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580 Ky Duration of the Early Jurassic Flood Basalt Event in Eastern North America Estimated Using Milankovitch Cyclostratigraphy

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ABSTRACT: Early Jurassic-age tholeiitic flood basalts of the Newark Supergroup of the eastern United States are interbedded with strata composed of a hierarchy of lake-level sedimentary cycles of Milankovitch climate cycle origin. Based principally on the Newark basin section, known from continuous core, these cycles constrain the duration of the extrusive and associated intrusive event in exposed basins to 580±100 Ky at ~201 Ma, immediately postdating the Triassic-Jurassic boundary. Subsurface basalts of the southeastern U.S. and basalts of the early Mesozoic basins of Morocco and Iberia also appear to have been extruded contemporaneously with those of the Newark Supergroup. In addition, most if not all, early Mesozoic tholeiitic dikes and plutons in Eastern North America, West Africa, and Iberia were intruded at about the same time.

INTRODUCTION

Early Mesozoic-age extrusive tholeiites of eastern North America, Morocco, and Iberia comprise a major flood basalt province preserved in isolated rift basins (Manspeizer, 1988; McHone, 1996a) and as extensive sheets in the subsurface over large areas of South Carolina, Georgia, and the continental shelf (Fig. 1; McBride *et al.*, 1989). The rift sequences of the exposed basin of eastern North America are collectively termed the Newark Supergroup, while the buried basins or those of Morocco or Iberia have no collective name. The extrusive and associated intrusive rocks in these basins were emplaced in the Early Jurassic (Cornet and Olsen, 1985) and have been implicated in the tectonic evolution of the Atlantic passive margin (Manspeizer, 1988) and mass extinctions (Simms and Ruffell, 1989; McHone, 1996a). Collectively, the extrusive and associated intrusive rocks delineate a huge flood basalt province originally covering perhaps 2.3 million km^2 (McHone, 1996b).

Because of limits on the precision and accuracy of radioisotopic ages, the lack of fine-scale biostratigraphic ties to calibrated time scales, and the previous lack of a calibrated geomagnetic polarity stratigraphy for the early Mesozoic, estimates of the duration of the extrusion event (*e.g.*, McHone and Butler, 1984; Seidemann, 1988; Olsen *et al.*, 1989) have varied by an order of magnitude. Here we estimate the duration of the early Mesozoic extrusive event in the United States primarily by using the cyclostratigraphy of the surrounding and interbedded lake-level sequences.

LAKE-LEVEL CYCLES

Most lacustrine strata of the Newark Supergroup consist of a hierarchy of lake-level sequences made up of transgressive-regressive lake-level sequences called Van Houten cycles that are modified in their expression by three orders of modulating cycles termed the short modulating cycle, the McLaughin cycle, and the long modulating cycle (Fig. 2A; Olsen, 1986; Olsen and Kent, 1986). At least in the Newark basin (Fig. 1), which is by far the best known part of the Newark Supergroup, this cyclical pattern is a property of the entire 4-km-thick lacustrine section, as seen in recently acquired continuous cores (Olsen *et al.*, 1996; Olsen and Kent, 1996, Kent *et al.*, 1995). Also demonstrated in the Newark basin, the Van Houten cycles and the modulating cycles they comprise are traceable laterally nearly basin wide (Olsen *et al.*, 1996). Fourier analysis of these cycles using sediment fabrics ranked according to interpreted water depth (see Olsen and Kent, 1996) reveals a corresponding hierarchy of cycle thicknesses, the durations of which correspond to the predictions of the Milankovitch theory of climate change (Fig. 2B) (Olsen and Kent, 1996).

Van Houten cycles were produced by fluctuations in lake level that resulted from changes in precipitation and evaporation rates apparently controlled by the climatic precession cycle, which currently averages 21 Ky (Berger, 1977). The modulating cycles that regulated the expression of the Van Houten cycles were controlled by the cycles of the precession of the longitude of perihelion and the eccentricity of the Earth's orbit, which now

