Position of the Triassic–Jurassic boundary and timing of the end-Triassic extinctions on land: Data from the Moenave Formation on the southern Colorado Plateau, USA

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ABSTRACT

Strata of the Moenave Formation on and adjacent to the southern Colorado Plateau in Utah–Arizona, U.S.A., represent one of the best known and most stratigraphically continuous, complete and fossiliferous terrestrial sections across the Triassic–Jurassic boundary. We present a synthesis of new biostratigraphic and magnetostratigraphic data collected from across the Moenave Formation outcrop belt, which extends from the St. George area in southwestern Utah to the Tuba City area in northern Arizona. These data include palynomorphs, conchostracans and vertebrate fossils (including footprints) and a composite polarity record based on four overlapping magnetostratigraphic sections. Placement of the Triassic–Jurassic boundary in strata of the Moenave Formation has long been imprecise and debatable, but these new data (especially the conchostracans) allow us to place the Triassic–Jurassic boundary relatively precisely in the middle part of the Whitmore Point Member of the Moenave Formation, stratigraphically well above the highest occurrence of crurotarsan body fossils or footprints. Correlation to marine sections based on this placement indicates that major terrestrial vertebrate extinctions preceded marine extinctions across the Triassic–Jurassic boundary and therefore were likely unrelated to the Central Atlantic Magmatic Province (CAMP) volcanism.

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1. Introduction

The end of the Triassic has long been described as the time of one of the "big five extinctions," one of the most devastating mass extinctions of the Phanerozoic (Sepkoski, 1982). However, the hypothesis of a single end-Triassic extinction of overwhelming suddenness and severity has been questioned, and some workers propose instead that the latest Triassic records a series of extinctions that are poorly resolved stratigraphically (Hallam, 2002; Tanner et al., 2004; Lucas and Tanner, 2008; Deenen et al., 2010). Given that the end-Triassic extinctions took place on both land and in the sea, the correlation of terrestrial and marine events across the Triassic–Jurassic boundary (TJB) is crucial to distinguishing the chronology of the extinctions (Lucas and Tanner, 2007b).

We have extensively studied one of the world's best known and most stratigraphically continuous, complete and fossiliferous terrestrial sections across the TJB—strata of the Moenave Formation on and adjacent to the southern Colorado Plateau in Utah–Arizona, USA (Fig. 1). We present here an analysis of new biostratigraphic and magnetostratigraphic data collected from the Moenave Formation across its outcrop belt, from the St. George area in southwestern Utah to the Tuba City area in northern Arizona (Fig. 1), including palynomorphs, conchostracans and vertebrate fossils (bones and footprints) and the polarity record of four magnetostratigraphic sections. Two localities where the upper, Whitmore Point Member of the formation is well exposed – Johnson Farm in Utah and Potter Canyon in Arizona – are of particular biostratigraphic importance (Fig. 1).

Placement of the TJB in strata of the Moenave Formation has long been imprecise and debatable, but new biostratigraphic and magnetostratigraphic data allow us to place the TJB relatively precisely (within a few meters) in the middle part of the Whitmore Point Member of the Moenave Formation (Fig. 2). This placement has important implications for the timing of the end-Triassic extinctions, and supports the conclusion that terrestrial vertebrate extinctions preceded marine extinctions at the end of the Triassic Period and are unrelated to the CAMP eruptions.

2. Study area, lithostratigraphy and database

Strata of the Moenave Formation, the basal formation of the Glen Canyon Group (Harshbarger et al., 1957), are exposed in southwestern

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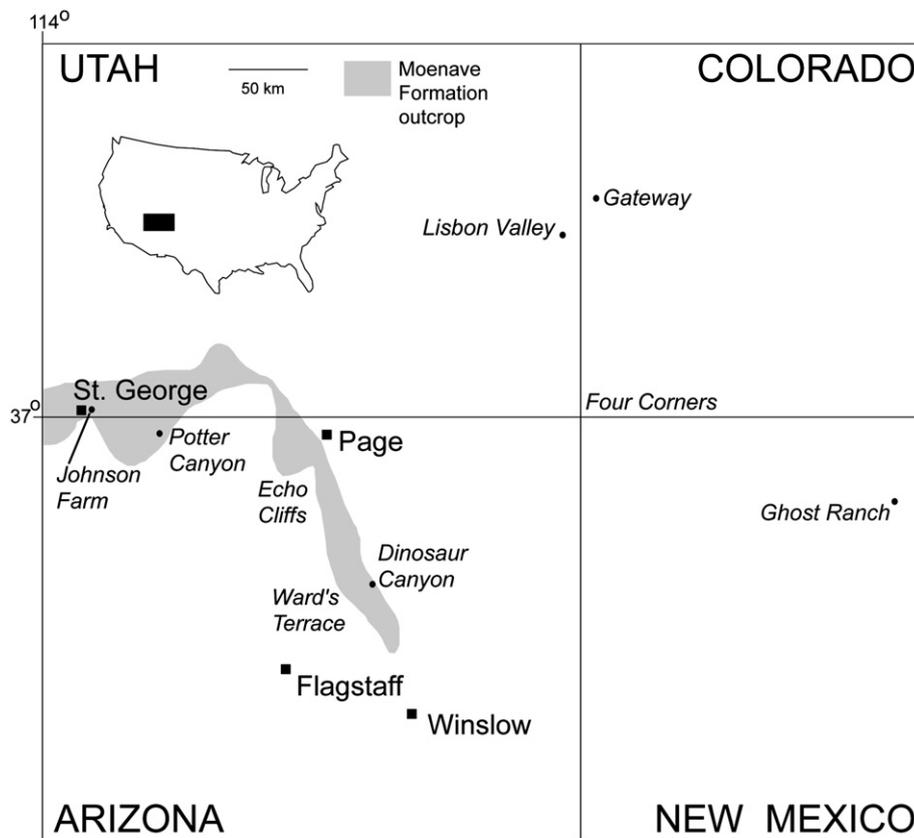E-mail address: spencer.lucas@state.nm.us (S.G. Lucas).

Fig. 1. Map of part of the southern Colorado Plateau (inset map shows location in USA) showing Moenave Formation outcrop belt and localities mentioned in the text.

Utah and northwestern Arizona, north of the Grand Canyon, and to the southeast on the Navajo Nation in north-central Arizona (Fig. 1). The Moenave Formation encompasses two members—the Dinosaur Canyon and Whitmore Point. The widespread, mixed fluvial and eolian Dinosaur Canyon Member both underlies and is (in its upper part) laterally equivalent to the dominantly lacustrine Whitmore Point Member, which has a much more limited outcrop area (Lucas and Tanner, 2007a; Tanner and Lucas, 2007, 2009) (Fig. 2). The Moenave Formation rests disconformably on Upper Triassic strata of the Owl Rock Formation of the Chinle Group, and some of its lowermost strata (basal part of the Dinosaur Canyon Member) are laterally equivalent to the upper part of the Rock Point Formation of the Chinle Group, strata that also disconformably overlie the Owl Rock Formation (Fig. 2). The Owl Rock–Moenave/Rock Point unconformity was long termed the J-0 unconformity because it was thought to coincide with the TJB (Pipiringos and O'Sullivan, 1978), but it is now referred to as the Tr-5 unconformity, a within-Triassic hiatus (Lucas, 1993, 1997; Lucas and Tanner, 2007a). The Springdale Sandstone Member of the Kayenta Formation disconformably overlies the Moenave Formation at the sub-Springdale unconformity (Marzolf, 1994; Lucas and Tanner, 2006).

Across its outcrop belt, the Moenave Formation is about 100 m thick and is mostly fine-grained sandstone, siltstone and shale (Harshbarger et al., 1957; Wilson, 1967; Tanner and Lucas, 2007, 2009, 2010). The thickest part of the formation is the Dinosaur Canyon Member, a succession of brightly colored, reddish-orange to light brown, eolian and fluvial sandstone and siltstone beds. In the Moenave type section, near Tuba City, Arizona, the formation consists entirely of the Dinosaur Canyon Member, as it does throughout the Moenave outcrop belt in the Navajo Nation of northern Arizona. However, north of the Grand Canyon in Arizona and in southwestern Utah (i.e., St. George area), the upper part of the Moenave Formation comprises the lacustrine strata of the Whitmore Point Member (Wilson, 1967)—laminar gray, ocher and red shale and siltstone up to 26 m thick.

