

# *The Triassic/Jurassic boundary in continental rocks of eastern North America; A progress report*

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## ABSTRACT

Newark Supergroup rocks of eastern North America provide a fine-scale record of continental faunal and floral change spanning all of the Late Triassic and most of the Early Jurassic (Carnian/Pliensbachian). Lake-level cycles controlled by orbitally induced climate changes permit calibration of biotic change at a 20,000-year level of resolution. The patterns of both the faunal and floral changes suggest that the Triassic/Jurassic biotic changes consisted of a large number of extinctions without replacement: the succeeding assemblages consist of survivors. The Triassic/Jurassic Newark faunal and floral transition appears synchronous with the massive marine extinctions noted elsewhere in the world. Preliminary data suggest the Newark pollen and spore transition took place in less than 20,000 years (within one lake-level cycle), whereas available bone and footprint data suggest the extinction of ecologically dominant Late Triassic terrestrial vertebrates could have taken as long as 700,000 years. Although we are still in the early stages of investigation, what we know about the Newark Triassic/Jurassic episode is consistent with a very large and abrupt mass extinction event. The penecontemporaneous Manicouagan impact still seems a plausible cause. A search has only now begun for evidence of an impact-derived fallout layer in the Newark Supergroup, but it is far too early to confirm or deny a causal role for a bolide impact for the Triassic/Jurassic extinctions, in the Newark Supergroup or elsewhere.

## INTRODUCTION

Exposed rift basins of the Atlantic passive margin in eastern North America are filled with thousands of meters of continental rocks termed the Newark Supergroup (Olsen, 1978; Froelich and Olsen, 1984; Fig. 1); these rift basins provide an unprecedented opportunity to examine the fine-scale structure of the Triassic/Jurassic extinctions in continental environments. Time control, vital to understanding the mechanisms behind mass extinctions, is provided by lake-level cycles apparently controlled by orbitally induced (Milankovitch-type) climate change (Olsen, 1986) potentially allowing resolution at the <20,000-year level (Olsen and others, 1989). Correlation with areas outside the Newark Supergroup is provided by magnetostratigraphy (Witte and Kent,

1989; Witte and Kent, in preparation), palynological biostratigraphy (Cornet, 1977; Cornet and Olsen, 1985), and to a lesser extent, vertebrate osteological, and ichnological biostratigraphy (Olsen and Galton, 1977, 1984; Olsen and Sues, 1986; Olsen and Baird, 1986).

## NEWARK BASIN SECTION

The Newark basin section (Figs. 1, 2) is the most intensely studied in the Newark Supergroup. A cumulative stratigraphic thickness in excess of 7 km is preserved. Based on pollen and spore biostratigraphy (Cornet, 1977; Cornet and Olsen, 1985) the strata range in age from at least middle Carnian of the Late Triassic to at least the Hettangian of the Early Jurassic. The Newark basin section is largely lacustrine; major exceptions are the tholeiitic flows interbedded with the Early Jurassic age strata and the fluvial Stockton Formation that contains the oldest basin

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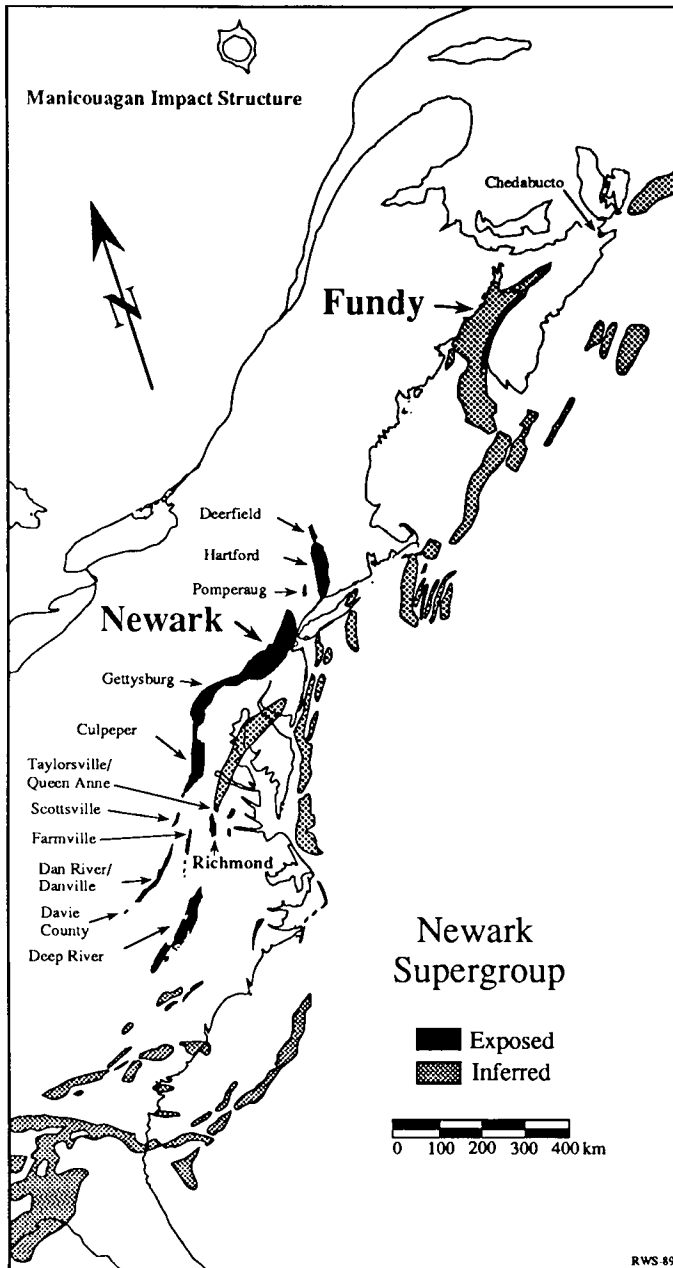


