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*by*

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# TRACKING EARLY JURASSIC DINOSAURS ACROSS SOUTHWESTERN UTAH AND THE TRIASSIC-JURASSIC TRANSITION

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## INTRODUCTION

The Colorado Plateau and surrounding areas preserves one of the most extensive and complete examples of the terrestrial Triassic-Jurassic transition in North America, and arguably one of the best in the world. Rich in fossil resources, this region records a major, northwest-draining river system. In southwestern Utah, a wet, tropical, Late Triassic landscape slowly dried out and became, in the latest Triassic and Early Jurassic, an inland, Okavango Delta-like subtropical system that fluctuated between lake systems (Lake Dixie) and dry salt pans as ergs flanking the region to the east expanded and contracted. It is within this conceptual context that the geographic and temporal distribution of fossils can truly be understood and that the nature of the Triassic-Jurassic transition in the American Southwest can be appreciated.

This field trip will take participants across southwestern Utah to view spectacular, Early Jurassic dinosaur tracksites, associated fossils, and outcrops that span the Triassic-Jurassic transition. Portions of this guidebook are taken from other publications (e.g., DeBlieux et al. 2006; Kirkland and Milner 2006; Milner and Lockley 2006; Milner and Spears 2007).

The inaugural day (Fig. 1) begins with a visit to the St. George Dinosaur Discovery Site at Johnson Farm (SGDS) in St. George, Washington County, Utah (Stop 1), which houses an *in situ* dinosaur tracksite in the latest Triassic-Early Jurassic Moenave Formation. The site is one of the most diverse and spectacularly preserved, Early Jurassic ichnological lagerstätten in the world and forms the basis for examining faunal change through

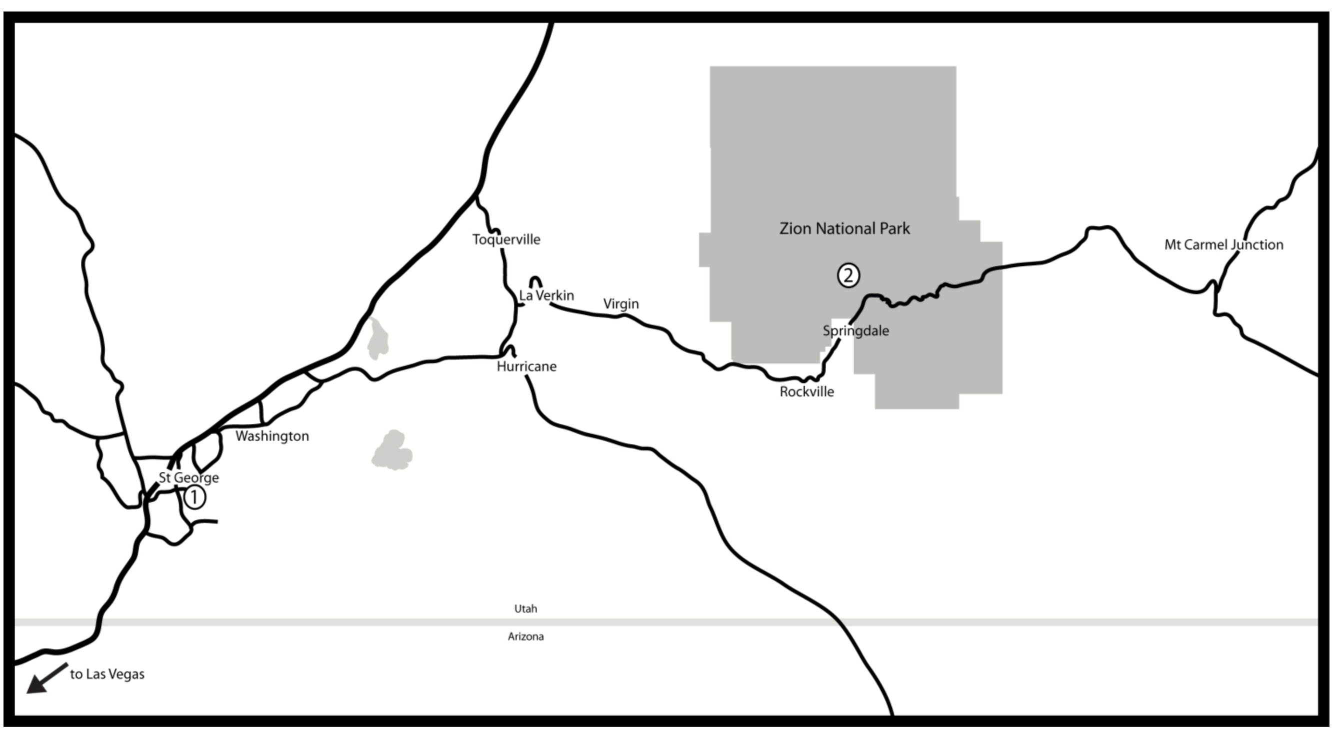


Figure 1. Day 1 field-trip route and stop locations.

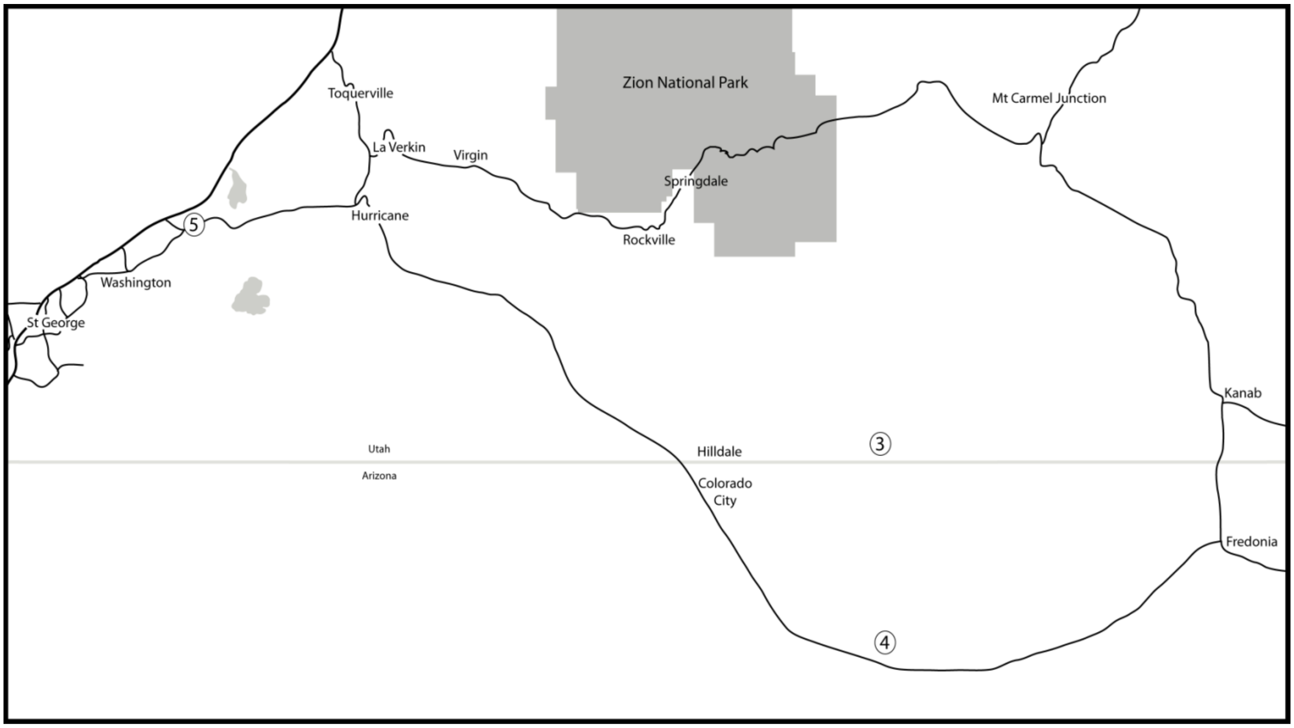


Figure 2. Day 2 field-trip route and stop locations.

the Late Triassic-Early Jurassic for the remainder of the trip. The trip then drives past exemplary outcrops of the Lower Jurassic Kayenta Formation, which overlies the Moenave Formation, along the northwestern edge of the Virgin Anticline. These outcrops also preserve many excellent dinosaur tracksites, some of which have hundreds of footprints on multiple track horizons. Several vertebrate body fossil sites have also been found in the Washington County area in the Kayenta, Moenave, and underlying Chinle formations. The day concludes with an overview of the stratigraphy and paleontology of Zion National Park (Stop 2). We will spend the first night in Mount Carmel Junction, north of Kanab, Utah.

The second day (Fig. 2) of the trip begins with a visit to the North Moccasin Mountain Dinosaur Tracksite (Stop 3), located in the upper part of the Early Jurassic age Navajo Sandstone Formation near Kanab, Utah. The tracks at this site not only formed under different conditions, and are therefore preserved differently than those around St. George, but differ faunally as well. We then proceed into Arizona and stop near the type section of the Whitmore Point Member of the Moenave Formation (Stop 4) near Colorado City, Arizona. We will conclude the day (time permitting) with a visit to the Spectrum Dinosaur Tracksite (Stop 5) near St. George, Utah, which is in the Springdale Sandstone Member of the Kayenta Formation. The evening will be spent in St. George, with a reception at the SGDS for those who wish to attend.

The entire third day (Fig. 3) is spent visiting paleontological and geological localities in Warner Valley, southeast of St. George. Participants will have the opportunity to see the famous Warner

Valley Dinosaur Tracksite (Stop 6), situated on top of the Springdale Sandstone Member of the Kayenta Formation, at which recent excavations have exposed hundreds of new tracks. Nearby outcrops expose the unconformity at the contact between the Chinle and Moenave formations (Stop 7). Lunch will be spent at the ruins of historic Fort Pierce (Stop 8), with a short trip to view the Native American petroglyphs and historic graffiti nearby. After lunch, we then visit the Olsen Canyon Tracksite (Stop 9) to view footprints in the lower part of the Dinosaur Canyon Member of the Moenave Formation. This part of the formation has been considered Late Triassic in age, but the footprints may suggest an Early Jurassic age or at least an age postdating the end-Triassic extinction (ETE). We will then view the stratigraphy and paleontology of Warner Valley (Stop 10), from the upper part of the Chinle Formation to the base of the "silty facies" of the lower Kayenta Formation. This survey will include visits to fossil fish localities in the Moenave Formation and in the lower Kayenta Formation. Along this hike, the potential to discover new paleontological localities is very high. The trip ends with a return to Las Vegas.


Figure 3. Day 3 field-trip route and stop locations.

## DAY 1 ROAD LOG

| Incremental Mileage | Cumulative Mileage | Description |
|---|---|---|
| 0.0 | 0.0 | DAY 1. Paris Hotel main entrance in Las Vegas, Nevada. |
| 0.3 | 0.3 | Turn right (north) onto Las Vegas Boulevard. |
| 0.2 | 0.5 | Turn left (west) onto Flamingo Boulevard. The mountains to your east are the Frenchman Mountains, separated from the Las Vegas Basin by the Miocene, strike-slip Las Vegas Valley Shear Zone (Duebendorfer and Black 1992). The Frenchman Mountains are tilted 50-60° east; the stratigraphy in the mountains is very similar to that in the Grand Canyon, ranging in age from Precambrian to Permian (Longwell et al. 1965). The eastern side of the Frenchman Mountains, in the Valley of Fire region, exposes Lower Triassic (Moenkopi Formation), Upper Triassic (Chinle Formation), Lower Jurassic (Aztec Sandstone Formation), and Lower Cretaceous strata (Willow Tank Formation; see Bonde et al. this volume). |
| 0.4 | 0.9 | Enter I-15 heading north toward St. George, Utah. |
| 19.6 | 20.5 | Exposures on both sides of the road of the Neogene Muddy Creek Formation, which extend from Las Vegas, Nevada to Littlefield, Arizona (Schmidt et al. 1996). |
| 7.5 | 28.0 | Carboniferous marine limestones of the Callville Formation, which contain abundant fossils, including tabulate coral bioherms. |
| 9.6 | 37.6 | Continue past exit 75 (exit for Valley of Fire). |
| 4.9 | 42.5 | Past exit 80 (exit for Ute on Moapa Reservation), note white, marl-rich siltstone outcrops of the White Narrows Formation (Lockley et al. 2007). This formation fills graben structures within the Muddy Creek Formation that resulted from faulting along the southern edge of the Arrow Canyon Range, which you can see to the north (Lockley et al. 2007). Based on fossil rodents, the White Narrows Formation is earliest Blancan (early Pliocene, ~4.7 Ma) (Schmidt et al. 1995; Woodburne and Swisher 1995; Reynolds and Lindsay 1999). Important vertebrate tracksites, containing tracks of ungulates, proboscideans, carnivorans, and birds have been reported from the White Narrows Formation in the area (Lockley et al. 2007). |

| | | |
|---|---|---|
| 42.6 | 85.1 | Cross into Arizona from Nevada. |
| 2.7 | 87.8 | Cross bridge over Sand Hollow Wash. The next bridge crosses Coon Creek. |
| 7.9 | 95.7 | Continue past Littlefield exit #8 (Highway 91). Outcrops here are the easternmost extent of the Neogene Muddy Creek Formation in this area (Schmidt et al. 1995). |
| 3.0 | 97.4 | Enter the Virgin River Gorge. |
| 0.5 | 97.9 | Here, a north-northwest-oriented fault separates the Mississippian Monte Cristo Group from the latest Middle Cambrian Bonanza King Formation, Dunderberg Shale, and Nopah Dolomite. Thin, interbedded, green shales and dolostones of the Dunderberg Formation are visible in road cuts between mileposts 13.9 and 16.8. |
| 1.4 | 99.3 | The Sullivan's Canyon Tear Fault (SCTF) and Cedar Wash Fault intersect and cross the highway here. We pass from Cambrian-Devonian rocks west of the fault into Mississippian Monte Cristo Group and Permian strata to east of the fault (Reynolds et al. 2006). Looking back to the S-SW, you can see the upturned, Permian Toroweap Formation on the east side of SCTF, and the Monte Cristo Group dipping steeply in the opposite direction on the west side of the fault (Reynolds et al. 2006). |
| 1.1 | 100.4 | Prior to Cedar Pocket exit, pass red sandstone outcrops of cross-bedded, eolian Supai Group of Permian age (Reynolds et al. 2006). |
| 2.8 | 102.8 | Continue past exit #18 to Cedar Pocket. |
| 6.0 | 108.8 | Pass Permian Supai Group and Coconino Sandstone located in the bottom of the gorge. These are overlain by Lower Permian Toroweap and Kaibab formations. The Coconino-Toroweap contact can be seen at milepost 25.5 (Reynolds et al. 2006). |
| 1.4 | 110.2 | Pass contact between Permian marine Toroweap and Kaibab formations. |
| 0.5 | 110.7 | Continue past the Black Rock Road exit (#27). |
| 0.1 | 110.8 | Pass over disconformable contact between Lower Permian Harrisburg Member of the Kaibab Formation and Lower Red Member of the Moenkopi Formation. The Moenkopi Formation is Early to early Middle Triassic in age and is divided (in ascending order) into the Rock Canyon Conglomerate (restricted occurrences that will not be observed on this field trip), Timpoweap, Lower Red, Virgin Limestone, Middle Red, Shnabkaib, and Upper Red members. The ridge-forming unit above the Moenkopi is the Upper Triassic Shinarump Member of |

| | | |
|---|---|---|
| | | the Chinle Formation. These ridges are visible to the northwest and northeast (Reynolds et al. 2006). |
| 0.1 | 110.9 | Passing by roadcuts of the marine Virgin Limestone Member of the Moenkopi Formation. Fossils, including brachiopods, echinoids, crinoids, bivalves, gastropods, and invertebrate traces, are common in this member. *Tirolites* ammonites were reported by Poborski (1954) to the northwest. |
| 3.2 | 114.1 | Cross into Utah from Arizona. |
| 2.1 | 116.2 | Pass through the Middle Red Member of the Moenkopi Formation, which is capped by lightly-colored sabkha deposits of the Shnabkaib Member. |
| 1.0 | 117.2 | Pass through Shnabkaib Member of the Moenkopi Formation, which is overlain by the Upper Red Member. Amphibian and reptile tracks are locally common in the Upper Red Member, which is late Early Triassic to early Middle Triassic in age. |
| 0.9 | 118.1 | Pass Bloomington exit (#4). Cliffs around you are the Upper Red Member of the Moenkopi Formation capped by sandstones and conglomerates of the Shinarump Member, the basal member of the Upper Triassic Chinle Formation. The Chinle Formation in the St. George area is divided into the Shinarump and Petrified Forest members (Biek et al. 2003). Although Lucas and Heckert (see Heckert et al. 2006) identified the Blue Mesa, Sonsela, and Painted Desert members of the Petrified Forest Formation and the overlying Owl Rock Formation of Chinle Group in southwestern Utah (Lucas 1991, 1993), the Utah Geological Survey does not use their defined units (Biek et al. 2003; DeBlieux et al. 2006). The Glen Canyon Group lies above the Chinle Formation and is subdivided in southwestern Utah into the Moenave, Kayenta, and Navajo Sandstone formations. Both the Chinle Formation and Glen Canyon Group consist of exclusively terrestrial deposits. |
| 0.2 | 118.3 | Cross the Santa Clara River and prepare to exit at Bluff Street on the right. |
| 1.6 | 119.9 | Exit I-15 at Bluff Street (Exit #6). |
| 0.3 | 120.2 | Turn right at the stoplight at the top of the exit ramp onto Riverside Drive; continue through stoplight at Convention Center Drive intersection. Continue straight on Riverside Drive, which follows the north shore of the Virgin River. |
| 1.6 | 120.3 | Stoplight at River Road intersection, continue straight. |
| 0.1 | 121.9 | Cross the St. George fault, a normal fault with small displacement, downfaulted to the west (Hintze 2005, p. 188). |

| | | |
|---|---|---|
| 0.2 | 122.0 | Outcrops of Petrified Forest Member of the Chinle Formation in roadcut below Middleton Black Ridge to your left (north). The cap rock on this ridge is the Middleton lava flow, which is Pleistocene in age (1.5±0.1 Ma). This flow is a quartz-rich, basaltic trachyandesite (Willis and Higgins 1995). The Virgin River can be seen in the valley to the right (south). The cliffs on the south side of the Virgin River are comprised of the Upper Red Member of the Moenkopi Formation (not Permian Kaibab Formation as mistakenly indicated in Milner and Spears 2007) capped by the Shinarump Member of the Chinle Formation. |
| 0.7 | 122.2 | Passing through roadcuts of Chinle Formation, consisting of the Petrified Forest Member at the base (south), a middle sandstone/conglomerate unit, the upper Petrified Forest Member, and an upper unit referred to as the Owl Rock Member by Lucas and Tanner (2006). |
| 0.3 | 122.9 | Reddish-brown and poorly exposed outcrops to the left (west) include the unconformable contact between the underlying Chinle Formation and overlying Dinosaur Canyon Member of the Moenave Formation (Kirkland and Milner 2006, p. 292). |
| 0.1 | 123.2 | Foremaster Drive to left, continue straight through stoplight. |
| 0.1 | 123.3 | Reddish-brown outcrops of Dinosaur Canyon Member. |
| 0.2 | 123.4 | Mall Drive intersection, continue straight. |
| 0.2 | 123.6 | Prepare for right turn on 2200 East Street; the green-roofed SGDS museum building is visible on the right side of the road. |
| 0.1 | 123.7 | Turn right on 2200 East Street and into the SGDS museum parking lot. |

## STOP 1. ST. GEORGE DINOSAUR DISCOVERY SITE AT JOHNSON FARM (SGDS)

**Part 1 discussion leaders: Andrew R. C. Milner and Tylor Birthisel**

### INTRODUCTION

The St. George Dinosaur Discovery Site at Johnson Farm (SGDS) is owned by the City of St. George and is now operated by the museum's 501(c)3 non-profit arm, the DinosaurAH!torium Foundation. The first dinosaur tracks were discovered accidentally at this location by Dr. Sheldon Johnson on February 26, 2000, while he was leveling a hill on this property, which is situated within St. George city limits (Figs. 1, 4). A few months after the initial discovery, paleontologists from Cedar City, the Utah Geological Survey (UGS), and Natural History Museum of Utah (UMNH) investigating the tracksite and surrounding area recognized abundant fish fossils and bones on an undisturbed hill north-northwest of the present location of the SGDS (no. 13 on Fig. 5).


Figure 4. The St. George Dinosaur Discovery Site at Johnson Farm facility.

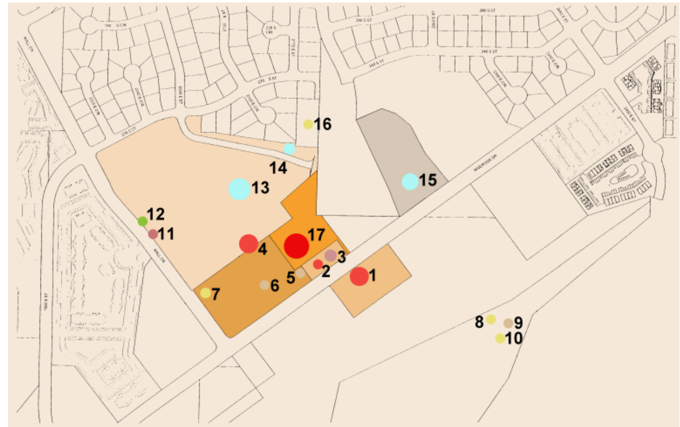


Figure 5. Map of the immediate vicinity of the SGDS in St. George, Washington County, Utah. Locality numbers: (1) SGDS first phase museum and original discovery site, (2) Hildale Tracksite, (3) Stewart-Walker Tracksite, (4) Swim Tracksite, (5) Walt's Quarry #1, (6) Walt's Quarry #2, (7) DS Plant Locality, (8) JO Plant Site #1, (9) Jensen Ridge Tracksite, (10) JO Plant Site #2, (11) Mall Drive Tracksite, (12) Mall Drive Stromatolite Site, (13) Ah!Quarium Fish Stick Site, (14) Freeman Quarry, (15) Chapman Fish Site, (16) Kayenta Tree Site, and (17) LDS Tracksite. Nearly all of the above localities are correlated with locality abbreviations shown on figure 6 stratigraphic section below.

Soon after its discovery, the site received much public and media attention, and by late June 2000, more than 50,000 people had visited the site. Following this, scientific interest was greatly increased by further discoveries at many nearby localities within the Moenave Formation. These localities, to which reference will be made throughout this section of the paper, include the Darcy Stewart site, Washington County School District property, Church of Jesus Christ of Latter-day Saints property (LDS), and Paul Jensen/Layton Ott property. A few of these localities are no longer owned by their eponyms: for example, the LDS and some Darcy Stewart properties, a total of 5.5 acres

(2.2 hectares), are now owned by the City of St. George for use by SGDS. Other discoveries at the original site, including the trace of a crouching theropod dinosaur (Milner et al. 2009a) also attracted international media attention.

Researchers from the SGDS, the Utah Geological Survey (UGS), the University of Colorado at Denver Dinosaur Trackers Research Group, Dixie State College, and many others have worked closely with the City of St. George, resulting in many publications (Kirkland et al. 2002; Lockley et al. 2004a; Lucas et al. 2005; Cornet and Waanders 2006; Hudson and Chan 2006; Kirkland and Milner 2006; Hunt and Lucas 2006; Lucas and Milner 2006; Lucas et al. 2006a, b; Milner and Kirkland 2006; Milner and Lockley 2006; Milner et al. 2006b, c, d; Schudack 2006; Tidwell and Ash 2006; Williams et al. 2006; Milner and Kirkland 2007; Milner and Spears 2007; Milner et al. 2009a, b). The March 2005, international "Tracking Dinosaur Origins: The Triassic-Jurassic Terrestrial Transition" symposium (Harris 2005) resulted directly from this initial flurry of research. The SGDS was also the focus and host of the annual meeting of the Rocky Mountain Section of the Geological Society of America in 2007, the 2008 Colorado Plateau Coring Project meeting, and two conference in 2009: the 8th Conference on Fossil Resources (Foss et al. 2009) and "Advances in Western Interior Late Cretaceous Paleontology and Geology" (Titus et al. 2009).

The importance of the SGDS has further grown by the discovery of plant fossils (Cornet and Waanders 2006; Tidwell and Ash 2006), enormous collections of fossil fishes (Milner and Kirkland 2006; Milner and Lockley 2006; Milner et al. 2006b; Milner and Kirkland 2007), invertebrate body fossils (Lucas and Milner 2006; Schudack 2006; Kozur and Weems 2010; Lucas et al. 2011), and theropod dinosaur remains (Kirkland et al. 2005; Milner and Kirkland 2007), all found in close association with the tracks and other traces. Hunt and Lucas (2006) classified the SGDS as a Konzentrat-Ichnolagerstätte, although it could also be considered a Konzentrat-Lagerstätte because of the abundance of associated plants, conchostracans, ostracods, a variety of fishes, and tetrapod material (Milner and Spears 2007). Collectively, the SGDS provides a window into an Early Jurassic ecosystem associated with the shores of a large lake called Lake Dixie (cf. Kirkland et al. 2002; Milner et al. 2004; Milner and Spears 2007). This is the only tracksite in the western United States that rivals the preservation quality and abundance of the famous sites in eastern North America, largely discovered in the 19th century (e.g. Hitchcock 1858, 1865; Lull 1903, 1915, 1953).

Dinosaur tracks and other tetrapod footprints considered to be Early Jurassic in age are well known in the southwestern United States (Lockley and Hunt 1995). However, until the SGDS discovery, only a small number of tracksites (e.g., the Warner Valley Tracksite; Miller et al. 1989) had been scientifically documented in southwestern Utah, none of which are in the Moenave Formation. Not only does the SGDS fill a gap in the fossil record of this area, but it has also generated local interest, resulting in the discovery and reporting of many additional sites in the region, including multiple track and bone localities in the Lower-early Middle Triassic (Smithian-early Anisian) Moenkopi Formation, Upper Triassic Chinle Formation, and Lower Jurassic Moenave, Kayenta, and Navajo Sandstone formations (Lucas et al. 2005a; DeBlieux et al. 2006; Hamblin 2006; Hamblin et al. 2006; Kirkland et al. 2006; Lockley and Milner 2006; Lockley et al. 2006b; Lucas and Tanner 2006; Lucas et al. 2006b; Lucas et al. 2007; Milner and Kirkland 2006; Milner and Lockley 2006; Milner et al. 2006a, b; Milner and Spears 2007; Spears et al. 2009).

## STRATIGRAPHY AT SGDS

The Moenave Formation (Rhaetian-Hettangian or latest Triassic to earliest Jurassic in age) in the area of the SGDS is 73.97 m thick, and is divided into the Dinosaur Canyon Member (56.41 m thick) and the overlying Whitmore Point Member (17.56 m thick) (Kirkland and Milner 2006). The Moenave unconformably overlies the Upper Triassic Chinle Formation and is itself unconformably overlain by the Lower Jurassic Springdale Sandstone Member of the Kayenta Formation (Fig. 6). The Triassic-Jurassic boundary plausibly lies within Moenave Formation (Molina-Garza et al. 2003; Cornet and Waanders 2006; Donohoo-Hurley et al. 2006; Kirkland and Milner 2006; Tanner and Lucas 2007; Downs 2009), but its precise stratigraphic location has not been narrowed down in southwestern Utah as of yet, although there are several recent hypotheses regarding its stratigraphic location (Donohoo-Hurley et al. 2010; Kozur and Weems 2010; Lucas et al. 2011). This controversial topic will be discussed in detail with the Whitmore Point type section on Day 2.

At the SGDS, the predominantly fluvial facies of the Dinosaur Canyon Member (Fig. 7) is divided into three intervals: (1) a basal conglomerate about 80 cm thick, immediately above the unconformity at the top of the Chinle Formation, (2) a lower mudstone interval about 34.8 m thick, and dominated by mudstone, and (3) an upper sandstone interval about 20.46 m thick (Kirkland and Milner 2006). The uppermost part of the upper sandstone interval of the Dinosaur Canyon Member preserves plant and trace fossils. Though *Grallator* tracks are by far the most abundant, *Eubrontes* and *Batrachopus* tracks suggest an age that postdates the ETE which could be very latest Triassic (Late Rhaetian) or Early Jurassic (e.g., Olsen et al. 1998; Olsen and Padian 1986), although both of these ichnotaxa should also be found in the latest Triassic because larger theropods and basal crocodylomorphs did exist at that time (e.g., Carpenter 1997; Clark et al. 2000; Lucas et al. 2006c; Nesbitt et al. 2007; Irmis 2011). It is thus necessary to be much more specific about the ichnotaxa and the general context of the ETE and Triassic-Jurassic boundary (see the discussion on Day 2).

In 1967, Wilson described the Whitmore Point Member as 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 and in southwestern Utah west of Kanab. Wilson (1967) also defined the contact between the Dinosaur Canyon and Whitmore Point members in

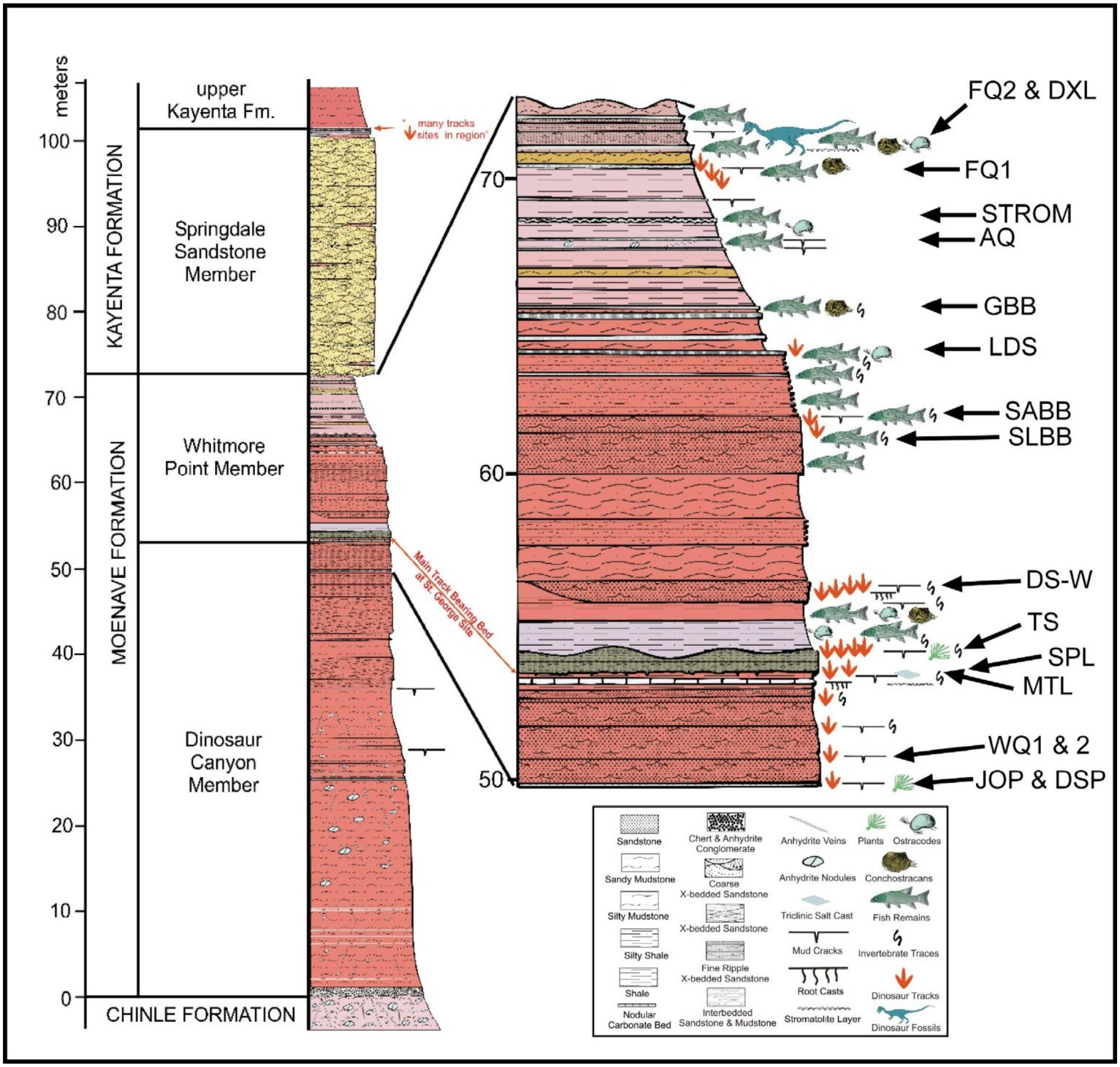


Figure 6. Stratigraphic section of the Moenave Formation at the SGDS showing the positions of significant fossils. Abbreviations (followed by corresponding localities from Fig. 5): AQ, Ah!Quarium Fish Stick Quarry (loc. nos. 13 and 15); DSP, Darcy Stewart Plant locality (loc. no. 7); DS-W, Stewart-Walker tracksites (loc. no. 3); DXL, Dixie Lube Locality (not discussed in this paper); FQ1, Freeman Quarry lower fish beds (loc. nos. 14, 15); FQ2, Freeman Quarry upper fish beds (loc. nos. 14, 15); GBB, "Green Burrow Bed" (loc. nos. 11, 15, 17); JOP, Jensen Ridge Plant localities (loc. nos. 8, 10); LDS, "Jesus Christ of Latter-day Saints property tracksite" and "Mall Drive tracksite" (loc. nos. 12, 17); MTL, "Main Track Layer" at the base of the "Johnson Farm Sandstone Bed" or main track-bearing sandstone (loc. nos. 1–5, 9); SABB, "Sally's Burrow Bed" (loc. nos. 15, 17); SLBB, "Slauf Burrow Bed" (loc. nos.15, 17); SPL, "Split Track Layer" of the Johnson Farm Sandstone Bed (loc. nos. 1-3); STROM, Stromatolite Bed (loc. nos. 12, 13); TS, "Top Surface" of the Johnson Farm Sandstone Bed (loc. nos. 1–3, 5); WQ1 & 2, Walt's Quarry 1 (loc. nos. 5) and Walt's Quarry 2 (loc. nos. 6) (modified from Kirkland and Milner 2006).

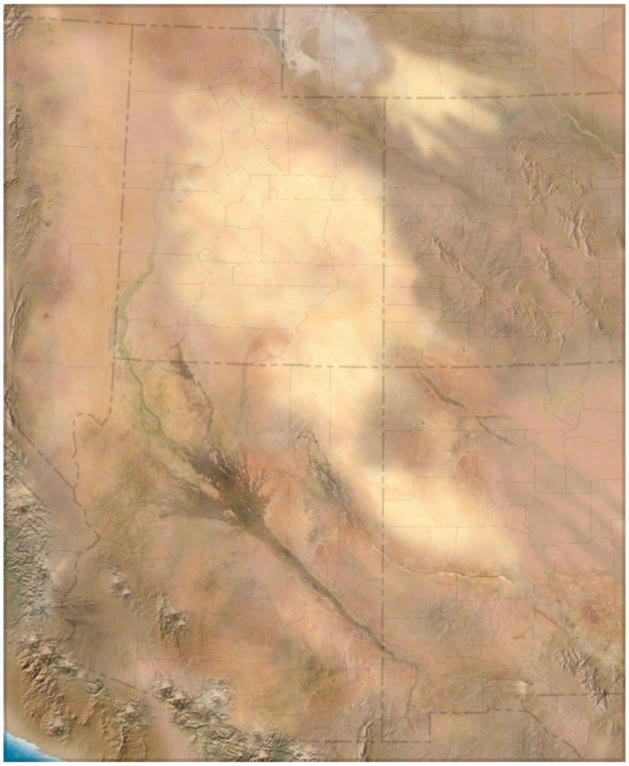

Figure 7. Paleogeographic map of the American Southwest during Dinosaur Canyon Member time showing river systems flowing from the southeast toward the northwest, and the growing sand sea of the Wingate erg. Map courtesy of Ron Blakey.

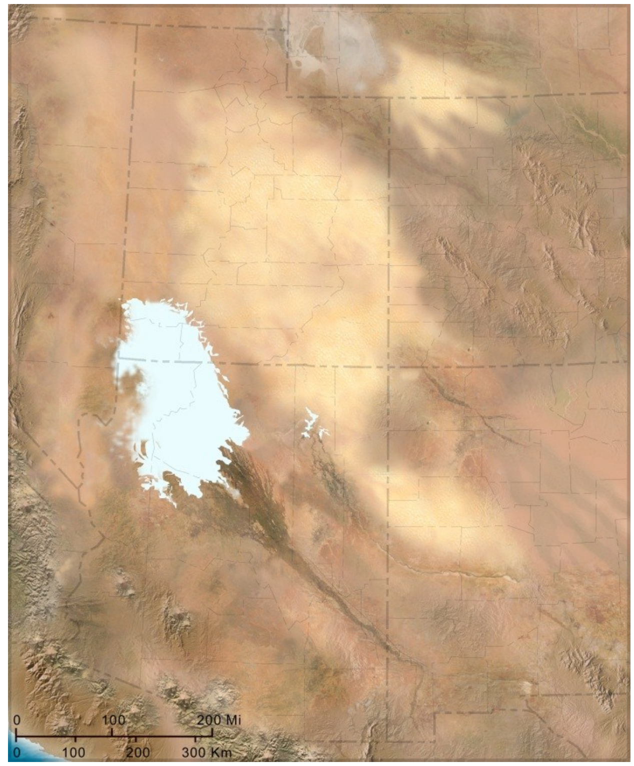


Figure 8. Paleogeographic map of the American Southwest during Whitmore Point Member time showing the estimated maximum extent of Lake Dixie. Map courtesy of Ron Blakey.

the Leeds, Utah area as a limestone bed partially replaced by red chert. This bed defines the contact between these members over much of southwestern Utah, including at SGDS.

The Whitmore Point Member at the SGDS has a lower, complex interval (4.48 m thick) composed of shoreline deposits, laid down in subaerial and subaqueous environments, that display lake level transgressions and regressions along the western margin of Lake Dixie (Kirkland and Milner 2006) (Fig. 8). This lower interval largely represents deepening and then shallowing of Lake Dixie (Kirkland and Milner 2006). Above this are a middle sandstone (7.64 m thick) interval and an upper, shale-dominated (6.55 m thick) interval that represents an upper lake cycle that is best developed in the St. George region, thus two major deepening and shallowing cycles are represented (Kirkland and Milner 2006). The upper, shale-dominated interval is unconformably overlain by the Springdale Sandstone Member of the Kayenta Formation (Kirkland and Milner 2006).

**PALEONTOLOGY**

Tracks have been identified on 25 stratigraphic levels in the immediate vicinity of the SGDS (Fig. 6), and many of these layers have been mapped *in situ*.