On the Navajo Nation lands, the lower part of the Dinosaur Canyon Member grades laterally into the upper part of the Rock Point Formation, which is generally included in the Chinle Group (Harshbarger et al., 1957; Lucas and Tanner, 2007a), although some authors now consider it the basal unit of the Glen Canyon Group (e.g., Marzolf, 1994; Dickinson and Gehrels, 2009). To the east of the Moenave outcrop belt, in the Four Corners, the Wingate Sandstone is the lateral equivalent of the Moenave Formation (Harshbarger et al., 1957; Edwards, 1985; Clemmensen et al., 1989; Tanner and Lucas, 2007) (Fig. 2). The Wingate is usually 100 m thick and consists almost exclusively of thick beds of eolian sandstone that often form spectacular cliffs (Harshbarger et al., 1957; Clemmensen et al., 1989). Similar, albeit much thinner, beds of eolian sandstone are found in parts of the Dinosaur Canyon Member of the Moenave Formation to the west, supporting the concept of the dry, eolian-dominated system of the Wingate (to the east) being laterally equivalent to the wet, mixed eolian/fluvial system of the Moenave (to the west) (Edwards, 1985; Clemmensen et al., 1989; Blakey, 1994; Lucas and Tanner, 2007a; Tanner and Lucas, 2007). Also, strata of the Rock Point Formation in this region include extensive eolian-dominated beds, further supporting the concept of a gradational contact between the Rock Point and Wingate formations (Lucas et al., 1997; Lucas and Heckert, 2001). Indeed, detailed stratigraphic work (e.g. Lucas et al., 1997; Lucas and Tanner, 2007a) confirms most of the basic stratigraphic relationships among the Rock Point, Wingate and Moenave formations originally advocated by Harshbarger et al. (1957) (Fig. 2).

The Whitmore Point Member, as established by Wilson (1967), comprises purple and gray laminated mudstones and shales in the upper part of the Moenave Formation. The type location is just east of Potter Canyon, at Whitmore Point (Fig. 1), a south-facing promontory of the Vermillion Cliffs in Mohave County, Arizona, where the unit comprises 22 m of fish- and coprolite-bearing shales, siltstones, sandstones, and minor limestones. At the type location, the strata form a tripartite vertical sequence comprising a lower, finer-grained
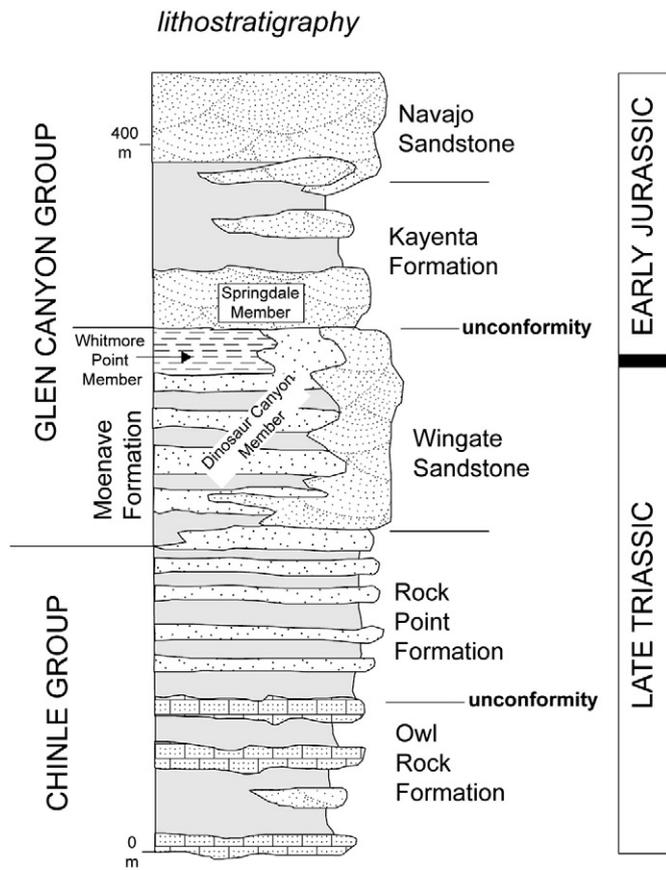
lithostratigraphy

Fig. 2. Synoptic chart of lithostratigraphy across the Triassic–Jurassic boundary on the southern Colorado Plateau, USA. Position of the Triassic–Jurassic boundary is based on data in this paper.

unit, a middle sandy interval and an upper thin-bedded interval, recording two distinct cycles of deepening and shallowing of a lacustrine basin. The outcrops at St. George, Utah, display a similar vertical organization (Kirkland and Milner, 2006). The measured section for Potter Canyon (Figs. 1 and 3) is at a south-facing promontory in Mohave County in northern Arizona at 36° 52.872′ N, 112° 52.083′ W, about 3.9 km WNW of the Whitmore Point type location (Tanner and Lucas, 2009, 2010). A distinct change in color of the rocks, from the orange-reddish mudstone and very fine-grained sandstone of the Dinosaur Canyon Member to grayish and purple red hues, and an increased proportion of mudstone in the Whitmore Point Member, delineate the boundary between the Dinosaur Canyon Member and the overlying Whitmore Point Member. The Whitmore Point Member at Potter Canyon consists of 26.2 m of gray, purple, reddish-brown and ocher-hued shale, siltstone and sandstone capped by 1.8 m of lenticular bodies of fine-grained sandstone displaying trough cross-bedding and containing discontinuous (laterally truncated) lenses of mudstone. We assign the upper sandstones to the Moenave Formation, as they resemble sandstones that occur in the strata underlying the Whitmore Point Member, and are unlike the coarse-grained sandstones and intraformational conglomerates that occur immediately above, which we assign to the Springdale Sandstone Member of the Kayenta Formation (Fig. 2).

The Whitmore Point Member at Potter Canyon consists of shale, mudstone and siltstone beds that are decimeters to meters thick and exhibit lateral continuity on outcrop scale (up to hundreds of meters). Shale and mudstone beds are 20 cm to 2.6 m thick, black to reddish purple, and locally contain conchostracans, fish scales and coprolites. These beds commonly contain thin (cm-scale), interbedded laminae of rippled, very fine-grained sandstone or siltstone and are interbedded with siltstone and very fine-grained sandstone beds that are

up to 1.8 m thick, brown to gray to ocher-hued and blocky to ripple-laminated. Tanner and Lucas (2010) determined that these strata were deposited in a mosaic of shallow, perennial meromictic to ephemeral lakes and dry mudflats on the terminal floodout of the northward-flowing Moenave stream system. The lakes were small, as indicated by the limited evidence of shoreline features and for the growth of deltas, but high productivity and possible salinity stratification allowed preservation of organic-rich facies during highstand intervals. Changes in base level, likely forced by climate change, forced the variations between mudflat and lacustrine conditions (Tanner and Lucas, 2010).

3. Biostratigraphy

3.1. Palynostratigraphy

3.1.1. Moenave palynology

The Moenave Formation was long considered to be of Jurassic age primarily based on palynomorphs from a single black shale bed in the Potter Canyon section (Figs. 3 and 4). Thus, Cornet (in Peterson and Pipiringos, 1979, p. B31; also see Peterson et al., 1977) reported a *Classopollis*-dominated assemblage from the lower part of the Whitmore Point Member (see our Potter Canyon section: Figs. 3 and 4) and assigned it an Early Jurassic age. Litwin (1986) described similar palynomorph assemblages from the upper part of the Dinosaur Canyon Member near Kanab, Utah, where the Whitmore Point Member is not present. Cornet and Waanders (2006) documented the Potter Canyon palynological assemblage and re-evaluated Litwin's (1986) identifications to conclude that all Moenave palynological assemblages are of Early Jurassic age. Furthermore, Cornet and Waanders (2006) identified *Classopollis torosus* in the Moenave palynomorph assemblage, and thus correlated it to the Portland Formation of the Newark Supergroup, strata of likely late Hettangian age (Kent and Olsen, 2008).

