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ARIZONA'S JURASSIC FOSSIL VERTEBRATES AND THE AGE OF THE GLEN CANYON GROUP

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Abstract—Most fossil vertebrates of Jurassic age from Arizona are derived from the Glen Canyon Group on the southern Colorado Plateau in the northeastern part of the state. Glen Canyon Group strata of Jurassic age in Arizona that yield fossils include the upper Dinosaur Canyon and the Whitmore Point members of the Moenave Formation, the Kayenta Formation, and the Navajo Sandstone. All of these units yield both trace (principally dinosaur footprint) and body fossils of tetrapods. To date, only the Kayenta Formation fauna is particularly diverse (more than 10 taxa), and the Kayenta fauna is one of the best known Dawan (Early Jurassic: Sinemurian) tetrapod faunas in North America, and includes numerous type specimens, representing important records of tritylodonts, theropod dinosaurs, amphibians, turtles, and mammals. Non-Glen Canyon Group records of Jurassic vertebrates from northern Arizona are limited to scattered occurrences of footprints in the Middle-Upper Jurassic Summerville Formation and a single documented *Apatosaurus* vertebra from the Morrison Formation. The only Jurassic vertebrates from southern Arizona are fragmentary tetrapods from the Gardner Canyon Formation in the Santa Rita Mountains and undescribed osteichthyans from Upper Jurassic marine strata in the Chiricahua Mountains.

Keywords: Early Jurassic, Glen Canyon Group, vertebrate fossils, Kayenta Formation, Moenave Formation, Navajo Sandstone

INTRODUCTION

The Jurassic vertebrate fossil record of Arizona derives primarily from strata of the Glen Canyon Group in the northeastern part of the state (Fig.1; Tables 1-2), so the primary focus of this paper is on their stratigraphic occurrence and age. Other records include: (1) a crocodylomorph and tritylodontid from the Gardner Canyon Formation in the Santa Rita Mountains near Tucson, but this has never been documented other than a brief mention in Tegowski and McCord (1996); (2) a few tetrapod footprints (assigned to theropod dinosaurs and pterosaurs) from the Middle-Upper Jurassic Summerville Formation in northeastern Arizona (Stokes, 1957; Lockley et al., 1996; Lockley and Mickelson, 1997); (3) some undescribed osteichthyans from Upper Jurassic marine strata in the Chiricahua Mountains (Lawton and Olmstead, 1995); and (4) a single caudal vertebra of the diplodocid sauropod Apatosaurus from the Morrison Formation of northern Arizona described by Curtice (1999) and included in Foster's (2003) analysis of Morrison Formation paleoecology. Hereafter, this review focuses on Arizona's vertebrate fossil record of and the age of the Glen Canyon Group.

HISTORY OF STUDY

Fossils from the Glen Canyon Group in Arizona were first reported by Brown (1933) and deposited at the American Museum of Natural History (AMNH) in New York. Later, Brady (1935, 1936) and Camp (1936) reported records that appear to have been recovered as byproducts of Camp's extensive collecting program in the Triassic of Arizona and New Mexico for the University of California Museum of Paleontology (UCMP) at Berkeley. Shortly after this, the AMNH returned to northern Arizona (e.g., Colbert and Mook, 1951), and the UCMP collected additional vertebrates, principally from the Kayenta Formation, both in the middle part of the century (Welles, 1954, 1970, 1984) and later in the 1980s (e.g., Curtis, 1989; Curtis and Padian, 1999). These latter fossils, and

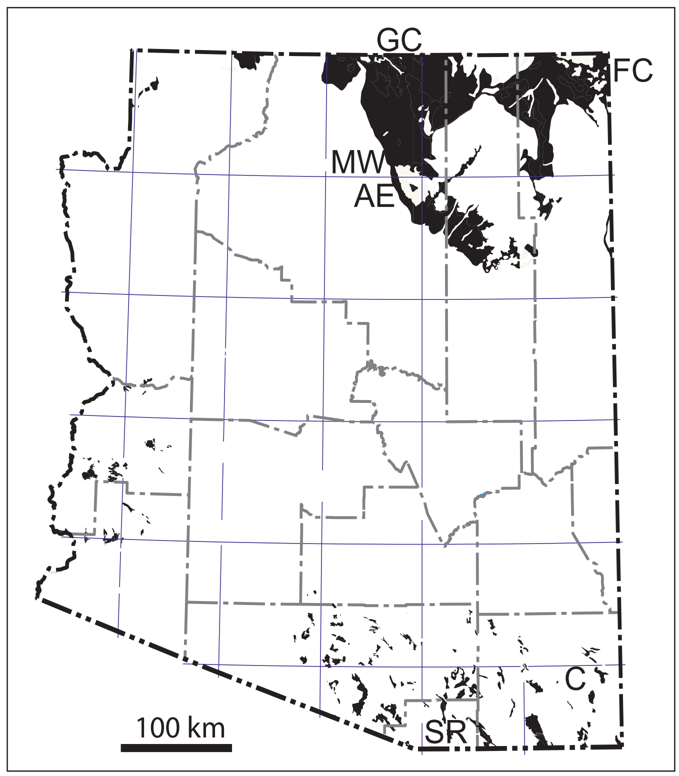

FIGURE 1. Map of Arizona showing distribution of Jurassic strata and Jurassic vertebrate fossil localities. AE = Aedii Eechii Cliffs, C= Chiracahua Mountains, FC = Four Corners, GC = Glen Canyon, MW = Moenkopi Wash, SR = Santa Rita Mountains.

indeed most of the Kayenta Formation fauna collected over this time interval, were reposited at the Museum of Northern Arizona (MNA) in Flagstaff. In addition to the UCMP and MNA collectors,

TABLE 1. Vertebrate taxa from the Glen Canyon Group in Arizona

Moenave Fm (Dinosaur Canyon Mbr)

Protosuchus
Lepidosauria indet.
Megapnosaurus (=*Syntarsus*)

Moenave Fm (Whitmore Point Mbr)

Semionotidae indet.
Reptilia indet.