Four track-producing layers have been recognized in the uppermost part of the Dinosaur

Canyon Member at the SGDS (Fig. 6). Two very important localities, Walt's Quarry 1 and Walt's Quarry 2, named in honor of Walter Jessop who discovered both sites, were mapped *in situ* during careful excavation on former Darcy Stewart property in 2004-2005 (nos. 5 and 6 in Fig. 5). Part of the Walt's Quarry 1 site was recovered as a single, 23.59 metric ton block now displayed in the SGDS museum (Fig. 9). It was originally mapped and described as having 47 *Grallator* tracks in 11 trackways (Milner et al. 2006d), but remapping in 2011 revealed 58 *Grallator* in 13 trackways, and is by far one of the most visually spectacular specimens in the SGDS collection. Part of Walt's Quarry 2 was incorporated into a 13.11 m long by 4.57 m high wall (SGDS 567) during the first phase of the SGDS museum construction and development; it now occupies much of the rear (west) wall of the museum building. About 200 dinosaur tracks (mostly *Grallator*), fish swim traces, and crocodylomorph tracks are on the blocks comprising this wall.

The first tracks discovered at the SGDS are from a horizon called the Main Track Layer (Fig. 6), which is at the base of the Johnson Farm Sandstone Bed (Kirkland and Milner 2006), a unit that is quite extensive and mapable in the St. George area. Tracks from the Main Track Layer (Fig. 10) are preserved as robust, natural sandstone casts (positive hyporelief) and associated with mud cracks, possible sulfate salt-crystal casts, flute casts, and many other sedimentary structures. Internally the bed displays several 15-25 cm thick sets of climbing ripple bedding as do sandstones in the upper Dinosaur

Figure 9. A 23.59 mton-block of sandstone preserving 58 *Grallator* tracks in 13 trackways (SGDS 568).

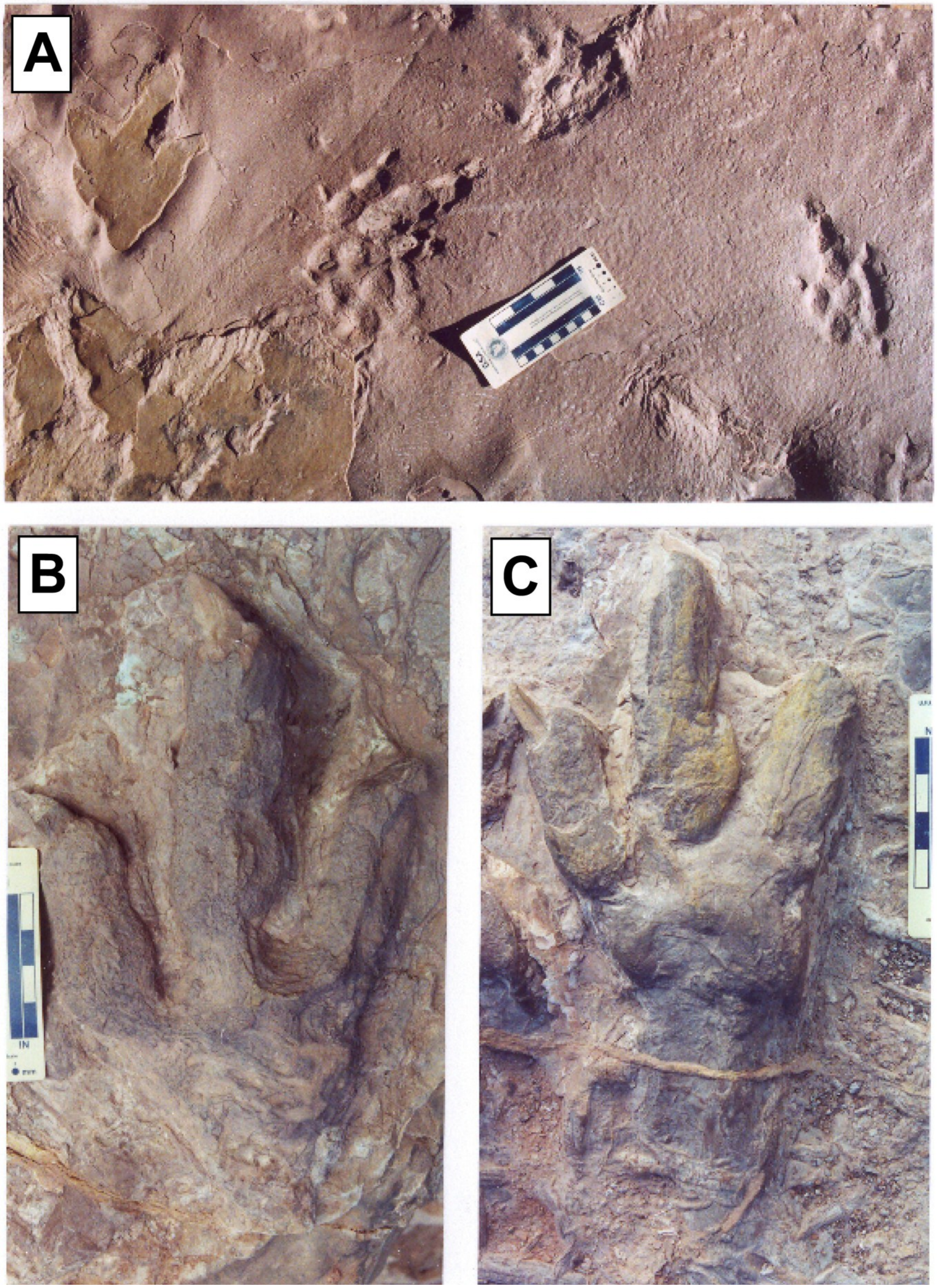


Figure 10. Photos of theropod dinosaur tracks from the SGDS. A, *Grallator* tracks (SGDS 197A). B, *Eubrontes* natural cast track (SGDS 9). C, *Eubrontes* natural cast showing a hallux and metatarsal impression (SGDS 8) (from Milner et al. 2006d).

Canyon Member. The Johnson Farm Sandstone Bed generally varies in thickness between 30 and 70 cm, although it has been eroded away by overlying units in some areas. It is well-sorted, fine-grained sandstone about 53 m above the base of the Moenave Formation (Fig. 6). The track casts (Fig. 10B-C) have up to 20 cm of relief and can only be seen after blocks of the Johnson Farm Sandstone Bed have been turned over. This process requires heavy equipment and necessitated removing blocks from their original *in situ* positions to their current locations in the SGDS building and elsewhere.

Another track-bearing horizon within the Johnson Farm Sandstone Bed is the Split Layer, which lies approximately 4-15 cm above the Main Track Layer horizon within the Johnson Farm Sandstone Bed (Figs. 6, 10A; Milner et al. 2006d). Also, four additional track-bearing horizons are on top of the Johnson Farm Sandstone Bed, all referred to as the Top Surface (Fig. 6). An enormous portion of the Top Surface still remains preserved *in situ* within the SGDS museum building. These important, complex, undulating surfaces comprise several, laterally variable layers in a thin stratigraphic interval, and display a complex of irregular current ripples (Fig. 11B), regular oscillation ripples, ridges, swales, mud cracks (Fig. 11A), scour, and other depositional features in addition to tracks and/or undertracks with variable preservation.

One of the most striking features of the SGDS is the relation between trackways, topography, and the local paleogeography. We cannot map the paleogeography at every track level because surfaces are exposed only sporadically and the cost of additional excavation would be prohibitive. However, it is possible to map the Main Track Layer, on which most of the trackways were made by walking animals on an undulating surface. In contrast to this onshore location, an extensive track-bearing continuation of the Main Track Layer surface discovered to the northwest on Washington County School District and Darcy Stewart properties preserves abundant dinosaur swim tracks (*Characichnos*—see below) representing an offshore facies equivalent to the onshore surface marked by well-preserved *Eubrontes* tracks (Fig. 12; Milner et al. 2006c). This same marginal lacustrine onshore-offshore relationship can be seen in the sedimentary structures. Off- or near-shore, submerged sedimentary structures include a variety of current and symmetrical ripples (Fig. 11B-C), tool marks (Fig. 11D), flute casts, and scratch circles (Fig. 11E). Likewise, onshore, subaerial sedimentary structures include mud cracks (Fig. 11A), possible evaporative salt-crystal casts (Fig. 11F), and raindrop impressions (Fig. 11G).

Many fish remains have been recovered from areas to the north and northwest of the SGDS museum site on the Darcy Stewart, Washington County School District, and LDS properties; especially from higher stratigraphic levels of the Whitmore Point Member (Figs. 5 and 6; Milner et al. 2006a, b). This indicates that at the time the Top Surface layers of the Johnson Farm Sandstone Bed were deposited, the lake shoreline ran somewhere between the SGDS and Darcy Stewart sites, probably with a NNE–SSW trend (Figs. 5, 12). Fish

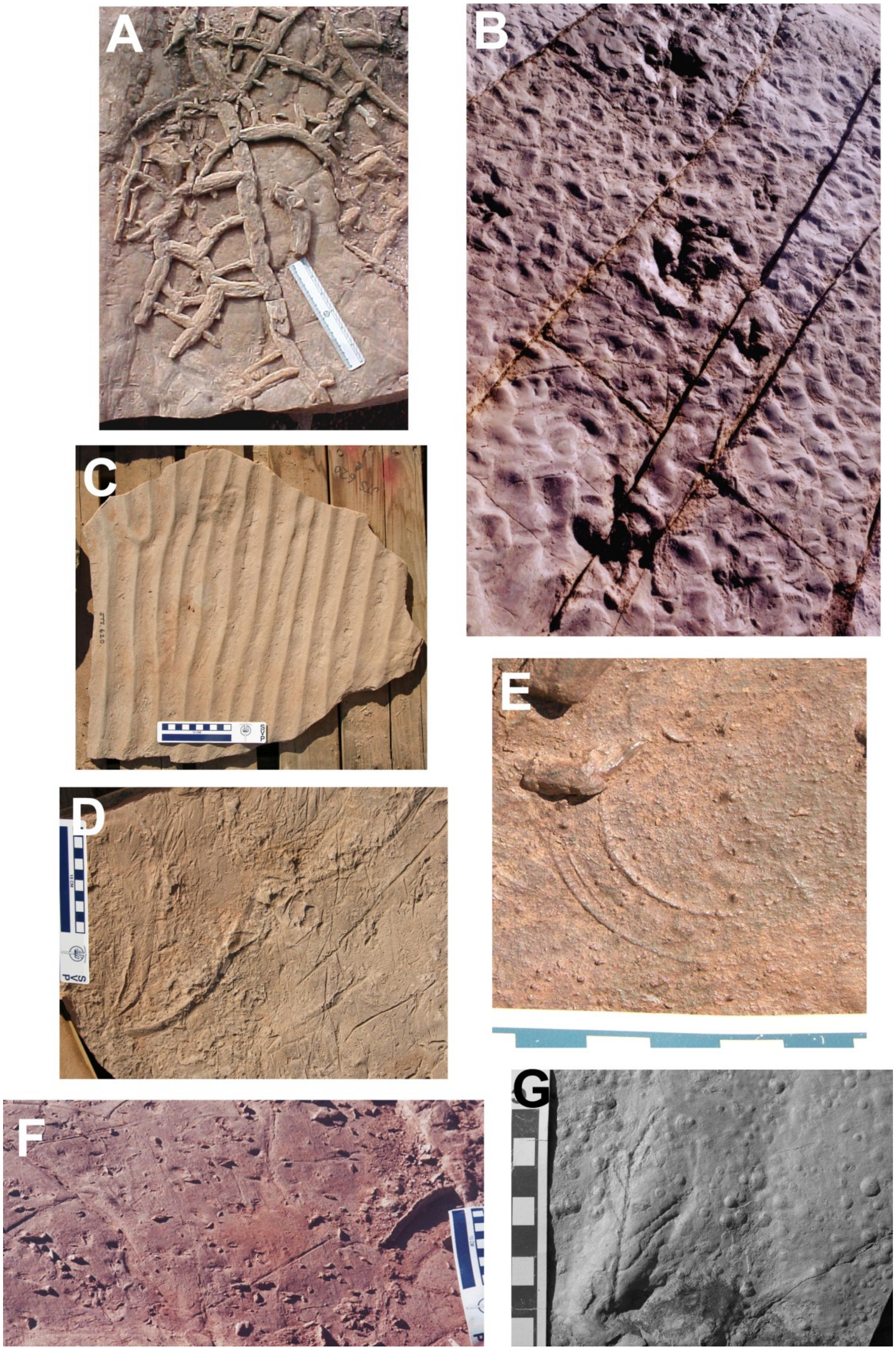

Figure 11. Some common sedimentary structures from the SGDS and vicinity. A, Mud-crack natural casts (SGDS 10). B, *Eubrontes* and *Grallator* trackways with current ripples and joints (SGDS 18.T1). C, Symmetrical wave-formed ripples (SGDS 620). D, Tool mark marks (SGDS 262), sedimentary structures formed by objects such as mud clasts, rock, plant fragments, etc., bouncing and scraping along a submerged substrate. E, Scratch circles (specimen number pending). F, Structures originally believed to be sulfate salt-crystal casts, but some suggest they may be the trace fossil *Lockeia* (SGDS 40). G, Raindrop impressions around a *Pagiophyllum* conifer branch (SGDS 491).

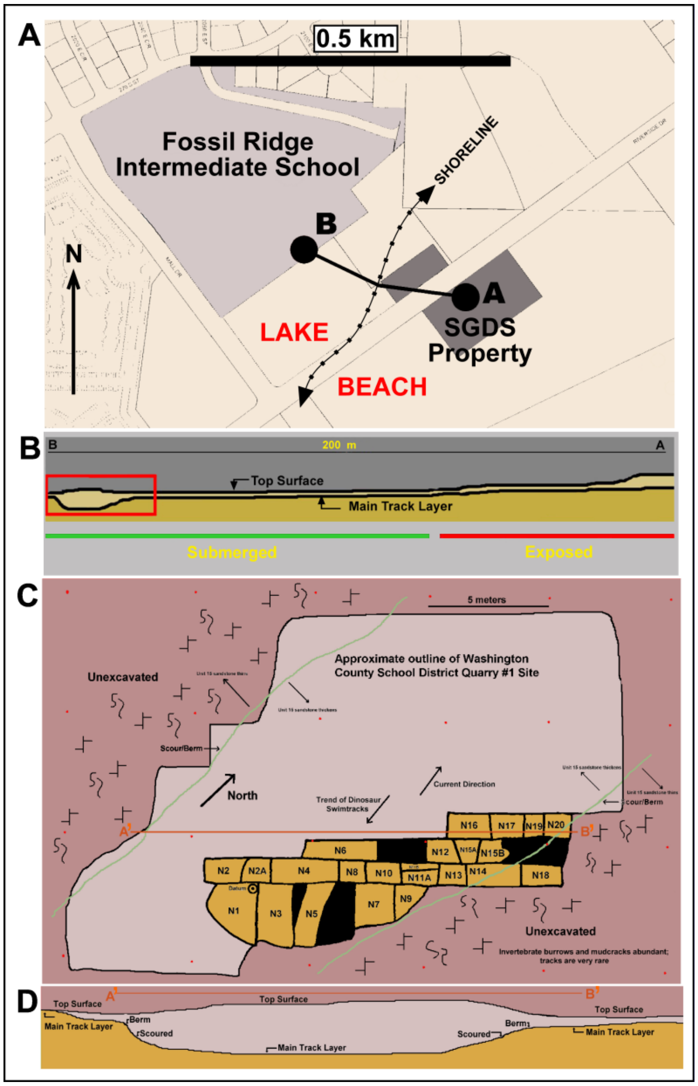

Figure 12. Map and paleoenvironmental interpretation of the SGDS MTL surface. A, Transect from museum site (A) on SGDS property (in gray) to swim track quarries (B) on WCSD and former DS (or Bodega Bay, LLC Property) properties. The estimated position of the paleoshoreline is indicated (hatched line) for the MTL based on orientation and preservation types of tracks, invertebrate traces, and sedimentary structures. B, Cross-section of transect A–B in A showing variation in bed thicknesses of the MTL and Top Surface. The estimated shoreline is for the MTL only. C, Map of the swim track quarries showing position of trough and transect A'–B' in B. D, Cross-section showing trough containing abundant swim tracks on the MTL surface, the variability in thickness of the MTL sandstone, and the Top Surface topography.

scales have been found in mudstones that were deposited directly on top of the Top Surface tracksites, suggesting a lacustrine transgression soon after track formation (Milner and Lockley 2006).

Further support for this interpretation of shoreline trend comes from trackway orientations, symmetrical wave-form and current ripple marks, and other sedimentary structures (Figs. 11, 13). On the Top Surface are a series of large ridges and swales with a WNW–ESE trend (Fig. 14), and between the ridges are abundant, unidirectional current ripples that suggest a somewhat consistent flow pattern toward the WNW. Other sedimentary structures that support this WNW current flow direction include chevron marks, flute casts, and rill marks, all of which formed during high runoff in the direction of the lake (Kirkland and Milner 2006; Milner and Lockley 2006). Locally, this topography has been eroded and reworked by small-scale water action; however, on a much larger scale, the ridges and swales are erosive megaripples that formed during a deeper lacustrine phase by large wave action flowing from the NE toward the SW across a partially exposed beach shoal or spit (Figs. 13, 14; Kirkland and Milner 2006). Furthermore, symmetrical wave-form ripples (Fig. 11C), with a N30°E ripple crest orientation, suggest small-scale waves lapping parallel to the paleoshoreline and perpendicular to the ridge and swale topography (Kirkland and Milner 2006; Milner and Lockley 2006).

Many of the dinosaur trackways at the SGDS parallel the paleoshoreline, although some are perpendicular to shoreline trends (Fig. 13). This

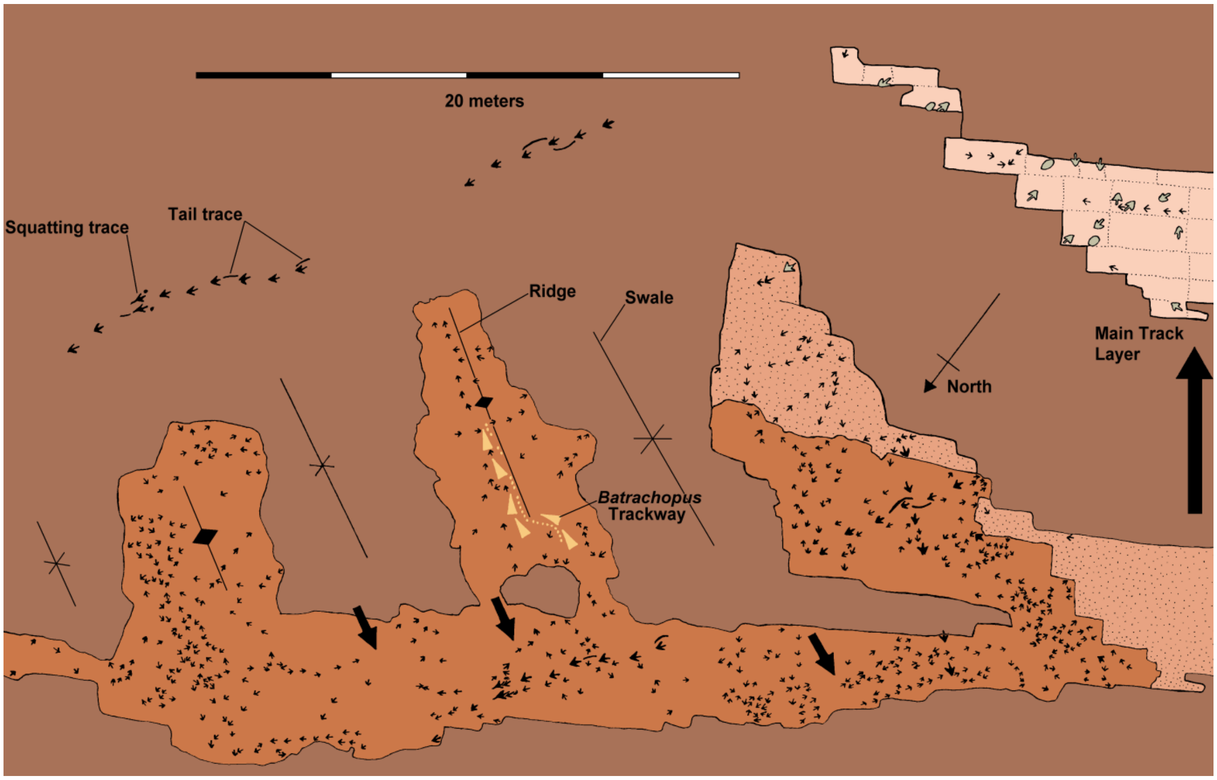


Figure 13. Map of the in situ SGDS "Top Surface" tracksite and portion of the "Main Track Layer" (MTL) (no. 1 on Fig. 4). Note the difference between lower MTL level, showing block outlines (top right), as map of the underside of the JFSB, and upper level, or "Top Surface" (bottom; catalog no. SGDS 18), which remains in situ. For clarity, cf. *Eubrontes* trackway with tail and crouching traces is shown separately (upper left) in the same orientation as it appears on the map. Note ridge and swale topography (erosive megaripples) and black arrows indicating selected local flow indicators on the "Top Surface." The yellow arrows and dots represent a long *Batrachopus* trackway following the crest top of an erosive megaripple. Joints directed N57°E.

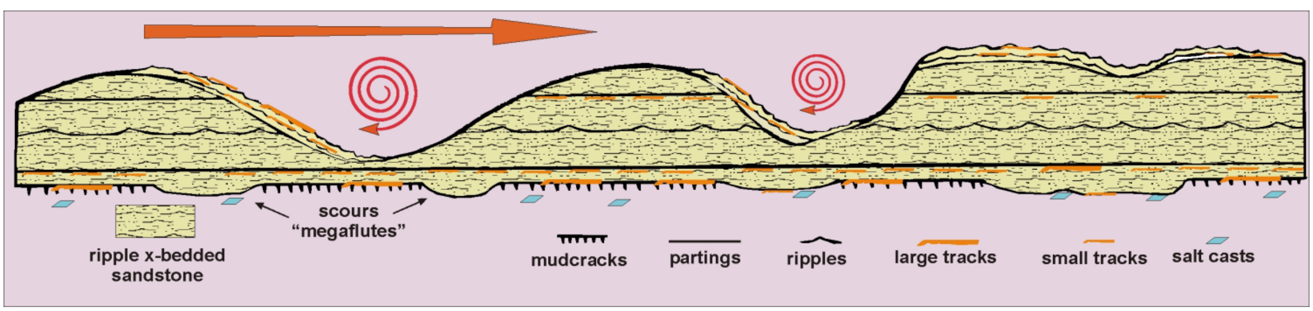


Figure 14. Diagram showing the most likely model of erosive megaripple formation of the JFSB at SGDS museum site (based on Reineck and Singh 1975, figure 8). Dinosaur track distribution and other associated sedimentary structures indicated (modified from Figure 14. Diagram showing the most likely model of erosive megaripple formation of the JFSB at SGDS museum site (based on Reineck and Singh 1975, figure 8). Dinosaur track distribution and other associated sedimentary structures indicated (modified from Kirkland and Milner 2006, figure 14E). Note: "salt casts" may be *Lockeia* trace fossils.

same kind of trend for trackways is noted at many other tracksites elsewhere in the world (Lockley and Hunt 1995). The shore-perpendicular trackways tend to follow the orientations of the ridges and swales on the SGDS Top Surface. Although many quadruped trackways also tend to parallel the Top Surface paleoshoreline, a concentration of *Batrachopus* tracks along ridge tops (i.e., shore-perpendicular) indicate track makers preferentially walked across higher terrain (Fig. 13; Milner and Lockley 2006; Milner et al. 2006d).

The Stewart-Walker Tracksite is approximately 1–1.5 m above the Johnson Farm Sandstone Bed upper surface (Kirkland and Milner 2006; Milner and Lockley 2006; Milner et al. 2006d). It is on an exposed surface immediately to the northwest of the SGDS museum and Riverside Drive (Figs. 5, 6). At this site (really, a complex of closely associated sites), about 60 tracks have been mapped on four different stratigraphic levels separated by about 50-65 cm in a reddish-orange sandstone complex (Figs. 6, 15; Kirkland and Milner 2006; Milner and Lockley 2006; Milner et al. 2006d). The first indisputable *Anomoepus* (ornithischian dinosaur; Lull 1904, 1915, 1953; Haubold, 1971, 1984; Olsen and Baird, 1984; Gierliński, 1991; Olsen and Rainforth, 2003) tracks were discovered on one of these track horizons in August 2005 associated with cf. *Kayentapus* footprints (Figs. 6, 16A; Milner and Lockley 2006;

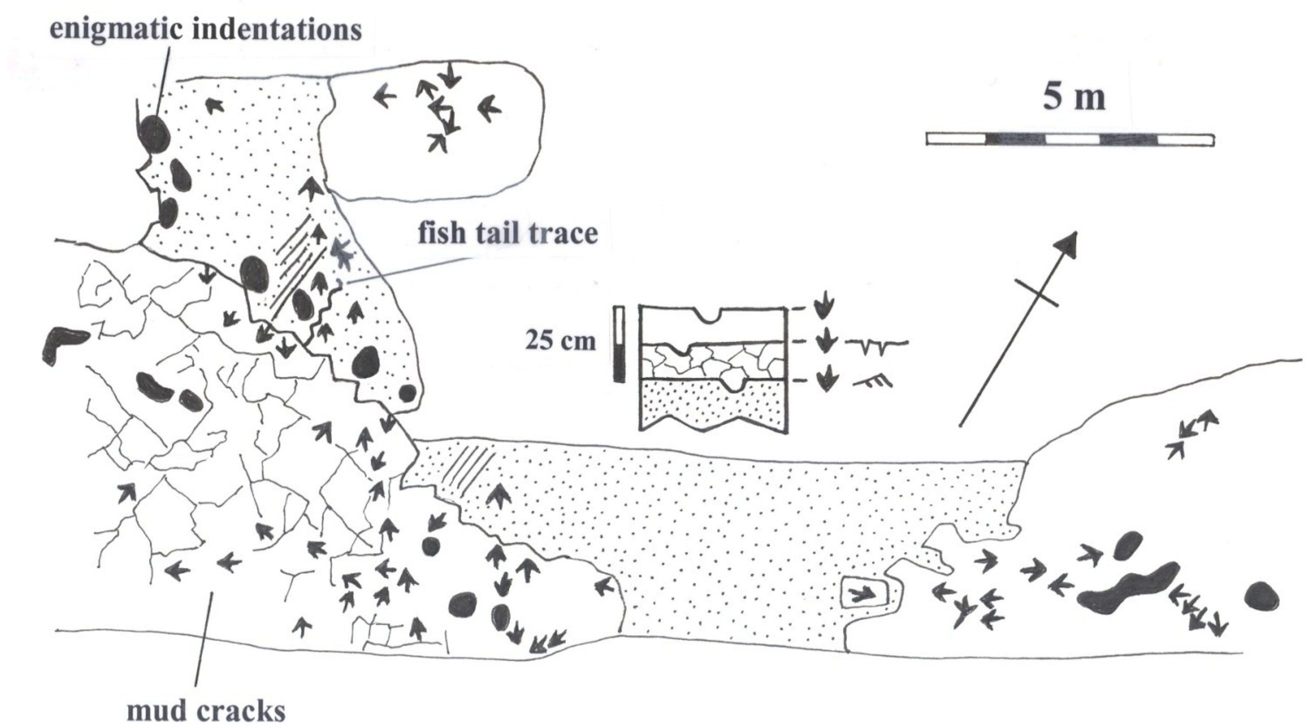


Figure 15. Tracksite map of exposures at the Stewart-Walker Tracksite (DS-W in Fig. 6) north of the SGDS museum and Riverside Drive (no. 2 on Fig. 5). Enigmatic indentations are possible fish nesting structures (from Milner et al. 2006d).

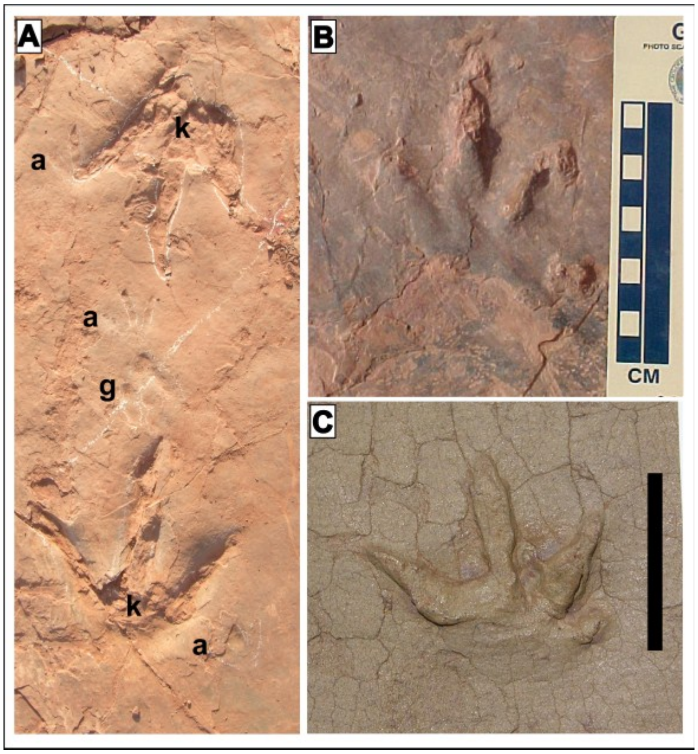


Figure 16. Examples of *Anomoepus* tracks from the SGDS. A, Several tracks *in situ* from the "Unit 19 Roadcut Site" (site no. 2 on Fig. 5). Abbreviations: a, *Anomoepus* footprints; g, *Grallator* track; k, cf. *Kayentapus* footprints. B, Isolated track assigned to *Anomoepus* showing a fourth digit (SGDS 166). C, Well-preserved, small *Anomoepus* pes natural cast track (SGDS 867). Scale bar = 2 cm.

Milner et al. 2006d). Prior to this discovery, tracks possibly referable to *Anomoepus* had been found, but their identity could not be confirmed due to poor preservation until the 2005 find was made (Fig. 16B). The SGDS specimens could be the oldest known *Anomoepus* footprints in the western United States, along with those recorded from the Lisbon Valley area in southeastern Utah (Lockley and Gierliński 2006). In May 2006, a pes track of *Anomoepus* measuring 2.6 cm long by 2.8 cm wide (Fig. 16C) was discovered in a bed correlative to the Top Surface near one of the Stewart-Walker Tracksite localities (Fig. 6). It is the smallest known specimen of this ichnotaxon from the western United States (Lockley and Gierliński 2006; Milner and Lockley 2006; Milner et al. 2006d).

Other sites at various stratigraphic levels above the Stewart-Walker Tracksite have also been mapped or at least recognized (e.g., LDS Tracksite described by Williams et al. 2006; Fig. 17). Together, the mapped areas document approximately 3000 tracks (not including some 3000 theropod swim track claw marks) in their *in situ* orientations and stratigraphic contexts. A similar number of additional tracks are preserved on isolated blocks from the Main Track Layer and other stratigraphic intervals from many sites within the immediate vicinity of the SGDS museum (Figs. 5, 6). Undoubtedly, many additional tracks and body fossils have yet to be excavated, particularly on the north side of Riverside Drive (Milner and Lockley 2006; Milner et al. 2006b, d).

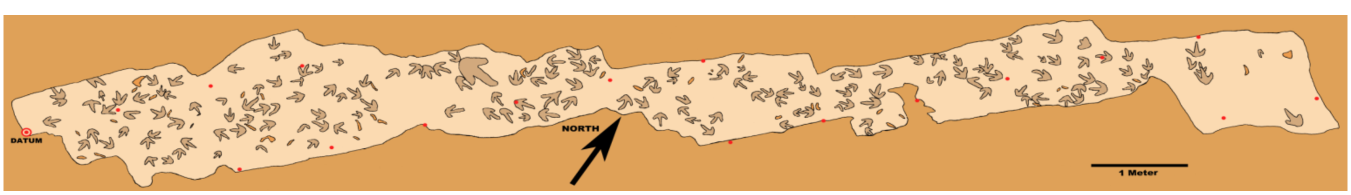


Figure 17. Map of the LDS Tracksite surface showing datum point, track orientations, and the position of a single *Eubrontes* footprint. Red dots indicate meter marks used during the mapping of the tracksite (modified from Williams et al. 2006).

## Ichnology

Tetrapod tracks from the SGDS have been assigned to the theropod dinosaur (e.g., Olsen et al. 1998) ichnotaxa *Grallator*, *Eubrontes*, and *Kayentapus,* the ornithischian dinosaur ichnotaxon *Anomoepus*, the crocodylomorph ichnotaxon *Batrachopus* (e.g., Olsen et al. 1998; Olsen and Padian 1986; Lockley et al. 2004), and the possibly sphenodontian ichnotaxon *Exocampe.* This ichnoassemblage is remarkably similar to those described by Hitchcock (1858) and Lull (1953) from the Early Jurassic of New England and strata of similar age from elsewhere around the world (Olsen et al. 2002), including elsewhere in the western United States (Lockley and Hunt 1995).

Theropod tracks from the SGDS have a remarkable size range. The smallest are only about 1.8-3 cm long, but several of these tracks have exceptionally long steps between footprints (Figs. 18A, B, D). In fact, one of the smallest track makers, with a footprint length of 2 cm, has step lengths of 23-36 cm, suggesting locomotory speeds of 3.2-6.4 m/s presuming animals with hip heights equal to five times track length. Another track maker, with a footprint length of 5.2 cm, has a step of 57 cm (Fig. 18C; Milner and Lockley 2006; Milner et al. 2006d). Other small tracks (footprint lengths 8 cm, including heel traces) have short steps and exhibit metatarsal and hallux impressions (Fig. 18E; Milner and Lockley 2006; Milner et al. 2006d).

*Grallator* footprints (Figs. 9, 10A) are the most common ichnites at the SGDS. *Grallator* tracks at the site range in size from 10-25 cm long and 8-11 cm wide, whereas *Eubrontes* tracks tend to have foot lengths >32 cm. Very few intermediate track sizes (foot lengths between 25-32 cm) are know from the SGDS, and few *Grallator* footprints actually exceed 20 cm in length (Milner and Lockley 2006; Milner et al. 2006d). With no intermediate footprint sizes, this strongly suggests the likelihood that *Grallator* and *Eubrontes* trackmakers were different theropod species, and may not represent an ontogenetic series of tracks produced by the same species as suggested by Olsen et al. (1998).

Many small, non-dinosaurian tracks have been found at the SGDS; most resemble the well-known, Early Jurassic ichnogenus *Batrachopus* (Fig. 19A, F; Olsen and Padian 1986). These tracks typically range from 1-5 cm in length, though maximum lengths of about 8 cm are known, although very rare. Pes prints, which are more commonly preserved, are always larger than the manus. In fact, the pes sometimes overprints the manus, occasionally leading to misinterpretations of the trackways and the potential track makers. A classic example is *Selenichnus*, described by Lull (1953), which was produced by animals passing through a soft substrate. Lull (1953) interpreted these tracks as being produced by bipedal dinosaurs, but discoveries at the SGDS (Fig. 19B) suggest that *Selenichnus* was produced by a quadrupedal crocodylomorph whose pedes overprinted its manus tracks (Lockley et al. 2004; Milner et al. 2006d). *Batrachopus* trackways are often hard to follow in detail, although several trackways have been recorded at the SGDS, including one trackway that can be traced for 5.8 m paralleling the crest of an


Figure 18. Examples of small theropod footprints and trackways from SGDS. A, Smallest dinosaur track (*Grallator*) from the Stewart-Walker Tracksite level measuring 1.8 cm (SGDS 1215). B, *Grallator* footprint collected from the Top Surface Tracksite (SGDS 928). C, *Grallator* trackway on Top Surface Tracksite. Footprints measure 5.2 cm with a step of 57 cm. D, Small 2 cm theropod footprint on Top Surface Tracksite. E, *Grallator* trackway with a wider gauge than normal for this ichnotaxon and with metatarsal impressions (SGDS 286). This kind of stance was likely used to stabilize the animal on slipper substrates. Scale bar = 5 cm.

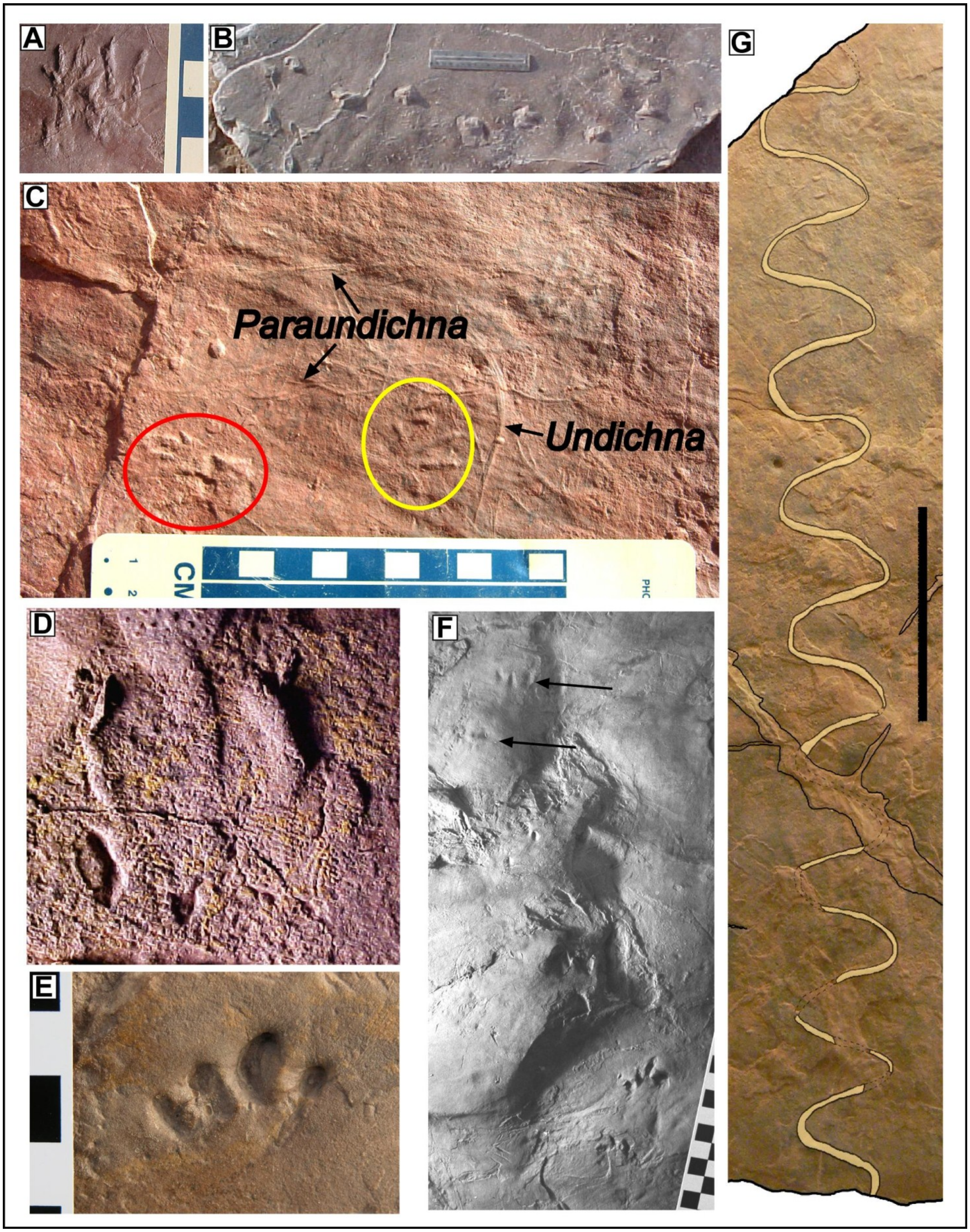


Figure 19. Examples of quadruped tracks at the SGDS. A, Manus and pes set of *Batrachopus* (SGDS 170). B, *Selenichnus* trackway showing overprinting and tail-drag marks (SGDS 175). C, Possible *Exocampe* manus and pes (in yellow circle) set next to a *Batrachopus* manus and pes (in red circle), and a cf. *Parundichna* fish swim trace (SGDS 509). D, Possible synapsid track with skin impressions (SGDS 176). E, Possible synapsid pes track (SGDS 190). F, *Batrachopus* trackway that transitions from walk to swim (SGDS 18.T5). Black arrows point to beginning of swim track sequence. G, *Undichna* fish swim trace (SGDS 917). Scale bar = 10 cm.

erosive megaripple on the Top Surface tracksite (Fig. 13).

