

Continental Triassic-Jurassic boundary in central Pangea: Recent progress and discussion of an Ir anomaly

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ABSTRACT

The Triassic-Jurassic (Tr-J) boundary marks one of the five largest mass extinctions in the past 0.5 b.y. In many of the exposed rift basins of the Atlantic passive margin of eastern North America and Morocco, the boundary is identified as an interval of stratigraphically abrupt floral and faunal change within cyclical lacustrine sequences. A comparatively thin interval of Jurassic strata separates the boundary from extensive overlying basalt flows, the best dates of which (ca. 202 Ma) are practically indistinguishable from recent dates on tuffs from marine Tr-J boundary sequences. The pattern and magnitude of the Tr-J boundary at many sections spanning more than 10° of paleolatitude in eastern North America and Morocco are remarkably similar to those at the Cretaceous-Tertiary boundary, sparking much debate on the cause of the end-Triassic extinctions, hypotheses focusing on bolide impacts and climatic changes associated with flood basalt volcanism.

Four prior attempts at finding evidence of impacts at the Tr-J boundary in these rift basin localities were unsuccessful. However, after more detailed sampling, a modest Ir anomaly has been reported (up to 285 ppt, 0.29 ng/g) in the Newark rift basin (New York, New Jersey, Pennsylvania, United States), and this anomaly is directly associated with a fern spike. A search for shocked quartz in these rift basins has thus

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far been fruitless. Although both the microstratigraphy and the biotic pattern of the boundary are very similar to continental Cretaceous-Tertiary boundary sections in the western United States, we cannot completely rule out a volcanic, or other non-impact, hypothesis using data currently available.

INTRODUCTION

The Triassic-Jurassic (Tr-J) boundary (ca. 202 Ma) marks one of the five largest mass extinctions of the Phanerozoic (Sepkoski, 1997), arguably at least as large in magnitude as that at the much better known Cretaceous-Tertiary (K-T) boundary (Fig. 1). The extinctions occurred in a hothouse world during a time of extremely high CO₂ (Ekart et al., 1999) and the existence of the supercontinent of Pangea. In continental environments, the Tr-J extinctions mark the end of a regime dominated by nondinosaurian tetrapods and the beginning of the dinosaurian dominance that would last the succeeding 135 m.y.

Pangean rift basins developed during the Middle to Late Triassic along a broad zone from Greenland through the Gulf of Mexico in the ~40 m.y. preceding the Jurassic opening of the central Atlantic Ocean. Many of these rift basins preserve a detailed record of the Tr-J boundary in mostly continental environments characterized by relatively high sedimentation rates (Fig. 2). In this chapter we report on recent progress in documenting the biotic transition around the Tr-J boundary, including the recently reported evidence for an associated Ir anomaly, and the relationship between these boundary events and the Central Atlantic magmatic province.

IDENTIFICATION OF THE CONTINENTAL TR-J BOUNDARY

Rift basins of central Pangea developed largely in a continental milieu. Comparison of the Tr-J boundary in the marine realm with that in continental environments is largely based on studies of Alpine marine sections correlated to other European, mostly continental, areas by palynomorphs and scant marine invertebrates (Schulz, 1967; Brugman, 1983; Beutler, 1998). Cornet and others (Cornet et al., 1973; Cornet and Traverse, 1975; Cornet, 1977; Cornet and Olsen, 1985) first identified the Tr-J boundary in the tropical Pangean basins, most notably in the Jacksonwald syncline of the Newark basin. This palynological work was augmented by subsequent studies in the Newark and other basins in eastern North America by Fowell (1994; Fowell et al., 1994; Fowell and Traverse, 1995; Olsen et al., 1990).

Within eastern North America, Olsen and Galton (1977, 1984), and Olsen and Sues (1986) identified a transition in the terrestrial tetrapod assemblages that coincides, albeit at a coarser level, with that seen in the palynomorphs. Additional vertebrate paleontological studies have refined the correlation of the Tr-J boundary in these continental rifts to the marine

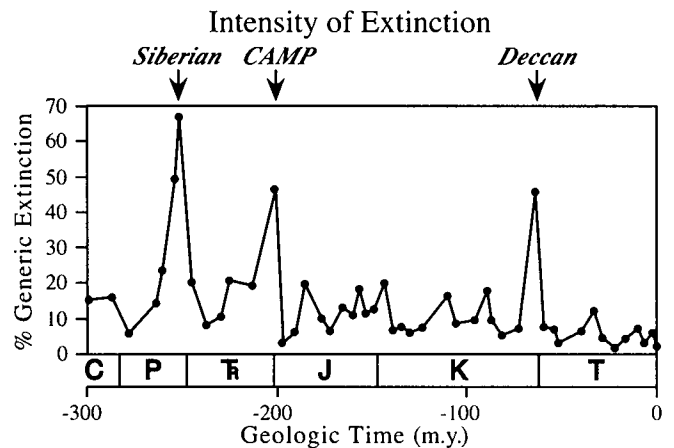


Figure 1. Generic-level extinctions of marine, shelly organisms during past 300 m.y., and distribution of giant flood basalt provinces (in italics). Modified from Sepkoski (1997) to reflect our estimate of age of Triassic-Jurassic boundary. CAMP is Central Atlantic magmatic province.

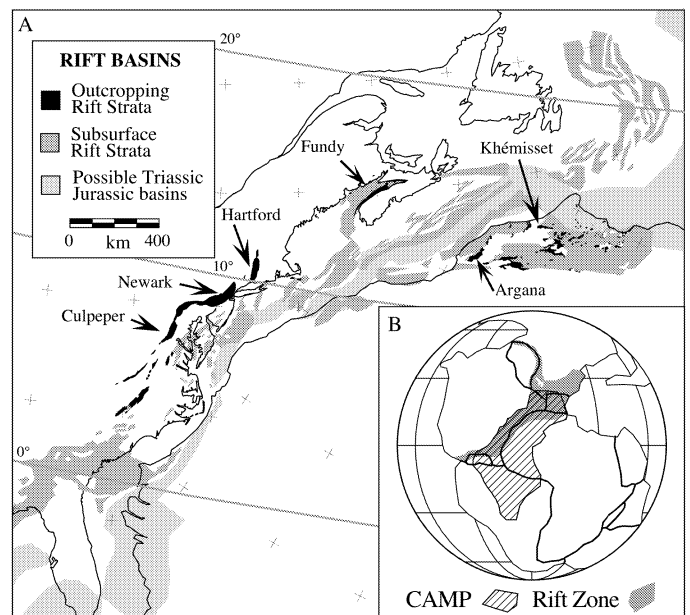


Figure 2. Distribution of central Atlantic margin rift basins of central Pangea and temporal distribution of Central Atlantic magmatic province (CAMP). A: Rift basins of central Atlantic margins of North America and western Africa in predrift coordinates (for Late Triassic) showing basins discussed in this chapter (modified from Olsen, 1997). B: Pangea during earliest Jurassic showing distribution of CAMP, overlapping much of Triassic-Jurassic rift zone (based on Olsen, 1999).

realm, in which very rare terrestrial vertebrates are found (Olsen et al., 1987; Huber et al., 1996; Lucas, 1998).

Two significant problems in the biostratigraphy of the Tr-J boundary are the interpretation of negative evidence and the presence of distinct biotic provinces in the early Mesozoic. We believe that the Tr-J boundary is marked by a catastrophic mass extinction. As in the case of the Cretaceous-Tertiary boundary, we expect the immediate postboundary biotic assemblages to consist of survivor taxa, not new appearances. However, there is a long tradition of identification of the Tr-J boundary on the basis of new appearances, notably the first appearance of the ammonite *Psiloceras planorbis* in marine sections (e.g., Page and Bloos, 1998), and this approach has been carried over to the palynological analyses (e.g., Morbey, 1975).

It is arguable that global correlation of a boundary marked by a mass extinction with a very rapid and global cause using the first appearances of taxa is inappropriate. The boundary is more appropriately marked by the last appearances of taxa and not the appearance of new taxa that might appear thousands if not millions of years in the study area after the event.

A second problem with traditional biostratigraphy across the boundary is a very strong climatic gradient (Kent and Olsen, 2000b). The central European sections that form the basis of much of the palynological and vertebrate biostratigraphy were located ~2000 km north of the tropical Pangean basins of North America on the opposite (northern) side of the northern subtropical arid belt (Kent and Muttoni, 2001; Olsen and Kent, 2000). The marked floral and faunal provinciality, probably related to the Pangean climatic belts, was reviewed by Cornet and Olsen (1985) and Olsen and Galton (1984), but the possible effects of this very strong climatic gradient on floral assemblages, particularly palynomorphs, has been either ignored or discounted in attempts at long-distance correlation.

Reliance on first appearances and the discounting of the effects of climatic gradients have led some workers to cite the absence of certain critical palynological taxa characteristic of western Europe and the abruptness of the transition as evidence of a major hiatus at the Tr-J boundary, especially in eastern North America and Greenland (e.g., Pedersen and Lund, 1980; van Veen et al., 1995; Tourani et al., 2000). It is critical to point out that there is no physical stratigraphic or sedimentologic evidence of such a hiatus in these areas; detailed cyclostratigraphic and magnetostratigraphic evidence indicates continuous deposition across the palynologically identified boundary, especially where it has been examined in the most detail in the Newark basin (Kent et al., 1995; Olsen et al., 1996a, 1996b, 2002a, 2002b).

There is no question that there are significant differences between the stratigraphic distribution of palynomorph taxa in tropical Pangean basins and in western Europe. This difference shows up very obviously in the concurrence of the rise of abundance of *Corollina (Classopollis)* and persistence of *Patinasporites densus* in eastern North America over the last 15 m.y.

of the Triassic (Cornet, 1977); this pattern has no described European counterpart. The abrupt disappearance of *Patinasporites densus* is a signature of the Tr-J boundary in tropical Pangea. If the same kind of typological biostratigraphic philosophy were applied to the western North American continental K-T boundary, a major hiatus would be required. It is significant that the K-T boundary also exhibits dramatic climate-related floral provinciality (Sweet et al., 1990).

