Harris et al., eds., 2006, The Triassic-Jurassic Terrestrial Transition. New Mexico Museum of Natural History and Science Bulletin 37.

THE MOENAVE FORMATION AT THE ST. GEORGE DINOSAUR DISCOVERY SITE AT JOHNSON FARM, ST. GEORGE, SOUTHWESTERN UTAH

JAMES I. KIRKLAND[1] AND ANDREW R.C. MILNER[2]

[1]Utah Geological Survey, PO Box 146100, Salt Lake City, UT 84114-6100, E-mail: jameskirkland@utah.gov;
[2]St. George Dinosaur Discovery Site at Johnson Farm, City of St. George, 2180 East, St. George, UT 84790, E-mail: amilner@sgcity.org

Abstract—Extensive development in the St. George, Utah area resulted in the temporary exposure of fresh rock at and near the St. George Dinosaur Discovery Site at Johnson Farm (SGDS), facilitating examination and description of the Lower Jurassic stratigraphy of the vicinity in some detail. Since this study, construction has covered much of what we observed, making this the only detailed record of the Moenave Formation in the SGDS area. We measured a total thickness for the Moenave Formation of 73.97 m. The formation is divided into a lower Dinosaur Canyon Member (56.41 m thick) and upper Whitmore Point Member (17.56 m thick).

A poorly cemented chert and anhydrite pebble conglomerate approximately 1 m thick overlies an unconformable contact (J-0 unconformity of previous authors) of the Moenave with the older (Late Triassic) Chinle Formation. Overlying the conglomerate is 34.8 m of slope-forming, mudstone-dominated rocks with anhydrite nodules and secondary gypsum veins in the lower portion, and thin, ripple-bedded sandstone layers with mudcracks that become increasingly abundant up-section. Fine- to medium-grained sandstone beds, each 10 to 100 cm thick, constitute a ledge-forming sandstone unit 18.9 m thick at the top of the Dinosaur Canyon Member. Medium-scale trough cross-bedding characterizes the thicker beds in the lower half, and ripple-drift cross-bedding that preserves dinosaur tracks dominates the beds near the top. A poorly sorted, yellowish-tan to green sandstone bed 5 m from the top preserves abundant, identifiable plant debris.

The Whitmore Point Member has a more varied lithology. The lower, conformable contact is placed at the base of a distinctive, cherty limestone bed above the ledge-forming sandstones at the top of the Dinosaur Canyon Member. The member can be divided into three intervals at the SGDS: (1) a basal, complex interval that includes the main track-bearing sandstone; (2) a middle, sandstone-dominated interval similar to the upper few meters of the Dinosaur Canyon Member; and (3) an upper, thin-bedded interval.

The main track layer (MTL) at the base of the main track-bearing sandstone is impressed into a mudstone. Two episodes of dinosaur track emplacement and preservation are recognized on the MTL. To the northwest, the MTL preserves scours (northward-directed currents), tool marks, and abundant dinosaur swim tracks, suggesting deeper water. The top surface of the main track-bearing sandstone is eroded into a series of large (meter-scale) megaripples that are draped by thin, ripple-bedded sandstone beds that preserve additional dinosaur tracks and rare fossil plants.

The basal, complex interval is capped by lacustrine mudstones with an additional track-bearing sandstone interval that pinches out to the south and is similar to the main-track-bearing sandstone.

The middle, sandstone-dominated interval is 7.64 m thick and is characterized by interbedded, reddish-brown sandstone and mudstone. These sandstones are similar in color and lithology to those in the upper part of the Dinosaur Canyon Member and preserve mudcracks, tracks, and ripple cross-beds. These sandstones are also interpreted as representing lake-margin sand deposits emplaced by longshore currents; along with the basal complex interval, this interval records the rising and falling of lake levels along the margin of Lake Dixie.

Thin-bedded, lacustrine sediments make up the upper 6.55 m of the Whitmore Point Member. This sequence consists mostly of coarsening-upward cycles about 20-50 cm thick, characterized by basal shales containing fossil fishes and ostracodes, and capped by sandstones that preserve algal laminae, stromatolites, mudcracks, many isolated bones, and dinosaur tracks.

The overlying Springdale Sandstone Member of the Kayenta Formation is 27.85 m thick and lies on an erosional surface having a meter or more of relief that represents the J-0' or J-sub K unconformity of previous investigators. Locally, large clasts of Whitmore Point lacustrine sediments are present at this unconformity at the SGDS. The Springdale Sandstone is a medium- to coarse-grained, cross-bedded sandstone deposited by a braided-river system. The lower, unnamed, mudstone-dominated member of the Kayenta Formation conformably overlies the Springdale Sandstone. The base of this unit likely represents a lacustrine environment, where the uppermost Springdale fluvial sediments have been reworked into lake-margin deposits. This surface also preserves common dinosaur tracksites in the St. George and Zion National Park areas.

Detailed descriptions of these strata provide a basis for understanding the local depositional history just prior to, during, and following the preservation of the fossil-bearing rock layers at the SGDS.

INTRODUCTION

All of the documented dinosaur tracks and other fossils at the St. George Dinosaur Discovery Site at Johnson Farm (SGDS), Washington County, Utah (Fig. 1), are in the Lower Jurassic Moenave Formation, specifically in the upper part of the Dinosaur Canyon through the Whitmore Point members (Kirkland et al., 2002; Milner and Lockley, 2006; Milner et al., this volume b, c). Elsewhere in southwestern Utah, the overlying Kayenta Formation hosts the majority of known Lower Jurassic dinosaur tracks. At the SGDS, strata dip to the north-northwest at about 7°, exposing the Chinle Formation through the lower Kayenta Formation in the SGDS area (Fig. 2). Detailed description of these strata provide the basis for understanding the history just prior to, during, and just after the preservation of the fossil-bearing rock layers at the SGDS.

As construction activities led to the discovery of the fossils, the exposure of fresh rock during this development also permitted us to examine and describe the rocks spanning the SGDS in some detail. Since this study was undertaken, building construction has covered much of what we observed, making this report the first detailed record of the Moenave Formation in this area and the most detailed description of the Whitmore Point Member (Fig. 3) yet published.

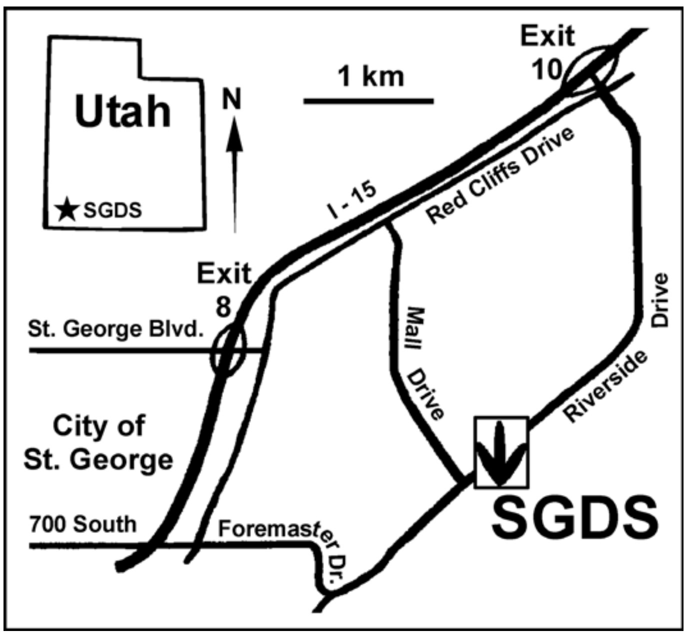

FIGURE 1. Location of the St. George Dinosaur Discovery Site at Johnson Farm (SGDS).

PREVIOUS WORK

Stratigraphic Nomenclature

Early researchers in the region included strata now separated out as the Moenave Formation within the Upper Triassic Chinle Formation. Gregory (1950), in his monograph on the geology of the Zion National Park region, defined the Springdale Sandstone Member in the upper Chinle Formation. This member was named for the town of Springdale at the mouth of Zion Canyon (Fig. 4A), where the unit forms a sandstone cliff 20-35 m thick.

Harshbarger et al. (1957), working in the area of the Navajo Indian Reservation of northeastern Arizona, designated the Moenave Formation for a mappable sequence of red-colored, fluvial, arkosic sandstones at the top of the Chinle Formation that are well exposed near the Hopi village of Moenave west of Tuba City (Fig. 4A). They included the formation in the lower part of the Glen Canyon Group, and they reported that it overlay the eolian deposits of the Wingate Sandstone. Subsequent researchers have recognized that the Wingate is actually a lateral equivalent of the Moenave Formation that replaces it to the northeast (e.g., Blakey, 1994; Peterson, 1994).

Harshbarger et al. (1957) further recognized that the Moenave Formation could be divided into two members on the Navajo Reservation. A basal, fine-grained, orange-red sandstone interval had been named the Dinosaur Canyon Sandstone Member based on exposures on Ward Terrace, about 10 km east of Cameron, Arizona (Fig. 4A). They also recognized that the Springdale Sandstone Member can be traced southeastward from southwestern Utah, along the Utah-Arizona border, and into the Navajo country, where it rests upon the Dinosaur Canyon Member, forming their upper member of the Moenave Formation.

In 1967, Wilson identified a series of thin-bedded shales, limestones, and sandstones that separated the Dinosaur Canyon Member from the overlying Springdale Sandstone Member along the Arizona Strip (the region of northwestern Arizona and southwestern Utah north of the Grand Canyon) and in southwestern Utah, west of Kanab. He named this series of thin beds the Whitmore Point Member after Whitmore Point in northwestern Arizona (Fig. 4A). Wilson (1967) also defined the contact between the Dinosaur Canyon and Whitmore Point members in the area of Leeds, Utah, at the base of a limestone bed partially replaced by red chert. This bed defines the contact between these members over much of southwestern Utah. The Whitmore Point Member was deposited in a lacustrine environment referred to in the St. George area as Lake Dixie (Kirkland et al., 2002).

Pipiringos and O'Sullivan (1978) identified a series of regional unconformities within Triassic and Jurassic strata on the Colorado Plateau that they proposed had regional lithostratigraphic significance in defining packages of related rocks, and provided a framework for paleogeographic and paleoenvironmental reconstructions. The relative

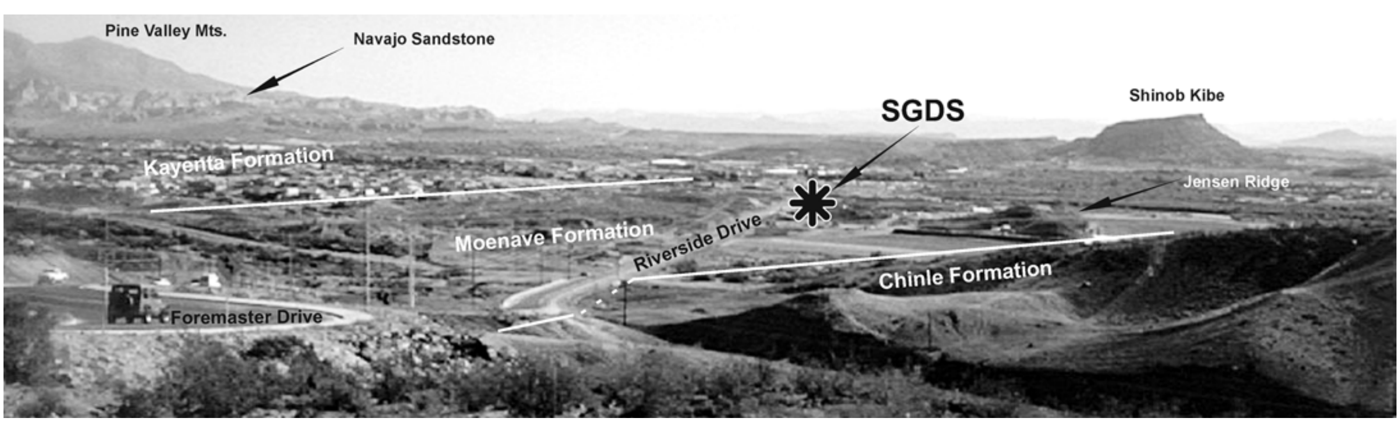

FIGURE 2. Overview of the SGDS and surrounding area, looking north from Foremaster Drive on Middleton Black Ridge.

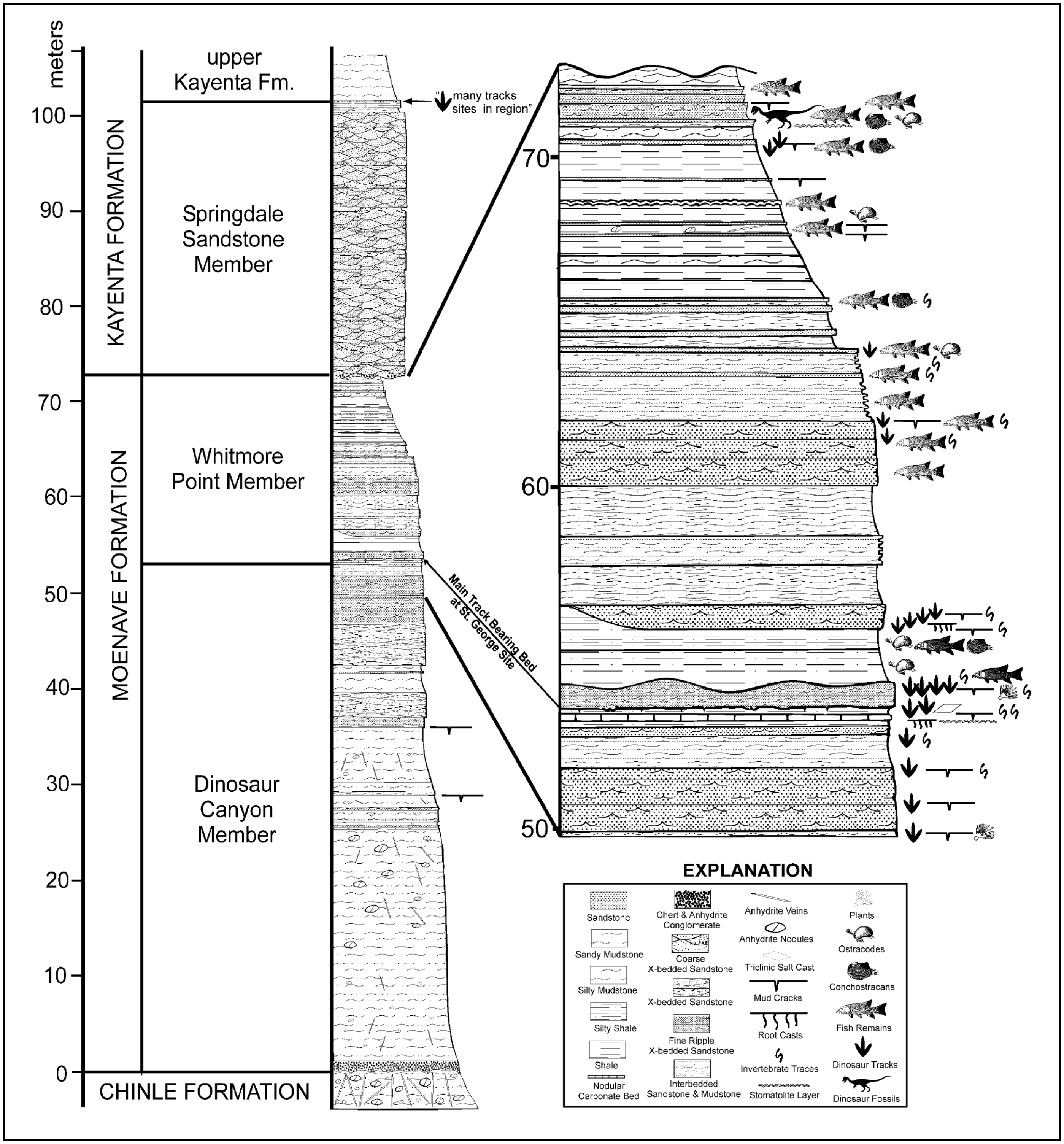

FIGURE 3. Stratigraphic section of the Moenave Formation at the SGDS with the stratigraphic positions of descriptive units used in the text, significant fossils, and sedimentological features indicated.

chronostratigraphic importance of some of these surfaces has been disputed, but clearly this publication provided a starting point for many important lines of research both for and against the presence of a distinct series of regional erosional surfaces within the Jurassic System on the Colorado Plateau. Their J-0 unconformity was defined as occurring at the bases of the Moenave Formation (to the southwest) and the Wingate Sandstone (to the northeast). This surface has been considered as marking the Triassic-Jurassic boundary across the Colorado Plateau. The J-1 unconformity truncates the top of the Navajo Sandstone at the top of the Glen Canyon Group (Pipiringos and O'Sullivan, 1978; Blakey, 1994).