Kürschner and Batenburg (W. Kürschner, pers. comm.) recently re-examined the palynofloral record of the Moenave Formation. They found the Dinosaur Canyon Member largely barren, but described a diverse assemblage from dark gray to black mudstones in the lower third of the Whitmore Point Member at Potter Canyon. In contrast to earlier reports, they found *Classopollis torosus* to be rare. Most of the specimens Cornet and Waanders (2006) identified as *C. torosus* are described as a morphotype without striation. Striation, however, is the key feature of *C. torosus*, whereas *Classopollis meyerianus* lacks striation (see Cirilli, 2010: Fig. 12 for illustrations of the different species of *Classopollis*). Thus, the identification of *C. torosus* in the Moenave assemblage is largely incorrect, and these palynomorphs should be assigned to *C. meyerianus*. Kürschner and Batenburg (W. Kürschner, pers. comm.) described an assemblage dominated by pollen of the *Circumpollis* group, mainly *C. meyerianus*, but also *C. murphyi*. Other elements in the pollen assemblage present in very low numbers include bisaccates such as *Alisporites* spp., *Pytiosporites* sp., *Araucariacites punctatus*, *A. fissus*, *A. australis*, *Cycadopites deterius*, *C. jansonii*, *Camerosporites reductiverrucatus* and *Cerebropollenites macroverrucosus*. The Moenave assemblage is thus dominated by *Classopollis meyerianus*, but also yields other much less common palynomorph taxa, none of which are, by themselves, demonstrative of a Triassic or a Jurassic age. Indeed, assemblages dominated by *C. meyerianus* are found in both Upper Triassic (Rhaetian) and Lower Jurassic (Hettangian) strata, and are often indicative of arid paleoenvironments, so they do not provide a precise age within the TJB interval (Lucas and Tanner, 2007b).

3.1.2. Comparison to other sections

At many of the TJB sections in the Northern Calcareous Alps, *C. meyerianus* is recorded in peak abundance in both the (Rhaetian) Eiberg Member of the Kössen Formation and the overlying upper Schattwald Beds of the Tiefengraben Member, Kendelbach Formation
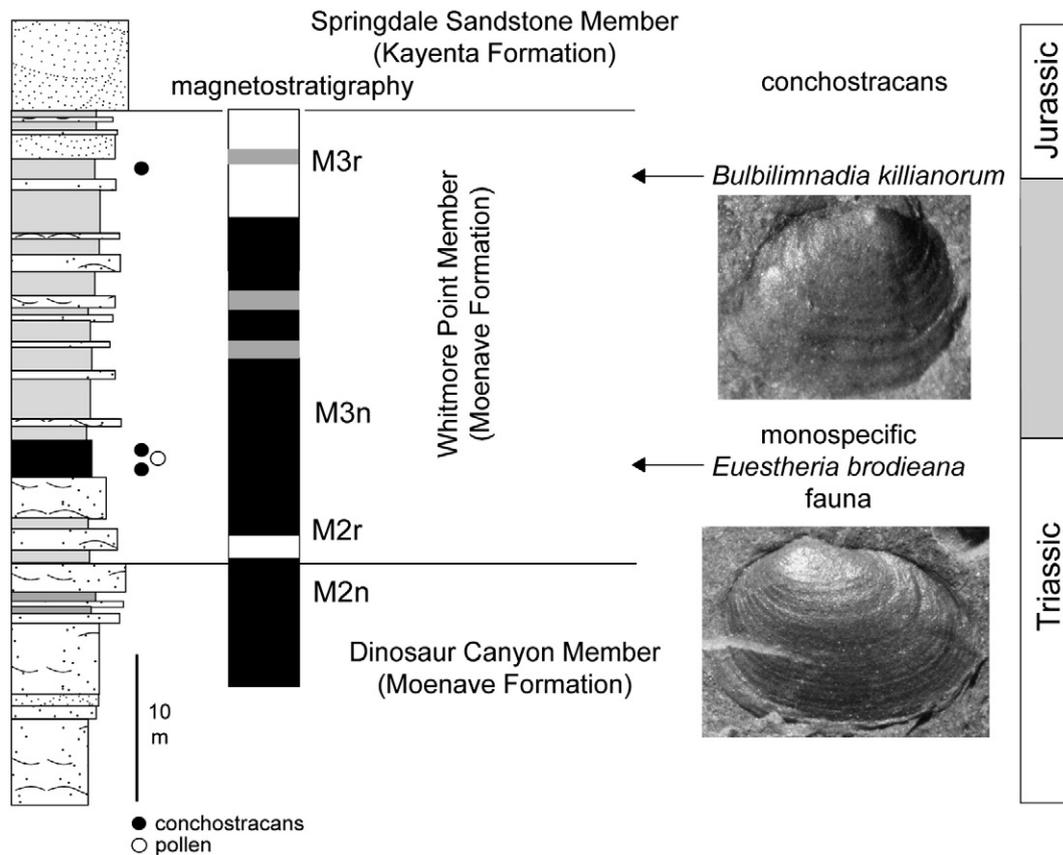
Fig. 3. Stratigraphic section of the Moenave Formation exposed at Potter Canyon showing magnetostratigraphy and distribution of conchostracans. TJB is between Rhaetian record of monospecific *Euestheria brodieana* fauna and lowest occurrence of *Bulbilimnadia killianorum*.

(Kürschner et al., 2007; Bonis et al., 2009). *C. meyerianus* occurs stratigraphically higher in these sections, in strata of the Tiefengraben Member that are of definite Hettangian age, but the abundance is less than in the underlying Rhaetian strata. Similarly, at St. Audrie's Bay, *C. meyerianus* displays a peak in the middle of the Lilstock Formation, at a stratigraphic level that correlates with the initial carbon isotope excursion, then decreases sharply upward before reaching dominance at the base of the Blue Lias Formation, well below the TJB (Bonis et al., 2010). Thus, a *C. meyerianus* dominated assemblage is not indicative of a Jurassic age, and in fact is more likely to indicate a latest Triassic age. The Moenave palynomorph assemblages lack taxa considered definitive of Late Triassic assemblages, such as *Ovalipollis ovalis*, *Vallasporites ignacii*, or *Patinasporites densus*, although, in the Germanic Basin, *P. densus* has its highest occurrence in the lower Rhaetian (Schulz and Heunisch, 2005), nor are there palynomorph taxa present that are unambiguously demonstrative of an Early Jurassic age, such as *Cerebropollenites thiergartii* (cf. Cirilli et al., 2009). We thus conclude that the palynomorphs from the Whitmore Point Member, considered in isolation from other data, most likely identify a latest Triassic age, but an earliest Jurassic age is not excluded.

For decades, the TJB in the terrestrial succession of the Newark Supergroup of eastern North America was placed at a stratigraphic level that coincides with a modest palynological turnover one precession cycle (~20 ka) beneath the lowest basalt flow of the CAMP (e.g., the Orange Mt. Basalt in the Newark basin, Mt. Zion Church Basalt in the Culpeper basin, or the North Mountain Basalt in the Fundy basin) (see reviews in Whiteside et al., 2007; Kozur and Weems, 2010) (Fig. 5). According to numerous studies (reviewed in Whiteside et al., 2007), the system boundary was defined on the basis of the following: (1) last appearances of specific Triassic species (e.g. *Ovalipollis ovalis*, *Vallasporites ignacii*, and *Patinasporites densus*); (2) a dramatic increase in the abundance of "*Corollina*" spp. (= *Classopollis*

and *Gliscopollis*); and (3) a bloom of trilete spores (fern spike), considered as the expression of a palynofloral recovery after the end-Triassic mass extinction. Consequently, all the strata immediately below, overlying and interlayered with the CAMP lava flows have been assigned to the Jurassic, and the ages of the oldest CAMP basalts have been considered to be earliest Jurassic. Calculations based on the cyclostratigraphy of the Newark basin strata were interpreted to suggest that the onset of CAMP volcanism postdates the putative system boundary in the Newark basin by about 20 to 40 ka, and that the entire basalt succession in these basins should have then been erupted during the earliest Jurassic during normal polarity chron E24n (e.g., Kent and Olsen, 2000, 2008) (Fig. 5).