Radiometric dating of the Tr-J boundary provides support for the correct identification of the Tr-J boundary in the tropical Pangean rifts. Ages from lavas (and associated intrusive feeders; e.g., Ratcliffe, 1988) just above the palynological Tr-J boundary in eastern North America provide U-Pb ages of 201.3 ± 1 Ma (Gettysburg sill, Dunning and Hodych, 1990), 200.9 ± 1 Ma (Palisade sill, Dunning and Hodych, 1990), and 201.7 ± 1.3 Ma (North Mountain Basalt, Hodych and Dunning, 1992) and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 202.2 ± 1 , 200.3 ± 1.2 , and 201.2 ± 1.3 Ma (Palisade sill and Culpeper basin plutons, respectively; Sutter, 1988).

Until recently, these have been the only ages directly applicable to the boundary; however, Palfy et al. (2000a, 2000b) provided a date of 199.6 ± 0.3 Ma for a tuff just below the marine Tr-J boundary in British Columbia. Palfy et al. (2000a) argued that the difference between their marine date and the continental dates from eastern North America implies that the continental extinctions occurred prior to the marine extinctions. However, the differences in ages are very small, and thus we regard all these dates as indistinguishable, given reasonable, but unstated, geological and interlaboratory uncertainties. Furthermore, recent dates on the Orange Mountain Basalt of 201 ± 2.1 Ma (Hames et al., 2000) and its feeder, the Palisade sill, of 201 ± 0.6 Ma (Turrin, 2000), both from the Newark basin, are indistinguishable from the data cited by Palfy et al. (2001a). The similarity between the marine and continental dates provides powerful support for the age of the Tr-J boundary being ca. 200 Ma, which is substantially younger than in recent time scales (e.g., Harland et al., 1990; Gradstein et al., 1994; Palfy et al., this volume).

More precise dating of the boundary requires interlaboratory cross-calibration and a better understanding of the systematics of the K-Ar system in tholeiites than currently exists (e.g., Turrin, 2000). We favor a date of 202 Ma for the boundary, based on the assumption that the average of available Newark igneous dates is close to the middle of the extrusive section, and adding the duration of the older half of the interval based on Milankovitch cyclostratigraphy, then rounding to the nearest 0.5 m.y. (Olsen et al., 1996b). We believe that realistic geological uncertainties for the Newark-based radiometric boundary dates are ~2 m.y.

NEWARK BASIN BOUNDARY SECTIONS

Of all of the Tr-J Pangean rifts, the stratigraphy of the Newark basin is arguably the best known, due to more than 100

yr of field work, extensive scientific coring by the Newark Basin Coring Project (NBCP) (Olsen et al., 1996a), geotechnical coring by the Army Corps of Engineers (ACE) (Fedosh and Smoot, 1988), and petroleum industry exploration. Virtually the entire >5 km section has been recovered with redundancy in the existing >10 km of continuous core. In addition, the continental Jurassic boundary is better known in the Newark basin than elsewhere. In particular, the boundary is best known in the Jacksonwald syncline in the southwestern part of the basin (Fig.

3), because of ongoing commercial real-estate development and rich fossil content.

It has long been known that much of the Newark basin section is composed of cyclical lake deposits (Van Houten, 1962), and with the recovery of the NBCP and ACE cores, the cyclicity of virtually the entire section has been described (Olsen et al., 1996a, 1996b) (Fig. 4). Van Houten ascribed the hierarchical cyclicity in the Lockatong and Passaic Formations of the Newark basin to lake-level fluctuations controlled by

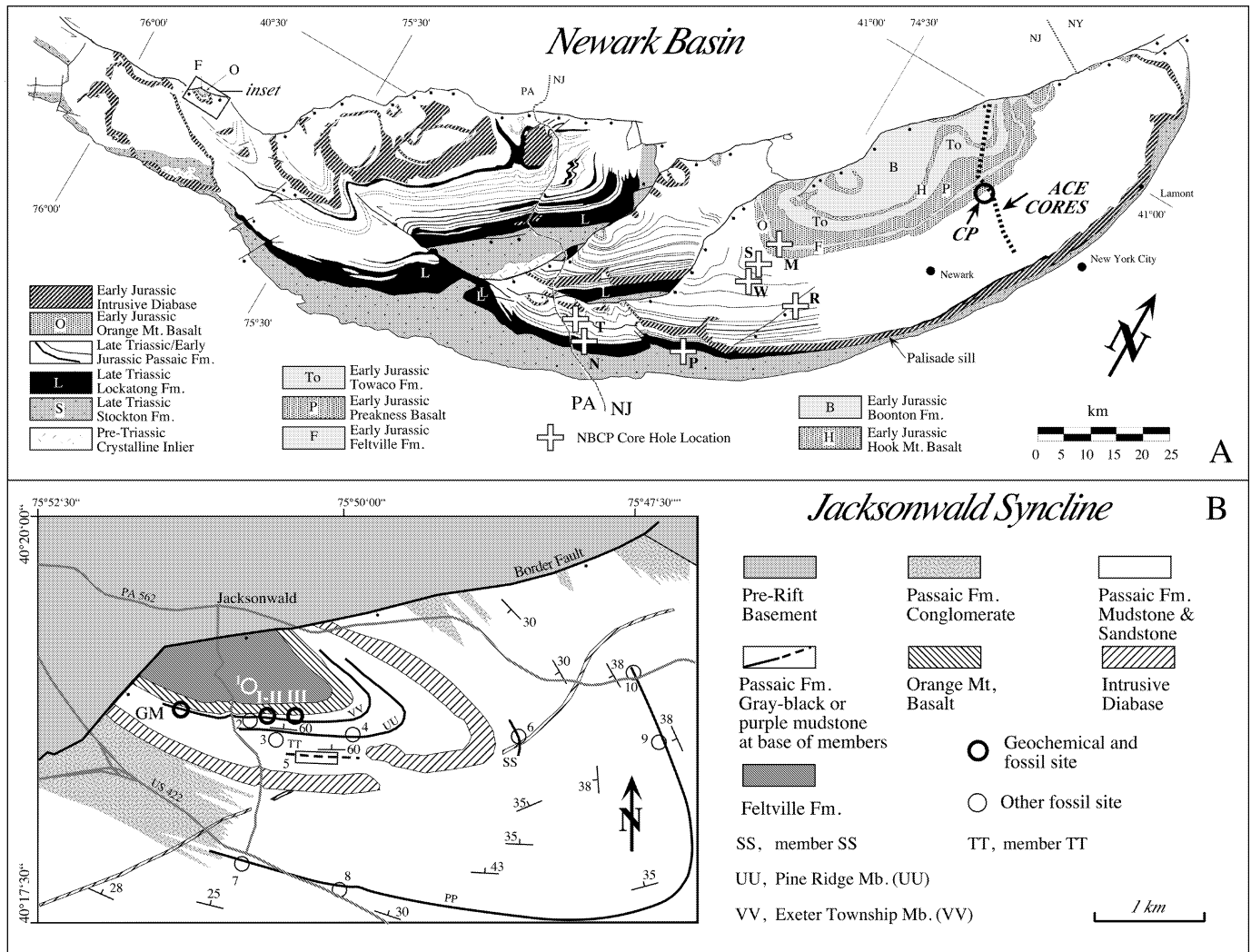


Figure 3. Position of key sections and cores within Newark basin of New Jersey, New York and Pennsylvania. A: Newark basin. Cores of Newark Basin Coring Project (NBCP): M, Martinsville; N, Nursery; P, Princeton; R, Rutgers; S, Somerset; T, Titusville; W, Weston. CP indicates Clifton-Paterson area and area in box outlines Jacksonwald syncline map of B. B: Map of Jacksonwald syncline showing positions of sections discussed in text. Locations for four sections shown in Figure 8 are as follows: GM, Grist Mills (lat 40°18'85", long 075°51'20"); I, section I (lat 40°18'76", long 075°50'56"); II, section II (lat 40°18'76", long 075°50'55"); III, section III (lat 40°18'81", long 075°50'38"). Other paleontological localities are: 1, Exeter Golf Course Estates (Feltville Formation locality for *Eubrontes giganteus*); 2, original palynological boundary sections of Cornet (1977) and Fowell (1994); 3, Wingspread footprint locality of Szajna and Silvestri (1993); 4, Pine Ridge Creek locality for pollen and footprints; 5, Pathfinder Village bone assemblage in member TT (discovery site at lat 40°18'55", long 075°50'10"); 6, Walnut Road phytosaur tooth locality in member SS; 7, Shelbourne Square (Ames) footprint locality of Szajna and Silvestri (1993) and Silvestri and Szajna (1993); 8, Heisters Creek development footprint locality; 9, Tuplehocken Road footprint locality; 10, pollen localities OLA1 and OLA3 of Cornet (1977). Specific latitude and longitude coordinates not given here are listed in Olsen et al. (2001b).