Figure 1. The Newark Supergroup, genetically related subsurface basins, and the Manicouagan impact structure.

fill. Strata along the edges of the basin also contain a significant fluvial and alluvial component. The regular and repetitive sedimentary sequences that make up the lacustrine rocks of the Newark basin and the rationale for assigning their origin to orbital forcing of climate have been described in detail by Olsen (1984, 1986) and Olsen and others (1989, 1990). The highest frequency lake-level cycles were apparently controlled by the cycle of the precession of the equinoxes and allow calibration in time at the 20,000-year level through most of the basin section (Olsen and others, 1989).

### Pollen and spores

Cornet (1977) used pollen and spores to identify the Triassic/Jurassic boundary in the uppermost Passaic Formation (Jacksonwald syncline, southeastern Pennsylvania; Fig. 3). In this section, the Passaic Formation is almost entirely lacustrine, and the pattern of lake-level cycles continues upward to the Jacksonwald (= Orange Mountain) Basalt. In this section the palynological transition is apparently abrupt, occurring within one lake-level cycle (ca. 20,000 years), and exhibits the largest qualitative microfloral change seen in the approximately 35-m.y. Newark Supergroup record. Based on our ongoing study of many samples, typical "Triassic" taxa such as *Patinasporites densus*, *Vallisporites ignacii*, *Ovalipollis ovalis*, and *Triadispora* spp., are last seen in unit B (Fig. 3), occurring with diverse nonstriate bisaccates, including many species assignable to the genera *Alisporites*, *Colpectopollis*, *Cuneatisporites*, *Lorisporites*, *Pityosporites*, *Platysaccus*, *Podocarpidites*, *Protodiploxypinus*, and *Rugubivesiculites*. Also present in unit B is a diverse suite of bennettitalean, cycad-like, and angiosperm-like pollen, as well as the taxa characteristic of the succeeding Jurassic-age sections. This assemblage resembles others recovered from the upper 1,000 m of the Passaic Formation in the Newark basin, and many of the constituent species (particularly bisaccate and circum-saccate taxa) are found throughout the Passaic Formation (below the Triassic/Jurassic boundary). The "typical" Triassic forms have not been found in hundreds of samples examined from the Jurassic-age sections of the Newark Supergroup. The next stratigraphically higher interval (unit A) in the Jacksonwald syncline (first identified by R. Litwin, U.S.G.S., Reston, Virginia, in sample number R4099c; [Smith and others, 1989], and subsequently intensively sampled by us) lacks these taxa but is dominated by spores that can be assigned to the genera *Anapiculatisporites*, *Convruccosisporites*, *Deltoidospora*, *Dictyophyllidites*, *Granulatisporites*, *Kyrtomispors*, *Porcellispora*, *Reticulatisporites*, *Todisporites*, *Verrucosisporites*, and uncommon *Corollina meyeriana* (R. Litwin, personal communication, 1989). We additionally note *Carnisporites* and very rare angiosperm-like pollen (R. Litwin, personal communication, 1989). No other such interval is known (out of hundreds) in the Newark Supergroup. Younger palyniferous intervals in the Jacksonwald syncline and elsewhere in the Newark Supergroup produce palynoflorules that are generally of very low diversity—dominated (+90 percent) by *Corollina meyeriana*. Bisaccate pollen and spores are uncommon and represented by few taxa (Cornet and Olsen, 1985). As recorded in the Jacksonwald syncline, the palynological transition records the elimination of a high-diversity floral assemblage, a relatively brief fern-dominated perturbation (or "spike"), which is replaced with a very low-diversity cheirolepidaceous conifer assemblage that shows little change through the remainder of the Newark Supergroup.

