Short-term survival of ammonites in New Jersey after the end-Cretaceous bolide impact

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A section containing the Cretaceous/Paleogene (= Cretaceous/Tertiary) boundary in Monmouth County, New Jersey, preserves a record of ammonites extending from the end of the Cretaceous into possibly the beginning of the Danian. The section includes the upper part of the Tinton Formation and lower part of the Hornerstown Formation. The top of the Tinton Formation is represented by a richly fossiliferous unit (the *Pinna* Layer) that contains many bivalves in life position as well as ammonite jaws preserved inside body chambers. Ammonites include *Pachydiscus* (*Neodesmoceras*) *mokotibensis*, *Sphenodiscus lobatus*, *Eubaculites carinatus*, *E. latecarinatus*, *Discoscaphites iris*, *D. sphaeroidalis*, *D. minardi*, and *D. jerseyensis*. The *Pinna* Layer probably represents a relatively short interval of time lasting tens to hundreds of years; it is conformably overlain by the Burrowed Unit, which contains a single fragment of *Discoscaphites* sp. and several fragments of *E. latecarinatus*, as well as several isolated specimens of ammonite jaws including two of *Eubaculites*. Examination of the mode of preservation of the ammonites and jaws suggests that they were fossilized during deposition of the Burrowed Unit and were not reworked from older deposits. Based on the ammonites and dinoflagellates in the *Pinna* Layer and the Burrowed Unit, these strata traditionally would be assigned to the uppermost Maastrichtian, corresponding to calcareous nannofossil Subzone CC26b. However, a weak iridium anomaly (500–600 pg/g) is present at the base of the *Pinna* Layer, which presumably represents the record of the bolide impact. Correlation with the iridium layer at the Global Stratotype Section and Point at El Kef, Tunisia, would, therefore, imply that these assemblages are actually Danian, provided that the iridium anomaly is in place and the ammonites and dinoflagellates are not reworked. If the iridium anomaly is in place, or even if it has migrated downward from the top of the *Pinna* Layer, the ammonites would have survived the impact at this site for a brief interval of time lasting from a few days to hundreds of years.

Key words: Ammonoidea, biostratigraphy, extinctions, iridium anomaly, Cretaceous/Paleogene boundary, New Jersey.

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Introduction

The end-Cretaceous extinctions have convincingly been attributed to an asteroid impact (Schulte et al. 2010). Ammonites may have briefly survived this event based on studies of stratigraphic sections in the Netherlands (Smit and Brinkhuis 1996; Jagt et al. 2003; Machalski et al. 2009) and Denmark (Machalski and Heinberg 2005). While this contradicts earlier suppositions about the nature of the extinctions at the erathem boundary, it is perhaps more consistent with expectations about the response of communities to catastrophic perturbations. However, such claims need to be carefully documented on the basis of detailed stratigraphic, paleontologic, sedimentologic, taphonomic, and geochemical work (Machalski and Heinberg 2005). It is essential to differentiate ammonites that were fossilized at the time of deposition of the surrounding sediment versus those that were reworked from older deposits.
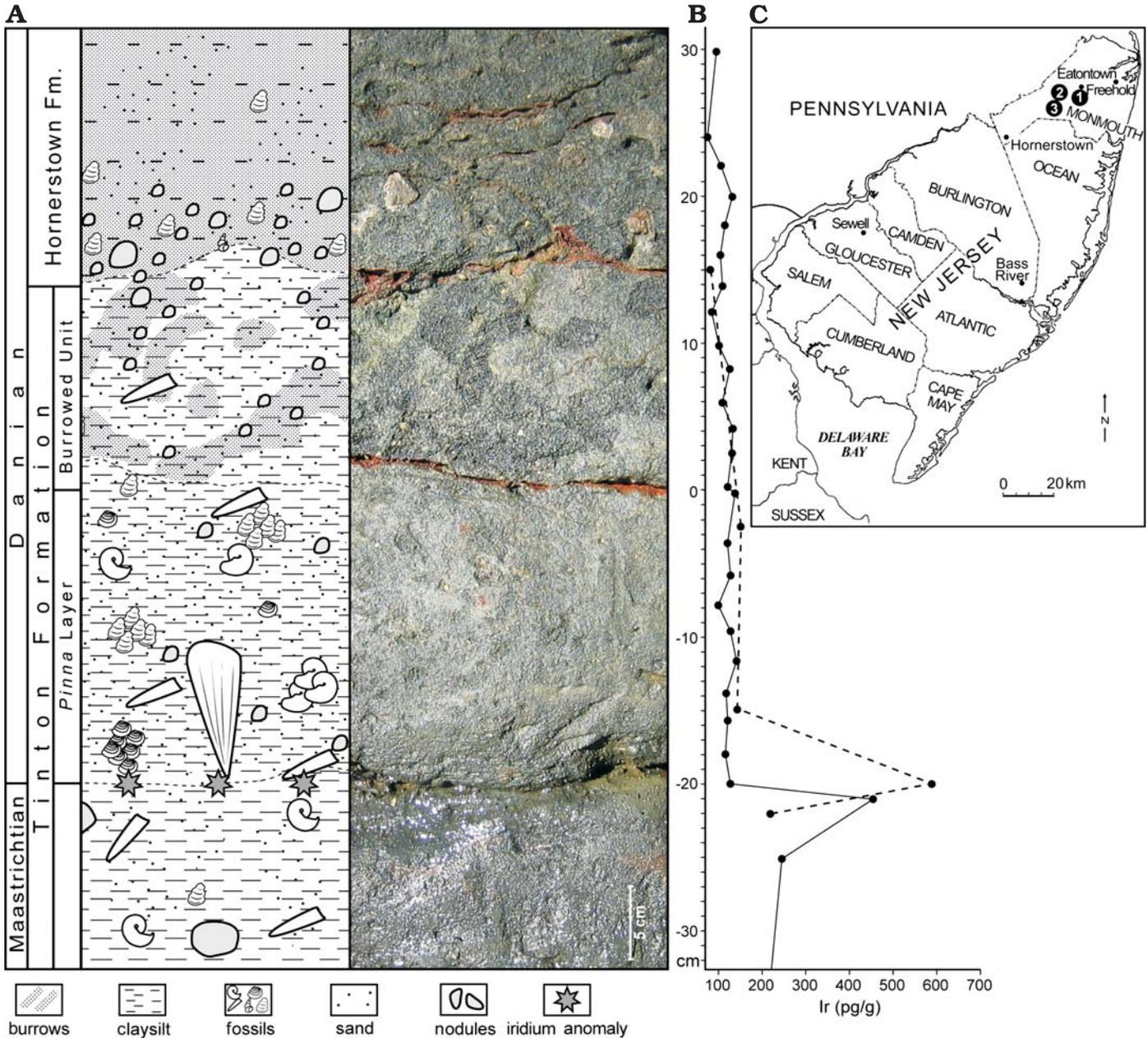
Fig. 1. Stratigraphic section in the Manasquan River Basin, Monmouth County, New Jersey. **A**. The top of the Tinton Formation consists of the *Pinna* Layer overlain by the Burrowed Unit, which is overlain, in turn, by the Hornerstown Formation. An enriched concentration of iridium occurs at the base of the *Pinna* Layer (indicated by the stars). The position of the Cretaceous/Paleogene boundary in this figure is based on the assumption that the enriched concentration of iridium is in place. **B**. Iridium profile from two sites (represented by the solid and dashed lines) in the Manasquan River Basin (Landman et al. 2007a). **C**. Map of part of New Jersey showing localities mentioned in the text: 1, Manasquan River Basin; 2, Buck's Pit; 3, Ivanhoe Creek.

