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TRANS-ATLANTIC CORRELATIONS OF UPPER CRETACEOUS MARINE SEDIMENTS: THE MID-ATLANTIC (USA) AND MAASTRICHT (NETHERLANDS) REGIONS

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ABSTRACT: Upper Cretaceous marine deposits from the Mid-Atlantic region of North America (Delaware, Maryland, and New Jersey) and the Maastricht area (southern Netherlands, and nearby Belgium and Germany) are correlated across the Atlantic using a variety of macroinvertebrates, nannofossils, and sequence stratigraphy. Four late Cretaceous Mid-Atlantic sequences, the Marshalltown, Englishtown, Merchantville, and Navesink, span the upper Santonian to lowermost Danian, and have direct correlatives in the Maastricht area. Correlations between the Mid-Atlantic and the Maastricht regions (respectively) are as follows: the upper Santonian to lower Campanian Merchantville and Matawan formations with the Achen and lower Vaals formations; the middle Campanian upper Englishtown Formation with the upper Vaals Formation; the uppermost middle Campanian to upper Campanian Marshalltown, Wenonah, and Mount Laurel formations with the lower Gulpen Formation; the Navesink and lower Severn formations with the middle Gulpen Formation; and the New Egypt and upper Severn formations with the upper Gulpen and Maastricht formations. Additionally, deposits of the Maastricht area also provide support for several proposed subdivisions in the Marshalltown and Navesink sequences. The correlations proposed here can serve to refine the biostratigraphy of large marine vertebrates known from both sides of the Atlantic.

Keywords: Upper Cretaceous, biostratigraphy, sequence stratigraphy, Atlantic

INTRODUCTION

Late Cretaceous marine sediments in the Mid-Atlantic region of North America (New Jersey, Delaware, and Maryland; Figs. 1 and 2) and the Maastricht area of Europe (southern Netherlands, and nearby deposits in Belgium and Germany; Fig. 3) share a rich history of vertebrate paleontology investigations. The marine vertebrate faunas of these two regions are broadly similar, represented by sharks, osteichthyans, turtles, mosasaurs, plesiosaurs, and marine crocodylians. Many genera among these groups are shared across the Atlantic (see Gallagher et al. 2004 for a recent review), and the identification of latest Cretaceous trans-Atlantic species among sharks (Gallagher et al. 2004), mosasaurs (Mulder 1999), and marine crocodylians (Gallagher 1993; Mulder et al. 1998) strongly suggests that, for large marine vertebrates, this region can be viewed as a single Atlantic biogeographic province.

Until now, the temporal correlations among these important trans-Atlantic sections have suffered from a lack of refinement, despite significant work in individual localities during the last two decades. As it stands, the relationship between the North American and European deposits is not self-evident, because the lithologies of the Mid-Atlantic region and the Maastricht area are dramatically different. Clastic, glauconite-rich deposits of New Jersey (Gallagher 1993; Sugarman et al. 1995; Miller et al. 2004) and Maryland (Minard et al. 1977) stand in sharp contrast to the chalks of the Maastricht area (Jagt 1999).

This synthesis of late Cretaceous lithostratigraphy, biostratigraphy, and sequence stratigraphy of the Mid-Atlantic region and the Maastricht area offers a more highly resolved framework for understanding biotic events within the theater of an Atlantic biogeographic province. Our

correlation is based upon macroinvertebrates (ammonites and belemnites), nannofossils (calcareous nannofossil and dinoflagellates), and sequence stratigraphy, which combine to form a robust series of temporally bracketed lithostratigraphic packages.

The identification and correlation of these packages facilitates the reconstruction of penecontemporaneous trans-Atlantic paleobiological events, including the sequence, timing and pace faunal changes, migrations, and, extinctions. For example, Ross (in review) employed the correlations proposed here to quantitatively analyze mosasaur extinction within the Atlantic biogeographic province during the Maastrichtian. The correlations proposed here thus provide the framework for such investigations.

TEMPORAL CORRELATION

We begin our discussion with the Mid-Atlantic region, and follow with correlation of deposits from the Maastricht area. Figure 4 summarizes our correlation of the trans-Atlantic biogeographic province in the late Cretaceous.

Stratigraphy of the Mid-Atlantic Region

The litho- and biostratigraphy of New Jersey, Delaware, and Maryland are well understood (Gallagher 1993; Sugarman et al. 1995; Kennedy et al. 2000; Miller et al. 2004; Landman et al. 2004ab). In recent sequence stratigraphic analyses utilizing physical stratigraphy, calcareous nannofossils, foraminifera, and Sr-isotope age estimates, Sugarman et al. (1995) and Miller et al. (2004) indicate that there are four sequences of importance to this study: the Santonian-middle Campanian Merchantville sequence, the Middle Campanian Englishtown sequence, the Upper Campanian Marshalltown sequence, and the Maastrichtian-lowest

