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

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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.

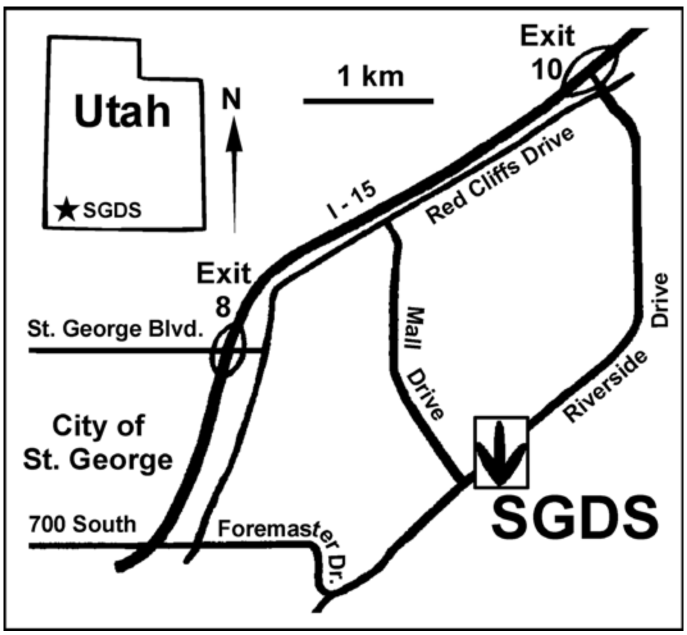

FIGURE 1. Location of the St. George Dinosaur Discovery Site at Johnson Farm (SGDS).

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

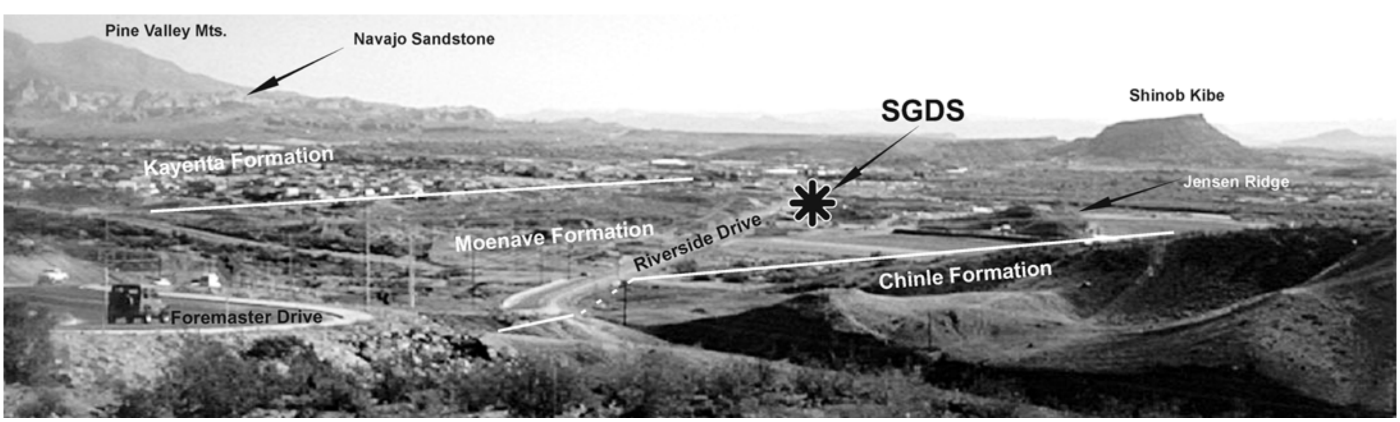

FIGURE 2. Overview of the SGDS and surrounding area, looking north from Foremaster Drive on Middleton Black Ridge.