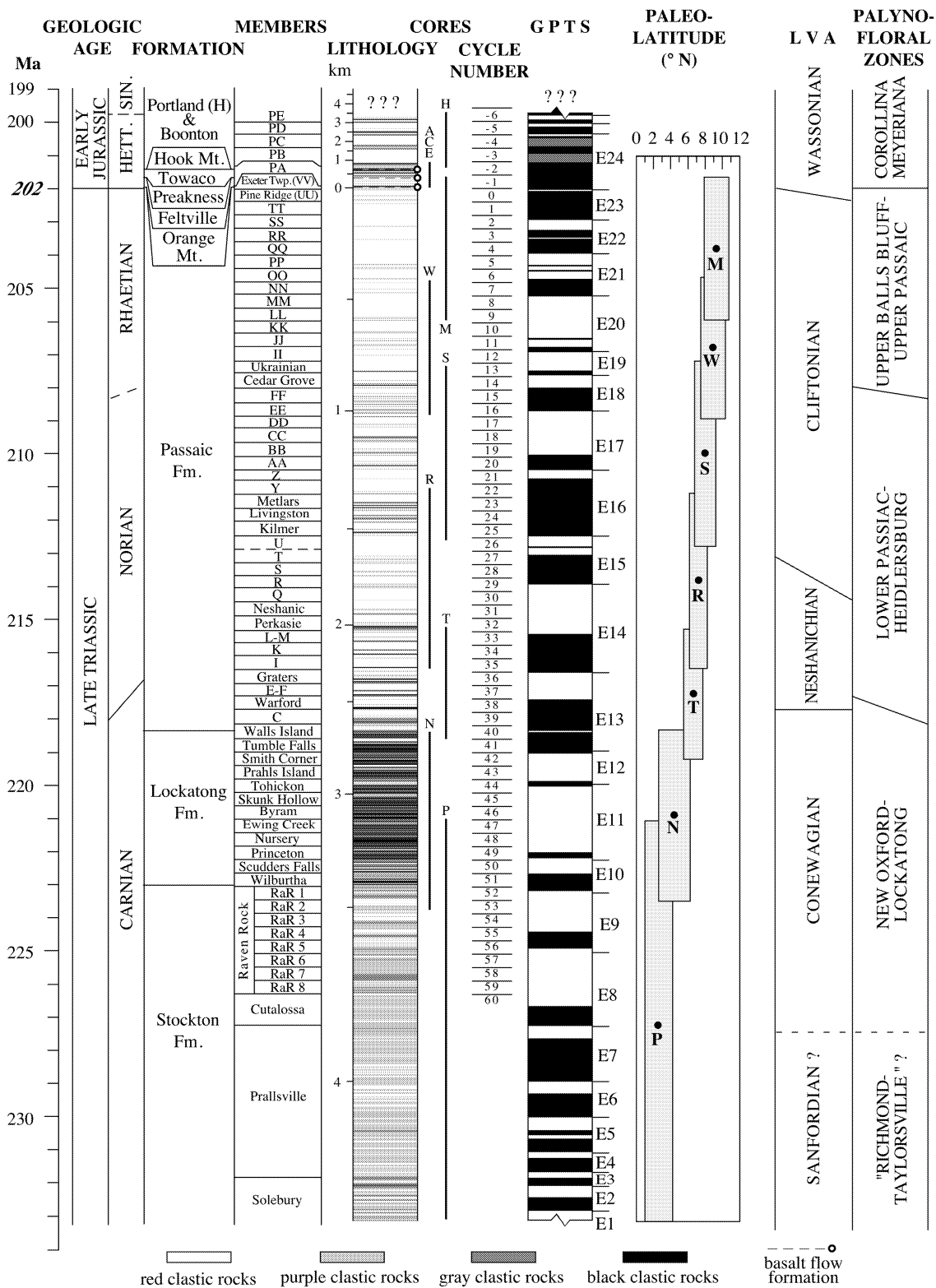


Figure 4. Time scale for Late Triassic and Early Jurassic based on geomagnetic polarity time scale (GPTS) and astronomical calibration from Newark Basin Coring Project (NBCP) Kent and Olsen, 1999a; Olsen and Kent, 1999), Army Corps of Engineers (ACE) cores (Olsen et al., 1996), and preliminary results from Hartford basin (Kent and Olsen, 1999b). Biostratigraphic data are from Huber et al. (1996), Lucas and Huber (2002), Cornet (1977), and Cornet and Olsen (1985). For GPTS, black is normal polarity, white is reversed polarity, and gray represents intervals for which there is incomplete sampling (Hartford basin section only). H, Hartford basin section; HETT, Hettangian; L.V.A., Land Mammal Ages; M, Martinsville (NBCP) core; N, Nursery (NBCP) core; P, Princeton (NBCP) cores; R, Rutgers (NBCP) cores; S, Somerset (NBCP) cores; SIN., Sinemurian; T, Titusville (NBCP) core; W, Weston Canal (NBCP) cores. Cycle number refers to 404 k.y. cycle of eccentricity with lines placed at calculated minima.

Milankovitch climate cycles (Van Houten, 1962, 1964, 1969), and his interpretation has proven applicable to the entire cyclical lacustrine sequence (Olsen et al., 1996a; Olsen and Kent, 1996, 1999). Similarly, the magnetostratigraphy of the Newark basin section has been determined from cores and outcrops (Kent et al., 1995). The magnetostratigraphy, Milankovitch cyclostratigraphy, and radiometric dates from the lavas together have provided the basis for an astronomically tuned time scale for the Late Triassic (Kent and Olsen, 1999a, 2000a) and earliest Early Jurassic (Olsen et al., 1996b; Kent and Olsen, 1999b) (Fig. 4).

Recent work on outcrops in the Hartford basin (Fig. 1) has resulted in a preliminary magnetostratigraphy and cyclostratigraphy that allows astronomical calibration of the 2 m.y. of section postdating the Jurassic lava flows in the Hartford basins that are precisely correlative with those in the Newark basin (Fig. 4) (Kent and Olsen, 1999b). This interval includes the oldest reversed polarity zones in the Early Jurassic, providing a tie to marine sections in the Paris basin as well as an upper bound to the normal polarity zone enclosing the exposed Central Atlantic magmatic province lavas.

The Jacksonwald syncline of the Newark basin has an unusually thick latest Triassic–earliest Jurassic section, marked by accumulation rates greater than anywhere else in the basin, and capped by the Orange Mountain Basalt and Feltville Formation (Fig. 3). The cyclicity and paleontological richness of the latest Triassic age sections here are better developed than anywhere else in the Newark basin. A series of largely temporary exposures created for houses over the past 15 yr have allowed detailed paleontological and cyclostratigraphic analyses of the uppermost Passaic Formation, including the Tr-J boundary (Figs. 5–7), and it is these sections that we concentrated on for the new geochemical analyses.

The boundary section exhibits strongly cyclical sediment variation; well-developed gray and black shales occur periodically (in terms of thickness) in the Milankovitch pattern typical of Newark basin lacustrine sequences. In general, gray strata produce pollen and spores and thus the boundary section is better defined biostratigraphically here than elsewhere (e.g., northern Newark basin). Over the years boundary sections have been exposed over a distance of ~2 km along strike, the easternmost (i.e., most basinward) exposures being the finest grained and having the highest proportion of gray strata. All of the Newark basin boundary sections are characterized by laterally consistent lithostratigraphy and biostratigraphy, despite the lateral changes in facies and accumulation rate (Fig. 5).

A very prominent gray shale is ~25–30 m below the Orange Mountain Basalt (Figs. 5 and 8). This unit contains palynoflorules that are dominated (60%) by *Patinasporites densus* with variable amounts (5%–20%) of *Corollina*, and other pollen and spores. This is typical of many older Late Triassic palynoflora assemblages from the Jacksonwald syncline. Above this gray shale are variegated red and gray shales and sandstones that have a lower abundance (5%–40%) of *Patinasporites den-*

sus. Another prominent marker bed, a brown to blue-gray sandstone with abundant comminuted charcoal and wood, which we refer to as the blue-gray sandstone bed (Figs. 5, 6, and 8), is 8–12 m below the Orange Mountain Basalt. This unit generally is directly above a thin (1–10 cm) coal bed or carbonaceous shale. The highest stratigraphic occurrence of *Patinasporites densus* occurs ~1 m below the sandstone (Fig. 9). This palynoflora (sample 6-2 of Fowell, 1994) is dominated by *Corollina* (73%) and ~10% *Patinasporites*. This is the highest assemblage that we regard as having a Triassic-aspect palynomorph assemblage.

In the 40 cm below the blue-gray sandstone, palynomorph assemblages are consistently dominated by trilete spores belonging to taxa usually attributed to ferns (Fig. 9) (first discovered by Litwin, cited in Smith et al., 1988). Within a couple of centimeters of the base of the blue-gray sandstone, the proportion of spores reaches a maximum of 80% (Fowell et al., 1994). *Patinasporites densus* is absent from these assemblages, and we consider these assemblages to be of earliest Jurassic age. Such fern-dominated assemblages are unknown elsewhere in Newark basin strata of Triassic age. We refer to this very anomalous high proportion of fern spores as a fern spike, in parallel with the terminology used for the K-T boundary (e.g., Tschudy et al., 1984; Nichols and Fleming, 1990). It is within this fern spore-rich interval that the Ir anomaly occurs (see following). Above the blue-gray sandstone, palynoflorules are dominated by *Corollina*; *Patinasporites* and other Triassic-type taxa are absent. The character of these assemblages is similar to that of the Jurassic strata overlying the basalts throughout the Newark Supergroup, and we consider them to indicate a Jurassic age for the uppermost Passaic Formation. Thus, in analogy to the K-T boundary, we hypothesize that the fern spike at least approximates the base of the Jurassic, and hence the Tr-J boundary (Fig. 7). On the basis of the cyclostratigraphically defined accumulation rate, the last Triassic aspect palynoflora occurs, conservatively, within 25 k.y. of the base of the Orange Mountain Basalt. The interval of time between this Triassic assemblage and the lowest definitive Jurassic assemblage (Jb-6 of Cornet, 1977) is less than 10 k.y. Similarly, the Tr-J boundary, as defined here by the fern spike, occurs within 20 k.y. of the base of the Orange Mountain Basalt.