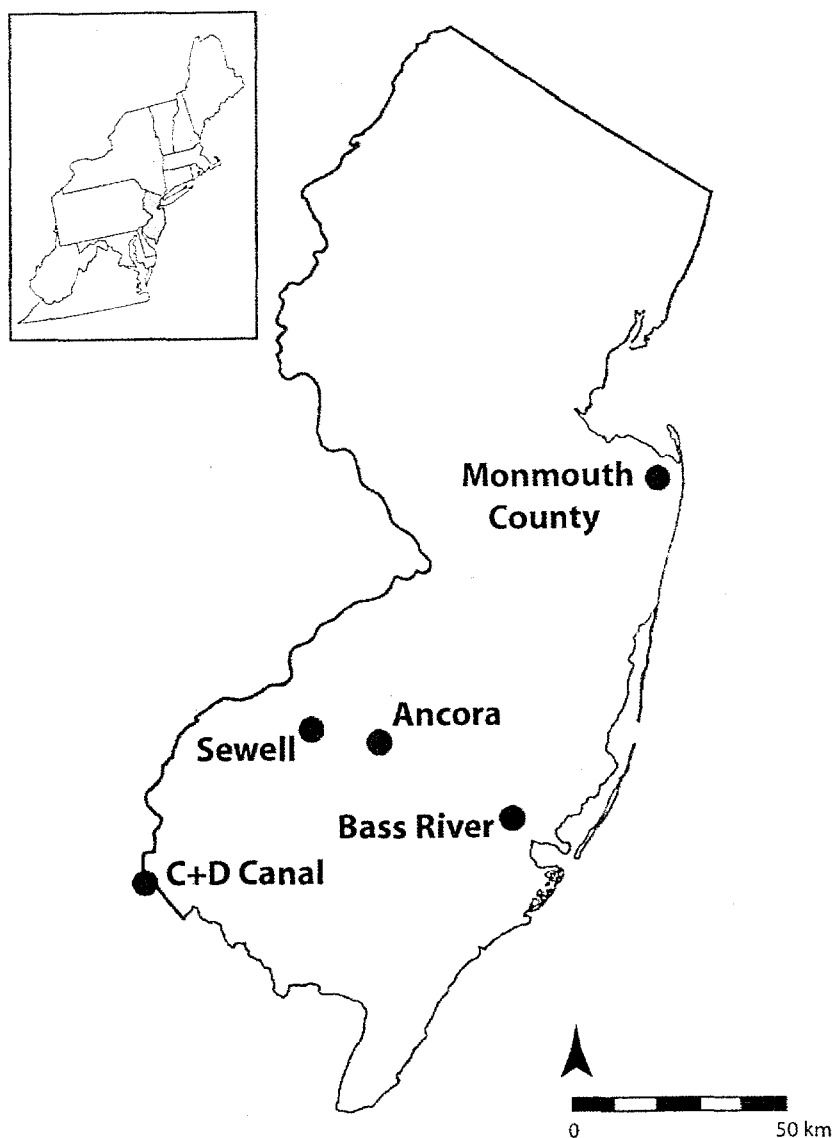


Figure 1. The state of New Jersey, with east-central and northeastern United States (insert). Relevant localities noted, see text for discussion.

Paleocene Navesink sequence. Additionally, Miller et al. (2004) recognize three smaller sub-sequence packages within the Merchantville sequence, and two sub-sequences within the Navesink. The formations of the Mid-Atlantic region will be discussed below in the context of their respective sequences following Sugarman et al. (1995) and Miller et al. (2004).

The Merchantville Sequence(s): Santonian to Middle Campanian.-- Miller et al. (2004) identified the Merchantville sequence in borehole cores at Ancora and Bass River (Fig. 1). The base of the sequence is dated $84.3 \text{ Ma} \pm 1 \text{ myr}$ by marine $^{87}\text{Sr}/^{86}\text{Sr}$ ratios plotted against geologic time (Miller et al. 2004), and is defined by a short-duration (0.4 Ma) unconformity at the base of the Merchantville Formation. The complete sequence includes

the Merchantville, Woodbury, and basal Englishtown Formations (Miller et al. 2004). The entire Merchantville sequence correlates to UZA3.4 through UZA4.1 sea-level cycles of Haq et al. (1987). The sequence boundary, as represented by an unconformity within the basal Englishtown Formation, spans an estimated 1 myr, from 77.8-76.8 Ma (Miller et al. 2004; see Fig. 4).

Miller et al. (2004) tentatively subdivide the Merchantville sequence into three smaller sequences, Merchantville I-III. The lower two sequences, Merchantville I and II, contain only the Merchantville Formation at both cores. Sr-isotope plots give the Merchantville I and II sequences an age range of 85.2 - 83.5 Ma (but see below for a re-evaluation of this range), and the unit is correlated to UZA3.4 and UZA3.5 (Miller et al. 2004). Miller et al. (2004) state that

UPPER CRETACEOUS TRANS-ATLANTIC CORRELATIONS

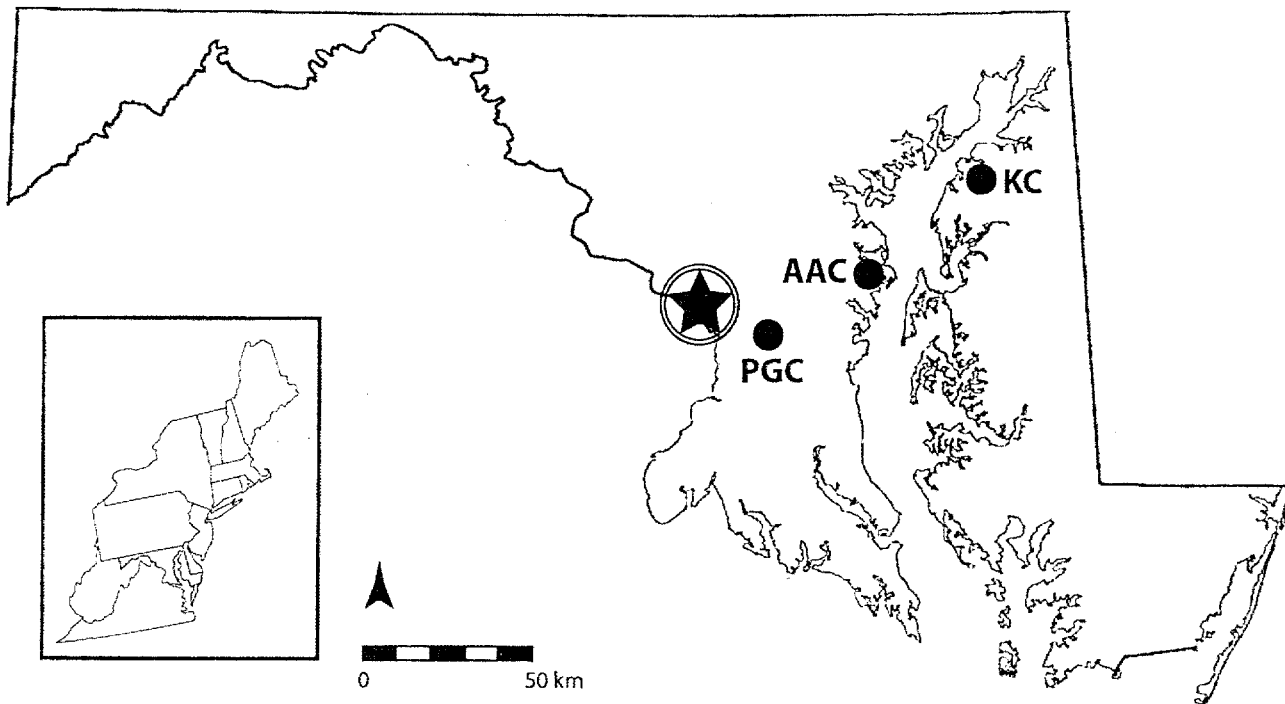


Figure 2. The state of Maryland, with east-central and northeastern United States (insert). Relevant localities noted, see text for discussion. PGC = Prince Georges County, AAC = Anne Arundel County, KC = Kent County, circled star = Washington, D.C.