Riggs and Blakey (1993) recognized another unconformity between the J-0 and J-1 unconformities at the base of the Springdale Sandstone within the Moenave Formation, which they termed the J-sub-k unconformity. This same unconformity was independently identified by Marzolf (1993) as the J-0' unconformity. They all recognized that this erosional surface could be traced to the contact at the base of the Kayenta

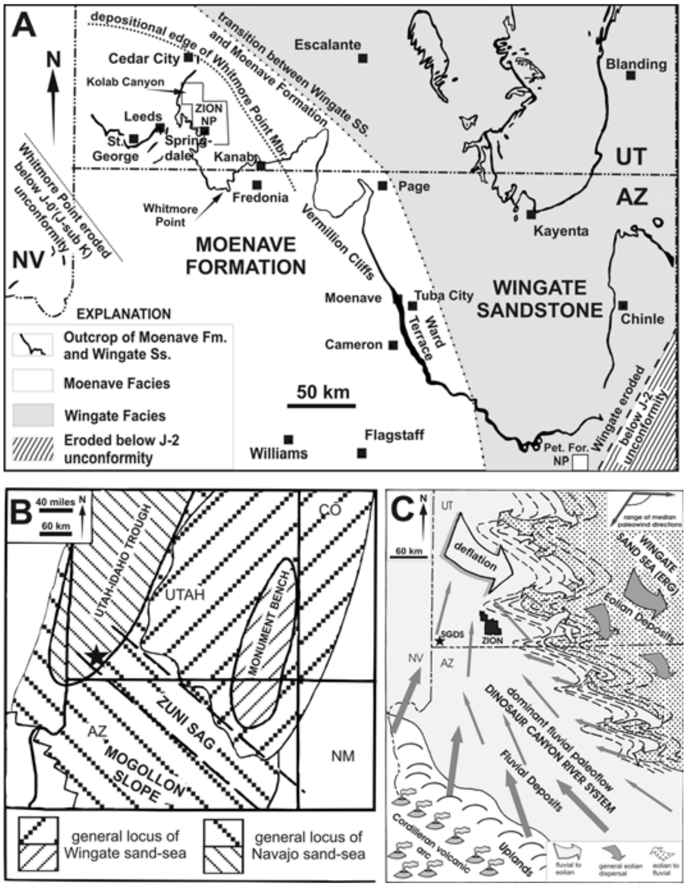

FIGURE 4. **A**, Outcrop map of Moenave Formation and Wingate Sandstone with large scale facies patterns and geographic features discussed in text. **B**, Structural setting for deposition of uppermost Triassic and Lower Jurassic eolian deposits in the southwestern United States (after Blakey, 1994). **C**, Depositional model for interrelationships between fluvial sediments of the Dinosaur Canyon Member of Moenave Formation and eolian deposits of the Wingate Sandstone (after Blakey, 1994).

Formation to the northeast where it directly overlies the Wingate Sandstone. Thus, the Springdale Sandstone Member of the Moenave Formation was equivalent to the basal Kayenta Formation to the northeast. Marzolf (1993, 1994) removed the Springdale Sandstone from the Moenave Formation, including it as the basal member of the overlying Kayenta Formation. This stratigraphic revision has been followed by several subsequent researchers (Lucas and Heckert, 2001; Lucas et al., 2005; Lucas and Tanner, this volume) and is now applied to new geological maps of the area to be published by the Utah Geological Survey (G. Willis, personal commun., 2005).

Three previously published papers claimed to specifically address the Moenave Formation in the St. George area (Davis, 1977a, b; Miller et al., 1989). Unfortunately, all three papers actually described outcrops of the overlying lower Kayenta Formation that is superficially similar to the Moenave Formation. At least two unpublished theses also discuss the unit in the area (Day, 1967; Queen, 1988).

Higgins and Willis (1995) measured a section south of the SGDS, in a drainage located northeast of Middleton Black Ridge and southwest of and subparallel to Mall Drive (Figs. 1, 2). They identified the Dinosaur Canyon, Whitmore Point, and Springdale Sandstone members with a total thickness of 127 m. Their section overlaps, in part, the section described herein, which we measured at a total thickness of 101.8 m for the same stratigraphic interval.

Age of the Moenave Formation

The Whitmore Point Member preserves abundant, thick-scaled, semionotid fish (see Milner and Kirkland, this volume) of the variety that had previously been used to date these beds as Early Jurassic or Late Triassic (Harshbarger et al., 1957). An Early Jurassic age for the Moenave Formation is now widely accepted, based on comparisons of these fossil fish with those preserved in the Newark Supergroup of the eastern seaboard (Olsen et al., 1982). This Early Jurassic age has since been substantiated biostratigraphically by pollen (Peterson and Piperingos, 1979; Litwin, 1986; Cornet and Waanders, this volume), crocodylomorphs (Clark and Fastovsky, 1986; Lucas et al., 2005a), dinosaurs (Lucas and Heckert, 2001; Lucas et al., 2005b), and fossil tracks (Olsen and Padian, 1986; Milner et al., this volume a).

The discovery of Late Triassic fossils in the basal Glen Canyon Group (Lockley et al., 1992) and, in particular, within the lower Wingate Sandstone (Morales and Ash, 1993; Lucas et al., 1997a, b, 2005, this volume a; Lockley et al., 2004, Odier et al., 2004) provided convincing evidence that the Triassic-Jurassic boundary lies within the Dinosaur Canyon Member of the Moenave Formation and within the correlative Wingate Sandstone to the northeast. Magnetostratigraphy provides independent evidence to support this view (Molina-Garza et al., 2003; Donohoo-Hurley et al., 2006). Therefore, evidence is accumulating that the Triassic-Jurassic boundary lies between the J-0 and J-0' (J-sub K) unconformities. However, while certain kinds of dinosaur and crocodylomorph tracks that suggest an Early Jurassic age are present in the upper part of the Dinosaur Canyon Member, no Triassic fossils, or indeed fossils of any kind, have yet been found in the lower Dinosaur Canyon Member in southwestern Utah.

Structural and Paleogeographic Setting

Blakey (1994) provided a model for the relationship between the predominantly fluvial sediments of the Dinosaur Canyon Member of the Moenave Formation and the eolian sediments of the Wingate Sandstone to the east. The thickest sections of the Glen Canyon Group are along the southwestern margin of the Colorado Plateau, extending from the Ward Terrace area of the Painted Desert, east of Cameron, Arizona, northwestward along the Echo and Vermillion Cliffs to the area around St. George in southwestern Utah. This belt of thick Glen Canyon Group strata marks the approximate position of a paleotopographic low termed the Zuni Sag (Blakey, 1994; Fig. 4B). Current indicators show that Early Jurassic river systems preserved in the Dinosaur Canyon Member of the Moenave Formation and in the western outcrops of the Kayenta Formation flowed from the southeast to the northwest along the Zuni Sag, transporting sediment largely derived from the south and east. Eolian beds preserved in the Wingate Sandstone indicate easterly wind directions that transported sand from west to east in central Utah, and to the southeast further south. Blakey's (1994) model has sediment being transported northwest along the Zuni Sag into the area of west-central Utah where the prevailing westerly winds would blow the sand into dune fields on the central Colorado Plateau and then to the southeast, where a portion would be reworked into the rivers flowing back up to the northwest (Fig. 4C).

STRATIGRAPHIC SECTION AT THE SGDS

Lower Contact with the Chinle Formation

Higgins and Willis (1995) mapped the Petrified Forest Member of the Chinle Formation as unconformably underlying the Moenave Formation in the St. George area. They followed other geologists in the region by dividing the Chinle Formation into a basal Shinarump Conglomerate Member and a much thicker, mudstone-dominated Petrified Forest Member. Lucas (e.g., 1993) proposed raising the Chinle to a group and its members to formations. At St. George, and extending eastward past Zion National Park, he (Lucas, personal commun., 2004) has identified the Owl Rock Member of the Chinle Group as unconformably underlying the Moenave Formation across this region based on the dramatic increase in the abundance of carbonate nodules in well-developed paleosols. While the pale red-purple color of the highest Chinle mudstone below the contact is similar to that seen elsewhere across the Colorado Plateau, it differs in the absence, or near absence, of well-developed paleosols with distinct calcrete. Instead, small to large (1-40 cm) irregular masses of anhydrite are abundantly distributed through the mudstone. Anhydrite accumulates in sediment under arid conditions in a manner similar to carbonate. Additionally, secondary veins of anhydrite and gypsum are abundant.

The best exposures of the upper Chinle Formation in the immediate vicinity of the SGDS are around a small hill just to the east where Foremaster Drive crosses Middleton Black Ridge (Figs. 2, 5). A pebbly sandstone lens, several meters thick by several tens of meters across, is exposed in this hill, representing a fluvial channel in the upper part of the Chinle Formation. To the south, across the Virgin River, the basal Shinarump Conglomerate caps the prominent mesas. Higgins and Grant (1995) estimated the thickness of the Petrified Forest Member (Chinle Formation above the Shinarump Conglomerate) as 215 m from map relationships.

Trenching the section through the contact, at the color change from pale reddish-purple below to reddish-brown above, south of the SGDS, just below Foremaster Drive (Figs. 1, 2), revealed a poorly cemented conglomerate at the base of the Moenave Formation containing pebbles of chert and anhydrite. The pebbles of anhydrite are particularly important because they demonstrate that the anhydrite nodules in the upper Chinle Formation were formed in the sediment during the Triassic and were not formed secondarily, long after burial, as were the associated veins of anhydrite and gypsum.

Dinosaur Canyon Member, Moenave Formation

We measured the Dinosaur Canyon Member at 56.41 m thick and broke it into three distinct intervals: a basal conglomerate, a lower mudstone, and an upper sandstone (Fig. 3). This total thickness was calculated from a partial section of the basal Dinosaur Canyon crossing Foremaster Drive, measured to the east of Middleton Black Ridge, and another section of the Dinosaur Canyon with no base exposed, that was measured starting on the east flank of "Jensen Ridge," and extending west to the SGDS southeast of Riverside Drive (Figs. 1, 2). These sections were tied together using a pale greenish sandstone marker bed in the lower mudstone at the highest occurrence of anhydrite nodules (Fig. 3).

Approximately 0.5 km south of the SGDS, on the northeast flank of Middleton Black Ridge, Higgins and Willis (1995) measured the thickness of the Dinosaur Canyon Member at 76 m. The discrepancy between this measurement and the measurement presented above is difficult to resolve except by a possible miscorrelation of the pale green marker bed in the lower mudstone. However, because the marker bed separates mudstones with large anhydrite nodules and secondary veins below from mudstones with only a very few small anhydrite nodules above, the correlation seems to be good. A more likely error would have been in projecting the section across Foremaster Drive, for although the exposures overlapped, there were no potential marker beds on which to base this correlation. This measurement was checked on two separate occasions. Given either possibility for possible error, the discrepancy would appear to be in the lower part of the Dinosaur Canyon Member. As construction now obscures both areas of outcrop, only the description of these rocks in other, nearby areas or drilling a core through them would permit a resolution of this discrepancy.

The Basal Conglomerate

The conglomerate at the base of the Dinosaur Canyon Member was first recognized during this study. Adjacent to Foremaster Drive, it rests on an erosional surface with 10-20 cm deep scours and includes pebbles 1-3 cm in diameter concentrated in the deepest scours. About 80 cm of mottled green and red mudstone, with additional lenses of conglomerate, overlie the basal conglomerate layer. As with the anhydrite pebbles, the chert pebbles are thought to have originated via erosion of the upper Chinle Formation and are similar to those present in its channel sandstones.

Examination of this contact in other areas has led to the recognition of the basal conglomerate southeast of St. George in Warner Valley (Fig. 5B, C), northeast of St. George along the exposure at East Reef southeast of Leeds, and near the mouth of Zion Canyon above the town of Springdale. At Springdale, the conglomerate is not well-developed but is represented by scattered chert pebbles in a prominent anhydrite bed formed along the contact. Locally, along the west end of Warner Valley, the conglomerate is cemented well enough to be visible in outcrop without the need for trenching (Fig. 5B, C). This conglomerate represents the J-0 unconformity of Pipiringos and O'Sullivan (1978) in this area.

The Lower Mudstone Interval

The Dinosaur Canyon Member is readily recognized by its uniform, medium to dark reddish-brown, fine- to medium-grained sandstone beds along most of its known outcrop on the Navajo Reservation in Arizona. However, in the St. George area, a lower, mudstone-dominated interval 34.8 m thick can be recognized below the more characteristic sandstones (Figs. 3, 5A, D, E). The basal 24.2 m is mostly mudstone, with only a few pale green, rippled sandstone and siltstone layers (Fig. 5D). Anhydrite nodules with secondary veins of anhydrite and gypsum are abundant in the upper half of this mudstone interval (the middle of the Dinosaur Canyon Member). A sandstone interval about 18 cm thick, bleached to a pale green, marks the beginning of an interval 10.61 m thick, with common ripple-bedded sandstone layers, 10-30 cm thick, that are commonly associated with small mudcracks (Fig. 3). The top of the lower mudstone is sharp and is penetrated by sandstone-filled mudcracks more than 50 cm deep.

The lower mudstone interval represents floodplain environments that were situated some distance from major rivers. No fossils are recognized from this interval in the St. George area as of yet. However, Alan Titus (personal commun., 2005) has observed ganoid scales in this interval east of Kanab, Utah.

Because of a general similarity in appearance and stratigraphic position, we speculate that this interval may be equivalent to the Church Rock (= Rock Point) Member of the Chinle Formation below the Wingate Sandstone farther east (Lucas, 1993; Lucas et al., 2005a). Such a correlation of the basal Moenave Formation with the Church Rock and Rock Point Members of the Chinle Formation has been proposed for northern Arizona (Lucas et al., 2005b).

The Upper Sandstone Interval

The ledge-forming upper sandstone interval was measured at 20.46 m thick. Pale-reddish-brown sandstone beds, averaging 0.5-1.5 m thick, separated by thinner beds of sandy mudstone, characterize this interval. The sandstone beds are less laterally continuous, and preserve medium-scale trough cross-beds in the lower half, and are much more tabular, with a dominance of ripple drift laminae in the upper half (Fig. 6). Five meters from the top, a laterally extensive, shaley layer with claystone pebbles preserves abundant plant debris, including identifiable conifer branches and cones with fragments of ferns and horsetails (Tidwell and Ash, this volume). Many of these fossil fragments (Fig. 6D) are stained green by copper minerals.