Reptile footprint taxa broadly follow the same pattern as the palynological stratigraphy as described in Olsen et al. (2002b). Footprint faunules have been recovered at many levels within the Jacksonwald syncline and there is a concentration of productive levels near the palynologically identified Tr-J boundary (Silvestri and Szajna, 1993; Szajna and Silvestri, 1996; Szajna and Hartline, 2001; Olsen et al., 2002b). Assemblages in rocks of Triassic age contain abundant *Brachychirotherium* (suchian) and more rare *Apatopus* (phytosaur), a form informally designated “new taxon A” of Szajna and Silvestri (1996) (suchian), as well as *Rhynchosauroides* (lepidosauro-morph), *Batrachopus* (crocodylomorph suchian), a form referred to “new taxon B” (Szajna and Silvestri, 1996) (su-

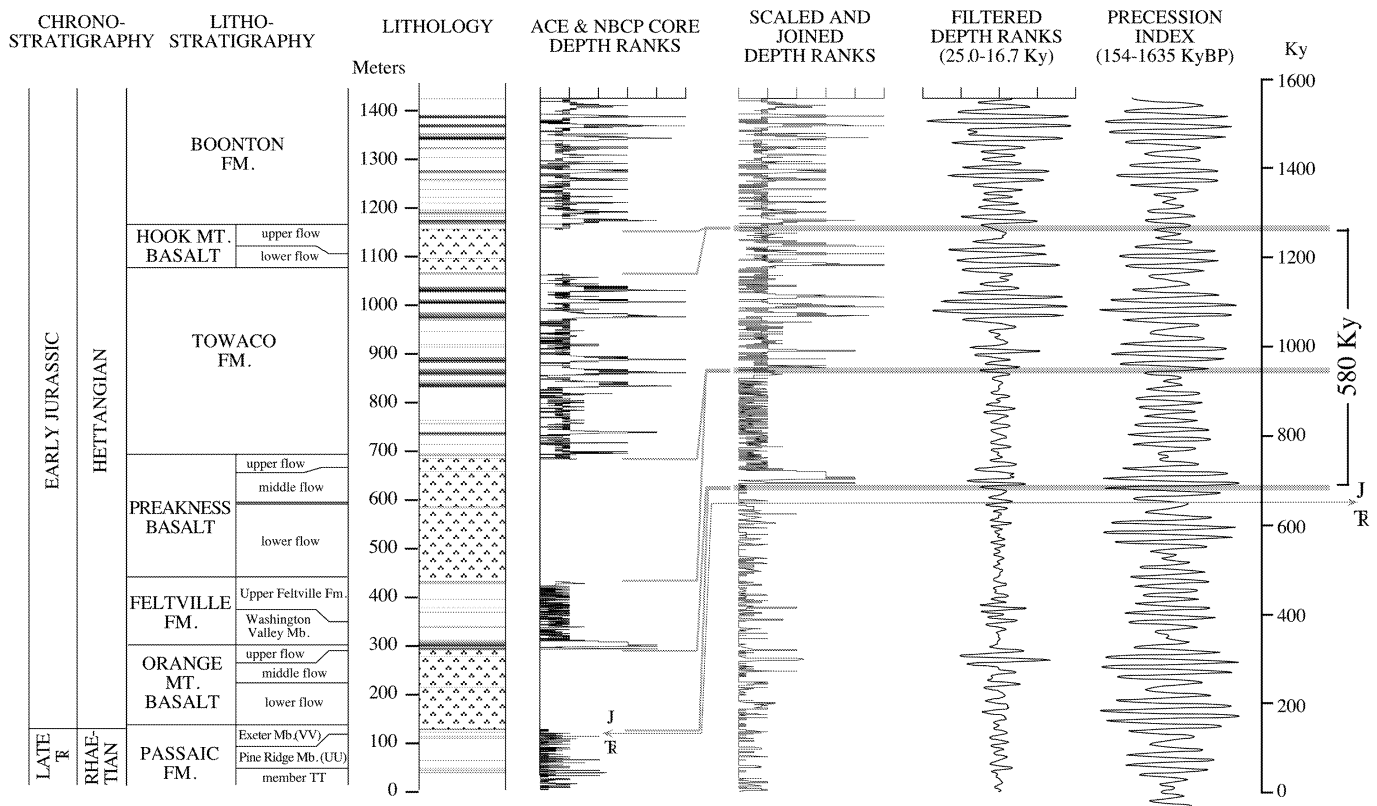


Figure 5. Cyclostratigraphic calibration of Triassic-Jurassic (Tr-J) boundary and succeeding extrusive zone flows and interbedded and overlying sedimentary strata (adapted from Olsen et al., 1996b). Depth ranks are numerical classification of sedimentary facies sequences in order of increasing interpreted relative water depth (Olsen and Kent, 1996). Comparison of depth rank curves with arbitrary segment of precession index curve indicates that it is not necessary to assume that any significant time is represented by lava flow formations and that entire flow sequence was probably deposited during interval of <600 k.y. Note also that Tr-J boundary (correlated to Jacksonwald syncline by magnetostratigraphy and lithostratigraphy; Fig. 7) is ~20 k.y. below Orange Mountain basalt. Depth rank record from strata above Preakness Basalt is based on Army Corps of Engineers Army Corps of Engineers (ACE) cores, whereas that from Passaic and Feltville Formations is based on Martinsville no. 1 core of Newark Basin Coring Project (NBCP).

chian), and abundant small- to medium-sized dinosaurian tracks usually referred to as various species of *Grallator* and *Anchisauripus* (i.e., *Eubrontes* spp. in the terminology of Olsen et al., 2002b). *Brachychirotherium*, *Apatopus*, and “new taxon B” have never been found in strata of Jurassic age, despite the global abundance of Early Jurassic footprint assemblages. The highest footprint assemblage with *Brachychirotherium* and “new taxon B” occurs ~11 m below the blue-gray sandstone and the fern spike (Fig. 5). Even closer to the boundary is a poorly sampled footprint-bearing level with *Rhynchosauroides*, *Batrachopus*, and *Grallator* and *Anchisauripus* (*Eubrontes* spp.) that is ~7 m below the blue-gray sandstone and fern spike. Although the localities are thus far not very productive, only *Grallator* and *Anchisauripus* (*Eubrontes* spp.) have been found above the blue-gray sandstone in the Jacksonwald syncline.

Abundant tetrapod bones occur in a zone ~400 m below the Orange Mountain Basalt in the Jacksonwald syncline in member TT (Fig. 3). This interval has produced numerous skeletal remains, including skulls and articulated skeletons of the

procolophonid parareptile *Hypsognathus fenneri*, and the crocodylomorph cf. *Protosuchus*, as well as other as yet unidentified remains, including probable phytosaur teeth. These bone occurrences are ~800 k.y. older than the Tr-J boundary, and help define the ranges of Triassic-type taxa.

Correlation of the Jacksonwald syncline sections with the Newark basin cores is fairly straightforward, despite the muted cyclicity in the uppermost Passaic Formation in the cores. A thin but well-defined interval of reversed polarity (E23r) occurs ~17 m below the Orange Mountain Basalt in the Martinsville no. 1 core (Kent et al., 1995; Kent and Olsen, 1999a). This reversed interval is between two very thick normal polarity intervals (E23n and E24n). Magnetic polarity chron E23r has also been identified in the Jacksonwald syncline section (Olsen et al., 1996a). The pattern of prominent gray beds in the Jacksonwald syncline sections and their relationship to chron E23r are matched very closely by the relationship between very thin gray and purple bands and chron E23r in the Martinsville no. 1 core. This laterally repeated pattern permits precise outcrop and core