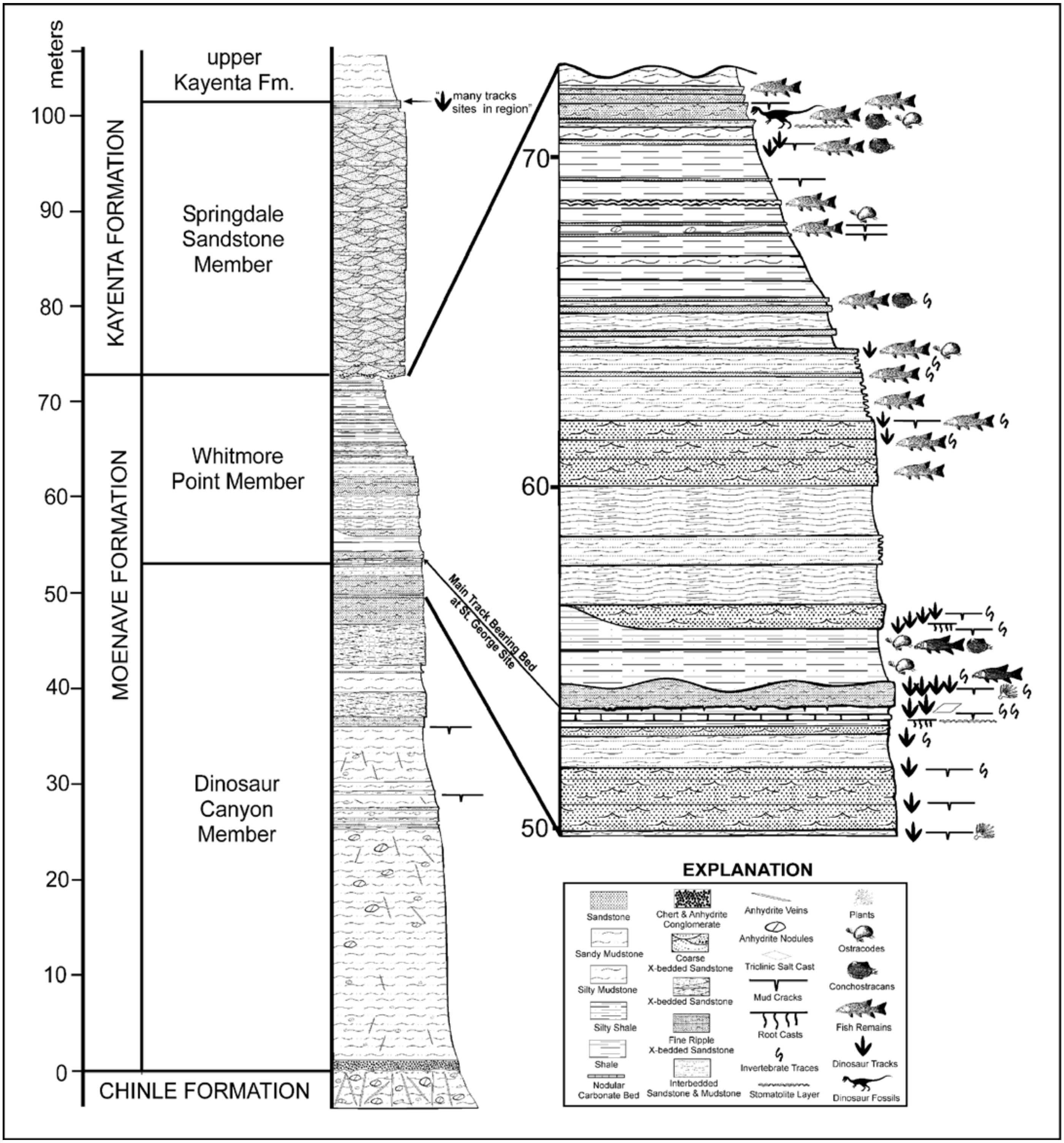

FIGURE 3. Stratigraphic section of the Moenave Formation at the SGDS with the stratigraphic positions of descriptive units used in the text, significant fossils, and sedimentological features indicated.