Track surfaces occur in this upper interval, above the plant layer, on the partings between major sandstone beds. Since large, tridactyl theropod tracks (*Eubrontes*) and tracks attributed to crocodylomorphs (*Batrachopus*) are recognized on these surfaces, this interval can be positively identified as the lowest identified Lower Jurassic stratum in the St. George area (*sensu* Olsen and Padian, 1986; Olsen et al., 2002). Unfortunately, the exact stratigraphic level from which Litwin (1986) reported Early Jurassic pollen from the Dinosaur Canyon Member to the north, near Leeds, is unknown (Cornet and Waanders, this volume). However, we found a plant-bearing level on the north side of Leeds at about the same stratigraphic position in the Dinosaur Canyon Member as the

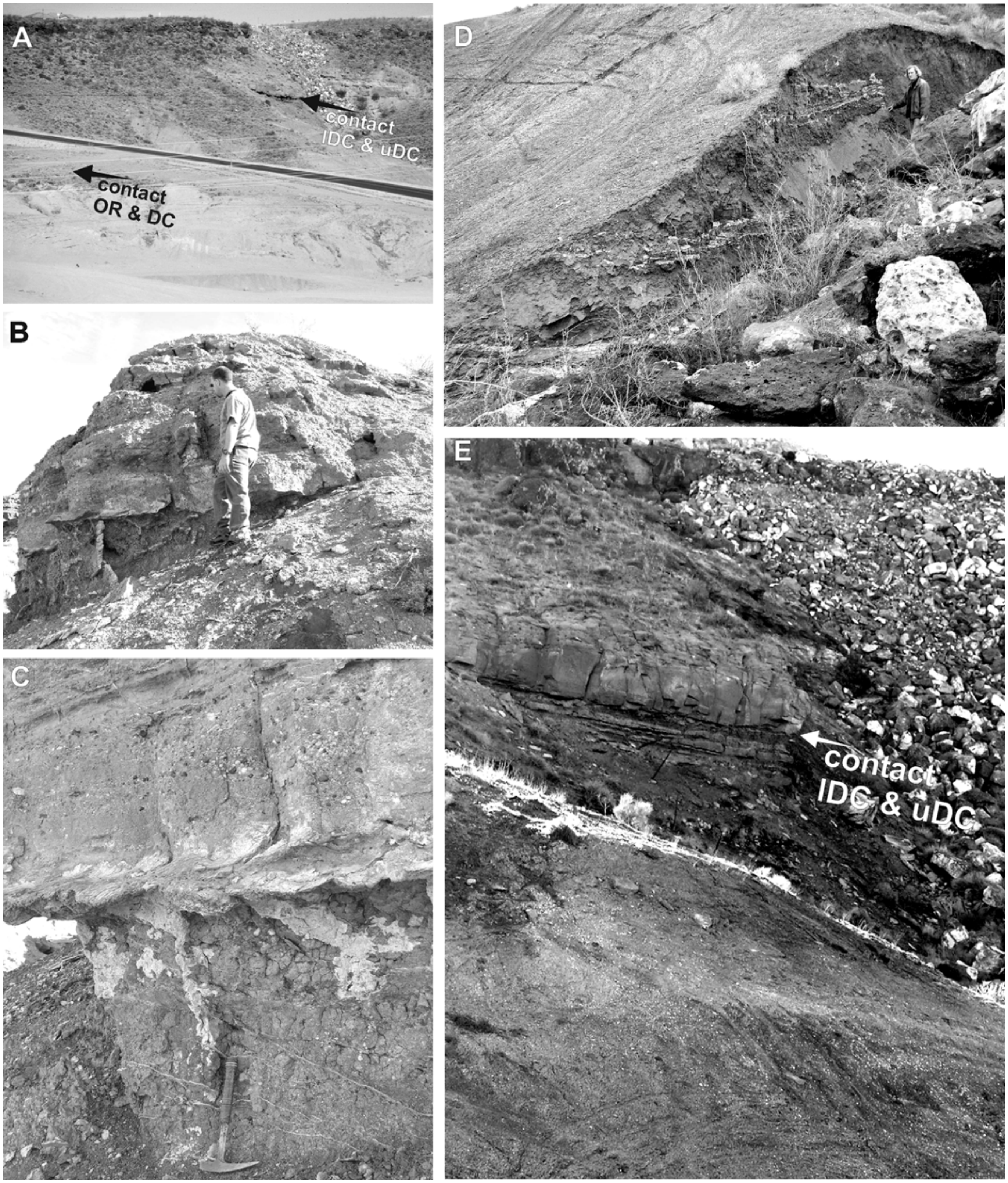

FIGURE 5. Dinosaur Canyon Member of Moenave Formation below Middleton Black Ridge and at Warner Valley. **A**, Upper Triassic through basal Jurassic section exposed on southeastern side of Middleton Black Ridge. View to the west looking across Foremaster Drive. Present Riverside Drive extends across outcrops of the Owl Rock Member of Chinle Formation in the foreground. **B**, Conglomerate at the base of Dinosaur Canyon Member of the Moenave Formation as exposed in Warner Valley with Jerry Harris for scale. **C**, Close-up of the conglomerate in **B** with rock hammer for scale. **D**, Lower mudstone interval of Dinosaur Canyon Member as exposed below Middleton Black Ridge. **E**, Detail of the contact between lower mudstone and upper sandstone intervals as exposed northwest of Foremaster Drive. Abbreviations: lDC & uDC, lower mudstone and upper sandstone intervals of the Dinosaur Canyon Member; OR & DC, Owl Rock Member of the Chinle Formation and Dinosaur Canyon Member of Moenave Formation.

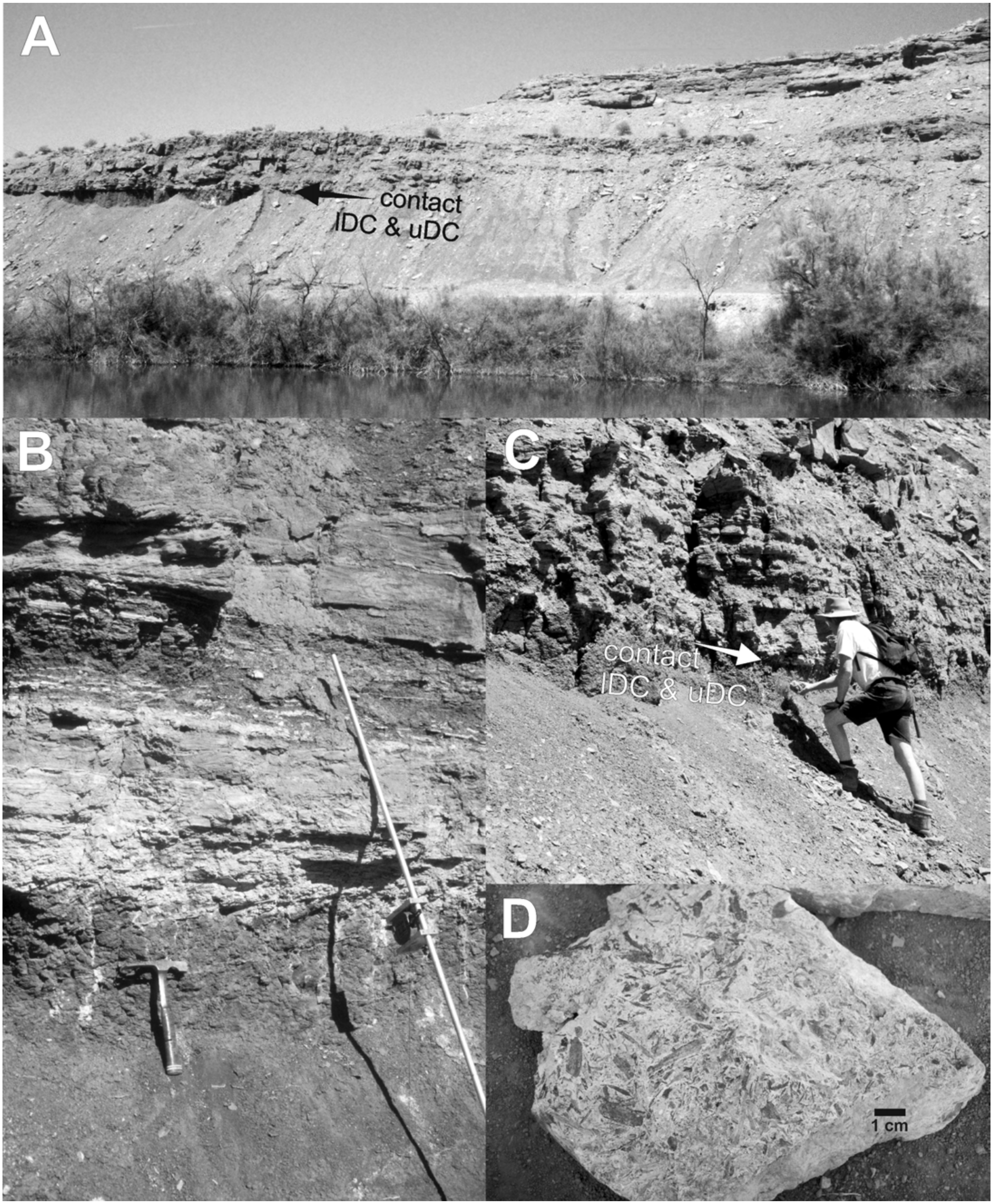

FIGURE 6. Dinosaur Canyon Member of the Moenave Formation on the southeast side of Riverside Drive. **A**, Exposure of the Dinosaur Canyon Member on the east side of Jensen Ridge, southeast of the SGDS. Contact with the underlying Chinle Formation lies below the surface of the pond. **B-C**, Close-up views of the contact on Jensen Ridge. **D**, Plant debris from the upper Dinosaur Canyon Member. Abbreviations: lDC & uDC, lower mudstone and upper sandstone intervals of the Dinosaur Canyon Member.

plant-bearing horizon at the SGDS. Although this site did not yield pollen, perhaps it represents the same stratigraphic level from which Litwin (1986) obtained his specimens. The first tracks indicating a Jurassic age occur just above this plant-bearing bed at the SGDS (Fig. 3).

The uppermost 1.58 m of this interval consists of reddish mudstone with increasing amounts of ripple-bedded sandstone up-section. This may reflect an increasing dominance of lacustrine (versus fluvial) environments during the final stages of Dinosaur Canyon deposition.

Following Wilson (1967) and current UGS mapping (e.g., Biek, 2003b), we recognize the upper contact of the Dinosaur Canyon Member at the base of a limestone containing red chert. This contact also marks the beginning of the more variable rock types characteristic of the overlying Whitmore Point Member.

The upper sandstone interval of the Dinosaur Canyon Member is interpreted as having been deposited in an aggradation of river channels crossing the floodplain, with an increasing influence of lacustrine shoreline environments toward the top. In overall character, this interval best compares to the Dinosaur Canyon Member at its type area of northeastern Arizona (Harshbarger et al., 1957; Luttrell and Morales, 1993).

Whitmore Point Member, Moenave Formation

Higgins and Willis (1995) measured the Whitmore Point Member in the drainage below Middleton Black Ridge at 19 m. The rocks described herein were from outcrops exposed during construction northwest of Mall Drive and Riverside Drive with the described stratigraphic section crossing much of the site presently occupied by Fossil Ridge Intermediate School. The Whitmore Point Member was found to be 17.56 m thick at this location.

Placement of the basal contact of the Whitmore Point Member at the SGDS has been a matter of debate. Bob Biek (personal commun., 2000), while initially introducing the lead author to the stratigraphy of the Moenave Formation in the St. George area, indicated that the basal contact of the Whitmore Point Member should be placed below the main track-bearing sandstone. This was based on his experience mapping the contact to the north in the area of Leeds, Utah (Biek, 2003a, b), wherein he followed Wilson's (1967, p. 36) definition of the Dinosaur Canyon-

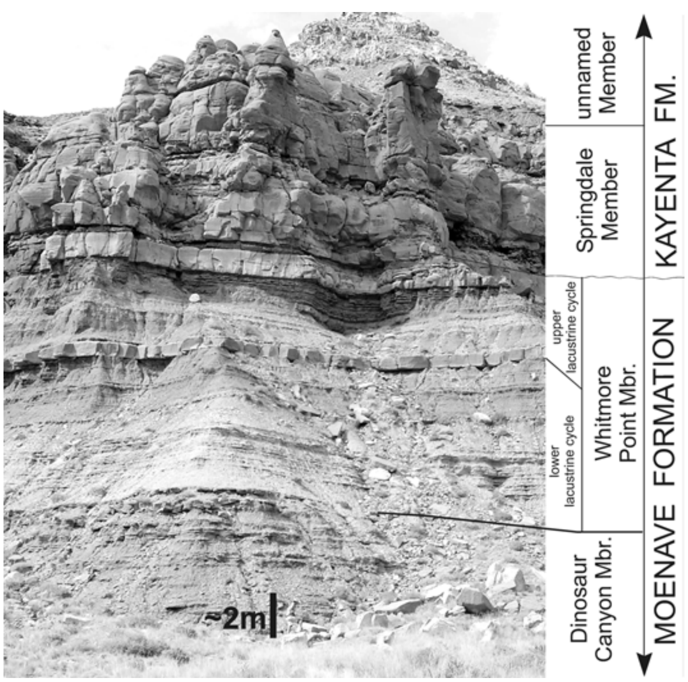

FIGURE 7. Exposure of the Moenave Formation about one kilometer west of Whitmore Point, northern Arizona, with upper and lower lacustrine intervals ("cycles") of Whitmore Point indicated.

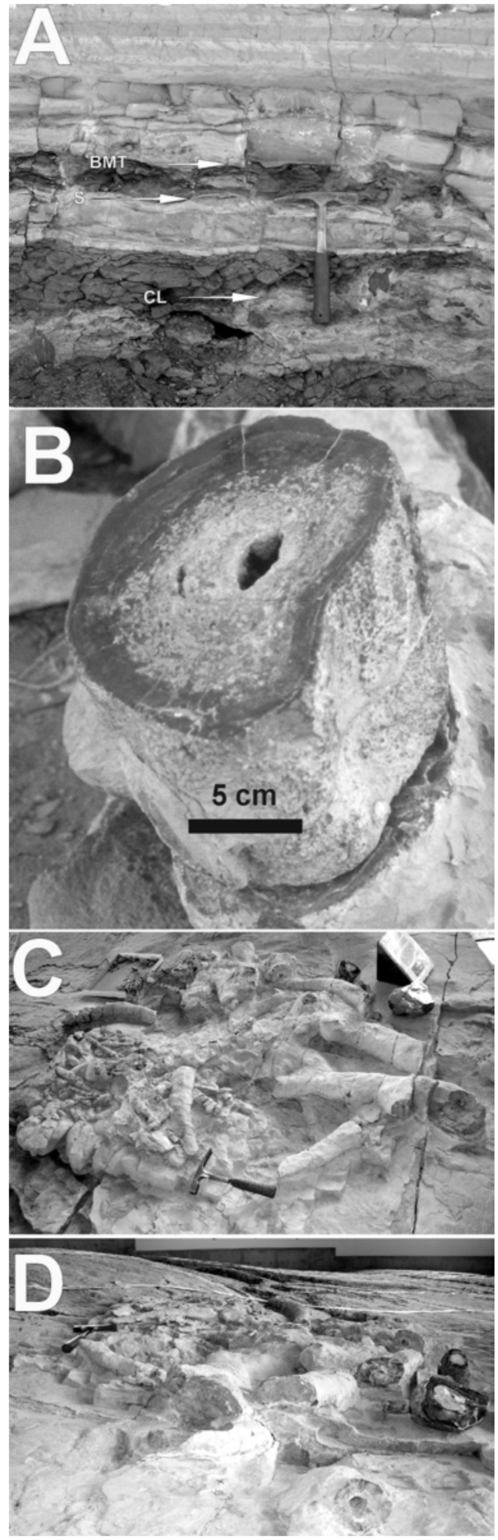

FIGURE 8. Partially silicified tufa structures. **A**, Base of the Whitmore Point Member below the north side of the SGDS building. Note the stromatolitic limestone (S) between base of main track-bearing sandstone (BMT) and the cherty limestone layer (CL) that were only observed during the excavation made for this part of the building. **B**, Close-up of a chert-replaced tufa structure from the contact with the Dinosaur Canyon Member. **C**, Accumulation of similar chert-replaced tufa structures from the top surface of the track-bearing sandstone preserved in the SGDS museum building (SGDS.18). **D**, Lateral view of the same accumulation of chert-replaced tufa structures (SGDS. 18). Rock hammers for scale in **A**, **C**, **D**.