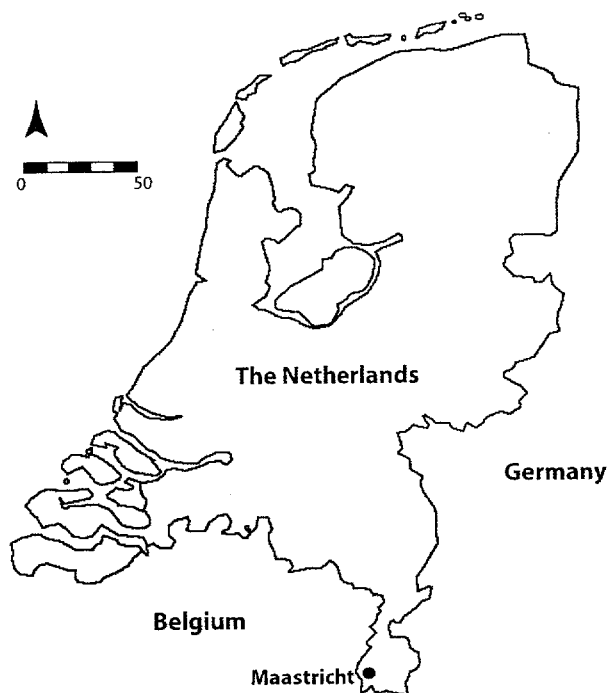


Figure 3. Map of the Netherlands, with Maastricht (Limburg Province) located.

Merchantville I and II occur within the nannofossil zones CC16 through CC18 (upper Santonian to lower Campanian), where CC18 is found in the Merchantville II sequence.

Likewise, the foraminifer *Dicarinella asymetrica* (lower Campanian) has been identified from the Merchantville II portion of the upper Merchantville Formation.

In outcrop studies, Owens (1970) assigned the Merchantville Formation a lower Campanian age based on ammonites. This assignment is corroborated by subsequent studies (Kennedy and Cobban 1993; Kennedy et al. 1997b), which identified the middle lower Campanian taxon *Scaphites hippocrepis* III, which has an eponymous index zone in the Western Interior. The Merchantville Formation can be directly tied to the Maastrichtian area, where *S. hippocrepis* co-occurs with *Baculites vaalsensis* in portions of the Vaals Formation in Germany (Kennedy et al. 1997b). Miller et al. (2004) proposed a tentative sequence boundary between Merchantville II and III, within the lower Campanian nannofossil zone CC18. They estimated a temporal gap of approximately 2 myr ($83.1 - 81 \pm 1$ mya). However, if outcrop sections of the Merchantville Formation record ammonites from the *S. hippocrepis* III zone, the temporal gap is smaller by at least half, as $^{40}\text{Ar}/^{39}\text{Ar}$ ages determined by Obradovich (1993) provide a date of $81.71 \text{ Ma} \pm 0.34$ myr for the lower portion of the *S. hippocrepis* II zone in the Western Interior. We therefore conservatively estimate that the temporal gap between the Merchantville II and III sequences is 82 - 81 Ma (Fig. 4).

Merchantville III is composed of the Woodbury and basal Englishtown Formations, though at the Ancora borehole

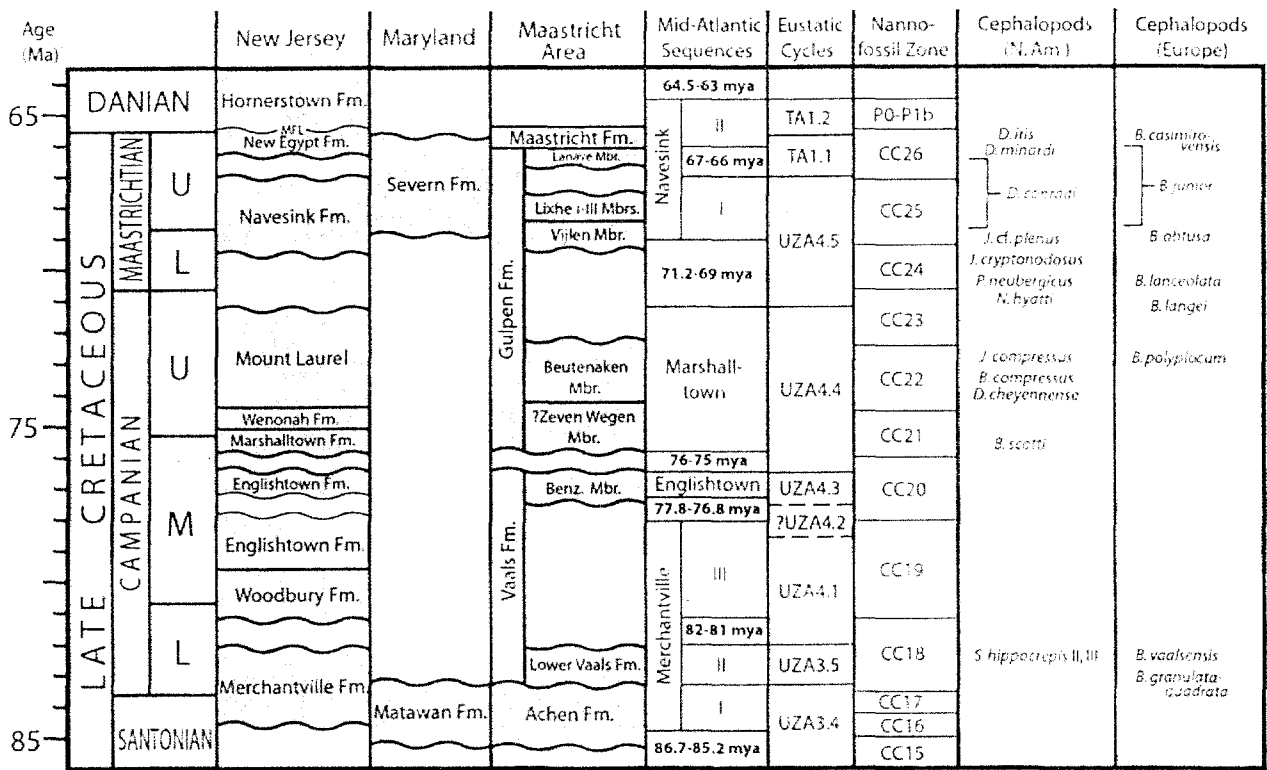


Figure 4. Correlation diagram of Mid-Atlantic and Maastricht area Upper Cretaceous marine deposits. Time scale from Ogg (2004). Ages in bold represent the duration of hiatuses for Mid-Atlantic sequences (from Miller et al. 2004).