Various other quadruped tracks suggest the possibly that there are sphenodontian ichnotaxon *Exocampe* (Fig. 19C), although the true ichnotaxonomic status of *Exocampe* needs to be resolved. *Brasilichnium*-like footprints that may have been produced by mammalian relatives (probably cynodont synapsids) are also present at SGDS (Fig. 19D-E). “Protomammal” tracks are known from other Triassic-Jurassic boundary sequences in the western United States, though they are most common in eolian deposits, unlike those represented in the Whitmore Point Member of the Moenave Formation. Both *Batrachopus* and the possible “protomammal” tracks are quite common transitioning from walking tracks to swim tracks and vice-versa (Fig. 19F; Milner et al. 2006c).

Two very important dinosaur track associations are preserved at the SGDS. First is the largest and best preserved collection of dinosaur swim tracks in the world (Milner et al. 2004, 2005a, b, 2006c; Milner and Lockley 2006; Milner and Spears 2007), which resolved a long-standing controversy among paleontologists as to what these kinds of structures truly represent. Tridactyl swim tracks of dinosaurs are usually arranged in sets of three parallel scrape marks that taper at each end, corresponding to the three functional digits of the theropod dinosaur pes. The longer digit III left a more elongate and deeper scrape mark compared to shorter digits II and IV (Fig. 20). Dinosaur swim tracks from the Middle Jurassic of England were described and given the name *Characichnos* by Whyte and Romano (2003). A varying arrangement of theropod swim track morphotypes are represented in the SGDS collection: (1) those showing animals swimming against a current (Fig. 20D-E), (2) animals swimming with the current that produced claw and digit impressions vertically (Fig. 20B) or clear *Grallator*-type footprints with claw scrape marks directed caudally from the footprints (Fig. 20C), (3) and animals that were swimming cross-current (Fig. 20F) (Milner et al. 2006c). Many of these swim tracks preserve spectacular details such as skin impressions, scale scratch lines, and details on claw cuticle (Fig. 20G, H).

The other important association at the SGDS is a 22.3 m-long, *Eubrontes* trackway (SGDS 18.T1) on the Top Surface within the SGDS museum. This trackway displays very rare tail drag marks along much of its length (Figs. 13, 21A). Near the beginning of this same trackway are crouching traces produced when the track maker sat down on the substrate (the side of one of the large ridges mentioned previously), then shuffled forward and sat down a second time, creating two overlapping but distinct crouching impressions consisting of pes prints with hallux impressions, ischial callosities, tail traces, and even scale scratch lines (Fig. 21B-C) (Milner et al. 2009a). In addition, this unique trace fossil has clear, associated manus impressions (Milner et al. 2004; Milner and Lockley 2006, Milner et al. 2006d; Milner et al. 2009a). Both tail drag and crouching traces produced by theropod dinosaurs are extremely rare, and the manus impressions are unique among known theropod traces (Weems [2006] reported possible manus

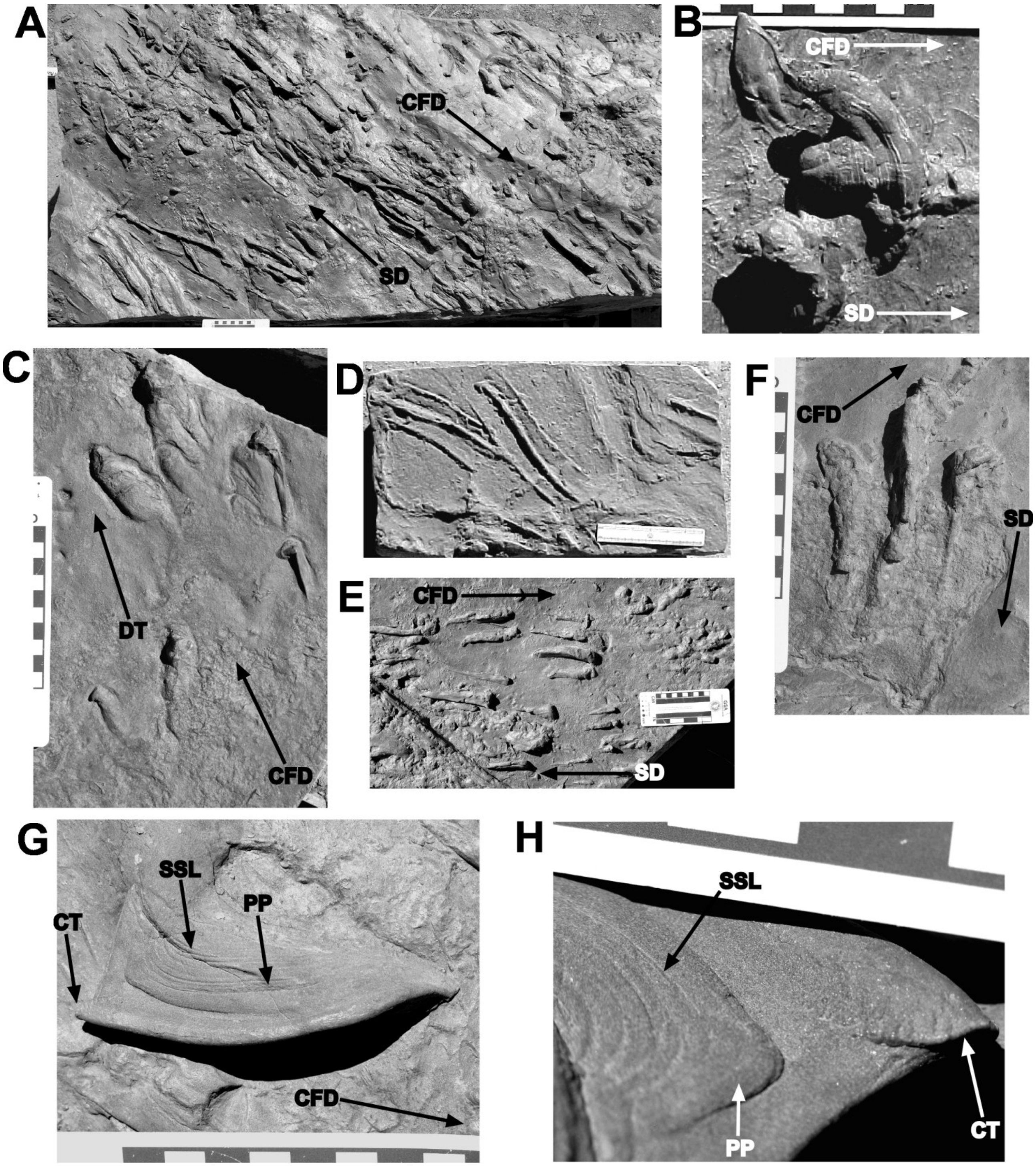


Figure 20. *Grallator*-type swim tracks from the SGDS MTL. A, Block showing high density of parallel swim tracks (Field # SW.29). B, Down-current swim track set (Field # SW.104). C, "Normal" *Grallator* track in a down-current orientation (Field # SW.90). D, Elongate, up-current swim tracks (SGDS 167-4). E, Shorter, up-current swim tracks (Field # SW.103). F, Swim track set cross-cutting current in a more up-current direction (Field # SW.77). G, *Grallator*-type swim track showing claw mark, claw tip and scale scratch lines (SGDS 361). H, Close-up of claw tip, from G showing possible cuticle details (SGDS 361). Abbreviations: CFD, current flow direction; CT, claw tip; DT, direction of travel; PP, distal phalangeal pad; SD, swim direction; SSL, scale scratch lines. Scale in cm (from Milner et al. 2006c).

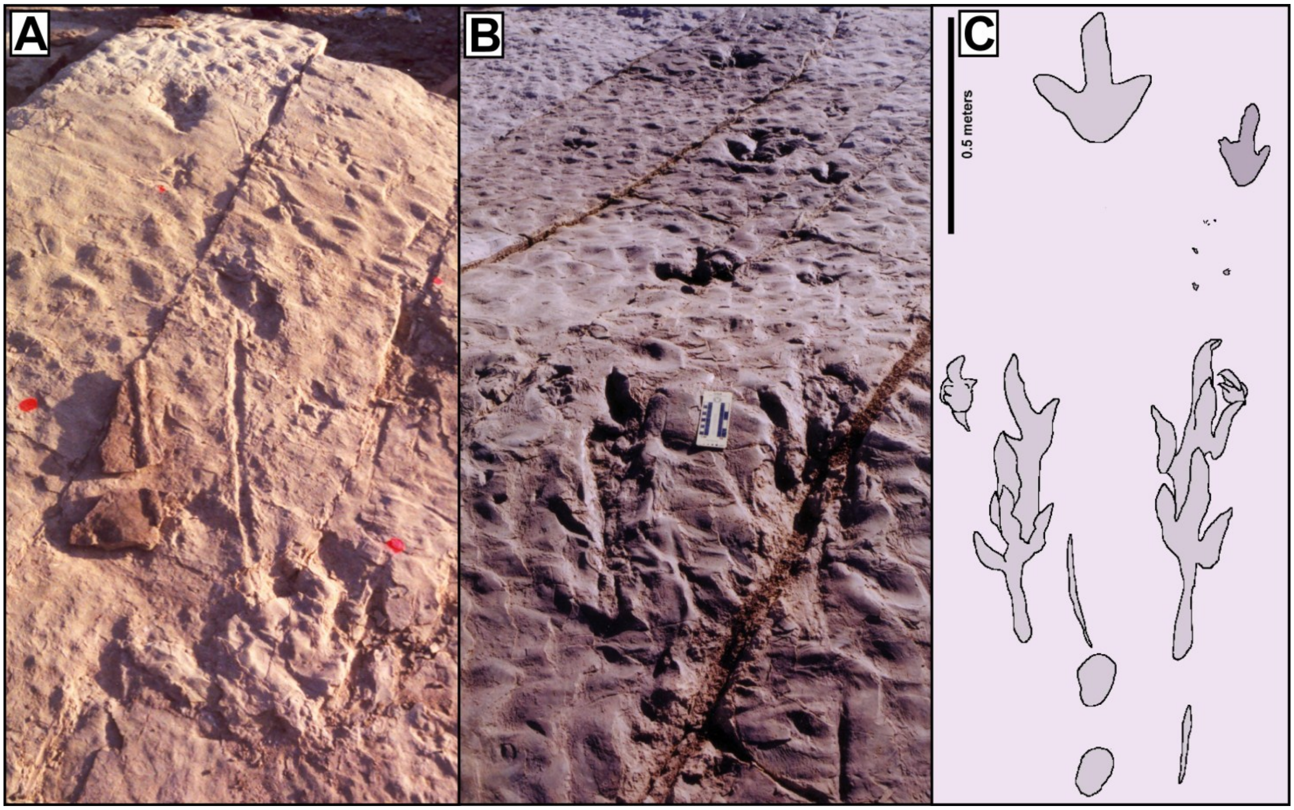


Figure 21. Portions of *Eubrontes* theropod trackway on SGDS “Top Surface” (SGDS 18-T1). A, Photo taken soon after 2000 discovery of tail drag marks. B, Photo of theropod crouching trace soon after 2004 discovery. C, Interpretive drawing of a double set of crouching traces that include pes footprints with metatarsal impressions, ischial callosities, and manus impressions associated with the first crouching trace. Tail drag marks from the same large theropod are associated with the crouching traces and trackway, along with tracks of *Grallator* and *Batrachopus*.

traces associated with *Kayentapus* tracks from the Early Jurassic of Virginia, but the manus impressions lack detail). The trackmaker proceeded through sediments of differing consistencies and gradients, providing an opportunity to better understand their effects on track morphology (Milner et al. 2004; Milner and Lockley 2006; Milner et al. 2006d; Milner et al. 2009a).

The SGDS also has a large number of fish swim trails and coprolites. Fish swimming traces include fine examples of *Undichna* (Fig. 19G), formed by the caudal fin (and sometimes other fins) of a fish scraping on a submerged lacustrine substrate (Seilacher 2007), and *Parundichna* (Fig. 19C), probably made by pectoral and pelvic fins of a coelacanth scraping along a muddy substrate (Simon et al. 2003; Seilacher 2007). *Parundichna* traces are known elsewhere from the Middle Triassic (Ladinian) Lower Keuper of Rot am See, Baden-Württemberg, Germany (Simon et al. 2003).

A low-diversity, invertebrate ichnofauna occurs in close association with tetrapod traces, sedimentary structures, and some body fossils at and around the SGDS (Lucas et al. 2005b; Lucas et al. 2006a). Arthropod locomotion trails of *Kouphichnium* isp. (Fig. 22A), cf. *Bifurculapes* isp.

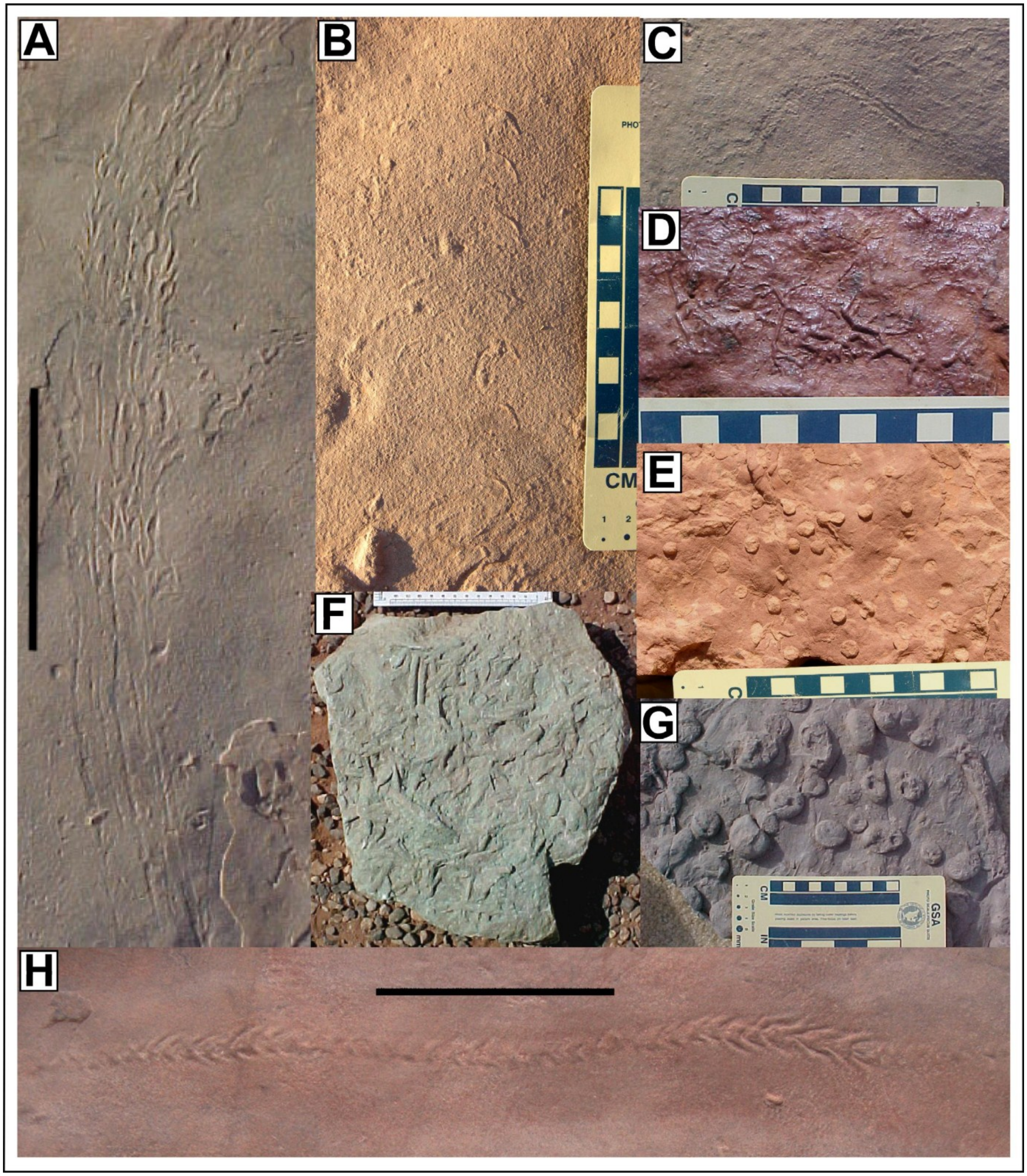

Figure 22. A selection of invertebrate ichnofossil types from the SGDS. A, Trackway of cf. *Kouphichnium* isp. (SGDS 258). Scale equals 10 cm. B, cf. *Bifurculapes* isp. trackway (SGDS 197). C, *Diplichnites triassicus* trackway (SGDS 197). D, Grazing trails of *Helminthoidichnites tenuis* (SGDS 375). E, *Skolithos* isp. burrows from the "Slauf Burrow Bed" (SGDS 505). F, *Palaeophycus tubularis* burrows preserved in convex epirelief from the base of the "Green Burrow Bed" (SGDS 191). G, Possible *Margaritichnus*-like invertebrate traces that Lucas et al. (2006a) interpret as mud lumps or load casts (SGDS 438) from SGDS "Top Surface." H, Chevron marks originally interpreted as larval dragonfly traces called *Protovirgularia* (SGDS 38). Scale bar = 5 cm.

(Fig. 22B), and *Diplichnites triassicus* (Fig. 22C) are all present on both the Split Layer and Top Surface at the SGDS (Fig. 5). Structures originally identified as *Protovirgularia* from the SGDS Top Surface (Fig. 22H; Milner and Lockley 2006), initially interpreted as made by dragonfly larvae in fluvial and lacustrine settings (Metz 2002), are now interpreted as non-biotic chevron marks based on recently discovered, *in situ* examples (Lucas et al. 2006a).

Horizontal grazing trails of the ichnospecies *Helminthoidichnites tenuis* (Fig. 22D) and possibly *Scoyenia* isp. are the only invertebrate traces found in the Dinosaur Canyon Member at the SGDS to date. Both are also present in marginal lacustrine beds in the lower part of the Whitmore Point Member (Milner and Lockley 2006). Abundant *Skolithos* isp. burrows (Fig. 22E) cover enormous areas in association with mud cracks, hundreds of *in situ* dinosaur tracks, semionotid fish body fossil remains, and coprolites on the LDS Tracksite surface (Figs. 5, 6; Williams et al. 2006). One of the best *Skolithos* layers is the Slauf Burrow Bed, which also preserves occasional dinosaur tracks and fish fossils, while Sally's Burrow Bed is located approximately 1.5 m above the Slauf Burrow Bed (Fig. 6). These beds are named after David Slauf and Sally Stephenson, both dedicated volunteers at the SGDS and Utah Friends of Paleontology members. Extensive surfaces of *Palaeophycus* isp. burrows (Fig. 22F) are present approximately 12 m above the Main Track Layer at the base of a heavily bioturbated, green sandstone bed containing abundant fish bones, coprolites, and conchostracans (Fig. 6).

**Body Fossils**

An unusual feature of the SGDS is the co-occurrence of ichnofossils with body fossils in the Whitmore Point Member. Most of the associated body fossils pertain to invertebrates, including the ostracods *Darwinula* sp. and Cypridoidea indet. (Schudack 2006), and two species of conchostracan *Euestheria brodieana* and *Bulbilimnadia killianorum* (Lucas and Milner 2006; Kozur and Weems 2010; Lucas et al. 2011). Extensive collections of Early Jurassic fishes from the SGDS and surrounding area are currently being prepared and studied (Milner and Kirkland 2006; Milner and Lockley 2006; Milner et al. 2006b; Milner and Spears 2007). Fishes that have already received some study include two new species described by Milner and Kirkland (2006): the hybodontoid shark *Lissodus johnsonorum* (Fig. 23A, B) and the lungfish *Ceratodus stewarti* (Fig. 23C). Other fishes, including a palaeoniscoid (Fig. 23E), many semionotids probably all belonging to the genus *Semionotus* (Fig. 23F, G), and a large, new species of *Chinlea*-like coelacanth (Fig. 23D) consisting of many isolated elements including a disarticulated and associated skull and articulated caudal fin. Although far rarer than the fishes, tetrapod remains from the SGDS have also been recovered, all of which pertain to theropod dinosaurs thus far (Kirkland et al. 2005; Milner and Lockley 2006; Milner and Kirkland 2007). At least two types of theropod teeth and a single, well-preserved dorsal vertebra (Fig. 24A-C) have been found. The larger teeth, which are conical and sometimes preserve serrations under the right circumstances (Fig. 24F),

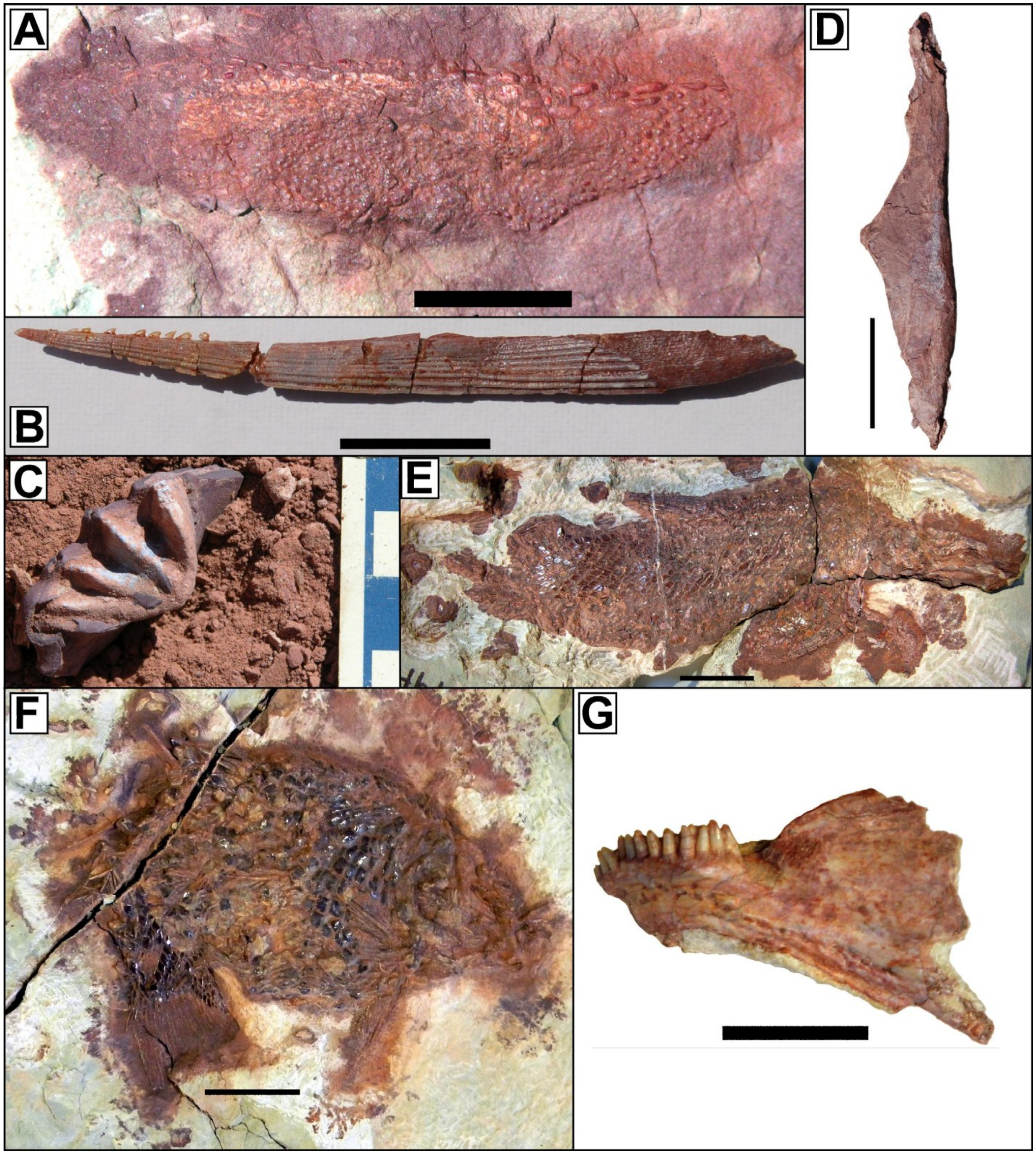


Figure 23. Examples of fishes from the SGDS and surrounding areas. A, Holotype specimen of *Lissodus johnsonorum* Milner and Kirkland 2006 lower left jaw with complete tooth sets (SGDS 857). Scale bar = 1 cm. B, *Lissodus johnsonorum* dorsal fin spine in left lateral view (SGDS 828). Scale bar = 2 cm. C, Holotype *Ceratodus stewarti* Milner and Kirkland 2006 lungfish tooth plate (UMNH-VP 16027). D, Large left angular from a new species of *Chinlea*-like coelacanth (SGDS 892). Scale bar = 5 cm. E, Nearly complete, unidentified palaeoniscoid fish (SGDS 1241). Scale bar = 2 cm. F, Nearly complete *Semionotus* fish (SGDS 1193). Scale bar = 5 cm. G, Lower jaw of a semionotid fish (SGDS 814). Scale bar = 1 cm.

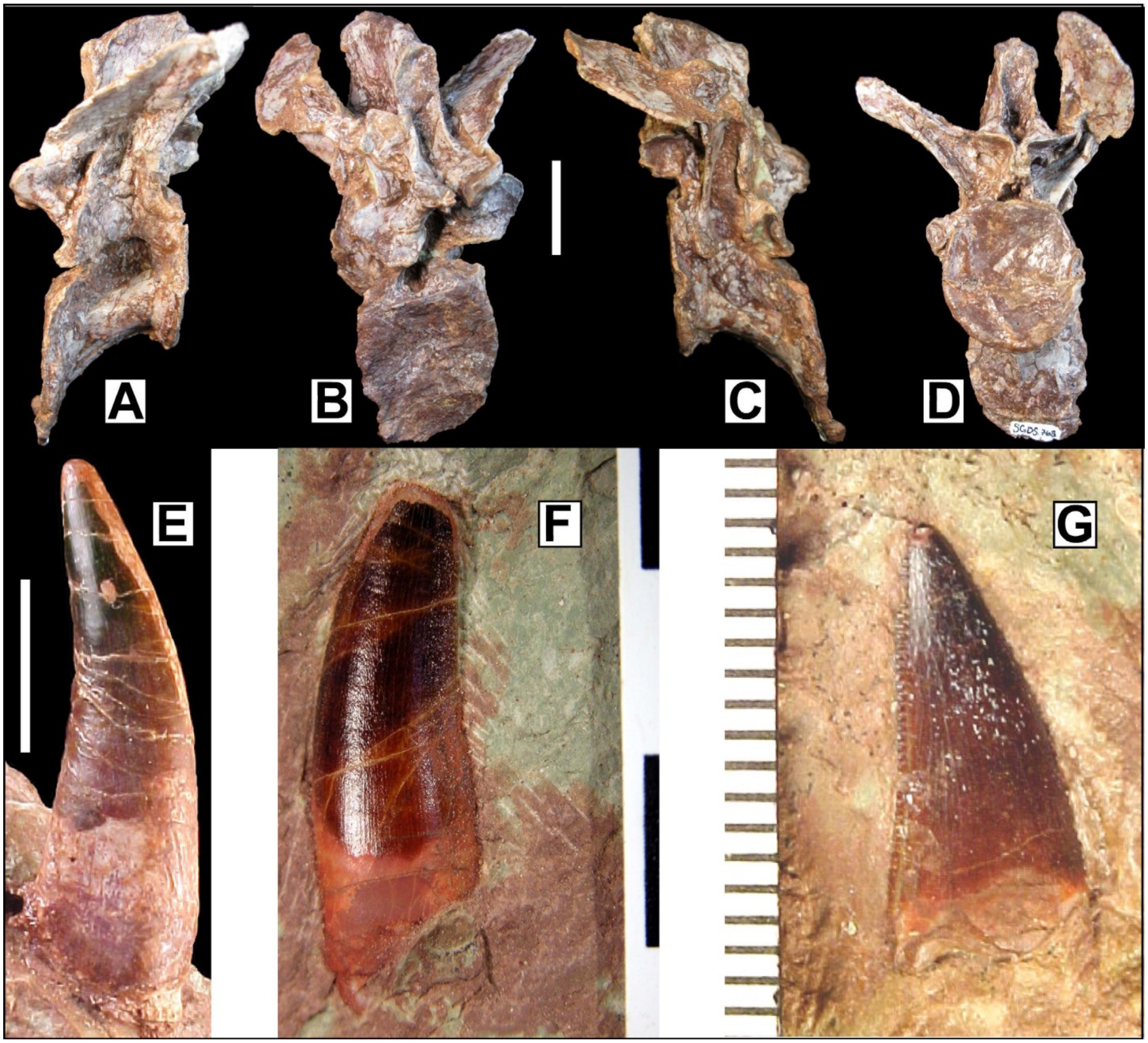


Figure 24. Theropod dinosaur remains from the SGDS. A–D, Theropod cranial thoracic (anterior dorsal) vertebra (SGDS 768). A, Left lateral view. B, Anterior view. C, Right lateral view. D, Posterior view. Scale bar = 3 cm. E, Large theropod tooth (SGDS 852). Scale bar = 2 cm. F, Large theropod tooth that was broken while still articulated in the jaw. It preserves serrations and wear facet (SGDS 1335). G, Small serrated tooth, possibly from a coelophysoid theropod (SGDS 851).

have an overall shape similar to those of spinosaurids from the Early Cretaceous of North Africa and elsewhere (Fig. 24 D, E), although they are not spinosaurids. Teeth like these have not been reported in any Early Jurassic theropod and thus likely pertain to a new taxon. Smaller, serrated, blade-like teeth (Fig. 24G) may belong to *Megapnosaurus*/*Syntarsus*, fragmentary remains of which have been reported from the Dinosaur Canyon Member of the Moenave Formation (Lucas and Heckert 2001), or to an unknown coelophysoid theropod. It is likely that theropod dinosaurs were entering the waters of Lake Dixie to actively fish (Fig. 25) (Milner and Kirkland 2007).

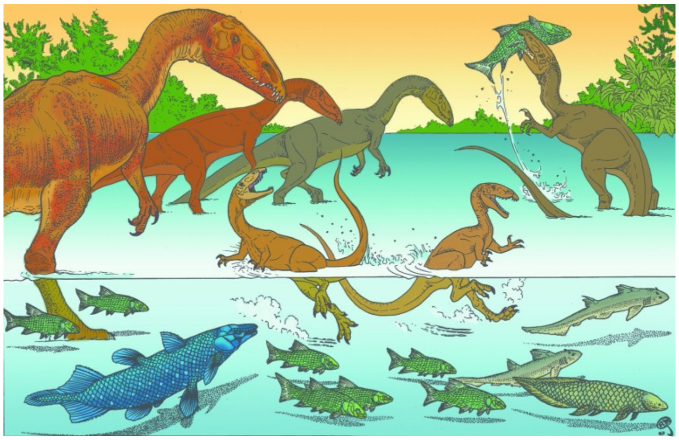

Figure 25. Theropod dinosaur swimming and fishing in Lake Dixie. Drawing courtesy of Russell Hawley.

Two localities in the upper part of the Dinosaur Canyon Member on the Darcy Stewart and Paul Jensen properties (formerly owned by the late Layton Ott), and plant impressions preserved on the Top Surface within the SGDS museum, document a low diversity flora that consists at present of seven species of conifers, ferns, and horsetails (Tidwell and Ash 2006). Conifer taxa include *Araucarites stockeyi* (Fig. 26A, B), *Saintgeorgeia jensenii* (Fig. 26C-D), *Milnerites planus* (Fig. 26E), *Pagiophyllum* sp. (Fig. 11G), and cf. *Podozamites* sp. The horsetail impressions pertain to *Equisetum* sp. (Fig. 26F), and the fern to *Clathropteris* sp. (Fig. 26G; Tidwell and Ash 2006).

## 3D IMAGE CAPTURE AND CLOSE-RANGE PHOTOGRAMMETRY: AN OVERVIEW OF FIELD CAPTURE METHODS

**Part 2 discussion leaders: Neffra Matthews and Brent Breithaupt**

### INTRODUCTION

Photogrammetry is the science, and technology of obtaining reliable measurements from photographs. The basic requirement for photogrammetry is an overlapping pair of photographs taken to mimic the perspective centers of human stereoscopic vision. In 1997, during the early days of 3D photodocumentation at the Red Gulch Dinosaur Tracksite, Wyoming, the process was very labor intensive and required as much as a week to obtain a final dataset for a single footprint (Breithaupt et al. 2004; Matthews et al. 2006). As both documentation of the Red Gulch Dinosaur Tracksite and technology advanced, stereoscopic photographs, captured at a variety of heights from a number of different platforms, provided a wealth of 3D data for interpretation and analyses. Not only do these efforts increase the knowledge of the unique, paleontological resources at the site, they also provided a visual and quantifiable baseline that is being used to evaluate and better understand changes that occur to the track surface.

In the years since its beginnings at the Red Gulch Dinosaur Tracksite, close-range photogrammetry has been used to document and interpret fossil footprints sites throughout the western United States. Following the model established at the Red Gulch Dinosaur Tracksite, the camera and, in some cases, the photographer has taken to the air, using blimps, helicopters, and ladders to obtain the needed photographic perspectives of the subject. Individual tracks, trackways, and even entire track surfaces have been documented using close-range photogrammetry on lands managed by the Bureau of Land Management, U.S. Forest Service, National Park Service, and

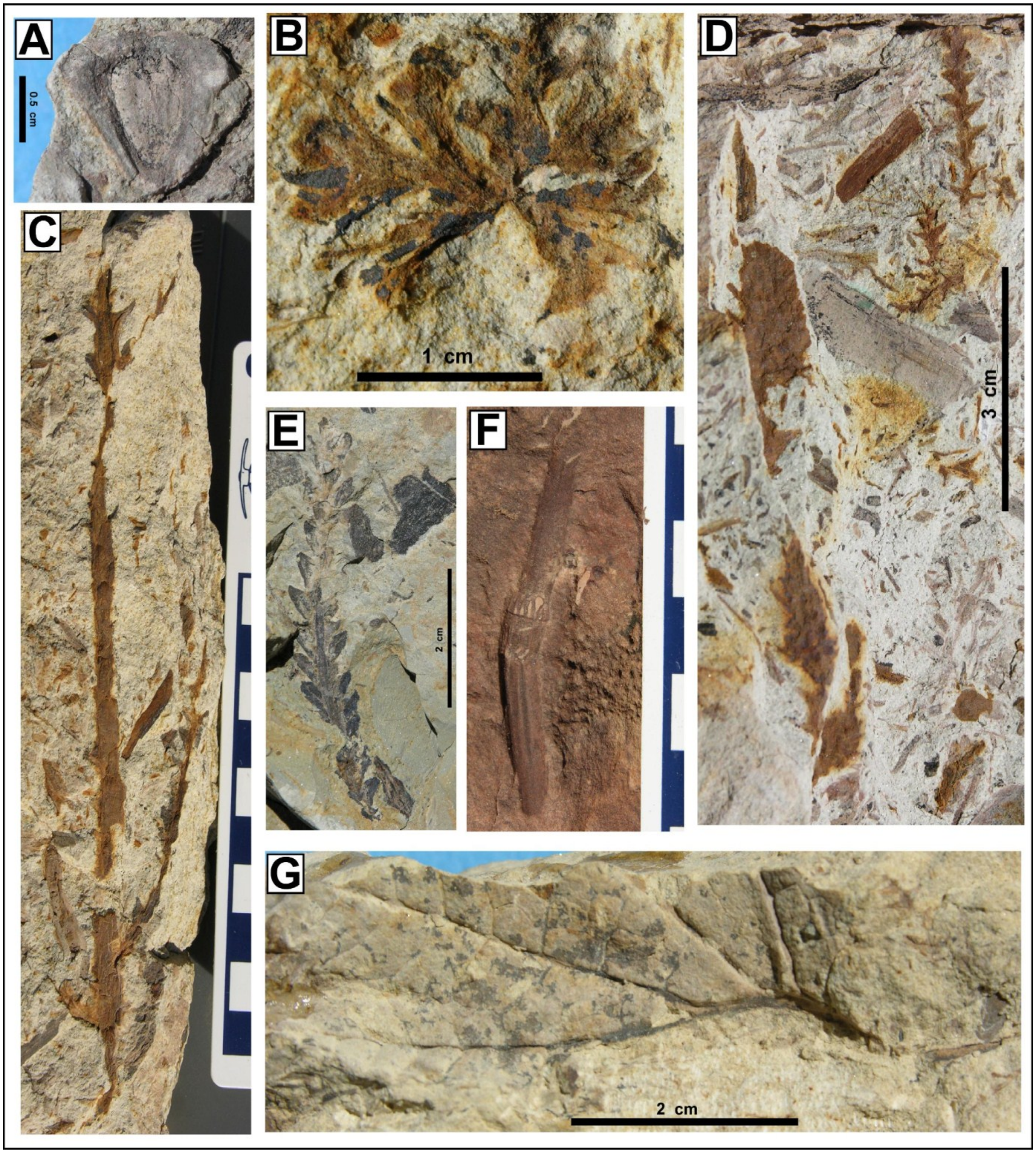


Figure 26. Plant fossils from the SGDS. A, *Araucarites stockeyi* holotype cone scale (SGDS 515). Scale bar = 0.5 cm. B, cf. *Araucarites stockeyi* cone (SGDS 516). Scale bar = 1 cm. C, Holotype specimen of *Saintgeorgeia jensenii* (SGDS 627). D, *Saintgeorgeia jensenii* with cones attached to branch (SGDS 517). Scale bar = 3 cm. E, *Milnerites planus* conifer branch (SGDS 513). Scale bar = 2 cm. F, Horsetail *Equisetum* sp. stalk (SGDS 569). G, *Clathropteris* sp. fern leaf (SGDS 465). Scale bar = 2 cm.

Bureau of Reclamation in Wyoming, Utah, Colorado, Nebraska, Oklahoma, New Mexico, Arizona, California, South Dakota, Idaho, and Alaska (Breithaupt and Matthews 2011a).