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

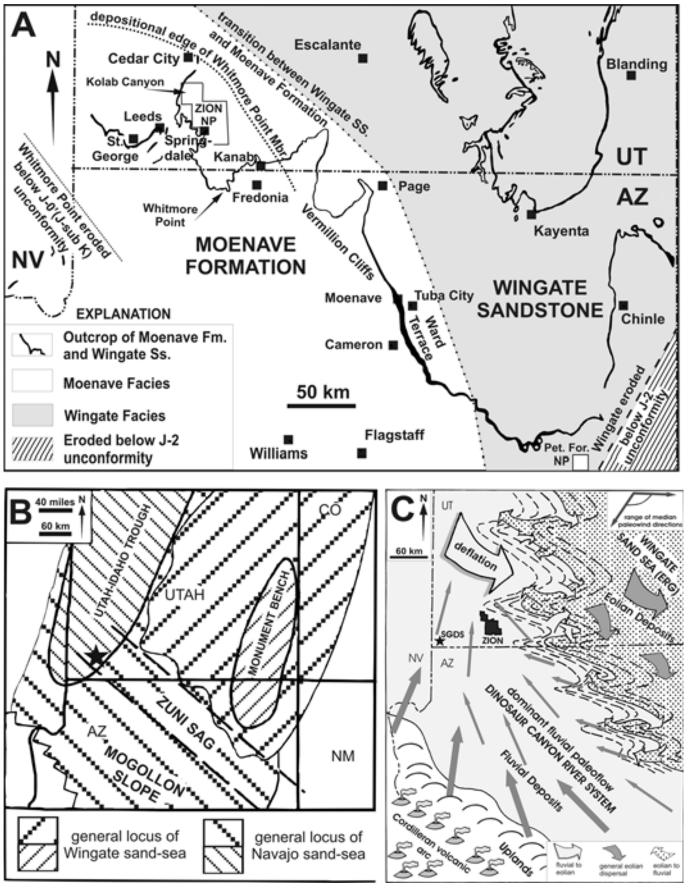

FIGURE 4. **A**, Outcrop map of Moenave Formation and Wingate Sandstone with large scale facies patterns and geographic features discussed in text. **B**, Structural setting for deposition of uppermost Triassic and Lower Jurassic eolian deposits in the southwestern United States (after Blakey, 1994).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