the uppermost Merchantville Formation is included (Miller et al. 2004). Most age estimates of the Woodbury and Englishtown Formations have been based on microfossil assemblages from cores (Owens et al. 1970; Olsson 1975; Miller et al. 2004). Calcareous nannofossils are in zones CC18 (upper) and CC19 (and an undifferentiated CC19/20 at the Bass River borehole). In outcrop, the Woodbury and Englishtown Formations are known from few existing sites, as many were temporary or are now overgrown (see Keuhne 1993). The known macroinvertebrate faunas (mainly pelecypods and some ammonites) are consistent with an upper lower to middle Campanian assignment (Gallagher 1993; Keuhne 1993), though high-precision material is lacking. Miller et al. (2004) correlate Merchantville III to the third-order eustatic cycle UZA 4.1 (Haq et al. 1987).

The Englishtown Formation: Middle Campanian.— In bores from Ancora and Bass River, an unconformity within the Englishtown Formation represents a sequence boundary of 1.0 myr separating the Merchantville and Englishtown sequences (Miller et al. 2004; Fig. 4). The upper sequence boundary is located at the unconformable Englishtown/Marshalltown contact (Miller et al. 2004). Based on limited calcareous nannofossil material, Miller et al. (2004) place this unit within the middle Campanian CC20 zone. They correlate the Englishtown sequence to UZA4.3 (Haq et al. 1987). Ammonite assemblages are consistent with assignment to lower- and middle Campanian, but high-

resolution taxa have not been recovered (Gallagher 1993; Keuhne 1993).

The Marshalltown Sequence: ?Middle Campanian-Upper Campanian.— The Marshalltown sequence includes the upper Campanian Marshalltown, Wenonah, and Mount Laurel Formations (Sugarman et al. 1995; Miller et al. 1999, 2004). An unconformable contact is located at the base of this sequence between the upper Englishtown and Marshalltown Formations. Sr-isotope curves indicate that the unconformity represents approximately myr, lasting from ~76 to 75 Ma ± 1 myr, though Miller et al. (2004) note that this sequence boundary is rather poorly constrained.

The Marshalltown Formation lies at the base of the Marshalltown sequence, conformably overlain in some areas of New Jersey by the Wenonah Formation. The Wenonah Formation crops out in the Atlantic Highlands region and areas to the immediate southwest (Kennedy and Cobban 1994a), and pinches out to an unconformity at the Chesapeake and Delaware (C+D) Canal in Delaware (Kennedy and Cobban 1997). Cores from New Jersey indicate that the Wenonah Formation is not always present in the subsurface (Sugarman et al. 1995; Miller et al. 2004).

From core samples, Sugarman et al. (1995) placed the Marshalltown Formation in nannofossil zone CC20/21.

An updated analysis by Miller et al. (2004) placed only the lowest portion of the Marshalltown Formation in CC20 at Ancora, and in CC21 at Bass River. The remaining Marshalltown and Wenonah Formations are found entirely within middle- to upper Campanian zone CC21.

Ammonite assemblages described by Kennedy and Cobban (1997) suggest that ammonites from the Marshalltown Formation, including *Menuites portlocki complexus* and *Didymoceras binodosum*, are known from the uppermost middle Campanian *Baculites scotti* zone of the Western Interior. Likewise, in the Wenonah Formation, *Didymoceras* n. sp. and *Baculites* cf. *B. scotti* indicate correlation to the uppermost middle Campanian *Baculites scotti* zone of the Western Interior. Thus both the Marshalltown and Wenonah Formations are partially to wholly within the *B. scotti* zone.

The Mount Laurel Formation includes CC21 in its basal portion, and the remaining portion of the formation ranges through upper (but not uppermost) Campanian zone CC23a and uppermost Campanian foraminifera zone *Globotruncana havanensis* (Miller et al. 2004). This correlates well with the ammonite fauna described by Kennedy and Cobban (1994b, 1997). These authors (1997) note that the basal Mount Laurel Formation (unconformably overlying the Marshalltown Formation in the Chesapeake and Delaware Canal area (Fig. 1) contains an ammonite fauna including *Didymoceras stevensoni* and *Exiteloceras jenneyi*, index species of successive and eponymous ammonite zones in the lower upper Campanian Western Interior.

The rest of the Mount Laurel Formation contains an upper (but not uppermost) Campanian ammonite fauna including *Didymoceras cheyennense* (an index taxon in the Western Interior) and *Anaklinoceras reflexum*, which is restricted to the *Baculites compressus* zone of the Western Interior (Kennedy and Cobban 1994b, 1997).

Obradovich (1993) has dated the *B. compressus* zone as 73.35 Ma \pm 0.39 myr, using $^{40}\text{Ar}/^{39}\text{K}$ from sanadines.

Kennedy and Cobban (1994b) correlated this ammonite assemblage to upper Campanian cephalopod zones in Europe. They noted that two Mount Laurel taxa, *Jeletzkytes compressus* and *Hoploscaphites vistulensis* are known from the upper Campanian of Germany and Poland, respectively, and that *J. compressus* is, at a minimum, found within the European ammonite zones of *Bostrychoceras polyplacum* and *Didymoceras donezianum*. The ranges of the taxa may extend further (particularly into the upper Campanian), but likely does not extend into the uppermost Campanian. In the Maastricht area, the *Bostrychoceras polyplacum* zone is known from the Beutenaken Member of the Gulpen Formation in Germany (Jagt 1999). The bulk of the biostratigraphic evidence indicates that the top of the Mount Laurel Formation (and thus the top of the Marshalltown

sequence) is upper (but not uppermost) Campanian in age. This estimate corroborates the Sr-isotope age of 71.2 Ma \pm 0.5 myr for the top of the sequence (Miller et al. 1999, 2004).