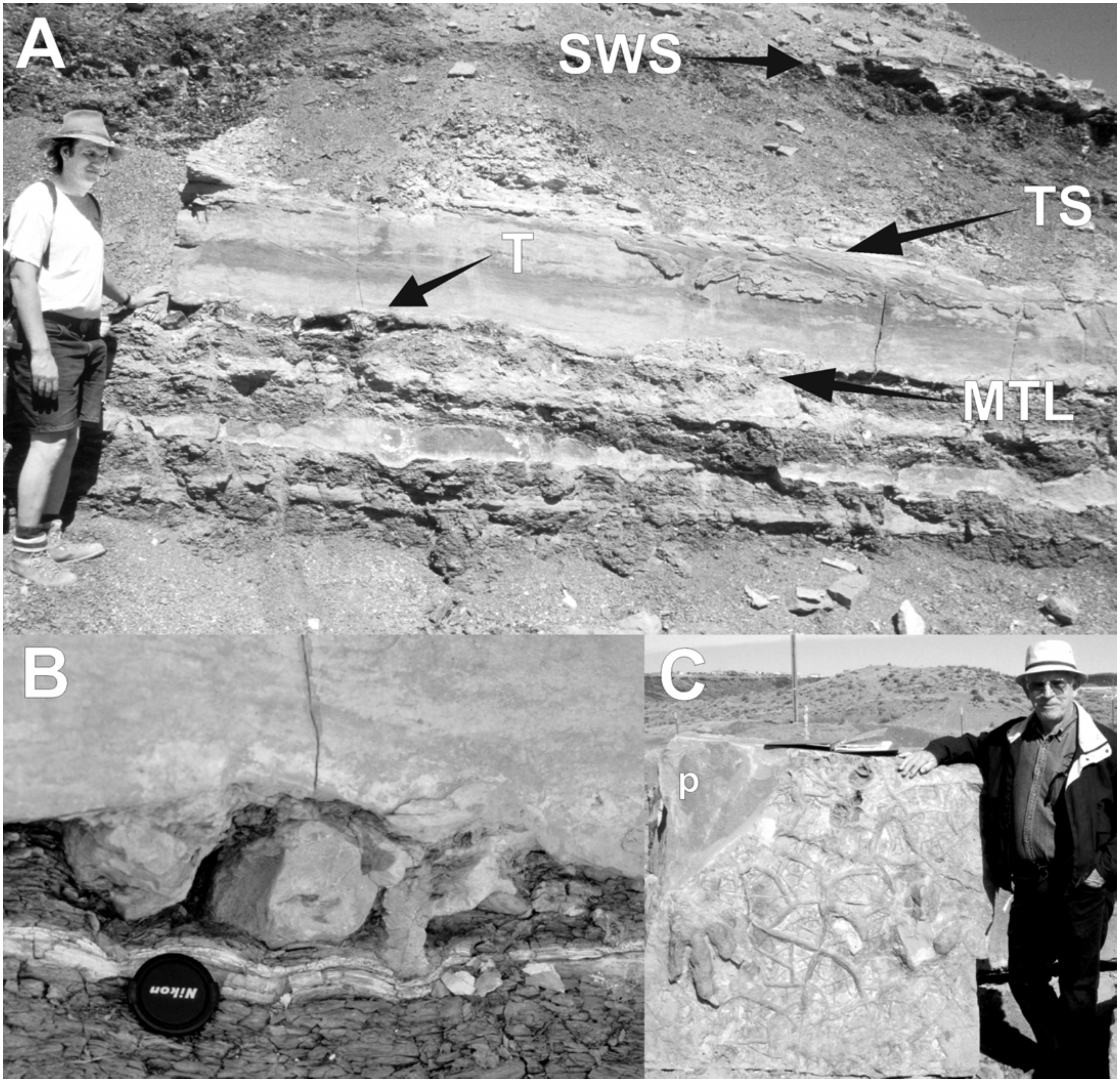

FIGURE 9. Sedimentary features preserved at base of the main track-bearing sandstone northwest of Riverside Drive at the SGDS. **A**, Cross-section of the main track-bearing sandstone in a road-cut on north side of Riverside Drive, opposite the SGDS. Abbreviations: MTL, base of main track-bearing sandstone; SWS, pinchout of upper sandstone preserving Stewart-Walker tracksite; T, natural *Eubrontes* cast; TS, top surface of main track-bearing sandstone. **B**, Close-up of *Eubrontes* track in **A**. **C**, Sheldon Johnson with the underside of a block of the main track-bearing sandstone preserving *Eubrontes* and mudcracks. p, parting surface about 10 cm above base of main track-bearing sandstone ("split layer").

Whitmore Point contact in the area north of St. George as "a 6 inch thick bed of brownish gray siliceous limestone at the base of the member in Sec. 21, T. 42 S., R. 14 W. on the southwest flank of the Harrisburg Dome." Higgins and Willis (1995), on their open-file map of this area, placed the contact at the color change at the top of the red sandstone interval, which is significantly higher in the section at the SGDS. Tanner and Lucas, during their initial research at the SGDS in 2004, placed the contact at this same stratigraphic position (S. Lucas, personal commun., 2005). To resolve this conflict in boundary placement, the UGS sponsored a field review of these rock units in August, 2005. It was found that Wilson's (1967) limestone bed with red chert could be recognized throughout southwestern Utah. Additionally, it was noted that, at its type section at Whitmore Point in northern Arizona, the Whitmore Pont Member consists of two major, superposed, deepening and shallowing lacustrine cycles: (1) a lower cycle, dominated by red-colored sediments cored by a very, dark gray, deep-water shale preserving a diverse palynomorph assemblage (Peterson and Piperingos, 1979; Litwin, 1986; Cornet and Waanders, this volume), and (2) an upper cycle dominated by mauve-colored sediments that appears better developed than the lower cycle in southwestern Utah (Fig. 7). The UGS has decided to use Wilson's (1967) cherty limestone bed to define the base of the Whitmore Point Member for future mapping in southwestern Utah (B. Biek and G. Willis, per-

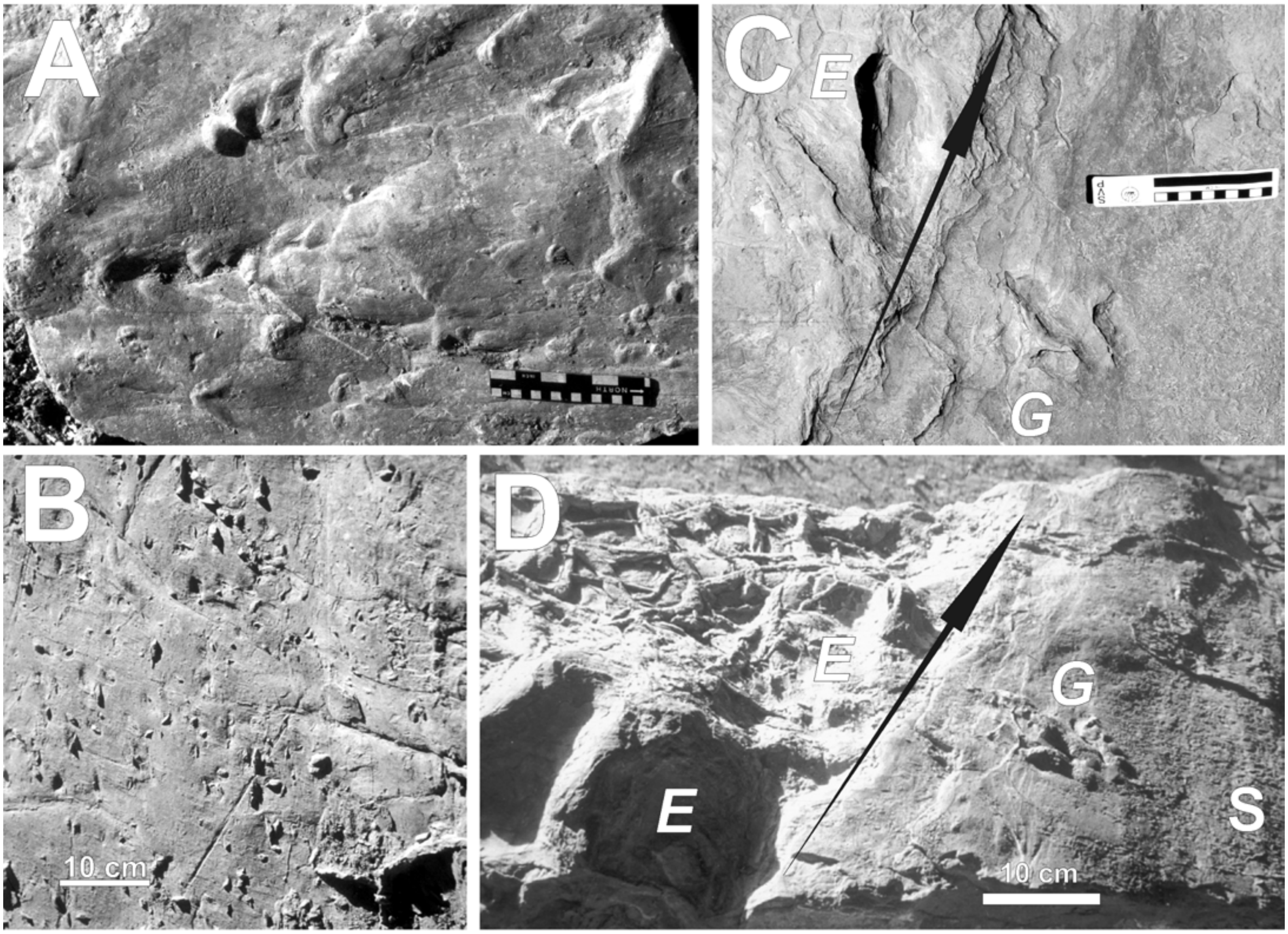

FIGURE 10. Sedimentary features associated with scours preserved at base of main track-bearing sandstone to southeast of Riverside Drive at the SGDS. **A**, Small flute casts at base of main track-bearing sandstone. **B**, Triclinic salt casts exposed on scoured surface at base of main track-bearing sandstone (SGDS.40). **C**, Natural cast of large scour (flute cast) cutting through initial tracked and mud-cracked surface in lower oblique view (SGDS.25). **D**, Same natural cast of large scour (flute cast) cutting through initial tracked and mud-cracked surface viewed from below (SGDS. 25). Abbreviations: *E*, *Eubrontes*; *G*, *Grallator*, S, poorly preserved triclinic salt casts. Elongate arrows marks margin of scour (flute cast).

sonal commun., 2006).

For the purpose of the following discussion, the Whitmore Point Member at the SGDS is divided into three stratigraphic intervals: (1) a basal, complex interval, (2) a middle, sandstone-dominated interval, and (3) an upper, shale-dominated interval (Fig. 3). The basal, complex interval and the middle sandstone dominated interval are hypothesized to correlate with the lower, red-colored lacustrine cycle, and the upper shale dominated interval to represent the upper, mauve-colored lacustrine cycle.

Lower Complex Interval

The lower 4.48 m of the Whitmore Point Member is particularly complex in both its vertical and horizontal distribution of rock types, sedimentary features, and fossils. The base of the section is placed at a 10-30 cm thick limestone that preserves red chert, superficially resembling petrified wood with hollow centers. These red cherts have been interpreted both as rhizoconcretions and as pieces of driftwood coated by tufa that have been secondarily replaced by red chert (Fig. 8). The driftwood hypothesis, favored by us, was lent credence by the discovery of an accumulation of similar red chert structures on the top of the main track-bearing sandstone preserved *in situ* within the SGDS museum building (Fig. 8C, D). These examples of the red chert structures have the appearance of having been washed together in a depression. Wood that drifted along the shoreline would become coated with calcium carbonate (most likely aided by algae and/or bacteria); eventually, the wood rotted away, leaving a thick tube of banded carbonate that, in this case, was later replaced by red chert. Similar tufa structures have been observed by one of us (JIK) in association with the Bonneville Shoreline of the Pleistocene-age Lake Bonneville near Wellsville, on the west side of the Cache Valley in northern Utah. Additionally, stromatolites are also locally preserved in association with this bed. Stromatolites are a common feature along the margin of Lake Bonneville and its modern expression, the Great Salt Lake.

This basal limestone is, in turn, capped by a dark-red claystone 10-20 cm thick into which the initial discovery surface (“main track layer” or MTL) at the SGDS is impressed. Tracks in this mudstone unit are not preserved, because the claystone dried, crumbled, and cracked as soon as it was exposed below the main track-bearing sandstone.

The main track-bearing sandstone is vertically and horizontally complex. At the initial discovery site, on the southeast side of Riverside Drive, the base of the MTL (Milner et al., this volume a) is covered by large, deeply impressed natural casts of dinosaur tracks and mudcracks (Fig. 9). This surface was scoured, forming large flute casts ranging from tens of centimeters to more than one meter across and indicate water currents directed toward the southeast (Fig. 10). The surfaces of these scours preserve additional (usually smaller) dinosaur tracks (mostly

FIGURE 11. Large flute cast preserved *in situ* in mudstone below the main track-bearing sandstone at the SGDS east of Riverside Drive indicating a current direction 125° to the southeast. Note the *Eubrontes* track, which was obliterated by weathering of this unconsolidated surface within a few weeks after exposure.

Grallator) and common, roughly diamond-shaped (triclinic) salt crystal casts that may represent borate salts such as trona or perhaps a soluble sulfate salt. Only one large flute cast was observed *in situ* at the initial SGDS discovery site: upon turning over of a large block of the main track-bearing sandstone, it was noted that a mold of a large flute cast was preserved in the underlying mudstone, indicating a paleocurrent direction to the east locally (Fig. 11).

A scenario for the development of the MTL in the area of the museum building on the southeast side of Riverside Drive would be: 1) a mud flat was exposed near the side of Lake Dixie that, while drying, formed extensive mudcracks and served as a substrate into which dinosaur tracks were impressed, 2) water flooded across this area from the west, eroding this surface and exposing salt crystals in the firm mud, 3) additional dinosaurs then impressed tracks into the softer mudstone exposed in the scoured areas, and 4) sands covered the entire mudflat surface. Thus, at least two episodes of dinosaur track formation and preservation are recorded on the MTL at the base of the main track-bearing sandstone (Fig. 10).

Across Riverside Drive, to the northwest, the MTL preserves more evidence of scouring and fewer mudcracks, indicating the direction toward deeper water to the west. Invertebrate burrows and crawling traces are common here, as are dinosaur swim tracks (Milner et al., this volume b; Fig. 12). Tool-marks and crescent marks produced by plant fragments penetrating this surface are also common and indicate a northward paleocurrent in this area (Milner et al., this volume c).