Kayenta Fm

Chondrichthyes
Hybodontidae indet.
Osteichthyes
Osteichthyes indet.
Amphibia
Prosalirus bitis Shubin and Jenkins
Eocaecilia micropodia Jenkins and Walsh
Anapsida
Kayentachelys aprix Gaffney et al.
Diapsida
Sphenodontidae indet.
Eopneumatosuchus colberti Crompton and Smith
Protosuchus (=*Archaeeosuchus richardsoni* Brown)
Kayentasuchus walkeri Clark and Sues
Rhamphinion jenkinsi Padian
Dilophosaurus wetherilli (Welles)
Syntarsus kayentakatae Rowe
"Shake and Bake Coelophysid"
Massospondylus sp.
Scelidosaurus
Scutellosaurus lawleri Colbert
Synapsida
Kayentatherium wellesi Kermack
Dinneibitodon amarali Sues
Oligokyphus
Dinnetherium nezorum Jenkins et al.

Navajo Sandstone

Tritylodontidae indet.
Protosuchidae indet.
Segisaurus halli Camp
Ammosaurus

Complete binomen including auther = type specimen

the Museum of Comparative Zoology (MCZ) at Harvard has also been active in the area, collecting much from the Kayenta Formation in northeastern Arizona during the 1970s and 1980s. Indeed, the bulk of the body fossil records from the Kayenta Formation are based on the Harvard collections (e.g., Sues, 1983, 1985a,b, 1986a,b,c). Most recently, specimens from a crocodilian locality in the Navajo Sandstone discovered and collected by Gerry Bryant during his master's thesis work are now reposited at the New Mexico Museum of Natural History (NMMNH) (Rinehart et al., 2001).

The bulk of the collecting records listed above are those of body fossils. The history of study of vertebrate trace fossils in the Glen Canyon Group is even more straightforward—with the exception of Brady (1960) and Baird (1980), no workers identified and scientifically described tracks from the Glen Canyon Group until the 1990s. During the 1990s, as part of the general renaissance in dinosaur ichnology, numerous workers described and illustrated tracks and trackways from every formation-rank unit in the Glen Canyon Group (e.g., Irby, 1993a,b, 1995, 1996; Lockley and Hunt, 1995; Bulkley, 1996; Morales, 1996; Nations et al., 1996; Rainforth and Lockley, 1996a,b; Lockley et al., 2004). It is important to note that most of these tracks and tracksites are uncollected, so specimens are not reposited in museums. Indeed, most are on Native American (principally Navajo Nation) lands, so researchers must obtain permission from the relevant authorities to study them.

TABLE 2. Vertebrate ichnogenera from the Glen Canyon Group in Arizona

Moenave Fm (Dinosaur Canyon Mbr)

Eubrontes
Tetrasauropus

Wingate Sandstone (Triassic interval)

Brasilichnium
Tetrasauropus
Grallator

Kayenta Fm

Eubrontes
Grallator

Navajo Sandstone

Brasilichnium
Eubrontes
Tetrasauropus
Otozoum
Anomoepus

LITHOSTRATIGRAPHY

Strata that overlie the Chinle Group in northeastern Arizona have long been assigned to the Glen Canyon Group (Fig. 2) and were typically thought to be of Late Triassic, Triassic-Jurassic or Early Jurassic age (e.g., Averitt et al., 1955; Harshbarger et al., 1957; Pipiringos and O'Sullivan, 1978; Blakey, 1994; Peterson, 1994). These are the (in ascending order) Moenave, Wingate, Kayenta and Navajo formations (Fig. 2). Recent study (e.g., Lucas et al., 1997a,b; Lucas and Heckert, 2001; Tanner et al., 2002; Molina-Garza et al., 2003; Lockley et al., 2004) confirms two important points advocated by some early students of the Glen Canyon Group: (1) the Chinle and Glen Canyon Groups have an interfingering and transitional (not unconformable) contact; and (2) the lower part of the Glen Canyon Group is of latest Triassic age. Current data thus indicate that the Triassic-Jurassic boundary is in a relatively conformable ("continuously" deposited) rock succession within the Moenave and Wingate formations, not at an unconformity at the base of the Glen Canyon Group, as advocated by some workers (e.g., Pipiringos and O'Sullivan, 1978). Our work also confirms the proposal of Marzolf (1994) that the Rock Point, Moenave and Wingate formations together constitute a single, unconformity-bounded tectonosequence.