The Navesink Sequence(s): Lower Maastrichtian to Lowest Paleocene.-- Deposits of the Navesink sequence (Navesink, Red Bank, Tinton, New Egypt, and basal Hornerstown Formations; Sugarman et al. 1995; Miller et al. 1999, 2004; Olsson et al. 2002) are perhaps the best known and thoroughly studied upper Cretaceous deposits in the Mid-Atlantic region. Numerous authors have discussed the fauna of these deposits (see below), and collection of fossil material has been ongoing since the mid- to late-1800s. Recent investigations, particularly those addressing the New Egypt Formation, bring greater resolution to our understanding of this sequence.

The Navesink Formation unconformably overlies the Mount Laurel Formation. This unconformity represents a sequence boundary of approximately 2.2 myr that spans the Campanian-Maastrichtian boundary and separates the Marshalltown and Navesink sequences (Miller et al. 1999, 2004; Sugarman et al. 1995). A basal deposit at the Mount Laurel/Navesink contact appears to be a condensed section, and produces an ammonite fauna of latest Campanian to earliest Maastrichtian age, and includes the uppermost Campanian *Nostruceras hyatti* and the lowermost Maastrichtian *Pachydiscus neubergicus* (Kennedy et al. 2000). Kennedy et al. (2000) correlated ammonite taxa from the basal Navesink to the cephalopod (ammonite and belemnite) zones of northwest Europe. They note that, of the specimens recovered, *Nostruceras hyatti* can be directly correlated to the uppermost Campanian *Belemnitella langei* zone, while *Pachydiscus neubergicus* occurs in the lowest Maastrichtian *B. lanceolata* zone, and is a marker species for the base of the Maastrichtian stage in Europe (Ogg 2004).

Above the sequence boundary, the Navesink Formation is placed in the lower Maastrichtian by dinoflagellates (*Palaeohystrichophora infusorioides* zone) in three sites in New Jersey (Monmouth County, New Egypt, and in a well core south of Sewell; Koch and Olsson 1977). The ammonite fauna of Monmouth County indicates a lower Maastrichtian age for the Navesink Formation, largely based on the presence of *Jeletzkytes criptonodosus* and *J. cf. plenus* (Cobban 1974; Kennedy et al. 2000). *Jeletzkytes criptonodosus* and *J. cf. plenus* occur in the Lower Maastrichtian *Baculites eliasi* and *B. baculus* zones of the Western Interior (Kennedy et al. 2000). In Maryland, the Severn Formation (=Monmouth Formation; see Minard et al. 1977) consists of clay- and silt-rich bioturbated sandstones (see Kennedy et al. 1997a; Landman et al. 2004a). Exposures of the Severn Formation in Prince Georges County, Maryland (Fig. 2), record ammonites of the *Discoscaphites conradi* zone and dinoflagellates

correlate to nannofossil zone CC25b (Landman et al. 2004a), correlative to part of the Navesink Formation.

Calcareous nannofossils place the Navesink Formation in the lower Maastrichtian (CC25a) to upper Maastrichtian (lower CC26) at the Bass River borehole (Miller et al. 2004). The Navesink is not differentiated from the New Egypt Formation updip at Ancora, and ranges from the lower Maastrichtian to the K/T boundary (Miller et al. 2004). However, a minor unconformity separates the Navesink Formation into two units at Ancora. This unconformity is correlated to the Navesink/New Egypt boundary at Bass River, and the unconformity may represent an ~1 m.y. hiatus from 67 - 66 Ma \pm 0.5 myr (Miller et al. 2004). Miller et al. (2004) tentatively propose that the unconformity represents a small sequence boundary, one that divides the Navesink sequence into Navesink I and II and is likely correlative to the UZA4.6/TA1.1 cycle boundary. Taken together, the biostratigraphic and sequence stratigraphic data indicate that the Navesink Formation (in Navesink I) spans the lower Maastrichtian to lower upper Maastrichtian in the subsurface. However, updip at surface exposures in Monmouth County the Navesink Formation is older both at its base and (likely) at its contact with the overlying Red Bank Formation, based on the ammonite fauna (see above). Miller et al. (2004) correlate the Navesink I sequence with UZA4.5 (Haq et al. 1987).

The Red Bank Formation overlies the Navesink Formation in Monmouth County. The Red Bank Formation and the overlying Tinton Formation are of upper Maastrichtian age based on ammonites (Owens et al. 1970) and dinoflagellates (Koch and Olsson 1977). They are equivalent to the New Egypt Formation to the south (Koch and Olsson 1977; Staron et al. 2001).

Though once considered to be an upper Maastrichtian portion of the Navesink Formation (Gallagher 1993, 2002; Kennedy et al. 2000), it is the New Egypt Formation that is exposed at the classic K/T boundary section at the Inversand pit mine in Sewell, NJ (Koch and Olsson 1977; Staron et al. 2001; William Gallagher, pers. comm., May 2004). The New Egypt Formation as exposed at Sewell and Monmouth County is upper to uppermost Maastrichtian in age. Koch and Olsson (1977) noted uppermost Maastrichtian dinoflagellates (*Deflandrea cretacea* zone) from the New Egypt Formation both at Sewell and in a nearby well core to the southeast. Staron et al. (2001) added that this dinoflagellate assemblage is found in the Tinton Formation but not the older Red Bank Formation. However, nearby boreholes show that correlations to the older dinoflagellate (*Deflandrea magnifies* to *Svalbardella australina*) and foraminifer (*Globotruncana gansseri*) zones found in the Red Bank Formation exist in the subsurface (Koch and Olsson 1977).

To the north, in Monmouth County, Landman et al.

(2004b) have identified upper to uppermost Maastrichtian dinoflagellates from surface exposures of the New Egypt Formation. According to their findings, the lower to middle portion of the New Egypt Formation is upper Maastrichtian, correlative to the upper nannofossil zone CC26a and lower 26b. The upper New Egypt Formation has produced the uppermost Maastrichtian *Palynodinium grallator*, which they correlate to the upper portion of nannofossil zone CC26b.