Landman et al. (2007a, 2010a) investigated outcrops in Monmouth County, New Jersey, that contain ammonites and dinoflagellates associated with an iridium anomaly. These fossils are traditionally assigned to the uppermost Maastrichtian, but appear above the iridium anomaly, suggesting that they may actually be Danian. The fossils occur in two layers: the lower layer, known as the *Pinna* Layer, is very fossiliferous and has been thoroughly documented by Landman et al. (2007a, 2010a). The upper layer, known as the Burrowed Unit, contains a depauperate assemblage of ammonites and dinoflagellates, and has received much less attention. In this paper,

we focus on the ammonites in this unit to determine if they were fossilized at the time of deposition of the surrounding sediment, having lived and/or died during this time interval, or if they were reworked from older deposits. The ultimate explanation of the sequence of events at this site depends, however, on whether the iridium anomaly represents the record of the bolide impact and, if so, whether it is in place or has migrated downward (Landman et al. 2007a; Miller et al. 2010).

Institutional abbreviations.—AMNH, American Museum of Natural History, New York, USA; MAPS; Monmouth Amateur Paleontological Society, Long Branch, New Jersey.

Geological setting

Sediments spanning the Cretaceous/Paleogene (= Cretaceous/ Tertiary) boundary in New Jersey crop out in a belt extending from the Sandy Hook embayment in the northeast to the Delaware embayment in the southwest. These sections have been extensively investigated in both surface exposures and cores (Minard et al. 1969; Gallagher 1993; Olsson et al. 1997; Owens et al. 1998; Landman et al. 2004a, b; Miller et al. 2004). The study area of this report is in the upper Manasquan River Basin, Monmouth County, and occupies approximately 6.5 km^2 (Fig. 1). The stratigraphic section has been described by Landman et al. (2007a), and is slightly modified in this paper. The section consists of approximately 2 m of the Tinton Formation overlain by 2 m of the Hornerstown Formation (Fig. 1).

Material and methods

Bulk samples were extracted from the *Pinna* Layer, Burrowed Unit, and Hornerstown Formation. Approximately 90 kg of Burrowed Unit were processed. The samples were allowed to dry and were then broken down in the lab using small chisels, picks, and a small rock crusher. In the Burrowed Unit, the material forming the burrows was carefully separated from the surrounding matrix. The location of fossils in the Burrowed Unit was recorded relative to the position of the burrows. Fossils were extracted using scalpels, razors, and pliers, and identified down to species level wherever possible. Fossils are reposited at the American Museum of Natural History (AMNH) and the Monmouth Amateur Paleontological Society (MAPS).

The grain size distribution of the sediments was analyzed as described in Landman et al. (2007a). It is important to emphasize that much of the sediment consists of large glauconitic pellets composed of mud. Therefore, the reported grain size distribution does not necessarily reflect the original muddy composition of the sediment as it accumulated on the sea floor.

Description

***Pinna* Layer**.—This unit is approximately 20 cm thick and is laterally extensive (Fig. 1). It is grayish green on fresh exposures and orange-brown on weathered exposures. It consists of 62% mud and 38% coarser sediments. It is finely bioturbated without any evidence of bedding. Although it is homogeneous, it tends to break along horizontal planes. All of the fossils are internal and external molds, without any calcareous shell preserved. In general, the internal molds are composed of glauconitic minerals and weather orange-brown. However, a small percentage of them (approximately 10%) are composed of sideritic clay. They are more indurated than the surrounding sediment and weather orange-tan.

The *Pinna* Layer is very fossiliferous and contains approximately 110 species of bivalves, gastropods, cephalopods, echinoids, sponges, serpulids, bryozoans, crustaceans, and dinoflagellates, as reported in Landman et al. (2007a, 2010a). Bivalves are the most common invertebrates, both in terms of numbers of species and numbers of individuals, especially *Cucullaea vulgaris* Morton, 1830. The ammonites include *Pachydiscus* (*Neodesmoceras*) *mokotibensis* Collignon, 1952, *Sphenodiscus lobatus* (Tuomey, 1856), *Eubaculites carinatus* (Morton, 1834), *E. latecarinatus* (Brunnschweiler, 1966), *Discoscaphites iris* (Conrad, 1858), *D. sphaeroidalis* Kennedy and Cobban, 2000, *D. minardi* Landman, Johnson, and Edwards, 2004a, and *D. jerseyensis* Landman, Johnson, Garb, Edwards, and Kyte, 2007a (Fig. 2). This assemblage of ammonites is characteristic of the uppermost Maastrichtian *D. iris* Zone. This zone is also present in other parts of the US Gulf and Atlantic Coastal Plains (Stephenson 1955; Hansen et al. 1993; Kennedy and Cobban 2000; Landman et al. 2004a, b).

The dinoflagellates in the *Pinna* Layer are abundant and very diverse and include *Palynodinium grallator* Gocht, 1970, *Thalassiphora pelagica* (Eisenack, 1954) Eisenack and Gocht, 1960, *Deflandrea galeata* (Lejeune-Carpentier, 1942) Lentin and Williams, 1973, and *Disphaerogena carposphaeropsis* Wetzel, 1933. This assemblage of dinoflagellates is characteristic of the uppermost Maastrichtian *Palynodinium grallator* Zone, probably the *Thalassiphora pelagica* Subzone of Schiøler and Wilson (1993), which correlates with the upper part of calcareous nannofossil Subzone CC26b (Edwards et al. 1999; Landman et al. 2004a, b). Thus, the age of the dinoflagellates is consistent with that of the ammonites in the same unit.

Many fossils in the *Pinna* Layer appear in clusters. *Cucullaea vulgaris* is very abundant and occurs in large concentrations, with most specimens articulated. Echinoids occur in aggregations of hundreds of individuals. Surprisingly, baculites and scaphites also appear as monospecific clusters of as many as 30 specimens. *Pinna laqueata* Conrad, 1858 (after which the layer is named) is almost always preserved in vertical life position. It occasionally appears in clusters, but never forms a dense framework. Jaws of *Discoscaphites* occur both as isolated specimens and inside body chambers.