Cirilli et al. (2009) re-examined the palynology of the Newark succession exposed in the Fundy basin. At Partridge Island, the palynological content of the terrestrial Blomidon Formation, which lies below the North Mountain Basalt, is characterized by the dominance of circumpolles group species, represented in order of decreasing abundance by *Classopollis meyerianus*, *Corollina murphyae*, *Classopollis torosus* and *Corollina simplex*. The total abundance of the circumpolles group varies slightly through the section, decreasing with the decrease of total organic matter due to poor preservation, but the sporomorph group crosses the putative boundary established previously (Whiteside et al., 2007) without a marked change in content. *Patinosporites densus* is present from the lowermost sampled level of the section up to the presumed system boundary. Among bisaccates, *Alisporites parvus*, *A. tenuicorpis* and *Ovalipollis septimus* are generally quite common. Most notably, the Scots Bay Member of the McCoy Brook Formation, which overlies the North Mountain Basalt in the Fundy basin, yielded a palynological assemblage of similar diversity and structure as is found in the Schattwald Beds of the basal Kendelbach Formation in the Northern Calcareous Alps (Bonis et al., 2009). This assemblage is dominated by bisaccate pollen (e.g.,
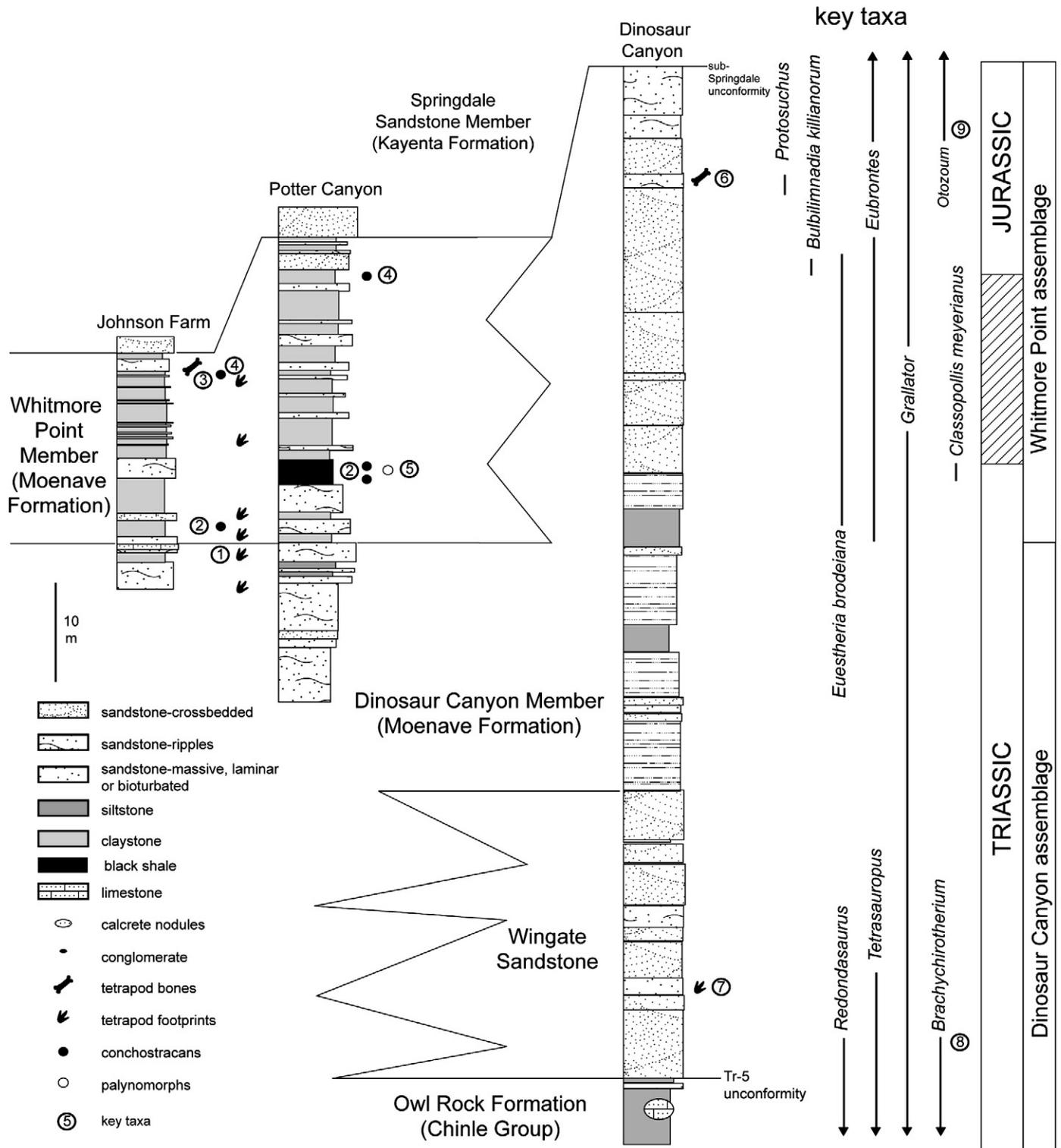
Fig. 4. Biostratigraphy of the Moenave Formation across the Triassic–Jurassic boundary showing distribution of key taxa of palynomorphs, conchostracans and vertebrates (body fossils and footprints). Key taxa indicated by numbers are: 1 = lowest occurrence of *Eubrontes*, 2 = monospecific *Euestheria brodieana* fauna; 3 = indeterminate theropod; 4 = *Bulbilimnadia killianorum*; 5 = *Classopollis*-dominated pollen assemblage; 6 = *Protosuchus*; 7 = *Eosauropus*; 8 = stratigraphically highest *Brachychirotherium* (in basal Wingate Sandstone: Lockley et al., 2004); and 9 = stratigraphically lowest *Otozoum* (in upper Wingate Sandstone: Lockley et al., 2004).

Lunatisporites acutus, *L. rhaeticus*, *Lueckisporites* sp., *A. parvus*, *Klausipollenites* sp., and *Platysaccus* sp.) in association with *Calamospora mesozoica* and minor amounts of *Classopollis meyerianus* and *C. torosus*. Thus, the circumpolles group is less abundant than in the underlying Blomidon Formation. These data indicate unequivocally that strata of Late Triassic age overlie the North Mountain Basalt in the Fundy basin, so they are younger than the estimated numerical age of

that basalt, which is provided by a high precision U–Pb zircon age of 201.27 ± 0.03 Ma (Schoene et al., 2006) that has subsequently been refined to be 201.38 ± 0.02 Ma (Schoene et al. 2010) (Fig. 6). Similarly, Marzoli et al. (2004) published a comprehensive set of isotopic age determinations and magnetostratigraphic and palynostratigraphic data for the CAMP basalt interval in the High Atlas of Morocco. These authors also found a Triassic palynomorph assemblage including *P. densus* that
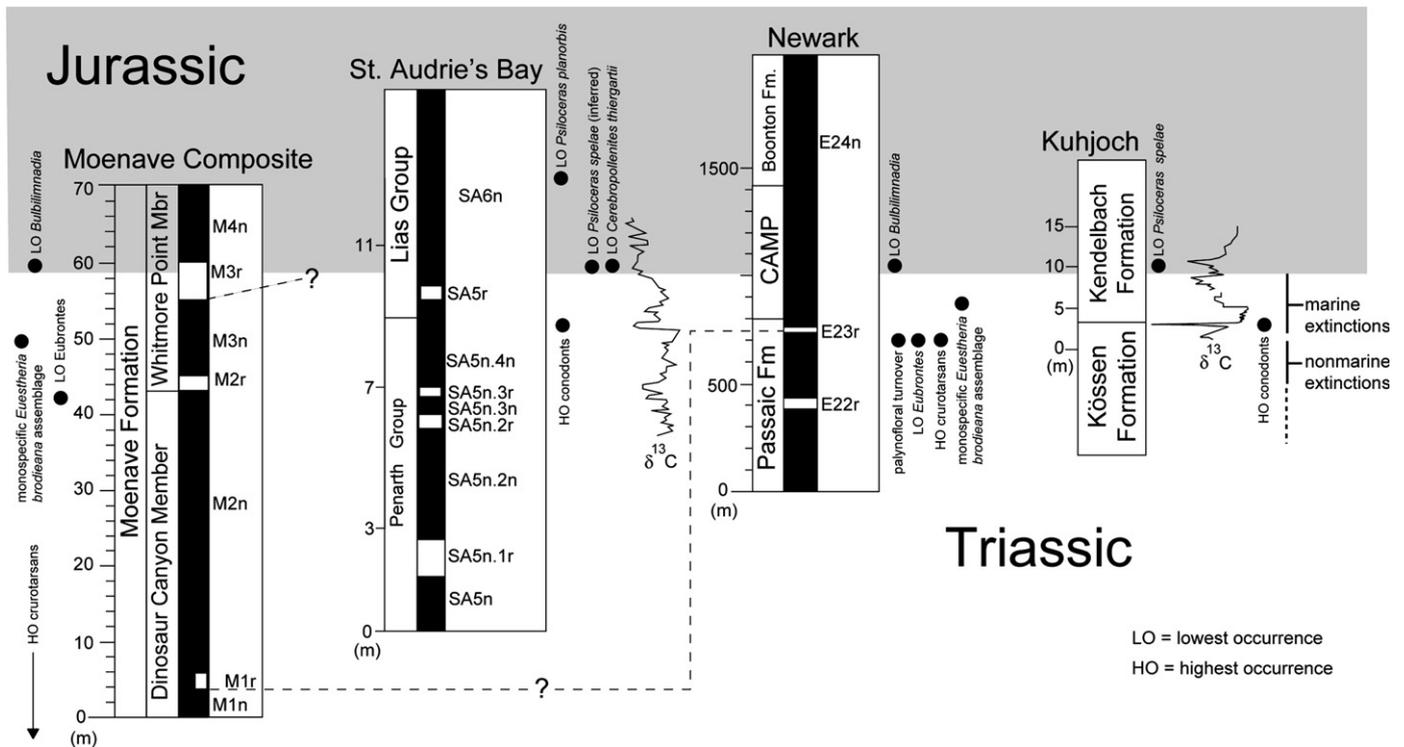
Fig. 5. Correlation of the composite Moenave Formation magnetostratigraphy (modified from Donohoo-Hurley et al., 2010) to St. Audrie's Bay, England, the Newark basin, USA and Kuhjoch, Austria. Key biostratigraphic indicators for all sections are presented, as is carbon-isotope stratigraphy for St Audrie's Bay and Kuhjoch (Austria). Kuhjoch section lacks a magnetostratigraphic record but is the GSSP for the base of the Jurassic (see Von Hillebrandt et al., 2007). See text for discussion.