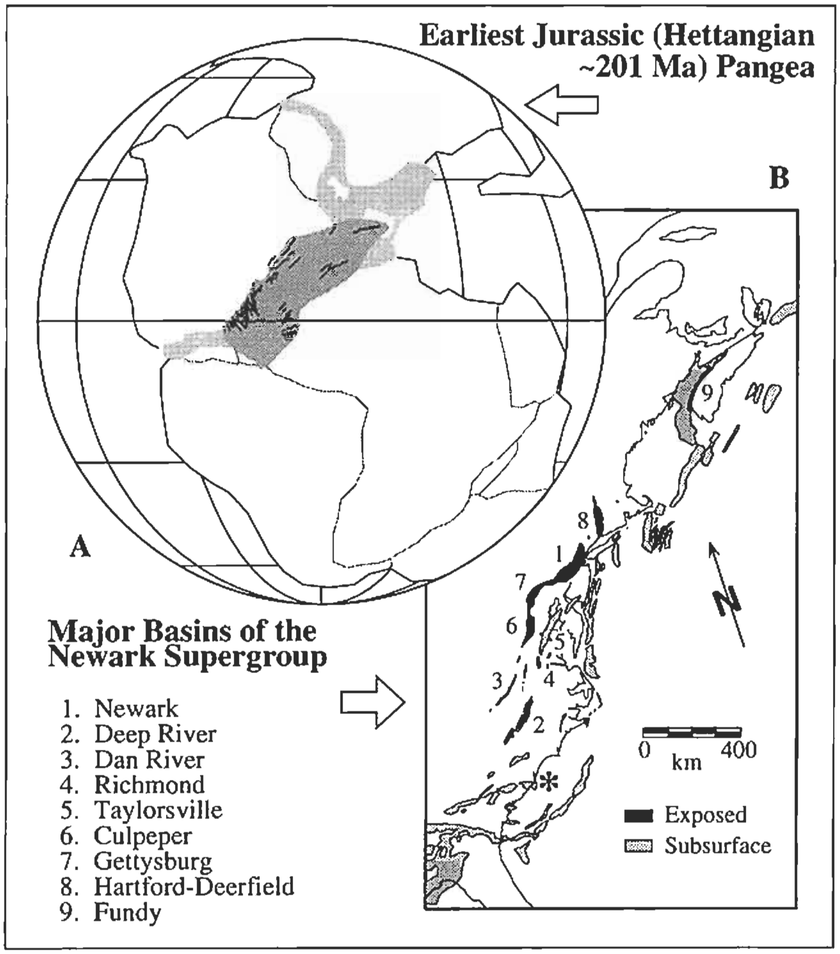

FIGURE 1. Pangea and the Newark Supergroup. A, Pangea during the earliest Jurassic (based on Olsen *et al.*, 1996), showing the rifting zone (light gray), the probable former distribution of early Mesozoic Flood basalts (dark gray) (from McHone 1986b), and the position of major tholeiitic dikes (short black lines) (from McHone 1986b). B, Early Mesozoic rift basins of eastern North America (modified from (Olsen *et al.*, 1995). * is adjacent to position of Club House Crossroads basalt.

average 109 Ky (short modulating cycle), 413 Ky (McLaughlin cycle), and about 2 my (long modulating cycle) (Berger, 1977; Kent and Olsen, 1996). Because of the long-term recession of the moon, the precession cycle should have been somewhat shorter during the early Mesozoic, probably averaging 20 ky (Berger *et al.*, 1989), but periods of the modulating cycles should have changed only very slightly (Berger *et al.*, 1989, 1992). These cycles allow a calibration of the duration of the extrusive event in the early Mesozoic rifts.

CYCLOSTRATIGRAPHY OF THE JURASSIC PART OF THE NEWARK BASIN AND DURATION OF THE NEWARK BASIN EXTRUSIVE EVENT

A total of over 12 km of core makes the Newark basin the most completely known rift basin along the Atlantic passive margin. These cores come from two sources: the Army Corps of Engineers and the Newark Basin Coring Project. In 1985-95 the Army Corps of Engineers (ACE) drilled a series of short cores (45 - 120 m) along a 32 km transect across the northern Newark basin making a cumulative 5587 m of core (Fedosh, 1987). The cored intervals include virtually the complete cyclostratigraphy of the extrusive zone and post-flow sequence (Fig. 3). In addition, in 1990-1993 nearly the entire Feltville Formation, the Orange Mountain Basalt, and virtually all of the pre-extrusive section were cored in the Newark Basin Coring Project (NBCP) which recovered a total of 6770 m of core (Olsen *et al.*, 1996).

A composite section of the ACE cores was constructed by patching together the sections of the geographically adjacent cores using the portions that stratigraphically overlap for registry (Fig. 3). Correlation between cores was obvious in nearly all cases, and because of the geographic proximity of stratigraphically adjacent core holes, no scaling of sections was necessary.