Burrowed Unit.—The *Pinna* Layer is conformably overlain by the Burrowed Unit, which is 15–20 cm thick (Fig. 1). The matrix of the Burrowed Unit is similar to that of the *Pinna* Layer, and consists of glauconitic pellets and non-glauconitized clay. The most distinctive feature of the Burrowed Unit is the presence of large *Thalassinoides* burrows that pipe down material from the overlying Hornerstown Formation. In fresh exposures, the matrix of the Burrowed Unit is light grayish green and the burrows are dark grayish green. In weathered exposures, the matrix is orange-brown and the burrows are dark greenish black. The burrows are very large, e.g., 10 cm long by 2.5 cm wide. They form an extensive

2 cm

3 mm
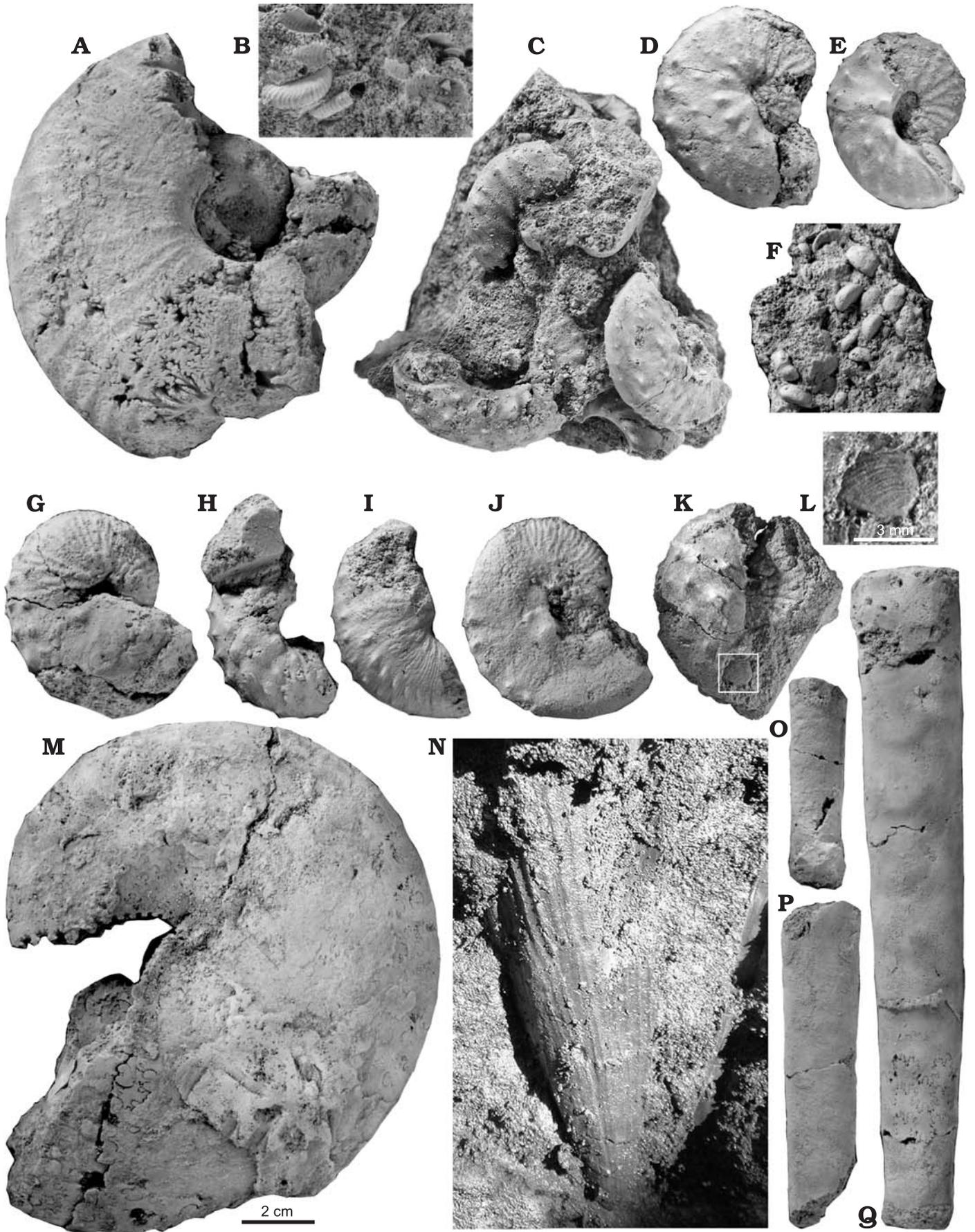
anastomozing complex but rarely penetrate into the *Pinna* Layer, usually turning sideways at the contact.

In contrast to Landman et al. (2007a, 2010a), we consider the Burrowed Unit as the top of the Tinton Formation rather than the base of the Hornerstown Formation because the lithology and fauna of the Burrowed Unit are more similar to those of the *Pinna* Layer than to those of the Hornerstown Formation. For example, the Burrowed Unit consists of 55% mud, the *Pinna* Layer, 62% mud, and the Hornerstown Formation, 38% mud. In addition, the glauconitic pellets in the Burrowed Unit are mostly light pale green or tan, as in the *Pinna* Layer, whereas they are greenish black, shiny, and botryoidal in the Hornerstown Formation.

The Burrowed Unit is much less fossiliferous than the *Pinna* Layer (Fig. 3, Table 1). The fossils are internal and external molds without any calcareous shell. In general, the internal molds are composed of glauconitic pellets and weather orange-brown. Occasionally, however, they are composed of sideritic clay and are more indurated than the surrounding sediment. The clay is the same color as that in the matrix. Fossils also occur inside and adjacent to the burrows and are piped down from the overlying Hornerstown Formation.

The Burrowed Unit contains approximately 20 species of bivalves, gastropods, cephalopods, echinoids, bryozoans, crustaceans, and dinoflagellates (Fig. 3, Table 1). The most common fossils are *Pecten venustus* Morton, 1833, and *Margaritella pumila* Stephenson, 1941. We have recorded only a single specimen of *Cucullaea vulgaris*, in contrast to its abundance in the *Pinna* Layer. None of the bivalves occur in life position. All of them are disarticulated except for one specimen of *Granocardium* sp. (Fig. 3L).

Most significantly, the Burrowed Unit differs from the *Pinna* Layer in the paucity and fragmentary preservation of the ammonites and dinoflagellates. There is only a single fragment of *Discoscaphites* sp. (Fig. 3E) and five fragments of *Eubaculites latecarinatus* (Fig. 3A–D). All of the specimens of *E. latecarinatus* are small with a maximum whorl height of 18 mm and a maximum length of 47 mm. For example, AMNH 64419 is a piece of a body chamber 32 mm long oriented in a vertical position and terminating in a burrow (Fig. 3B). It is composed of glauconite, but is slightly sideritized on the edges, and retains a faint trace of iridescent shell.

The Burrowed Unit also contains two light tan clay pods, both of which are adjacent to burrows. The pods are more indurated than the surrounding sediment. One pod bears a

Table 1. Invertebrate fossils in the matrix of the Burrowed Unit at the top of the Tinton Formation, Monmouth County, New Jersey. The authors of the species are listed in Landman et al. (2007a: table 1).