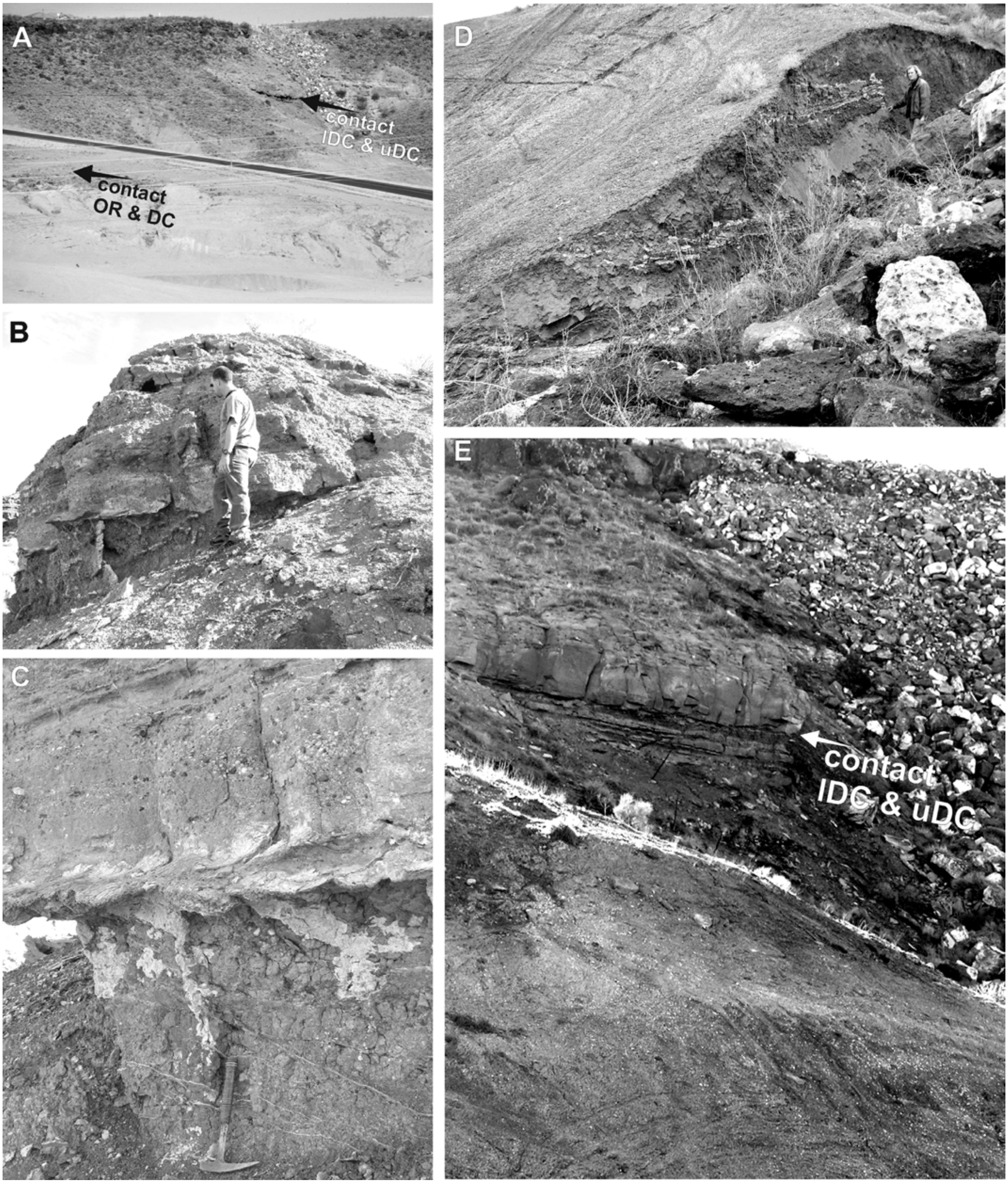

FIGURE 5. Dinosaur Canyon Member of Moenave Formation below Middleton Black Ridge and at Warner Valley. **A**, Upper Triassic through basal Jurassic section exposed on southeastern side of Middleton Black Ridge. View to the west looking across Foremaster Drive. Present Riverside Drive extends across 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.