Deeper water also appears to be documented to the east of the SGDS at Jensen Ridge (Fig. 2), where the main track-bearing sandstone capped a small area on the north end of the ridge. The MTL at this site preserves a scoured surface with tool-marks, large flute casts and no tracks. This distribution of sedimentary feature suggests that the exposed mudflats exposed in the area of the museum building may have

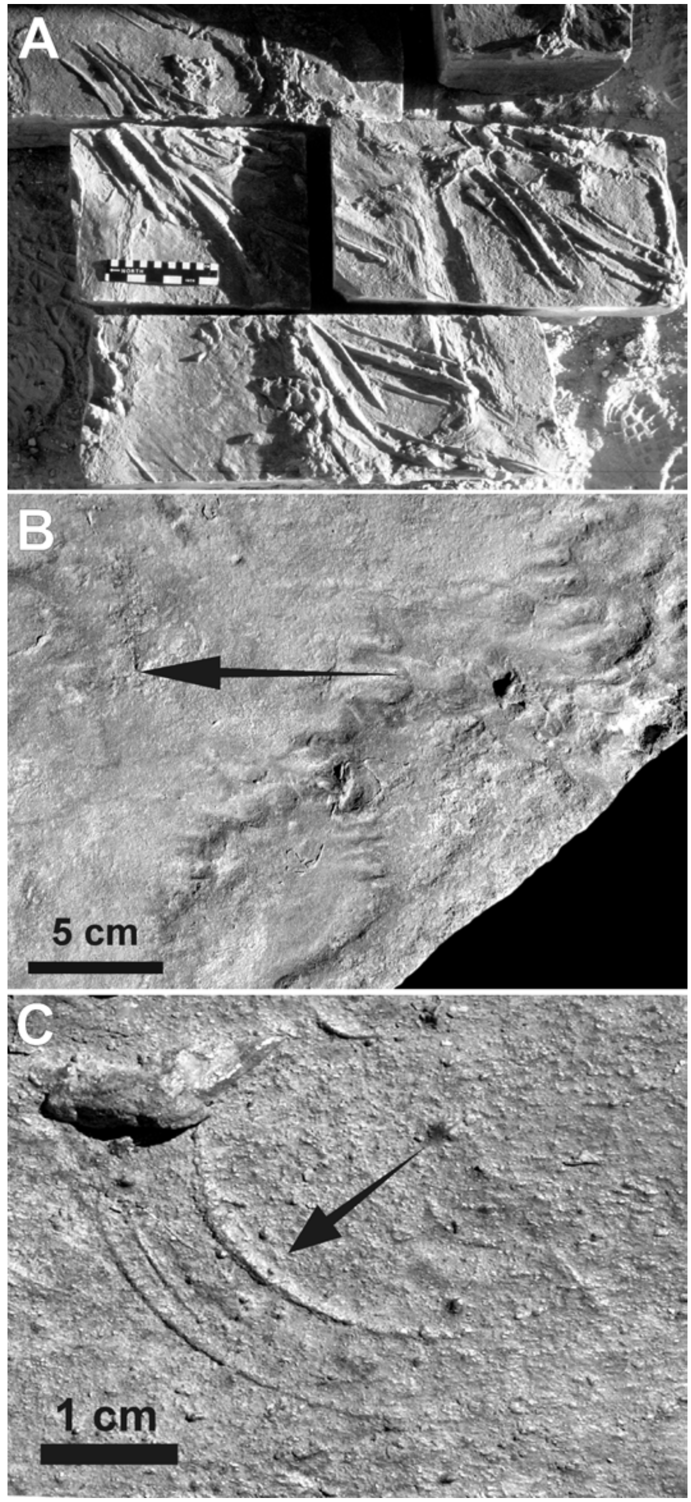

FIGURE 12. Sedimentary features preserved at the base of the main track-bearing sandstone northwest of Riverside Drive at the SGDS. **A**, Swim tracks from the main track-bearing layer (MTL) at the base of the main track-bearing sandstone west of Riverside Drive (SGDS.167). **B**, Flute casts from the MTL at base of main track-bearing sandstone west of Riverside Drive. **C**, Example of crescent structure formed by plant waving in current (scratch circle) (specimen number pending). Arrows indicate current directions.

been isolated from the actual shoreline of Lake Dixie, which is thought to be to the northeast.

At the SGDS museum, on the southeast side of Riverside Drive, a

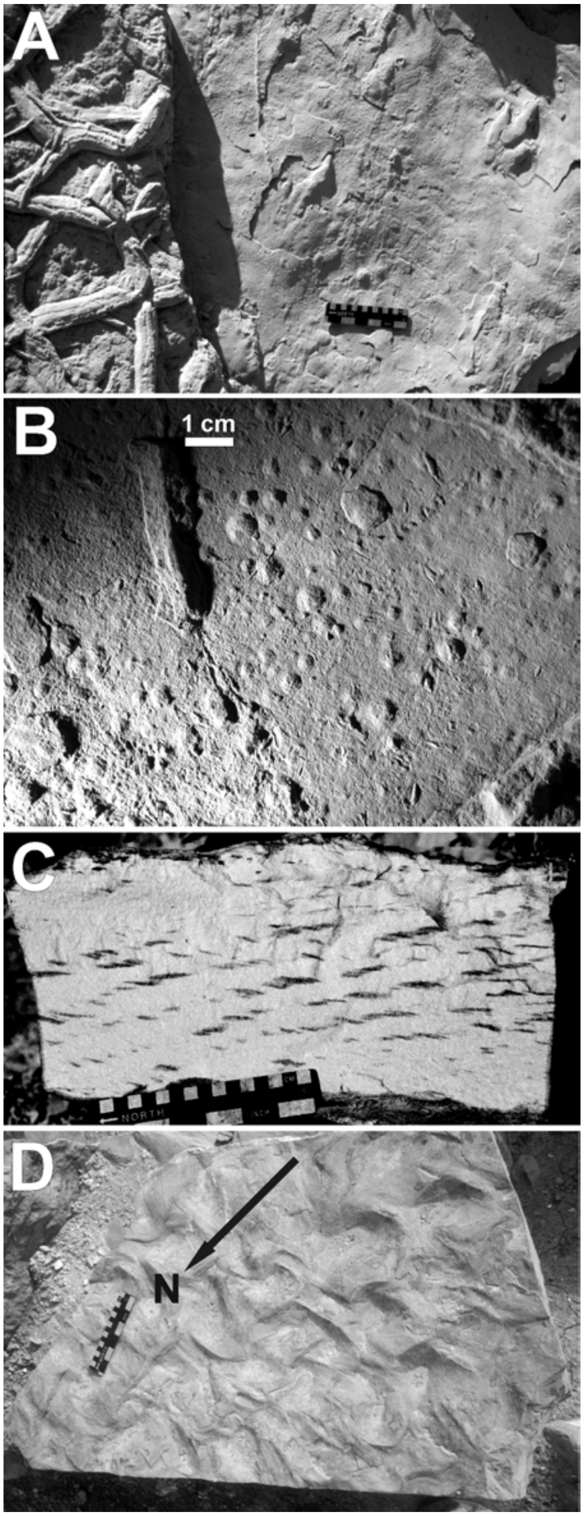

FIGURE 13. Sedimentary features preserved within the main track-bearing sandstone at the SGDS. **A**, Block showing the position of the "split layer" parting, with natural *Grallator* casts and asymmetric ripple marks about 10 cm above mudcracks preserved on the main track layer at the base of main track-bearing sandstone (specimen number pending). **B**, Close-up of the "split layer" parting surface with natural casts of rain drop impressions (SGDS.235). **C**, Cross-section of a portion of main track-bearing sandstone, displaying climbing ripple cross-bedding (SGDS.842). **D**, Interference ripples preserved on a major parting surface near the middle of the main track-bearing sandstone at the SGDS on the east side of Riverside Drive. Arrow points north.

parting referred to as the "split layer" by Milner et al. (this volume b) is developed about 10 cm above the MTL. The "split layer" preserves abundant small dinosaur tracks, invertebrate traces, and raindrop impressions (Fig. 13A, B). Fine puckering of the surface also suggests the presence of microbial mats and films binding the surface.

Internally, the main track-bearing sandstone preserves climbing ripple cross-bedding, indicating deposition under flowing water (Fig. 13C). Where partings occur, undulatory ripples are preserved (Fig. 13D). Although recognized across the entire area, the main track-bearing sandstone is cut completely away in small areas by later erosion, as discussed below. The main track-bearing sandstone typically varies from 10 cm to nearly one meter thick.

In the SGDS museum, a series of long ridges, spaced several meters apart and with as much as one-half meter of relief, are recognized at the top of the main track-bearing sandstone (Fig. 14). These ridges trend N70ºW. The relationship of the ridges and troughs to parting surfaces within the sandstone indicate that these are erosive megaripples formed by currents from the southwest crossing an initial sand bed about one meter thick (Reineck and Singh, 1975). The entire sandstone unit had been removed in one of the troughs between the erosive megaripples. Thin, ripple-marked sandstone beds 1-5 cm thick are present, mostly to the northeast of these megaripple crests, but also draping across them. These thin sandstone beds were formed from the sand eroded from the troughs between the megaripples. These thin sandstone beds are dominated by asymmetrical ripples demonstrating a southeast current direction, with fewer surfaces preserving either asymmetrical ripples indicating a northwest current direction or symmetrical wave ripples (Fig. 14). The northwest-southeast current directions indicated by the ripple-marks nearly parallel the crests of the erosive megaripples. Additionally, these thin ripple-marked sandstones preserve abundant dinosaur and crocodylomorph tracks together with relatively rare plant impressions (Fig. 15). Rill marks are also present, indicating water draining off this surface to the northwest (Fig. 14D) with microdeltas occasionally extending into the troughs from the sides of the megaripples.

The top surface of the main track-bearing sandstone (TS) is interpreted as a partially exposed beach, shoal, or spit along the coast of a large lake (Lake Dixie) that was being modified by waves impinging on it. The majority of the trackways mapped on the TS are directed either north or south (Milner et al., this volume b); because dinosaur trackways from other sites predominantly parallel ancient marine and lacustrine shorelines (e.g., Lockley, 1991), the shoreline is interpreted to also have been directed largely north-south. Therefore, the erosive megaripples preserved on the east side of Riverside Drive were formed at a high angle to the shoreline and may reflect the dominant angle at which large waves impinged on the shoreline, transporting sand along the shore. The smaller-scale, rippled sandstone beds preserved in the troughs and draped over the megaripples, together with other sedimentary structures, indicate that the megaripples focused water from smaller-scale waves onto the beach between the megaripples to the southeast. Subsequent drainage back off the beach was to the northwest, also between the megaripples. The predominance of asymmetric ripples indicating current directions to the southeast suggests that the dominant effect of sediment transport with "fair weather" waves was onshore. A simple model for the deposition of the main track-bearing sandstone is shown in Figure 14E.

One meter of reddish-purple shale overlies the main track-bearing sandstone (Figs. 9A, 16A). Near its base and middle, two thin volcanic ashes were recognized but proved to not be suitable for radiometric dating (B. Kowallis, personal commun., 2004). This shale also preserves partings that are covered with ostracodes (Schudack, this volume). The shale is, in turn, overlain by 70 cm of reddish-brown mudstone preserving disseminated ostracodes and conchostracan shells and isolated fish bones and scales (Fig. 3). These fine-grained sediments represent offshore lacustrine environments, and are penetrated from the top by sandstone-filled mudcracks up to 40 cm deep.

Where measured on the northwest side of Riverside Drive, a 65

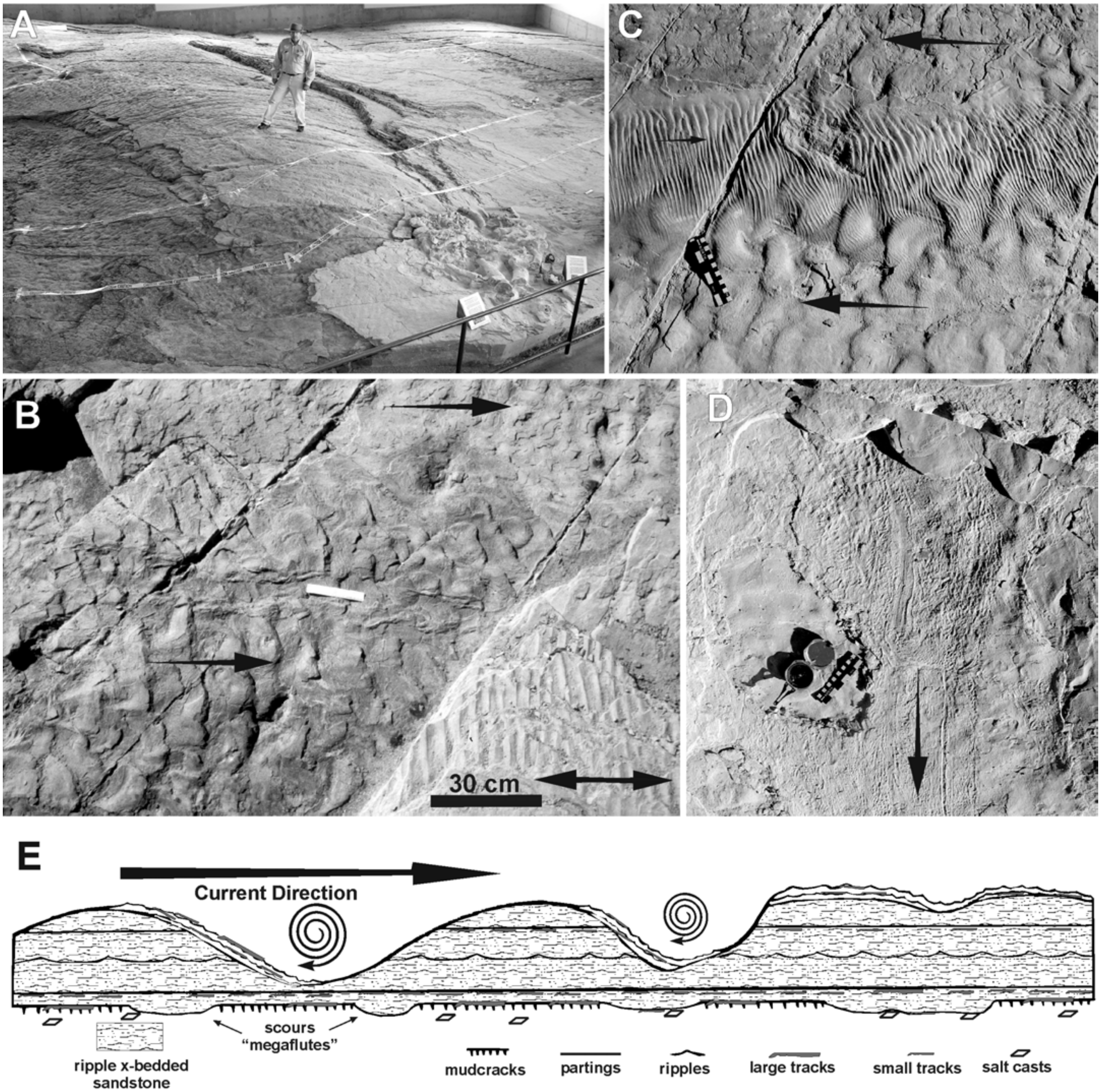

FIGURE 14. Sedimentary features preserved at the top of the main track-bearing sandstone at the SGDS in museum building (all SGDS.18). **A**, SGDS volunteer Monte Johnson standing on erosive megaripples at the top of the main track-bearing sandstone. **B,** Symmetric and asymmetric ripples on the top surface of the main track-bearing sandstone. Depressions represent poorly preserved *Grallator* tracks. Symmetrical ripple crests oriented N30ºE; joints directed N57°E. **C**, Large, northwest-directed, asymmetrical ripples superposed by small, northeast-directed, asymmetrical ripples on the north margin of the trough between the erosive megaripples. Joints directed N57°E. **D**, Branching rill marks formed by water draining NW, down the axes of troughs between the erosive megaripples. **E**, Model for the formation of the main track-bearing sandstone, based on Reineck and Singh, (1975, fig. 8), with the distribution of dinosaur tracks indicated.

cm thick, reddish-orange sandstone complex overlies these fine-grained strata; however, this sandstone pinches out to the south (Figs. 9, 16). The unit consists of four sandstone beds, each 10-25 cm thick and separated by mudstone partings. These sandstone beds preserve mudcracks and root casts with moderately well-preserved reptile tracks (*Eubrontes* and *Grallator* with rare *Anomoepus* and small quadruped tracks) on their upper surfaces (Fig. 16). This area is known as the Stewart-Walker Tracksite (SWS) (Milner et al., this volume b).