Based on calibration by lake-level cycles, the pollen and spore transition in the Newark basin took place during an interval of less than 20,000 years. It may have taken less time, and sam-

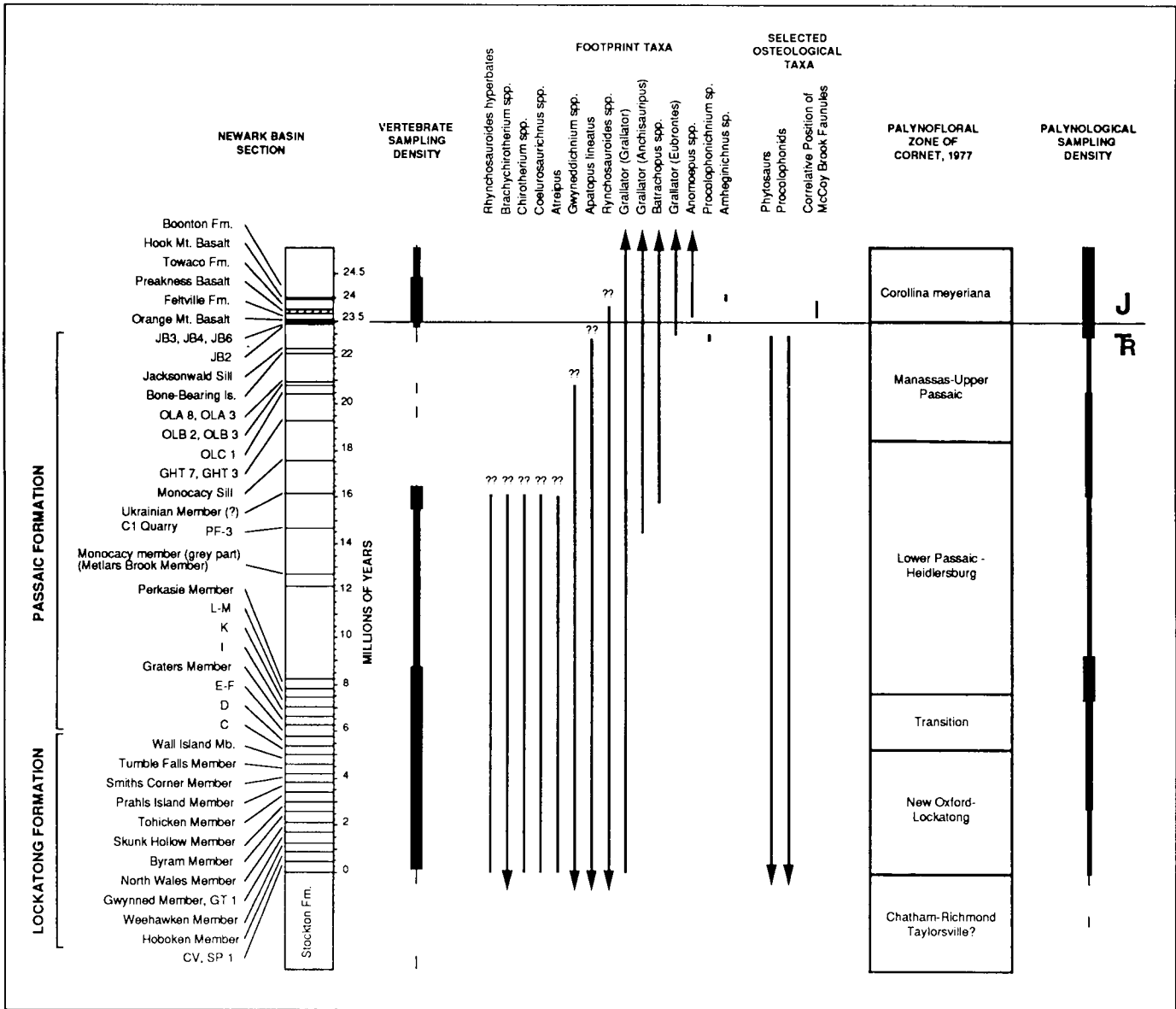


Figure 2. The Newark basin section showing distribution of major vertebrate footprint taxa and corresponding pollen and spore zones. Time scale is based on lake-level cycles as described by Olsen and others (1989); note change in scale above Triassic/Jurassic boundary. Figure is modified from Olsen and others (1989).

ples needed to more tightly constrain the duration of the transition have been collected and are under study. Viewed in the context of floral changes at the Cretaceous/Tertiary boundary (Tschudy and others, 1984), it is especially intriguing that the elimination of the Triassic-aspect palynoflora is succeeded by what might be called a fern spike. Obviously the pattern seen in the Jacksonwald syncline needs to be tested against sections from a larger geographic area, and such studies are underway. Preliminary data from a variety of other sections as far away as Virginia (R. Litwin, personal communication, 1989) and Nova Scotia are, in fact, compatible with the general pattern, although the

apparent palynofloral change in these areas has not yet been resolved to a 10-m interval as in the Jacksonwald syncline.