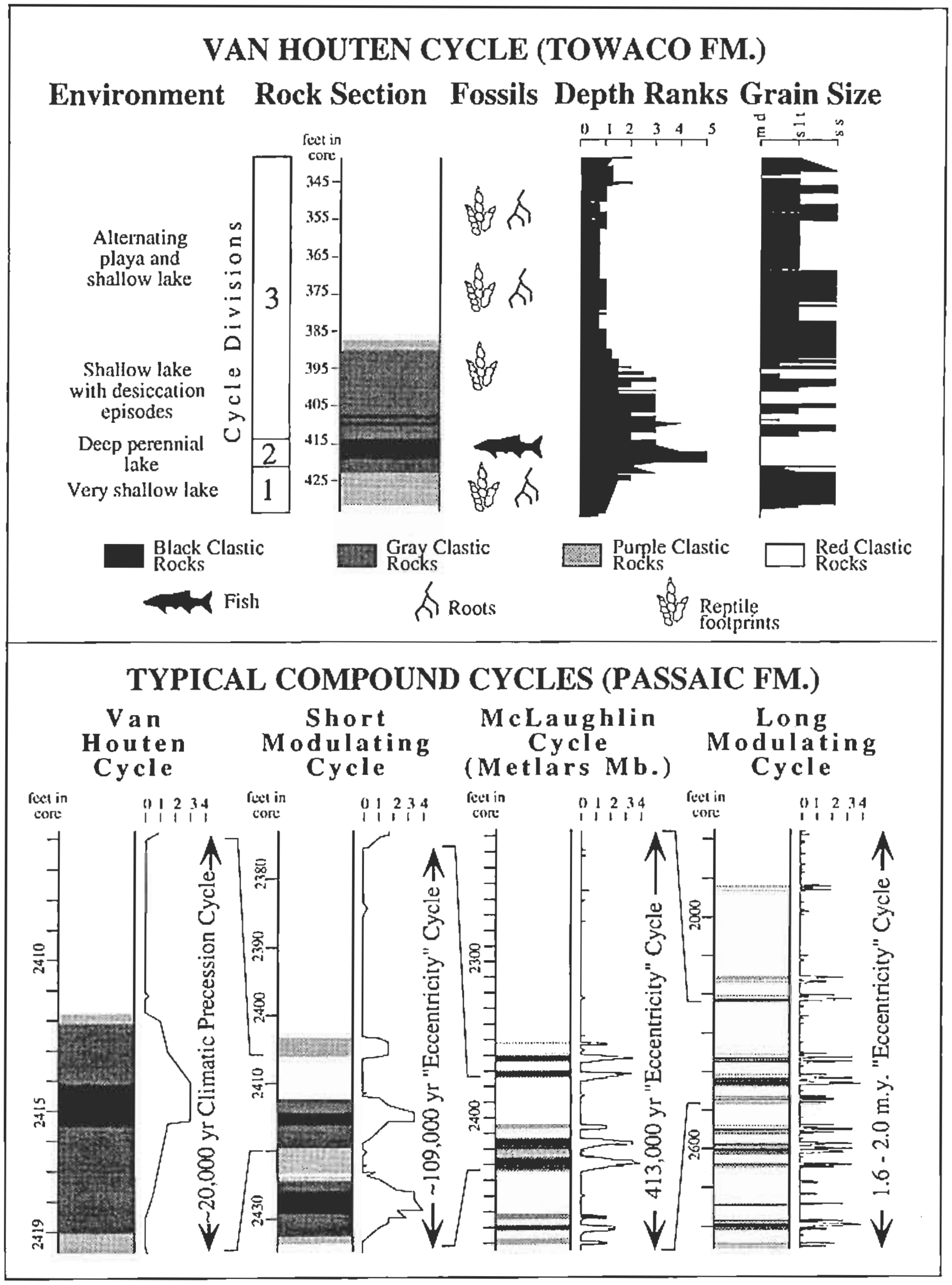

FIGURE 2. Arrangement of Van Houten cycles into compound cycles in the Newark Supergroup. Van Houten cycle from Towaco Formation is from ACE core PT-14. Compound cycles are from the Somerset no. 1 of the Newark Basin Coring Project cores. Driller's footages are in feet.

However, in the Feltville Formation, there is some ambiguity in correlating between ACE cores because of the very short length of some of the cores and because of their very small amounts of stratigraphic overlap. It is therefore possible that some section is not represented by core in the ACE transect of the middle part of the Feltville Formation, and it is even possible that we have miscorrelated some of the cores.

In the NBCP cores, all but the uppermost meter or so of the Feltville Formation, all of the Orange Mountain Basalt, and the upper 863 m of the Passaic Formation were cored in the Martinsville no. 1 core. Because this interval was cored without any ambiguity of continuity or superposition, we use it, instead of the ACE cores, as representative of the Feltville Formation, Orange Mountain Basalt, and upper Passaic Formation. This section is patched on to the base of the ACE cores at the Preakness Basalt - Feltville Formation contact (Fig. 3).

In these cored sections, the cyclical uppermost Passaic Formation directly underlying the Orange