One of these surfaces preserves large depressions 25-60 cm across and 10-30 cm deep (Figs. 16B, D). These depressions were, at one point, thought to perhaps represent sauropod tracks, although the site is much older than any strata in North America preserving any tracks or body fossils of large sauropods. It has been proposed that perhaps these "pot holes" represent depressions made by fish nesting in the shallows, given their close association with fish swim traces (*Undichna*) on the same bedding surface. In at least one of these "pot holes," ripple marks indi-

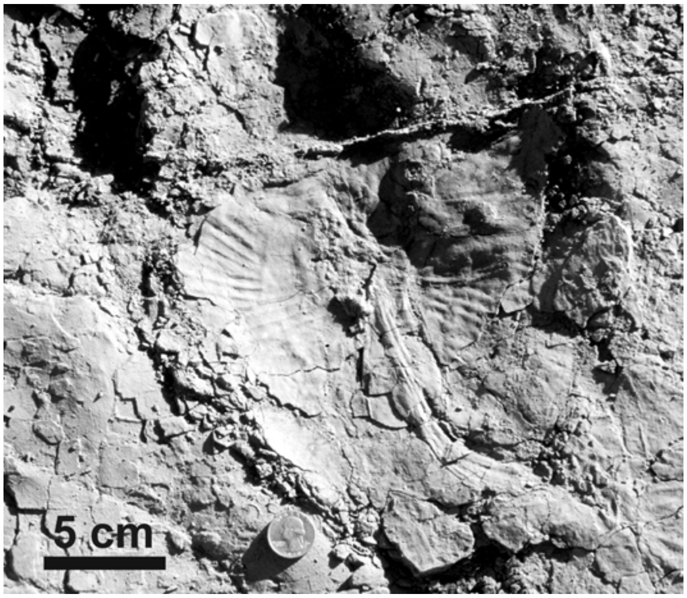

FIGURE 15. Unidentified plant impression preserved in a large *Eubrontes* track on the top surface of main track-bearing sandstone. This specimen is now preserved only as a cast at the SGDS (SGDS.913).

cate a subaqueous environment. These sandstones are interpreted as representing sand deposited near the lake margin.

These track-bearing sandstones are, in turn, overlain by 1.25 m of reddish-brown mudstone with scattered, thin layers of fine-grained sandstone (Fig. 3). These beds are lithologically similar to those at the contact between the Dinosaur Canyon and Whitmore Point members.

This intermixing of sedimentary features that indicate both subaerial and subaqueous environments documents significant lake level rise and fall during this interval of Whitmore Point Member deposition.

Middle Sandstone Dominated Interval

The next 7.64 m of section is characterized by interbedded, reddish-brown sandstone and mudstone (Fig. 17). The sandstones are much like those in the upper part of the Dinosaur Canyon Member in that they preserve mudcracks and dinosaur tracks and are internally ripple cross-bedded. However, these sandstones tend to be less well cemented, and the tracks are not quite so well preserved (e.g., the LDS Tracksite; Williams et al., this volume) (Fig. 17D). Invertebrate burrows are particularly abundant in this interval (Lucas et al., this volume b), along with common bones, fish scales and coprolites (Williams et al., this volume).

As with most of the ripple-bedded sandstones preserving tracks in the upper Dinosaur Canyon Member, these sandstones are interpreted as representing lake margin sand deposits emplaced by longshore currents. The sand entered the margin of the lake system outside the study area via fluvial channels presumably similar to those preserved in the lower part of the cliff-forming portion of the Dinosaur Canyon Member. Waves impinging on these sediments would have transported them laterally along the shore to some point where they were at equilibrium with overall energy conditions along the lakeshore.

Other outcrops of this interval of the Whitmore Point Member examined in the St. George area preserve notably less sandstone than to the west of Riverside Drive at the SGDS. The limited aerial extent of these sandstones at the SGDS suggests that they may represent an isolated spit or shoal that was only developed in the immediate vicinity of the SGDS.

Upper Shale Dominated Interval

The uppermost 6.55 m of the Whitmore Point Member consist of thin-bedded shale, siltstone, and fine-grained sandstone with minor, thin beds of limestone. This sequence consists mostly of coarsening upward cycles ~20-50 cm thick; each cycle is characterized by shale at its base containing fossil fish, conchostracans, and ostracodes, and capped by sandstone preserving algal laminae, stromatolites, mudcracks, mostly isolated bones and teeth, and locally abundant dinosaur tracks made up exclusively by *Grallator* (Figs. 18, 19). This bedding pattern may represent climatic cycles as are frequently reflected in finer-grained lacustrine facies. Other, less common features, such as sandstone dikes and soft sediment deformation features, also occur (Fig. 18).

Natural exposures of the upper shale interval northeast of Riverside Drive were relatively poor prior to preparation of the site for construction of Fossil Ridge Intermediate School. This process led to the development of low relief, clean exposures of these sediments on which we observed subtle sedimentary features such as mudcracks and poorly preserved dinosaur tracks (Fig. 18). Additionally, a great many vertebrate fossils were found (Kirkland et al., 2005; Milner et al., 2005; Milner and Lockley, 2006; Milner and Kirkland, this volume). Of particular interest was a sandstone bed near the top of the interval that preserved large bones, including many skull elements from large coelacanths (Milner and Kirkland, this volume) and isolated bones and teeth of theropod dinosaurs (Fig. 3). While the site preserving the dinosaur fossils has been set aside by the Washington County School District for further research, Fossil Ridge Intermediate School overlies most of these interesting strata. Attempts are underway to acquire additional acreage to preserve a large area of undeveloped properties to the east and south of Fossil Ridge Intermediate School and adjacent to the SGDS.

Many of the fossil vertebrates preserved in this interval are coated by reddish siderite concretions. They range from small, flat disks about one centimeter across, formed around isolated ganoid fish scales, to large masses tens of centimeters across, surrounding concentrations of isolated scales and bone (Fig. 20) and, in some cases, large, articulated fish. Some of these accumulations are unusual in being circular in cross-section and more than a meter long; they frequently contain concentrations of fish fossils and are thus referred to as “fish sticks” (Chin et al., 2003; Milner et al., 2005). The “fish sticks” are superficially similar to the chert-replaced tufa preserved at the base of the Whitmore Point Member and are currently under study by Karen Chin (University of Colorado).

Continued construction in the St. George area temporarily exposes new outcrops of the upper shale interval of the Whitmore Point Member. One particularly interesting exposure is below West Black Ridge (below the airport), along Bluff Street near 700 South, and is known as the “Dixie Lube Site.” At this site, a vertical exposure of the upper Whitmore Point Member to lower Springdale Sandstone Member of the Kayenta Formation is visible (Fig. 19). Thin sandstone beds are exposed at the top of the Whitmore Point Member below the scoured surface at the base of the coarser-grained sandstones of the Springdale Sandstone.

At the SGDS, the Springdale Sandstone unconformably overlies fine-grained lacustrine sediments of the Whitmore Point Member. Elsewhere, such as at the Dixie Lube Site (Fig. 19) and at Zion National Park, fine-grained sandstone beds are present below this unconformity and may represent sand accumulating along the margin of a shrinking Lake Dixie. Although commonly mapped with the Springdale Sandstone Member of the Kayenta Formation, these sandstones are genetically part of the Whitmore Point Member of the Moenave Formation.

Springdale Sandstone Member, Kayenta Formation

At the SGDS, the overlying Springdale Sandstone lies on an erosional surface with a meter or more of relief and represents the J-sub K (J-0’) unconformity of previous authors (e.g., Blakey, 1994; Marzolf, 1994; Lucas and Tanner, this volume). Locally, large clasts (10 cm and greater in diameter) of Whitmore Point lacustrine sediments are present in the basal Springdale Sandstone above this unconformity.

As nearly as can be determined, the Springdale Sandstone was measured herein close to the same path as Higgins and Willis (1995), who

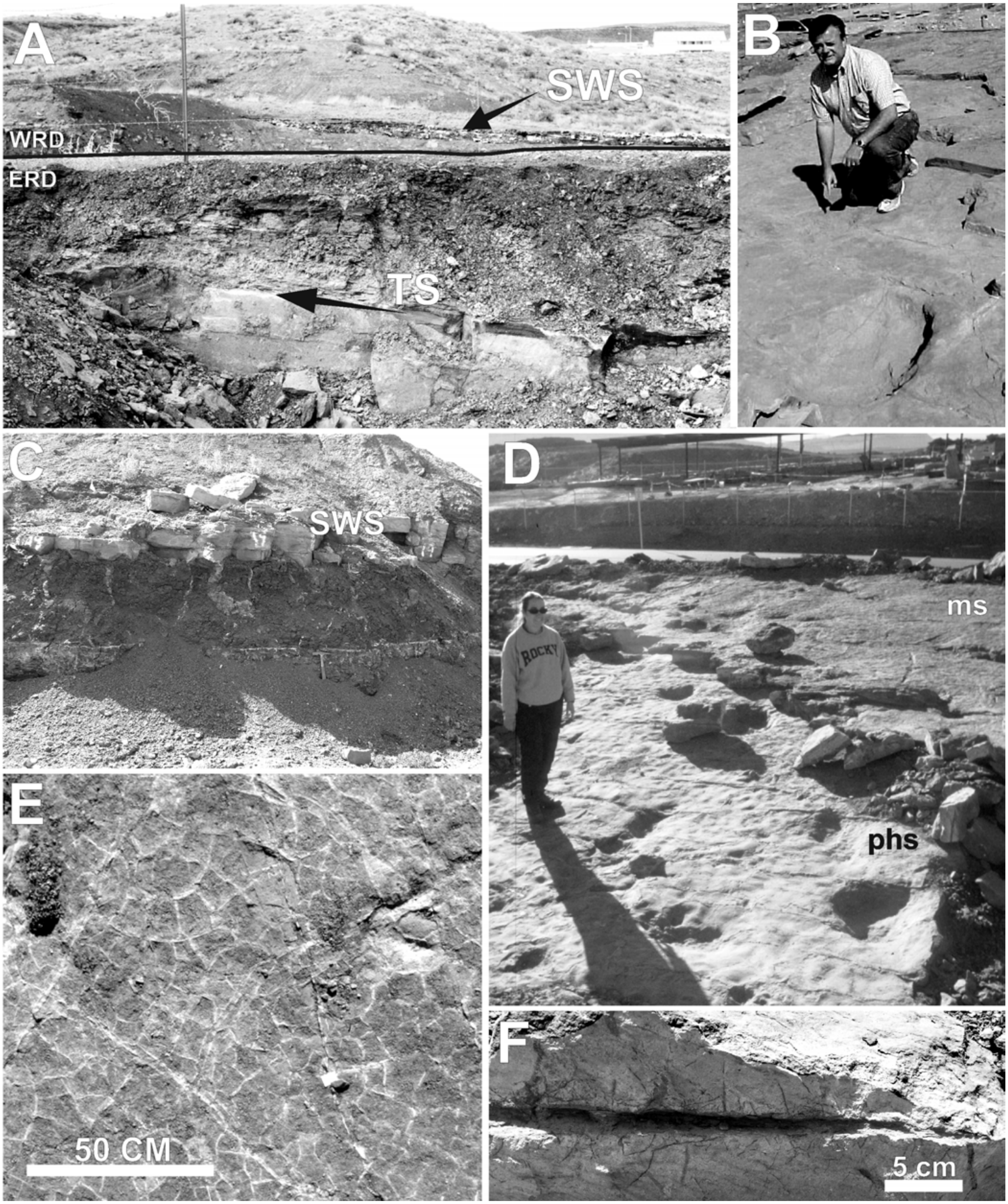

FIGURE 16. Sediments overlying the top of main track-bearing sandstone. **A**, Exposure on the east side of Riverside Drive in 2000 (fine-grained sediments have subsequently been removed from above the main track-bearing sandstone across the entire area). View to the west across Riverside Drive. **B**, Darcy Stewart by a “pot hole” (possible fish nesting structure) at the Stewart-Walker Tracksite on the east side of Riverside Drive. **C**, Close-up of sediments overlying the main track-bearing sandstone on the west side of Riverside Drive. The top surface of the main track-bearing sandstone is approximately at bottom of photograph. Rock hammer for scale. **D**, Upper sandstones at the Stewart-Walker Tracksite. **E**, Surface of the uppermost, mud-cracked sandstone at the Stewart-Walker Tracksite. **F**, Rhizolith in sandstone fill taken from the “pot hole” in **B** (SGDS.915). Abbreviations: ERD, east side of Riverside Drive; ms, uppermost mud-cracked sandstone; phs, sandstone with large “pot-hole” structures that may be fish nesting structures; SWS, upper sandstones preserving the Stewart-Walker Tracksite on the west side of Riverside Drive; TS, top surface of main track-bearing sandstone; WRD, west side of Riverside Drive.

FIGURE 17. Middle sandstone interval of Whitmore Point Member of the Moenave Formation west of Riverside Drive. **A**, Former construction site of the present-day Fossil Ridge Intermediate School exposing the middle sandstone interval. **B**, Resulting exposure of the middle sandstone interval from the northwest. **C**, Same exposure from the west. **D**, LDS Tracksite near the top of the middle sandstone interval. Abbreviations: bs, base of middle sandstone interval; ts, top of middle sandstone interval.

measured a total thickness of 35 m as compared to 27.85 m measured by us. The Springdale Sandstone is mostly pale yellowish-brown and stands out in contrast to the dominantly red to mauve-colored sediments above and below it (Fig. 21). It is a medium- to coarse-grained, 0.5-1.0 m scale, planar and trough cross-bedded fluvial sandstone with minor, discontinuous mudstone partings. Chert pebbles are locally concentrated at the bases of some of the larger cross-bed sets. Small amounts of petrified wood, including large logs, are also present in this member. Where the Springdale Sandstone was measured below Middleton Black Ridge, a couple of thin (2 cm) dikes (veins) of possible igneous material were observed in joints (Fig. 21B). The Springdale Sandstone represents an extensive braided river system that developed across southwestern Utah and north-central Arizona. Because it is well cemented, the Springdale Sandstone Member serves as a stable substrate for many of the homes that have been constructed east of the SGDS.

The lower, unnamed member of the Kayenta Formation conformably overlies the Springdale Sandstone (Higgins and Willis, 1995). The lower unnamed member is dominantly fine grained near its base and appears to represent a large lacustrine unit. Ganoid scales are present in these sediments at Zion National Park (DeBlieux et al., 2004, this volume). The uppermost Springdale below this contact consists of sheet sandstones with ripple marks interpreted to represent the fluvial Springdale reworked into lake margin deposits (Fig. 21). Dinosaur tracksites are common along this contact in the St. George and Zion National Park area (Miller et al., 1989; Smith et al., 2002; DeBlieux et al., 2004, this volume; Hamblin, 2006; Hamblin et al., this volume; Lockley et al., this volume). The abundance of dinosaur tracks at the top of the Springdale Sandstone Member apparently extends southeast to Tuba City, Arizona and has been referred to as the Springdale Megatracksite (Lucas et al., 2005a).

CONCLUSIONS

Lower Jurassic strata in the St. George area have received little attention, but the ongoing and rapid development of the region has provided, and is providing, numerous excellent, although short-lived, exposures that provide excellent research opportunities. The numerous dinosaur track sites preserved at the SGDS are all preserved in marginal and shallow lacustrine paleoenvironments, as indicated by the intimate association of mudcracks, ripple marks, and ripple cross-bedding. Additionally, the interbedding of coastal and shallow lacustrine facies indicates that lake levels fluctuated considerably over relatively short time spans, reflecting alternating periods of drought and high rainfall; larger time spans perhaps reflect climatic cycles.

The main track-bearing sandstone in particular preserves a complex history of rising and falling lake levels. The large-scale scours and erosive megaripples (Fig. 14) provide direct evidence of large waves supporting the hypothesis that Lake Dixie was a large lake that may have extended across the entire Whitmore Point outcrop belt when lake levels were high.