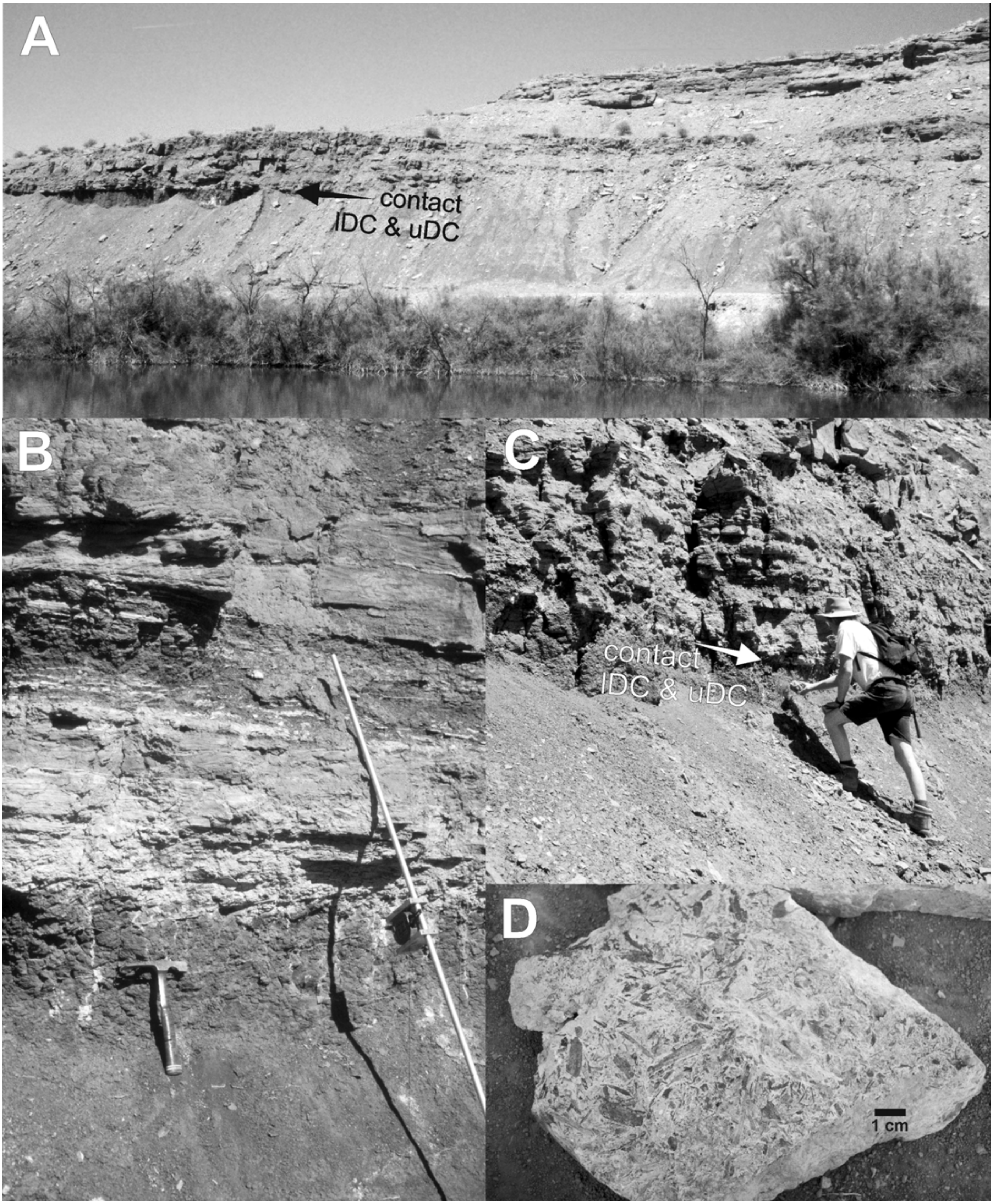

FIGURE 6. Dinosaur Canyon Member of the Moenave Formation on the southeast side of Riverside Drive. **A**, Exposure of the Dinosaur Canyon Member on the east side of Jensen Ridge, southeast of the SGDS. Contact with the underlying Chinle Formation lies below the surface of the pond. **B-C**, Close-up 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-

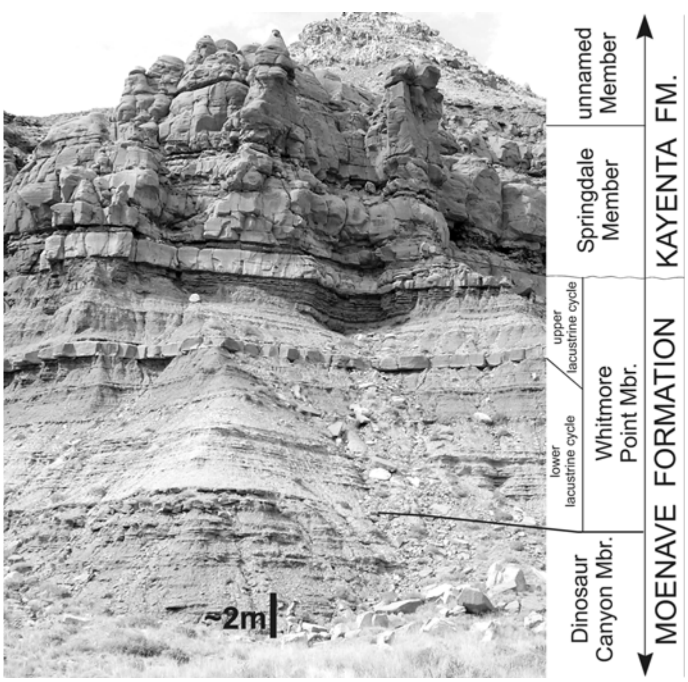

FIGURE 7. Exposure of the Moenave Formation about one kilometer west of Whitmore Point, northern Arizona, with upper and lower lacustrine intervals ("cycles") of Whitmore Point indicated.