persisted up to the base of the CAMP basalt sequence and thus concluded that the TJB must lie above the base of the CAMP in Morocco.

3.2. Conchostracan biostratigraphy

Conchostracans are bivalved crustaceans that live in freshwater lakes and ponds. Their minute, drought-resistant eggs can be dispersed by the wind, and this guaranteed some conchostracan taxa a broad geographic range across much of Triassic–Jurassic Pangea. Recently, Kozur and Weems (2005, 2007, 2010) have developed a conchostracan biostratigraphy for Europe and North America that can be used to identify the TJB based on distinctive conchostracan taxa.

The Dinosaur Canyon Member of the Moenave Formation has yielded no conchostracans, but they are known from the Whitmore Point Member (Wilson, 1967; Lucas and Milner, 2006; Kozur and Weems, 2010). Critical are collections made by Andrew Milner at Johnson Farm (Lucas and Milner, 2006) and collections made by us and W. M. Kürschner at Potter Canyon (Kozur and Weems, 2010) (Figs. 3 and 4). Lucas and Milner (2006) documented specimens of *Euestheria brodieana* (Jones) from the lower part of the Whitmore Point Member at Johnson Farm. Specimens from the upper part of the Whitmore Point Member at Johnson Farm collected by Milner are mainly *E. brodieana*, but also include a few *Bulbilimnadia killianorum* Kozur, Weems and Lucas (Kozur and Weems, 2010).

The collections from Potter Canyon show a similar stratigraphic distribution (Fig. 3). Thus, an assemblage collected stratigraphically low in the Whitmore Point Member at Potter Canyon encompasses more than 400 well-preserved conchostracan specimens that all belong to *Euestheria brodieana*; no specimens of *Bulbilimnadia killianorum* are present. Conversely, a remarkably well-preserved conchostracan assemblage from the upper part of the Whitmore Point Member is dominated by *E. brodieana* but also has common *B. killianorum* (Kozur and Weems, 2010).

A monospecific *Euestheria brodieana* assemblage is characteristic of the upper Rhaetian, upper *E. brodieana* conchostracan zone (Kozur and Weems, 2005, 2007, 2010). The co-occurrence of *E. brodieana* and *Bulbilimnadia killianorum* in the upper part of the Whitmore Point Member is indicative of the *B. killianorum* conchostracan zone of earliest Hettangian (earliest Jurassic) age. This co-occurrence is also known from Lower Jurassic strata in Poland (lower Hettangian Sołtyków exposure, Holy Cross Mountains) and in strata of the Newark Supergroup, (i.e. in the middle third of the Midland Formation above the demonstrably Rhaetian strata of this formation that overlie the Mt. Zion Basalt in the Culpeper basin in Virginia, USA) (Kozur and Weems, 2010). Thus, conchostracan biostratigraphy indicates that the Triassic–Jurassic boundary lies within the Whitmore Point Member, in the ~20 m thick interval between the two conchostracan levels at Potter Canyon (Fig. 3).

Of particular importance to this conclusion is the fact that *Bulbilimnadia killianorum* has not been found anywhere in demonstrably Rhaetian strata, i.e., it is not present in the uppermost Rhaetian strata of either the Germanic Basin or England (Kozur and Weems, 2010). Latest Rhaetian conodonts (which include *Misikella posthernsteini* Kozur and Mock) are present in England at the stratigraphic level where a monospecific *E. brodieana* fauna occurs in the absence of *B. killianorum*, and this level is below the equivalents of the marine *Psiloceras spelae* Zone (not present in England but correlated by carbon isotope trends), which defines the base of the Jurassic (Kozur and Weems, 2010). This suggests that, in continental beds, the *B. killianorum* Zone is not older than the TJB and, indeed, the base of the zone may closely coincide with the TJB.

Studies of conchostracan biostratigraphy in the Newark Supergroup (Kozur and Weems, 2005, 2007) have demonstrated that the oldest lava flow of the CAMP volcanism in the Newark Supergroup belongs to the late Rhaetian and that only the second and third lava flows are of Hettangian age. The results of Cirilli et al. (2009) confirmed the results of Kozur and Weems (2005, 2007) (Fig. 5). Notably, the former authors assumed that the entire CAMP is

Rhaetian. However, in the Fundy basin, the only CAMP extrusive unit is the North Mountain Basalt; although this unit comprises three individual flow units, there are no intervening sedimentary strata, and the entire basalt sequence correlates geochemically with the basal CAMP units in other Newark Supergroup basins. The Rhaetian sporomorph age immediately above the North Mountain Basalt (Cirilli et al., 2009) therefore may correspond to the late Rhaetian conchostracan age in strata immediately above the oldest CAMP lava flow of the Newark Supergroup elsewhere (Kozur and Weems, 2005, 2007, 2010). The numerical age of the TJB has been recalibrated; Schaltegger et al. (2008) measured an age of 201.58 ± 0.17/0.28 Ma, slightly older than the age of 201.31 ± 0.18/0.38/0.43 Ma estimated more recently for the TJB in the Pucara basin, northern Peru, by Schoene et al. (2010). These dates are in general compatible with the latest Rhaetian age of the oldest CAMP lava flow when the levels of uncertainty in the radioisotopic dates are considered.

Whiteside et al. (2010) recently published composite carbon-isotope curves for terrestrial organic matter from Newark Supergroup strata in the Newark and Hartford basins. They correlated these curves to the isotope data for the St. Audrie's Bay section published by Hesselbo et al. (2002). Although the proposed marker taxon for the base of the Hettangian (the ammonoid *Psiloceras spelae*) does not occur at St. Audrie's Bay (see above), correlation of the position of the system boundary from the GSSP at Kuhjoch based on isotope stratigraphy allows an approximation of this horizon at St. Audrie's Bay and thus in the Newark section (Fig. 5). Therefore, Whiteside et al. (2010) place the base of the Jurassic in the Newark Basin not at the sporomorph turnover (one precession cycle) below the first CAMP lava flow, but in the lower part of the sediments between the first and second CAMP lava flows of the Newark Supergroup. This correlation is fully consistent with the position of the Jurassic base determined by conchostracans (Kozur and Weems, 2005, 2007, 2010).