The dramatic spore and pollen transition seen in the Jacksonwald syncline of the Newark basin is similar (but not identical) to the transition through the Triassic/Jurassic boundary in Europe, and is hence hypothesized to be correlative (Cornet, 1977; Morbey, 1975; Fisher and Dunay, 1981). Many taxa that disappear at the Triassic/Jurassic boundary in the Newark basin are found in Jurassic-age strata elsewhere in the world. Although some Newark forms only disappeared locally and did not become extinct in the strict sense of the word, this

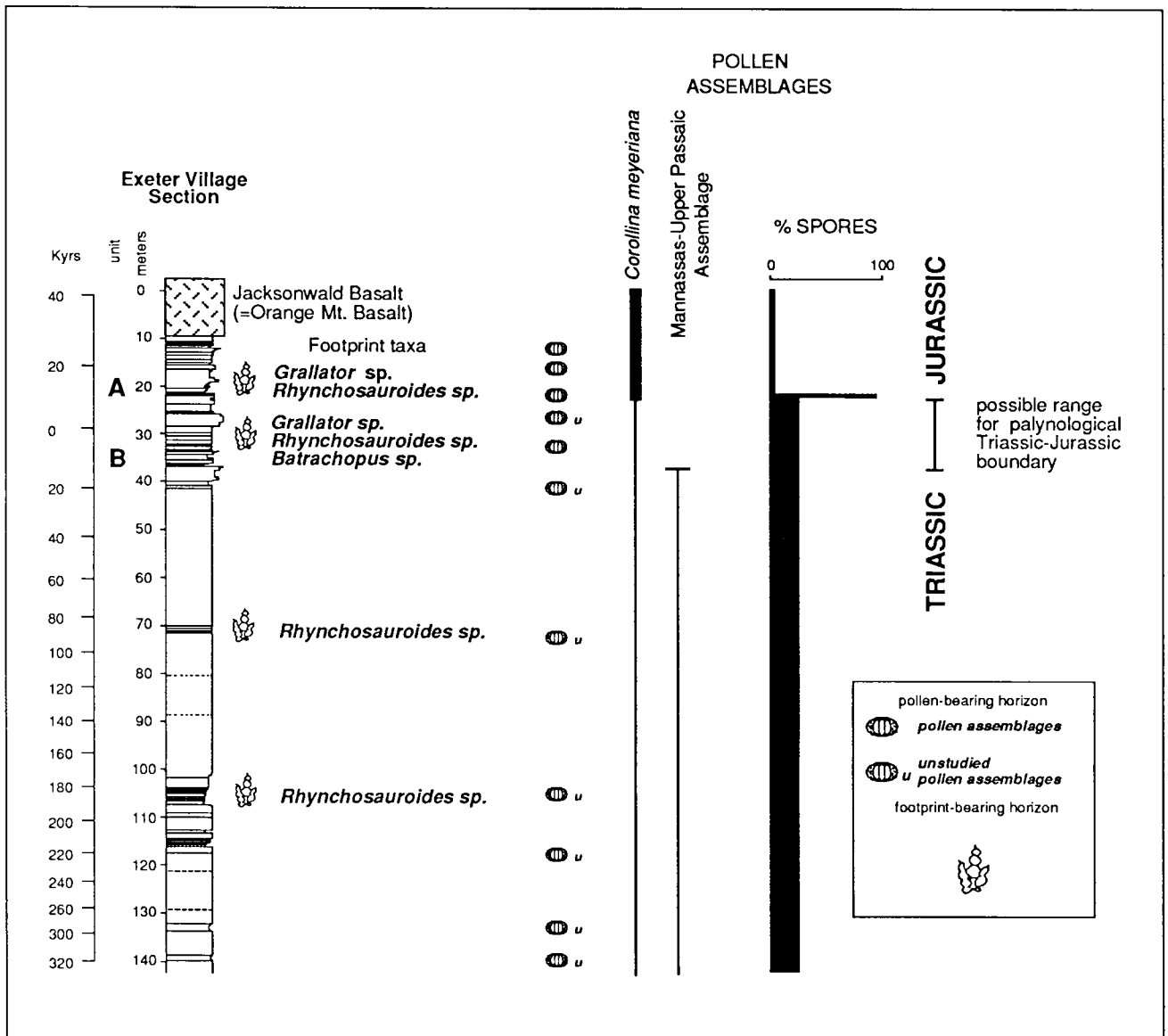


Figure 3. Jacksonwald syncline section of the Newark basin showing occurrences of footprint-, pollen-, and spore-bearing intervals. Time scale based on lake-level cycles as in Figure 2. A and B are units referenced in the text (brackets). Note that the relative abundance of pollen and spores and the distribution of the pollen assemblage zones are shown diagrammatically using the range-through method in combination with data from Early Jurassic-age strata above and Late Triassic-age strata below the interval shown in this diagram. Also note that the pollen assemblages marked as unstudied are processed and are of obvious Triassic character, although specific frequency counts are as yet not complete.

should not detract from the profound floral change this transition represents.