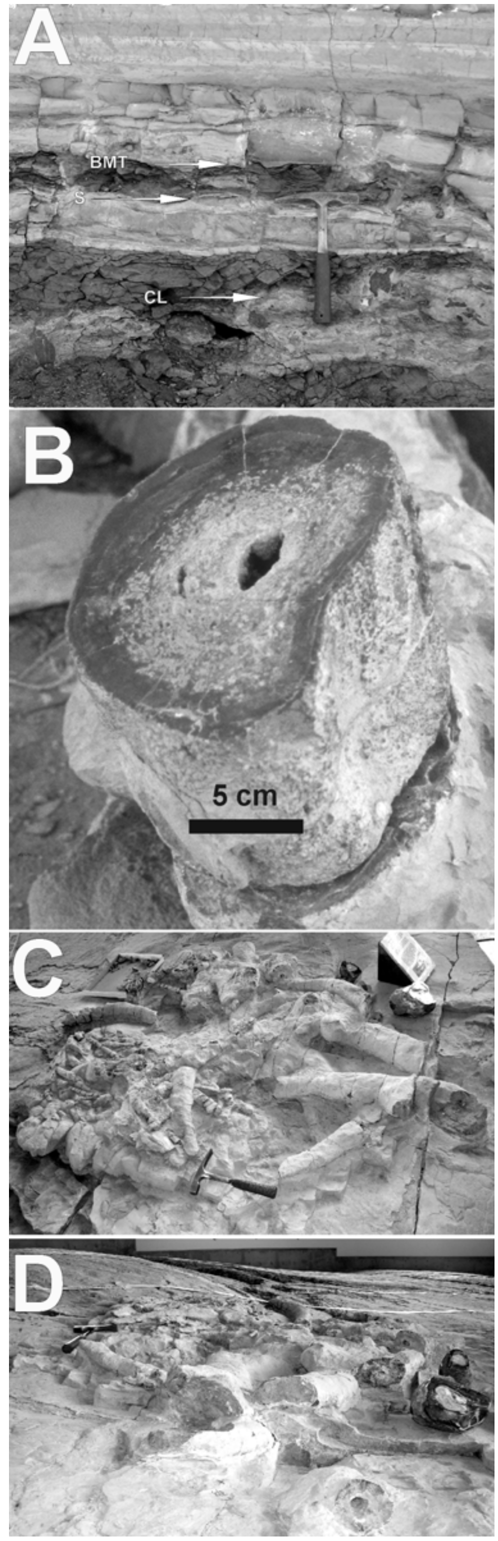

FIGURE 8. Partially silicified tufa structures. **A**, Base of the Whitmore Point Member below the north side of the SGDS building. Note the stromatolitic limestone (S) between base of main track-bearing sandstone (BMT) and the cherty limestone layer (CL) that were only observed during the excavation 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**.