During the construction of the museum at the SGDS, the trace left by a crouching dinosaur was uncovered (Fig. 20). This unique, well-preserved, Early Jurassic ichnofossil is part of a longer *Eubrontes* trackway, which includes tail drag marks and a pair of footprints with associated metatarsal, ischial callosity, and manus impressions (Milner et al. 2009a). In the spring of 2004, before the full extent of this amazing ichnofossil was completely known, detailed photodocumentation was conducted at the site (Fig. 27A, B). Close-range photogrammetric methods (established procedure for capturing detailed information about paleontological site) included both oblique and stereoscopic image capture. These images were analyzed using three-dimensional measuring and modeling software and softcopy stereoscopic instruments. The results of this analysis yielded detailed digital terrain data that can be used to generate 3-D surfaces and detailed microtopographic contour maps (Fig. 27C-D). This state-of-the-art documentation method provides important digital information about dinosaur activity at this unique Early Jurassic dinosaur tracksite.

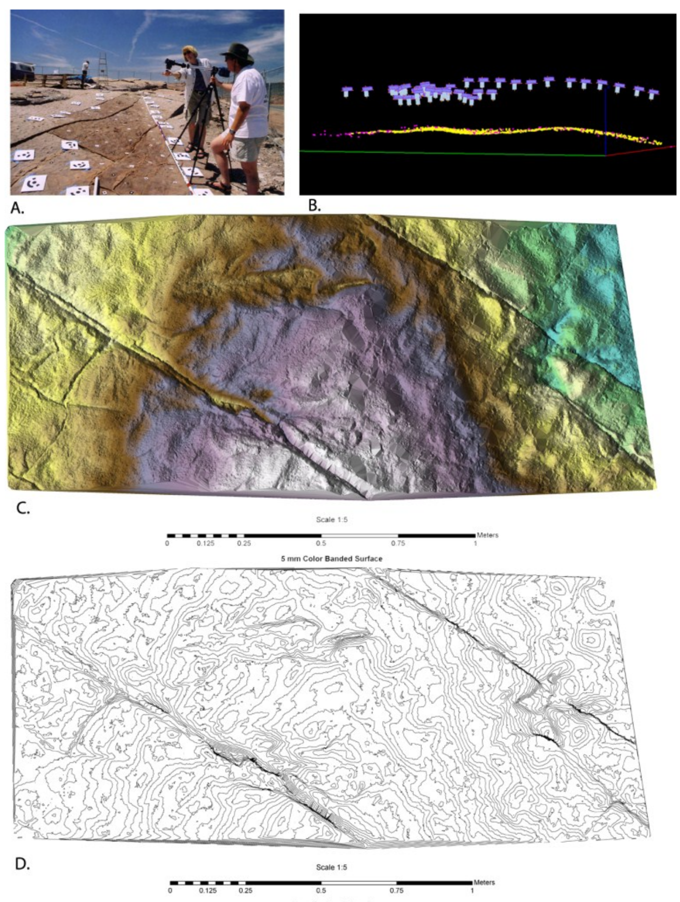


Figure 27. A, Photogrammetric setup for documenting the SGDS crouching trace prior to construction of the museum (SGDS 18-T1). B, Graphic showing the camera locations (depicted in lavender) occupied during the previously mentioned photogrammetric documentation. Surface data points are depicted in yellow and magenta. C, Photogrammetrically produced 3D surface color coded by elevation of the SGDS crouching trace. D, Topographic contour map of the SGDS crouching trace.

## BACKGROUND

Since its inception, the principles of photogrammetry—deriving measurements from photographs—have remained constant. Even today, when following the fundamentals, mathematically sound and highly accurate results can be achieved (Matthews 2008; Matthews and Noble 2010). Although requirements, such as overlapping (stereoscopic) images remain, technological advances in digital cameras, computer processors, and computational techniques, such as sub-pixel image matching, make photogrammetry an even more portable and powerful tool. Extremely dense and accurate 3D surface data can be created with a limited number of photos, equipment, or image capture time. An overlap of 60% has traditionally been required for analytical photogrammetry providing a very strong base to height ratio. Now, because of the highly automatic image correlation algorithms available today, a perfect photogrammetry sequence of photos would be 66% overlapping images. Points matched in at least three images (tri-lap) provide a high level of redundancy and a more robust solution (Matthews 2008; Matthews and Noble 2010). Though there are a number of commercial software packages available (3DM Suite by ADAM Technology, PhotoModeler by Eos Systems, TopoMap by 2d3, PhotoStruct by Alice Labs, etc.) the basic principles for capturing robust stereoscopic images and the photos needed for camera calibration remain consistent.

## BASICS OF STEREOSCOPIC PHOTOGRAMMETRY

A crucial element of a successful photogrammetric process is obtaining high-quality photographs (Matthews 2008; Matthews and Noble 2010). Herein, the term "high-quality" refers to a series of sharp pictures that have uniform exposure, high contrast, and fill the frame with the subject. The final accuracy of the resulting, dense surface model is governed by the image resolution, or ground sample distance (GSD). The GSD is a result of the resolution of the camera sensor (higher is better), the focal length of the lens, and the distance from the subject (closer is better). The resolution of the images is governed by the number of pixels per given area and the size of the sensor. The camera should be set to aperture priority (preferably F8 or higher) and the ISO, shutter speed, white balance, and other settings be adjusted to achieve properly exposed images. To obtain the highest order results, it is necessary to ensure that focal distance, physical distance, and zoom do not change for a given sequence of photos. This can be achieved by taking a single photo at the desired distance using the autofocus function, then turning the camera to manual focus and taping the focus ring in place. Then the rest of the photos can be taken at the same distance from the subject as the first photo.

The first consideration when designing the stereo photo layout is the needed precision, and therefore the scale that is required to adequately represent the subject. As in traditional film photogrammetry, the scale is a function of the height of the sensor and the focal length of the lens (Hussain and Bethel 2004).

$$\text{scale} = \frac{\text{focal length}}{\text{height above terrain}}$$

For example:

$$\frac{0.5 \text{ ft.}}{2000 \text{ ft.}} = 0.00025$$

$$\frac{1}{0.00025} = 4000$$

Therefore, scale = 1:4000.

When using a commercial digital camera, the resolution of the camera can be factored into the above equation to determine the resolution, or GSD, of the resulting image:

$$GSD=\left(\frac{SPS}{1{,}000{,}000}\right)\left(\frac{H}{f/_{1000}}\right)$$

where SPS is the sensor pixel size (microns), H is the camera height, or distance from the object (meters), and f is the focal length of the lens (millimeters). The GSD value will be in meters; multiply by 1000 for GSD in millimeters.

The best stereo photo pairs have an overlap of 66% (Fig. 28). Once the GSD and the resolution of the camera are determined, the camera height and distance between camera stations can be calculated (Matthews 2008; Matthews and Noble 2010).

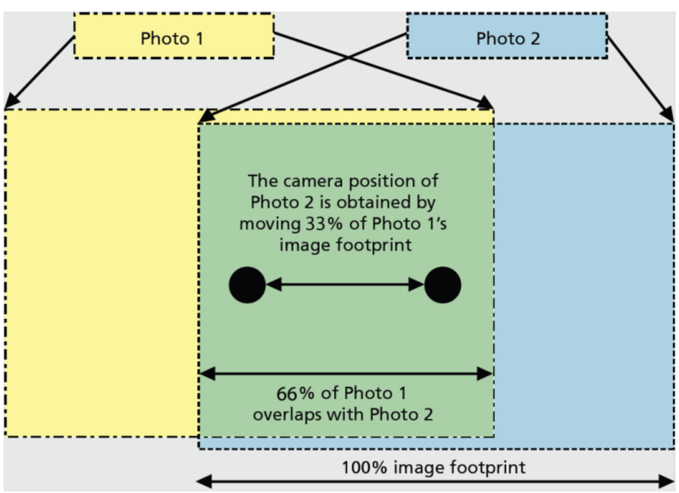


Figure 28. The best stereophoto pairs overlap each other by 66%. The black dots indicate the center of each photo, and are separated by a distance of 34% of the image footprint.

A simple way to determine the image footprint in the field is to mark points on the ground on either side of the frame of the viewfinder when the camera is at the appropriate distance from the subject. Measure the distance between these points and calculate 34% of that distance. With that value, physically move the camera that distance for the next photo. The orientation of the camera/sensor to the subject is also an important consideration. It is most desirable to have imagery that is taken with the camera as perpendicular to the subject as possible. A tripod (with an extension arm when shooting down) can greatly aid in positioning the lens directly over the subject (Fig. 27A). In turn, this positions the plane of the sensor parallel to the subject and helps to minimize perspective distortions in the image. To ensure the entire subject is covered by at least two overlapping photos, position the left extent of the subject in the center of the first frame. Proceed systematically from left to right along the length of the subject and take as many photos as necessary to ensure complete stereo coverage (Fig. 27B) (Matthews 2008; Matthews and Noble 2010).

## CAMERA CALIBRATION SEQUENCE

All camera lens systems have distortions due to the curvature of the lens and the alignment of the lens with respect to the sensor. In order to quantify these distortions and effectively remove them, three-dimensional measurement and modeling (3DMM) software provides camera calibration functions as part of the project work flow (Fig. 29). The main purpose of the camera calibration is to determine and map the distortions in the lens with respect to the

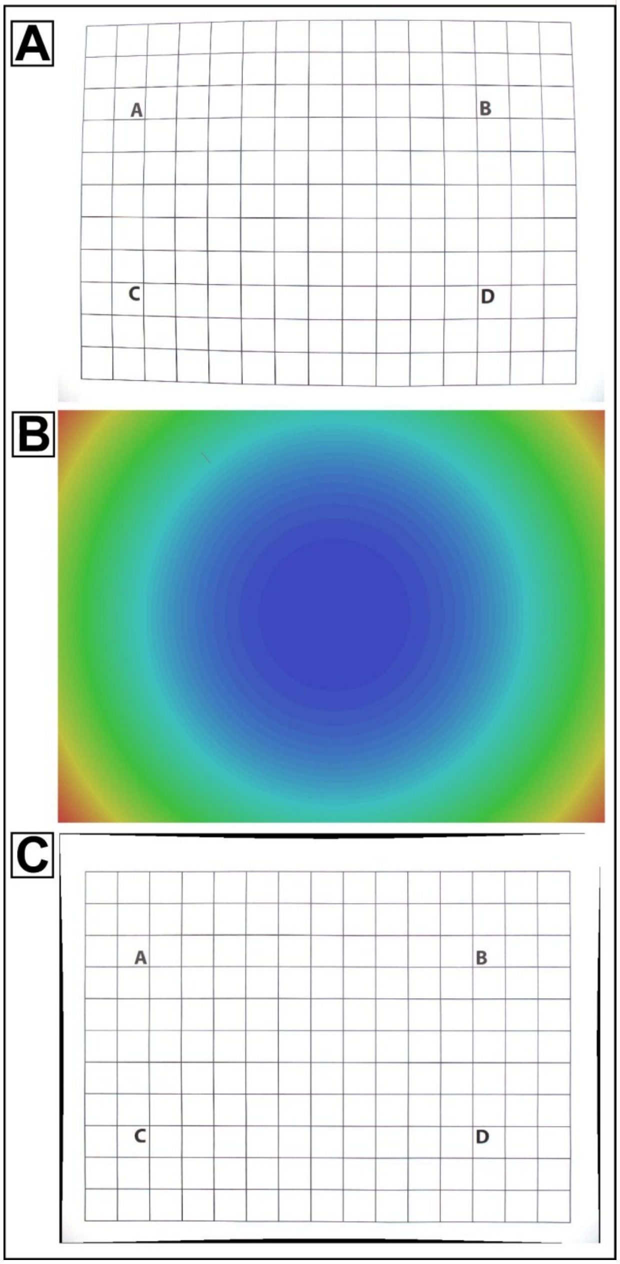

Figure 29. A, Photograph of a straight-line rectangular grid. The curvature of the lines is due to the most common type of lens distortion, which is barrel distortion. B, Graphic representation of lens distortion. The least distorted portion of the lens is in the center (depicted in dark blue). During the camera calibration process, the focal length, format size, principal point, and distortion coefficients (K1, K2, K3, P1, and P2) of the camera–lens system are calculated. C, The corrected photograph from a after the lens distortion parameters were applied. The results can be seen in the straightening of the grid lines and a visible change of the image.

sensor location. This can be accomplished most effectively when there are a large number of auto-correlated points in common between the stereoscopic images and the additional set of calibration photographs. The camera calibration photographs must be captured at the same settings as the stereo photos (Matthews 2008; Matthews and Noble 2010). At least four additional photos are required; two taken with the camera physically rotated 90° to the previous line of stereoscopic photos and two additional photos with the camera rotated 270° (Fig. 30). The additional four camera calibration photos may be taken at any location along the line of stereo photographs, but the best results occur in areas where the greatest number of auto-correlated points can be generated.

## ADDING MEASURABILITY

In addition to maintaining a proper base to height for 66% overlap and the camera calibration photo sequence, the next most important component needed to acquire geometrically correct dense surface models is the ability to introduce real world values, or scale, to a project (Matthews 2008; Matthews and Noble 2010). This is accomplished by simply adding an object (Fig. 31) of known dimension (meter stick or other object) that is visible in at least two stereo models (three photos). It is preferable to have two or more such objects, to ensure visibility and for accuracy assessment. Calibrated target sticks may be used in addition to, or in place of, the object of known dimension. These objects may then be assigned their proper lengths during processing, and most photogrammetrically

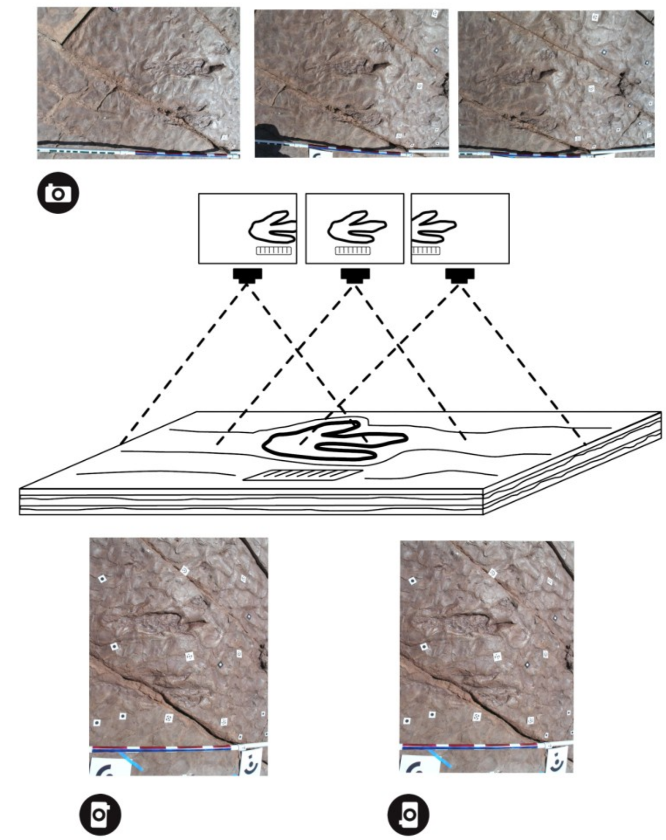

Figure 30. Illustration of the sequence of images needed to capture a basic stereoscopic project and perform a camera calibration. The dashed outlines highlight a pair of photographs that overlap each other by 66%. Arrows, indicating the rotation at which photos were taken, show a 0° degree (or landscape) orientation. The solid outlines highlight the four photos required for the camera calibration process. These photos are taken at 90° (or portrait) orientation. By stacking the camera calibration photos over the previously taken stereoscopic photos, maximum benefit will be achieved. Areas of minimum overlap are illustrated by shading of the photographs. Note the calibrated target sticks positioned along the subject.

based software packages conduct a mathematical procedure knows as a bundle adjustment. Once an object length is established, the bundle adjustment passes those measurements to all photos and reduces error in the project. High accuracy may be extended for a long distance along a series of photos allowing for the object of know dimension to be placed so as to not detract visually from the subject.

Capturing photographs for stereoscopic photogrammetric processing may be accomplished in as few as six photos for a small subject, and can provide extremely dense, high-resolution, geometrically and orthometrically correct, three-dimensional (3D), digital data sets (Matthews 2008; Matthews and Noble 2010). Because of the flexibility of this technique, it is possible to obtain highly accurate 3D data from subjects that are at almost any orientation (horizontal, vertical, above, or below) to the camera position. However, it is important to keep the plane of the sensor and lens as parallel as possible to the subject and to maintain a consistent height (or distance) from the subject (Fig. 27B). Although low- or no-cost automatic image matching alternatives currently are not available for typical analytical photogrammetric processing, the same sub-pixel-matching algorithms developed for use in structure from motion and gigapixel panoramas will undoubtedly lead to this niche being filled. Regardless, incorporating the basic photogrammetric image capture steps described above (correct base to height, addition of camera calibration photos, and adding an object of known dimension), to other capture methods will undoubtedly increase their geometric accuracy. The extra images required to provide these improvements can be captured with very little additional time or cost. The resulting, dense surface model and image texture may be output directly and indirectly to a variety of file formats as well as a variety of solid model printouts.

## CONCLUSION

Today, advances in digital cameras, computer architecture, and multi-view-matching software make it possible to take photos and produce a final dataset in a matter of minutes. In addition, the technique is much more portable, allowing the capture of stereoscopic photos to be conducted by field personnel. This makes close-range photogrammetry an effective method for capturing important data about a wide variety of resources. Often, the use of photogrammetry can be more efficient, less labor-intensive, and more cost-effective than other types of field 3D data collection.

Very recent advancements in software now provide low and no cost solutions for successfully processing stereoscopic photography that has been taken with 60 to 75% overlap. This will significantly increase the use of close-range photogrammetry for resource documentation by allowing the field photographer to receive almost immediate feedback on the success of image capture. With the introduction of low/no cost software, the processing of close-range photogrammetric images is no longer confined to a few locations, thus reducing the limitations on generating, using, and sharing 3D date of ichnological features.

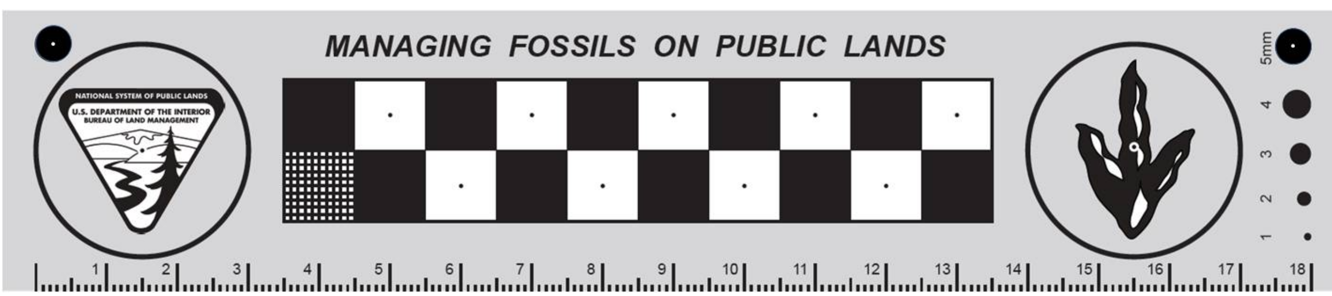


Figure 31. Example of an object of known dimensions that must be included in the overlapping area of a stereoscopic pair of images in order to scale the resulting 3D model to real world coordinates. The scale must *not* be moved while taking the overlapping imagery.

| | | |
|---|---|---|
| 0.1 | 123.3 | Leave museum, turn right onto Riverside Drive heading east. |
| 2.2 | 125.5 | Red Cliff Drive/Telegraph Road intersection and stoplights. Continue straight. |
| 0.1 | 125.6 | Turn right onto I-15 northbound at Exit 10 onramp. |
| 0.4 | 126.0 | Merge onto I-15. |
| 1.8 | 127.8 | Pass Washington Parkway Exit 13, driving through outcrops of the Lower Jurassic (Sinemurian) silty facies of the Kayenta Formation. An important dinosaur tracksite, the Spectrum Tracksite (Hamblin 2004, 2006; Hamblin et al. 2006; Milner and Spears 2007), is located on top of the Springdale Sandstone |

| | | |
|---|---|---|
| | | Member of the Kayenta Formation to the south. We will visit this site on day 2 if time permits. Northwest of the highway is the Washington Water Tank Tracksite, which is in the uppermost silty facies (Hamblin et al. 2006; Milner and Spears 2007) immediately below the “Kayenta-Navajo Transition Zone” and the Navajo Sandstone Formation. |
| 1.0 | 128.8 | Cross Grapevine Pass Wash and view roadcuts north and south of I-15, which display columnar-jointed basalt of the Washington Flow capping the silty facies of the Kayenta Formation. Radiometric ages for the Washington Flow in this area range from 0.87 ± 0.004 Ma to 0.97 ± 0.02 Ma (Biek 2003b). Looking up Grapevine Pass Wash to the north of I-15, outcrops of the upper Kayenta Formation can be seen transitioning into the Navajo Sandstone Formation. |
| 2.5 | 131.3 | Kayenta Formation outcrops on both sides of the road and Pine Valley Mountains to the northwest. The Pine Valley Mountains are composed of intrusive volcanics of early Miocene quartz monzonite porphyry; part of the Pine Valley laccolith; at 1000 m thick and ~161 $km^2$ (62 $mi.^2$) in area, it is the largest laccolith in North America and one of the largest in the world (Hurlow and Biek 2003). |
| 1.6 | 132.9 | Driving over the Petrified Forest Member of the Chinle Formation. The northwestern end of the Harrisburg Dome (part of the Virgin Anticline) can be seen on the right, capped by a prominent ridge of the resistant Shinarump Member of the Chinle Formation. |
| 1.3 | 134.2 | Cross Cottonwood Creek Wash. |
| 0.4 | 134.6 | Cross Quail Creek Wash. |
| 0.2 | 134.8 | Chinle Formation outcrops on both sides of the highway. |
| 1.0 | 135.8 | Driving through Chinle Formation, channel sandstones, possibly the Moss Back Member, on Leeds Reef to the left (northwest). |
| 0.6 | 136.4 | Pass Leeds Exit 22. |
| 0.6 | 137.0 | Go under overpass crossing I-15. Outcrops of Chinle Formation (possibly Moss Back Member) can be seen on Leeds Reef, part of the Leeds anticline immediately to the left (northwest) of I-15. The Leeds anticline turns abruptly to the north and can be seen in cross-section through Buckeye Reef (north and northwest), where outcrops of the Moenave (Dinosaur Canyon and Whitmore Point members) and Kayenta (Springdale Sandstone Member) formations are folded upward (Biek 2003a). Immediately adjacent to Buckeye Reef to the east |

| | | |
|---|---|---|
| | | on Big Hill, and also on the right (east) side of I-15, are very good exposures of the Moenave Formation capped by the Springdale Sandstone of the Kayenta Formation. |
| 0.8 | 137.8 | Old mine shaft and tailings can be seen on the left (north and northwest) on Big Hill and Buckeye Reef, and to the right (east) on and below the Springdale Sandstone. Spectacular dinosaur tracksites are known to the south of here in the historic Babylon region (Lockley et al. 2006b; Milner and Spears 2007; Milner et al. 2009b). Although we will not stop at these localities, they are described below since they are relevant to the field trip discussion. |

**DESERT TORTOISE TRACKSITES**

In the historic "Babylon" area near Leeds are five major tracksites at three stratigraphic levels. An additional four track-bearing stratigraphic levels are known from this valley, for a total of seven track-producing layers thus far identified. The preliminary study of Lockley et al. (2006b) mapped four of the five major sites and measured the lower portion of the stratigraphic section (Fig. 32). The first tracksite discovery in this valley (Desert Tortoise tracksite 1) was made by the first author during the field trip for the 2005 *Tracking Dinosaur Origins* conference (Harris 2005).

The tracksites described here are on steeply dipping, structurally tilted slopes (35°–50°) of the silty facies in the Kayenta Formation (Fig. 33). The silty facies in this area consists of alternating mudstones, siltstones, sandstones, and thin, carbonate sandstone beds with tracksites mostly on the carbonate sandstone and sandstone surfaces. The mudstones and siltstones were chiefly deposited in shallow and marginal lacustrine environments,

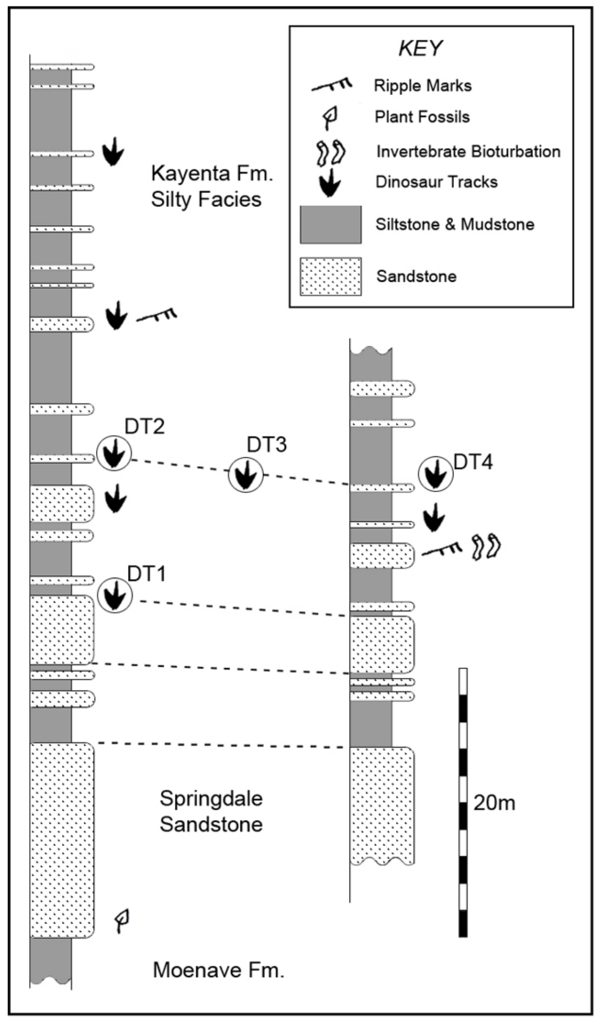


Figure 32. Generalized stratigraphic section showing the positions of the Desert Tortoise tracksites (DT1–DT4) in the silty facies of the Kayenta Formation. The section on the left shows the northeastern area and on the right is the southwestern area (from Lockley et al. 2006b).

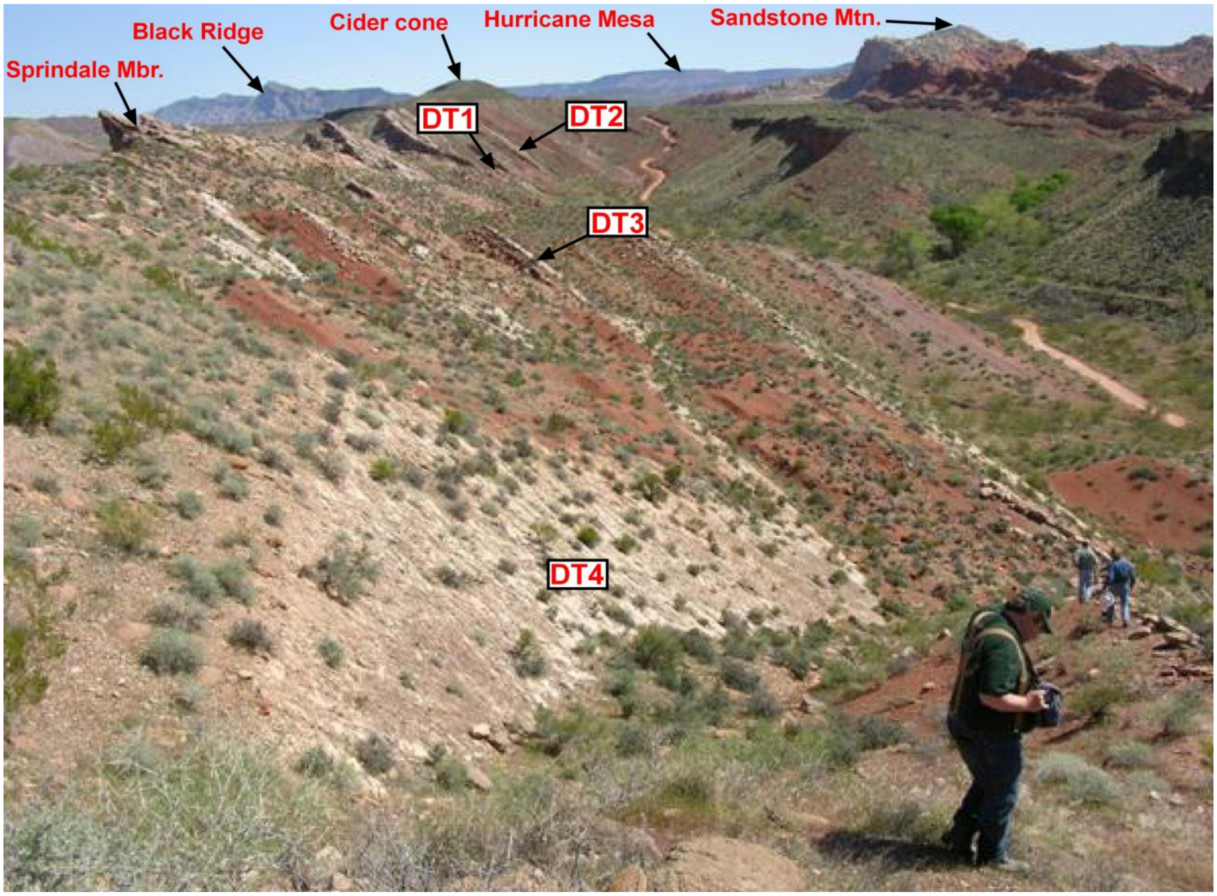

Figure 33. View to the north–northeast showing the Desert Tortoise tracksites (DT1–DT4) on the eastern flank of the Virgin Anticline. The prominent ridge (East Reef) stratigraphically below the tracksites is the Springdale Sandstone Member of the Kayenta Formation. Below this are the Moenave Formation (out of view) and the Upper Triassic Chinle Formation (partially visible in the upper left corner in Grapevine Wash valley). Sandstone Mountain in the upper right is comprised of Navajo Sandstone. Other geologic features discussed elsewhere in this guidebook are indicated on the horizon (Hurricane Mesa, a cinder cone volcano, and Black Ridge).

although some are interpreted as possible paleosols (Lockley et al. 2006b). Some thin, fine-grained sandstone beds are also interpreted as shallow lacustrine and/or marginal lacustrine environments because they preserve stromatolites, *Grallator*-type theropod swim tracks, disarticulated semionotid fish remains, and rare coprolites. Sandstones were deposited in fluvial channel, reworked marginal lacustrine, and occasional eolian deposits, particularly toward the top of the silty facies. The major tracksites are preserved on red-brown sandstone (Desert Tortoise tracksite 1) and white siliciclastic sandstones bound by carbonate cement (Desert Tortoise tracksites 2-4).

Desert Tortoise Tracksite 1 is divided into north and south sites that were mapped separately (Fig. 34) and first illustrated and described by Lockley et al. (2006b; Figs. 3 and 4). The smaller, strike-parallel north site has 16 *Eubrontes* tracks in at least five trackways (Fig. 34A-B; Lockley et al. 2006b). The larger south tracksite has at least 60 recognizable tracks in 17 identified trackways, plus

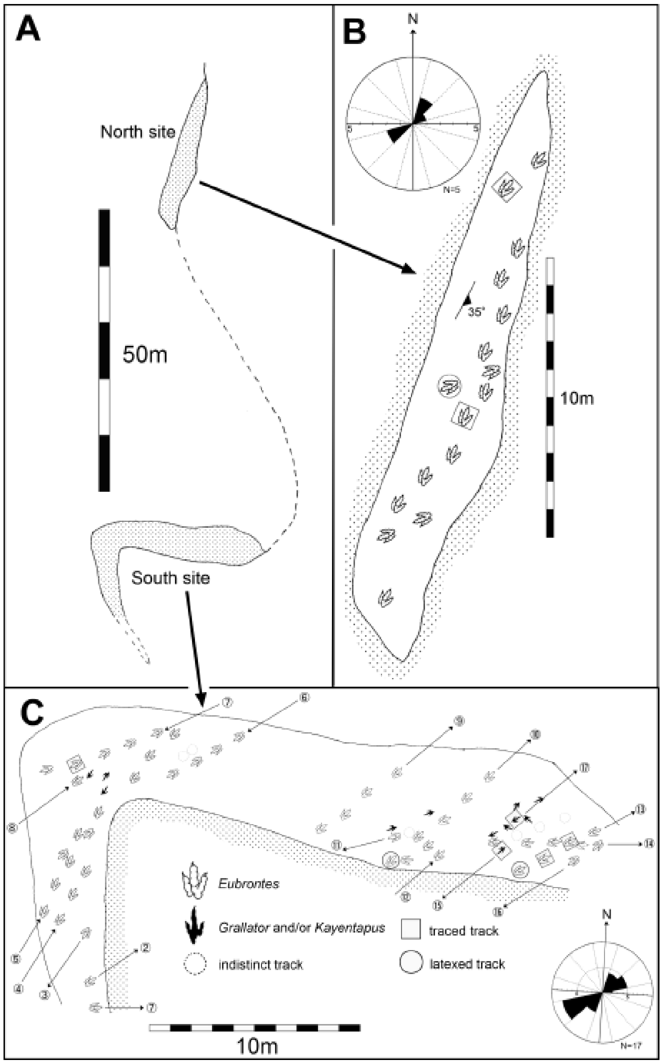


Figure 34. A, Map showing the relation between Desert Tortoise 1 (DT1) north (N) and south (S) sites. Both DT1 north and south tracksites are about 50 m apart. B, Detail of DT1 (N) tracksite. C, Detail of DT1 (S) tracksite. From Lockley et al. (2006b).

several isolated footprints. This site has better track preservation and is dominated by larger *Eubrontes* tracks (Fig. 35A), although *Grallator* tracks are also present (Fig. 34C). The trackways exhibit a strong, bimodal orientation along a NE-SW trend (Lockley et al. 2006b).

Desert Tortoise tracksites 2–4 are much larger surfaces that and are stratigraphically higher

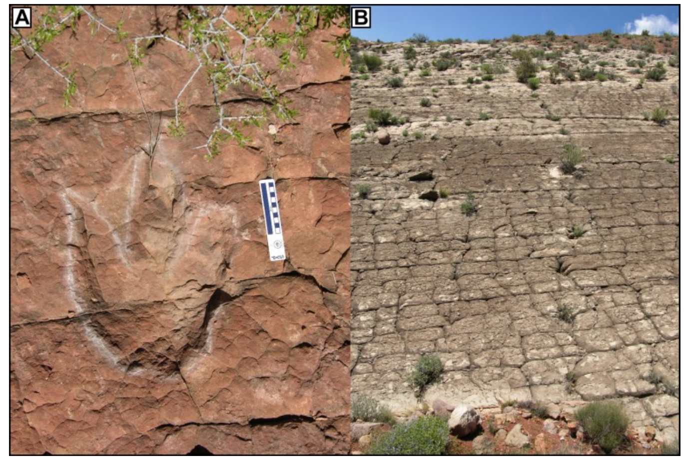


Figure 35. Examples of large theropod tracks from DT1 and DT2 tracksites. A, *Eubrontes* footprint from DT1 (S) tracksite. B, Trackways 3 (right) and 4 at the DT2 tracksite (also referred to as the “Plant Pot Tracksite” by the first author).

(Fig. 32). Of these, tracksite 2 is the largest, measuring approximately 60 x 20 m (Figs. 35B, 36A). More than 100 poorly preserved footprints have been mapped in 13 trackways (Fig. 36A; Lockley et al. 2006b). Most of the tracks at this site are deep, elongate (12-44 cm long), and possess metatarsal impressions, probably because of soft substrate conditions during the time of track formation. These tracks are probably *Eubrontes*, but due to the severe weathering and track depth and elongation, their true identities are uncertain. Shorter strides suggests that the track makers were progressing much more slowly, again probably because of the soft substrate, than animals of the same size on a firmer substrate, such as at sites like Desert Tortoise tracksite 1 or the Spectrum Tracksite (Lockley et al. 2006b). At tracksite 2, five trackways (1, 3, 4, 6, and 7) are parallel, suggesting gregarious behavior on the part of the track-making taxon or taxa (Fig. 36A; see Lockley et al. 2006b for further discussion).

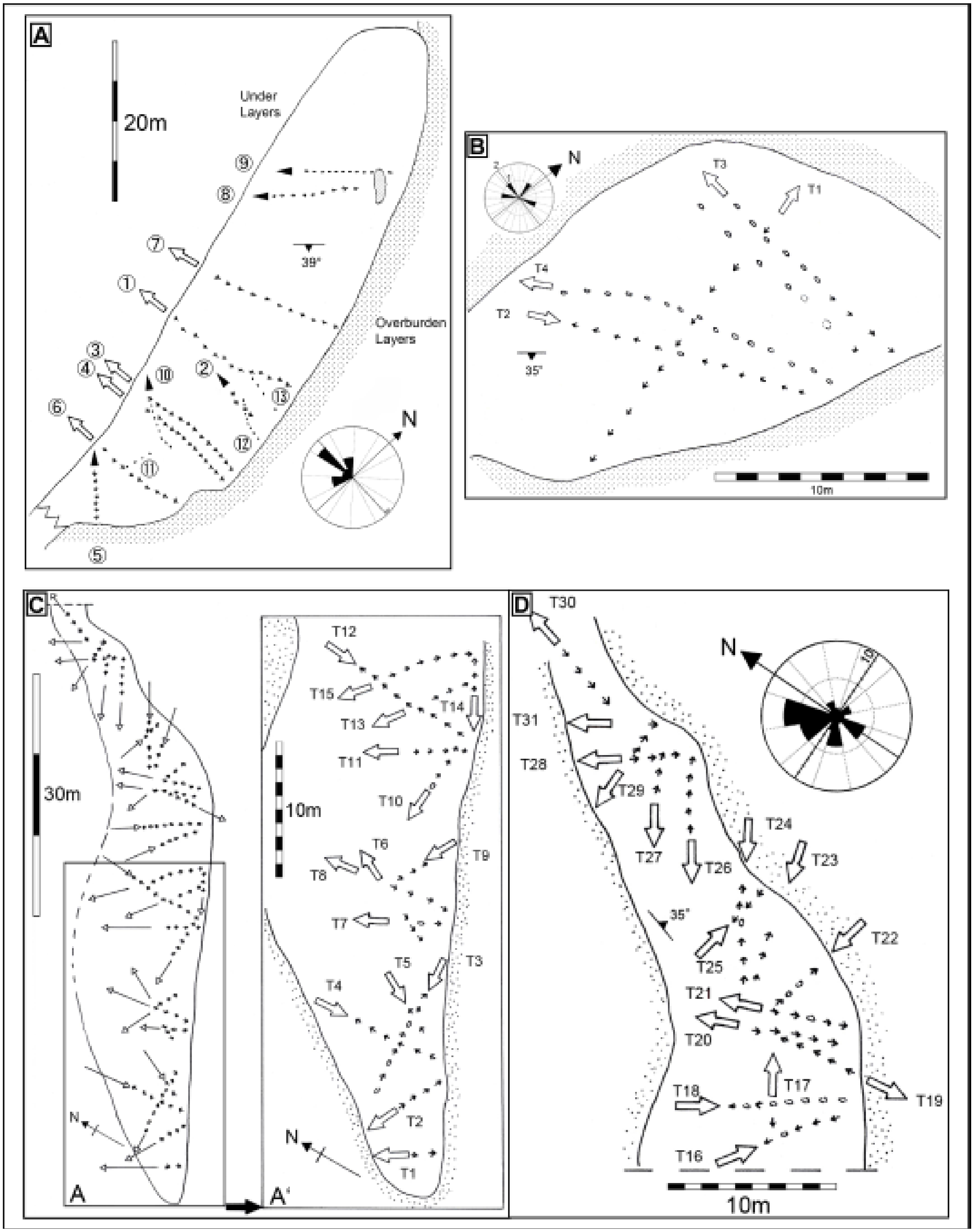


Figure 36. Maps of Desert Tortoise Tracksites DT2, DT3, and DT4 showing trackway orientations on the maps and in rose diagram form. A, Map of DT2 Tracksite showing 13 trackways. B, Map of DT3 Tracksite showing five trackways, but orientation can only be recognized on four. C, A shows map of whole Desert Tortoise Tracksite DT4 preserving 31 trackways. A' Detail of trackways 1–15 from the western half of DT4 Tracksite. D, Detail map showing trackways 16–31 on the eastern half of DT4 Tracksite. All illustrations from Lockley et al. (2006b).