Bivalvia	*Anatimya lata*
	Crenella serica
	Cucullaea vulgaris
	Eriphyla decemnaria
	Granocardium sp.
	Ostrea tecticosta
	Pecten argillensis
	Pecten venustus
	Pycnodonte sp.
Gastropoda	*Anchura* sp.
	Arrhoges sp.
	Calliomphalus sp.
	Margaritella pumila
	Trachytriton holmdelense
Cephalopoda	*Discoscaphites* sp.
	Eubaculites latecarinatus
	jaws of *Eubaculites* and *Discoscaphites*
Echinodermata	echinoid spines
Arthropoda	crab bits
Annelida	*Hamulus squamosus*
	Longitubus lineatus
Coelenterata	*Micrabacia* sp.
Dinoflagellata	*Dinogymnium* sp.
	unidentifiable fragments

specimen of *Heteropora americana* Richards, 1962, without any sediment in its zooids (Fig. 4C), and three small fragments of *Eubaculites latecarinatus* that are oriented parallel to each other (Fig. 4A). One of these fragments contains a small telescoped specimen of *Eubaculites* inside (Fig. 4B). The other pod bears two hollow fragments of *E. latecarinatus* (Fig. 4D, E) and a fragment of *H. americana*.

The most surprising finds in the Burrowed Unit are ammonite aptychi (= lower jaws) (Fig. 5). Five aptychi are present, all of which occur as isolated specimens. They weather orange brown and are surrounded by the matrix of the Burrowed Unit. Two of the aptychi are long, rectangular, and nearly flat (Fig. 5A, D). The ratio of length to width in these two specimens ranges from 2.5 to 2.6. The commissure is long and straight and the surface is covered with fine commarginal lirae. Based on comparisons with aptychi in Land-

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Fig. 2. Fossils in the *Pinna* Layer near the top of the Tinton Formation, Monmouth County, New Jersey. **A**. *Pachydiscus* (*Neodesmoceras*) *mokotibensis* Collignon, 1952, MAPS A2051a1, in right lateral view. **B–E**. *Discoscaphites iris* (Conrad, 1858). **B**. MAPS A2060b1, accumulation of juvenile specimens. **C**. MAPS A2058b3, cluster of adult microconchs. **D**. AMNH 50540, adult macroconch in right lateral view. **E**. MAPS A2060b9, adult microconch in right lateral view. **F**. MAPS A3601g3, accumulation of echinoids. **G**, **H**. *Discoscaphites sphaeroidalis* Kennedy and Cobban, 2000. **G**. AMNH 50752, adult macroconch in right lateral view. **H**. AMNH 50713, adult microconch in right lateral view. **I**. *Discoscaphites jerseyensis* Landman, Johnson, Garb, Edwards, and Kyte, 2007a, AMNH 50393, adult macroconch in right lateral view. **J**. *Discoscaphites minardi* Landman, Johnson, and Edwards, 2004a, AMNH 50411, adult macroconch in right lateral view. **K**, **L**. *Discoscaphites iris*. **K**. MAPS A2060b11, lower jaw preserved inside the body chamber in right lateral view. **L**. MAPS A2062a8, close-up of lower jaw inside the body chamber. **M**. *Sphenodiscus lobatus* (Tuomey, 1856), MAPS A2002g2, in left lateral view. **N**. *Pinna laqueata* Conrad, 1858, MAPS A2402p2, in vertical life position. **O**, **P**. *Eubaculites latecarinatus* (Brunnschweiler, 1966). **O**. AMNH 51877, ?adult microconch in right lateral view. **P**. AMNH 51888, ?adult macroconch in right lateral. **Q**. *Eubaculites carinatus* (Morton, 1834), MAPS A2058b1, adult macroconch in right lateral view.
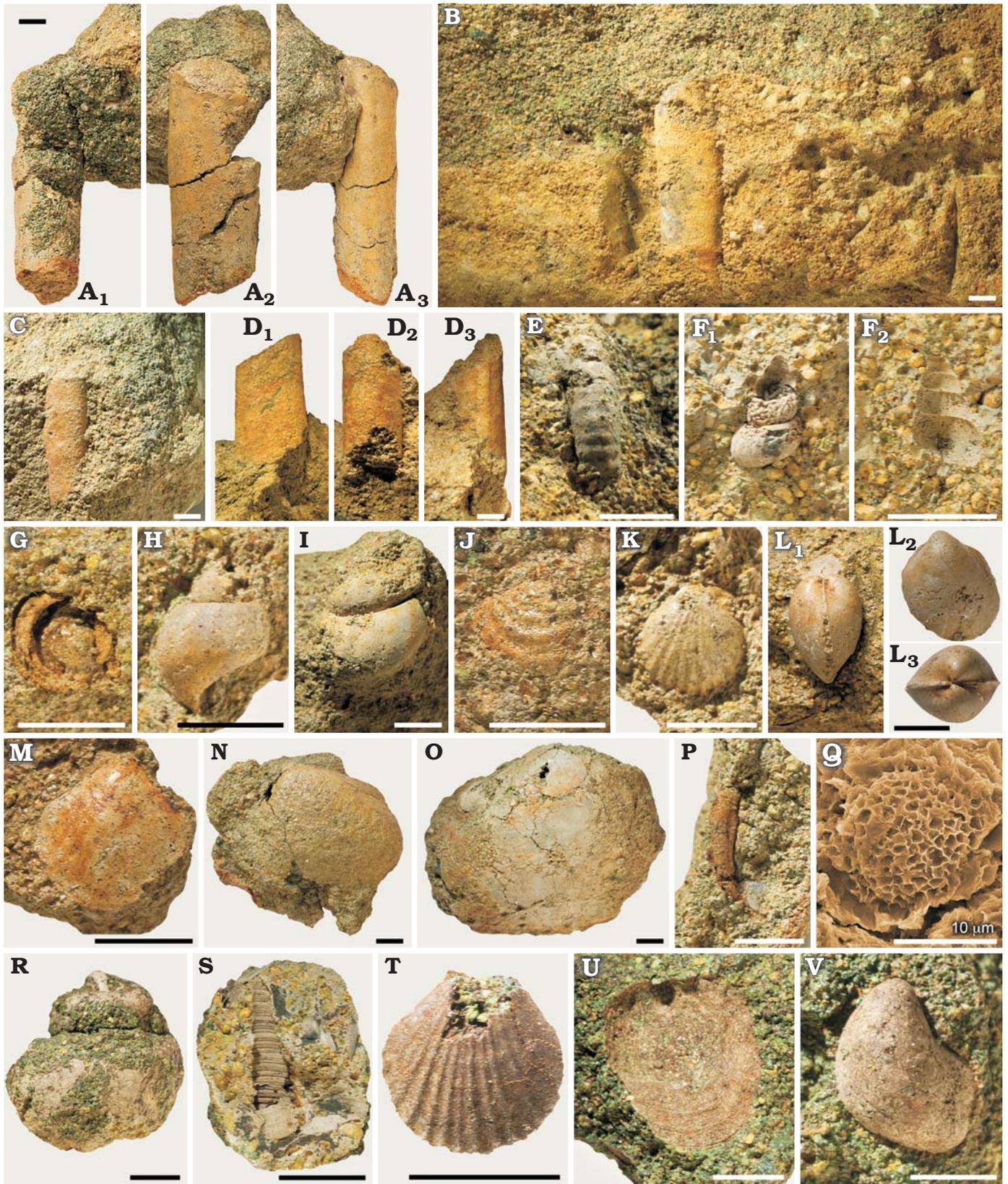
Fig. 3. Fossils in the Burrowed Unit at the top of the Tinton Formation and in the overlying Hornerstown Formation, Monmouth County, New Jersey. **A–Q**. Fossils in the matrix of the Burrowed Unit, non-reworked. **A–D**. *Eubaculites latecarinatus* (Brunnschweiler, 1966). **A**. AMNH 72338 in dorsal (A_1), right lateral (A_2), and ventral (A_3) views. **B**. AMNH 64419 in lateral view. **C**. AMNH 69508 in lateral view. **D**. AMNH 73321 in left lateral (D_1), dorsal (D_2), and ventral (D_3) views. **E**. *Discoscaphites* sp., AMNH 69499 in ventral view, in matrix, adjacent to burrow. **F**. *Anchura* sp., AMNH 69506; internal mold (F_1), impression (F_2). **G**. *Margaritella pumila* Stephenson, 1941, AMNH 72348. **H**. *Trachytriton holmdelense* Whitfield, 1892, AMNH 72315. →
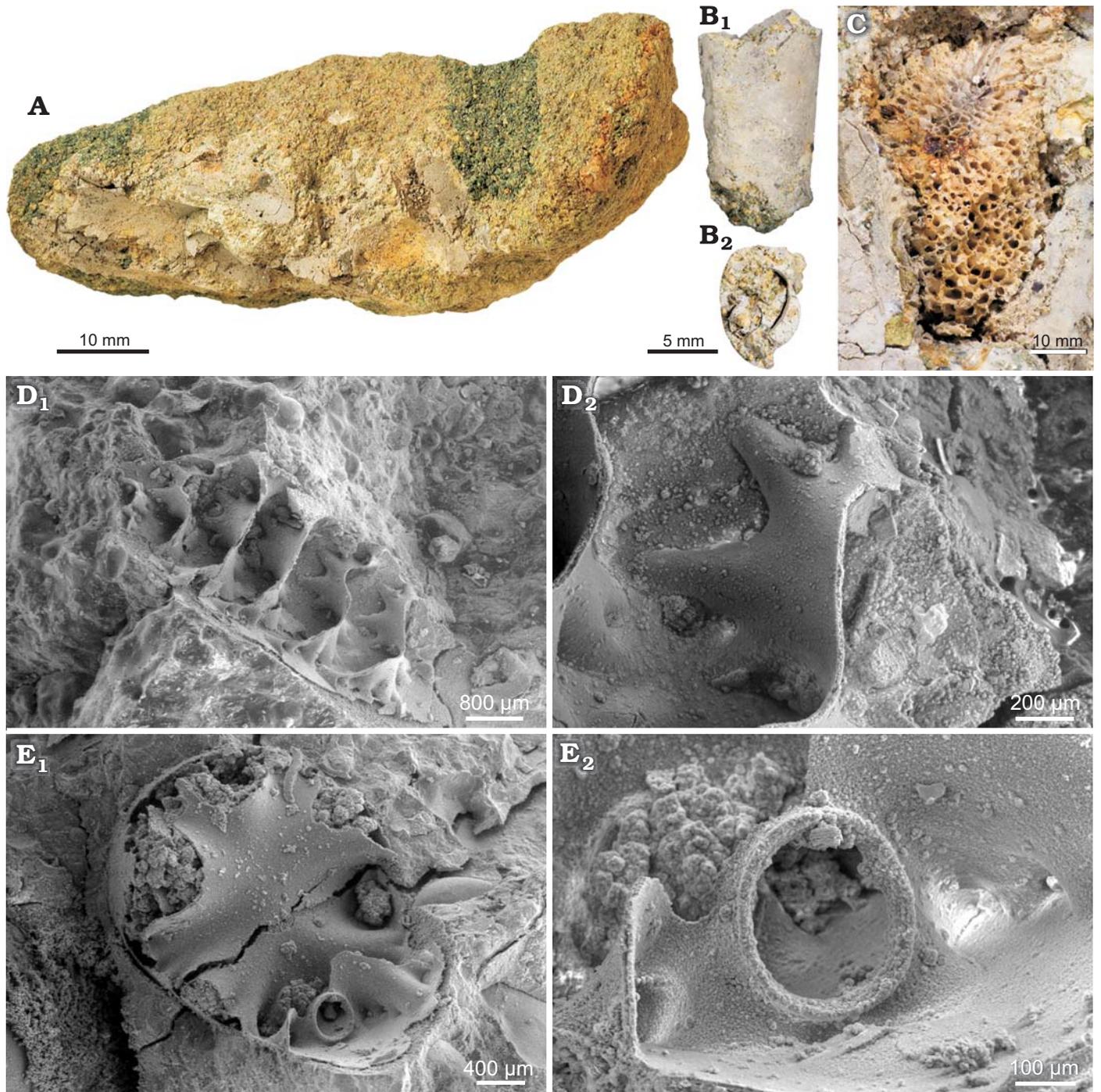
Fig. 4. Clay pods in the matrix of the Burrowed Unit adjacent to burrows, Monmouth County, New Jersey, probably reworked from the *Pinna* Layer, and piped down into the Burrowed Unit. **A–D**. Single pod adjacent to a burrow. **A**. Overview. **B**. *Eubaculites latecarinatus* (Brunnschweiler, 1966), AMNH 66312 in left lateral view (B_1); whorl cross-section at adoral end showing a specimen of *Eubaculites* telescoped inside (B_2). **C**. *Heteropora americana* Richards, 1962, AMNH 51309; without any sediment in the zooids. **D**. *Eubaculites* sp., hollow specimen, AMNH 66313; view of hollow chambers (D_1), close-up of septum (D_2). **E**. *Eubaculites* sp. in another clay pod adjacent to a burrow, AMNH 66314; septal face (E_1), close-up of septal neck (E_2).