#### ***Tetrapod skeletal remains***

Tetrapod osteological remains, with few exceptions, are not common in the Newark Supergroup, but those that have been found can be rigorously placed into relative stratigraphic order and calibrated in time using lake-level cycles. Some dominant

taxa of the Late Triassic, such as phytosaurs and procolophonids, have been found in the upper Passaic Formation in strata about 600,000 years older than the palynologically based Triassic/Jurassic boundary and are known from many levels in older Newark strata. In Early Jurassic-age strata, abundant bones are found only in the McCoy Brook Formation of the Fundy basin in Nova Scotia. These assemblages completely lack the dominant "Late Triassic forms" found lower in the Newark Supergroup and appear to postdate the palynologically dated Triassic/Jurassic

boundary by less than 100,000 years (Olsen and others, 1987). Although nearly identical assemblages are known in Jurassic-age strata from outside the Newark Supergroup, all of the families (except perhaps the Trithelodontidae, N. H. Shubin, University of Pennsylvania, Philadelphia, Pennsylvania, personal communication, 1989) represented in the McCoy Brook assemblage have also been found in Triassic deposits. In other words, this assemblage appears to consist only of survivors from the Triassic. At this time, the duration of the period of extinction of characteristic Late Triassic tetrapods (based on osteological data) is restricted to less than 700,000 years, based on lake-level cycles. Although new bone localities are found fairly often, it seems unlikely that enough vertebrate skeletal remains ever will be found to constrain the duration of the tetrapod extinctions at the degree of resolution possible with palynomorphs and vertebrate ichnotaxa.

### Footprint assemblages

Newark Supergroup strata are famous for their rich and well-preserved tetrapod footprint assemblages. Footprints are common in the coarser facies of the shallow-water portions of many lake-level cycles throughout the Newark basin section and are much more abundant than bones. Their predictable occurrence in specific facies make them ideal for studying faunal change at a fine level of stratigraphic resolution. However, what is gained in stratigraphic and temporal resolution is lost in taxonomic resolution. At best, footprint genera probably correspond to family-level osteological taxa (Padian and Olsen, 1984; Olsen and Baird, 1986). Nonetheless, footprint taxa should give an overview of the ecologically dominant taxa in the shallow lake margin communities.

We recognize little ichnotaxonomic turnover in the first 16 m.y. of the Newark basin lacustrine record (Lockatong to middle Passaic Formation; Fig. 2; Silvestri and Olsen, 1988). Dominant taxa in this interval include the quadrupedal dinosaurian form *Atreipus*, the bipedal theropod dinosaurian track *Grallator*, and the lepidosauromorph footprint *Rhynchosauroides*. Other genera include: the archosauromorph tracks *Coelurosaurichnus*, *Brachychirotherium* and *Chirotherium*; the probable phytosaur footprint *Apatopus*; the probable tanystropheid footprint *Gwyneddichnium*; and the very rare procolophonid track *Procolophonichnium*. A locality at Douglasville, Pennsylvania, is the youngest well-sampled and well-studied footprint assemblage that contains the most common of these taxa. It occurs stratigraphically close to the Ukrainian Member of the Passaic Formation (C1 Quarry, Fig. 2), estimated at about 7 m.y. before the Triassic/Jurassic boundary (based on lake-level cycles). Also present is the oldest record of the crocodylomorph track *Batrachopus*, which becomes a dominant taxon in the Jurassic-age part of the section. The next higher well-sampled assemblage is from just above the Triassic/Jurassic boundary at the very top of the Passaic Formation at several localities. *Grallator* spp., *Batrachopus deweyii*, and *Rhynchosauroides* sp.

are the only taxa present, even though thousands of well-preserved tracks have been found. Above this level the ornithischian dinosaurian form *Anomoepus* appears, *Rhynchosauroides* is very rare, the rare, possible crocodylomorph track *Otozoum* occurs, as does the extremely rare mammal or mammal-like reptile footprint *Ameghinichnus* sp. (Olsen and Galton, 1984). This assemblage comprises a classic Connecticut Valley-type footprint assemblage (Olsen and Galton, 1977, 1984). There appear to be no further changes in footprint assemblages throughout the rest of the Newark basin or the supergroup (Fig. 2).