Desert Tortoise tracksite 3 (Fig. 36B) is the smallest site, with only five trackways (Lockley et al. 2006b) that show clear trackway patterns. Preservation at this site is very poor, although tracks are deep as at tracksites 2 and 4.

Desert Tortoise tracksite 4 site is very large, with 30 recorded trackways (Fig. 36C-D; Lockley et al. 2006b). At least 30 recognized trackway segments provide reliable information on orientations. The trackways are mostly deep, as at Desert Tortoise tracksites 2 and 3, but the preservation is slightly better in some trackways, particularly toward the north end of this site where they are not as badly weathered.

Desert Tortoise tracksite 5 (also called Babylon 5) was discovered in 2005 by SGDS volunteer David Slauf (Fig. 37). This is the youngest of the Desert Tortoise tracksites because it is situated near the top of the silty facies. The site is unique because, unlike the previous sites, *Eubrontes* tracks are rare (Fig. 37A) whereas much smaller *Grallator* footprints (Fig. 37B) are common. This tracksite also preserves quadruped footprints of *Batrachopus*. The 50° slope on which the tracks are located, plus extensive vegetation on the surface, render mapping difficult.

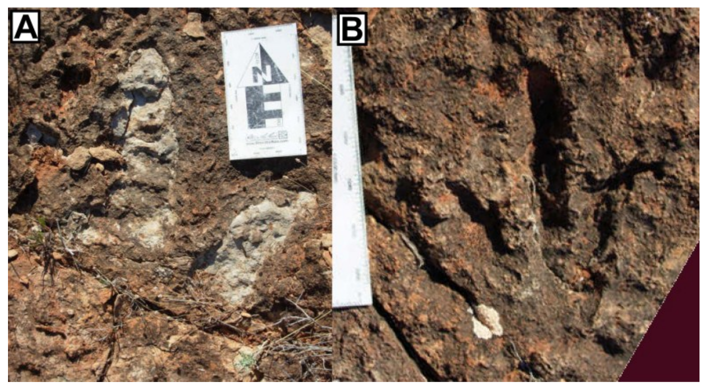


Figure 37. Some examples of tracks for the Desert Tortoise DT5 Tracksite. This site is near the top of the silty facies. A, Rare *Eubrontes* track at the DT5 locality. B, Example of a *Grallator* footprint in fine-grained sandstone.

| | | |
|---|---|---|
| 1.2 | 139.0 | Poorly exposed outcrops of Lower Jurassic (Sinemurian-Pliensbachian?) Navajo Sandstone Formation in hills to the right (east) and left (west). The Middle and Upper Permian Queantoweap, Toroweap, and Kaibab formations immediately ahead form the white cliffs of Black Ridge (Fig. 38).<br>The high cliff of Black Ridge is the scarp of the Hurricane Fault, which runs along the base of the cliff and displaces the west half of the Kanarra anticline down to the west. |
| 1.4 | 140.4 | Hills to the right (east) are basalts that are part of the Pintura Flow that originated from the Pintura volcanic center located to the north in Iron County. The Pintura Flow has yielded ages from 0.81 ± 0.10 Ma to 0.89 ± 0.02 Ma (Hurlow and Biek 2003). Here the Pintura Flow caps the Lower Jurassic Navajo Sandstone Formation. Hills to the left (west) consist of Navajo Sandstone Formation. |

| | | |
|---|---|---|
| 1.2 | 141.6 | Exit at I-15 at Toquerville (Exit #27; also known as Anderson Junction). Rocky hills to the northwest are outcrops of quartz monzonite porphyry, part of the Pine Valley laccolith of early Miocene age (20.32 ± 0.08 Ma to 20.9 ± 0.6 Ma [Hurlow and Biek 2003]). |
| 0.2 | 141.8 | Stop sign; turn right (east) on Highway 17 toward Toquerville. |
| 1.9 | 143.7 | Prepare for sharp left turn and view to the east of Toquerville. |
| 0.6 | 144.3 | Cross Ash Creek and enter Toquerville. |
| 0.5 | 144.8 | Pass through Center Street intersection and continue east on Highway 17. |
| 1.8 | 146.6 | Directly ahead is a basalt flow covering Pleistocene alluvium. |
| 0.6 | 147.2 | Cross bridge over unnamed wash and enter town of La Verkin. |
| 0.6 | 147.8 | Turn left at stoplight onto State Road 9 toward Zion National Park. |
| 0.3 | 148.1 | While climbing the hill (going up and over the Hurricane Fault), you are passing outcrops of Permian Kaibab Formation capped by the Lower Triassic Timpoweap Member of the Moenkopi Formation to your right (east). To your left and west of La Verkin are light-colored outcrops of the Middle Jurassic Carmel Formation and cinder cone volcanoes to the south of the Carmel outcrops. The Hurricane Fault is an active, steeply dipping westward normal fault with an east-up displacement of 1500 m (Biek et al. 2010). The fault extends approximately 250 km from the Grand Canyon in Arizona to Cedar City, Utah in the north (Biek et al. 2010). |
| 1.0 | 149.1 | View of the Pine Valley Mountains on the northwest horizon and the Lower Red Member of the Moenkopi Formation in the foreground. |
| 0.6 | 149.7 | Cross the contact between the Timpoweap and Lower Red members of the Moenkopi Formation. The cliffs to your left (east) are the base of Hurricane Mesa; they are composed of the Lower Red, Virgin Limestone, Middle Red, Shnabkaib, and Upper Red members of the Lower–early Middle Triassic Moenkopi Formation. The cliffs are capped by the Shinarump Member of the Upper Triassic Chinle Formation. |
| 3.0 | 152.7 | Continue straight past turnoff for Mesa Road (1250 W) up onto Hurricane Mesa. From here you can see the Petrified Forest Member of the Chinle Formation above the Shinarump Member; the Petrified Forest Member is capped by the Moenave Formation and the lower part of the Kayenta Formation. The Springdale Sandstone Member of the Kayenta Formation forms the top of Smith Mesa, which lies directly on top of Hurricane Mesa. Hurricane Mesa is famous |

| | | |
|---|---|---|
| | | for the U.S. Air Force Hurricane Mesa Test Facility, which was constructed in 1954 to test ejector seats and other aviation systems. Since 1963, the facility has been used by private enterprises and is presently the Goodrich Supersonic Test Site. The test track is 12,000 feet (3658 meters) long. Along with Little Creek and Gooseberry mesas to the south, Hurricane Mesa is a popular “rockhounding” area (Stowe and Perry 1979; Kappele 1996). These areas have always been popular for the collection of petrified wood, agate, and vertebrate fossils, particularly phytosaur and metoposaur teeth (federal policy prevents the unlawful collection of these vertebrate fossils). Illegal collection of fossils from this region is an ongoing problem (Milner et al. 2009b). |
| 0.2 | 152.9 | Enter the town of Virgin. Gooseberry Mesa lies to the south (right), and a cinder cone volcano (Crater Hill) on top of Smith Mesa to the east (ahead and to the left). This volcano is located in the southwestern corner of Zion National Park. The peak north of Crater Hill is Cougar Mountain. |
| 7.7 | 160.6 | Crossing the bridge over Coalpits Wash, which cuts through the Shnabkaib and Upper Red members of the Moenkopi Formation, capped by the Shinarump Member of the Chinle Formation. Above this, to the southwest toward the Canaan Mountain Wilderness Area, the Petrified Forest Member of the Chinle Formation is capped by the Moenave, Kayenta, and Navajo Sandstone formations. |
| 1.4 | 162.0 | Cross Huber Wash and enter town of Rockville. Smithsonian Butte lies to the south and Eagle Crags to the southeast; Canaan Mountain can be seen farther south of Eagle Crags. |
| 2.0 | 164.0 | Outcrops of Upper Red Member of the Moenkopi Formation in this area have produced well-preserved, early Middle Triassic reptile and amphibian tracks (Peabody 1948, 1956). |
| 1.8 | 165.8 | Enter the town of Springdale. |
| 0.7 | 166.5 | Exposures of Upper Triassic Petrified Forest Member of the Chinle Formation to the left. Mount Kinesava in Zion National Park can be seen to the west. |
| 1.4 | 167.9 | Enter Zion National Park. |
| 0.8 | 168.7 | Turn left and enter the Zion National Park information center and museum. The mountains around you include The Sentinel and Angels Landing to the north, West Temple to the west, The Watchman to the south, and Bridge Mountain to the east. |


Figure 38. View of Black Ridge, which is the scarp of the Hurricane fault. The light-colored, cliff-forming Paleozoic rocks from the valley to the top of Black Ridge are the Queantoweap Sandstone (lower and upper members), Toroweap Formation (Brady Canyon, Seligman, and Woods Ranch members), and the Kaibab Formation (Fossil Mountain and Harrisburg members).

## STOP 2—ZION NATIONAL PARK

**Discussion Leaders: Jim Kirkland and Vince Santucci**

### INTRODUCTION

Zion National Park is a geological wonderland, with over 2100 m of sedimentary strata exposed within its cliffs and canyons. These strata were deposited over a period of 275 million years, and record a multitude of environments, including shallow marine, coastal, desert sand dunes, rivers, and lakes. The park is home to extensive exposures of Upper Triassic and Lower Jurassic strata, including the Chinle, Moenave, Kayenta, and

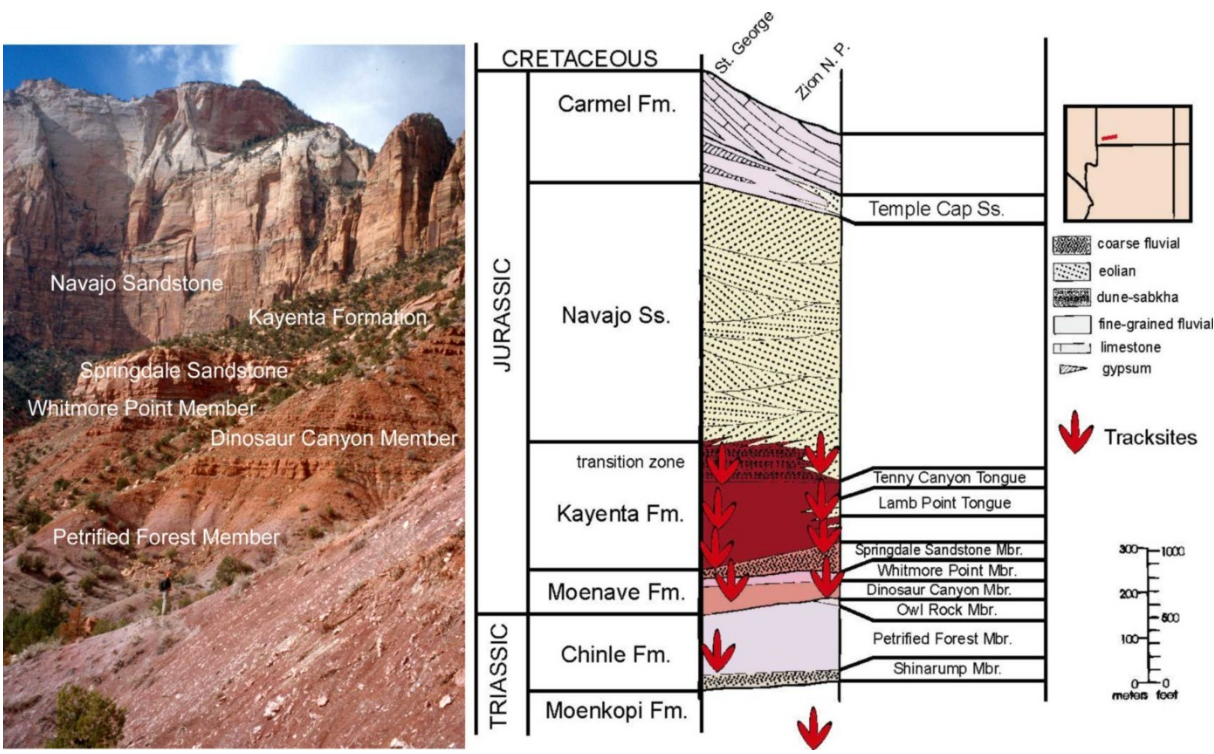


Figure 39. A, Overview of some of the strata (labeled) in Black Canyon, Zion National Park. B, Stratigraphic column of track-bearing rocks in the Zion National Park and St. George areas of southwestern Utah, indicating track horizons.

Navajo Sandstone formations (Fig. 39). From 1999-2003, several National Park Service interns, in cooperation with the UGS, completed a comprehensive inventory of paleontological resources within Zion National Park (DeBlieux et al. 2006), and identified over 120 new sites. Here we give a brief description of the Upper Triassic and Lower Jurassic strata and fossils found in the park.

**Chinle Formation (Late Triassic, ~226–210 Ma)**

The Chinle Formation consists primarily of sandstone, siltstone, and mudstone. The two members recognized in Zion National Park are the basal Shinarump Member and the overlying Petrified Forest Member (Fig. 39). The Shinarump Member was deposited mainly by braided streams, whereas the Petrified Forest Member was deposited in floodplains, lakes, and stream channels in a low basin (Stewart et al. 1972; Dubiel 1994; Biek et al. 2003). The majority of vertebrate body fossils in the park come from the Petrified Forest Member. The Chinle Formation is exposed in the Kolob Canyons District and in the southwest region of the park, notably along the Chinle Trail.

**Shinarump Member**

The Shinarump Member ranges in thickness from 18 to 41 m within the park and is mainly composed of conglomerates and coarse-grained sandstones. This unit is well known for its petrified wood, and may include the taxa *Araucarioxylon* sp. and *Woodworthia* sp. (Santucci 2000). In addition to the plant material, bones and bone fragments are found in the Shinarump Member. A well-preserved reptile vertebra was discovered, but not collected, in Shinarump strata in a dry wash north of Crater Hill (DeBlieux et al. 2006).

**Petrified Forest Member**

The Petrified Forest Member of the Chinle is one of the more distinctive rock units in the park, comprising many variegated purple, gray, red, green, and brown mudstones, claystones, and sandstones. These strata range in thickness from 136 to 152 m (Gregory 1950; Stewart et al. 1972; Biek et al. 2003). The rocks of the Petrified Forest Member contain bentonitic clays that swell when wet, so they weather with a distinctive "popcorn"-like profile. These clays also make this member susceptible to slumping and landslides; in many areas of the park and surrounding region, these strata are covered by landslide debris. Chinle Formation strata are not found in the main canyon, but are exposed primarily in the southwest portion of the park in the areas around Huber and Coalpits washes, around Cougar Mountain, and in the Kolob Canyons District.

Petrified logs at the boundary between the Shinarump and Petrified Forest members of the Chinle are one of the most abundant and vulnerable paleontological resources in the park. Although petrified logs can be found throughout the Shinarump Member, it appears that in Zion National Park the greatest concentration of logs, locally abundant enough to form "petrified forests," is in the lower Petrified Forest Member near its contact with the Shinarump Member. This is also the case in other parts of southwestern Utah where the contact between the Shinarump and Petrified Forest members outcrops (Milner et al. 2009b).

In addition to the plant fossils, this unit also has the highest potential for containing the bones and teeth of vertebrate animals. An important phytosaur site with at least three individual animals recognized, located adjacent to the park, was surface collected during the mid-1990s by the College of Eastern Utah; work there has been continued by teams from the SGDS, and a new quarry will be opened by them in the near future. Many vertebrate sites found within the park have produced bone fragments and teeth (commonly within nodules) belonging to fishes, metoposaurs, phytosaurs, and aetosaurs, as well as coprolites, petrified wood, plant material, and invertebrate burrows (DeBlieux et al. 2006).

## Moenave Formation (Late Triassic–Early Jurassic, ~200–196 Ma)

The Moenave Formation lies above the Petrified Forest Member of the Chinle Formation and is separated from it by the J-0 unconformity, thought to represent roughly 10 million years (Pipiringos and O'Sullivan 1978). The Moenave Formation is a continental deposit 71 to 118 m thick in the Zion National Park region and is divided into the lower Dinosaur Canyon and upper Whitmore Point members (Fig. 39).

### Dinosaur Canyon Member

The basal Dinosaur Canyon Member is composed of slope-forming, reddish-brown, fine-grained sandstone and siltstone deposited in river and floodplain environments (Biek 2000). Despite its name, the Dinosaur Canyon Member typically contains few fossils. Nevertheless, several paleontological sites in this member in the park and surrounding area produce primarily trace fossils, including invertebrate burrows and tridactyl dinosaur tracks (DeBlieux et al. 2006). A site in the Kolob Canyons District contains well-preserved plant remains (DeBlieux et al. 2006) similar in preservation to those at SGDS (Tidwell and Ash 2006).

### Whitmore Point Member

The Whitmore Point Member is a distinctive unit that, along with reddish-brown sandstone and siltstone beds found in the underlying Dinosaur Canyon Member, also contains reddish-purple to greenish-gray mudstone and claystone beds and thin, dolomitic limestone beds (Biek 2000; Biek et al. 2003). The Whitmore Point Member in Zion National Park was deposited in marginal lacustrine and floodplain environments that also included some lake deposits. Zion National Park is situated closer to the northern shoreline of Lake Dixie (Fig. 8) and thus is dominated by shoreline deposits and distinctive lacustrine facies are much more difficult to differentiate. A similar sandstone-dominated sequence is apparent near where the Whitmore Point Member pinches out to the east in the Kanab area. Fine-grained sandstones at the top of the Whitmore Point are often difficult to separate from the coarse-grained sandstones of the Springdale Sandstone Member of the Kayenta Formation in this region, particularly where they form cliffs as in Zion National Park. For this reason the J-0 unconformity is often mapped within the Springdale Sandstone Member.

This unit is best known for its ichnofauna (Kirkland et al. 2002; Milner et al. 2004, 2006a, b). A well-known, historical site within Zion National Park, located along Highway 9 near the bridge across Pine Creek, produced fossils of *Semionotus kanabensis* (Hesse 1935; Schaeffer and Dunkle 1950; Day 1967), but only a few isolated fish scales can be still found at this site. Plant fossils are also present in the form of disseminated plant fragments and rare sections of petrified wood. In addition, many horizons within the Whitmore Point Member, primarily the thin, dolomitic beds, contain algal structures that indicate the lacustrine nature of the deposits.

Trace fossils are the most abundant fossils found in the Whitmore Point Member in Zion National Park. Invertebrate burrows are common in many horizons and can be found in virtually any exposure of this member, but the most significant trace fossils found in the unit are the tracks and trackways of dinosaurs (Fig. 40A). Tridactyl theropod dinosaurs of the ichnogenera *Eubrontes* and *Grallator* are common in many horizons in Zion National Park, and dozens of localities have been discovered (Smith and Santucci 1999; Smith et al. 2002; DeBlieux et al. 2006). The tracks of the

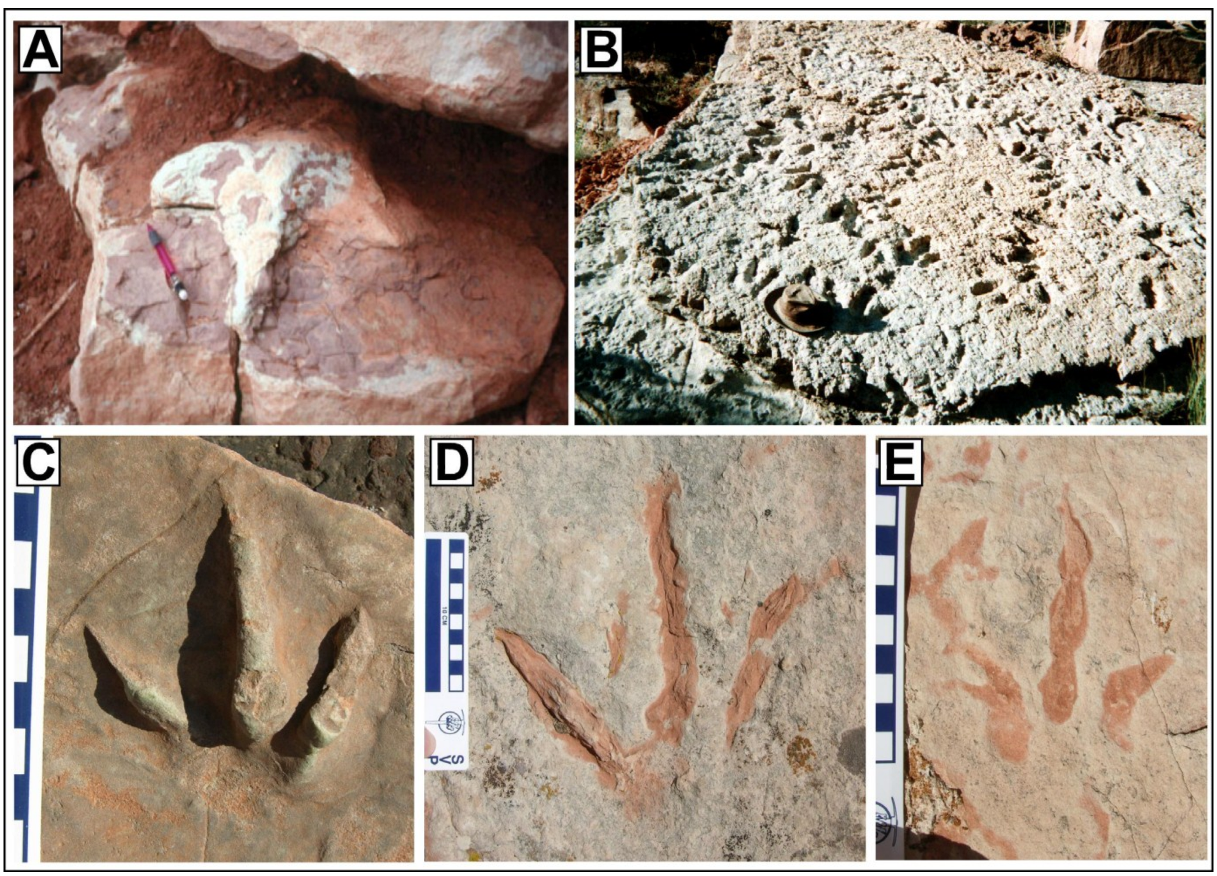


Figure 40. Examples of dinosaur tracks from Zion National Park. A, *Eubrontes* natural cast footprint from the Whitmore Point Member, Moenave Formation from locality 42Ws260T. Note pen for scale. B, Portion of the “Subway” tracksite from the Kayenta Formation along the Left Fork of North Creek. Note hat for scale. C, Small theropod track from the Kayenta Formation (ZION 15801). D, *Kayentapus*-like theropod tracks from the Kayenta Formation. E, *Grallator* footprint from the Kayenta Formation.

Whitmore Point Member in Zion National Park are one of the more significant paleontological resources within the park, second only to the tracksites of the Kayenta Formation. Tracks appear to be concentrated in the greenish-gray, dolomitic beds. Blocks of these beds can be easily seen from a distance because of their contrast with the predominately brown and red, surrounding beds.

**Kayenta Formation (Early Jurassic, ~ 196–184 Ma)**

The Kayenta Formation ranges from 194 to 258 m thick in the Zion region and forms the prominent slope below the Navajo Sandstone Formation cliffs (Fig. 39). Its base is marked by the cliff-forming Springdale Sandstone Member. The Kayenta Formation is exposed in many areas of the park, including lower Zion Canyon, Parunuweap Canyon, the West Temple and Cougar Mountain areas, Kolob Terrace, and Kolob Canyons. Talus from the overlying Navajo Sandstone Formation cliffs covers the Kayenta in many places. Strata within the Kayenta Formation are similar to those in the underlying Moenave Formation: primarily interbedded, thin- to medium-bedded, siltstone, sandstone, and mudstone that are mainly reddish-brown in color. Additionally, the lower part of the main body of the Kayenta contains greenish-gray-weathering, dolomitic beds reminiscent of those in the Whitmore Point Member of the Moenave Formation.

**Springdale Sandstone Member**

The Springdale Sandstone Member, named for the town of Springdale near the entrance to Zion Canyon, was originally the top of the Moenave Formation but is now the basal member of the Kayenta Formation (Lucas and Tanner 2006). The Springdale Sandstone Member forms a prominent cliff in the slopes below the Navajo Sandstone Formation in the Zion National Park region and consists of reddish-brown sandstone and conglomerate deposited in braided-stream channels and minor floodplain environments. Fossils in the Springdale Sandstone consist primarily of poorly preserved plant fragments, petrified wood, bioturbated horizons (invertebrate burrows), and rare dinosaur tracks (DeBlieux et al. 2006). Because the Springdale Sandstone Member forms steep cliffs in the park, it lacks exposures conducive to finding fossils. Nevertheless, one of the most significant track horizons in Zion National Park occurs at the top of the unit. Where streams and drainages expose the top of the Springdale, large theropod tracks, attributed to *Eubrontes*, are common, and numerous localities have been discovered at this horizon (DeBlieux et al. 2006).

**"Main Body"**

The "main body" (= "silty facies" elsewhere in this paper) of the Kayenta Formation was deposited in fluvial, distal fluvial/playa, and minor lacustrine environments (Blakey 1994; Peterson 1994). A tongue of eolian sandstone, called the Lamb Point Tongue (part of the Navajo Sandstone Formation), is present in the Kayenta Formation in Parunuweap and Zion Canyons (Averitt et al. 1955). The Lamb Point Tongue pinches out to the west and is not present in most of the western portions of the park.

In southwestern Utah, fossils in the Kayenta Formation are mainly tracks, though a diverse body-fossil assemblage exists in the unit from northern Arizona. Of the track-bearing formations in Zion, the Kayenta Formation has the greatest concentration of dinosaur tracks. Stokes and Bruhn (1960) first reported dinosaur tracks from a spectacular site in the Kayenta Formation from the Left Fork of North Creek, now known as the “Subway’ tracksite (Fig. 40B). Many sites contain just a few tracks, but this is because only small areas are exposed (Figs. 40C-F). These layers probably have hundreds, thousands, and even millions of tracks, which would be visible if the entire layer where exposed.

**Navajo Sandstone Formation (Early Jurassic, ~184–180 Ma)**

The Navajo Sandstone Formation forms the towering vertical cliffs that give Zion National Park its distinctive, scenic character. This unit ranges from 545 to 667 m thick in the Zion region (Fig. 39) (Gregory 1950; Biek et al. 2003). The transition from the water-laid deposits of the Kayenta Formation to the wind-blown sands of the Navajo Sandstone Formation is well documented in Zion. The Navajo Sandstone Formation was deposited in a desert environment similar to that of parts of the modern Sahara, and records a part of what is thought to be the largest ancient dune field in the world (Blakey et al. 1988; Blakey 1994; Peterson 1994; Chan and Archer 1999; Loope et al. 2001; Loope and Rowe 2003). For a sedimentary formation of such great thickness and areal extent, the Navajo Sandstone Formation preserves relatively few fossils. However, tracks are known from the unit in Zion National Park and elsewhere. Peterson (in Santucci 2000; Santucci and Kirkland 2010) reported several dinosaur footprints in the formation along the trail to Observation Point in Zion Canyon. The tracks of several different animals were found on the weathered surface of a large, rock-fall boulder in a side canyon of Parunuweap Canyon (DeBlieux et al. 2006). A number of new tracksites in the Navajo Sandstone Formation in Washington County have recently been discovered by workers from the UGS while conducting a paleontological inventory of BLM wilderness areas. Tracks in the formation actually may be fairly common, but the weathering conditions required to reveal them are such that most of these will never be seen: the bedding planes on which tracks were made are not generally exposed in Zion National Park because the sandstone forms cliffs, and bedding planes are only exposed on fallen blocks and on the tops of the cliffs.

| | | |
|---|---|---|
| 0.6 | 169.3 | Cross the Virgin River and continue east past the Floor of Canyon Road. |
| 0.5 | 169.8 | Begin switchbacks up to the tunnel through Bridge Mountain. |
| 3.0 | 172.8 | Enter tunnel through Bridge Mountain and the Lower Jurassic Navajo Sandstone Formation. |
| 1.4 | 174.2 | Exit tunnel and pass parking area for Canyon Overlook. |

| | | |
|---|---|---|
| 1.3 | 175.8 | Enter short tunnel. |
| 0.1 | 175.9 | Exit short tunnel. |
| 3.8 | 179.7 | View of spectacular, cross-bedded eolian sequences of the Navajo Sandstone Formation on Checkerboard Mesa. |
| 1.0 | 180.7 | Leave Zion National Park. |
| 5.8 | 186.5 | Pass outcrops of Upper Cretaceous (Turonian-Cenomanian) Tropic Shale on your right (south) resting on Lower-Upper Cretaceous Dakota Formation. |
| 5.0 | 191.5 | Begin passing through outcrops of Middle Jurassic Temple Cap and Carmel formations. |
| 1.7 | 193.2 | Enter Mount Carmel Junction and stop at Thunderbird Lodge. End of Day 1. |

## DAY 2 ROAD LOG

| **Incremental** ***Mileage*** | ***Cumulative Mileage*** | ***Description*** |
|---|---|---|
| 0.0 | 0.0 | DAY 2. Main entrance of Thunderbird Lodge in Mount Carmel Junction, Utah. In the Mount Carmel Junction area the Middle Jurassic Carmel Formation is divided into four members: (1) Co-op Creek Limestone Member is 50-60 m thick and was deposited in shallow marine environments and unconformably overlies the Middle Jurassic White Throne Member of the Temple Cap Formation (Imlay 1980; Blakey et al. 1983; Hayden 2008). This member is composed of micritic and sandy limestone, and is very fossiliferous containing echinoderms (especially crinoid columnals of *Isocrinus nicoleti*), bivalves, gastropods, brachiopods, invertebrate trace fossils, and rare marine reptile teeth and fish bones. (2) Crystal Creek Member consists of alternating beds of thin, reddish-brown, gypsiferous siltstone, fine sandstone, and interbedded pinkish-gray mudstone and gypsum. This member is 35-45 m thick and was deposited in tidal flat and coastal sabkha environments (Imlay 1980; Blakey et al. 1983; Hayden 2008). (3) Paria River Member is between 25-40 m thick. It is composed of pinkish-gray to pale pink siltstone and thin-bedded yellowish gray to grayish-orange-pink limestone and micritic limestone. Gypsum deposits are very common in this member and fossil mollusks are locality abundant. The Paria River Member was deposited in shallow marine and coastal sabkha environments (Imlay 1980; Blakey et al. 1983; Hayden 2008). (4) Winsor Member is mostly yellow to yellowish gray, |

| | | |
|---|---|---|
| | | fine to medium-grained sandstone that is between 18-25 m thick, and was deposited on broad, sandy coastal mudflats (Imlay 1980; Blakey et al. 1983; Hayden 2008). The Lower-Upper Cretaceous Dakota Formation rests on top of the Winsor Member of the Carmel Formation. |
| 2.3 | 2.3 | Crossing the active Sevier Fault Zone which extends 480 km in a north-south orientation extending 48 km south of the Grand Canyon in Arizona to central Utah (Doelling and Davis 1989). This series of high-angle normal faults strike north-northeastward with down-to-the-west displacement of approximately 500 m (Hayden 2008). |
| 1.0 | 3.3 | Turn right (south) onto frontage road toward Coral Pink Sand Dunes State Park. |
| 0.3 | 3.6 | Turn right onto Yellowjacket Road. |
| 8.7 | 12.3 | Pass turn for Hancock Road. |
| 3.0 | 15.3 | Pass entrance to Coral Pink Sand Dunes Recreation Area. |
| 2.9 | 18.2 | Turn left (south) onto Moccasin Mountain Trailhead, BLM Road #30 (large turn-off area) for the Moccasin Mountain Tracksite (sign indicates "4x4 and high clearance required, minimum; $750 for towing). |
| 2.2 | 20.4 | Arrive at parking area for the Moccasin Mountain Tracksite (STOP 3). Park to the north of the fence. A short walk is required along the wash and to reach the site. |

## STOP 3—MOCCASIN MOUNTAIN TRACKSITE

**Discussion Leaders: Neffra Matthews and Brent Breithaupt**

### Introduction

In the fall of 2007, dinosaur tracks were reported to the BLM Kanab Field Office by a group of hunters. The tracks are located near Coral Pink Sand Dunes State Park in a popular off-highway vehicle (OHV) area. Investigation by the BLM proved the site to be a spectacular vertebrate paleontological resource (Matthews et al. 2008, 2009, 2010). The Moccasin Mountain Tracksite comprises multiple track levels in the Navajo Sandstone Formation (age ~185 Ma) in a roughly 1000 $m^2$ slickrock sandstone area. This site provided an ideal opportunity for the successful synergy of management, science, technology, interpretation, and recreation. OHV recreational activity is extremely popular in southern Utah: Coral Pink Sand Dunes State Park and nearby areas have experienced a rapid increase in use, including the Warner Valley area we will visit on Day 3. OHV activity has impacted the track surface at the Moccasin Mountain Tracksite necessitating, in close coordination with county officials, the closure of the track-bearing area to vehicular traffic to protect this significant paleontological resource.

**Location and Use**

The Moccasin Mountain Tracksite is located in Kane County, about 5.6 kilometers (3.5 miles) southwest of the Coral Pink Sand Dunes State Park (see below) entrance on land managed by the BLM Kanab Field Office (Fig. 41).

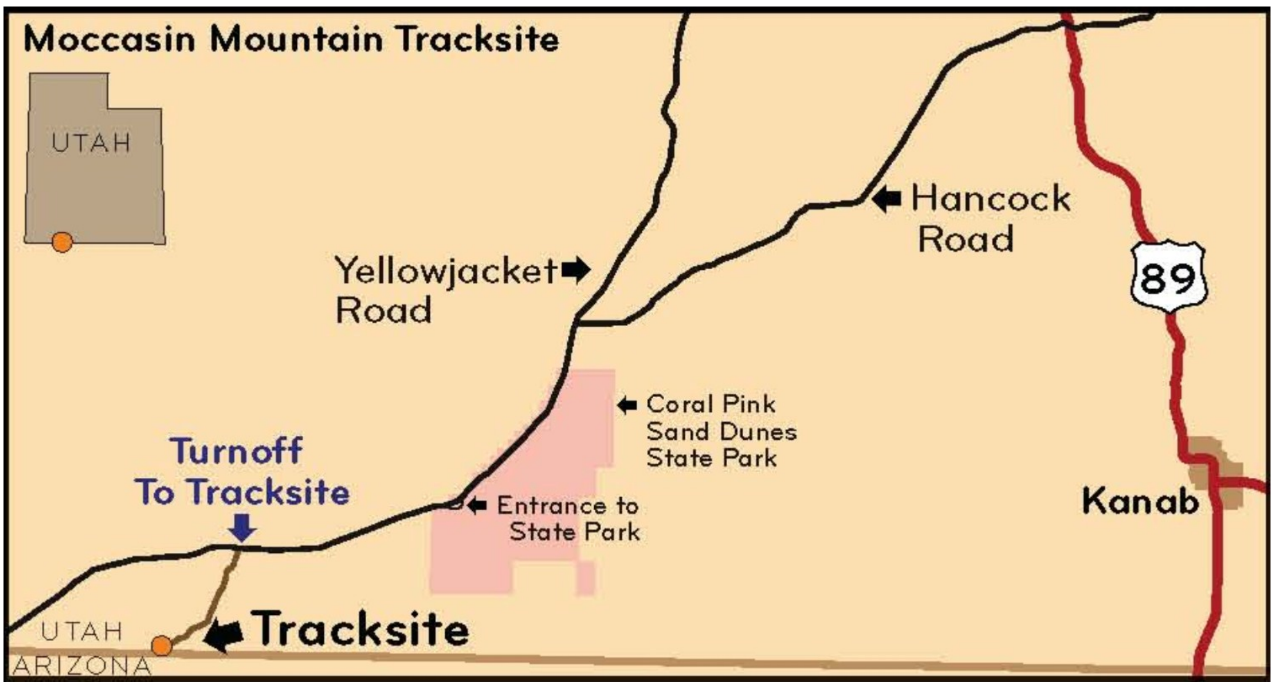


Figure 41. The Moccasin Mountain Tracksite is located southwest of Kanab, Utah along Hancock Road. The road to the site is unimproved and deep sand can be an issue during certain times of the year.

Coral Pink Sand Dunes State Park lies 12 miles (20 km) off U.S. Highway 89 near Kanab, Utah. At an elevation of 6,000 feet (1818 m), the park covers 3730 acres (1509 hectares) and provides recreational activities including camping, hiking, and OHV riding. Established in 1963 with land acquired from the Bureau of Land Management, the park provides for recreation on and protection of the sand dunes. BLM-managed lands border the park, extending the opportunity for OHV recreation. Coral Pink Sand Dunes State Park is one of two major dune field on the Colorado Plateau (the other being Great Sand Dunes National Park in Colorado. The dunes consist of sand eroded from Moccasin Mountain. This wind-blown sand is funneled through a geographic gap where Moquith Mountain acts as a barrier, which slows the wind velocity, dropping the sand out in the dune field. Barchan and transverse dunes are the most common types; a few reach 30 m in height. This area provides a nearby modern analog for the ancient dune field preserved at the Moccasin Mountain Tracksite.

Recreational use at the Moccasin Mountain Tracksite is difficult to quantify at present. A traffic counter installed in the winter of 2008 was subsequently stolen. However, the proliferation of cross-country, OHV trails in the immediate area and increased use in Coral Pink Sand Dunes State Park suggests that site visitation is currently heavy and increasing rapidly. As witnessed at other such locations, widespread knowledge of a site among the public invariably accelerates degradation. Tire skid marks and churned gravel veneers over tracks were observed in several places in October 2007. In addition, vandalism in the form of outlining footprints and amateur molding of the tracks has been observed (Fig. 42A). In some cases, caulk is still present on the surface, suggesting that a pre-constructed form was used for plaster casting. Such activity is not only illegal but highly damaging to tracks because the plasters and epoxies used by the perpetrators bonded very tightly to the outer sand grain layer of the track, literally shaving it down when the replica was removed. Such practices also leave unsightly stains of oil, epoxy, caulk, and casting materials that degrades the scientific value and visitor experience.