The Moenave Formation is generally about 100-m thick and consists primarily of fine-grained sandstone, siltstone and shale (Harshbarger et al., 1957; Wilson, 1967; Irby, 1996). The Dinosaur Canyon Member, a succession of brightly colored, reddish orange to light brown fluvial and eolian sandstone and siltstone

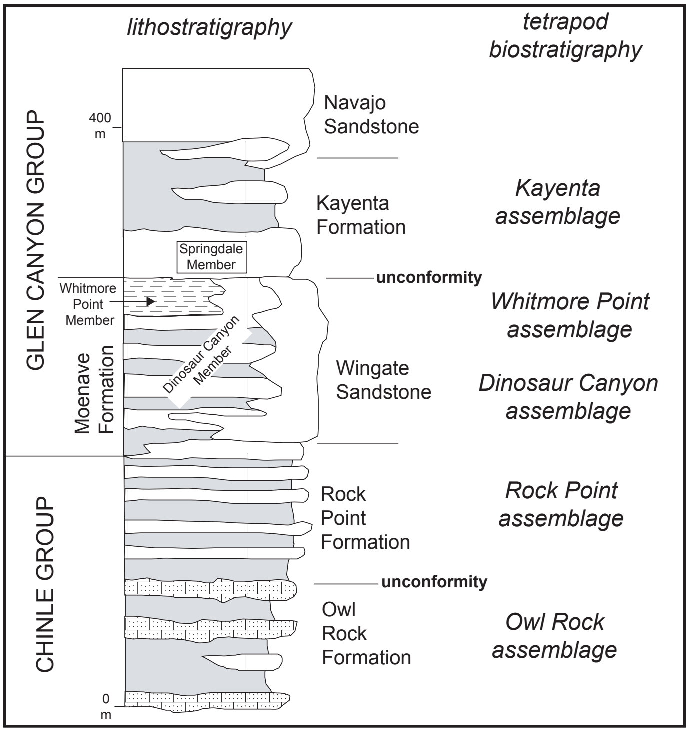

FIGURE 2. Summary of lithostratigraphy of the Glen Canyon Group on the southern Colorado Plateau and the distribution of the biostratigraphic assemblages of tetrapod fossils.

comprises most of the formation thickness. In the Moenave type section, near Tuba City, Arizona, the entire thickness of the Moenave section is Dinosaur Canyon Member, as it is throughout the Moenave outcrop belt along the Echo Cliffs and Ward's Terrace of northeastern Arizona. However, north of the Grand Canyon in Arizona and in southwestern Utah, the upper part of the Moenave Formation consists primarily of strata of lacustrine origin. These strata of the Whitmore Point Member (Wilson, 1967) are gray to red shale and siltstone and minor limestone up to 25-m thick (Fig. 2). The Whitmore Point lacustrine system has been called "Lake Dixie," but the lateral extent of the individual lakes in which the Whitmore Point sediments were deposited is uncertain (Kirkland et al., 2002).

Across its outcrop belt, the Springdale Sandstone disconformably overlies the Moenave Formation (above the Whitmore Point Member north and west of the Grand Canyon, above the Dinosaur Canyon Member to the south and east) (Fig. 2). Originally assigned to the Chinle Formation (Gregory, 1950), the Springdale Sandstone was later included in the Moenave Formation (Harshbarger et al., 1957). However, because of its basal unconformity and lithologic similarity to overlying strata of the Kayenta Formation it is more logical to include the Springdale as the basal member of the Kayenta Formation (Olsen, 1989; Marzolf, 1994; Lucas and Heckert, 2001; Tanner et al., 2002; Tanner and Lucas, in review). The Springdale Sandstone is as much as 32-m thick and consists of medium- to coarse-grained sandstone, conglomerate and minor mudstone lenses. Trough crossbeds and laminar beds of fluvial origin are the common bedforms (e.g., Edwards, 1985; Luttrell and Morales, 1993).

In the Tuba City-St. George area, the Kayenta Formation above the Springdale Sandstone is mostly fine-grained sandstone, siltstone and mudstone deposited in smaller river systems and on floodplains (Luttrell, 1987). However, to the east, the Kayenta becomes more sandstone-rich, and the upper part of the formation is interbedded with eolian facies of the lower part of the Navajo Sandstone (e.g., Harshbarger et al., 1957; Luttrell, 1996). The Kayenta Formation is up to 300 m thick in northern Arizona (Blakey, 1994).

The Navajo Sandstone is a very thick (up to 750 m in northern Arizona: Blakey, 1994) quartzose sandstone unit famous for its spectacular, large scale eolian crossbeds. The lower part of the formation is equivalent to, and indeed intertongues with, the fluvial deposits of the Kayenta Formation, whereas the upper part is almost entirely of eolian origin and represents the uppermost stratigraphic interval of the Glen Canyon Group (Marzolf, 1983; Blakey, 1994). The Middle Jurassic (Bajocian) Carmel Formation disconformably overlies the Navajo Sandstone regionally, and the youngest Navajo strata (Page Member) are laterally equivalent to the Middle Jurassic (Aalenian?) Temple Cap Sandstone to the north (Peterson, 1994; Blakey, 1994; Lucas and Anderson, 1997).