There are only scattered examples of footprints known from the assemblage just above the Triassic/Jurassic boundary to the Douglasville, Pennsylvania, assemblage, which is about 7 m.y. older. One as yet poorly categorized assemblage comes from a thin red siltstone and sandstone sequence between units A and B in the Jacksonwald syncline. So far, *Grallator* spp., *Rhynchosauroides* sp., and *Batrachopus* sp. have been found (Silvestri and Olsen, 1989). Too few footprints have been found to suggest that typically Triassic-aspect taxa such as *Atreipus* or *Brachychirotherium* are demonstrably absent from this interval. A single *Apatopus* sp. manus-pes set has been found in the upper Passaic Formation; it is estimated to be about 800,000 years older than the Triassic/Jurassic boundary (Olsen and others, 1987). Otherwise, there are only sporadic occurrences of *Grallator* and *Rhynchosauroides*—too few to tell if there was any faunal change through this poorly sampled interval. We have targeted this interval for intense scrutiny. The occurrence of a few tracks now known from this interval suggests many more will probably be found.

### SYNCHRONEITY OF EXTINCTIONS

Presently, it is not possible to determine if the faunal and floral changes reported in the Newark Supergroup are synchronous within the resolution of one lake-level cycle (ca. 20,000 years). Key intervals of the upper Passaic Formation of the Newark basin are still too coarsely sampled. Research is now focused on closing this gap in our biostratigraphic knowledge by systematic study of the upper Passaic Formation and correlative units in the adjoining Gettysburg and Culpeper basins (Olsen and others, 1989).

Correlation of the biotic changes seen in the Newark Supergroup with those of European sections is even less well understood. Correlation between continental and marine sections in Europe is not very well constrained, and all sections lack the fine-scale temporal control afforded by the Newark lake-level cycles. Nonetheless, the faunal and floral changes in the Newark Supergroup appear consistent with those seen in the European sections (Olsen and Galton, 1977, 1984; Olsen and Sues, 1986 [see Hallam, this volume; and Sepkoski, 1986; for discussions of the magnitude of the marine extinctions]), suggesting that the hypothesis of simultaneous vertebrate, invertebrate, and floral extinctions is viable.

The overall faunal and floral pattern seen in the Newark Supergroup suggests that a large number of vertebrate (continental tetrapods) and palynomorph extinctions are concentrated around the period boundary; the earliest Jurassic assemblages consist of survivors, virtually without the introduction of new taxa (an exception is trithelodontids; Shubin and others, unpublished). On a global basis, with roughly 45 percent of all osteological families disappearing (Olsen and others, 1987), the Triassic/Jurassic mass extinction of nonmarine tetrapods appears to be proportionally larger than the Cretaceous/Tertiary mass extinction (36 percent; Archibald and Bryant, 1988). Although much more intensive sampling of the last 7 m.y. of the Triassic is needed in the Newark Supergroup, the pattern currently known is consistent with a hypothesis of an extremely rapid, perhaps catastrophic, taxonomic turnover at the Triassic/Jurassic boundary, possibly synchronous in continental and marine realms.

No taxonomic turnover of comparable magnitude is apparent in Newark Supergroup strata palynologically dated as straddling the Carnian/Norian boundary. A large faunal turnover is seen, however, within middle Carnian-age Newark strata (Cornet, 1977; Cornet and Olsen, 1985). This departs from literature tabulations (Sepkoski, 1986) that suggest a marine mass extinction at the Carnian/Norian boundary. Either Newark strata are misdated or the marine and terrestrial extinctions were not synchronous (Silvestri and Olsen, 1988). Parenthetically, Sepkoski (1986) suggested the apparent marine Carnian/Norian mass extinction could be an artifact of very high ammonite evolution rates during this time. Therefore, our current evidence from the Newark Supergroup does not suggest a mass extinction event at any boundary except the Triassic/Jurassic boundary.

## CAUSATION

Plausible causes for the major extinctions such as those seen at the Cretaceous/Tertiary or Triassic/Jurassic boundary include: (1) competitive superiority of newly evolved taxa; (2) climate change, perhaps driven by sea-level change or other mechanisms; (3) very large-scale volcanic eruptions; and (4) giant bolide impacts. The competitive replacement hypothesis is not supported by the observed pattern of taxonomic change because the surviving taxa coexisted with those that went extinct for millions of years before the boundary event. Jurassic strata indicate changes in climate at many places in the world, but these changes seem neither synchronous with each other nor with the large-scale faunal and floral changes (Cornet and Olsen, 1985). Thick and extensive tholeiitic extrusives characterize Early Jurassic-age sequences in the Newark Supergroup, as well as in penecontemporaneous rift basins in western Africa and the Karoo basins in southern Africa. The oldest of these are the extrusives of the Newark Supergroup, which *postdate* the palynologically identified Triassic/Jurassic boundary and the associated extinctions by about 40,000 years (Olsen and others, 1989; Olsen and others, in preparation), which is close in time but hard to invoke as the primary causative agent.