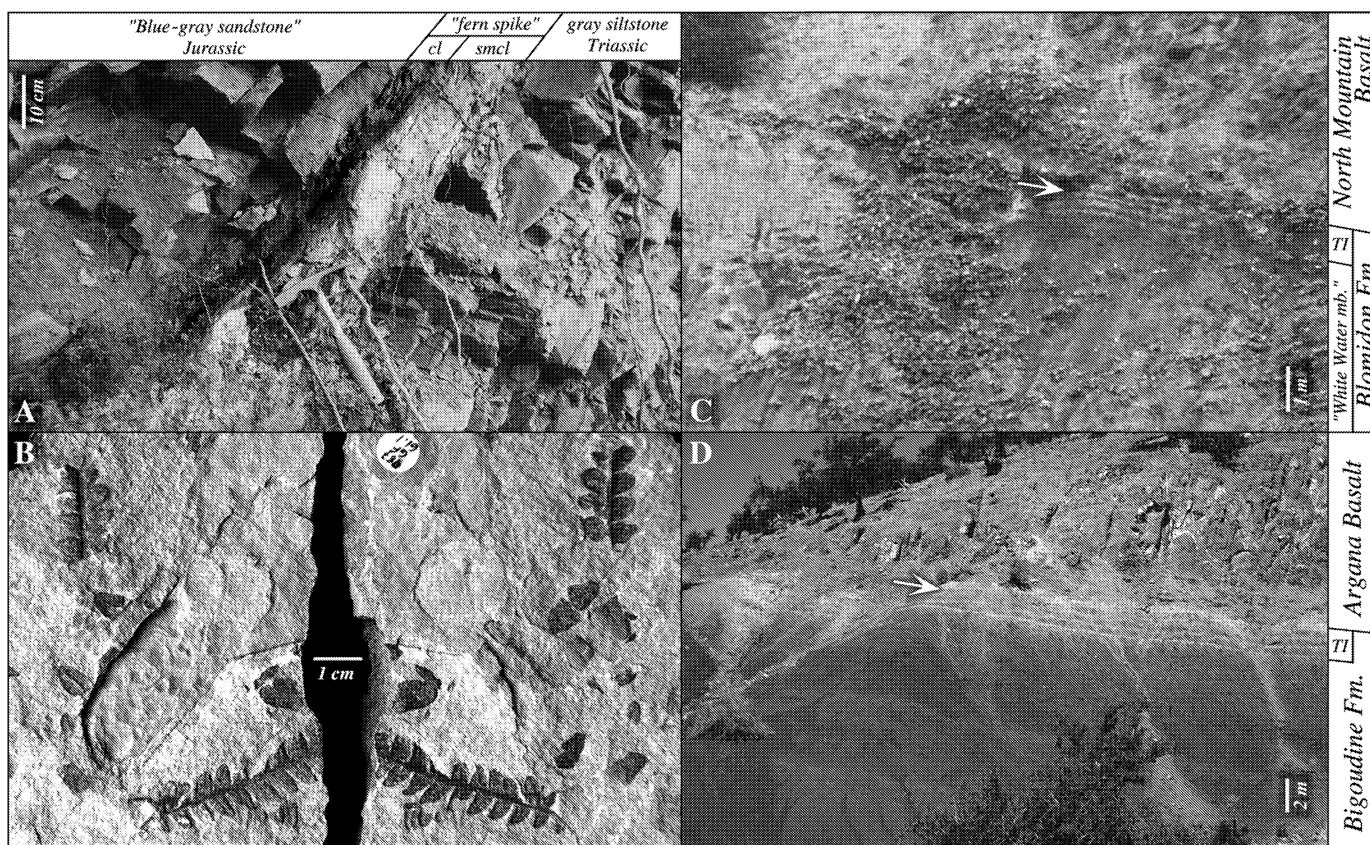


Figure 6. Photographs of sections and ferns of Triassic-Jurassic (Tr-J) boundary. A: Tr-J boundary at section I (Figs. 2 and 7). cl, coal and carbonaceous shale; smcl, smectitic claystone. Note that strata dip 60° to north (left). B: Part and counterpart of slab bearing fronds of fern *Cladophlebis* from Tr-J boundary of Fundy basin at Central Clarence (Nova Scotia Provincial Museum no. 982.GF.G1.1). C: Tr-J boundary at Partridge Island, Nova Scotia (studied by Fowell and Traverse, 1995); TI indicates palynological transition interval and arrow shows position of palynological Tr-J boundary. D: Tr-J boundary near Argana, Morocco, in Argana basin (Olsen et al., 2000).

correlation (Fig. 5) (Olsen et al., 1996a), in particular tying the Jacksonwald sections to the stratigraphy in the northern Newark basin, where the cyclostratigraphy of the bulk of the Jurassic section has been established by study of the ACE cores (Fig. 5) (Olsen et al., 1996b).

Exposures in quarries and at construction sites in the vicinity of Paterson and Clifton, New Jersey, in the same areas in which the ACE cores were drilled, have produced a series of important fossil assemblages within the upper Passaic Formation. Although there is no magnetic stratigraphy for this area of the Newark basin section, the pattern of purple intervals in the ACE cores matches that seen in the Martinsville no. 1 core, allowing lithostratigraphic correlation. On the basis of this correlation, the Martinsville no. 1 core and the ACE cores appear to have nearly the same accumulation rate for the uppermost Passaic Formation.

The uppermost few meters of the Passaic have produced an enormous number of footprints from a variety of exposures. These footprint assemblages contain only *Rhynchosauroides*, *Batrachopus*, and small to large *Grallator*, *Anchisauripus*, and *Eubrontes* (*Eubrontes* spp.). As reported in Olsen et al. (2002b),

these assemblages contain the oldest examples of *Eubrontes giganteus*, a dinosaurian track $\sim 20\%$ larger than any older ichnospecies. At one locality within the footprint-bearing sequence, a gray lens of sandstone and shale has produced a macroflora dominated by the conifers *Brachyphyllum* and *Pagiophyllum*, and the fern *Clathropteris meniscoides*, as well as a poorly preserved palynoflora dominated by *Corollina* and lacking Triassic-type taxa. This footprint and plant assemblage is thus of earliest Jurassic age, an interpretation supported by its stratigraphic position compared to the Martinsville no. 1 core (Fig. 5).

In close proximity to these footprint and plant localities are the exposures that yielded skeletal remains of *Hypsognathus fenneri*, including the holotype specimen (Sues et al., 2000). These occurrences are ~ 45 m below the Orange Mountain Basalt. On the basis of correlation with the Martinsville no. 1 core and the Jacksonwald syncline sections, these represent the youngest examples of typical Triassic osteological taxa in eastern North America. On the basis of cyclostratigraphy, the *Hypsognathus*-bearing horizons are within 500 k.y. of the palynologically defined Tr-J boundary.

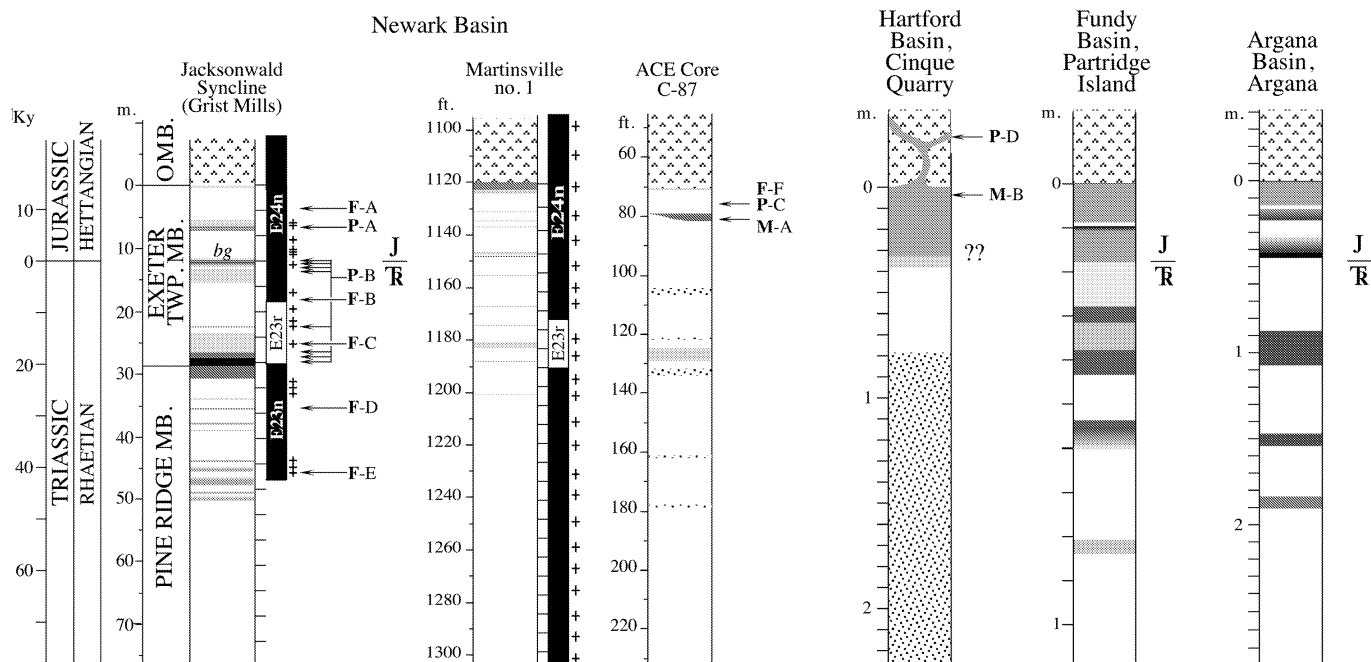


Figure 7. Detailed stratigraphy of Newark, Hartford, Fundy, and Argana basin boundaries. In all cases Triassic-Jurassic (Tr-J) boundary is based on palynomorph transitions. Newark section is from Olsen et al. (2001b). Abbreviations: F-A, highest footprint bearing level in Jacksonwald syncline with small grallatorids only (projected from Exeter Village sections); F-B, footprint assemblage with *Batrachopus* cf. *B. deweyii*, *Rhynchosauroides*, and small grallatorids (projected from Exeter Village sections); F-C, highest footprint level with new taxon B and *Brachychirotherium* and cf. *Apatopus*, also with *Rhynchosauroides* and small grallatorids; F-D, *Brachychirotherium*, new taxon B, *Batrachopus*, and small grallatorids; F-E, level with abundant *Brachychirotherium*, new taxon B, *Batrachopus*, and small to medium sized grallatorids; F-F, Clifton-Patterson area quarries and exposures with small to large grallatorids, including lowest occurrence of *Eubrontes giganteus*, also with *Batrachopus deweyii*, and *Rhynchosauroides*; P-A, lowest definitive Jurassic-type palynomorph level; P-B, palynomorph assemblages of Triassic aspect (lower) or dominated by spores (upper); P-C, palynomorph assemblage with *Corollina* only (poorly preserved); P-D, palynomorph assemblage with *Corollina* only in matrix between basalt pillow (Robbins, in Heilman, 1987); M-A, macrofossil plant assemblage dominated by *Brachyphyllum* and *Clathropteris*; M-B, macrofossil plant assemblage dominated by *Brachyphyllum* (Heilman, 1987). ACE is Army Corps of Engineers; bg indicates position of blue-gray sandstone.

Above the Orange Mountain Basalt are many horizons in the Feltville, Towaco, and Boonton Formations that have yielded very abundant tetrapod footprints of typical Connecticut Valley aspect (Olsen, 1995; Olsen et al., 2002b), as well as several well-preserved *Corollina*-dominated palynoflorules of typical Early Jurassic aspect (Cornet and Traverse, 1975; Cornet, 1977; Cornet and Olsen, 1985).

Thus, the paleontology and Milankovitch cyclostratigraphy of the upper Passaic Formation and succeeding units confines the Tr-J biological transition to within 10 k.y. based on palynology, and within 30 k.y. based on footprints (Olsen et al., 2002b). Because there are no assemblages of bones from Jurassic strata of the Newark basin, limitations based on osteological taxa are discussed in a regional context that follows.