To the east and north of the Moenave outcrop belt, in the Four Corners region, the Wingate Sandstone occupies essentially the same stratigraphic position as the Moenave Formation; the Wingate overlies the Rock Point Formation and is overlain by the Kayenta Formation or younger strata. This suggests at least partial lateral equivalence of the Moenave and Wingate (Harshbarger et al., 1957; Edwards, 1985; Clemmensen et al., 1989; Tanner and Lucas, in review). The Wingate is usually about 100-m-thick and consists almost exclusively of thick beds of eolian sandstone (Harshbarger et al., 1957; Clemmensen et al., 1989). Similar beds of eolian sandstone are found in parts of the Moenave Formation to the west, supporting the concept of the dry eolian system of the Wingate (to the east) being laterally equivalent to the wet eolian system of the Moenave (to the west) (Edwards, 1985; Clemmensen et al., 1989; Blakey, 1994; Tanner and Lucas, in review).

Furthermore, detailed stratigraphic work from southern Utah southward to the edge of the Wingate outcrop belt in west-central New Mexico, confirms that there is no pervasive unconformity at the Wingate base across this region. Instead, Rock Point strata become coarser-grained and display an up-section increase in bed thickness and the size of eolian-style cross-bedding, so that the Wingate base is usually mapped at the base of the stratigraphically lowest eolian sandstone cliff that is 10 or more meters thick. Sandstone beds of similar eolian aspect, but thinner are found throughout the Rock Point section at many localities. Indeed, this is why Harshbarger et al. (1957) did not posit an unconformity at the Wingate base, and included the Rock Point and Lukachukai (current Wingate) members in the same formation.

VERTEBRATE FOSSILS

Moenave Formation

On Ward's Terrace on the Navajo Nation, the Dinosaur Canyon Member of the Moenave Formation has a sparse tetrapod body fossil and footprint record. The body fossils are confined to several occurrences of the crocodylomorph *Protosuchus* (Fig. 3), an undocumented report of a lepidosaur and two incomplete pelves of a theropod dinosaur identified as cf. *Megapnosaurus* (Brown, 1933; Colbert and Mook, 1951; Crompton and Smith, 1980; Clark and Fastovsky, 1986; Lucas and Heckert, 2001). The *Protosuchus* records and the cf. *Megapnosaurus* record are stratigraphically high in the Moenave Formation. Tetrapod footprint records are of the theropod ichnogenus *Eubrontes* and the crocodylomorph ichnogenus *Batrachopus* (Olsen and Padian, 1986; Irby, 1993a,b, 1995, 1996). These records are also stratigraphically high in the Moenave Formation (Lucas et al., 2005).

Near Fredonia, Arizona, north of the Grand Canyon, the Whitmore Point Member of the Moenave Formation yields fragmentary fossils of semionotid fishes and unassigned reptiles (Wilson, 1967; Clark and Fastovsky, 1986). These fossils, however,

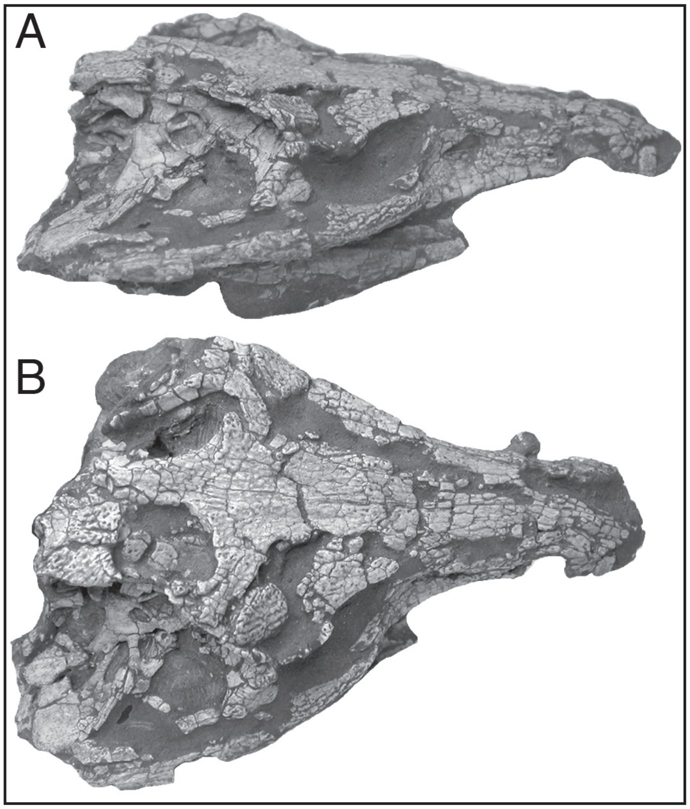

FIGURE 3. Skull of the holotype of *Protosuchus richardsoni* (Brown) in **A**, ventral and **B**, dorsal views. ~0.7 actual size. Photographs by S. Nesbitt.

have not been described in greater detail.

Wingate Sandstone

Tongues of the Wingate Sandstone crop out within the lower part of the Dinosaur Canyon Member of the Moenave Formation on Ward's Terrace. Morales (1996) reported a fossil footprint locality within such a tongue at the mouth of Dinosaur Canyon, and it includes tracks we assign to *Grallator, Tetrasauropus* and cf. *Brasilichnium*. This is a Late Triassic footprint assemblage; no Jurassic age footprints have been reported from the Wingate Sandstone in Arizona, though they are known from the upper Wingate in Colorado (Lockley et al., 2004).