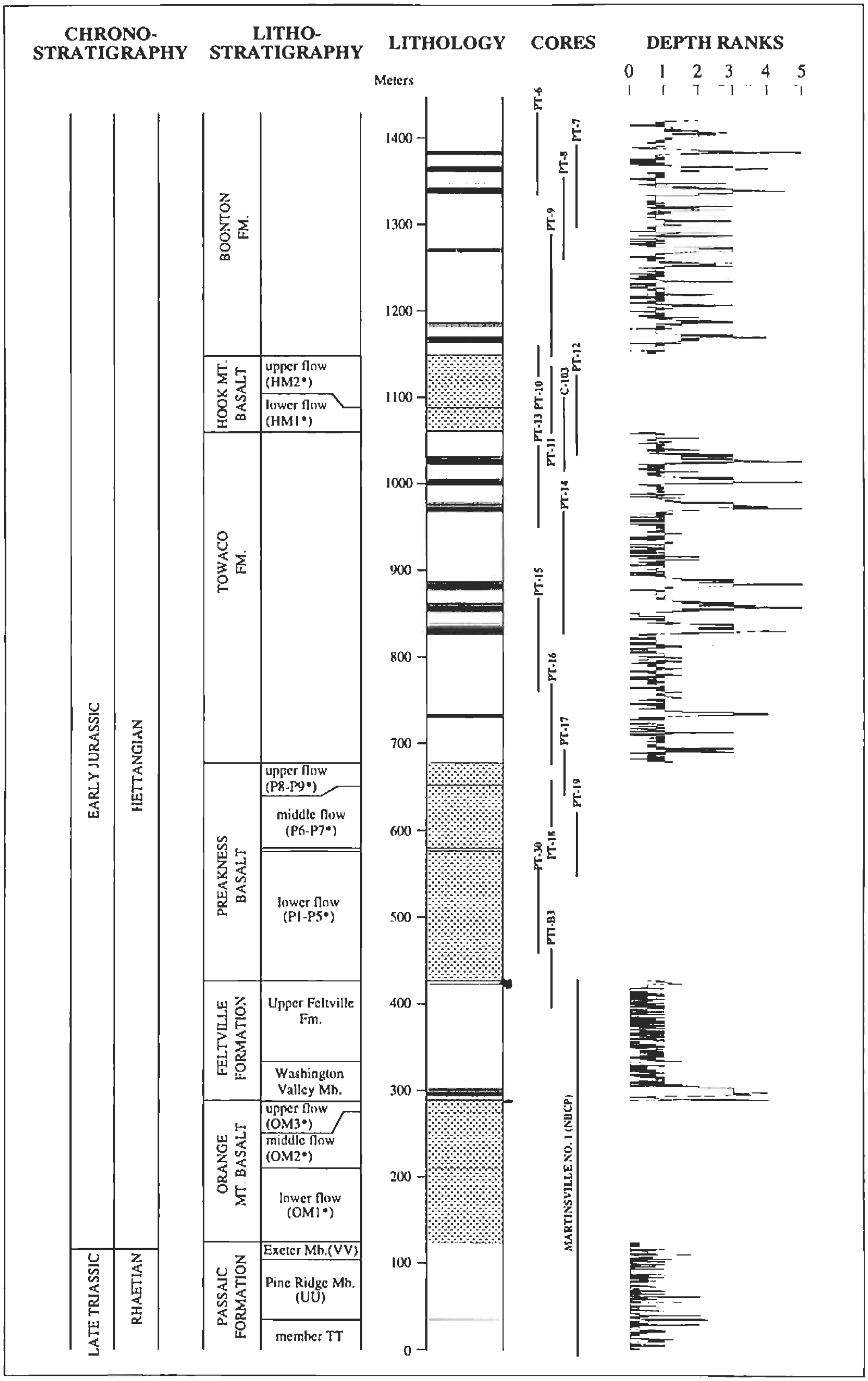

FIGURE 3. Latest Triassic-Early Jurassic-age section of the Newark basin based on Army Corps of Engineers cores and uppermost Passaic Formation from Newark basin coring project cores (Olsen et al., 1990; Olsen et al., 1996). Detailed logs of the cores are given in Fedosh (1987).

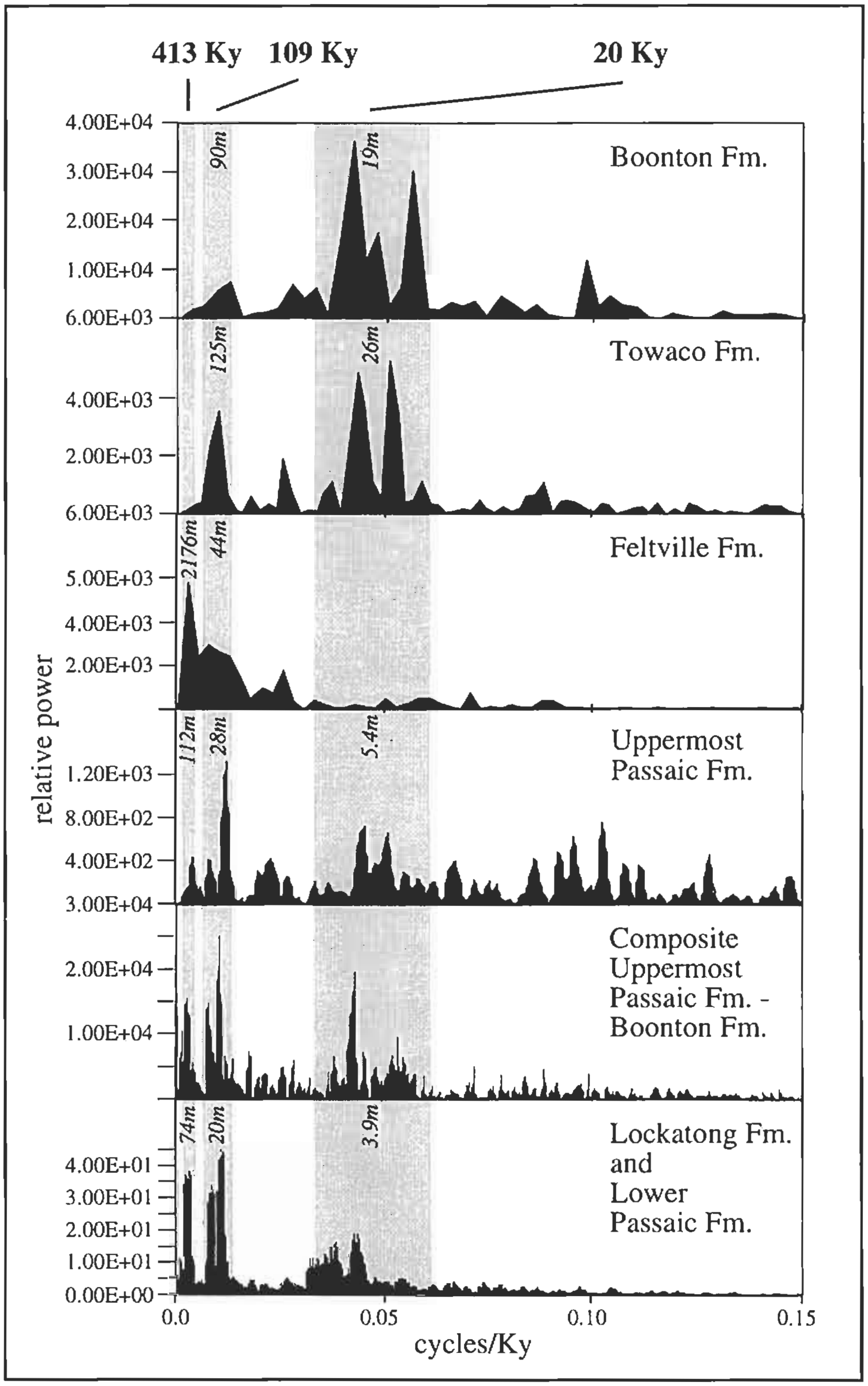

FIGURE 4. Power spectra of composites of depth rank sections from the Jurassic age formations of the Newark basin and the uppermost Passaic Formation. All spectra have been adjusted to a common time scale using the higher frequency components of the spectra (Van Houten cycles in cases except the Feltville, where the short modulating cycle was used. Numbers above main peaks in the spectra indicate the mean thickness of the cycles in original core dimensions.