Although the present research provides considerable new data

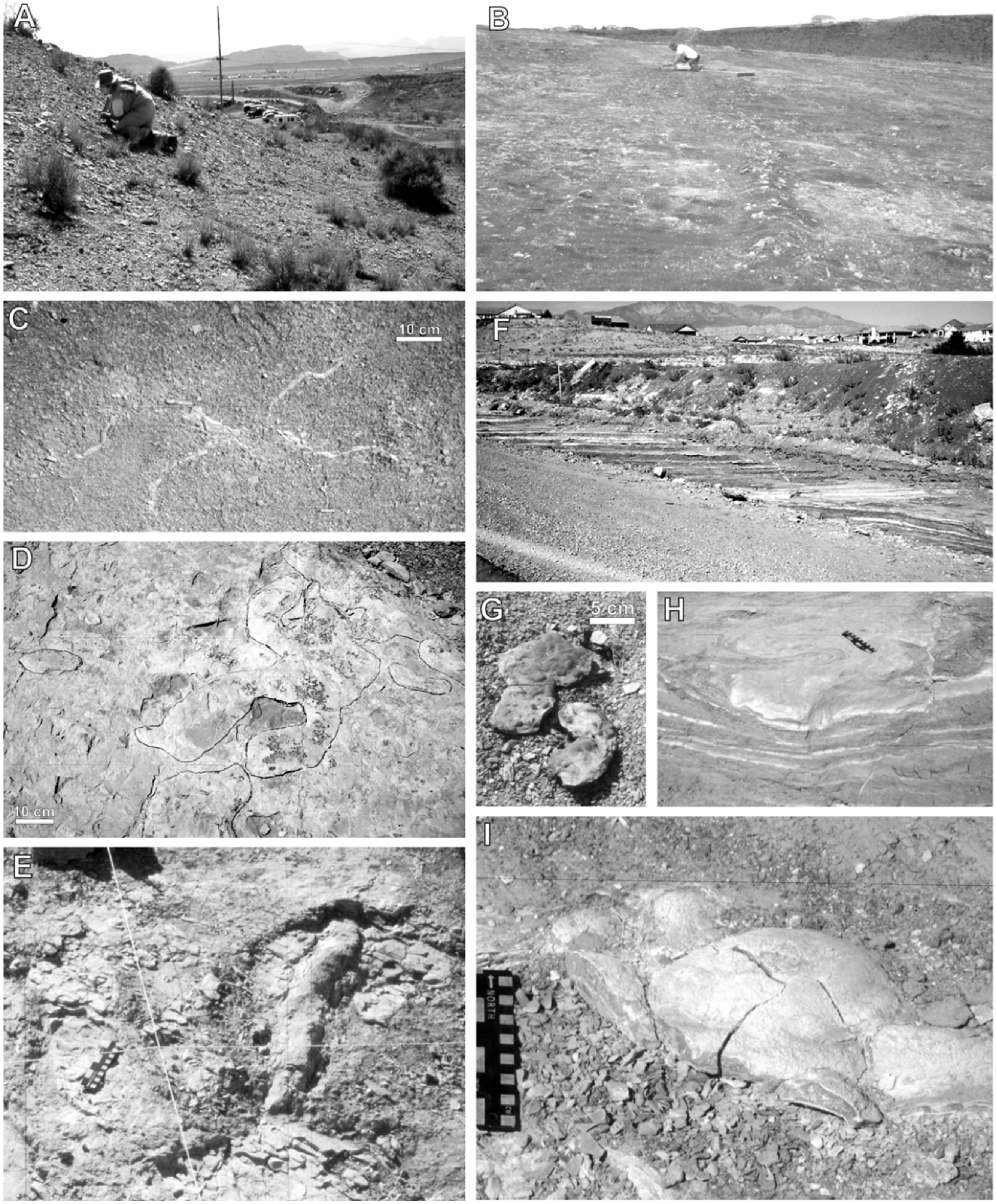

FIGURE 18. Upper shale interval of the Whitmore Point Member of the Moenave Formation west of Riverside Drive. **A**, Natural exposure of the Whitmore Point Member in 2000. **B**, Exposure of the Whitmore Point Member following initial leveling for Fossil Ridge Intermediate School. **C**, Mudcracks exposed on a weathered bedding surface. **D**, Flat siderite concretions exposed on a bedding surface. Small black flecks are ganoid scales. **E**, Elongate siderite concretion ("fish stick") naturally exposed parallel to bedding. **F**, Temporary exposure of the upper shale interval of the Whitmore Point Member in a gully along Mall Drive (currently below the sidewalk in front of Fossil Ridge Intermediate School. **G**, Typical siderite concretions from the upper shale interval. Dark lumps are built up around ganoid scales. **H**, Load and flame structures previously exposed along Mall Drive. **I**, Stromatolite layer previously exposed along Mall Drive.

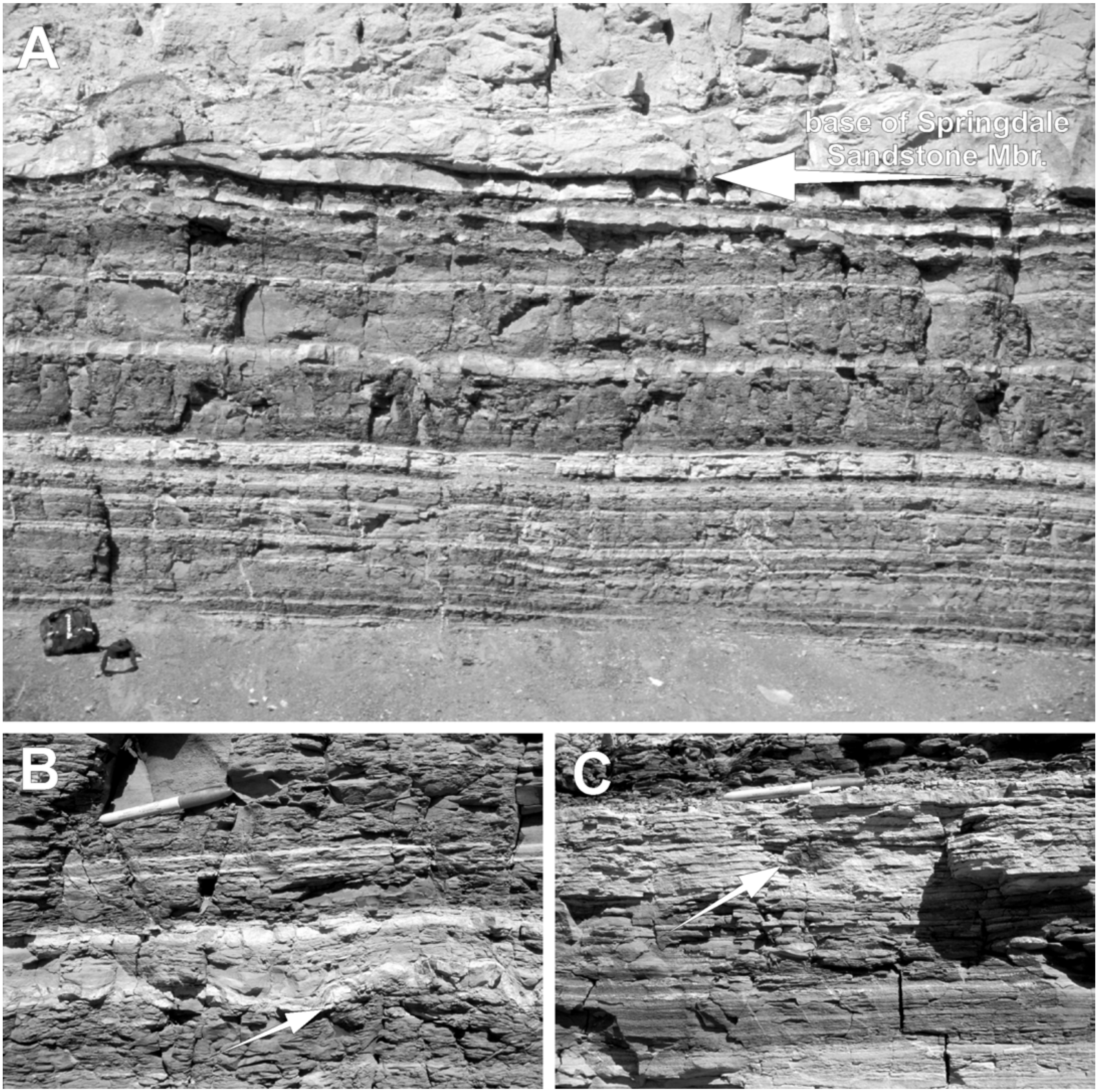

FIGURE 19. Upper shale interval of the Whitmore Point Member exposed below West Black Ridge along Bluff Street near 700 South (Dixie Lube Site). **A**, Vertical exposure of the upper shale interval showing its contact with the overlying Springdale Sandstone Member of Kayenta Formation. Backpack in foreground is about 50 cm (20 in) across. **B**, Stromatolite layer with "Sharpie" pen for scale. Arrow points to a stromatolite layer. **C,** Cross-section through a siderite concretion preserving bone with "Sharpie" pen for scale. Arrow points to a siderite concretion.

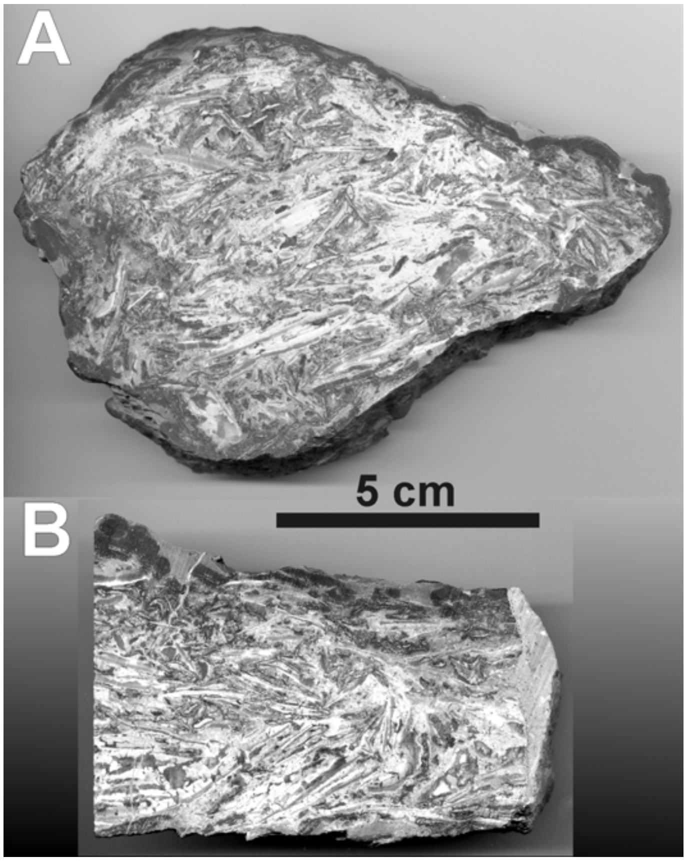

FIGURE 20. Cross-sections of typical masses of siderite concretions as in Figure 18G, preserving masses of disarticulated fish bones and scales. **A,** Cross section. **B,** Cross section at 90º to cross section in **A**.

concerning the Moenave Formation in this area, the extensive outcrop belt of these sediments across southwestern Utah calls out to future researchers to examine this fluvial-lacustrine system in more detail, putting these interesting rocks into a fuller temporal and paleogeographic context.

ACKNOWLEDGMENTS

We thank Sheldon and LaVerna Johnson, Darcy Stewart and Bodega Development Corporation, Theresa Walker (former City of St. George Tracksite Coordinator at the SGDS), Washington County School District, Quality Excavation, City of St. George, Willie, Aaron and Lester Jessop of Steed-RW Construction, and Gonzalez Excavation for outstanding contributions to the SGDS, and in the preservation and protection this incredible site. We are indebted to all of dedicated volunteers at the SGDS and from the Utah Friends of Paleontology. Partial funding provided by the Utah Geological Survey, City of St. George, and the DinosaurAh!Torium Foundation. Thanks to Jennifer Cavin, Don DeBlieux, Mike Lowe, and Robert Ressetar for reviewing the manuscript for UGS. Jerry Harris, Bob Biek, Grant Willis, and Spencer Lucas provided technical reviews of the manuscript making suggestions and comments that have greatly improved it.

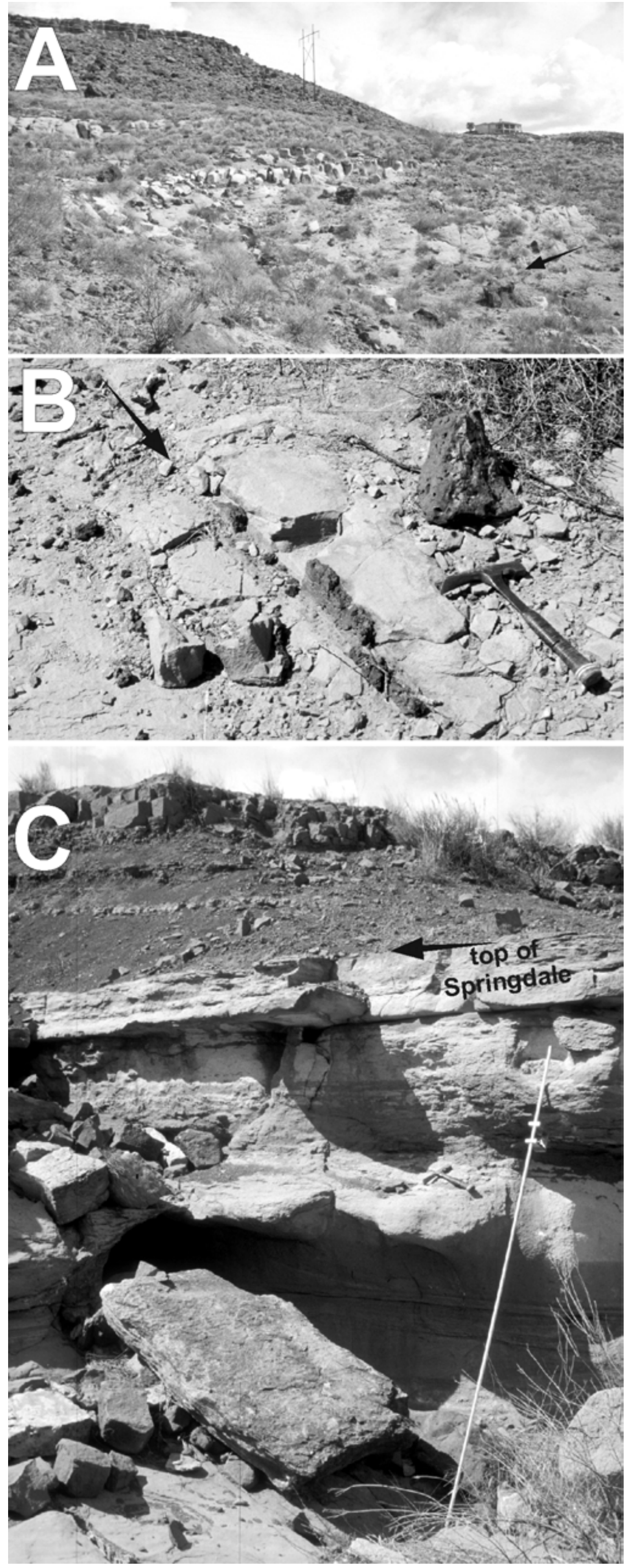

FIGURE 21. Springdale Sandstone Member of the Kayenta Formation below Middleton Black Ridge. **A**, Outcrop of the Springdale Sandstone; base indicated by arrow. The top of the member is obscured by basalt talus from a lava flow capping the ridge. **B**, Thin igneous dike (arrow) along a joint in the Springdale Sandstone. Hammer for scale. **C**, Contact between the Springdale Sandstone and unnamed lower shale member of Kayenta Formation.