A more plausible cause is the great bolide impact that produced the Manicouagan structure of Quebec (Olsen and others, 1987). The estimated size of the bolide that produced Manicouagan (ca. 7 km) is the same magnitude as that hypothesized for the Cretaceous/Tertiary mass extinctions (Simonds and others, 1978; Alvarez and others, 1980). The best available radiometric dates from Manicouagan range from  $206 \pm 6$  to  $215 \pm 4$  Ma (summarized in Olsen and others, 1987); these are indistinguishable from the Triassic/Jurassic boundary in most recent published time scales (e.g., 213 Ma, Harland and others, 1982; 208 Ma, Palmer, 1983; 204 Ma, Odin and Letolle, 1982). However, these published time-scale boundary dates are based on interpolation, and very few radioisotopic dates are known from igneous rocks found really close to a paleontologically dated boundary. The massive tholeiitic flows of the Newark Supergroup should yield directly relevant dates. However, the lava flows themselves have yielded a tremendously wide scatter of dates spanning 100 m.y., even though the cyclostratigraphy of the enclosing and interbedded sedimentary strata suggests a duration of the extrusive event of about 550,000 years (Olsen and others, 1989; Olsen and others, in preparation). This very broad scatter is probably due to post-cooling, relatively low-temperature argon loss (Sutter, 1985) and argon addition (Seidemann, 1988). Accordingly, the best radiometric dates for the whole igneous suite actually come from associated intrusives that originally fed the flows (Ratcliffe, 1988), and that have yielded  $^{40}\text{Ar}/^{39}\text{Ar}$  dates (on hornblende and biotite) averaging  $201 \pm 3$  Ma (root mean square error) from minerals known to exhibit excellent closed-system behavior (Sutter, 1988). The date of  $201 \pm 3$  Ma should therefore be indistinguishable from the date of the Triassic/Jurassic boundary at present levels of analytical precision (Sutter, 1988; Ratcliffe, 1988). The only other isotopic system data available for these rocks are U-Pb dates (mean age  $201 \pm 1$  Ma) from zircons and baddeleyites, which are completely compatible with the  $201 \pm 3$  Ma  $^{40}\text{Ar}/^{39}\text{Ar}$  date (Dunning and Hodych, 1990).

We believe that the existing Manicouagan dates are not reliable because of the probability of a contribution of  $^{39}\text{Ar}$  derived from the Precambrian country rock in which Manicouagan was formed to the apparent age of the melt rock. We therefore do not regard the apparent conflict in ages between the Newark Supergroup igneous rocks and the Manicouagan impact structure as necessarily real. Therefore, we are resampling and re-dating (using multiple isotopic systems) the impact structure.

If the Manicouagan event caused the Triassic/Jurassic extinctions, some physical record of the impact should be present in Newark Supergroup deposits (Olsen and others, 1987). Newark Supergroup sections are very thick, and therefore the search for an impact layer has focused on the paleontologically dated Triassic/Jurassic boundary. Two boundary sections have been examined for Ir: the uppermost Passaic Formation of the Jacksonwald syncline of the Newark basin (Fig. 3) and the upper Blomidon Formation in the Fundy basin. According to Smith and others (1989), Ir amounts in unit A of Figure 3 (the spore-rich interval) in the Jacksonwald syncline are below detectable limits using

their techniques. The same is true for the upper 100 m of the Blomidon Formation sampled by M. Anders (Lamont-Doherty Geological Observatory, Palisades, New York) and processed by F. Asaro (University of California, Berkeley, personal communication, 1989). This is not necessarily evidence against an impact cause of the boundary extinctions because Manicouagan melt rocks show very little or no Ir enrichment (~0.02 ppb; Palme, 1982; Palme and others, 1978, 1982). Therefore, there is little reason to suspect that a fallout layer from the impact should have an Ir anomaly.

Quartz grains with "shock lamellae" should be present if a fallout layer exists, however. To date, there have been no concerted attempts at a search for shocked quartz in Newark Supergroup boundary sections. M. Anders (personal communication,

1989) examined Blomidon Formation for shocked quartz but suspended his analysis after only 10 percent of the samples were examined because of the difficulty in discriminating very abundant tectonic deformation lamellae from possible shock lamellae. We have collected samples from the Jacksonwald syncline in the Newark basin section, but these have not been processed. The tedious search for shocked quartz in the Newark Supergroup remains to be done.

There have been two reports of shocked minerals at the Triassic/Jurassic boundary in Europe. Bice and McCauley (1990) have identified shocked quartz and feldspar at a Triassic/Jurassic marine boundary section in Tuscany, Italy. The shocked minerals occur immediately above the last occurrence of *Rhaetavicula* bivalve association (Newton and McRoberts,