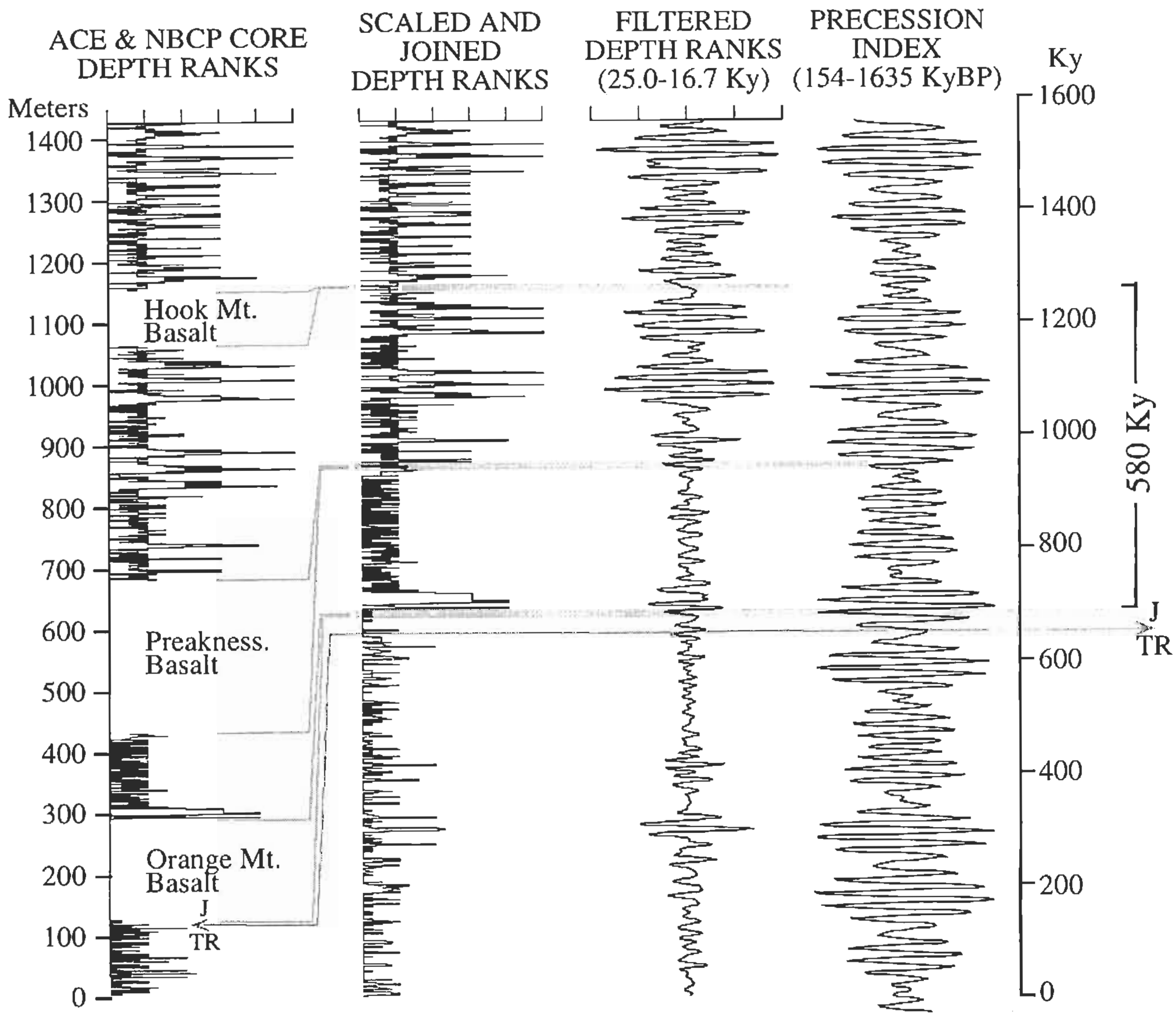

FIGURE 5. Newark basin depth rank section and filtered cycles, compared to index of climatic precession (from Berger and Loutre, 1991).

Mountain Basalt lacks the pollen and spores used to define the Triassic-Jurassic boundary. The Triassic-Jurassic boundary (Fig. 3) is placed in the NBCP section by correlation of the NBCP cores with the well-studied palynologically productive Jacksonwald syncline section from the southwestern Newark basin that (Olsen et al., 1990; Fowell, 1993; Fowell and Olsen, 1995) using the base of the oldest basalt flow as a marker horizon, very distinctive magnetic polarity stratigraphy, and the pattern of underlying lacustrine cycles (see Fig. 27 in Olsen et al., 1996 for details).