I. *Arrhoges* sp., AMNH 69525. **J**. *Eriphyla decemnaria* (Conrad, 1869), AMNH 72310. **K**. *Pecten venustus* Morton, 1833, AMNH 72353. **L**. *Granocardium* sp., AMNH 72340; in the matrix (L_1), lateral (L_2), and umbonal (L_3) views. **M**. *Pecten argillensis* Conrad, 1869, AMNH 72316. **N**. *Anatimya lata* (Whitfield, 1886), AMNH 72339. **O**. *Cucullaea vulgaris* Morton, 1830, AMNH 72303. **P**. *Hamulus squamosus* Gabb, 1859, AMNH 72323. **Q**. Unidentified microfossil, AMNH 66332. **R–V**. Fossils in the burrows of the Burrowed Unit representing material piped down from the basal Hornerstown Formation. **R**. *Euspira* sp., AMNH 69515, eworked. **S**. *Turritella* sp., AMNH 72322, reworked. **T**. *Pecten venustus*, AMNH 72325, non-reworked. **U**. *Gryphaeostrea vomer* Morton, 1828, AMNH 72349, non-reworked. **V**. *Ostrea pulaskensis* Harris, 1894, AMNH 72351, non-reworked. Scale bars 5 mm, except indicated otherwise.
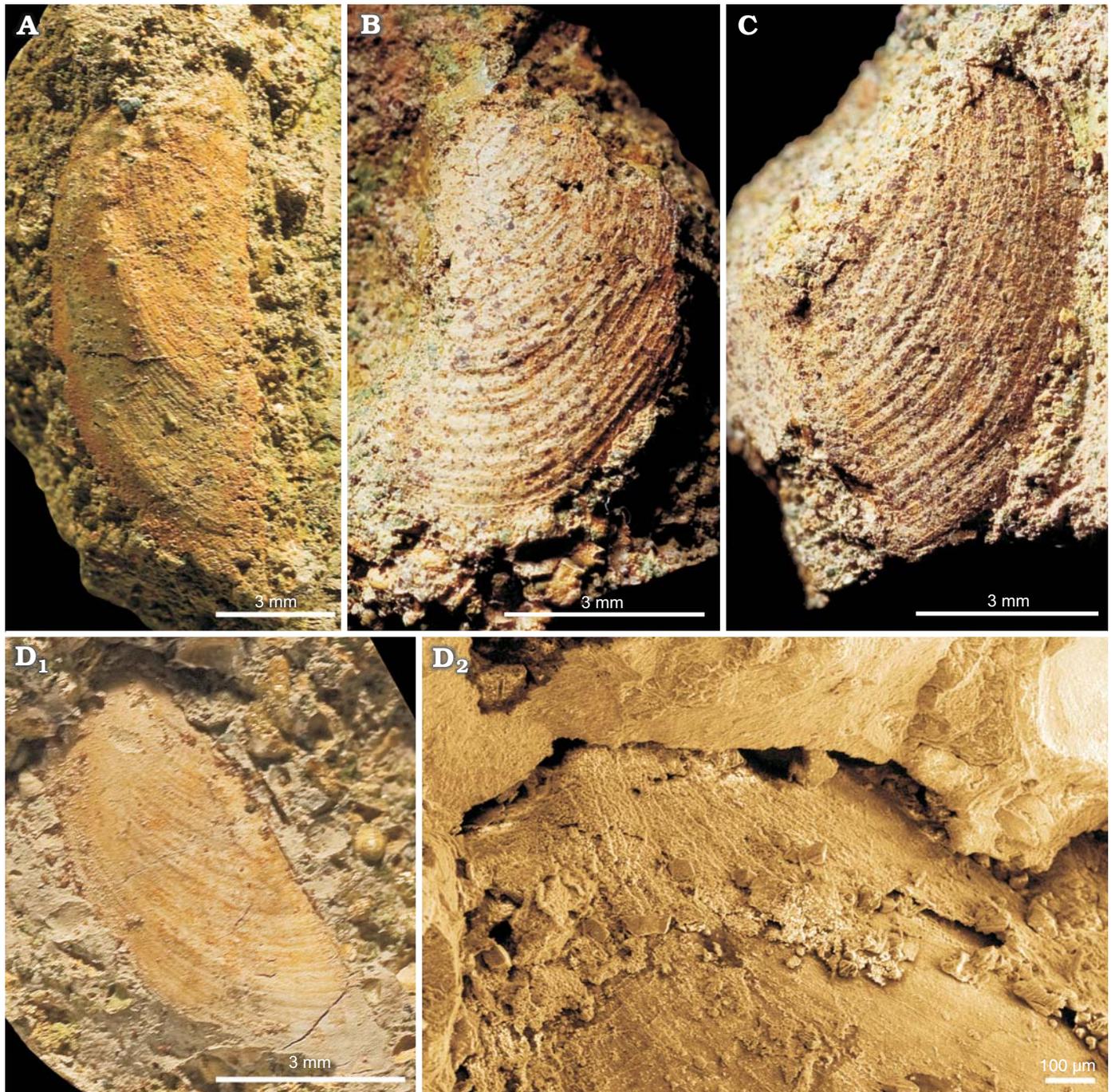
Fig. 5. Ammonite aptychi (= jaws) in the matrix of the Burrowed Unit. **A**, **D**. Lower jaws attributed to *Eubaculites*. **A**. AMNH 69496, right valve. **D**. AMNH 69492, view of right valve (D₁), close-up of aptychus at the anterior end (D₂). **B**, **C**. Lower jaws attributed to *Discoscaphites*. **B**. AMNH 69497, left valve. **C**. AMNH 69498, left valve.