As described above, Kozur and Weems (2005, 2007, 2010) established a succession of conchostracan zones in the Newark basin and correlated this conchostracan succession to Upper Triassic strata of the Chinle Group in the southwestern USA, the Keuper and early Hettangian of the Germanic Basin, and to Upper Triassic to Jurassic strata in China and Indochina. They placed the base of the Hettangian at the base of their *Bulbilimnadia killianorum Z*one, comprising approximately the middle third of the Midland Formation (above the basal Midland Formation strata of late Rhaetian age) of the Culpeper basin, which lies above the first CAMP flow unit of the Newark Supergroup (Fig. 5). This concurs with the findings of Cirilli et al. (2009) of Rhaetian sporomorphs above the North Mountain Basalt of the Fundy basin, which corresponds to the first CAMP lava flow in other basins with the Newark Supergroup.

3.3. Vertebrate biostratigraphy

Lucas and Tanner (2007a) reviewed the vertebrate biostratigraphy of the Moenave Formation, which we summarize briefly here. They assigned the vertebrate fossils, including the footprints, to two stratigraphically successive assemblages, the Dinosaur Canyon assemblage and the stratigraphically higher Whitmore Point assemblage (also see Lucas et al., 2005) (Fig. 4). For illustrations of the vertebrate taxa and ichnotaxa discussed here, see Lucas and Tanner (2007a) as well as Lucas et al. (2005, 2006, 2010).

The Dinosaur Canyon assemblage encompasses tetrapod fossils from strata of the lower to middle part of the Dinosaur Canyon Member of the Moenave Formation and laterally equivalent strata of the Wingate Sandstone. These strata yield only a sparse tetrapod bone record (one phytosaur skull and some fragmentary coelophysoid dinosaur postcrania), but contain numerous tetrapod footprints. The phytosaur skull, from the lower part of the Wingate Sandstone in the Lisbon Valley of southeastern Utah, belongs to the Apachean index taxon *Redondasaurus* (Lucas et al., 1997). Lucas and Heckert (2001)

reported some fragmentary coelophysoid theropods from the Dinosaur Canyon Member as well. The footprints are of small theropods (*Grallator*), crurotarsans (*Brachychirotherium*), sauropodomorphs (*Eosauropus*) and synapsids. Other than the synapsid tracks, which are numerous and diverse in the Wingate Sandstone in the Gateway area, where they co-occur with abundant *Grallator* tracks (Schultz-Pittman et al., 1996; Lockley et al., 2004), the tetrapod footprints of most of the Dinosaur Canyon assemblage are similar to those found in the Rock Point Formation of the Chinle Group and correlatives (Lucas and Tanner, 2007a; Lucas et al., 2010).

The Whitmore Point assemblage of Lucas and Tanner (2007a) comprises the tetrapod fossil assemblage of the uppermost Dinosaur Canyon Member, the entire Whitmore Point Member of the Moenave Formation and the uppermost Wingate Sandstone (Fig. 4). Fossils were little known in this interval until the discovery in 2000 of the remarkable bone and track sites in the upper Dinosaur Canyon and Whitmore Point members at Johnson Farm near St. George (e.g., Milner et al., 2006). These localities yield plants, vertebrate body fossils and invertebrates, especially conchostracans, semionotid fishes, and theropod dinosaurs. Also significant are skeletons of the small terrestrial crocodylomorph *Protosuchus* from the upper part of the Dinosaur Canyon Member on the Navajo Nation in Arizona (Colbert and Mook, 1951; Crompton and Smith, 1980). The tetrapod footprint record of the Whitmore Point assemblage is dominated by tracks of large theropods (ichnogenus *Eubrontes*) but also includes many small theropod tracks (*Grallator*) and sauropodomorph tracks (including a remarkable trackway of *Otozoum* from the upper Wingate near Gateway, Colorado: Lockley et al., 2004). The most striking difference between the Dinosaur Canyon and Whitmore Point tetrapod assemblages is the complete absence of crurotarsans in the Whitmore Point assemblage, either as body fossils (of phytosaurs, aetosaurs or rauisuchans) or footprints (e.g. *Brachychirotherium*).

There are compelling reasons to assign a Late Triassic age to the Dinosaur Canyon assemblage, including the presence of the phytosaur *Redondasaurus* (no phytosaur is known from Jurassic strata) and the crurotarsan footprint ichnogenus *Brachychirotherium,* which is not known anywhere from Jurassic strata. There are also compelling reasons to assign an earliest Jurassic age to the Whitmore Point assemblage, including: no *bona fide* Triassic index fossils are known from the Whitmore Point assemblage; *Protosuchus* records elsewhere (McCoy Brook Formation in Nova Scotia, upper Elliot Formation in South Africa) are in strata assigned an earliest Jurassic age (Shubin et al., 1994; Lucas and Hancox, 2001; Lucas, 2009); and no *bona fide* *Otozoum* footprints are known from Triassic strata (Rainforth, 2003). We note that although recent reexamination of the Fundy basin palynology by Cirilli et al. (2009) indicates that the basal McCoy Brook Formation strata are of Triassic age, these strata, which lie above the sequence of three CAMP basalt flows, are below the vertebrate-fossil-bearing interval (includes *Protosuchus*) of the formation.

Lucas and Tanner (2007a) placed the TJB at the boundary between the Dinosaur Canyon and the Whitmore Point vertebrate assemblages. However, a more precise assessment indicates that the TJB could be within the stratigraphic interval that yields the Whitmore Point assemblage. *Bona fide* Jurassic vertebrate fossils – the crocodylomorph *Protosuchus* and the footprint *Otozoum* – have their lowest occurrence stratigraphically high in the Moenave-Wingate stratigraphic interval, well above the base of the Whitmore Point assemblage (Fig. 4). Fossils that occur stratigraphically lower in this interval, including indeterminate theropod dinosaur bones and teeth, and the footprint ichnogenera *Grallator* and *Eubrontes*, are not definitive of either Triassic or Jurassic age. Particularly important is the stratigraphic distribution of *Eubrontes*, which has its lowest occurrence in the Moenave Formation at the top of the Dinosaur Canyon Member, just below the base of the Whitmore Point Member. Importantly, we note the placement of the Johnson Farm tracksite, in Whitmore Point strata, in the (Rhaetian) *E. brodieana* conchostracan zone of Kozur and

Weems (2010). Long considered by some to have its lowest occurrence at the base of the Jurassic (e.g., Olsen et al., 2002), *Eubrontes* is now recognized as having numerous Late Triassic records (Lucas et al., 2006).

The stratigraphically highest *bona fide* Triassic vertebrate fossils on the southern Colorado Plateau (the phytosaur *Redondasaurus* and the footprint ichnogenus *Brachychirotherium*) are in the basal Wingate and lower Moenave strata within the Apachean-age Dinosaur Canyon assemblage (Fig. 4). Therefore, a TJB based solely on conservative vertebrate biostratigraphy is loosely constrained as being in the lower or middle Whitmore Point assemblage interval, above the Johnson Farm locality, which is consistent with placement of the TJB in the middle part of the Whitmore Point Member as suggested by the conchostracan biostratigraphy (Fig. 4).

4. Magnetostratigraphy

Diverse documentation of the geomagnetic polarity record across the TJB indicates that polarity during this time interval (late Rhaetian–early Hettangian) was mostly normal (e.g., Channell et al., 2003; Molina-Garza et al., 2003; Hounslow et al., 2004; Gallet et al., 2007; Kent and Olsen, 2008; Donohoo-Hurley et al., 2010; Hounslow and Muttoni, 2010; Muttoni et al., 2010; Whiteside et al., 2010). Within this pattern of dominant normal polarity (a normal polarity multichron *sensu* Lucas, 2010), individual sections typically yield between two and four reverse polarity magnetozones that are inferred to be of very short duration (i.e., less than a few tens of ka). One-to-one matching of these reverse polarity magnetozones is the only way to achieve precise magnetostratigraphic correlations across the TJB, but such efforts are highly problematic due to depositional hiatuses as well as inter- and intrabasinal variations in sedimentation rates.

4.1. Correlation to St. Audrie's Bay

Magnetostratigraphy of the Moenave Formation developed by Donohoo-Hurley et al. (2010) indicates that the Moenave polarity record is characterized by mostly normal polarity, interrupted by three reverse polarity magnetozones (Fig. 5). Donohoo-Hurley et al. (2010) presented a detailed discussion of the correlation of the Moenave Formation magnetic polarity record to published records in the Newark Supergroup, United States, United Kingdom, Italy, Morocco and Turkey. The correlation between the Moenave Formation and the stratigraphic succession at St. Audrie's Bay, UK (Hounslow et al., 2004) is considered particularly critical for comparing the relative timing of T–J boundary events recorded in both marine and nonmarine strata. However, the new biostratigraphic data reviewed here contradict some of the magnetostratigraphic correlations of Donohoo-Hurley et al. (2010), so we present a revised correlation among the Moenave Formation, St. Audrie's Bay, and Newark Basin records based on the most recent biostratigraphic constraints (Fig. 5).