Kayenta Formation

The Kayenta Formation on Ward's Terrace yields both tetrapod footprints and body fossils. The footprints are mostly assigned to the theropod ichnogenera *Eubrontes* and *Grallator* (Lockley and Hunt, 1995). Particularly significant is the relatively thin (< 5 m thick) footprint-bearing interval at the top of the Springdale Member of the Kayenta. This narrow interval yields tracks (mostly of *Eubrontes*: Fig. 4) from St. George, Utah, to Tuba City, Arizona, so we refer to it as the Springdale megatracksite.

Tetrapod body fossils have an extensive record in the Kayenta Formation near Gold Spring, Arizona. The vertebrate fossil assemblage includes hybodont and osteichthyan fishes, a frog (*Prosalirus*), a caecilian (*Eocaecilia*), a turtle (*Kayentachelys*), sphendonts, crocodylomorphs (*Eopneumatosuchus*, *Calsoyasuchus valliceps,* Protosuchidae indet., Sphenosuchidae), a pterosaur (*Rhamphinion*), theropod dinosaurs (*Dilophosaurus*, *Megapnosaurus*, and at least one other ceratosaur), prosauropod dinosaurs (*Massospondylus*), thyreophoran dinosaurs (*Scelidosaurus*, *Scutellosaurus*), a heterodontosaurid, tritylodontid cynodonts (*Kayentatherium*, *Dinnebiton*, *Oligokyphus*), and other cynodonts and mammals (*Dinnetherium* and a haramyid) (Welles, 1954, 1970, 1984; Lewis, 1958; Lewis et al., 1961; Crompton and Smith, 1980; Colbert, 1981, 1986; Kermack, 1982; Sues, 1983, 1985a,b, 1986a, b, c; Jenkins et al., 1983; Padian, 1984, 1989; Attridge et al., 1985; Clark and Fastovsky, 1986; Olsen and Padian, 1986; Gaffney et al., 1987; Meszoely et al., 1987; Curtis, 1989; Rowe, 1989; Rowe and Gauthier, 1990; Sereno, 1991; Jenkins and Walsh, 1993; Sues et al., 1994; Shubin and Jenkins, 1995; Tykoski, 1998, 2005; Tykoski et al., 2002; Curtis and Padian, 1999; Gay, 2001).

FIGURE 4. Track of the theropod ichnogenus *Eubrontes* on top of the Springdale Sandstone at Tuba City, Arizona, a characteristic track of the Springdale megatracksite. Rock hammer is 28 cm long.

Navajo Sandstone

The Navajo Sandstone yields an extensive record of tetrapod footprints, but a sparse record of tetrapod body fossils. The footprint record encompasses tracks of theropod dinosaurs (*Grallator*, *Eubrontes*), prosauropod dinosaurs (*Otozoum*), ornithopod dinosaurs (*Anomoepus*) and cynodonts (*Brasilichnium*) (e.g., Brady, 1960; Stokes, 1978; Baird, 1980; Cuffey et al., 1997; Lockley and Hunt, 1995; Rainforth and Lockley, 1996; Nations et al., 1996; Santucci et al., 1998).

The body fossils from the Navajo Sandstone are of a protosuchid crocodylomorph (Figs. 5-6), the theropod dinosaur *Segisaurus*, the prosauropod dinosaur *Ammosaurus* and a tritylodontid cynodont (Brady, 1935, 1936; Camp, 1936; Galton, 1971; Attridge et al., 1985; Winkler et al., 1991; Rinehart et al., 2001).

AGE AND CORRELATION

The age and correlation of the formations of the Glen Canyon Group (Fig. 7), especially their relationship to the Triassic-Jurassic boundary, have long been a source of uncertainty and disagreement. Opinions of authors we cite in this paper have ranged from assigning the entire Glen Canyon Group a Late Triassic age, to assigning it an Early Jurassic age. Currently available data from vertebrate biostratigraphy, magnetostratigraphy and regional lithostratigraphic relationships provide for much more definitive age assignments and more precise correlations than were possible previously.

There are several compelling reasons to assign a Late Triassic (Apachean) age to the lower part of the Moenave Formation and laterally equivalent lower Wingate Sandstone: (1) the Apachean phytosaur *Redondasaurus* is present in the basal Wingate Sandstone