man et al. (2007b), these specimens probably belong to *Eubaculites*, and, as such, are the first aptychi of *Eubaculites* ever reported from North America. The other three aptychi are more convex and nearly triangular in shape (Fig. 5B, C). They probably belong to *Discoscaphites*, by comparison with Landman et al. (2007a, 2010b).

Dinoflagellates are very rare in the Burrowed Unit. Other than some unidentifiable fragments, we only recorded a single specimen of *Dinogymnium* sp., which is generally con-

sidered to be Cretaceous. The ammonites, although scarce, suggest that the Burrowed Unit is the same age as the *Pinna* Layer. However, it is evidently younger than the *Pinna* Layer inasmuch as it occurs above this unit.

Hornerstown Formation.—The contact between the matrix of the Burrowed Unit and the overlying Hornerstown Formation is sharp. However, the contact between the burrows of the Burrowed Unit and the overlying Hornerstown Forma-

Table 2. Fossils in the burrows of the Burrowed Unit comprising material piped down from the Hornerstown Formation, Monmouth County, New Jersey. The authors of the species are listed in Landman et al. (2007a: table 1). Abbreviations: [R] = potentially reworked from the *Pinna* Layer or an updip equivalent; [NR] = non-reworked.

Bivalvia	*Anomia* sp.[NR]
	Arca sp.[NR]
	Cardium eufaulensis [NR]
	Crassatella sp.[NR]
	Cucullaea vulgaris [NR, R]
	Cyclorisma? *pumila* [R]
	Gryphaeostrea vomer [NR]
	Ostrea pulaskensis [NR]
	Pecten venustus [R, NR]
	Pecten argillensis [NR]
	Pycnodonte sp.[NR]
	Unicardium concentricum [NR]
	Xylophagella irregularis [NR]
Gastropoda	*Bellifusus* sp.[?R]
	Epitonium sp.[R]
	Euspira sp. [R]
	Margaritella pumila [?NR,R]
	Turritella sp. [R]
Cephalopoda	*Discoscaphites iris* [R]
	Eubaculites latecarinatus [R]
Bryozoa	*Heteropora americana* [?R]
	unidentified bryozoan [NR]
Echinodermata	echinoid spines [NR]
Porifera	*Cliona* sp.[R]
Arthropoda	crab bits [NR,R]
Annelida	worm tubes [NR,R]
Foraminifera [NR]	
Dinoflagellata	*Areoligera senonensis* species complex[NR,R]
	Areoligera sp. indet.[NR,R]
	Diphyes sp.[NR,R]
	Unidentifiable small fragments (*Cordosphaeridium* complex)[NR,R]

tion is difficult to pinpoint, which is part of the reason why we initially assigned the Burrowed Unit to the base of the Hornerstown Formation (Fig. 1). The Hornerstown Formation consists of 38% mud and 62% coarser sediments. It is dark grayish green in fresh exposures and dark green to black in weathered exposures.