The Moenave Formation has three reverse magnetozones, one very well defined (M3r) and two less well defined (M1r and M2r) (Fig. 5) (Donohoo-Hurley et al., 2010). M1r and M2r are in strata that are of Late Triassic age, as indicated by biostratigraphy; M2r is in close stratigraphic proximity to the monospecific *E. brodieana* (Rhaetian) conchostracan assemblage, and M1r is stratigraphically well below these Rhaetian conchostracans. Late Norian conchostracans are known from the Rock Point Formation of the Chinle Group in north-central New Mexico (Rinehart et al., 2009), strata that are in part correlative to the lower Dinosaur Canyon Member of the Moenave Formation (Lucas and Tanner, 2007a). This suggests that M1r is in strata of late Norian age, but a precise age assignment remains tentative. At St. Audrie's Bay, by contrast, all of the short reverse magnetozones are of Late Triassic (Rhaetian) age. Thus, it is possible that M1r in the Moenave record predates all of the short reversals at St. Audrie's Bay (Fig. 5). The interval of time characterized by reverse

polarity magnetozone M2r of the Moenave Formation then could correlate to any of the intervals of time represented by reverse magnetozones SA5n.1r, SA5n.2r, SA5n.3r or Sa5r of the St. Audrie's Bay record, as all four magnetozones lie in strata of Rhaetian age. Conversely, much of the Norian section at St. Audrie's Bay (in the Mercia Mudstone Group) is dominantly reversed polarity (SA4r), but the Dinosaur Canyon Member is dominantly normal polarity. Therefore, M1r may instead record an early Rhaetian event that correlates with SA5n.1r.

Donohoo-Hurley et al. (2010) concluded that the well-defined magnetozone M3r correlates with magnetozone SA5r, which occurs below the TJB. However, the new conchostracan data described above demonstrate that the M3r reversal occurs within the *B. killianorum* zone, and thus is wholly or at least in part of basal Hettangian age, whereas the SA5r magnetozone is well below (by several meters) the TJB at St. Audrie's Bay (Fig. 5). Thus, we no longer consider the correlation proposed by Donohoo-Hurley et al. (2010) to be tenable, and it seems likely that M3r is equivalent to some part of SA6n at St. Audrie's Bay. Indeed, any magnetostratigraphic correlations between the Moenave and St. Audrie's Bay sections should be considered tentative due to the condensation of the St. Audrie's Bay section; the interval from the base of M1r to the top of M3r comprising almost 60 m of Moenave strata, may be equivalent to only 10(?) m of strata at St. Audrie's Bay that occur between the base of SA5n.1r and the top of SA5r.

Isotope stratigraphy of the relevant marine sections may help refine the magnetostratigraphy of the TJB interval. The initial negative excursion of carbon isotopes at St. Audrie's Bay is a latest Triassic shift that occurs within magnetozone SA5n.4n. In all marine sections where the initial isotope excursion has been measured, it occurs below the last conodont occurrence (Fig. 5). For example, the excursion at Csővár, Hungary correlates to a level 0.5–2 m below the top of the *Misikella ultima* conodont zone (Korte and Kozur, 2011). At St. Audrie's Bay, the main negative carbon isotope excursion, which encompasses the TJB, occurs ~6 m above the initial excursion in strata characterized by magnetozone SA5n, so the TJB is stratigraphically well above reverse magnetozone SA5r (Hesselbo et al., 2002). The base of the "main" negative isotope excursion at St. Audrie's Bay is about 2 m below the first appearance of clearly Jurassic palynomorphs (*Cerebropollenites thiergartii*) and is 2.5 m below the FAD of *P. planorbis* (*P. spelae* is not found at St. Audrie's Bay but its stratigraphic position can be inferred) (Fig. 5). Thus, the top of the SA5r reversal is located below the base of the TJB at St. Audrie's Bay, as defined by palynostratigraphy or chemostratigraphy. Because the earliest Hettangian *B. killianorum* conchostracan fauna at Potter Canyon occurs in the middle part of beds that belong to reverse polarity magnetozone M3r (Fig. 3), the TJB must occur within or below magnetozone M3r in the Moenave Formation. This implies that there is no equivalent reverse polarity chron recorded at St. Audrie's Bay (Fig. 5). Thus, either the relatively long M3r of the Potter Canyon section is entirely younger than the very short SA5r, or the lower part of M3r correlates with SA5r and the upper part of M3r cannot be correlated. We consider the latter option less likely; because a part of SA6n of Rhaetian age occurs above SA5r and below the TJB, for the lower part of M3r to be Triassic and the upper part to be Jurassic would require an unseen disconformity within the reverse polarity interval.

4.2. Correlation to the Newark basin

Hounslow et al. (2004) attempted a magnetostratigraphic correlation between the Newark record and the Upper Triassic–Lower Jurassic continental, brackish and marine section at St. Audrie's Bay, England, where the system boundary is above the Penarth Group (Fig. 5). They suggested that either their SA5r reverse polarity magnetozone, which is the stratigraphically highest short reverse polarity interval in the lower part of the Lias Group, or one of the

stratigraphically lower reverse magnetozones, SA5n.3r or SA5n.2r, must correlate to the short E23r reverse magnetozone that lies immediately below the palynofloral turnover event in the Newark section. These correlations imply that the E23r reverse magnetozone is older than the currently proposed definition of the Hettangian base in the marine realm (lowest occurrence of *Psiloceras spelae*), and correlation of the E23r reverse magnetozone to the two lower reverse magnetozones at St. Audrie's Bay would make magnetozone E23r older than the stratigraphically highest conodonts (Fig. 5). Whiteside et al. (2007) similarly correlated the E23r reverse magnetozone to one of the brief reverse magnetozones (chrons SA5n.3r and SA5r) of the St. Audrie's Bay section. Kozur and Weems (2005), however, demonstrated that E23r lies at a level with the youngest Norian conchostracans in the Newark Supergroup (e.g. Gallet et al., 2007; Muttoni et al., 2010). A solution to this problem is proposed by Whiteside et al. (2010), who assumed that the equivalent of reverse polarity magnetozone SA5r should be present in the Newark sediments above the oldest CAMP lava flow but has been missed in the initial sampling of this succession. We agree with this assumption because it is supported by the conchostracan correlation and the correlation of the carbon isotope chemostratigraphy. Ongoing development of the magnetostratigraphy of marine strata in Austria and Italy (e.g., Gallet et al., 2007; Muttoni et al., 2010) will provide better constraints on Rhaetian magnetostratigraphic correlations once a consistent and well-correlated marine Rhaetian magnetostratigraphic record is completed.

In the Newark basin, reverse magnetozones E22r and E23r are in Upper Triassic strata, below the oldest CAMP flow. In particular, E23r lies within the *Shipingia olseni* Zone that is determined to be of late Norian (Sevatian) age (Kozur and Weems, 2007, 2010). Donohoo-Hurley et al. (2010) tentatively correlated reverse polarity magnetozone M2r of the Moenave Formation to reverse polarity magnetozone E23r of the Newark record. However, this correlation contradicts the conchostracan biostratigraphy because E23r belongs to the late Norian *Shipingia olseni* conchostracan Zone, whereas M2r lies immediately below the late Rhaetian monospecific *Euestheria brodieana* fauna of the upper *E. brodieana* Zone in the lower Whitmore Point Member (Kozur and Weems, 2010). Therefore, the interval of time represented by reverse polarity magnetozone E23r of the Newark record may instead correlate with the less well-defined M1r interval of the lower Dinosaur Canyon Member of the Moenave Formation (Fig. 5). Significantly, no obvious correlation exists between the Moenave and the Newark magnetostratigraphy beyond the possible correlation of M1r to E23r (Fig. 5). Because M3r of the Moenave record appears to occur at or somewhat above the TJB, this reverse polarity magnetozone does not correlate with any specific magnetozone of the Newark polarity record. In addition, the three reverse polarity magnetozones (H24r, H25r, and H26r) reported by Kent and Olsen (2008) from the Lower Jurassic Portland Formation (Hartford basin) are in strata that are clearly younger than the Whitmore Point Member of the Moenave Formation.