Kennedy et al. (2000) reported a specimen of the ammonite *Discoscaphites gulosus* from Sewell, which they correlate to the *Hoploscaphites nicolletii* or *Jeletzkytes nebrascensis* zone of the Western Interior. These are the highest ammonite zones within the Western Interior, but their uppermost range in that region is unknown, as marine deposits in the Western Interior are not known that record a complete K/T boundary (see Dyman et al. 1994). Recent finds of ammonites from Monmouth County (Fig. 1), place the upper New Egypt Formation within the uppermost Maastrichtian North American ammonite zones of *Discoscaphites minardi* and *D. iris* (Landman et al. 2004).

From subsurface cores at Bass River, Miller et al. (2004) record a small unconformity at the Navesink-New Egypt contact, and suggest that a sequence boundary may exist there (see above). At the Ancora borehole, the New Egypt Formation is not lithologically distinguishable from the underlying Navesink Formation, which ranges to the K/T boundary. There the upper portion of the Navesink Fm is correlative to the New Egypt Formation at Bass River and in surface exposures. Miller et al. (2004) provide an Sr-isotope-derived date of 66 Ma \pm 0.5 myr for the base of the New Egypt. At each core, calcareous nannofossils place the New Egypt/upper "Navesink" Formation in the uppermost Maastrichtian (upper CC26, *Micula prinsii* subzone), as do dinoflagellates (*Globotruncana gansseri* and *Deflandrea cretacea* zones) and foraminifera (*Abathomphalus mayaroensis* zone). The unit is conformably overlain by a complete K/T boundary series (see below). Based on these data, Miller et al. (2004) correlated the Navesink II sequence with TA1.1 of Haq et al. (1987), but the inclusion of uppermost Maastrichtian and earliest Paleocene in the Navesink (Navesink II) sequence necessitates the correlation to TA1.2 as well.

Outcrops of the Severn Formation on east and west banks of the Chesapeake Bay, Maryland, are correlated with the New Egypt Formation (Landman et al. 2004ab; Fig. 4) on the basis of ammonites and dinoflagellates (Kennedy et al. 1997; Landman et al. 2004a,b). In Anne Arundel County (Fig. 2), the Severn Formation is upper Maastrichtian in age. They place the unit in the *Discoscaphites minardi* ammonite zone, and dinoflagellates correlated to the upper nannofossil zone CC26a to basal CC26b. On the eastern shore of the Chesapeake Bay, in Kent County, they record the upper- to uppermost Maastrichtian ammonite zone *D.*

iris and, based on the dinoflagellate *P. grallator*, assign the Severn Formation to the upper portion of nannofossil zone CC26b. The top of the Severn Formation may not reach the K/T boundary (Kennedy et al. 1997a; Landman et al. 2004a). Combined, the data indicate that the Severn Formation outcrops in Anne Arundel and Kent Counties were deposited during the Navesink II sequence of Miller et al. (2004) within cycle TA1.1, but perhaps not inclusive of TA1.2.

At Sewell, the New Egypt Formation is overlain by the Hornerstown Formation (Koch and Olsson 1977; Staron et al. 2001). The contact between the two units is smeared by bioturbation (Gallagher 1993; Staron et al. 2001). The dinoflagellate assemblage in the basal few centimeters of the Hornerstown Formation is uppermost Cretaceous in age (*Deflandrea cretacea* zones; Koch and Olsson 1977; Olsson 1987). Calcareous nannofossils are not present in outcrop, which appears to be leached of carbonate (Koch and Olsson 1977; Gallagher 1993). However, in the (non-leached) downdip well core to the southeast of Sewell, Koch and Olsson (1977) recorded the same pattern for planktonic foraminifera: uppermost Maastrichtian in the basal Hornerstown, and Danian in the remaining section. The currently accepted age of the K/T boundary is 65.5 Ma \pm 0.3 m.y. (Ogg 2004).

Within the basal Hornerstown Formation at Sewell is the Main Fossiliferous layer (MFL), a 30 cm thick, sedimentologically complex bone bed, within which are the youngest Cretaceous taxa known from New Jersey (Gallagher 1993, 2002; Staron et al. 2001). Gallagher (1993, 2002) considered the MFL to include the K/T boundary, a view consistent with Staron et al. (2001). On the other hand, Koch and Olsson (1977) argued, based on dinoflagellates, that the K/T boundary was located at the top of the MFL (which they termed the "Sewell bone bed") in the basal Hornerstown Formation. Olsson (1987) recorded lower Paleocene dinoflagellates (correlative to foraminifera zone P1a, but not zones P0-Pa) above the MFL, noting that the lack of earliest Paleocene fossils represented a temporal gap of approximately 100,000 years above the K/T boundary.

Using estimates of sedimentation rate, Gallagher (1993; reiterated in 2002) calculated that if the MFL is a condensed section, then the total time of formation for the MFL (time of erosion/nondeposition + time represented by eroded material) is approximately 300,000 years. If we accept this estimate, and recognize that part of the MFL formed during the 100,000 years missing from the Paleocene (an interpretation that is supported by the presence of some Paleocene macrofossils in the MFL), then the total time missing from the uppermost Maastrichtian is 200,000 years or less.

From exposures in Monmouth County, Landman et al. (2005) note the MFL at the New Egypt/Hornerstown

contact. They argue that the MFL is formed by reworking, based the preservation and taphonomy of Cretaceous fossils, potential misidentification of the New Egypt/Hornerstown contact at Sewell (which would place the MFL at the contact), preservation of some delicate Paleocene fossil material, and a lack of a complete K/T boundary section. Though the section is incomplete (no K/T boundary section as described below), Landman et al. (2004b, p. 33) postulate "[t]he amount of time missing is difficult to estimate, but is probably less than 100 k.y. equal to part of the late Maastrichtian and early Danian."

Downdip, two sedimentologically continuous K/T sections have been recorded in boreholes at the Ancora and Bass Rivers. In these locations, the K/T boundary is located at the New Egypt/Hornerstown Formation contact (Miller et al. 1999, 2004; Olsson et al. 1997, 2002). Within these sections are shocked quartz, spherules, and an iridium spike.