The fossils in the Hornerstown Formation show two different modes of preservation. In the first mode, internal molds are composed of whitish clay surrounded by dark green glauconitic pellets (Fig. 3R, S). The clay is indurated and much lighter in color than that in the *Pinna* Layer or Burrowed Unit. These fossils include *Cucullaea vulgaris*, *Euspira* sp., *Turritella* sp., *Eubaculites latecarinatus*, and *Discoscaphites iris*. Many of these fossils also occur in the

burrows that extend into the Burrowed Unit. We interpret these fossils as having been reworked from older deposits. They are accompanied by siderite nodules, most of which are unfossiliferous. However, some nodules contain poorly preserved dinoflagellate cysts and *Rugubivesiculites* pollen (Landman et al. 2007a: 40), supporting the interpretation that the nodules were also reworked.

The other group of fossils weather pinkish brown, possibly reflecting diagenetically altered shell (Fig. 3T–V). We interpret these fossils as having formed during deposition of the Hornerstown Formation. The fauna is very depauperate consisting of only 15 species including *Gryphaeostrea vomer* Morton, 1834, as well as echinoids and foraminifera. The most abundant fossil is *Ostrea pulaskensis* Harris, 1894, which first appears in the Gulf Coastal Plain in the lower Danian (Bryan and Jones 1989; Hansen et al. 1993; Cope et al. 2005). Dinoflagellates are scarce, consisting of members of the *Areoligera* group, which are not age-diagnostic. Thus, the basal Hornerstown Formation is lower Danian based on the presence of *O. pulaskensis*, although it is difficult to be any more precise than that.

Iridium analysis

We analyzed 37 samples of sediment for iridium across the outcrop in the Manasquan River Basin, following the procedure described in Schellenberg et al. (2004). The base of the *Pinna* Layer is marked by an enriched concentration of iridium, which may correlate with the iridium anomaly first reported by Alvarez et al. (1980). The maximum concentration of iridium at two sites in the basin, as reported in Landman et al. (2007a), is 457 and 589 pg/g (Fig. 1). The iridium profile is asymmetric with an abrupt drop off above the contact and a more gradual decline below the contact. A very similar pattern has been reported from the same site by Miller et al. (2010).

Discussion

Environment of deposition.—The mode of occurrence of the specimens in the *Pinna* Layer suggests an autochthonous assemblage that has undergone little or no time-averaging (see Kidwell and Bosence 1991, for a fuller description of such assemblages). Many of the bivalves are preserved in life position. *Pinna laqueata* is oriented vertically in the sediment, similar to that of modern members of the genus. *Cucullaea vulgaris*, which is semi-infaunal, occurs in associations of up to 50 specimens, with both valves commonly attached. Echinoids also appear in aggregations of hundreds of individuals, suggesting gregarious feeding behavior. In addition, there are monospecific clusters of baculites and scaphites, some of which consist of more than 30 adult specimens, which have been interpreted as reflecting post-mating

or post-spawning fatalities (Landman et al. 2007a). Scaphite jaws are present, both as isolated specimens and inside body chambers. All this evidence suggests rapid deposition with little or no post-mortem transport. The *Pinna* Layer may thus represent a relatively short interval of time ranging from tens to hundreds of years. Based on estimates of the sea level at the time, Landman et al. (2007a) inferred that the environment of deposition of the *Pinna* Layer was relatively shallow, with estimates of 20–30 m depth.

The mode of occurrence of the specimens in the Burrowed Unit, in contrast, suggests a mixed death assemblage that has been modified by hydraulic processes. Almost all of the bivalves are disarticulated and not in life position. The ammonites are fragmented pieces of larger specimens, suggesting post-mortem transport and breakage. None of the fossils occurs in clusters. The environment of deposition of the Burrowed Unit was probably similar to that of the *Pinna* Layer, approximately 20–30 m deep. Although it is difficult to estimate the rate of sediment deposition, the presence of ammonite jaws suggests relatively rapid burial, based on taphonomic experiments involving modern coleoid jaws (Kear et al. 1995). As such, the Burrowed Unit may represent a relatively short interval of time ranging from tens to hundreds of years or even less.

The contact between the Burrowed Unit and the Hornerstown Formation marks a hiatus, coinciding with an extensive period of reworking. At age-equivalent sites in northeastern Monmouth County, Landman et al. (2004b) estimated that this hiatus may have lasted 100 000 years. The environment of deposition of the Hornerstown Formation is inferred to be slightly deeper than that of the Burrowed Unit or *Pinna* Layer, as the result of a transgression starting in the late Maastrichtian, based on an interpretation of the sequence stratigraphy of the Upper Cretaceous of New Jersey (Cohen et al. 2010).

The burrows in the Burrowed Unit were produced during the deposition of the Hornerstown Formation. The burrows extend through a thickness of approximately 20 cm. The fact that they do not penetrate into the *Pinna* Layer suggests that this unit must have been indurated at that time. However, the sediment of the Burrowed Unit was apparently soft enough to allow the burrows to penetrate into it, but competent enough to maintain a sharp boundary between the sediment and the burrows.

Taphonomy.—The fossils in the *Pinna* Layer are preserved as internal and external molds without any original shell. The internal molds are usually composed of glauconitic minerals. More rarely, they are composed of sideritic clay, which must have hardened before the sediment was glauconitized, thus preserving its original texture. All of the fossils in the *Pinna* Layer are considered to have formed during deposition of this layer.

The fossils in the Burrowed Unit are preserved in the same way as those in the *Pinna* Layer. Most of the internal molds are composed of glauconitic minerals whereas a minority are composed of sideritic clay, which matches the clay in the matrix. We therefore conclude that these fossils also formed during deposition of the surrounding sediment. Similarly, the ammonite aptychi were probably fossilized during deposition of the Burrowed Unit. They are fragile and presumably would not have survived the process of reworking (for a discussion about the taphonomy of ammonite jaws see Wani et al. 2005 and Wani 2007). Another argument against reworking of the aptychi is the fact that jaws of *Eubaculites* have never previously been reported from the *Pinna* Layer or any other unit in North America.

As noted above, the Hornerstown Formation contains both reworked and non-reworked fossils. The non-reworked fossils are pinkish brown in color, probably representing diagenetically altered shell. The reworked fossils are composed of whitish sideritic clay surrounded by dark green glauconitic pellets. This clay is similar to that in the *Pinna* Layer and Burrowed Unit but is much lighter in color, suggesting that it was perhaps altered during the process of reworking.

The reworked fossils in the Hornerstown Formation are also piped down into the Burrowed Unit. It is possible that this is the origin of the two large clay pods containing hollow material in the Burrowed Unit. Both of the pods are adjacent to burrows. However, they are not as light colored as the other reworked fossils and clasts in the Hornerstown Formation.

The reworked material at the base of the Hornerstown Formation was probably derived from winnowing and erosion of the *Pinna* Layer at more updip sites during the early Danian transgression. Because the fauna and lithology of the reworked fossils are identical to those in the *Pinna* Layer, it seems unnecessary to invoke a ghost unit that is no longer preserved. Similarly, it is unlikely that the source of the reworked material was the Burrowed Unit itself because this layer is depauperate. For example, the most commonly reworked fossil in the basal Hornerstown Formation is *Cucullaea vulgaris*. This species is very abundant in the *Pinna* Layer whereas it is virtually absent in the Burrowed Unit. The *Pinna* Layer is still present along strike at a site 15 km to the southwest (Ivanhoe Creek; Fig. 1: number 3). However, in a more updip site 11 km to the northwest (Buck's Pit; Fig. 1: number 2), the Burrowed Unit as well as the *Pinna* Layer are absent (Cohen et al. 2010). Based on our recent investigations at this site, the Hornerstown Formation lies directly on sediments representing the lower part of the upper Maastrichtian (calcareous nannofossil Subzone CC25c). This suggests that the source material for the reworked fossils in the basal Hornerstown Formation was probably from the *Pinna* Layer at more updip locations.