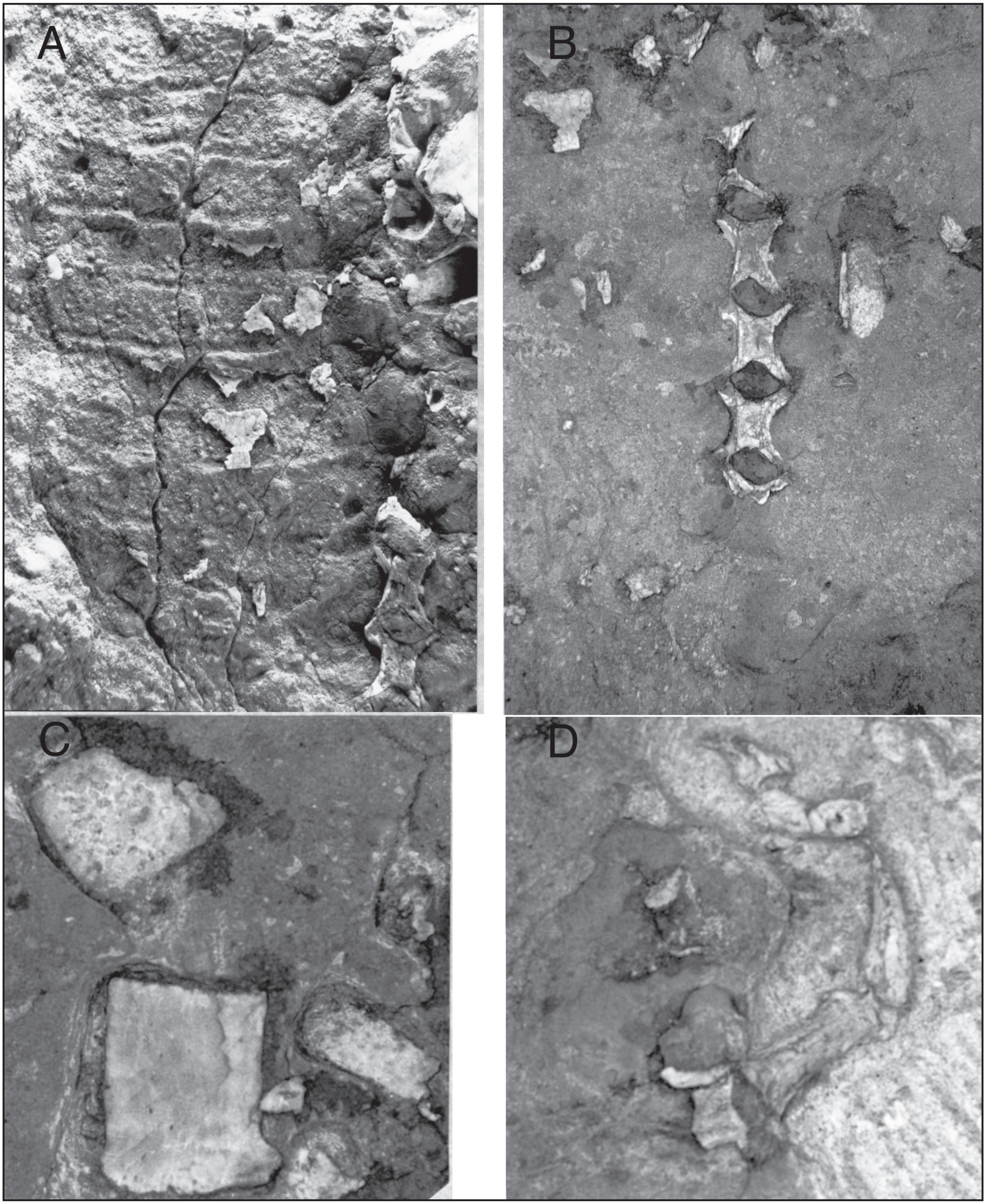

FIGURE 5. Photographs of NMMNH P-33097, protosuchid crocodylomorph fossil from the Navajo Sandstone at NMMNH locality 4576. **A**, bed of imbricated ventral scute impressions with scute fragments; each scute is ~ 7 mm scale, anterior toward top. **B**, articulated incomplete vertebrae and vertebral impressions, each ~ 11 mm long, anterior toward top. **C**, incomplete dorsal scute in dorsal view (upper) and complete dorsal scute in ventral view (lower), complete scute is 12 x 15 mm. **D**, phalanges of the articulated partial pes. (Modified from Rinehart et al., 2001).