REFERENCES

Biek, R.F., 2003a, Geologic map of the Hurricane quadrangle, Washington County, Utah: Utah Geological Survey Map 187, 61 p., scale 1:24,000.

Biek, R.F., 2003b, Geologic map of the Harrisburg Junction quadrangle, Washington County, Utah: Utah Geological Survey Map 191, 42 p., scale 1:24,000.

Blakey, R.C., 1994, Paleogeographic and tectonic controls on some Lower and Middle Jurassic erg deposits, Colorado Plateau, *in* Caputo, M.V., Peterson, J.A. and Franczyk, K.J., eds., Mesozoic systems of the Rocky Mountain region, USA: Denver, Rocky Mountain Section of the SEPM, p. 273-298.

Chin, K., Kirkland, J.I., Milner, A.R.C. and Mickelson, D.L., 2003, Distinctive accumulations of fossil fish debris in the Moenave Formation tell a story of life and death in a biotically productive, Early Jurassic lake near St. George, Utah: Journal of Vertebrate Paleontology, v. 23, p. 40A.

Clark, J.M. and Fastovsky, D.E., 1986, Vertebrate biostratigraphy of the Glen Canyon Group in northern Arizona, *in* Padian, K., ed., The beginning of the Age of Dinosaurs: faunal change across the Triassic-Jurassic boundary: Cambridge, Cambridge University Press, p. 285-301.

Cornet, B. and Waanders, G., this volume, Palynomorphs indicate Hettangian (Early Jurassic) age for the middle Whitmore Point Member of the Moenave Formation, Utah and Arizona: New Mexico Museum of Natural History and Science, Bulletin 37.

Davis, J.D., 1977a, Paleoenvironments of the Moenave Formation, St. George, Utah: Brigham Young University Geological Studies, v. 24, no. 2, p. 17-31.

Davis, J.D., 1977b, Dinosaur Canyon Member of the Triassic Moenave Formation of southwest Utah, *in* Heisey, E.L., Lawson, D.E., Norwood, E.R., Wach, P.H. and Hale, L.A., eds., Rocky Mountain Thrust Belt geology and resources: Wyoming Geological Association 29th annual field conference in conjunction with Montana Geological Society and Utah Geological Society: Casper, Wyoming Geological Association, p. 201-206.

Day, B.S., 1967, Stratigraphy of the Upper Triassic (?) Moenave Formation of southwestern Utah [M.S. thesis]: Salt Lake City, University of Utah, 58 p.

DeBlieux, D.D., Smith, J.A., McGuire, J.L., Kirkland, J.I. and Santucci, V.L., 2004, Zion National Park survey: National Park Service Technical Report TIC# D-177, 89 p.

DeBlieux, D.D., Kirkland, J.I., Smith, J.A., McGuire, J.L. and Santucci, V.L., this volume, An overview of the paleontology of Upper Triassic and lower Jurassic rocks in Zion National Park: New Mexico Museum of Natural History and Science, Bulletin 37.

Donohoo-Hurley, L.L., Geissman, J.W., Roy, M. and Lucas, S.G., 2006, Toward an improved definition of the J1-cusp: new paleomagnetic data from the Triassic to lowermost Jurassic, Moenave Formation, Utah: Museum of Northern Arizona, Bulletin 62, p. 162.

Gregory, H.E., 1950, Geology and geography of the Zion Park region, Utah and Arizona: U.S. Geological Survey Professional Paper, v. 220, p. 1-200.

Hamblin, A.H., 2006, Spectrum Tracksite – also known as the Grapevine Pass Wash Tracksite, *in* Reynolds, R.E., ed., Making tracks across the southwest: the 2006 Desert Symposium field guide and abstracts from proceedings: Zzyzx, Desert Studies Consortium and LSA Associates, Inc., p. 29-34.

Hamblin, A.H., Lockley, M.G. and Milner, A.R.C., this volume, More reports of theropod dinosaur tracksites from the Kayenta Formation (Lower Jurassic), Washington County, Utah: implications for describing the Springdale megatracksite: New Mexico Museum of Natural History and Science, Bulletin 37.

Harshbarger, J.W., Repenning, C.A. and Irwin, J.H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo Country: U.S. Geological Survey Professional Paper, v. 291, p. 1-74.

Higgins, J.M. and Willis, G.C., 1995, Interim geologic map of the St. George quadrangle, Washington County, Utah: Utah Geological Survey Open-File Report 323, 114 p., scale 1:24,000.

Kirkland, J.I., Lockley, M.G. and Milner, A.R.C., 2002, The St. George dinosaur tracksite: Utah Geological Survey, Survey Notes, v. 34, no. 3, p. 4-5, 12.

Kirkland, J.I., Milner, A.R.C. and Nesbitt, S.J., 2005, The case for theropod dinosaurs exploiting fish as a major food resource during the Early Jurassic: The Triassic/Jurassic terrestrial transition, abstracts volume, p. 9.

Litwin, R.J., 1986, The palynostratigraphy and age of the Chinle and Moenave formations, southwestern U.S.A. [Ph.D. dissertation]: State College, Pennsylvania State University, 266 p.

Lockley, M.G., 1991, Tracking dinosaurs: a new look at an ancient world: Cambridge, Cambridge University Press, 238 p.

Lockley, M.G., Conrad, K., Paquette, M. and Hamblin, A., 1992, Late Triassic vertebrate tracks in the Dinosaur National Monument area: Utah Geological Survey Miscellaneous Publications, v. 92-3, p. 383-391.

Lockley, M.G., Lucas, S.G., Hunt, A.P. and Gaston, R., 2004, Ichnofaunas from the Triassic-Jurassic boundary sequences of the Gateway area, western Colorado: implications for faunal composition and correlation with other areas: Ichnos, v. 11, p. 89-102.

Lockley, M.G., Milner, A.R.C., Slauf, D. and Hamblin, A.H., this volume, Dinosaur tracksites from the Kayenta Formation (Lower Jurassic), Desert Tortoise site, Washington County, Utah: New Mexico Museum of Natural History and Science, Bulletin 37.

Lucas, S.G., 1993, The Chinle Group: revised stratigraphy and biochronology of Upper Triassic strata in the western United States: Museum of Northern Arizona, Bulletin 59, p. 27-50.

Lucas, S.G. and Heckert, A.B., 2001, Theropod dinosaurs and the Early Jurassic age of the Moenave Formation, Arizona-Utah, USA: Neues Jahrbuch für Geologie und Paläontologie, v. 2001, p. 435-448.

Lucas, S.G., Heckert, A.B. and Tanner, L.H., 2005a, Arizona's Jurassic fossil vertebrates and the age of the Glen Canyon Group: New Mexico Museum of Natural History and Science, Bulletin 29, p. 95-104.

Lucas, S.G., Tanner, L.H. and Heckert, A.B., 2005b, Tetrapod biostratigraphy and biochronology across the Triassic-Jurassic boundary in northeastern Arizona: New Mexico Museum of Natural History and Science, Bulletin 29, p. 84-93.

Lucas, S.G., Heckert, A.B., Estep, J.W. and Anderson, O.J., 1997a, Stratigraphy of the Upper Triassic Chinle Group, Four Corners region: New Mexico Geological Society, Guidebook 48, p. 81-107.

Lucas, S.G., Heckert, A.B., Anderson, O.J. and Estep, J.W., 1997b, Phytosaur from the Wingate Sandstone in southeastern Utah and the Triassic-Jurassic boundary on the Colorado Plateau, *in* Anderson, B., Boaz, D. and McCord, R.D., eds., Southwest Paleontological Symposium proceedings, volume 1: Mesa, Mesa Southwest Museum and Southwest Paleontological Society, p. 49-59.

Lucas, S.G., Lockley, M.G., Hunt, A.P. and Tanner, L.H., this volume a, Biostratigraphic significance of tetrapod footprints from the Triassic-Jurassic Wingate Sandstone on the Colorado Plateau: New Mexico Museum of Natural History and Science, Bulletin 37.

Lucas, S.G., Lerner, A.J., Milner, A.R.C. and Lockley, M.G., this volume b, Lower Jurassic invertebrate ichnofossils from a clastic lake-margin, Johnson Farm, southwestern Utah: New Mexico Museum of Natural History and Science, Bulletin 37.

Lucas, S.G. and Tanner, L.H., this volume, The Springdale Sandstone Member of the Kayenta Formation, Lower Jurassic of Utah-Arizona: New Mexico Museum of Natural History and Science, Bulletin 37.

Lucas, S.G., Tanner, L.H. and Heckert, A.B., 2005, Tetrapod biostratigraphy and biochronology across the Triassic-Jurassic boundary in northeastern Arizona: New Mexico Museum of Natural History and Science, Bulletin 29, p. 84-94.

Luttrell, P.R. and Morales, M., 1993, Bridging the gap across the Moenkopi Wash: a lithological correlation: Museum of Northern Arizona, Bulletin 59, p. 111-127.

Marzolf, J.E., 1993, Palinspastic reconstruction of Early Mesozoic sedimentary basins near the latitude of Las Vegas: implications for the Early Mesozoic Cordilleran cratonic margin, *in* Dunne, G.C. and McDougall, K.A., eds., Mesozoic paleogeography of the western United States II: Los Angeles, Pacific Section of the SEPM, p. 433-462.

Marzolf, J.E., 1994, Reconstruction of the early Mesozoic Cordilleran cratonal margin adjacent to the Colorado Plateau, *in* Caputo, M.V., Peterson, J.A. and Franczyk, K.J., eds., Mesozoic systems of the Rocky Mountain region, USA: Denver, Rocky Mountain section of the SEPM, p. 181-216.

Miller, W.E., Britt, B.B. and Stadtman, K.L., 1989, Tridactyl trackways from the Moenave Formation of southwestern Utah, *in* Gillette, D.D. and Lockley, M.G., eds., Dinosaur tracks and traces: Cambridge, Cambridge University Press, p. 209-215.

Milner, A.R.C. and Lockley, M.G., 2006, History, geology and paleontology: St. George Dinosaur Discovery Site at Johnson Farm, Utah, *in* Reynolds, R.E., ed., Making tracks across the southwest: the 2006 Desert Symposium field guide and abstracts from proceedings: Zzyzx, Desert Studies Consortium and LSA Associates, Inc., p. 35-48.

Milner, A.R.C., Ferris-Rowley, D. and Kirkland, J.I., 2006, A BLM Paleontological Site Stewartship Program for Washington County, southwestern Utah: the beginning of a nation-wide program: New Mexico Museum of Natural History and Science, Bulletin 34, p. 145-151.

Milner, A.R.C. and Kirkland, J.I., this volume, Preliminary review of the Early Jurassic (Hettangian) freshwater Lake Dixie fish fauna in the Whitmore Point Member, Moenave Formation in southwest Utah: New Mexico Museum of Natural History and Science Bulletin, v. 37.

Milner, A.R.C., Kirkland, J.I., and Birthisel, T.A., this volume a, The geographic distribution and biostratigraphy of Late Triassic-Early Jurassic freshwater fish faunas of the southwestern United States: New Mexico Museum of Natural History and Science Bulletin, v. 37.

Milner, A.R.C., Kirkland, J.I., Chin, K. and Mickelson, D.L., 2005, Late Triassic-Early Jurassic freshwater fish faunas of the southwestern United States with emphasis on the Lake Dixie portion of the Moenave Formation, southwest Utah: The Triassic/Jurassic terrestrial transition, abstracts volume, p. 17.

Milner, A.R.C., Lockley, M.G. and Johnson, S.B., this volume b, The story of the St. George Dinosaur Discovery Site at Johnson Farm: an important new Lower Jurassic dinosaur tracksite from the Moenave Formation of southwestern Utah: New Mexico Museum of Natural History and Science, Bulletin 37.

Milner, A.R.C., Lockley, M.G. and Kirkland, J.I., this volume c, A large collection of theropod dinosaur swim tracks from the Lower Jurassic Moenave Formation, St. George Utah: New Mexico Museum of Natural History and Science, Bulletin 37.

Molina-Garza, R.S., Geissman, J.W. and Lucas, S.G., 2003, Paleomagnetism and magnetostratigraphy of the lower Glen Canyon and upper Chinle Groups, Jurassic-Triassic of northern Arizona and northeast Utah: Journal of Geophysical Research v. 108, p. 2181-2204.

Morales, M. and Ash, S.R., 1993, The last phytosaurs?: New Mexico Museum of Natural History and Science, Bulletin 3, p. 357-358.

Odier, G., Lockley, M. and Lucas, S., 2004, Vertebrate ichnology at the Triassic-Jurassic boundary in eastern Utah: new evidence from the Wingate Formation: Journal of Vertebrate Paleontology, v. 24, p. 99A.

Olsen, P.E. and Padian, K., 1986, Earliest records of *Batrachopus* from the southwestern United States, and a revision of some early Mesozoic crocodylomorph ichnogenera, *in* Padian, K., ed., The beginning of the Age of Dinosaurs: faunal change across the Triassic-Jurassic boundary: Cambridge, Cambridge University Press, p. 258-273.

Olsen, P.E., McCune, A.R. and Thomson, K.S., 1982, Correlation of the early Mesozoic Newark Supergroup by vertebrates, principally fishes: American Journal of Science, v. 282, p. 1-44.

Olsen, P.E., Kent, D.V., Sues, H.-D., Koeberl, C., Huber, H., Montanari, A., Rainforth, E.C., A., Fowell, S.J., Szajna, M.J. and Hartline, B.W., 2002, Ascent of dinosaurs linked to an iridium anomaly at the Triassic-Jurassic boundary: Science, v. 296, p. 1305-1307.

Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior basin, *in* Caputo, M.V., Peterson, J.A. and Franczyk, K.J., eds., Mesozoic systems of the Rocky Mountain region, USA: Denver, Rocky Mountain Section of the SEPM, p. 233-272.

Peterson, F. and Piperingos, G.N., 1979, Stratigraphic relations of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona: U.S. Geological Survey Professional Paper, v. 1035-B, p. 1-43.

Pipiringos, G.N. and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States – a preliminary survey: United States Geological Survey Professional Paper, v. 1035-A, p. 1-29.

Queen, E.B., 1988, A depositional environmental analysis of the Moenave Formation, Zion National Park, Springdale, Utah [M.S. thesis]: Nacogdoches, Stephen F. Austin State University, 80 p.

Reineck, H.-E. and Singh, I.B., 1975, Depositional sedimentary environments, with reference to terrigenous clastics: New York, Springer Verlag, 439 p.

Riggs, N.R. and Blakey, R.C., 1993, Early and Middle Jurassic paleogeography and volcanology of Arizona and adjacent areas, *in* Dunne, G.C. and McDougall, K.A., eds., Mesozoic paleogeography of the western United States II: Los Angeles, Pacific Section of the SEPM, p. 347-373.

Schudack, M.E., this volume, Basal Jurassic nonmarine ostracodes from the Moenave Formation of St. George, Utah: New Mexico Museum of Natural History and Science, Bulletin 37.

Smith, J.A., Sampson, S., Loewen, M. and Santucci, V., 2002, Trackway evidence of possible gregarious behaviour in large theropods, from the Lower Jurassic Moenave Formation of Zion National Park: Journal of Vertebrate Paleontology, v. 22, p. 108A.

Tidwell, W.D., and Ash, S.R., this volume, Preliminary report on the Early Jurassic flora at the St. George Dinosaur Discovery Site at Johnson Farm: New Mexico Museum of Natural History and Science Bulletin, v. 37.

Williams, J.A.J., Milner, A.R.C. and Lockley, M.G., this volume, The Early Jurassic (Hettangian) LDS Dinosaur Tracksite from the Moenave Formation in St. George, Utah: New Mexico Museum of Natural History and Science, Bulletin 37.

Wilson, R.F., 1967, Whitmore Point, a new member of the Moenave Formation in Utah and Arizona: Plateau, v. 40, p. 29-40.