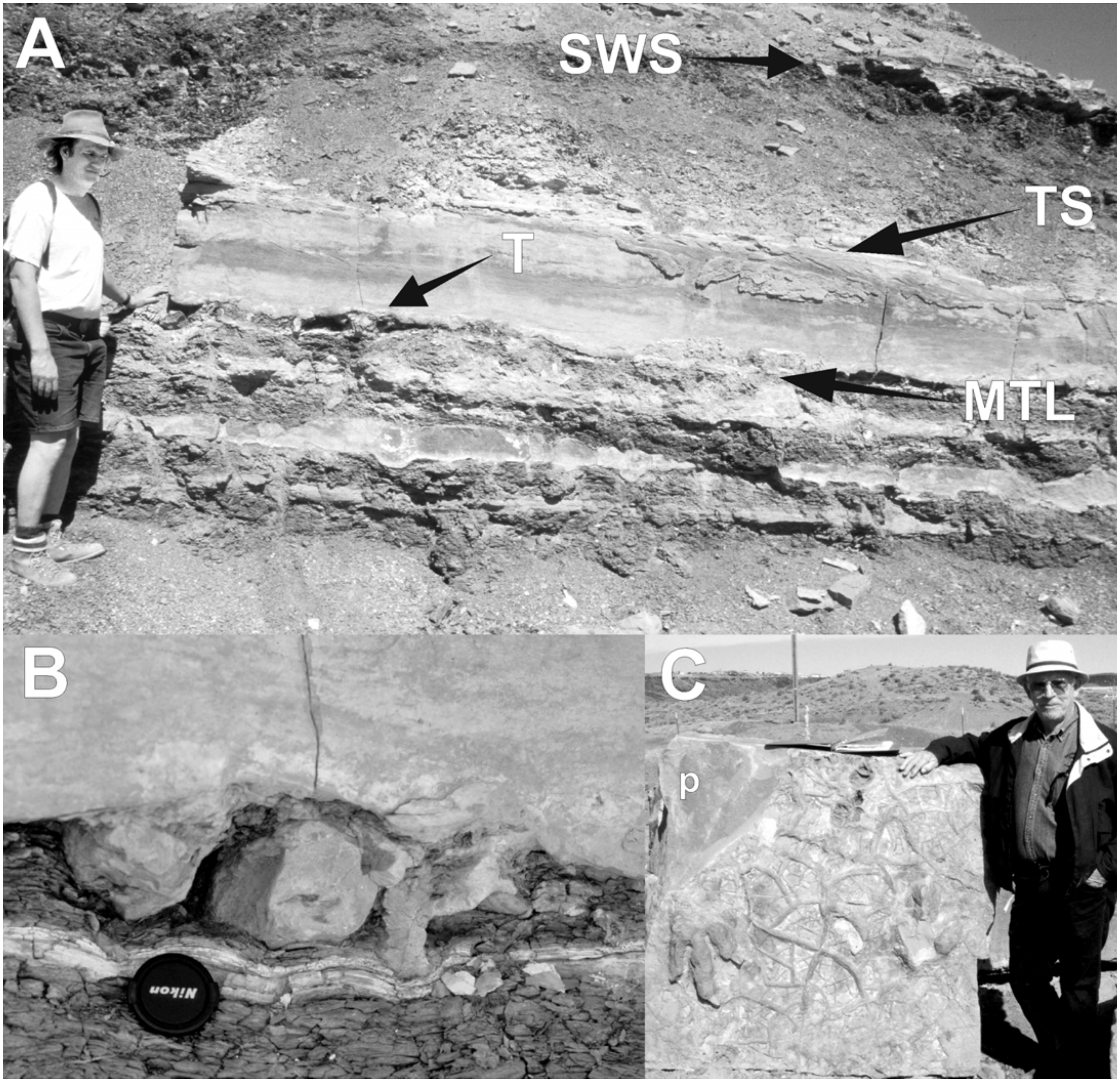

FIGURE 9. Sedimentary features preserved at base of the main track-bearing sandstone northwest of Riverside Drive at the SGDS. **A**, Cross-section of the main track-bearing sandstone in a road-cut on north side of Riverside Drive, opposite the SGDS. Abbreviations: MTL, base of main track-bearing sandstone; 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-