Above the MFL at Sewell, Koch and Olsson (1977) noted lower Paleocene dinoflagellates. Olsson (1987) later recognized a gap of an estimated 100,000 years in the record corresponding to foraminifera zones P0-Pa, and that dinoflagellates assigned to zone P1a are present in outcrop. Downdip in the Ancora and Bass River boreholes, sedimentation was continuous across the K/T boundary, and both cores record foraminifera zones Pa to P1a. A sequence boundary, spanning foraminifer zone P1b, marks the end of the Navesink/Navesink II sequence (Miller et al. 2004), and probably correlates to the top of the third-order cycle TA1.2 of Haq et al. (1987). At present, the lower boundary of TA1.2 in New Jersey- is uncertain, though its placement in the Maastricht area has been identified (see below). We posit that the base of TA1.2 may lie either at the New Egypt/Hornerstown contact, or within the MFL itself. The upper sequence boundary in the Hornerstown Formation spans foraminifer zone P1b, and lasts from approximately 64.5 - 63 Ma \pm 0.5 myr (Olsson 2002; Miller et al. 2004).

Stratigraphy of the Maastricht Area

Deposits in the Maastricht area have the benefit of numerous good exposures, easily recognized subdivisions, and excellent, long-term records of collection. Felder (1975a,b) and Albers and Felder (1979) proposed the modern stratigraphic framework for the Maastricht area, including formation and member names. Workers have benefited from the recent full litho- and biostratigraphic description of the Maastricht area by Jagt (1999), who compiled a reference section based on classic localities (mostly quarries) in Belgium, the Netherlands, and Germany.

Given the extensive treatment of the stratigraphy in the Maastricht area, we will focus our discussion on how these strata correlate to the Mid-Atlantic region. In particular, we

will focus on macroinvertebrate, microfossil, and sequence stratigraphic correlations (see also Jagt 1999).

Correlatives to the Merchantville Sequence(s).— The Achen Formation appears to correlate with the Merchantville (Merchantville I and II) sequence of Miller et al. (2004; Fig. 4). The primary evidence comes from calcareous nannofossils. The Merchantville I and II sequences (Merchantville and basal Woodbury Formations) are placed within nannofossil zones CC16 to lowest CC18, a range of upper Santonian to lower Campanian (see above). Jagt (1999) notes that calcareous nannofossils from the Achen Formation are placed within CC15 to CC17 (middle Santonian to Santonian/Campanian boundary). This age range is corroborated by a number of other biostratigraphic methods summarized by Jagt (1999 and references therein). His tabulation gave Middle- to Upper Santonian ages for palynomorphs and microfossils, while ammonites, belemnites, and bivalves may have ranges into the lower Campanian. The nannofossil age would indicate that the Achen Formation lies within Merchantville I and UZA3.4 (Miller et al. 2004).

The oldest beds within the Vaals Formation have been placed in the upper *Belemnitella granulataquadrata* zone (lower Campanian; Albers 1976). Kennedy and Jagt (1995) identified material of *Scaphites hippocrepis*, which is correlated to the lower (but not lowermost) Campanian in the Western Interior of North America, a date that corresponds to nannofossil material from zone CC18 (lower Campanian). This material co-occurs with *B. vaalsensis* (Jagt 1999), and Kennedy et al. (1997b) identified this co-occurrence in New Jersey. As noted above, ammonites from outcrops of the Merchantville Formation (most likely within Merchantville II) are also correlated to the *S. hippocrepis* zone. Since Miller et al. (2004) place their Merchantville II sequence within nannofossil zone CC18, the lower Vaals Formation would be placed in Haq et al.'s (1987) third-order cycle UZA3.5. Thus far, no strata from the Maastricht area have been identified as correlative to the Merchantville III sequence (Woodbury and basal Englishtown Formations).

Correlatives to the Englishtown Sequence.— The Benzenrade Member of the Vaals Formation (uppermost member) appears to have an ammonite fauna that spans the (European) lower/upper Campanian boundary, and is within nannofossil zone CC20 (Jagt 1999 and references therein). The Englishtown sequence (Fig. 4) includes a portion of CC20, which is middle Campanian in North America, and correlated to UZA4.3 (Miller et al. 2004).

Correlatives to the Marshalltown Sequence.— The two lower members of the Gulpen Formation, the Zeven Wegen and the Beutenaken, comprise the correlatives to the Marshalltown sequence (Fig. 4). An unconformity separates the Vaals and Gulpen Formations, and Felder (1996) interprets this unconformity as a hiatus. This hiatus may be correlative

to the sequence boundary at the base of the Marshalltown sequence in the Mid-Atlantic (Miller et al. 2004). Support for this comes primarily from invertebrate macrofossil and microfossil data.

Jagt (1999) summarized the macroinvertebrate record of the Zeven Wegen and Beutenaken members, noting that virtually all methods (e.g., ammonites, belemnites, and echinoderms) provide a date of upper Campanian, but little biostratigraphic data exist to correlate these units to deposits in the Mid-Atlantic region. Kennedy and Cobban (1994b) correlated the ammonite fauna of the Mount Laurel Formation to the upper Campanian belemnite *Bostrychoceras polyplacum* zone, which is known from the Beutenaken Member. Jagt (1999) noted that the microfossil data indicates that the Beutenaken Member is within nannofossil zone CC22. Though Jagt (1999) indicated that the Beutenaken Member spans the third-order cycles UZA4.3 and 4.4 of Haq et al. (1987), it appears that the Benzenrade Member correlates to only UZA4.3 (above). Given the current understanding of biostratigraphy, we suggest that the Beutenaken Member (and perhaps the Zeven Wegen Member) correlates to the Marshalltown sequence in the Mid-Atlantic. This correlation places the Beutenaken Member within the upper Campanian and part of UZA4.4.

Correlatives to the Navesink Sequence(s).— Within the Maastrichtian stage, the Vijlen Member of the Gulpen Formation ranges from upper lower Maastrichtian in age to lower upper Maastrichtian (Jagt 1999), approximately equivalent to the Navesink Formation in New Jersey (Fig. 4). Like the Navesink Formation, there is a pronounced unconformity at the base of the Vijlen Member, evidenced by a lag deposit at the Bonvenste Bosch horizon (Felder 1996). As noted above, Kennedy et al. (2000) correlated the basal lag of the Navesink Formation at least in part to the uppermost Campanian to lowermost Maastrichtian *Belemnitella langei* and *B. lanceolata* zones.

