hiatus associated with it, and the regional and interregional significance of this boundary is uncertain. In addition, the Kw1b sequence boundary could correlate with an ~20 Ma $\delta^{18}O$ increase that is poorly defined at present (Miller and Sugarman, 1995). The correlation of five early to middle Miocene sequence boundaries with five $\delta^{18}O$ increases indicates a glacioeustatic influence on the New Jersey sequences because the oxygen-isotope record reflects global ice-volume increases (Miller et al., 1991a).

As suggested above, the relationship between global sea-level change, sequences, and aquifer-confining bed couplets allows us to predict the continuity of hydrogeologic units, with accompanying implications for ground-water studies. For example:

(1) The composite confining bed, consisting of the Kw0 and lower Kw1a sequences, provides a continuous confining bed across most of the coastal plain (Figs. 5, 6). Identification of silty clays as correlative to these sequences using biostratigraphy (e.g., as ECDZ1 or 24–20.5 Ma using Sr-isotope stratigraphy) allows us to predict that the clays are continuous and form effective confining beds.

(2) Identification of sands correlative to the highstand systems tract of Kw1a or Kw1b (the Atlantic City 800-foot sand) using biostratigraphy (e.g., as ECDZ1 or ca. 20 Ma using Sr-isotope stratigraphy) allows us to predict an extensive and interconnected aquifer.

(3) Identification of silty clays as correlative to Kw2a or Kw2b (e.g., ECDZ2 or 18–16 Ma using Sr isotope stratigraphy) allows us to predict an extensive confining bed (the confining bed of Zapecza (1989) that pinches out updip toward the innermost coastal plain (Fig. 6; Fig. 3 in Sugarman et al., 1993).

(4) Identification of sands correlative to Kw2a (e.g., ECDZ2 or 17–16 Ma using Sr isotope stratigraphy) allows us to predict an areally restricted aquifer (the Rio Grande water-bearing zone).

(5) The poor predictability of confining beds within the Kw3 and younger sequences (including the Kirkwood–Cohansey aquifer system) is a result of large, rapid global sea-level changes in a slowly subsiding basin, resulting in less-marine facies.

6. Conclusions

Although sequence stratigraphy and global correlations have improved our understanding of local and regional hydrogeology, tectonics can limit the application of predictions. For example, basinal tectonic differences between the central New Jersey coastal plain and the Cape May–Delmarva peninsulas (Owens et al., 1988) result in a different distribution of hydrogeologic units. In fact, the composite confining bed and the Atlantic City 800-foot sand appear to be absent or thin in Maryland (Woolman, 1895), while additional aquifers may be present in the lower and middle Miocene at Cape May (Miller and Sugarman, 1995). In addition, localized changes in sediment supply can affect aquifer thickness. For example, the Kw1a sands thicken toward the east whereas the Kw1b sands thicken updip (section *A–A′*, Fig. 5), and the Kw1a and Kw1b sequences become coarser and thicker to the north (section *B–B′*, Fig. 6). As noted above, not all sequences have aquifer sands due to facies changes and/or erosional truncation of sequences. Finally, facies changes can affect aquifer permeability and yield due to changes in sand grain size. For example, the northerly increase in sand in the Kw1b sequence (Fig. 6) is accompanied by an increase in grain size; thus, the upper part of the Atlantic City 800-foot sand can be expected to yield more water at Island Beach than at Atlantic City. We conclude that while sequence stratigraphy is not a panacea for solving hydrogeologic problems, it does constitute a powerful predictive tool that can help in determining aquifer and confining-bed distributions.

Acknowledgements

This paper is dedicated to James P. Owens, who passed away in June 1995. Many of the concepts presented here are modifications of Jim's last publication (Owens et al., 1995b) and we sorely miss his input to this paper. This study was supported by National Science Foundation grants OCE89-11810, OCE92-03282, EAR92-18210, and EAR94-17108 and the New Jersey State Water Bond Issue. Cores were obtained by the New Jersey Coastal Plain Drilling Project, supported by the Continental Dynamics and Ocean Drilling Programs (Island Beach, Atlantic City, and Cape May) and by collaborative USGS and NJGS COGEOMAP drilling (Mays Landing and Clayton boreholes). We thank Mark Feigenson for Sr-isotopic analyses, Lloyd Mullikin for borehole data from Buena, and Rolf Aadland, Mimi Katz, James Miller, and Otto Zapecza for reviews.

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