NEWARK BASIN GEOCHEMICAL AND MINERALOGICAL ANOMALIES

The abundances and interelement ratios of the siderophile elements, such as Cr, Co, Ni, and especially the platinum group elements (PGEs) have been used to investigate the possible

presence of a meteoritic component in terrestrial rocks at several geological boundaries (e.g., Alvarez et al., 1980; references in Montanari and Koeberl, 2000). However, the expected concentrations of PGEs in terrestrial rocks, even with extraterrestrial enrichment, are exceedingly low. For example, the addition of ~0.1% of a meteoritic (congrite) component to a crustal rock would yield an enrichment of ~0.5 ppb Ir to the crustal abundance (~0.02 ppb Ir) in the resulting impact breccia (Koeberl, 1998). Due to these low abundances, only very sensitive analytical techniques, such as Ir coincidence spectrometry (ICS) and inductively coupled plasma source-mass spectrometry (ICP-MS), after chemical prepreparation of the PGEs, can be used.

There were two previous, unsuccessful, attempts to find geochemical and mineralogical anomalies at the Tr-J boundary in the Newark basin. Smith et al. (1988) looked specifically for an Ir anomaly in the same units in the Jacksonwald syncline that we examine here, but the amounts present were below their detectable limits. Mossman et al. (1998) looked for shocked quartz and Ir anomalies without reported success in the same interval.

Jacksonwald Syncline Triassic-Jurassic Boundary

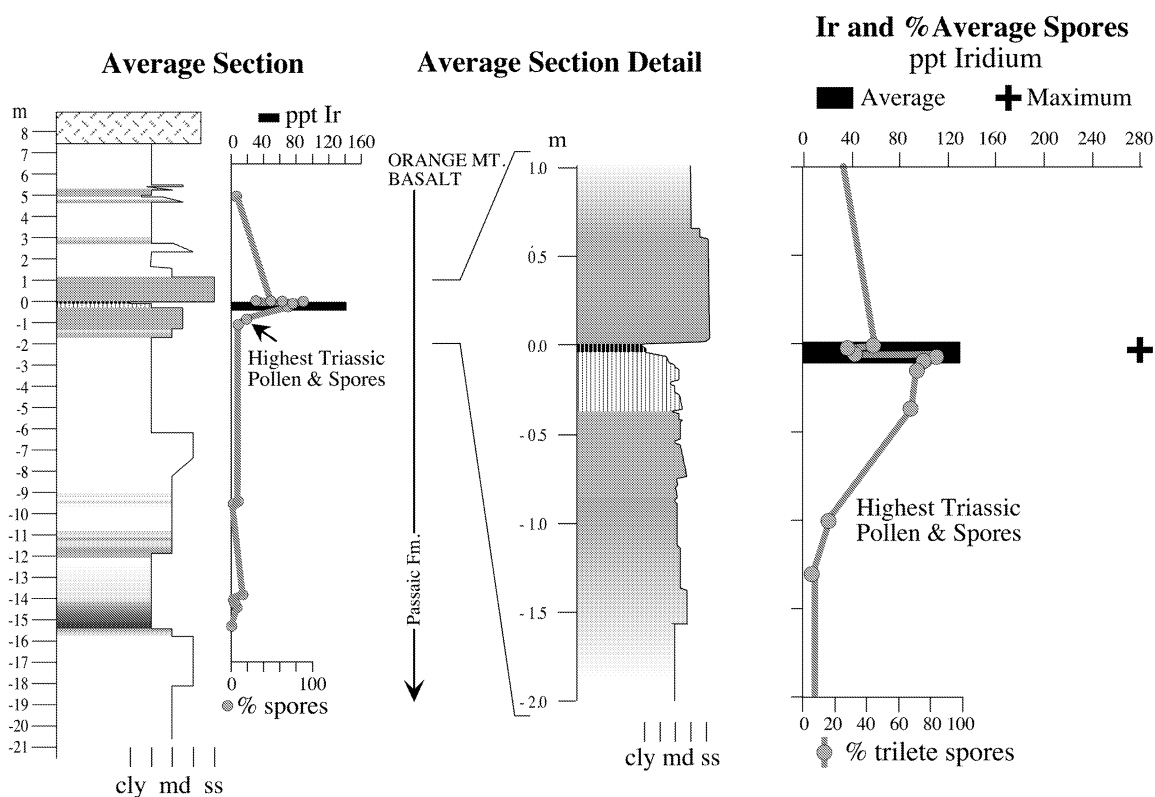


Figure 8. Summary of average Ir and pollen and spore data from Jacksonwald syncline. Color, grain size, and Ir are average values from four sections at the localities shown in Figure 3 based on Olsen et al., 2002b); pollen and spore data are from Fowell (1994). Details of the Ir anomaly are given in Olsen et al. (2002b). Spore and pollen data are from Fowell (1994).

RESULTS AND DISCUSSION

Undeterred by the previous unsuccessful attempts, Olsen et al. (2002b) examined Ir and other elemental concentrations at four sections along strike in the Jacksonwald syncline directly around the fern spike (Fig. 8). The samples show variations in Ir content from 19 to 285 ppt (0.2–0.29 ng/g) with an average maximum of 141 ppt (0.14 ng/g) (Olsen et al., 2002b). All sections except section I show a distinct Ir anomaly directly at the boundary with a distinct systematic association between Ir content and stratigraphy. The elevated levels of Ir are mostly associated with higher levels of Al in a white smectitic claystone (Smith et al., 1988), directly beneath the thin coaly layer (Figs. 6 and 7), although there is no correlation between Al and Ir in the data in general. The anomaly is directly associated with the previously identified fern spike in these sections, recalling the similar pattern at the K-T boundary in the western United States (Tschudy et al., 1984; Nichols and Fleming, 1990). It is possible that the relatively weak Ir anomaly (relative to the apparent background) seen thus far is a consequence of dilution by the coarse sampling level (~3 cm per sample) required by

the very high accumulation rates (~1 m/2 k.y.) in the sampled part of the Newark basin. We can probably rule out a simple diagenetic concentration of Ir along a redox boundary because of the good correlation between Ir and stratigraphy, despite the lateral facies change from gray and black strata in the east to virtually entirely red strata in the westernmost section (Grist Mills, Fig. 3). The sample with the highest Ir content at the Grist Mills section is red (177 ppt, Olsen et al., 2002b).

In the one section (section I) that did not show a systematic association between Ir content and stratigraphy (Olsen et al., 2002b), Ir levels were highest in the blue-gray sandstone rather than in the spore-rich clays just below it. This could be because our sample of this sandstone contained mud chips eroded from a presumably Ir-enriched layer upstream. The sandstone was bulk processed and it will be necessary to run separate analyses on the sandstone and clay pebble separates to test this hypothesis.

The situation does not, unfortunately, become any clearer when considering the concentrations of other elements. Although we recognize that much more might be done with the data presented by Olsen et al. (2002b). Comparing the trends

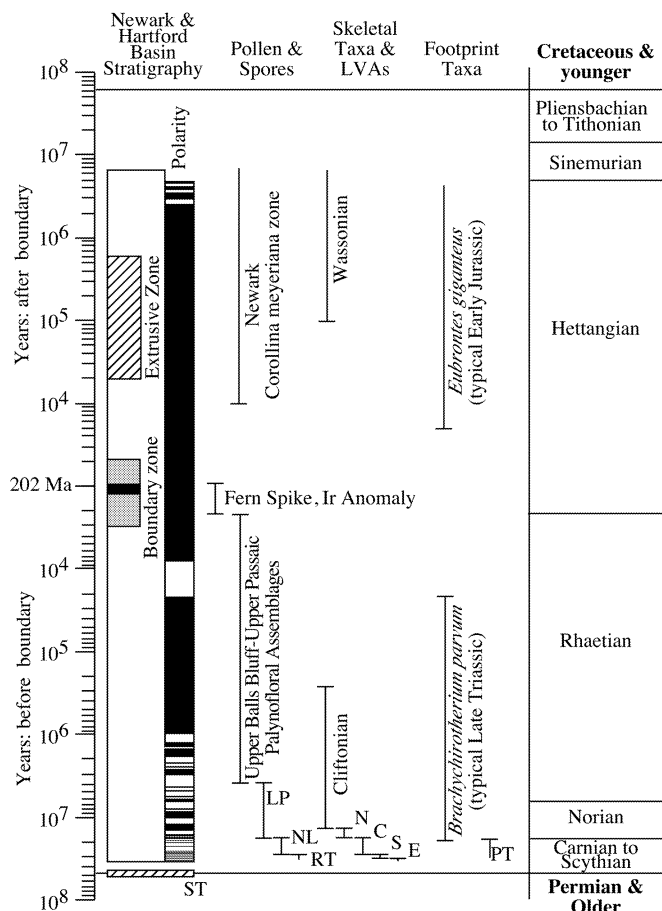


Figure 9. Summary of major physical and biotic events around Triassic-Jurassic boundary plotted on logarithmic scale. Data are primarily from Newark basin; time scale is based on Figure 4. LVAs, land vertebrate ages of Huber et al. (1996) and Lucas and Huber (2002): N, Neshanician; C, Conewagian; S, Sanfordian; and E, Economian. Pollen and spore zones are from Cornet (1977) and Cornet and Olsen (1985): LP, Lower Passaic Heidlersburg; NL, New Oxford, Lockatong; RT, Richmond Taylorsville. Footprint distribution is from Olsen et al. (2001b); PT, range of Pekin-type footprint assemblages (Olsen and Huber, 1996). Note that extrusive zone consists of lava flow formations interbedded with fossiliferous and cyclical sedimentary strata, with latter interpreted as representing nearly all of time shown. ST indicates position of Permian-Triassic Siberian Traps.

of the Ir data with those of other siderophile elements reported in Olsen et al. (2002b), such as Co, Ni, and Cr, which are often used as tracers of meteoritic components, does not yield distinct correlations.

The trace element data described by Olsen et al. (2002b) do not seem to support the idea that the Ir enrichments could be related to volcanic ash. Elements that might correlate in abundance with Ir if the source were altered volcanic material (e.g., Cs, Al, Cu, and V) reveal no significant correlations. The variations in these elements in section I are irregular and the concentrations of Cs vary with no correlation to the distinct Ir enrichment and associated Co and Ni abundance peaks. The

highest Cs abundances occur for samples outside the zone of siderophile element enrichment. Thus, we consider a volcanic interpretation of the Ir enrichments unlikely, although we refrain from more detailed comment on the trace element data until more thorough sampling, especially farther from the palynologically identified boundary, can be performed.