Above this basal lag, the lower (but not lowermost) Maastrichtian *Belemnitella* (*P. obtusa* occurs, and the Vijlen Member ranges to the lower upper Maastrichtian zone of *B. junior* (Jagt 1999). The Vijlen Member includes at least part of nannofossil zone CC24 (Jagt 1999), making the base of this unit slightly older than that of the Navesink Formation. The Vijlen Member and the Lixhe members (I-III) also include CC25a, and upper portions of the Lixhe contain CC25b, correlative to the Navesink Formation and lower Severn Formation (see above) Lixhe members I-III all contain the upper Maastrichtian belemnite *B. junior*. In general, then, the Vijlen Member and Lixhe members I-III fall within the range of the Navesink I sequence, correlated to UZA 4.5 by Miller et al. (2004).

The uppermost member of the Gulpen Formation is the Lanaye Member, which produces the upper Maastrichtian

belemnite *B. junior*, as do all the members of the overlying Maastricht Formation (Valkenberg, Gronsveld, Schippersberg, Emael, Nekum, and lower Meerssen members). These units appear to be entirely within CC26 (Jagt 1999 and references therein). Based on eustatic sea level curves of Haq et al. (1987) compared with dinoflagellate data, Schiøler et al. (1997) placed the boundary between the third order cycles UZA 4.5 and TA1.1 at the base of the Lanaye Member. This boundary is correlated to the Navesink/Red Bank (or New Egypt) contact in the Mid-Atlantic region (Miller et al. 2004). Zijlstra (1994) proposed a date of 66.5 mya for the base of the Lanaye Member, based on cycles of flint deposits that he tied to 20,000-year Milankovich cycles. This date corresponds closely to the 66 ± 0.5 mya Sr-isotope-anomaly based estimate for the base of the Navesink II sequence proposed by Miller et al. (2004). Given the similarity in biostratigraphic data from the New Egypt Formation, upper Severn Formation, and Lanaye Member of the Gulpen Formation, coupled with the temporal constraints on the base of the New Egypt Formation and Lanaye Member, we hypothesize that there may be a stratigraphic break within the Severn Formation separating Navesink subsequences I and II, similar to that in the Bass River and Ancora Cores (see above).

The upper Nekum Member is considered the base of TA1.2 by Schiøler et al. (1997), who record the first appearance of the uppermost Maastrichtian dinoflagellate *Palynodinium grallator*. *P. grallator* has been reported from the New Egypt and basal Homerstown Formations at the Inversand pit in Sewell (Koch and Olsson 1977) and Monmouth County, New Jersey (Landman et al. 2004b), and the upper Severn Formation in Maryland (Landman et al. 2004a). The upper Meerssen Member produces the uppermost Maastrichtian belemnite *B. casimirovensis* (Jagt 1996, 1999), which is known to co-occur with *Baculites vertebralis*, known from the Severn Formation (Kennedy et al. 1997; Landman et al. 2004a).

Working at the ENCI quarry in the Netherlands near Maastricht, Vonhof and Smit (1996) established a Sr-isotope curve, and compared it to northern European reference sections. With this curve and member thicknesses, they calculated a deposition rate of approximately 10 cm/k.y. \pm 2 cm/k.y. for the upper Maastricht Formation (Emael, Nekum, and Meerssen members), and a maximum time of deposition of 1 m.y. for the entire Maastricht Formation. Vonhof and Smit (1996) further estimated that the base of the Meerssen Member (the highest member of the Maastricht Formation) was deposited approximately 100 k.y. before the K/T boundary, which has been identified in the uppermost Meerssen Member by Smit and Brinkhuis (1996). This boundary section, like the one recovered in boreholes from New Jersey (see above), contains shocked mineral grains, a slightly elevated Ir anomaly (40 ppt), and an extinction of Maastrichtian nannofossils (Smit and Brinkhuis 1996).

Above the K/T section, the Meerssen Member ranges into the early Paleocene. Smit and Brinkhuis (1996) noted that this uppermost portion of the Meerssen Member (unit IVf-7) contains early Paleocene (P0) nannofossils, but may be missing earliest Danian taxa. Smit and Brinkhuis (1996) note that an early Danian age for IVf-7 is supported by high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios typical of early Danian seawater, but caution that nannofossil taxa may range into the middle Danian (though they do not assign a nannofossil zone). The bulk of the evidence indicates that IVf-7 is likely correlative to the lower Homerstown Formation, above the MFL and below the top of the Navesink II sequence (Fig. 4).

Three observations indicate that the Meerssen Member and the MFL are correlative: 1) the uppermost Maastrichtian dinoflagellate *P. grallator* first appears stratigraphically below both the MFL in New Jersey and the Meerssen Member in the Netherlands; 2) the time of formation of the MFL in New Jersey was deposited during at most the last 200,000 years of the Cretaceous, and the Meerssen Member was deposited during the last 100,000 years of the Cretaceous; and 3) a complete K/T boundary section brackets both units.

CONCLUSIONS

Direct and robust correlation of Upper Cretaceous sediment from the Mid-Atlantic region and the Maastricht area is possible utilizing a suite of sequence stratigraphic and paleontological data. In correlating the lithologic unit, we confirm the presence of the Merchantville, Englishtown, Marshalltown, and Navesink sequences (proposed by Miller et al. 2004) in the Maastricht area. Furthermore, we provide support for the existence of a number of sequence subdivisions. In the Maastricht area, the Aachen Formation and lower Vaals Formation support the Merchantville I-II sequences. The Vijlen and Lixhe members (Gulpen Formation) support a lower- to upper Maastrichtian Navesink I sequence, while the Lanaye Member (Gulpen Formation) and Maastricht Formation support an Upper Maastrichtian to lowermost Danian Navesink II sequence. Currently there is no correlative of the Merchantville III sequence in the Maastricht area. The correlations presented serve to solidify our understanding of the trans-Atlantic biogeographic province, and provide a framework for future investigations into the dynamics of its biota.

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