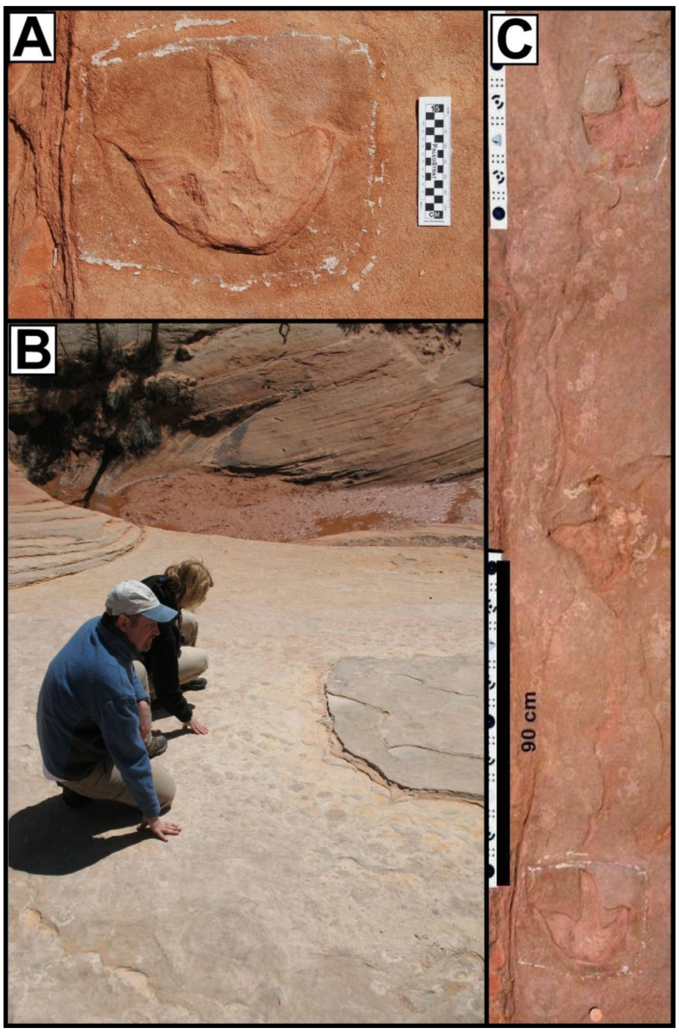

Figure 42. A, Example of a vandalized Moccasin Mountain track. Reproduction was conducted with an improper technique and without a valid BLM permit. B, Visitors to the Moccasin Mountain Tracksite can observe numerous areas which have a very high concentration of fossil footprints. C, Large theropod trackway attributed to *Eubrontes*.

Given its significance and estimated levels of visitation, the Moccasin Mountain Tracksite warrants protection. OHV traffic has been restricted and a fence has been put in place to keep vehicles out while encouraging foot traffic at the site. The BLM has increased its presence at the site by providing organized tours, promoting visitation, and educating the public about the significance of the site (Fig. 42B). Baseline data evaluation of the site has included preliminary ichnological studies, photography (including photogrammetry), and mapping (Matthews et al. 2008, 2009, 2010) at this and other Navajo Sandstone sites (Breithaupt and Matthews 2010, 2011b). These activities are critical to subsequent interpretation. Strategies to determine the level of visitation, the possibility of creating resource stewardship programs, promote the site as a heritage resource, and conduct resource monitoring will be formulated as part of a long-term site management plan.

**Stratigraphic Context**

The Moccasin Mountain Tracksite spans an area of about 1,000 $m^2$ in a southwest-trending, slickrock-bottomed drainage. The bedrock in this entire area consists of the middle and upper portions of the Lower Jurassic (180-190 Ma) Navajo Sandstone Formation. The Navajo Sandstone Formation is about 550 m thick in the Parunuweap Canyon area to the north of the Moccasin Mountains. The tracks and trampled areas present at the tracksite exhibit preservational features that would have been difficult to achieve in unconsolidated, dry sand, indicating that sand in the trampled, interdune area was periodically moist or seasonally saturated with water. In a number of areas, small oases or playa lakes in the Navajo Sandstone Formation are evinced by thin layers of grayish limestone, which often contain tracks and algal remains (Loope et al. 2004a, b; Milan et al. 2008). No matter the mechanism for the wetting events, the duration was sufficient to allow the accumulation of multiple (~30) levels.

**Ichnology**

The site contains an abundant, high-diversity ichnoassemblage with important preservational features (Matthews et al. 2008, 2009). Tracks are preserved in a variety of styles, including convex epirelief and hyporelief, concave epirelief, in cross section, and as hematite-stained undertracks, facilitated to various degrees by footprint-induced compaction. The morphology varies between individual tracks or trackways, from distinct preservation of anatomical features, such as toe pads and claws, to heavily trampled surfaces exhibiting the mottled bedding of dinoturbation. Tracks are preserved on dune foreset beds, interdune bounding surfaces, and dune slipface surfaces. At least six different track types have been observed, including bipedal (*Grallator* and *Eubrontes*) and quadrupedal forms (*Batrachopus, Brasilichnium,* and *Otozoum*) (Matthews et al. 2008, 2009). However, there are also a number of unique morphologies (created by slip and shear at the time of track formation and later by crosscutting erosion of the Navajo Sandstone Formation dunes) so more ichnogenera may well be present, especially *Anomoepus*, *Navahopus,* and *Kayentapus*.

The largest tridactyl tracks present at the Moccasin Mountain Tracksite are greater than 25 cm in length and exhibit digit divarication angles of less than 35. These are referable to *Eubrontes*, the most common large theropod track morphotype known from the Colorado Plateau (Lockley and Hunt 1995; Rainforth 1997; Irmis 2005). Several *Eubrontes* tracks occur in trackways (6–10 steps) along the dune face (i.e., more or less contour parallel) (Fig. 42C). Bulging and incipient avalanching indicate track maker weights were placed on the downslope sides of the feet, which generally makes it difficult to distinguish right from left foot impressions. In addition, slip and shear features, combined with surface exposures at various levels within the track formation continuum (from touch-down to toe-off), result in most uncommon morphologies (Fig. 43). The other large tridactyl tracks (roughly 25 cm long by 22 cm wide) exhibit widely splayed digit

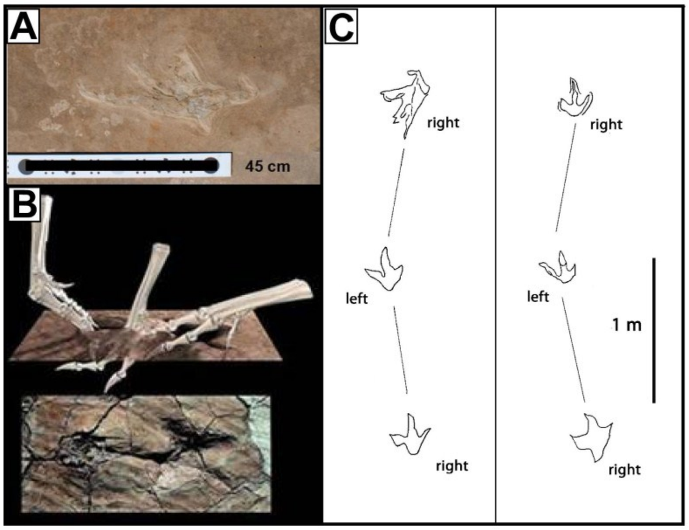


Figure 43. A, Slip and shear features, combined with surface exposures at various levels within the track formation continuum (from touch-down to toe-off), result in most uncommon morphologies. B, Graphic depicting the touch-down to toe-off motion as it interacts with the substrate. Courtesy Steven Gatesy; http://www.amnh.org/exhibitions/dinosaurs/. C, Trackways of a large theropod with consecutive footprints showing pronounced variation in preservation. Where well-preserved, tracks resemble *Eubrontes*.

impressions and divarication angles of about 45°. This rather high value of divarication, plus the large sizes of these tracks, may mean they pertain to *Kayentapus* or *Anomoepus*.

Smaller tridactyl tracks fall within two size ranges (Fig. 44A, B). The larger size tracks (approximately 10 cm long) exhibit narrow divarication angles and are assigned to *Grallator* (Lockley and Hunt 1995; Rainforth 1997; Irmis 2005). Tiny tracks, as small as 2.5 cm, are also present and may represent juveniles or a previously unnamed taxon (Fig. 44C-E).

Large (> 30 cm), tetradactyl tracks (Fig. 45) have rather symmetrically distributed digits (about 15° between each). Many individual tracks bear distinct claw impressions. The size and digit arrangement suggests that these forms represent the track genus *Otozoum* (Lockley and Hunt 1995; Rainforth 1997, 2003; Irmis 2005). Smaller tetradactyl forms (approximately 10 cm) may represent *Batrachopus* (Fig. 44F-I). Several longer trackways of *Batrachopus* somewhat oriented in the same direction are preserved on the uppermost track surface (Fig. 46). Pentadactyl tracks are also present; their general shape, symmetrical digit distribution, and small size (6-7 cm diameter and length) suggest they are likely *Brasilichnium* (Lockley and Hunt 1995; Rainforth 1997; Irmis 2005).

Invertebrate traces consist of horizontal forms (*Planolites*) found on the interdune bounding surfaces, with vertical forms crosscut dune bedding

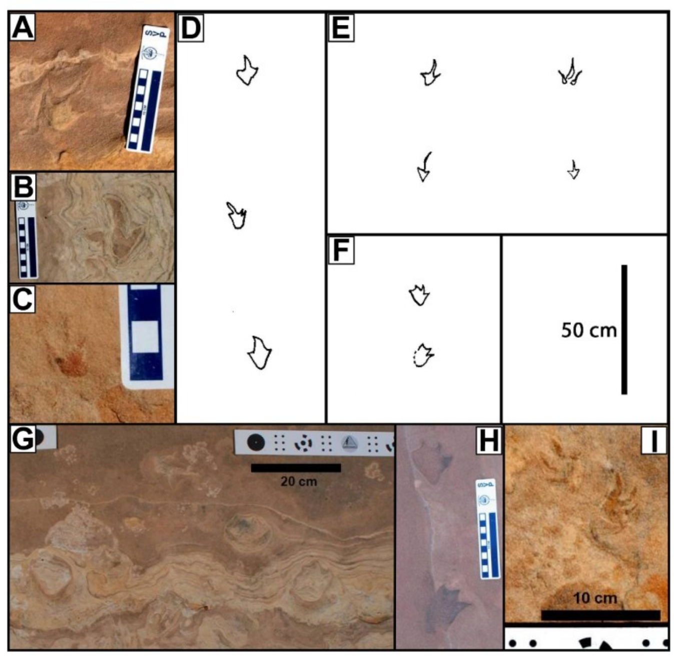


Figure 44. A–C, Three examples of small tridactyl tracks (cf. *Grallator*). D, Small theropod trackway (cf. *Grallator*). E, Four small, isolated theropod tracks (cf. *Grallator*). F, Drawing of two tetradactyl footprints in trackway in H. G, Several *in situ* tetradactyl tracks. H, Photo of two tetradactyl tracks in trackway. I, Two tetradactyl tracks that may pertain to *Batrachopus*.

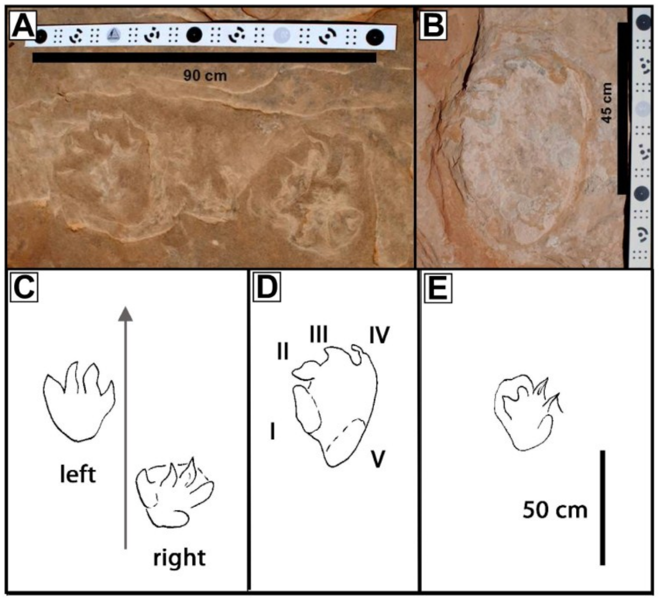


Figure 45. Examples of *Otozoum* tracks of various sizes. A and C, Two consecutive tracks with the right print showing traces of five digits. B and D, Isolated right footprints showing five digit traces, where digit V forms part of the heel trace. E, Small *Otozoum* track.

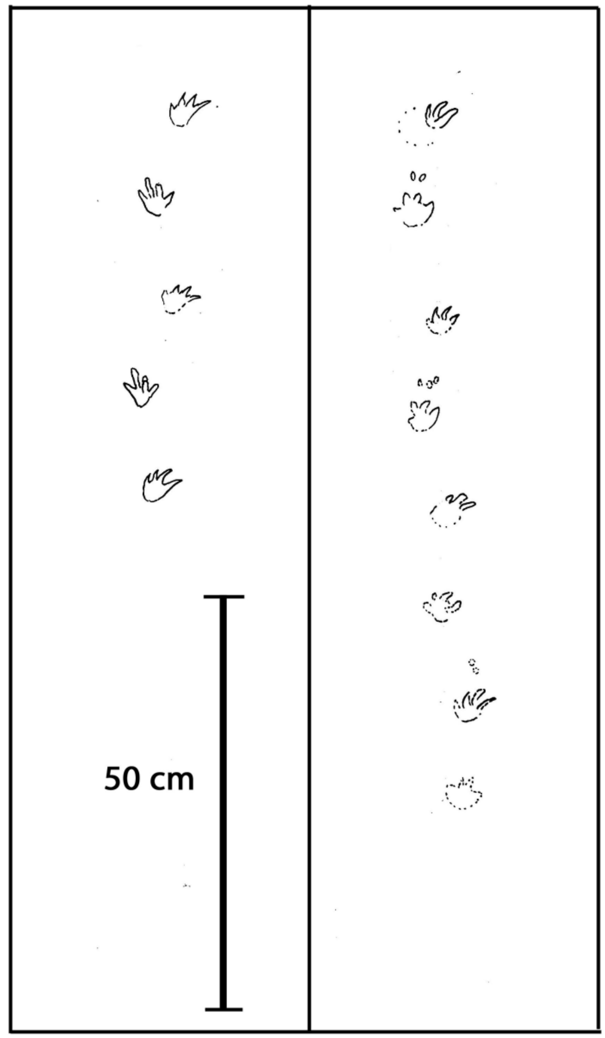


Figure 46. Examples of two partial *Batrachopus* trackways from the uppermost trace surface. The trackway on the left does not preserve manus trace while the trackway on the right has partially preserved manus impressions.

(see Ekdale et al. 2007).

**Site Documentation and Mapping**

Due to their high occurrence, ichnotaxonomic diversity, and morphological variations, the tracks at the Moccasin Mountain Tracksite provide an uncommon glimpse of a haven in the midst of a vast, Early Jurassic desert erg. The opportunity for scientific study, public interpretation, and recreational opportunities make the Moccasin Mountain Tracksite worthy of special consideration. Baseline documentation and mapping of the site began in March 2008 with a reconnaissance visit. At that time, the possible methods and resources needed to map the site as a whole were determined. In addition, selected tracks and trackways were documented using close-range photogrammetric techniques (Fig. 47) and acetate tracings (Matthews et al. 2008, 2009, 2010).

**Close-range Photogrammetry**

High-resolution digital photographs were processed in a 3D measuring and modeling photogrammetric software program to produce close-range photogrammetric images (Matthews et al. 2008, 2009, 2010). Photogrammetry makes precise measurements about a physical object and its

Figure 47. Photogrammetric documentation at the Moccasin Mountain Tracksite.

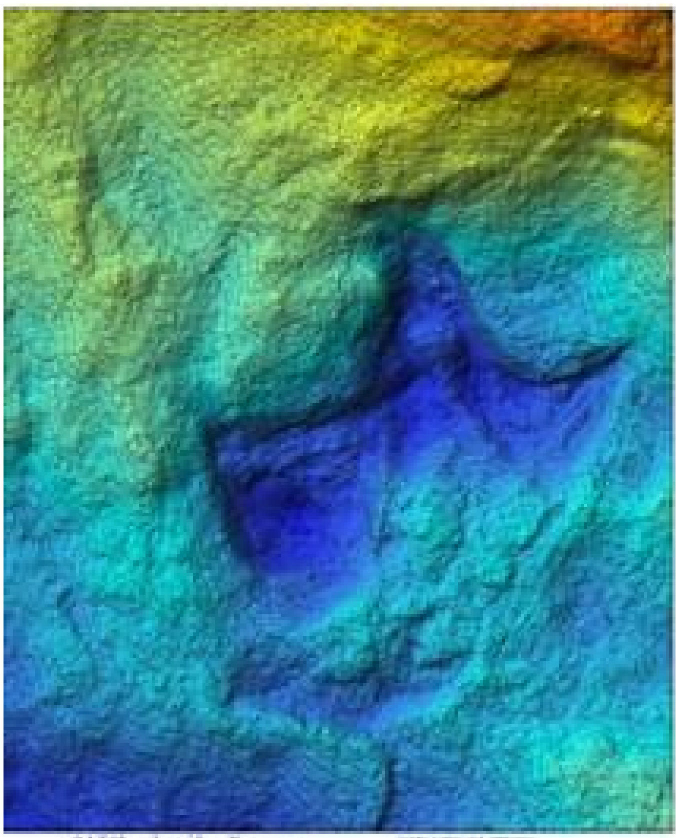

Figure 48. Photogrammetric images of tridactyl track from Moccasin Mountain Tracksite with the terrain surface represented as 1 mm contours.

environment from a series of overlapping stereoscopic digital photographs (see above).

Stereoscopic photographs are used to create 3D images datasets that can be viewed as 3D images or used to create microtopographic contour maps and color digital terrain models of individual tracks (Fig. 48) or trackways (Matthews et al. 2006; Matthews 2008). The contour maps provide details, such as depth of a track, equal-elevation contour lines that display the morphology of a track, and features of the rock surface. Three-dimensional image datasets such as these provide permanent digital records of the tracks, and are obtained via a non-destructive method to obtain 3D data for assessment.

**Low-level aerial photography**

In July 2008, low-level aerial photography (Fig. 49C) of the site was conducted through the joint efforts of the BLM and Bureau of Reclamation (Matthews et al. 2008, 2009, 2010). A specially outfitted Bell JetRanger helicopter (Fig. 49A) made a number of passes over the site. During these passes, high-resolution digital stereoscopic photographs and video footage were acquired from several altitudes (Fig. 49B). The resulting pixel resolution of the images ranged from 10 cm to 5 mm. Images from these flyovers were combined to make an overall mosaic of the area. The resulting maps and images will be used to document the ichnological diversity of the site, for monitoring, and for interpretative materials. The development of scientific, educational, and interpretative materials is proceeding as funding allows.

**Summary**

Scientifically, the Moccasin Mountain Tracksite contains a high ichnodiversity and density, and important preservational features on dune foreset beds and interdune-bounding and truncation surfaces. This important ichnofaunal assemblage, from the midst of a vast dune field, warrants a high-level of study and documentation, including photogrammetry. Digital virtual representations from this technology provide an effective tool for presenting the uniqueness of the site to OHV enthusiasts, land managers, and the scientific community, as well as, interpreting this unique site to the public and increasing awareness and concern for such natural treasures.

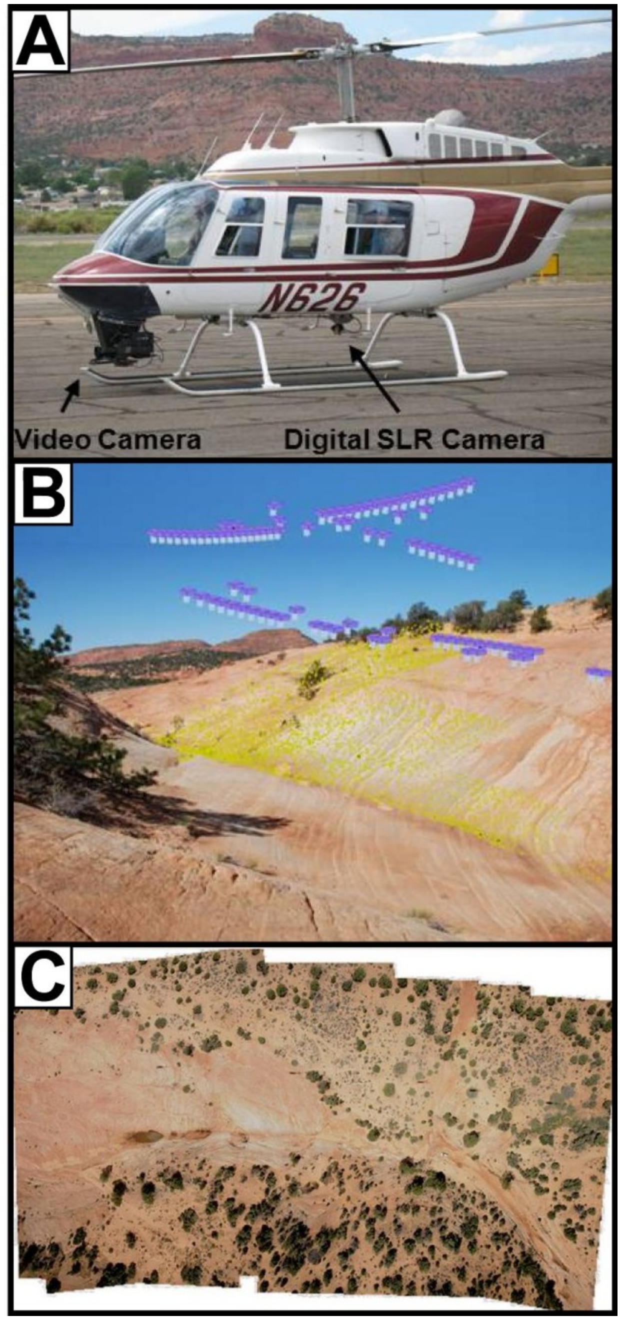


Figure 49. Aerial photogrammetric documentation. A, Helicopter showing camera mount positions. B, Image of site with aerial camera stations in lavender. C, Low-level aerial image of the Moccasin Mountain Tracksite.

| | | |
|---|---|---|
| 2.2 | 22.6 | Back-track to main road from tracksite parking area. Turn left onto Yellowjacket Road. |
| 4.1 | 26.7 | Cross Utah-Arizona state line. Pavement on Yellowjacket Road ends. Cross-bedding in Navajo Sandstone Formation. |
| 3.0 | 29.7 | Bear right at fork in road onto Cane Bed Road (County Road 237). Pass cliffs displaying Kayenta-Navajo contact. |
| 1.3 | 31.0 | Pavement returns on Cane Bed Road. |

| | | |
|---|---|---|
| 4.0 | 35.0 | Turn left (east) onto Highway 389. The Kaibab Plateau can be seen to the south. |
| 7.8 | 42.8 | Turn left and through gate into fields off Highway 389. This road leads into Potter Canyon, located west of the type section for the Whitmore Point Member of the Moenave Formation. We cannot visit the actual type section because it is located on the Indian reservation. |

## STOP 4—TYPE SECTION, WHITMORE POINT MEMBER OF THE MOENAVE FORMATION

**Discussion Leaders: Jim Kirkland and Andrew Milner**

### Previous Work

Early research in the region placed strata now recognized as the Moenave Formation within the Upper Triassic Chinle Formation. Gregory (1950), in his monograph on the geology in the Zion National Park area, recognized a Springdale Sandstone Member in the upper Chinle Formation, named for the village of Springdale at the mouth of Zion Canyon, where the unit forms a coarse-grained sandstone cliff 20-35 m thick (Kirkland and Milner 2006).

Harshbarger et al. (1957), working in the area of the Navajo Indian Reservation of north-central Arizona, defined the Moenave Formation for a mapable sequence of red, fluvial sandstones at the top of the Chinle Formation that were well exposed near the Hopi village of Moenave, west of Tuba City, Arizona. They included the Moenave Formation in the lower part of the Glen Canyon Group and they recognized that it overlay the sand dune deposits of the Wingate Sandstone Formation. In contrast, subsequent researchers (e.g., Blakey 1994) recognized that the Wingate Sandstone Formation is a lateral equivalent of the Moenave Formation that replaces it to the northeast (Fig. 50).

Harshbarger et al. (1957) recognized that the Moenave Formation could be divided into two members on the Navajo reservation. A basal, fine-grained, reddish-brown sandstone interval from an area about 10 miles east of Cameron, Arizona was named the Dinosaur Canyon Sandstone Member. The coarse-grained Springdale Sandstone Member could be traced southeast from southwestern Utah along the Utah-Arizona border into the Navajo country, where in rests on the Dinosaur Canyon Member, forming the upper member of the Moenave Formation (Fig. 50A).

Wilson (1967) recognized a series of thin-bedded shales, limestones, and sandstones that separate the Dinosaur Canyon Member from the overlying Springdale Sandstone Member along the Arizona Strip and in southwestern Utah west of Kanab, Utah. He named this the Whitmore Point Member, after Whitmore Point in northwestern Arizona, which you can see to the east of our location at this stop in Potter Canyon (Fig. 51). The Whitmore Point Member was deposited in a lacustrine environment referred to in the St. George area as Lake Dixie (cf. Kirkland et al. 2002; Milner et al. 2004; Milner and Spears 2007) (Figs. 8, 50B).

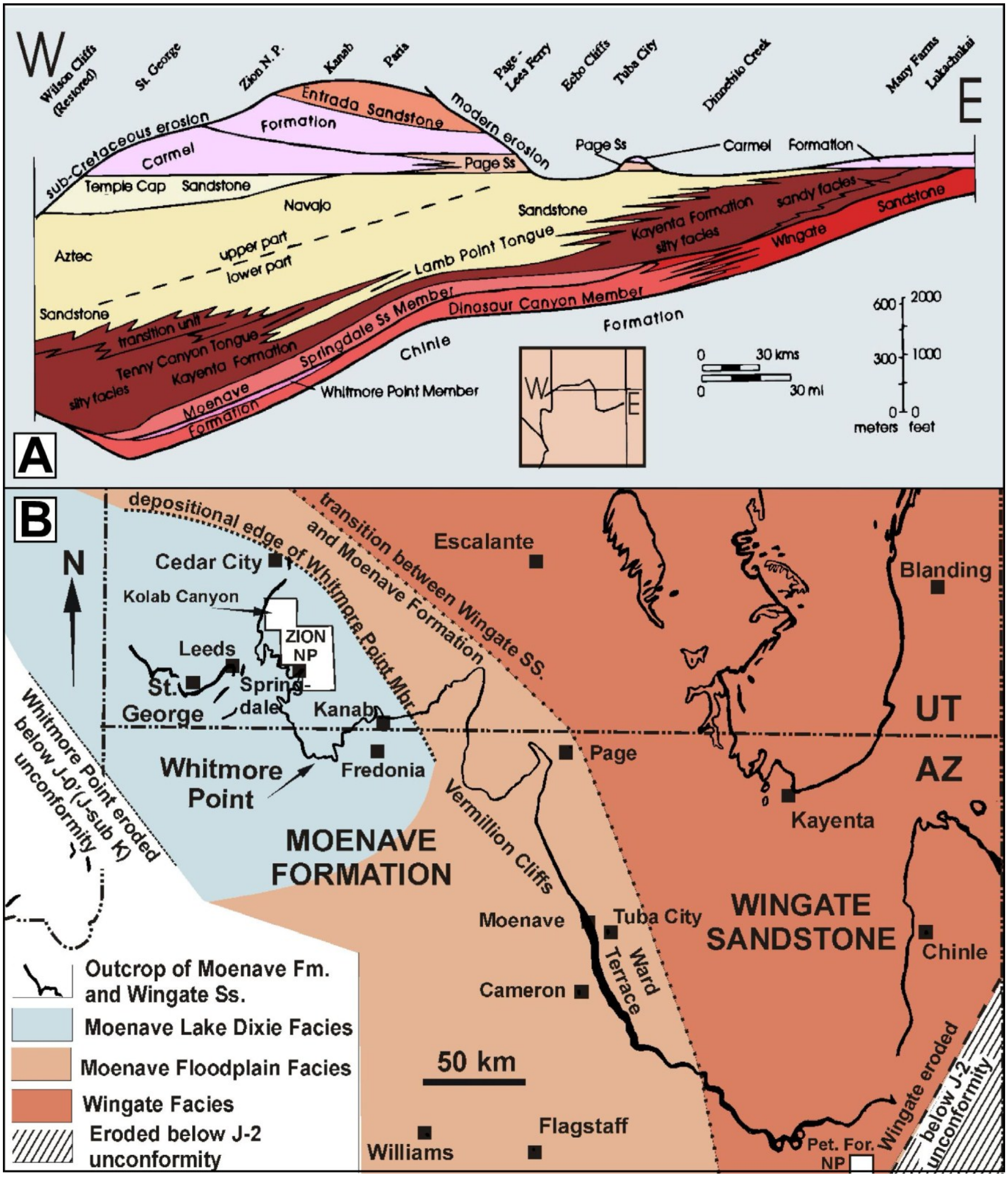


Figure 50. A, Generalized cross-section of the Lower to Middle Jurassic rocks along the Utah and Arizona border. Note that the Moenave and Wingate Sandstone formations of the lower Glen Canyon Group which rest unconformably on top of the Upper Triassic Chinle Formation are lateral equivalent to one another. The small inset map shows the approximate east–west transect of this cross-section. B, Map showing the paleogeographic distribution of the Wingate Sandstone Formation eolian facies in relationship to the fluvial and lacustrine facies of the Moenave Formation.

Figure 51. View looking east toward Whitmore Point from the Potter Canyon section. The Moenave, Kayenta, and Navajo Sandstone formations can be seen in this portion of the Vermillion Cliffs.

As in St. George, Kirkland and Milner (fig. 7, 2006) recognized two major lacustrine cycles in the type area of northern Arizona, although in this area the lower cycle is better developed than the upper cycle. Additionally, it should be noted that this area appears to represent the deepest lacustrine facies preserved in the Whitmore Point outcrop belt and the deepest parts of the lake were most likely situated to the south of the present erosional limits of these strata.

Pipiringos and O'Sullivan (1978) identified a series of regional unconformities within Triassic through Jurassic strata on the Colorado Plateau that they proposed had regional significance in defining packages of related rocks and provided a framework for paleogeographic and paleoenvironmental reconstructions. There has been dispute about the relative importance of some of these surfaces. Pipiringos and O'Sullivan (1978) defined the J-0 unconformity as occurring at the base of the Moenave Formation and, to the northeast, the Wingate Sandstone where this surface had been considered as marking the Triassic-Jurassic boundary across the Colorado Plateau. The J-0 unconformity in this area is referred to as the Tr-5 unconformity by others (Lucas and Tanner 2006; Tanner and Lucas 2007; Donohoo-Hurley et al. 2010). The J-1 unconformity truncates the top of the Navajo Sandstone at the top of the Glen Canyon Group.

Riggs and Blakey (1993) recognized another unconformity, between the J-0 and J-1 unconformities, at the base of the Springdale Sandstone Member within the Moenave Formation, which they termed the J-sub-Kayenta (J-sub-Kay; often spelled "J-sub-K") unconformity. This same unconformity was independently identified by Marzolf (1993) as the J-0' unconformity. Others (Tanner and Lucas 2007; Donohoo-Hurley et al. 2010) call this the "sub-Springdale unconformity". All recognized that this erosional surface can be traced to the contact at the base of the Kayenta Formation to the northeast where it directly overlies the Wingate Sandstone. Thus, the Springdale Sandstone Member of the Moenave Formation is equivalent to the basal Kayenta Formation to the northeast. Marzolf (1993, 1994) removed the Springdale Sandstone from the Moenave Formation and included 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 and Tanner 2006; Kirkland and Milner 2006) and has been applied to new geological maps of the area published by the Utah Geological Survey.

### Structural and Paleogeographic Setting

Blakey (1994) provided a straightforward model for the relationship between the fluvial sediments of the Dinosaur Canyon Member of the Moenave Formation and the eolian sediments of the Wingate Sandstone Formation to the northwest. The thickest sections of the Glen Canyon Group are along the southwestern margin of the Colorado Plateau, extending from Ward Terrace in the Painted Desert east of Cameron, Arizona northwestward along the Echo and Vermillion Cliffs to the area around St. George, Utah. This band of thick Glen Canyon Group strata marks the approximate position of what is termed the Zuni Sag (Blakey 1994) (Fig. 52). 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. Sand dune beds preserved in the Wingate and Navajo Sandstone formations indicate wind directions blew sand from west to east in central Utah and to the southeast farther south. The model of Blakey (1994) has sediment being transported northwest along the Zuni Sag into the area of west-central Utah where the prevailing westerly winds blew the sand into dune fields on the central Colorado Plateau and then to the southeast, where a portion would be reworked back into the rivers flowing back up to the northwest (Fig. 53).

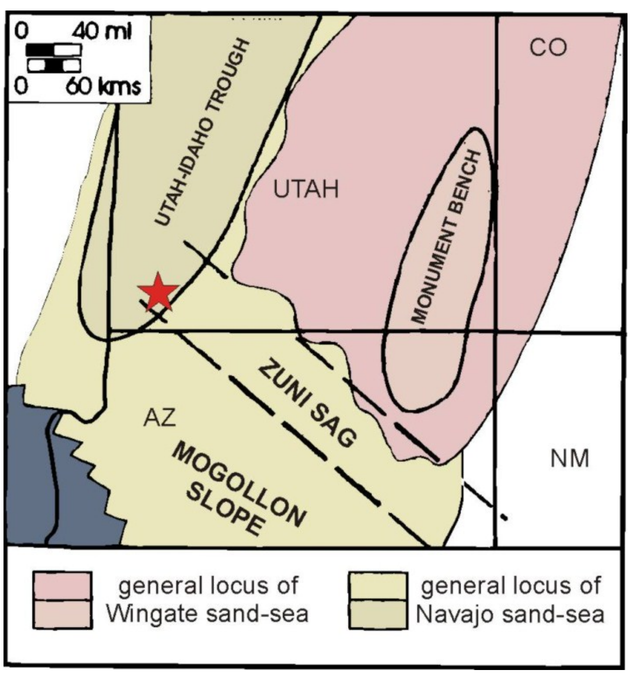


Figure 52. Outcrop map of the Moenave and Wingate Sandstone formations with large-scale facies patterns and geographic features.

Of particular interest while looking at the Whitmore Point Member at this locality are two repeating lake megacycles, a thicker lower cycle and a thinner upper one (Fig. 54).

### Age of the Moenave Formation

The Whitmore Point Member preserves thick-scaled, semionotid fish (Hesse 1935; Schaeffer and Dunkle 1950; Milner et al. 2005a; Milner and Kirkland 2006) that previously had been used to date these beds variably as Early Jurassic or Late Triassic (Harshbarger et al. 1957). An Early Jurassic age for the Whitmore Point Member had been accepted based on comparisons of these fossil fish with those preserved in the Newark Supergroup of the eastern U.S. (Olsen et al. 1982; Lucas and Tanner 2007). This Early Jurassic age was also supported by palynostratigraphy (Olsen and Galton; 1977; Litwin 1986; Cornet and Waanders 2006), crocodyliforms (Clark and Fastovsky 1986), dinosaurs (Lucas and Heckert 2001), and fossil tracks (Olsen and Galton;

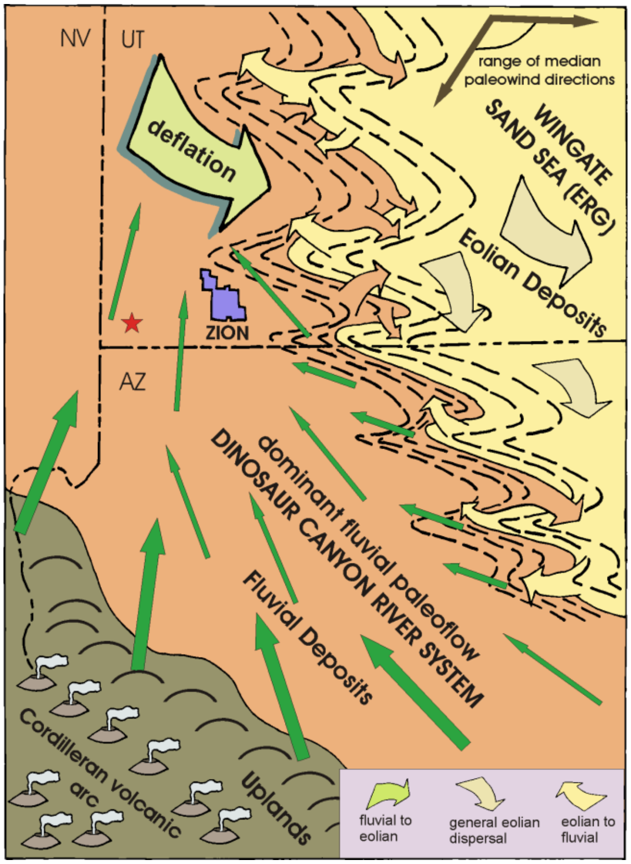

Figure 53. Depositional model for interrelationships between fluvial sediments of the Dinosaur Canyon Member of Moenave Formation and eolian deposits of the Wingate Sandstone Formation (after Blakey 1994).

1977; Olsen and Padian 1986; Lucas and Heckert 2001; Lucas 2009).

In the last two decades, fossils generally associated with the Triassic have been found in the lower Wingate Sandstone of the basal Glen Canyon Group (Lockley et al. 1992; Morales and Ash 1993; Lucas et al. 1997; Lockley et al. 2004b; Odier et al. 2004). On the assumption that the lower Wingate as seen where these fossil occur intertongues laterally with the Moenave Formation, these fossils have been used to argue that the Triassic-Jurassic boundary lies somewhere within the Dinosaur Canyon Member of the Moenave Formation and within the intertonguing Wingate Sandstone Formation to the northeast. However, this assumption is far from certain, and there is a conflation of arguments about the position of the Triassic-Jurassic boundary, the age of the Moenave and the level of the end-Triassic extinction that requires a digression.

In the past (~1970-2000s) there was a more or less loosely articulated, but widely followed, argument that correlation of the Triassic-Jurassic boundary from marine strata to continental strata could be accomplished by recognition of the level at which taxa (sporomorphs, tetrapods, fresh water arthropods) generally recognized to be “diagnostic” of the Triassic disappeared, and the much less common taxa thought “diagnostic” of the Jurassic appear. Some of these taxa are shared between the marine and continental environments (e.g., sporomorphs), while others are generally not (e.g., the terrestrial tetrapods). While there was no formally agreed definition of the marine Triassic-Jurassic boundary, either in terms of the taxa that marked it or geographic and stratigraphic relationship, the consensus was that the appearance of Jurassic-type ammonites corresponded closely to the extinction of many Triassic taxa, both marine invertebrates and terrestrial sporomorphs, and therefore this transition could be located in continental deposits.

With the hotly contentious recognition that the Triassic-Jurassic biotic transition could be a mass extinction with a catastrophic cause, a great deal more attention was focused on the details of this transition during the early 2000s (e.g., Ward et al. 2001; Olsen et al. 2002; Hesselbo et al. 2002; Guex et al. 2004; Hounslow et al. 2004; Marzoli et al. 2004; Tanner et al. 2004).