The uppermost Whitmore Point strata, within reverse polarity magnetozone M3r, contain an earliest Jurassic conchostracan fauna characterized by *Bulbilimnadia killianorum,* as do strata of the middle Midland Formation (above the upper Rhaetian basal Midland Formation) in the Culpeper basin, which are correlated with beds in the Newark basin that belong to normal polarity magnetozone E24n (Kent and Olsen, 2000; Kozur and Weems, 2010). Nevertheless, it is difficult to compare the thickness of a similar time interval of Moenave strata with Newark rift basin strata as well as with marine strata (e.g., St. Audrie's Bay) because sedimentation rates differ greatly, and also due to the possibility, based on conchostracan biostratigraphy, that part of the Rhaetian is missing in the Newark section (Kozur and Weems, 2010). This comparison is also hindered by the absence of an earliest Jurassic reverse polarity magnetozone in the Newark record. As the level of E23r has the youngest Sevatian conchostracan fauna of the Newark Supergroup, all of the youngest

Rhaetian reversed magnetozones observed at St. Audrie's Bay seem to be absent in the Newark Supergroup, consistent with a Rhaetian gap in the Newark of unknown duration (Kozur and Weems, 2005, 2007, 2010) (Fig. 5).

5. Timing of the end-Triassic vertebrate extinctions

Placement of the TJB in the strata of the Colorado Plateau allows effective correlation of the system boundary between fossiliferous marine and nonmarine strata for the first time (Fig. 6). Consequently, the temporal relationship between biotic events on land and in the oceans at and around the TJB can now be demonstrated. No substantial turnover of the global flora has been demonstrated at the TJB (e.g., Lucas and Tanner, 2008; Kürschner and Herngreen, 2010). Regional perturbations of the flora, based on palynostratigraphy, either predate CAMP eruptions (Newark: Lucas and Tanner, 2007b) or, in Germany, may be co-eval with and influenced by CAMP eruptions (Van de Schootbrugge et al., 2008, 2009). However, these are not demonstrably global events.

The lack of evidence for crurotarsans above the lower part of the Dinosaur Canyon Member of the Moenave Formation suggests their disappearance from the stratigraphic record during the Norian or early Rhaetian. Notably, this placement is consistent with evidence, primarily from conchostracan biostratigraphy, that most of the Rhaetian stage is missing from the Newark basin. Hence, the abrupt loss of crurotarsans (e.g. the ichnotaxon *Brachychirotherium*) in the Newark Supergroup is an artifact of a substantial unconformity just below the lowest CAMP flows between the Norian and the late Rhaetian. The lowest occurrence of footprints of large theropods (*Eubrontes*) in the Moenave Formation in the Dinosaur Canyon Member is in the vicinity of reverse polarity interval M2r, which is demonstrably Rhaetian (also based on conchostracan zonation) and well below the TJB. Magnetostratigraphic correlation of the Moenave composite section to the record for St. Audrie's Bay indicates that these *Eubrontes*-bearing strata are older than the initial carbon isotope excursion found in the latest Triassic strata at St. Audrie's Bay, where it occurs in magnetozone SA5n.4n. Therefore, both the extinction of crurotarsans and the appearance of large theropods (*Eubrontes*) on land well-preceded the TJB by a sufficient stratigraphic interval to suggest that these events took place before CAMP eruptions, which in turn, slightly preceded (and likely caused) the end-Rhaetian marine extinctions (Fig. 6).

The crurotarsan extinction has long been identified as the principal tetrapod extinction on land at the TJB, which was followed by a rapid rise to dominance of the dinosaurs (e.g., Colbert, 1958; Olsen et al., 2002). The evidence presented here indicates instead that this turnover from a crurotarsan-dominated archosaur fauna to a dinosaur-dominated archosaur fauna took place within the latest Triassic and preceded the eruptions of CAMP, which thus eliminates volcanic activity as a causal factor in these extinctions.

6. Conclusions: position of the TJB on the Colorado Plateau

Conchostracan and vertebrate biostratigraphy support placement of the TJB within the lower to middle Whitmore Point Member of the Moenave Formation. Although they do not provide such direct support, the revised palynostratigraphy of these strata and new magnetostratigraphic correlations are consistent with this age assignment. Therefore, most of the Moenave Formation, ~58 m of section, between the base of the Dinosaur Canyon Member and the middle of the Whitmore Point Member, was deposited during the latest Triassic (Fig. 4), coincident with the local change in facies from the eolian/fluvial Dinosaur Canyon Member to the mostly lacustrine Whitmore Point Member, in response to an inferred rise in local base level (Tanner and Lucas, 2009). The rich fossil assemblage – including *Eubrontes* and *Grallator* dinosaur tracks, theropod dinosaur bones/ teeth, semionotid fish, plant fossils and invertebrates – preserved at
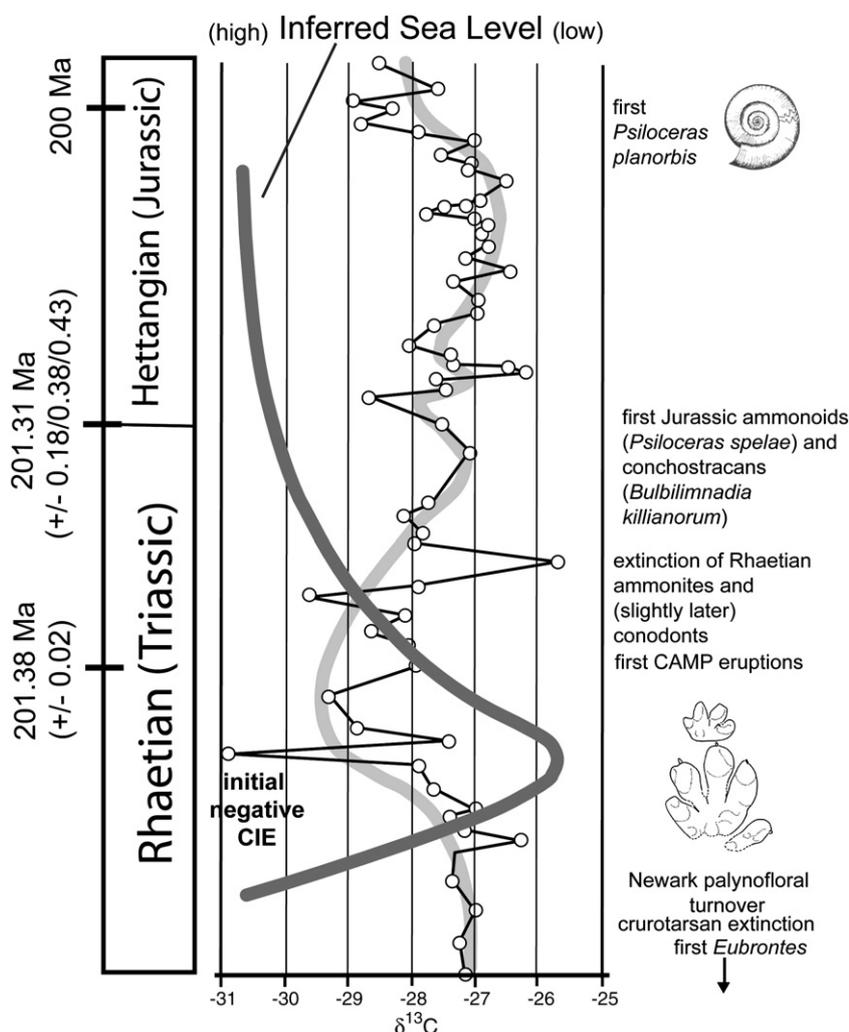
Fig. 6. Sequence of key events across the Triassic–Jurassic boundary. CIE = carbon isotope excursion. Carbon isotope data and inferred sea level curve are based on results from New York Canyon, western Nevada (Guex et al., 2004, 2008). Approximate duration of extinction interval across the Triassic–Jurassic boundary and absolute age determinations of the oldest CAMP volcanism and the TJB are from Schoene et al. (2010).

the Dinosaur Discovery Site at Johnson Farm, in strata about 4 m above the Dinosaur Canyon–Whitmore Point transition, is therefore of latest Triassic age, rather than earliest Jurassic age as previously interpreted by Kirkland et al. (2002), Cornet and Waanders (2006) and Milner et al. (2006).

Acknowledgments

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