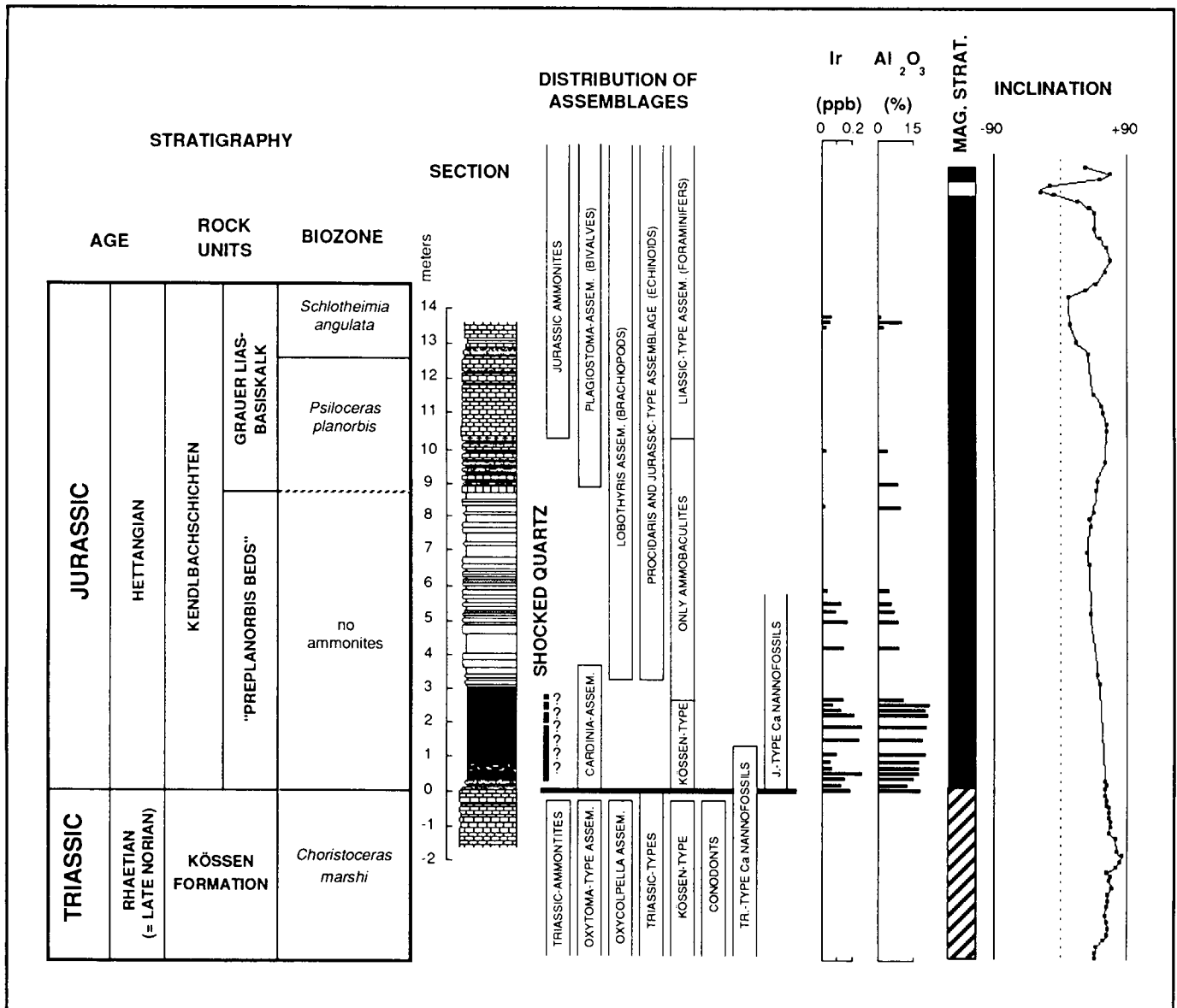


Figure 4. Kendelbach section of Triassic/Jurassic boundary. Data compiled from Goleblowski and Braunstein (1988), Zeissl and Mauritsche (1988), Badukov and others (1987, 1988).

1990), which is characteristic of the latest Triassic. According to Bice and McCauley (1990), the composition of the shocked mineral association is compatible with the Manicouagan impact structure. Badjukov and others (1987) reported a shocked quartz horizon in the marine Triassic/Jurassic boundary in the Kendelbach section in Austria (Fig. 4) in the same biostratigraphic position as the Tuscany shocked mineral assemblage. However, this occurrence has not yet been independently confirmed (Hallam, this volume), and no Ir anomaly is present in this interval (Fig. 4). As Lahodinsky (1988) noted in the case of the Cretaceous/Tertiary boundary, such mineralogical anomalies can be very hard to find.

## SUMMARY

In the Newark Supergroup, the faunal and floral extinctions that define the Triassic/Jurassic boundary stand in dramatic contrast to the background taxonomic turnover rates seen above or below (Olsen and Sues, 1986). The "boundary event" seems to have occurred during a period of increasing diversity (Olsen and others, 1987). There is no evidence of climate change across the period boundary within continental rocks of the Newark Supergroup. It is plausible that marine and terrestrial extinctions of fauna and flora were synchronous and very rapid. The impact that produced the Manicouagan structure is a plausible cause of

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