Sequence of events.—The interpretation of the sequence of events represented by the *Pinna* Layer, the Burrowed Unit, and the Hornerstown Formation depends on the significance and position of the enriched concentration of iridium. The iridum spike is very well defined and, although the concentration is not as high as that reported at some other Cretaceous/Paleogene boundary sections (Kiessling and Claeys 2002), including the Bass River core, New Jersey (Olsson et al. 1997), it is sufficiently above background level to suggest that this section re-

cords deposition of iridium from the bolide impact. The horizon with enriched iridium marks the Cretaceous/Paleogene boundary at the Global Stratotype Section and Point at El Kef, Tunisia (Cowie et al. 1989; Molina et al. 2009).

The crucial question is whether the iridium concentration in the Manasquan River Basin is in place, thereby marking the Cretaceous/Paleogene boundary (Fig. 1). Landman et al. (2007a) and Miller et al. (2010) enumerated the evidence in favor of and against displacement of the iridium anomaly. This evidence involves the shape of the iridium profile, the distribution and kind of fossils, and the presence or absence of spherules, shocked quartz, and other platinum group elements, in comparison with other sites. We present three possible scenarios of the sequence of events, depending on the interpretation of the original position of the iridium anomaly.

(i) The iridium was originally deposited at the base of the *Pinna* Layer. The lack of any trace of iridium in the rest of the *Pinna* Layer is consistent with this hypothesis. For example, at other sites where remobilization has been invoked, secondary peaks are still present at the original position of the iridium (e.g., Olsson et al. 1997). In addition, Bigolski et al. (2010) have shown high concentrations of nickel and cobalt in the Manasquan River Basin at the same horizon as the iridium. They argued that the nickel and cobalt were delivered to the site by Ni-rich bolide ejecta. Such concentrations also appear at nearby sites in New Jersey where the iridium anomaly coincides with the biostratigraphic markers usually interpreted as indicating the Cretaceous/Paleogene boundary (Denton et al. 2010).

If the iridium is in place, then the *Pinna* community was already established at the moment of impact and may even have flourished in the immediate aftermath of the bolide impact, perhaps due to enhanced nutrient runoff from the continent (Kump 1991). The community would have persisted a short interval of time, perhaps tens to hundreds of years, and may have been buried by one or more pulses of mud-rich sediment from overflowing rivers in the early Danian. The Burrowed Unit with its impoverished fauna may represent a subsequent interval, perhaps reflecting a collapse in marine productivity (Hsü and McKenzie 1985) that lasted tens to hundreds of years (Selpúlveda et al. 2009). In summary, the ammonites in the *Pinna* Layer and in the Burrowed Unit would have been short-term survivors of the bolide impact and would have persisted into the Danian.

(ii) The iridium was originally deposited at the top of the *Pinna* Layer and was subsequently displaced downward. In favor of remobilization is the absence, as yet, of a specific fallout layer containing spherules or shocked quartz at the same horizon as the iridium. Remobilization has also been postulated based on comparisons with other sites. In Cretaceous/Paleogene sections in Poland, the iridium spike occurs 10 cm below a clay layer that is interpreted as marking the boundary (Racki et al. 2010). The authors attributed this to remobilization due to humic acid-rich ground waters. In the Bass River Core in New Jersey, the iridium anomaly occurs at the base of a 6-cm-thick spherule layer (Olsson et al.

1997). The authors also attributed this to remobilization due to post-depositional diffusion. Miller et al. (2010) documented additional sites in New Jersey where the iridium anomaly coincides with the biostratigraphic markers usually interpreted as indicating the boundary and, therefore, they argued, by extension, that the iridium anomaly was displaced downward in the Manasquan River Basin. Indeed, at most sites around the world, the iridium anomaly and the biostratigraphic markers usually interpreted as indicating the boundary coincide (e.g., the type section in Tunisia).

In this scenario, the bolide impact would have caused the destruction of the *Pinna* community. If some animals were still alive at the time, they could have translated the iridium spike downward via bioturbation. Alternatively, the spike may have subsequently migrated downward due to chemical remobilization [see Guinasso and Schink (1975) and Rocchia and Robin (1998) for a further discussion about the effects of bioturbation and diffusion on the redistribution of iridium and other elements]. The Burrowed Unit would have been deposited in the immediate aftermath of the impact, still capturing some of the same community but only in a very reduced and modified state. The presence of ammonite jaws in the Burrowed Unit would suggest that some ammonites survived the bolide impact, although perhaps only momentarily.

(iii) The iridium was originally deposited at the top of the Burrowed Unit and was subsequently displaced downward by chemical remobilization through a thickness of 40 cm. This implies that the iridium anomaly and the biostratigraphic markers were originally coincident. In this scenario, the impact would have post-dated the *Pinna* community, but might have contributed to the end of the much less diverse community in the Burrowed Unit. The ammonites, at least at this site, would not have survived the impact.

In all three scenarios, the non-reworked fossils in the basal Hornerstown Formation probably represent the post-impact community, although it is difficult to determine how much time is missing at the contact between the Burrowed Unit and the Hornerstown Formation. The fauna consists of only 15 species, including several Cretaceous holdovers (e.g., *Margaritella pumila* and *Pecten venustus*) and is dominated by the small suspension-feeding oyster *Ostrea pulaskensis*. The predominance of this species is reminiscent of the high abundance of ferns following the collapse of the angiosperms in the terrestrial record of the Cretaceous/Paleogene boundary (Vajda et al. 2001).

Conclusions

This report emphasizes the importance of the Burrowed Unit in trying to resolve the events in the Manasquan River Basin, New Jersey, at the end of the Cretaceous. Of the scenarios described above, Scenario 1 does not involve any remobilization of the iridium. It implies that the *Pinna* community persisted and perhaps even thrived in the immediate aftermath of the impact, followed by the more impoverished com-

munity in the Burrowed Unit. Scenario 2 involves remobilization of the iridium through a thickness of 20 cm. It implies that the *Pinna* community was destroyed by the impact and the ensuing environmental maelstrom, and was replaced by the depauperate community in the Burrowed Unit. Scenario 3 involves remobilization of the iridium through a thickness of 40 cm. It implies that the ammonites perished at approximately the same time as the bolide impact. In Scenarios 1 or 2, the ammonites would have survived the impact at this site for a brief interval of time lasting from a few days to hundreds of years. Choosing among these three scenarios requires additional information about other geochemical markers in the Manasquan River Basin (spherules, shocked quartz grains), and comparison with K/Pg sites elsewhere on the Atlantic and Gulf Coastal Plains.

Acknowledgements

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