In addition, a large-scale international effort to define GSSPs (Global Boundary Stratotype Section and Points) resulted in a formal definition of the Triassic-Jurassic boundary (i.e., base Hettangian) that is not at the interval of the extinctions (Hillebrandt et al. 2007; Morton, 2008, 2012). The GSSP for the base Hettangian is as at the first appearance of the ammonite *Psiloceras spelae tirolicum* (a European subspecies: Hillebrandt and Krystyn 2009) at the Kuhjoch section, Karwendel Mountains, Tyrol, Austria. This level is significantly above the level of the last occurrence of typically Triassic ammonites, namely *Choristoceras marshi,* various genera of bivalves as well as levels in other areas marking the last occurrence of the conodonts. It is also above the sporomorph turnover associated with these invertebrate extinctions.

The fact that the Triassic-Jurassic boundary is **not an extinction interval** means that we have to be very careful not to conflate these two issues. We need to use a different term for the extinction interval, such as the end-Triassic extinction (ETE) that now cannot be at the Triassic-Jurassic boundary based on how it is presently defined. We also need to acknowledge that while the extinction interval may scream out for explanation, the appearance of one subspecies of ammonite is by contrast not particularly interesting. In addition, while the extinction interval, especially its inception, could be a globally isochronous event at the annual (if caused by some large external event), the appearance of a single species, is by its nature, as we understand the evolutionary process, is local and involves dispersal from its place of origin or refugium.

The above issues need to be kept in mind when talking about the age of the Moenave, or any unit thought to be in temporal proximity to the extinction interval or Triassic-Jurassic boundary. For example, it is entirely possible that the Triassic-Jurassic boundary could be within the Moenave, while the extinction interval could be represented by the Moenave-Chinle unconformity, or the Triassic-Jurassic boundary could be within the upper Moenave, while the extinction interval could be in the lower Moenave. If the continental extinction interval correlates to the marine then no matter what else, it must be of Triassic age, although that age assignment is of no particular interest in terms of biological or physical processes.

In the absence of ammonites and marine invertebrates in general, some other age-relevant criteria have to be used. Polarity magnetostratigraphy can provide an independent way to test a correlation hypothesis such as that posed by the hypothesis that the lower Moenave is Triassic in age based on its intertonguing relationship with the lower Wingate. Thus far however the application of polarity stratigraphy has proved spectacularly ambiguous in this regard.

Molina-Garza et al. (2003) show fairly unambiguously at Comb Ridge, Utah that the lower Wingate Formation is of dominantly reverse polarity while the upper is dominated by normal polarity. They also show, equally and clearly that the

Moenave Formation at Echo Cliffs near, Moenave, Arizona is predominately of normal polarity. Strangely, while Molina-Garza et al. (2003) support the hypothesis that the Wingate is equivalent to the Moenave and intertongues with it, the one clear conclusion that can be gleamed from their data is that the lower Wingate as seen at Comb Ridge **cannot** be the same age as any part of the Moenave at Echo Cliffs.

This latter point is very important, because the supposed equivalence of the Moenave and Wingate formation underpins the Lucas and Tanner's (2007) concept of the "Dinosaur Canyon Assemblage" which they then equate with the Apachean Land Vertebrate Age (Lucas et al. 2011). We do not know how the Triassic-aspect fossil bearing localities in lower Wingate relate to the Moenave, but we **do** know that the apparently equivalent lower Wingate at Comb Ridge cannot be the equivalent of the Moenave. We suspect, therefore, that the concept of the "Dinosaur Canyon Assemblage" as outlined by Lucas and Tanner (2007) and Lucas et al. (2011) is a chimera – a hypothesis that can easily be tested by looking at the

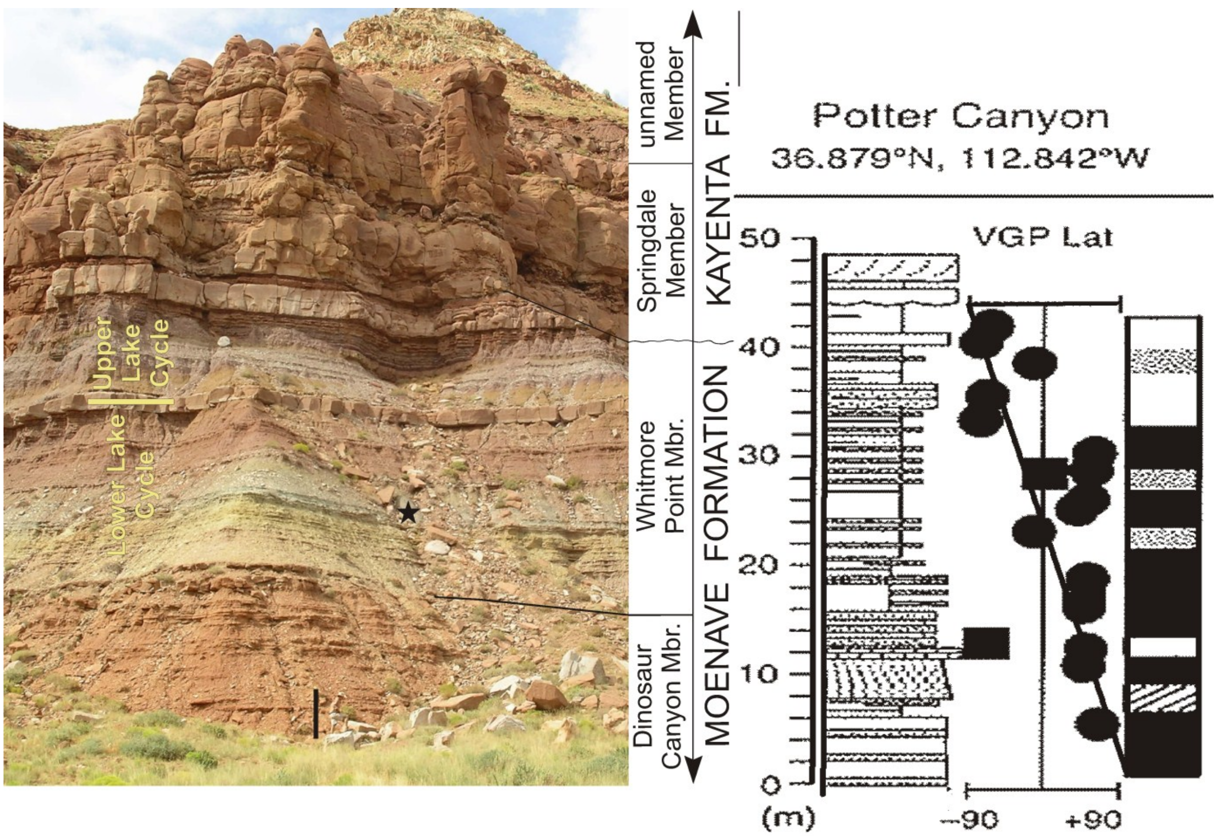


Figure 54. Potter Canyon outcrop photo on left showing the upper part of the Dinosaur Canyon Member and the entire Whitmore Point Member of the Moenave Formation. Above is the Springdale Sandstone Member and an unnamed member (= "silty facies" or "main body" elsewhere in the paper) of the Kayenta Formation. There are two lake cycles (indicated upper and lower on the photo), and the black star indicates the stratigraphic position of black shales containing fish remains, abundant conchostracans, ostracods, and palynomorphs. The black line in the bottom center of the photo shows a person for scale. To the right is a generalized stratigraphic section with paleomagnetic data from Donohoo-Hurley et al. (2010; fig. 9). VGP = virtual geomagnetic pole latitudes. Black = normal polarity; White = reverse polarity; Gray = ambiguous polarity; Angled lines = not sampled; Gray box = block sample site; Black circle = drill sample site.

polarity of the sections containing the Triassic-aspect fossils.

Donohoo-Hurley et al. (2006, 2010) provide polarity data from four additional sections in western Arizona and Utah all of which are broadly compatible with the Echo Cliffs data of Molina-Garza et al. (2003) in being predominately of normal polarity. This reinforces the argument that the lower Wingate as seen at Comb Ridge as no counterpart in the Moenave *sensu stricto*. Regrettably, and this is where the profound ambiguity sets in, the Triassic type fossils are not from Comb Ridge, but rather other areas where the polarity stratigraphy is not known. However, in as much as the Hettangian is clearly dominated by normal polarity (Yang et al., 1996; Hounslow et a 2004; Kent and Olsen, 2008), reverse polarity of the lower Wingate as seen at Comb Ridge, is strong evidence those strata are of Triassic age and well down in the Rhaetian at that.

Donohoo-Hurley et al. (2010) demonstrate the presence of at least two thin reverse polarity zones in Whitmore Point Member and a single site that has both normal and reverse polarity. One zone of reverse polarity is at the base of the Whitmore Point Member (labeled M2r), and another 8 m above (labeled M3r), while the remainder of the Moenave Formation displays normal polarity, except for the one mixed polarity site within 6 m of the base of the formation. They have identified these short reverse zones at three of their Moenave sections located near St. George in Leeds, Washington Dome, and here at the Potter Canyon section (Figs. 54-56), while at Warner Valley section they have only identified one. Their sampling density could easily account for the

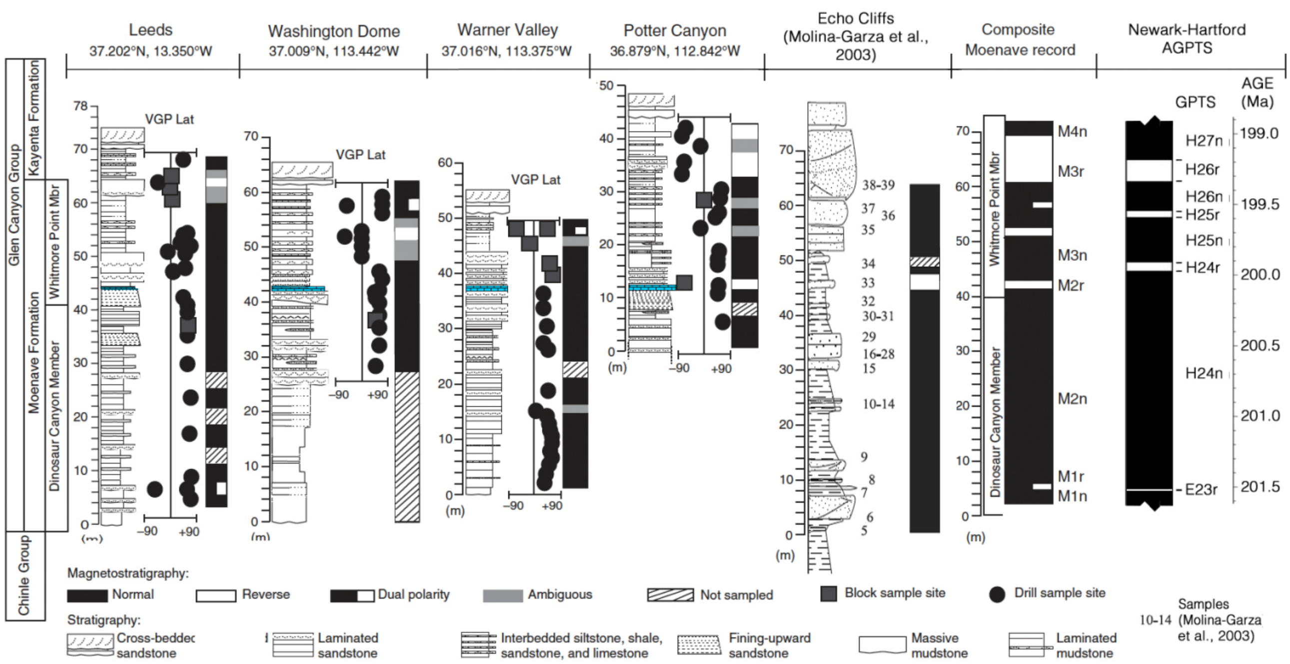


Figure 55. Paleomagnetic polarity stratigraphy of the Moenave Formation. We have modified the correlations of the sections described by Donohoo-Hurley et al. (2011) by correlating to the limestone level (blue) near the base of the Whitmore Point Member and adding the section at Echo Cliffs of Molino-Garza et al. (2003). Correlation of the latter to the sections of Donohoo-Hurley et al. (2011) based on the polarity stratigraphy. Newark Hartford GPTS modified from Kent and Olsen (2008).

discrepancies. They propose a correlation of these Moenave Formation reverse magnetozones with marine deposits at St. Audrie's Bay in Somerset England, Oyuklu in Turkey, and the Southern Alps in Italy, and within nonmarine rocks in Morocco and the Newark Supergroup in eastern North America (Donohoo-Hurley et al. 2010). Donohoo-Hurley et al. (2010) found their magnetostratigraphic results to be consistent with previous paleomagnetism studies undertaken in the Moenave Formation (see Ekstrand and Butler 1989; Hutny 2003; Molina-Garza et al. 2003).

Strangely, Donohoo-Hurley et al. (2010) attempt correlation of their composite section (Fig. 56) with only the putative latest Triassic and Early Jurassic part of the Newark basin section (which is oddly represented and deformed from the original in Kent and Olsen, 1999) and do not compare their composite with the full Rhaetian to Sinemurian section seen in Kent and Olsen (2008) although they do cite the latter (repeated in Lucas et al. 2011).

This omission is particularly unfortunate because the Moenave composite section looks remarkably similar to this Rhaetian to Sinemurian age part of the Newark plus Hartford basins AGPTS (astronomically tuned geomagnetic polarity time scale) (Fig. 55). If this correlation is meaningful, the M1r polarity zone in the Moenave could very well represent E23r of the Newark basin record and the top of the Moenave could be Sinemurian in age as seen in the Hartford basin section. We would also modify the correlation of the sections of Donohoo-Hurley et al. (2010) by correlating the thin limestone bed at the base of the Whitmore Point Member (Fig. 55). Doing this resulted in a composite stratigraphy that looks nearly identical to the Newark-Hartford AGPTS. While requiring additional denser sampling to test this correlation, the fossils found in the Moenave can now be looked at in this context.

The two questions that need to be asked are therefore, is the ETE in the Moenave Formation *sensu stricto* (since the Wingate evidence is thus far ambiguous), and where is the Triassic-Jurassic boundary?

It is clear there are no tetrapod taxa known exclusively from Triassic age strata in the Moenave and that includes both skeletal remains and ichnites. Instead, all of the tetrapod data are so far consistent with being post-ETE, which could be very latest Triassic or Early Jurassic.

The large (>30 cm) tracks, assigned to theropods, indistinguishable from *Eubrontes giganteus* are present in the upper Dinosaur Canyon Member and Whitmore Point Member. Such footprints are known only from post-ETE strata globally, including strata of very latest Triassic age (contra Lucas and Tanner 2007).

Donohoo-Hurley et al. (2010) and Lucas et al. (2011) incorrectly claim that *Eubrontes* and *Grallator* are only preserved in the lower Whitmore Point Member about 4 m above the Dinosaur Canyon-Whitmore Point contact, and do not mention these ichnotaxa's occurrence in the upper 8 m of the Dinosaur Canyon Member at the SGDS (Fig. 6; Milner et al. 2006d),

The ornithischian dinosaur ichnite *Anomoepus* occurs in the lower Whitmore Point Member (Milner et al. 2006d). Donohoo-Hurley et al. (2010) and Lucas et al. (2011) do not discuss the existence of this ichnotaxon from the base of the Johnson Farm Sandstone Bed, the Top Surface, and Stewart-Walker tracksites, all located at the SGDS as mentioned above (Figs. 6, 16; Milner et al. 2006d; Milner and Spears 2007). *Anomoepus* is thus far known exclusively from post-ETE Jurassic age strata, even as now defined by the Austrian GSSP (Lockley and Hunt 1994, 1995; Olsen and Galton 1984; Olsen and Rainforth 2003; Lucas and Tanner 2007; Lucas 2007, 2009). While ornithischians should occur in late Triassic, pre-ETE strata somewhere, definitive evidence of Triassic age skeletal remains is vanishingly scant and in fact limited to only one fragmentary maxilla (from Patagonia; see Baez and Marsicano 2001) that is confidently dated (Irmis et al. 2007; Brusatte et al. 2010; Olsen et al. 2011). In addition, this Patagonian fragment appears to be of heterodontosaurid affinities, and if possessed of the typically large manual digits seen in other heterodontosaurids, it could not have made *Anomoepus*, because the latter ichnite has decidedly short manual digit impressions (Olsen and Rainforth 2003). [Note that *Pisanosaurus* is definitely Late Triassic in age, but is so fragmentary and poorly preserved that it may not be ornithischian, and lacking manus or pedes and no obvious lower level affinities within the Ornithischia, it cannot compared to *Anomoepus* in any meaningful way.]

Until recently, no age-relevant fossils of any sort have been found in the lower Dinosaur Canyon Member in southwestern Utah (Milner et al. 2009b). We will visit the Olsen Canyon Tracksite tomorrow on Day 3. All of the tracks found thus far are consistent with post-ETE and no exclusively Triassic forms have been found.

It has been generally accepted that the basal crocodylomorph *Protosuchus* (Colbert and Mook 1951) from the Dinosaur Canyon Member of north-central Arizona is earliest Hettangian in age (Clark and Fastovsky 1986; Shubin et al. 1994; Sues et al. 1994; Gow 2000; Lucas and Heckert 2001; Lucas 2009; Lucas et al. 2011). However, other closely related protosuchids are known from presumptive Triassic strata, notably *Hemiprotosuchus* from the Argentinean Los Colorados Formation (Bonaparte 1969; Arcucci et al. 2004; Santi Malnis et al 2011) and isolated osteoderms indistinguishable from *Protosuchus* occur in the upper Passaic Formation below the ETE (Olsen et al. 2002). Finally, based on the correlation in Whiteside et al. 2007, 2010), the strata producing *Protosuchus micmac* (Sues et al. 1996) in Nova Scotia are post-initial-ETE, but still latest Triassic in age, thanks to the new GSSP for the base Hettangian. Thus, regrettably, the presence of *Protosuchus* is uninformative with respect to the Triassic-Jurassic boundary, and might not even inform the position of the ETE. It surely does however suggest a latest Triassic to Early Jurassic age.

In the Ward Terrace area in north-central Arizona where *Protosuchus richardsoni* was discovered (Colbert and Mook 1951; Clark and Fastovsky 1986), the Springdale Sandstone Member of the Kayenta Formation rests unconformably on top of the Dinosaur Canyon Member of the Moenave Formation. In southwestern Utah and northwestern

Arizona, the Whitmore Point Member of the Moenave Formation conformably lies on top of the Dinosaur Canyon Member and is unconformably covered by the Springdale Sandstone Member. Without any independently calibrated magnetostratigraphic data (Donohoo-Hurley et al. 2010), or other evidence for that matter, some authors (Lucas and Heckert 2001; Lucas and Tanner 2007; Donohoo-Hurley et al. 2010; Lucas et al. 2011) claim that the upper part of the Dinosaur Canyon Member on Ward Terrace where the Early Jurassic *Protosuchus* is found, is laterally equivalent with the upper part of the Whitmore Point Member in southwestern Utah and northwestern Arizona. This suggestion appears to rely solely on the unconformity between the Moenave and Kayenta formations, and the difference in time lost at this unconformity between these two regions is clearly unknown. Indeed the simplest correlation of the available magnetic polarity data from Echo Cliffs (Molina-Garza et al. 2003), the closest locality to Dinosaur Canyon for which there is data, is that the thin reverse polarity zone at the top of the Dinosaur Canyon Member correlates to M2r of Donohoo-Hurley et al. (2010) in basal part of the Whitmore Point Member and nearly all of the Whitmore Point Member has been cut out by the J-sub-Kay unconformity (Fig. 56).

Evidence provided by conchostracans (Lucas and Milner 2006; Kozur and Weems 2010; Lucas et al. 2011) has been interpreted to show that the lower part of the Whitmore Point Member is Rhaetian rather than early Hettangian in age, based on the presence of *Euestheria brodieana*. Kozur and Weems (2010) remark that the turnover in conchostracan faunas through the Rhaetian-Hettangian boundary is very gradual, where the monospecific taxa *Euestheria brodieana* (Jones) in the latest Rhaetian is followed by a basal Hettangian fauna still dominated by *E. brodieana* but has some *Bulbilimnadia killianorum* Kozur, Weems and Lucas 2010 (in Kozur and Weems 2010). The type locality for *B. killianorum* is Potter Canyon in a 0.5 m thick bed of purple mudstone in the Whitmore Point Member situated 3.5 m below the base of the Springdale Sandstone Member (Fig. 56). This same sequence of conchostracans is reported from both Potter Canyon, Arizona and the SGDS in Utah according to Lucas et al. (2010). Two additional conchostracan horizons at the SGDS have since been recognized in the uppermost Whitmore Point Member associated with vertebrate body fossils, and

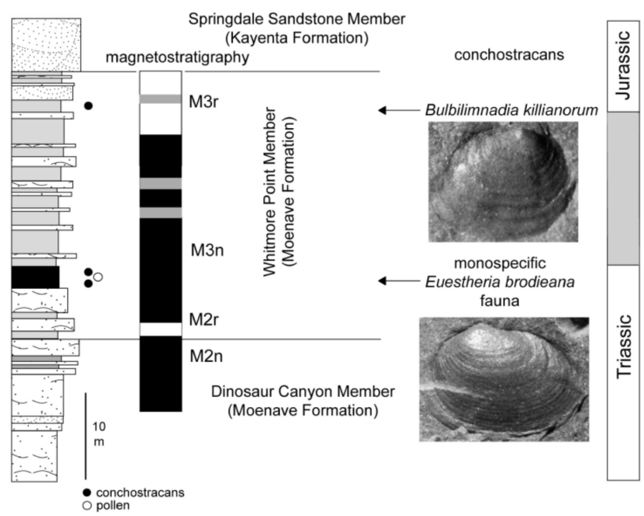


Figure 56. Stratigraphic section figure from Lucas et al. (2011, fig. 3) showing their magnetostratigraphy sample and conchostracan horizons, and from where pollen was sampled. On the right is their proposed position for the Triassic–Jurassic boundary based on the monotaxic occurrence of *Euestheria brodieana* and the lowest occurrence of *Bulbilimnadia killianorum*.

they are located between the samples provided to Spencer Lucas in 2006 for the New Mexico Museum of Natural History and Science collections. These new horizons having large sample sizes have not yet been studied in any detail. It may very well be that the interpretation that some part of the Moenave is Late Rhaetian in age is correct, but it may also be post-ETE as are all of the eastern North American strata in which *Euestheria brodieana* is overwhelmingly dominant.

*Euestheria brodieana* occurs in the latest Rhaetian, above the base of the ETE interval and above the initial carbon isotopic excursion in Great Britain (Kozur and Weems 2010; Lucas et al. 2011) where it is Late Rhaetian by the new definition of the base Hettangian. It is also abundant above the base-ETE in the Hartford, Newark, and Culpeper basins in association with a typical post-ETE assemblage of footprints and in the complete absence of any uniquely Triassic vertebrate taxa, and above the oldest lava of the Central Atlantic magmatic province (CAMP). Thus, the discovery of latest Rhaetian conchostracan taxa does not change the interpretation of the Moenave as being largely if not entirely post-ETE. Putting the position of the Triassic-Jurassic boundary in the middle of Whitmore Point Member, which is probably an over interpretation in any case, also does not change any interpretation of correlation units - only the name changes.

It has long been recognized that the sporomorphs of the Moenave are overwhelmingly dominated by *Classopollis* spp. and the apparent absence of taxa restricted to the Late Triassic led to the conclusion that the Moenave is Early Jurassic in age (Olsen and Galton 1977; Litwin 1986), with more recent suggestions, however that Triassic-Jurassic boundary lies in the formation (Cornet and Waanders 2006; Kürschner and Batenburg in Lucas et al. 2011). Again, where that boundary lies has little bearing on the great extinction event preceding it, which was previously the relevant datum.

Recently, Downs (2010) described sporomorph assemblages from the Moenave and concluded that there were examples of the otherwise pre-ETE *Patinasporites* and *Vallasporites* from an interval in the lower half of the Dinosaur Canyon Member of the Moenave at Kanab, Utah. However, based on the photographs, the purported, extremely rare *Patinasporites* are very badly preserved and are correspondingly dubious. *Vallasporites* is not illustrated. This very important occurrence needs to be further documented. If not reworked, these occurrences would suggest that the ETE lies within the Dinosaur Canyon Member.

Within this context, the specific views of some researchers, based on magnetostratigraphy, biostratigraphy, and palynology, that the entire Dinosaur Canyon Member and lower portion of the Whitmore Point Member of the Moenave Formation are Late Triassic in age, rather than Early Jurassic age can be examined (Donohoo-Hurley et al. 2007, 2010; Kozur and Weems 2010; Lucas et al. 2011). Donohoo-Hurley et al. (2007, 2010) place the Triassic-Jurassic boundary based on their magnetostratigraphic data approximately 3-13 m above the Dinosaur Canyon-Whitmore Point contact within the Whitmore Point Member. However, the biostratigraphic and magnetostratigraphic levels to which they refer in eastern North America and England lies within the latest Rhaetian.

The complete absence of characteristic Late Triassic tracks, such as *Brachychirotherium*, *Apatopus*, *Atreipus*, *Evozoum*, and *Gwynnedichnium*, anywhere in the Moenave Formation, so common in the Rhaetian Church Rock/Rock Point members of the Chinle Formation and lower Wingate Sandstone Formation (e.g., Lockley and Hunt 1995; Gaston et al. 2003; Hunt and Lucas 2007; Milner et al. 2011), argues that the ETE is **not** represented in the fossiliferous portions of Moenave Formation. The same is true for the absence of body fossils of non-crocodylomorph crurotarsans such as phytosaurs, aetosaurs, and 'rauisuchians' in the Dinosaur Canyon and lower part of the Whitmore Point members. If the ETE is preserved within the Moenave it should be in the lower part of the Dinosaur Canyon Member, likely in an interval that thus far has produced no fossils of any sort.

The position of the Triassic-Jurassic boundary is another matter and of far less interest as a paleobiological event. Available evidence suggests that it lies within the Moenave Formation, somewhere between the middle Dinosaur Canyon Member and the upper Whitmore Point Member.

Clearly this matter is far from resolved, but we believe that northwestern Arizona and southwestern Utah is slowly yielding evidence as to where the Triassic-Jurassic boundary and the ETE should be recognized, and that continued research in the region shall provide important data in the, hopefully, not too distant future.

| | | |
|---|---|---|
| 0.0 | 42.8 | Back-track to Highway 389 from Potter Canyon section. |
| 7.8 | 50.6 | Pass Cane Beds Road (County Road 237) turnoff and continue west on Highway 389. |
| 4.0 | 54.6 | Cross Arizona-Utah state line. Highway 389 changes to Highway 59 in Utah. |
| 8.0 | 62.6 | Pass turnoff on right for Gooseberry/Smithsonian Butte Scenic Byway. Smithsonian Butte is visible to your right (east) and forms the western end of the Vermillion Cliffs. View of Gray Knoll cinder cone resting on the Shinarump Member of the Chinle Formation. This resistant ledge forms the top of Little Creek Mesa. Gray Knoll is the southeastern-end of a five mile long (8 km) string of 28 cinder cone volcanoes. These Pleistocene cinder cones were controlled by a vertical joint partially occupied by a dike trending N 40° W (Moore and Sable 2001). |
| 3.6 | 66.2 | Continue past Apple Valley turnoff and potential rest stop on right. |
| 2.6 | 68.8 | Pass scoria quarry on cinder cone volcano to the left (south). |

| | | |
|---|---|---|
| 2.0 | 70.8 | Outcrops in cliffs to the right (north) make up the southern part of Gooseberry Mesa. This mesa contains the Middle Red, Shnabkaib and Upper Red members of the Moenkopi Formation capped by the Shinarump Member of the Chinle Formation. |
| 1.1 | 71.9 | Passing through exposures of the Virgin Limestone and Lower Red members of the Moenkopi Formation. |
| 2.5 | 74.7 | Passing outcrops of Permian Kaibab Formation. |
| 1.3 | 76.0 | Cross Hurricane Fault and columnar basalt jointing in Pleistocene lava flows. |
| 0.1 | 76.1 | Turn right onto Main Street in Hurricane (north), and an immediate left onto State Road 9 heading west. |
| 0.7 | 76.8 | Pass road to Warner Valley next to Chevron gas station. |
| 1.6 | 78.4 | Pass Volcano Hill cinder cone to the left (south). |
| 3.6 | 82.0 | Cross bridge over the Virgin River and pass through the western limb of the Virgin Anticline. Here we pass through most of the Moenkopi Formation and the lower part of the Chinle Formation. |
| 2.5 | 84.5 | Left onto Telegraph Road heading south. |
| 3.5 | 88.0 | Right on Washington Parkway (1475 East). |
| 0.7 | 88.7 | Right onto Grapevine Crossing Road. Notice outcrops of the Springdale Sandstone Member of the Kayenta Formation in roadcuts on the right (south). |
| 0.4 | 89.1 | Parking area for Spectrum Tracksite next to fence line. |

## STOP 5—THE SPECTRUM TRACKSITE

**Discussion Leaders: Martin Lockley and Andrew Milner**

The Spectrum Tracksite, also known as the Grapevine Pass Wash Tracksite (Fig. 57A assigned state locality number 42Ws201T by the State Paleontologist's Office of the Utah Geological Survey), is north of Grapevine Crossing Road along the east branch of Grapevine Pass Wash (Hamblin 2006; Hamblin et al. 2006). The site covers approximately 500 $m^2$ and was mapped and illustrated in detail by Hamblin (2004, 2006). A generalized map of the site was provided in Hamblin et al. (2006) and in figure 57B. Local popularity of the site and a need to establish an interpretive locality for regular public visitations has led State Institutional Trust Lands (SITLA) to fence off the site and provided an entrance gate (Milner et al. 2006a).

The footprints at the Spectrum Tracksite are preserved at the very top of the Springdale Sandstone, the lower member of the Kayenta Formation. The track-bearing bed is about 45-50 cm thick and approximately 5 m above the Kayenta Formation base (Hamblin et al. 2006). The tracksite surface slopes about 13°N and dips N 35° W

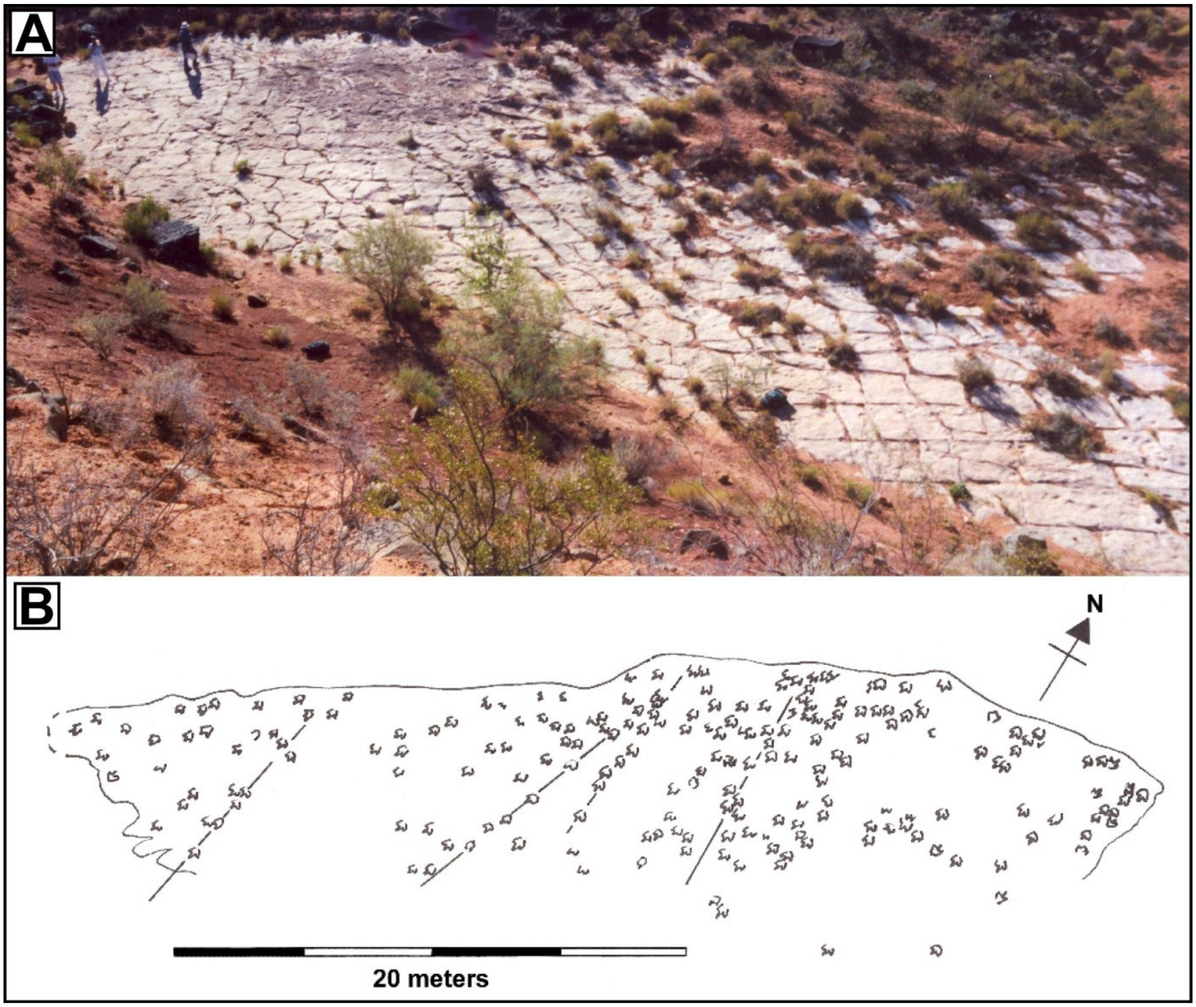


Figure 57. The Spectrum or Grapevine Pass Wash Tracksite. A, Photograph of the tracksite outcrop (courtesy Alden Hamblin). North is toward the left in the photo. B, Generalized map of the tracksite (from Hamblin et al. 2006).

(Hamblin et al. 2006). The tracks are preserved in a "very pale-orange, medium-bedded, very fine-to fine-grained sandstone that is overlain by thin-bedded, reddish-brown mudstone and siltstone" (Biek 2003b, p. 11; Hamblin et al. 2006). Silty facies beds of the Kayenta Formation can be seen in the wash immediately above the tracksite surface, and are primarily composed of mudstone and siltstone.

Hamblin (2004) mapped approximately 200 large, tridactyl theropod tracks attributed to *Eubrontes* (Hamblin et al. 2006). All footprints in sight are preserved as undertracks ranging from well-formed to severely weathered, visible with morning light conditions or showing only distal digit impressions. Tracks range in size from 30-46 cm long and 25-37 cm wide; the smallest footprint is 25 cm long by 18 cm wide (Hamblin et al. 2006). Trackways, although often difficult to identify, have stride lengths ranging from 2.6 to 4.2 m (Hamblin et al. 2006). Most of the tracks and trackways (96%) identified and mapped on this surface have a unidirectional, south-southwest trend; the remaining

4% are oriented more or less in the opposite direction (Fig. 57B; Hamblin et al. 2006).

The likelihood of smaller tetrapod tracks having been formed on finer-grained beds above has not been investigated at the Spectrum Tracksite and would be an important study to undertake. The substrate was probably rather firm, creating a taphonomic bias against the preservation of *Grallator* or smaller quadruped tracks at the site, like that seen on the Main Track Layer at SGDS (Milner et al. 2005). Lockley et al. (2006b) noted that low-diversity, theropod-dominated track assemblages, especially monospecific *Eubrontes* or *Kayentapus* sites, are very common in the Kayenta Formation, but recently, several new, well-preserved Kayenta Formation tracksites have been found in Washington County in finer-grained sediments at which *Grallator*, *Anomoepus*, and quadruped tracks are predominate. For example, Hamblin (2005) reported small, bird-like tracks from red-brown mudstone in the middle part of the Kayenta Formation silty facies in Washington County (Fig. 58A, B). In the early summer of 2011, this tracksite (now named the Hamblin Tracksite in honor of Alden Hamblin) was partially excavated revealing this particular trackway as *Anomoepus*, preserving manus and pes tracks with metatarsal impressions, which transitioned from a quadrupedal gait into a bipedal trackway (Fig. 58C). In addition, several new sites currently being studied have been found by the first author and SGDS volunteers within the past year in facies of mostly fine sandstones, siltstones, and mudstones. The lower part of the Kayenta Formation in southwestern Utah, particularly the silty facies, was deposited in fluvial, distal fluvial/playa, and minor lacustrine environments (Sansom 1992; Blakey 1994; Peterson 1994; Biek 2003b; Hamblin et al. 2006). This horizon has been interpreted as representing reworking of the Springdale fluvial system by the encroachment of a large-scale lacustrine system at the base of the Kayenta silty facies (Kirkland and Milner, 2006). The widespread occurrence of dinosaur tracks along this horizon in the St. George and Zion National Park (DeBlieux et al., 2004, 2006) regions leads to our interpretation that the Springdale-Kayenta silty facies contact may represent a megatracksite facies in southwestern Utah.

The top of the Springdale Sandstone Member, which was deposited in a fluvial channel complex, preserves a megatracksite that can be traced extensively from southwestern Utah, including both St. George and Zion National Park, as far east as Ward Terrace near Tuba City in north-central Arizona. The interpretation of the "Springdale megatracksite" (Lucas et al. 2005a), which includes the Spectrum Tracksite, has since been supported by several authors (DeBlieux et al., 2004, 2006; Hamblin et al. 2006; Lucas and Tanner 2006).