A significant problem with the analysis by Olsen et al. (2002b) of the association between Ir abundance and the fern spike in the Jacksonwald syncline sections is that the geochemical and palynological analyses were not conducted on the same samples, or even at the same sections, and there is considerable variability from section to section in both variables. In an attempt to mitigate this problem and facilitate comparison of the Ir and pollen and spore data, Olsen et al. (2002b) averaged the Ir data and combined the spore data from all of the Jacksonwald synclines sections examined to date, using the base of the blue-gray sandstone as the correlative datum (Figs. 8 and 9). No attempt was made to account for possible lateral changes in accumulation rate.

The averaged and combined data show a strong correlation between spore percentage and Ir content Olsen et al. (2002b). However, the spore maximum is below the Ir maximum and the spore spike appears quite broad. This could reflect an actual offset between the two data sets, or it could reflect small variations in either accumulation rate or depth of erosion of the overlying blue-gray sandstone at different sections. Existing data do not permit these hypotheses to be tested. It is clear that what is needed is very detailed sampling of sections, in which splits of the same samples are subjected to palynological and geochemical analyses. In addition, Ir measurements are clearly needed from a broader stratigraphic swath around the boundary to assess background Ir levels. The available data are, however, encouraging, and suggest that there is a modest Ir anomaly at the biologically identified boundary and that it is associated with a fern spike.

Olsen et al. (2002b) also reported negative results in their search for shocked quartz. All quartz grains observed were angular, and few were clear. Most of them contained mineral and fluid inclusions. In some cases, fluid inclusions were aligned and in a very few cases they seemed to be aligned along parallel lines, but none of these features are characteristic for shock metamorphism. Besides these very few cases, no planar features or lamellae potentially representing planar deformation features were observed. Thus, as was the case for Mossman et al. (1998), the search for shocked quartz grains was not successful.

TR-J BOUNDARY IN OTHER PANGEAN CONTINENTAL RIFTS

The patterns seen in boundary sections in other continental rift basins in the Newark Supergroup and Morocco are consistent with that seen in the Newark basin, but also provide important additional information. The most southern rift known to preserve the Tr-J boundary is the Culpeper basin of Virginia.

The boundary section there was described by Fowell (1994), but currently known outcrops and exposures have not permitted detailed stratigraphic or palynological analysis.

The next basin northward for which there is significant stratigraphic information relevant to the Tr-J boundary is the Hartford basin of Connecticut and Massachusetts (Fig. 2). A section exposed in the Cinque Quarry in East Haven, Connecticut, reveals the uppermost New Haven Formation and overlying pillowed base of the Talcott Basalt (Heilman, 1987). Nearly the entire New Haven Formation is fluvial, composed of brown and minor gray coarse clastic rocks and red mudstone. The uppermost 40 cm of the New Haven Formation at the Cinque Quarry is, in contrast, gray, and may represent marginal lacustrine environments (Fig. 7). The uppermost few centimeters of gray mudstone and sandstone preserve abundant *Brachyphyllum* shoots and cones and a palynoflorule of typical Early Jurassic aspect, dominated by *Corollina* (Robbins, quoted in Heilman, 1987). Because there is no dispute that most of the New Haven Formation is of Late Triassic age (Cornet, 1977), the Tr-J boundary probably is either within the gray sequence below the conifer-bearing level, or closely underlying it in the red beds.

Strata interbedded with and overlying the basalts of the Hartford basin preserve a cyclostratigraphy nearly identical to that of the Newark basin, implying nearly exact synchrony of climatic and eruptive events (Olsen et al., 1996b). However, compared to the youngest formation in the Newark basin (Boonton), the Portland Formation, which overlies the youngest basalt formation in the Hartford basin (Hampden Basalt), is much thicker (~4 km) and represents a much longer time than is preserved in the Newark basin. Hence, the Portland Formation provides an important supplement to the Newark basin astronomically calibrated time scale and allows the floral and faunal change seen at the Tr-J boundary to be placed into a more extensive temporal perspective. The lower Portland Formation exhibits a cyclostratigraphy virtually identical to that of the Boonton Formation of the Newark basin. However, whereas <300 k.y. of Boonton Formation was recovered by the ACE cores, at least 3 m.y. is represented by the Portland Formation. The magnetostratigraphy of ~2 m.y. of the lower parts of the Portland was determined from outcrop samples (Kent and Olsen, 1999b). Although clearly not known at the same level of detail as the Newark basin time scale, which is based on continuous core, the Portland Formation magnetostratigraphy does delimit the maximum duration of chron E24n, the top of which is not seen in the Newark basin record (Kent and Olsen, 1999a) (Fig. 4). The polarity reversal stratigraphy of the Portland Formation also provides a critical link to the marine polarity sequence from the Paris basin (Yang et al., 1996), indicating that the upper part of the Portland Formation is of Sinemurian age. Based on the Newark basin time scale, with the addition of the Portland Formation information, the duration of the Hettangian is thus ~2 m.y., in excellent agreement with new information from U-Pb dates from marine sections in British Columbia (Palfy et al., 2000b).

Palynoflorules from the Jurassic part of the Hartford basin section show only minor changes through time (Cornet, 1977; Cornet and Olsen, 1985), predominately involving the appearance of new taxa and species-level changes in the dominant pollen taxon *Corollina*. Vertebrate footprint and bone assemblages from Hettangian and Sinemurian strata of the Hartford basin show no obvious changes at all, except perhaps an increase in the size of some footprint forms (e.g., *Anomoepus*: Olsen and Rainforth, 2002). The slow change through the Hettangian and into the Sinemurian, spanning at least 3 m.y., contrasts dramatically with the extraordinarily abrupt change seen at the Tr-J boundary, which conservatively took less than 20 k.y.

In predrift configuration, the next continental rift basins north for which there is significant information on the Tr-J boundary are those in Morocco, particularly the Argana basin (Fig. 2). The stratigraphy of the boundary section in the Argana basin differs from that in the Newark basin in that cyclical gray and black strata are limited in outcrop to a couple of meters below the Argana Basalt (Olsen et al., 2000). Palynoflorules from these very thin (<20 cm) gray and black mudstones, which are interbedded with red mudstones, show a transition from an assemblage with *Patinasporites* to one without this taxon or any other forms typical of the Triassic. Instead it is dominated by *Corollina* (Olsen et al., 2000). The physical stratigraphy of this sequence, despite its very condensed appearance, as well as that of the overlying Argana Basalt and Amsekroud Formation, is closely comparable to that of the Newark basin section, implying a nearly identical sequence and timing of events (Olsen et al., 2002a).

Of special interest is the physical stratigraphy of the Khémisset basin in Morocco. In outcrop, the stratigraphy of the sedimentary section immediately below the oldest basalt is virtually identical to that seen in the Argana basin. However, in the subsurface, these cyclical red, gray, and black mudstones pass into interbedded black, red, and white halite and potash salts (Et-Touhami, 2000). Our preliminary palynological results from outcrop sections suggest that the Tr-J boundary is in the cyclical mudstone sequence just below the oldest basalt, and that the boundary should be present within the salt in the subsurface as well, a hypothesis we are examining.

Where studied, the physical stratigraphy of the sequence of basalts and the directly underlying and overlying sediments of the other Tr-J that crop out in basins of Morocco is very similar to that in the Newark and Argana basins, albeit very condensed. Thus, we argue for correlation of biotic and tectonic events at a very fine scale across the Moroccan basins. We hypothesize that the similarity, in detail, of the sequences just below the oldest basalts in all these basins to that seen in the Argana and Newark basins demarcates the position of the Tr-J boundary. However, published interpretations of the biostratigraphy of these basins differ dramatically from that presented here (Figs. 6 and 7). According to the summary of Oujidi et al. (2000), the ages of these homotaxial sequences are dramatically

different in different basins, ranging in age from Ladinian to Norian. We attribute these differences in interpretation to a lack of appreciation of floral provinciality, the importance of the fact that earliest Jurassic assemblages are characterized by survivor assemblages rather than the appearance of new taxa, and by reliance on ostracode and bivalve taxa of dubious identification and biostratigraphic utility. Our palynological work underway on various sections in Morocco will test our hypothesis.

The Fundy basin of the Maritime provinces of Canada is the next continental rift basin to the north that has outcrops, and it provides the most information on the Tr-J boundary after the Newark basin. Fowell and others (Fowell and Olsen, 1993; Fowell, 1994; Fowell et al., 1994) have shown that the Tr-J boundary is preserved within the uppermost few meters of the Blomidon Formation, below the North Mountain Basalt (Fig. 6) (Kent and Olsen, 2000b). The boundary section is very condensed and closely comparable to that in the Argana basin (Fig. 6). Like the Newark basin, the palynology of the boundary is marked by an abrupt disappearance of assemblages with *Patinasporites* and their replacement by assemblages dominated by *Corollina*. Although no fern spike has been found in the section studied in detail by Fowell and Traverse (1995) at Partridge Island (Cumberland County, Nova Scotia), outcrops of the uppermost few meters of Blomidon Formation at Central Clarence (Annapolis County, Nova Scotia) have one layer that produces a macroflora consisting entirely of the fern *Cladophlebis* (Carroll et al., 1972) (Fig. 6). This is the only foliage macroflora from the Fundy basin of Nova Scotia, and that it consists entirely of ferns, at the expected position of the Tr-J boundary, suggests to us that it may represent the fern spike. Unfortunately, the exposures at Central Clarence preclude a detailed study of this section without significant excavation.