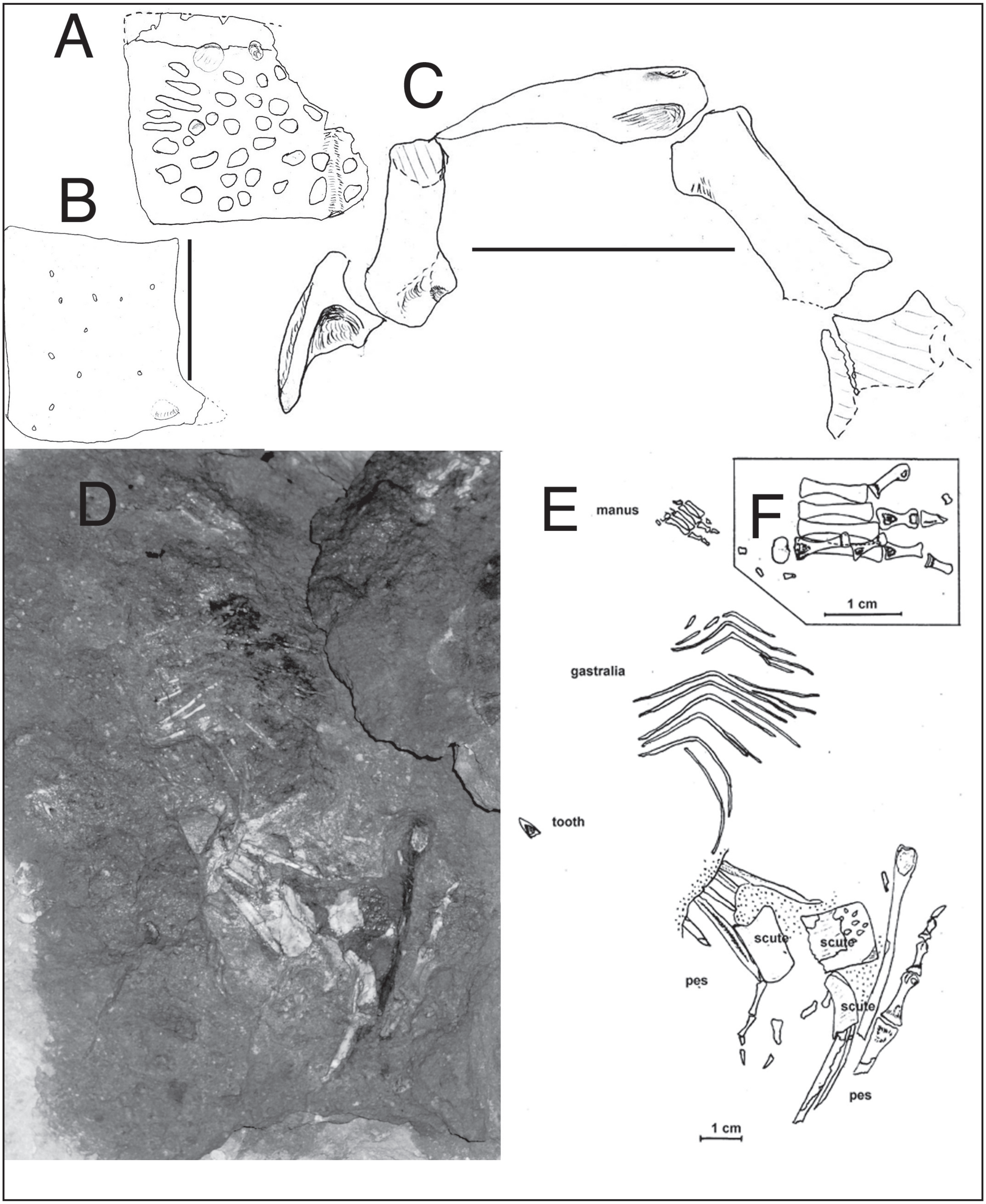

FIGURE 6. Interpretative sketches of NMMNH P-33097 (A-C) and photographs (D) and interpretative sketches (E-F) of NMMNH P-33098 from the Navajo Sandstone at NMMNH locality 4576. **A-B**, dorsal scutes of P-33097 illustrated in Figure 2C in **A**, dorsal, and **B**, ventral views. **C**, partial articulated pes illustrated in Figure 2D. **D**, photograph of block containing NMMNH P-33098 in its current state of preparation. **E**, interpretative sketch of NMMNH P-33098, more bones appear in the sketch than in the photograph because it is a composite of part and counterpart blocks. **F**, close-up sketch of manus illustrated in Figure 3E. All scale bars = 1 cm. (Modified from Rinehart et al., 2001).

in southeastern Utah (Lucas et al., 1997a,b), and no phytosaur is known from Jurassic strata; (2) the footprint ichnogenus *Brachychirotherium* is known from the lower Wingate in Colorado and Utah but not known elsewhere from demonstrably Jurassic strata; (3) the lower Dinosaur Canyon Member is laterally equivalent to strata of well established Late Triassic age (upper Rock Point Formation); (4) the Wingate Formation basal contact is gradational with underlying Upper Triassic strata of the Rock Point Formation; and (5) magnetostratigraphy of the lower Moenave interval is reasonably correlated to the magnetostratigraphy of uppermost Triassic strata of the Newark Supergroup in eastern North America (Molina-Garza et al., 2003).

Although it is possible to assign the lower Moenave Formation to the Late Triassic, its precise correlation to the marine timescale is uncertain. Probably it equates to part or all of Rhaetian time, simply because it is the youngest Triassic interval on the Colorado Plateau and is conformably overlain by strata that apparently correlate to the earliest part of the Early Jurassic (Hettangian).

Also, we note that the middle parts of the Dinosaur Canyon Member of the Moenave Formation and of the Wingate Sandstone lack age-diagnostic fossils. This means that the top of the Triassic cannot be placed with precision in the nonmarine strata in northeastern Arizona, but instead falls in a stratigraphic interval approximately 30 to 50 m thick. More fossil collecting with detailed stratigraphic data is needed to provide a more precise placement of the top of the Triassic here. This has obvious implications for the study of faunal turnover and putative extinction events at or near the Triassic-Jurassic boundary.

Similarly, there are several compelling reasons to assign an earliest Jurassic (Wassonian) age to the upper part of the Moenave Formation: (1) no *bona fide* Triassic index fossils are known from the upper Moenave; (2) *Protosuchus* records elsewhere (McCoy Brook Formation in Nova Scotia, upper Elliott Formation in South Africa) are in strata of earliest Jurassic age (Shubin et al., 1994; Lucas and Hancox, 2001); (3) *Otozoum* is present in the upper Wingate in Colorado, and no *bona fide Otozoum* are known from Triassic strata (Rainforth, 2003); (4) not all *Eubrontes* tracks are Early Jurassic, but most North American occurrences are (Lucas and Tanner, 2004; Lucas et al., 2005); (5) a palynomorph sample from the Whitmore Point Member near Fredonia is dominated by the conifer pollen taxon *Corollina meyeriana* (Peterson and Pipiringos, 1979; Litwin, 1986), a common occurrence in earliest Jurassic strata (however, this abundance peak occurs in some Upper Triassic strata as well, so it is not definitive of the earliest Jurassic); and (6) magnetostratigraphy of the upper Moenave is readily correlated to the magnetostratigraphy of the earliest Jurassic (Hettangian) interval of the Newark Supergroup in eastern North America (Molina-Garza et al., 2003).