Based on the ACE and NBCP cores the cyclostratigraphy of the Jurassic part of the Newark basins sequence is very similar in pattern to that seen in the Triassic age part of the section as described in detail by Olsen and Kent (1996), except that the thickness of the Van Houten and modulating cycles is generally much greater. It is apparent that the cyclostratigraphies the Feltville, Towaco, and cored part of the Boonton formations each comprise major portions of McLaughlin cycles, comprised in turn by short modulating cycles and Van Houten cycles. We have conducted Fourier analysis of the depth rank records each of these formations, as well as the upper Passaic Formation and then scaled the depth rank records to their common high frequency components (Fig. 4). On the assumption that the high frequency cycles (i.e., Van Houten cycles) represent the effects of the climatic precession cycle, this scaling places all the depth rank records of these formations on a common relative time scale. When these scaled depth rank records are patched together without inclusion of the intervening lava flows the combined record shows a complete pattern of McLaughlin cycles (Fig. 5). We have filtered this composite record with

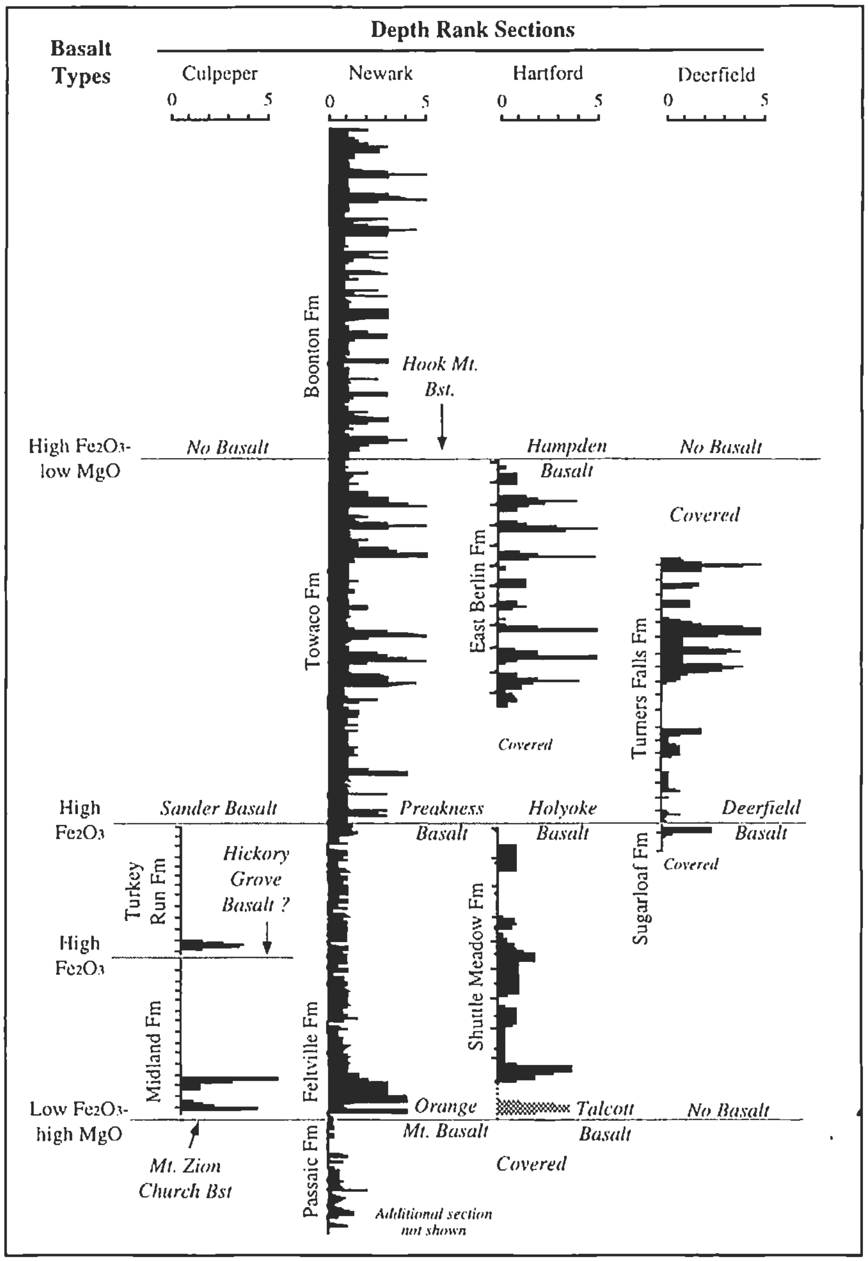

FIGURE 6. Correlation of depth rank curves of sedimentary formations and basalt geochemical types (after Tollo and Gottfried, 1992) in the extrusive zone of exposed Mesozoic basins Measured sections (except Culpeper basin) represent single continuous exposures or cores. Terminations of sections represent formation boundaries except as noted. All sections scaled to time based on Van Houten cycles; tick mark spacing is 10 m.

frequencies corresponding to the climatic precession cycle and compared it directly with a portion of the precession index for the interval from 154,000 to 1,635,000 ybp (from Berger and Loutre, 1991) (Fig. 5). There is a profound similarity in the cyclical pattern, especially in the Towaco and Boonton Formations. The pattern match further suggests that there are no significant gaps in time at the positions of the lava flows. If such gaps are present, they would have to be multiples of the short modulating cycles or the McLaughlin cycles to maintain phase coherence. We regard as very unlikely whole McLaughlin cycles are missing at the positions of the lava flows, but do regard it as possible that a short modulating cycle could be missing in either the position of the Preakness Basalt or the Orange Mountain Basalt (but not both). Therefore, based on counting Van Houten cycles and the enclosing modulating cycles the duration of the extrusive interval in the Newark basin is 580 Ky with an uncertainty of about ±100 Ky. Also based on the cyclostratigraphy, the extrusive event began about 40 Ky after the Triassic-Jurassic boundary.