The cyclostratigraphy of the lower McCoy Brook Formation, overlying the North Mountain Basalt, is closely comparable to that of the Feltville Formation of the Newark basin and its equivalents in other rifts in the eastern United States (Olsen et al., 1996b, 2002a). A rich vertebrate assemblage has been recovered from the lower McCoy Brook Formation and is notable for the abundance of well-preserved tetrapod bones and skeletons (Olsen et al., 1987). This assemblage is the oldest known from the continental Early Jurassic that is reasonably diverse and well dated. Despite the sampling of both terrestrial and aquatic habitats, typical Triassic osseous and footprint taxa are absent. In addition, while the remains of small tetrapods are very common at multiple levels, procolophonids are absent. Thus, this assemblage helps delimit the osseous record of at least some of the tetrapod extinctions to within 300 k.y. around the boundary. Footprint assemblages from the rest of the McCoy Brook Formation outcrops are consistent with this picture and are entirely of Connecticut Valley aspect (i.e., Early Jurassic).

Anders and Asaro (reported in Olsen et al., 1990) examined the upper 100 m of the Blomidon Formation for shocked quartz and Ir anomalies, but were unsuccessful. Mossman et al. (1998) examined the stratigraphic region near the Tr-J boundary, in-

cluding at Partridge Island, for shocked quartz and Ir. Although some planar features were seen, they concluded that none were characteristic of shocked metamorphism. They also concluded that although no distinct Ir anomaly was found, the highest Ir amounts were found in proximity to the Tr-J boundary. We stress that these results are not inconsistent with our results from the Newark basin, but that much tighter geochemical sampling directly tied to the stratigraphic interval with the biotic turnover needs to be conducted in the Fundy basin.

Thus, the emerging picture of faunal and floral change around the Tr-J boundary in eastern North America and Morocco is one of extraordinarily rapid, synchronous change over a very large area. This change, at least in the Newark basin and possibly in the Fundy basin, is associated with a geologically abrupt burst in fern abundance suggestive of major ecological disruption. It is important to note that within this context, with the exception of the appearance of the large dinosaurian ichnospecies *Eubrontes giganteus*, the earliest Jurassic floral and tetrapod assemblages consist entirely of survivor taxa with no originations and no apparent replacement of Triassic forms by Jurassic ecological vicars. It has been hypothesized that even the appearance of *Eubrontes giganteus* may represent a consequence of ecological release upon the extinction of Triassic competitor forms, largely members of the nondinosaurian Crurotarsi, such as rauisuchians and phytosaurs (Olsen et al., 2002b). It is also important to note that the Tr-J boundary marks the end of the persistent floral and faunal provinciality that characterized the Triassic, and the establishment of a nearly cosmopolitan terrestrial community (Cornet and Olsen, 1985; Olsen and Galton, 1984; Sues et al., 1994). The biological data available thus far are consistent with a catastrophic end to the Triassic comparable in magnitude and similar in pattern to that characterizing the terminal Cretaceous event. The results from the Newark basin Tr-J boundary reported by Olsen et al. (2002b) show a modest Ir anomaly associated with the biotic turnover and the fern spike that is remarkably similar to that described for the K-T boundary. We stress that these results need to be tested by much more widespread geochemical and palynological analyses, both stratigraphically and geographically.

RELATIONSHIP TO POSSIBLE IMPACT

It is clear that, at least superficially, there is a strong similarity between the K-T boundary in the western North American interior and the Tr-J boundary in eastern North America. This similarity includes the specific pattern of floral and faunal extinction, the fern spike, and the presence of an apparent Ir anomaly. The similar patterns might indicate similar cause, and an impact origin for both boundaries has been suggested (Dietz, 1986; Olsen et al., 1987, 1990). Although shocked quartz has not been reported from eastern North America, Bice et al. (1992) reported it from a Tr-J boundary section in Tuscany, and there is an additional report from the Kendelbach section in

Austria (Badjukov et al., 1987). However, in both cases the shocked quartz was identified only petrographically, which is now not considered definitive (e.g., Grieve et al., 1996; Mossman et al., 1998), and in neither case has there been a subsequent attempt at independent confirmation. Of course, if the impact site were very distant, or in oceanic crust, it is possible that shocked quartz would be very rare or absent.

Originally, the giant Manicouagan impact was suggested as a possible cause (Olsen et al., 1987) of the Tr-J mass extinctions. However, U-Pb dates from this feature by Hodych and Dunning (1992) suggest that its age is 214 ± 1 Ma, which is consistent with older $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb-Sr dates from the impact, but incompatible with the dates of the basalts overlying the boundary (ca. 200 Ma), which at least at the level of uncertainty of radiometric dates, should be the age of the boundary.

RELATIONSHIP WITH CENTRAL ATLANTIC MAGMATIC PROVINCE

A remarkable aspect of the Tr-J boundary is the very close proximity in both stratigraphic thickness and time (~ 20 k.y.) to the oldest exposed Central Atlantic magmatic province flood basalts in eastern North America and Morocco. The Central Atlantic magmatic province tholeiites may represent the largest known (in area at least) igneous event in Earth history, covering an area of 7×10^6 km² (e.g., Marzoli et al., 1999) (Fig. 2). The preerosion volume of the Central Atlantic magmatic province may have been in excess of 3×10^6 km³, making it larger than any other known continental flood basalt province. The close association between the Central Atlantic magmatic province lavas and the boundary has led to speculation that the extinctions might have been caused by climatic changes resulting from gas and aerosol emissions from the eruptions (Courtilot et al., 1994; McHone, 1996; Marzoli et al., 1999; Palfy et al., 2000a). McElwain et al. (1999) found that the stomatal density in a range of plant taxa drops significantly within the same taxa at the florally identified Tr-J boundary in Greenland (Kap Stewart Formation). This change is direct evidence suggesting a major increase in CO₂ at the boundary that they speculated might be due to Central Atlantic magmatic province volcanism. Smith et al. (1988) noted that a volcanic source could be responsible for the smectitic clay at the boundary in the Jacksonwald syncline of the Newark basin. It is also possible that an Ir anomaly, especially a modest one, could be explained by deep-seated basaltic volcanism as suggested by Olmez et al. (1986) for the K-T boundary, although this hypothesis is not supported by our geochemical analyses of associated elemental concentrations.

A significant problem with the volcanic hypothesis for the origin of the Tr-J mass extinction is that wherever the biological signature of the mass extinction and the oldest Central Atlantic magmatic province basalts have been observed in the same section, the basalts invariably postdate the extinctions, albeit by only a short time. However, the basalts that are known in su-

perposition with the boundary amount to a small part of the Central Atlantic magmatic province; their temporal relationship with the rest of the Central Atlantic magmatic province and the boundary is unknown at the required fine level of resolution.

Olsen (1999) and Olsen et al. (2002a) pointed out that there is some slim paleomagnetic evidence for Central Atlantic magmatic province eruption occurring just prior to the boundary, consisting of very rare dikes of Central Atlantic magmatic province radiometric age (i.e., 200 Ma) with reversed magnetic polarity. Because all the Central Atlantic magmatic province basalts above the boundary are uniformly of normal polarity, this shows that some of the Central Atlantic magmatic province igneous activity occurred at a different time than the known flows. The temporally closest interval of reversed polarity is E23r, located just below the boundary (Figs. 4–7). If further research confirms the reality of the reversed dikes, a significant portion of the Central Atlantic magmatic province could easily predate or be synchronous with the boundary. For example, a huge basaltic edifice that could predate the boundary includes the massive seaward-dipping reflectors off the southeastern United States that may be part of Central Atlantic magmatic province (Holbrook and Kelemen, 1993; Olsen, 1999; Olsen et al., 2002a) and could be volumetrically as large as the rest of the province. Thus we do not reject the possibility that at least part of the Central Atlantic magmatic province, perhaps even the largest part, could have been emplaced just before or during the Tr-J mass extinctions.

IMPACT AND VOLCANISM?

Rampino and Stothers (1988) and Courtilot et al. (1994), on the basis of a compilation of published radiometric dates of igneous rocks and literature ages for geologic boundaries, showed that there is a very good correlation between major continental flood basalts and mass extinctions over the past 300 m.y. Particularly prominent are the three largest Phanerozoic mass extinctions (Permian-Triassic, Tr-J, and K-T) and their remarkably tight association with the three largest Phanerozoic continental flood basalts (Siberian, Central Atlantic magmatic province, and Deccan, respectively). It seems very difficult to dismiss this correlation as a coincidence, and it is particularly interesting that at least two (Tr-J and K-T) have evidence of an impact (the latter impact evidence is unimpeachable). Thus, we cannot dismiss the possibility that the flood basalt volcanism was perhaps somehow triggered or enhanced by an impact (e.g., Boslough et al., 1996), despite the fact that preliminary models of the energetics of impacts suggest that causing volcanism de novo with an impact would be very difficult (e.g., Melosh, 2000).

CONCLUSIONS

The biotic pattern around the continental Tr-J boundary has many similarities with the much better understood K-T bound-

ary, including the very short duration of the extinction event, its selectivity, the composition of postboundary assemblages made up of only survivor taxa, and the presence of a regional fern spike at the microfloral extinction level. We have shown here new evidence of at least a modest Ir anomaly associated with the fern spike. A summary of the data for the Tr-J boundary based mostly on the Newark basin is shown in Figure 9. We have also shown the enormous area over which the stratigraphy of the continental boundary is remarkably consistent. Also shared with both the K-T and Permian-Triassic boundaries are temporally associated massive continental flood basalts. Unlike the K-T boundary, evidence for an impact at the Tr-J boundary is not yet conclusive. It is difficult to dismiss as coincidental the co-occurrence of mass extinctions and flood basalts, including that at the Tr-J boundary. The newly reported Ir anomaly could be consistent with either an impact or deep-seated volcanic origin, although the latter receives no support from the trace element concentrations or stratigraphic relationships reported here. The microstratigraphy is very similar to continental K-T boundary sections, and this lithological similarity is matched by a similar biotic pattern. However, without additional, more stratigraphically extensive sampling, we cannot completely rule out a volcanic or other nonimpact origin for this anomaly.

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