There is no doubt that the Kayenta tetrapod assemblage is of Early Jurassic age, as it well represents a cosmopolitan Early Jurassic tetrapod fauna with genera such as *Megapnosaurus*, *Dilophosaurus*, *Massospondylus* and an abundance of tritylodontids (Lufeng Formation of southern China, La Boca Formation of northern Mexico, upper Elliott Formation of the South African Karoo and Liassic fissure fills of Western Europe) (e.g., Luo and Wu, 1994; Lucas, 1994, 1996; Lucas and Hancox, 2001; Irmis, 2004). Furthermore, the type material of the dinosaur *Scelidosaurus* is known from lower Sinemurian marine strata in the United Kingdom, which suggests that the Kayenta assemblage is early Sinemurian in age (Padian, 1989a; Lucas, 1996). If so, the hiatus between the Kayenta and upper Moenave intervals represents part of Hettangian time.

The intertonguing relationship between the Kayenta Formation and lower Navajo Sandstone thus indicates an early Sinemurian age for the base of the Navajo Sandstone. The few body fossils known from the Navajo Sandstone include the prosauropod *Ammosaurus*, also known from the Portland Formation of the Newark Supergroup in Connecticut (Galton, 1976). Palynology and magnetostratigraphy suggest the Portland Formation is of Sinemurian-Pliensbachian age (Lucas and Huber, 2003). Other fossils from the Navajo Sandstone suggest an Early Jurassic age, but are not precise age indicators. The youngest age of the Navajo Sandstone is earliest Middle Jurassic based on its relationship to the Temple Cap Sandstone. Therefore, the Navajo encompasses part of Sinemurian time, all of the Pliensbachian and Toarcian and part of the Aalenian, at least 20 million years (Fig. 7).

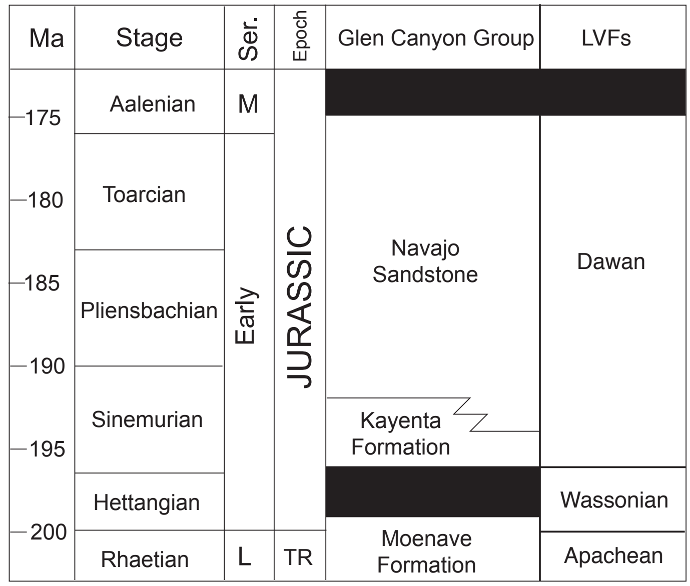

FIGURE 7. Age of the Glen Canyon Group. Numerical timescale from Gradstein et al. (2004).

SUMMARY

The Glen Canyon Group yields the vast majority of the Jurassic vertebrate fossil record of Arizona, including globally significant records of tracks and body fossils. Other records in Arizona are limited to isolated occurrences of bones and tracks that generally have received scant scientific attention. The Glen Canyon Group fossils are extremely important, as they include the oldest Jurassic vertebrates known from the American West. However, because the Triassic-Jurassic boundary appears to fall in a relatively unfossiliferous stratigraphic interval 30-50 m thick in the Dinosaur Canyon Member of the Moenave Formation, or in the middle of Wingate Sandstone, it is difficult to assess the tempo of Triassic-Jurassic faunal turnover in the American West. Indeed, because this interval appears to encompass the Triassic—Jurassic boundary (TJB), comparison of Early Jurassic assemblages found in rocks above this interval to Late Triassic faunas below the interval must allow for the time represented by 30-50 m of starata. That is, the tempo of evolutionary turnover from one of these faunas to the next is exaggerated when compared at the level of formation (or in terms of time, stage)—this is essentially the compiled correlation effect of Lucas (1994).

Definitive Early Jurassic vertebrate assemblages from the Kayenta Formation and Navajo Sandstone are both important, but for different reasons. The Kayenta Formation fauna is rich and contains numerous important records, including the first or very early North American records of caecilians, turtles, and tritylodontids, as well as numerous type specimens. The combined Navajo Sandstone body fossil and footprint records are important as they reveal a remarkable diversity of animals in what has long been thought to be an arid erg system.

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