COMPARISON WITH OTHER TRIASSIC-JURASSIC RIFT BASINS OF THE ATLANTIC MARGIN

Although no other rift basin of the Atlantic passive margin is known at the same level of detail as the Newark basin, there are five lines of evidence that suggests that the lava flows in the other exposed basins of the Atlantic passive margin were extruded during the same short interval as those in the Newark basin. These are: 1) biostratigraphy of the pre- post- and syn-extrusive sedimentary formations; 2) cyclostratigraphy of well exposed portions of the some basins; 3) geochemistry of the extrusive units; 4) magnetostratigraphy of basalts and surrounding deposits; and 5) radiometric dates.

Based on the palynostratigraphy of the surrounding strata, all basalt flows in the Newark Supergroup are of Hettangian age and belong to the Corollina (Classopollis) meyeriana biozone (Cornet and Olsen, 1985). In addition, Fowell (1993) and Fowell and Traverse (1995) have identified the palynological Triassic-Jurassic boundary in the strata within a few meters to tens of meters below the oldest extrusive unit in the Culpeper, Newark and Fundy basins of the eastern North America and the Argana basin of Morocco. This indicates a Hettangian age for these extrusive units. Older attempts at detailed correlation of syn- and post-extrusive deposits using fish (Olsen et. al, 1982) that suggested a complex correlation of basalt units have proved incorrect due to subsequent discoveries (Olsen, 1983; Olsen *et al.*, 1989).

Portions of the cyclostratigraphy of individual basin sections that are known in enough detail to compare with confidence with the Newark basin sections include: 1) the lower part of the Midland Formation of the Culpeper basin; 2) the East Berlin Formation of the Hartford basin; and 3) the lower Turners Falls Sandstone of the Deerfield basin (Fig. 6). Each depth-ranked section was subjected to Fourier analysis and scaled to the most prominent high-frequency elements of the power spectra corresponding to Van Houten cycles. The sections were correlated so that they match in phase with the modulating and Van Houten cycles and so that the geochemistry of the adjacent basalts (see below) correlate. The match between depth rank sections of the Towaco , the East Berlin, and the lower Turners Falls formations are striking, suggesting exact correlation. What is known about the cyclostratigraphy of the other inter- and post-flow units of the Culpeper through Deerfield basins is completely compatible with the Newark basin section.

Exposed flows of the eastern North American rifts show a consistent geochemical stratigraphy (Tollo and Gottfried, 1992; Puffer, 1992; Dostal and Greenough, 1992) that corresponds exactly with the available cyclostratigraphic and biostratigraphic correlation (Fig. 6). Thus, the flows lying immediately above the earliest Jurassic strata have compositions like that of the Orange Mountain Basalt (initial basalt trend of McHone, 1996a), while younger flows have a an orderly change in composition (subsequent basalt trend of McHone, 1996a).

The Late Triassic and Early Jurassic were times of mixed polarity (Kent et al, 1995; Yang *et al.*, 1996) yet all exposed flows and interbedded strata apparently lie within one minimally mostly normal magnetochron (Witte *et al.*, 1991). Thus, the extrusive zone should span only a part of the Hettangian, estimates of the duration of which range from 1 to 7 m.y. (Van Hinte, 1978; Harland *et al.*, 1990; Yang *et al.*, 1996). In addition, a magnetic excursion in the lowermost Preakness, Holyoke, and Deerfield basalts suggests exact temporal correlation (Prévot and McWilliams, 1989) of those units.

Based on the cyclostratigraphy presented above, isotopic dates of all lava flows throughout the Newark Supergroup should be analytically indistinguishable. However, K-Ar and $^{40}Ar/^{39}Ar$ dates from basalts in eastern North America span a range of >100 m.y., most of which is attributable to post-cooling alteration (Sutter, 1988; Seidemann, 1988). However, closed-system minerals from the Palisades sill, which was a feeder to the Newark basin lava flows (Ratcliffe, 1988), and show much less scatter, yielding $^{40}Ar/^{39}Ar$ dates averaging 201±2.7 Ma (Sutter, 1988) and U-Pb dates averaging 202±1 Ma (Dunning and Hodych, 1990). In addition, the North Mountain Basalt of the Fundy basin (Fig. 1) has produced U-Pb zircon dates averaging 202±1 Ma (Hodych and Dunning, 1992). As has been suggested by these authors, the data of 201-202 is the best available date not only for the flows, but also for the Triassic-Jurassic boundary as well.

RELATED EXTRUSIONS AND INTRUSIONS

Tholeiitic basalt flows in the subsurface of the southeastern United States and outcropping lavas in Iberia are probably also part of this early Mesozoic extrusive event, although there is vastly less data than for the flows of the Newark Supergroup and Morocco. What have been described as interbedded olivine-normative and quartz-normative flows lacking thick interflow sedimentary sequences underlie a large area of South Carolina and Georgia and the adjacent continental shelf (McBride *et al.*, 1989). According to Ragland (pers. comm., 1996) the apparent olivine-normative compositions of the flows may be a result of extensive alteration and it is most likely the flows are of essentially quartz-normative composition. Dates from these flows vary widely (97-217 Ma), and none are regarded as reliable (Ragland, 1990). Previously reported alternating magnetic polarity zones from the southern flows (Phillips, 1983), implying a much longer duration of extrusion, are also considered unreliable (J. D. Phillips, pers. comm., 1989). It is thus plausible that these southern flows were coeval with the northern flows.