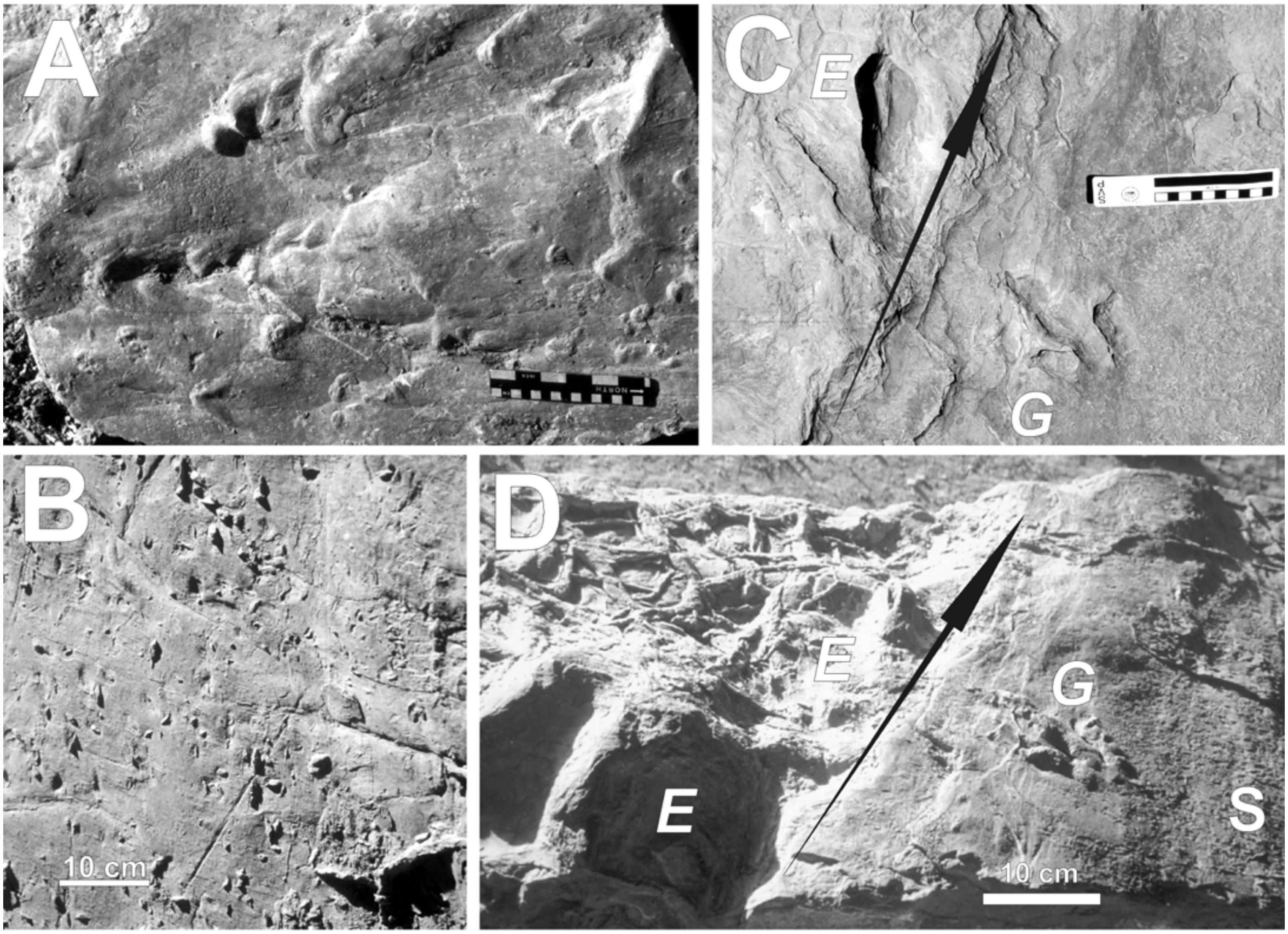

FIGURE 10. Sedimentary features associated with scours preserved at base of main track-bearing sandstone to southeast of Riverside Drive at the SGDS. **A**, Small flute casts at base of main track-bearing sandstone. **B**, Triclinic salt casts exposed on scoured surface at base of main track-bearing 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