Thoeliitic basalt flows from rift basins in Morocco are similar geochemically to those of the Newark Supergroup and are interbedded with Early Jurassic age continental strata (Manspeizer *et al.*, 1978), suggesting a close correlation with Newark Supergroup thoeliites (Manspeizer, 1988).

Basalt flows of southern Spain (Fig. 1) are interbedded with deposits extremely similar to those of Morocco, and like them are overlain by Early Jurassic marine sequences (Sanchez de la Torre *et al.*, 1977). There is no reason to expect these not to be part of the same sequence as seen in Morocco.

The Atlantic margins of North America, West Africa, Iberia, and France are host to a massive swarm of tholeiitic dikes forming a more or less radiating pattern. Sills and other plutons intrude the Early Mesozoic basins themselves in at least the United States and Morocco. All of these intrusives may have been emplaced during the same intervals as the Newark Supergroup and Moroccan lavas. Tholeiitic dikes, sills, and other plutons are present within the Culpeper, Gettysburg, Newark and Hartford basins, and chemically similar dikes occur in adjacent basement rocks (Puffer and Philpotts, 1988). Nearly all of these intrusives fall in the same geochemical categories as the flows (Puffer and Philpotts, 1988; McHone, 1996a, 1996b), and several of the dike systems in the Hartford basin (Philpotts and Martello, 1986) and the Palisade sill in the Newark basin (Ratcliffe, 1988) were feeders to the flows. No tholeiitic intrusions cut strata younger than the youngest flows. Therefore, the emplacement of the tholeiitic intrusions were almost certainly synchronous with the extrusions.

Further south in Eastern North America are two suites of tholeiitic dikes generally grouped by orientation as the NW-trending and N-S-trending suites (Ragland *et al.*, 1983). The temporal relationships between these dikes and the flows of the Newark Supergroup and Morocco is not completely clear. The NW suite is dominated by olivine normative diabase and are related to sills intruding the Deep River basin. The N-S suite is virtually all quartz normative, and is compositionally related to the dikes and flows in the northern Newark Supergroup basins. Cross-cutting field relationships suggest that the N-S suite is younger than the NW suite (Ragland *et al.*, 1983). At least one of the N-S suite of dikes exhibits reversed polarity, while the data from the NW suite is so far all of normal polarity (Smith, 1987). This indicates that at least some of the dikes differ in age, at least somewhat, from the flows of the Newark Supergroup and Morocco, although additional paleomagnetic work is clearly needed. Pole positions from the N-S suite suggest that these dikes may be younger than the Newark flows (Smith, 1987; Kent *et al.*, 1996). However radiometric ages reviewed by Ragland (1992) suggest that the NW and N-S suites yield $^{40}Ar/^{39}Ar$ ages (around 201 my) indistinguishable from each other and from the dates from the flows and feeder intrusions of the Newark Supergroup. The Newark basin magnetic polarity time scale for the Late Triassic (Kent *et al.*, 1995) and that of the Early Jurassic of the Paris basin in France (Yang, 1996) show that rare dikes of reversed polarity in the NW suite could have been intruded within a few tens of thousands to few million years of the flows, in the more northern basins. Thus it is plausible that all of the intrusive and extrusive tholeiites of the southeastern North America and the flows of northeastern North America, Morocco, and Iberia were emplaced during an interval of as little as 600-700 Ky.

DISCUSSION

The interval of massive outpourings of tholeiitic lavas and associated intrusions that characterize the Atlantic early Mesozoic rifting episode was apparently restricted to <0.7 m.y. This stands in marked contrast to igneous provinces of some other extensional provinces, notably the East African rift system (Baker *et al.*, 1971) and the Basin and Range (Gans *et al.*, 1989) in which there are a greater compositional range and a much longer interval of activity. Presumably, the major differences in igneous styles between extensional regions reflect important tectonic differences, which are as yet incompletely explored (*e.g.*, Keller and Hoover, 1988).

On the other hand, the duration of the Atlantic early Mesozoic extrusive interval is comparable to recent estimates of the duration (~0.5-0.6 m.y.) of both the Deccan (Jaeger *et al.*, 1989) and Siberian Traps (Renne and Basu, 1991), which were much more voluminous. Both extrusive events have been implicated in mass extinctions, because of what must have been extremely rapid extrusion rates coupled with massive outgassing at almost precisely the Cretaceous-Tertiary and Permo-Triassic boundaries, respectively. The circum-Atlantic extrusive event is also associated with the mass-extinction at the Triassic-Jurassic boundary (Olsen *et al.*, 1990). However, at least one complete Van Houten cycle and part of another separate the oldest basalt from the boundary identified on the basis of pollen and spore and vertebrate data (Fig. 3; Olsen *et al.*, 1990). Thus, the boundary and the associated mass extinctions predate the extrusive event in the Newark Supergroup by 20-40 Ky (Fig. 3). Because such a short interval is beyond the precision of isotopic dates, the 201 Ma date for the 600-ky-long extrusive event in eastern North America must also apply to the age of the Triassic-Jurassic boundary (Dunning and Hodych, 1990; Hodych and Dunning, 1992).

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