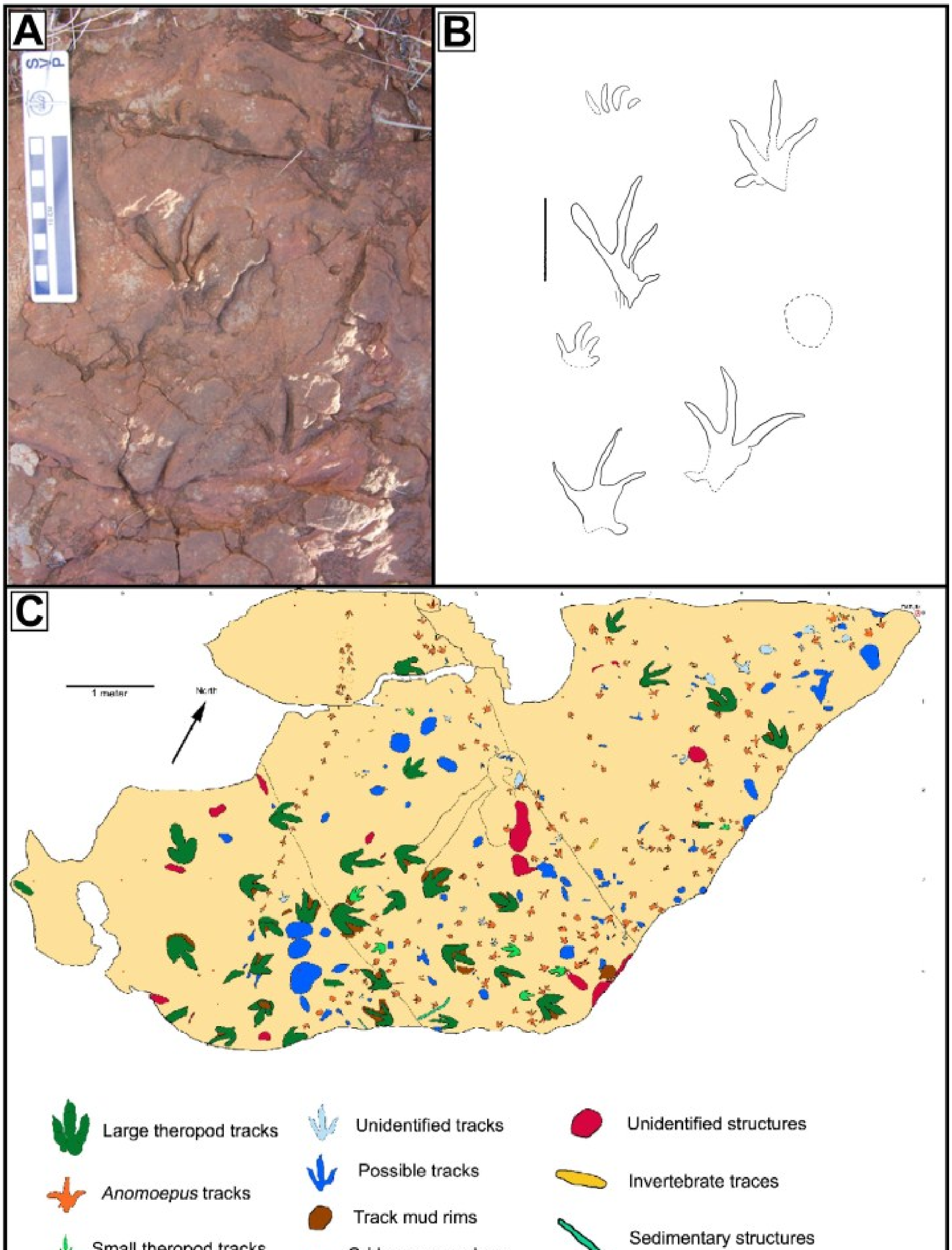


Figure 58. The Hamblin Tracksite. A, Partial trackway interpreted as bird-like theropod tracks by Alden Hamblin in 2006. This same trackway was interpreted by Milner in 2008 as possible crocodylomorph tracks because of the recognition of manus impression and the sprawling-like arrangement of tracks. B, April 2011 drawing of trackway shown in A before tracksite excavation in the summer of the same year. C, Partial map of the Hamblin Tracksite situated in the middle part of the silty facies, Kayenta Formation. The tracks figured in A and B is now positively identified as *Anomoepus*.

| | | |
|---|---|---|
| | 89.1 | Leave parking area for Spectrum Tracksite and backtrack to Washington Parkway. |
| 0.4 | 89.5 | Turn right (north) onto Washington Parkway. |
| 0.3 | 90.2 | Continue straight through roundabout. |
| 0.3 | 91.2 | Make a left onto I-15 heading south toward St. George. |
| 4.4 | 96.6 | Take Exit #8 for St. George Blvd. and prepare to turn right onto St. George Boulevard. |
| 0.3 | 102.3 | Lights at St. George Boulevard. Turn right. |
| 1.0 | 109.0 | Make a right turn into parking lot. End of day two. |

## DAY 3

| **Incremental** *Mileage* | ***Cumulative*** *Mileage* | *Description* |
|---|---|---|
| 0.0 | 0.0 | Make a right out of EconoLodge parking lot onto St. George Boulevard. |
| 0.8 | 0.8 | Pass over I-15 and prepare to turn right onto River Road. |
| 0.2 | 1.0 | Make a right (south) onto River Road. |
| 1.6 | 2.6 | Cross bridge over the Virgin River. |
| 0.2 | 2.8 | Make a left turn (east) at lights onto 1450 South. |
| 0.6 | 3.4 | The roadcut on your right (south) is the Upper Red Member of the Moenkopi Formation capped by the Shinarump Member of the Chinle Formation. |
| 1.4 | 4.8 | Make a left (east) onto 1580 South. |
| 1.5 | 6.3 | Make a right turn (south) on KD-JO Lane (830 East). Outcrops on the left (east) are Moenkopi Formation (Middle Red, Shnabkaib, and Upper Red members) capped by the Shinarump Member of the Chinle Formation. |
| 2.0 | 8.3 | Left (east) on Warner Valley Trail Road. |
| 3.9 | 12.2 | Sand dune has crosses road here so use caution (4 x 4 often required). |
| 2.0 | 14.2 | Fort Pierce trailhead on right (south). Passing through poorly exposed outcrops of the Petrified Forest Member of the Chinle Formation. Resistant outcrops of the Shinarump Member can be seen on the right (south) overlaying the Moenkopi Formation. The upper part of the Chinle, the Moenave, Kayenta and lowermost Navajo Sandstone formations can be seen on Sand Mountain on the left (north). Directly ahead (east) are the Hurricane Cliffs along the Hurricane Fault. Paleozoic rocks at the base of the cliffs include the Lower Permian Queantoweap |

| | | |
|---|---|---|
| | | Sandstone, Toroweap and Kaibab formations, capped by Lower Triassic marine sediments of the Timpoweap Member of the Moenkopi Formation. |
| 1.5 | 15.7 | Bear left remaining on main road (making a right here will take you to Hurricane). |
| 0.6 | 16.3 | Left turn (north) after the cattle guard toward Warner Valley Tracksite. |
| 0.5 | 16.8 | Parking area for the Warner Valley Tracksite. Due to the need to protect paleontological resources, we will not provide a detailed road log for the remainder of this trip. |

## STOP 6—WARNER VALLEY DINOSAUR TRACKSITE

**Discussion Leader: Tylor Birthisel and Andrew Milner**

### History

The Warner Valley Dinosaur Tracksite was discovered in 1982 by Gary Delsignore of Cedar City, Utah. A preliminary study by Miller et al. (1989) was the only formal documentation of an Early Jurassic fossil site from southwestern Utah until the discovery of the SGDS in 2000. Soon after the study by Miller et al. (1989), the Bureau of Land Management (BLM) erected interpretive signage and a steel barrier on the tracksite surface in an attempt to divert flash flood waters away from the better preserved *Eubrontes* tracks. In 2007, the St. George Field Office of the BLM began training volunteers to monitor important paleontological localities through the Color Country Site Stewardship Program. This includes monitoring of the Warner Valley Dinosaur Tracksite, among many other localities within Washington County, for signs of vandalism, theft, and erosion (Milner et al. 2006; Spears et al. 2008, 2009; Milner et al. 2009b; Birthisel 2011a, b). In early 2009, range fencing was erected around 40 acres of land surrounding and including the dinosaur tracksite in order to keep OHV traffic from driving across the tracksite surfaces. The public access road and parking area were also improved, and site etiquette signs were installed. Little scientific work was done on the site until 2010 with the creation of new interpretative signage and an excavation for a more detailed study by the SGDS (Birthisel et al. 2011a, b).

The site consists of a 700 $m^2$ area in an active wash. Erosion is a constant threat to the integrity of the site, and several scientifically significant specimens are in peril of being lost whenever there is substantial precipitation in the region. Of note, some previously observed tracks were destroyed by extensive erosion in 1983 and 1984 and were unable to be mapped in the Miller et al. (1989) study. Current work is being done to replicate specimens that are threatened, document the entire site using photogrammetric techniques in order to create a permanent record of the site, and stabilize the site against continued weathering.

## Geology

The Warner Valley Tracksite consists of four, closely-spaced track-bearing horizons at and immediately above the contact between the Springdale Sandstone Member and the overlying silty facies of the Kayenta Formation (Birthisel et al. 2011a, b). Miller et al. (1989) placed the site in the Dinosaur Canyon Member of the underlying Moenave Formation, which, at the time, was considered Late Triassic in age. In fact, the top of the Dinosaur Canyon Member is approximately 80 m below the top of the Springdale Sandstone Member and the track-bearing surfaces at the Warner Valley Dinosaur Tracksite.

The Springdale Sandstone Member consists of buff-colored sandstone that has sparse, subrounded chert clasts near the top of the unit as it grades into the silty facies. The silty facies is a series of mostly orange-brown mudstones, siltstones and sandstones with minor limestones above the Springdale Sandstone Member. In addition, several other tracksites have been discovered in at least five other track-bearing horizons in the silty facies of the Kayenta Formation in Warner Valley alone.

## Tracks

At the Warner Valley Dinosaur Tracksite there are three ichnotaxa preserved, four track-bearing horizons, and approximately 470 dinosaur tracks recognized (Fig. 59).

Most of the dinosaur tracks at the Warner Valley Tracksite are preserved as typical track molds, although a large number are concave epi-relief tracks (Fig. 60A). The convex epi-relief tracks, or "compression" tracks, are raised off the surface due to differential erosion. The mass of a trackmaker compacted the sediment within a track; after lithification, these compacted structures are slightly more resistant to weathering than the surrounding rock, so they weather into inverted topographic structures, raised relative to the surrounding surface (Fig. 60B).

The most common tracks at the site are assigned to the theropod dinosaur ichnotaxon *Grallator* (Fig. 61). *Grallator* tracks are found on all four track-bearing horizons at the Warner Valley Dinosaur Tracksite. There are a total of 290 *Grallator* tracks present in at least 20 trackways on the larger, upper track surface. Approximately 80 of these *Grallator* footprints are preserved as compression tracks. The small coelophysoid theropod "*Megapnosaurus*" *kayentakatae* is known from the Kayenta Formation and make a good model for the maker of *Grallator* tracks at this site.

Larger, *Eubrontes* theropod tracks (Fig. 62) are less common than *Grallator* tracks. *Eubrontes* footprints have only been recognized on the "main" track surface with a total of 53 *Eubrontes* tracks in 12 trackways. The trackmaker of *Eubrontes* were mistakenly attributed to prosauropods by some authors (Bock 1952; Miller et al. 1989; Weems 2003). However, track morphology of *Eubrontes* and *Gigandipus* more closely matches that of the feet of medium-sized theropod dinosaurs. The large, coelophysoid theropod *Dilophosaurus* is known

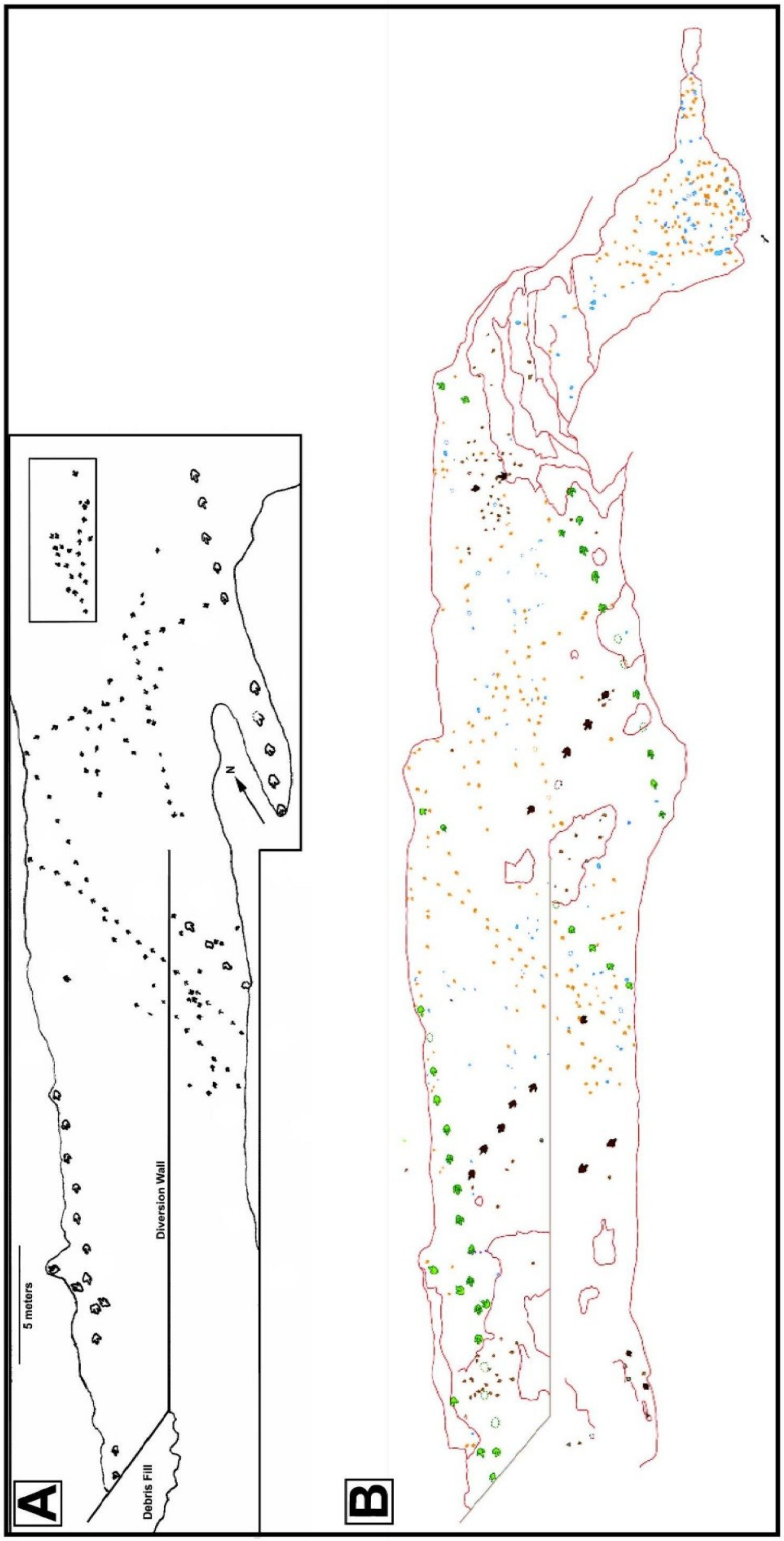


Figure 59. Maps of the Warner Valley Dinosaur Tracksite. A, Map from Miller et al. (1989). The inset in the top right corner of this figure correlates with the lower right edge in B. B, The new 2011 map by SGDS and Utah Friends of Paleontology.

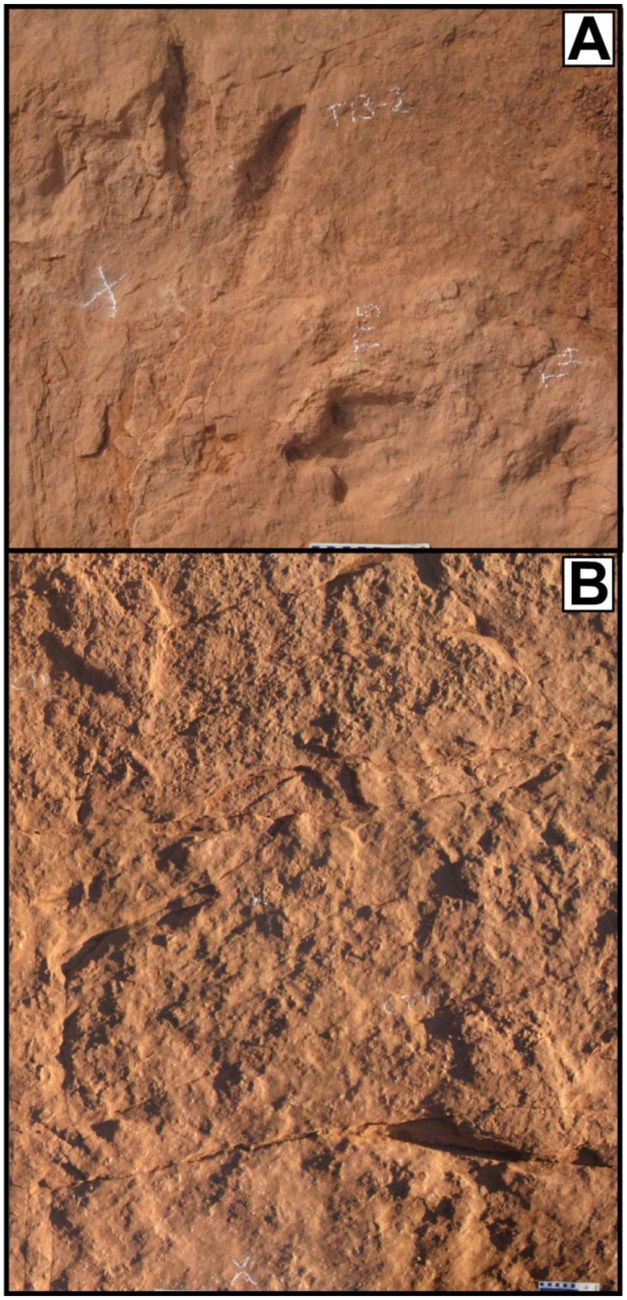


Figure 60. Track preservation types at the Warner Valley Dinosaur Tracksite. A, Typical concave epirelief or natural mold tracks of *Eubrontes* and *Grallator*. B, Convex epirelief or “compression” tracks preserved in a partial *Eubrontes* trackway.

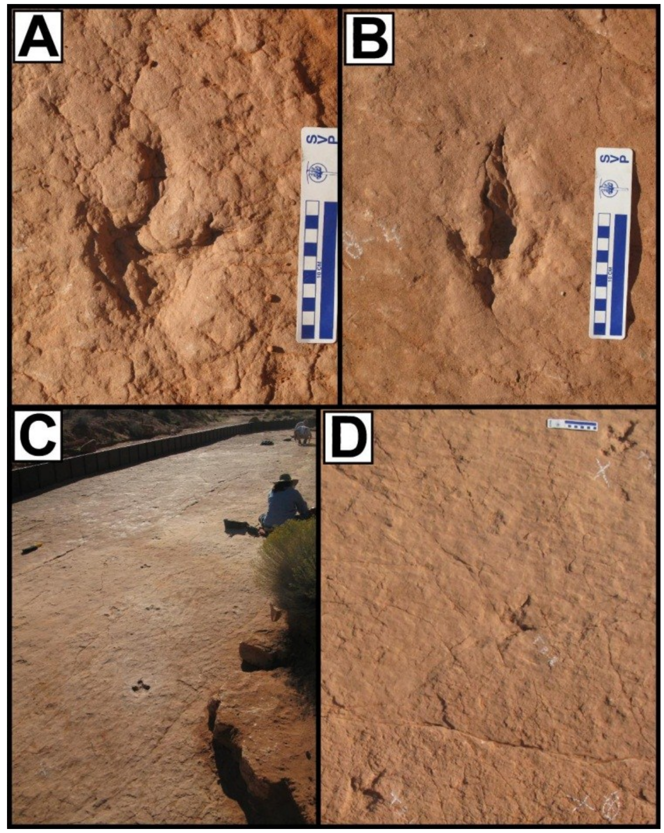


Figure 61. Examples of *Grallator* tracks and trackways from the Warner Valley Dinosaur Tracksite. A, Right *Grallator* footprint from trackway 8. B, Left footprint from trackway 8. C, View of trackway 4, which has 20 footprints. D, Part of trackway 3.

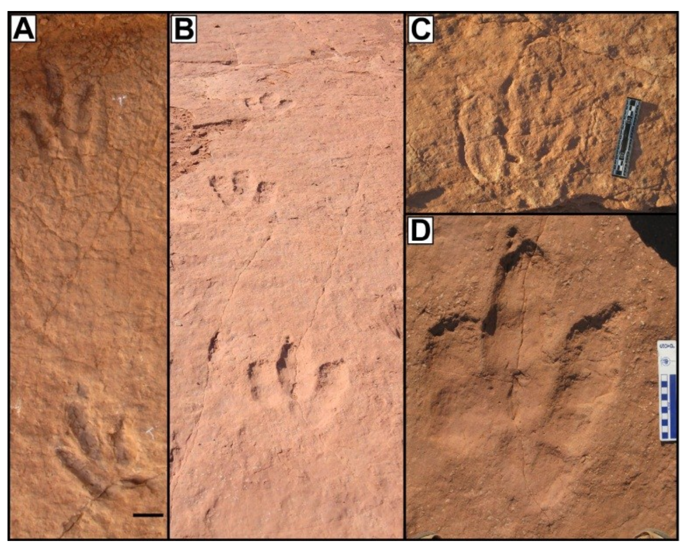


Figure 62. Examples of *Eubrontes* tracks and trackways from the Warner Valley Tracksite. A, Partial, unnumbered trackway. Scale = 10 cm. B, Part of trackway 2. Each step is just over 1 m. C, Right “compression” track 1 in trackway 12. D, Well-preserved, right *Eubrontes* footprint in trackway 2.

from the Kayenta Formation and makes a good model for the *Eubrontes* track maker, though more than one large theropod taxon could have made *Eubrontes* tracks.

A single trackway comprising four tracks on the “main” track surface is assignable to the ornithischian dinosaur ichnotaxon *Anomoepus*, the rarest track type at the site (Fig. 63). This *Anomoepus* trackway intersects with a prominent *Eubrontes* trackway. These tracks differ from the more common *Grallator* tracks by the way the digit III impression angles inward towards the trackway midline and wider divarication angles between digits. The basal ornithischian dinosaur *Scutellosaurus* is known from the Kayenta Formation and is a possible producer of *Anomoepus* tracks.

**STOP 7—CHINLE-MOENAVE CONTACT**

**Discussion Leader: Jim Kirkland**

This is a beautiful exposure of the J-0/Tr-5 unconformity. A chert-anhydrite pebble conglomerate, or pebble lag, occurs at the base of the Moenave Formation across all of southwestern Utah. In most areas, it is only observed by trenching the section as it is generally uncemented (Kirkland and Milner, 2006). At this stop, the conglomerate is well-cemented and thus readily examined (Fig. 64). Dr. Paul Olsen, on a visit to the site in 2007, noted that the large veins of gypsum extending down into the underlying Chinle Formation preserve pebbles within them indicating that these were large

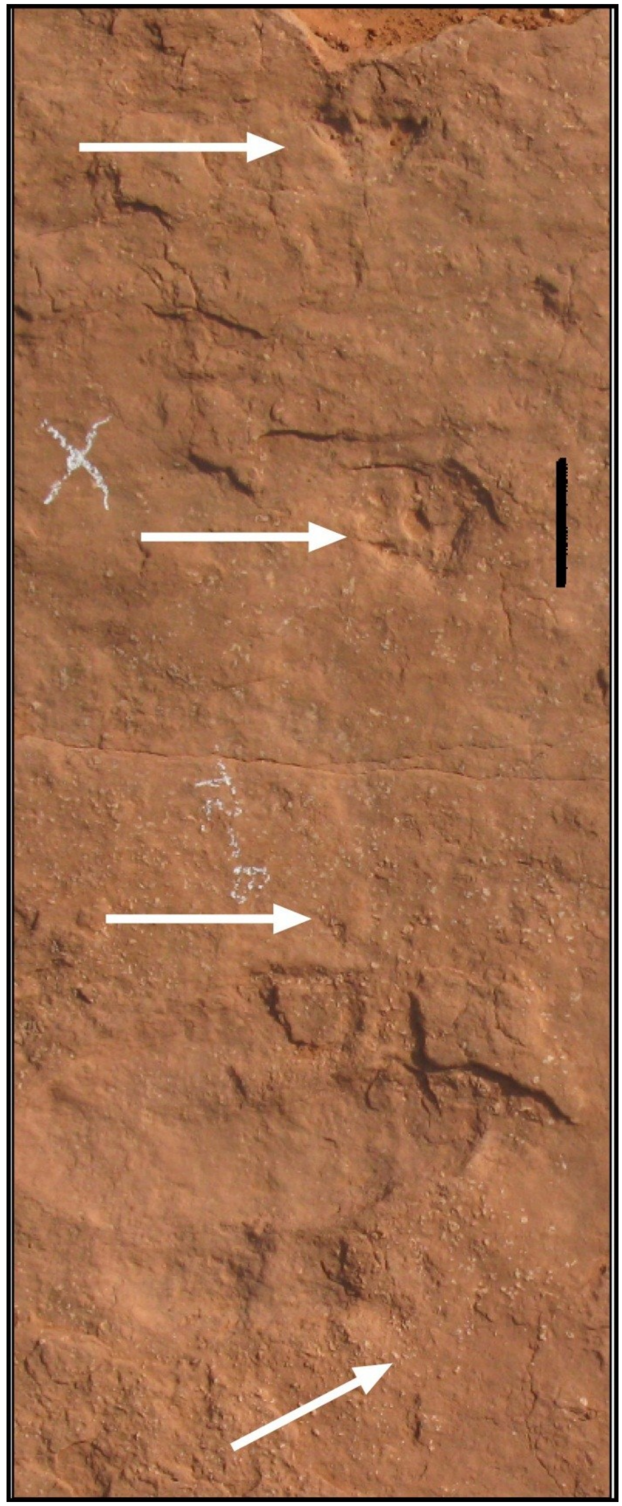

Figure 63. The only identifiable *Anomoepus* trackway (footprints indicated by white arrows) recognized at the Warner Valley Dinosaur Tracksite, which includes four small footprints that toe in. The footprints have wide divarication angles between the digits and shorter digits III than *Grallator*. The first two footprints span a *Eubrontes* footprint in trackway 2. Scale = 10 cm.

fractures into the Chinle prior to renewed deposition following the unconformity.

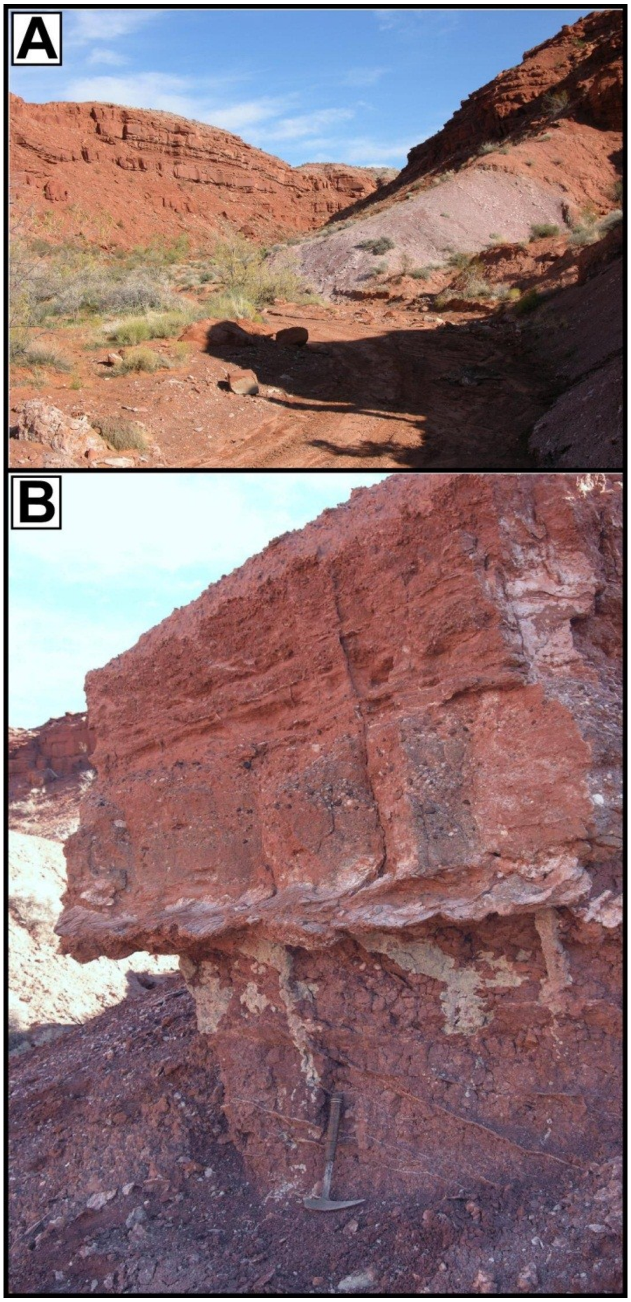


Figure 64. Photos of the Chinle–Moenave contact in Warner Valley. A, Light-colored upper Chinle Formation can be seen below the Dinosaur Canyon Member of the Moenave Formation. B, Close-up of well-cemented chert and anhydrite pebble conglomerate measuring approximately 1 m thick at the Chinle–Moenave unconformity.

The underlying Chinle Formation has abundant zones of anhydrite nodules and secondary veins of gypsum. The recognition of anhydrite pebbles in the conglomerate at this unconformity documents the change from calcretes to gypcretes with increasing aridity in southwestern Utah during the Late Triassic.

## STOP 8—HISTORIC FORT PIERCE

We will have lunch at nearby historic Fort Pierce where you can view the ruins (Fig. 65A) as well as Native American petroglyphs (Fig. 65B), and historic graffiti. All of these archaeological sites are on outcrops of the Shinarump Member of the Chinle Formation.

Old Fort Pierce was built by Mormon Colonists during the Black Hawk War of 1885-1888. This was a conflict between Mormon settlers and Ute and Navajo Indian tribes. This location was selected to block access to springs below.

## STOP 9—OLSEN CANYON TRACKSITE

**Discussion Leader: Andrew Milner**

The Olsen Canyon Tracksite was discovered in 2007 and named for its discoverer Dr. Paul Olsen (Columbia University). The tracksite is situated very low in the Dinosaur Canyon Member of the Moenave Formation. Until recently, the Triassic-Jurassic boundary was hypothesized to lie somewhere within the Dinosaur Canyon Member in southwestern Utah. The discovery at the Olsen Canyon Tracksite of abundant *Batrachopus* footprints along with *Grallator* tracks rather than a typical Late Triassic ichnofauna is intriguing, but a

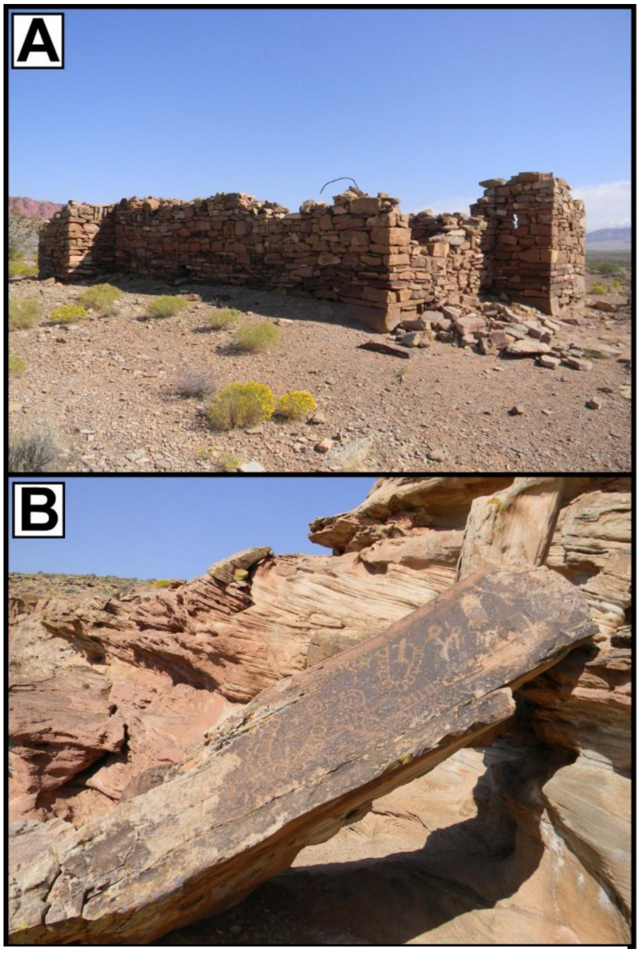


Figure 65. . Fort Pierce archaeological sites. A, Ruins of Fort Pierce. B, Native American petroglyphs on a block next to Fort Pierce ruins.

Triassic age cannot be completely ruled out at this time. The site is located just above the J-0/Tr-5 unconformity between definite Upper Triassic Chinle Formation sediments and the bottom of the Moenave Formation; this unconformity was visited at Stop 7 and can be seen at this site in the wash to the south.

Sedimentary structures such as flute casts, tool marks, current ripples, and fluvial scratch circles have been found mostly in float material, but some have been found *in situ* indicating an average current flow direction of approximately 35°NNW. Very few invertebrate trace fossils have been recognized so far, and those that have been found are tentatively identified as *Planolites*. Locally abundant raindrop impressions and mudcracks are also found at this site.

Most *Batrachopus* pedal footprints are small, ranging in size from 2.0 to 2.5 cm long by 2.0 to 2.5 cm wide. Overprinting of manus tracks is common and few partial trackways have been recognized because most specimens are found in fine sandstone beds that are only 1 to 3 cm thick and fragment easily. *Batrachopus* tracks are found as both natural casts and molds. Some specimens are very well preserved displaying toe pads and claw marks (Fig. 66).

Theropod footprints are less common than *Batrachopus*, although several have been found *in situ* preserved as natural casts (Fig. 67). All theropod tracks so far represent *Grallator*.


Figure 66. Examples of some of the *Batrachopus* tracks from the Olsen Canyon Tracksite. A, Partial *Batrachopus* trackway. B, Set on natural mold *Batrachopus* tracks showing overprinting. C, Natural cast pes print of *Batrachopus* with well-preserved toe pads.

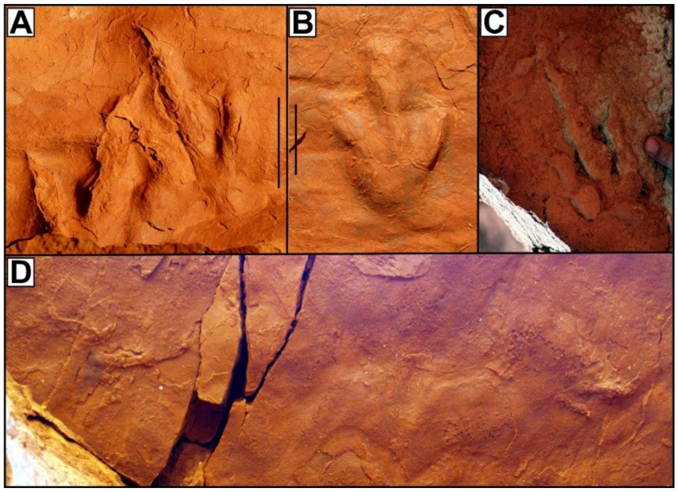


Figure 67. Example of *Grallator* tracks from the Olsen Canyon Tracksite. A, Two overlapping, partial, natural cast tracks. Scale = 5 cm. Photo by Rob Gay. B, Well-preserved natural cast track. Scale = 5 cm. Photo by Rob Gay. C, Well-preserved natural cast *Grallator* track *in situ*. Photo by Dan Whalen. D, *In situ Grallator* trackway on the underside of a ledge. Photo by Rob Gay.

## STOP 10—STRATIGRAPHY AND PALEONTOLOGY OF WARNER VALLEY

**Discussion Leader: Andrew Milner and Jim Kirkland**

Although we have not yet measured a detailed stratigraphic section at this locality, we can give a general overview of Warner Valley stratigraphy.

The stratigraphy of Warner Valley that we will observe on this hike will be from the uppermost part of the Chinle Formation to the base of the “silty facies” of the Kayenta Formation. The opportunity to view, and potentially discover, new paleontological localities on this relatively short hike are very high. Fossil fish localities in the Whitmore Point Member of the Moenave Formation and in thin limestone beds slightly above the Springdale Sandstone Member of the Kayenta Formation will be visited.

As mentioned at Stops 7, the contact between strata previously identified as the Owl Rock Member of the Chinle Formation (Lucas and Tanner 2006) and the basal Dinosaur Canyon Member of the Moenave Formation are mostly covered, although a clear color change from a light purplish gray in the Chinle to a light reddish brown in the Moenave is visible in many areas (Fig. 64A). The upper part of the Chinle Formation in Warner Valley is rich in anhydrite nodules and gypsum veins and unfossiliferous, suggesting very arid conditions. This is in stark contrast to the Petrified Forest Member of the Chinle Formation which at times (e.g. Blue Mesa

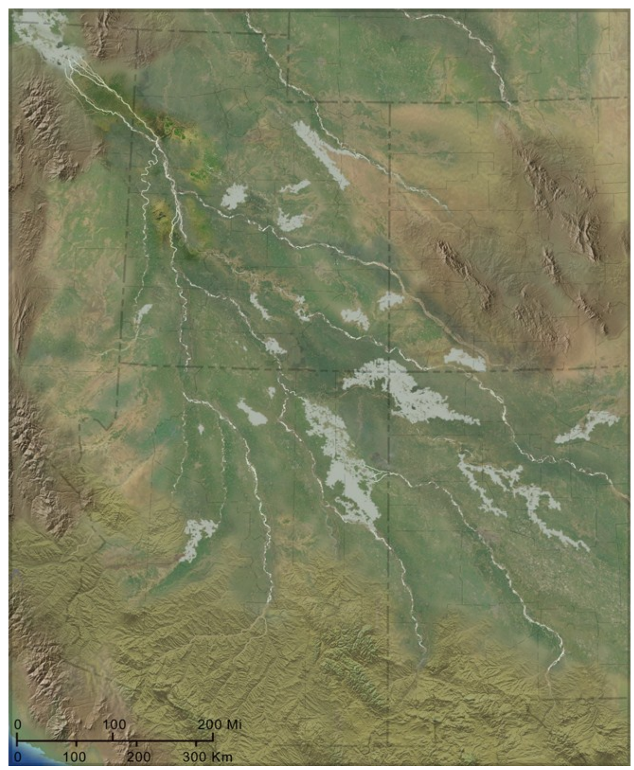


Figure 68. Paleogeographic map of the Late Triassic landscape for the Petrified Forest Member of the Chinle Formation. Map courtesy of Ron Blakey (Blakey and Ranney 2008).

Member) was deposited in a wet, tropical environment (Fig. 68; Blakey and Ranney 2008).

The lower part of the Dinosaur Canyon Member represents floodplain environments that were situated some distance away from major rivers and no fossils other than localized tracksites have been recognized in it so far (Kirkland and Milner 2006). A complex series of cliff- and ledge-formed fluvial channels make up the majority of the Dinosaur Canyon Member (Fig. 64A). As seen on the previous stop, vertebrate tracks of *Grallator* and *Batrachopus* have been found very low in this member, and fossils become more abundant higher in the member. Near the top, *Eubrontes*, *Batrachopus*, *Grallator*, and plant fossils have been found at several sites in Washington County.

As mentioned above, a red chert marker bed at or close to the contact of the Dinosaur Canyon and Whitmore Point members occurs everywhere in the region, although it may fluctuate by a few meters or less lower into the Dinosaur Canyon Member, or slightly higher in the Whitmore Point Member. No fossils have been observed in this marker bed, although vertebrate tracks, fish remains, ostracods, conchostracans, and stromatolites can be found in close proximity in many areas.

In Warner Valley, good exposures of the lacustrine and marginal lacustrine layers of the Whitmore Point Member are often difficult to trace because of the finer shales and mudstones. However, along this hike, a nicely exposed cross-section of the upper Whitmore Point Member situated immediately below the unconformity between the Moenave Formation and the Springdale Sandstone Member of the Kayenta Formation can be seen (Fig. 69). Fish fossils contained in iron concretions are extremely abundant (especially semionotids) in the Whitmore

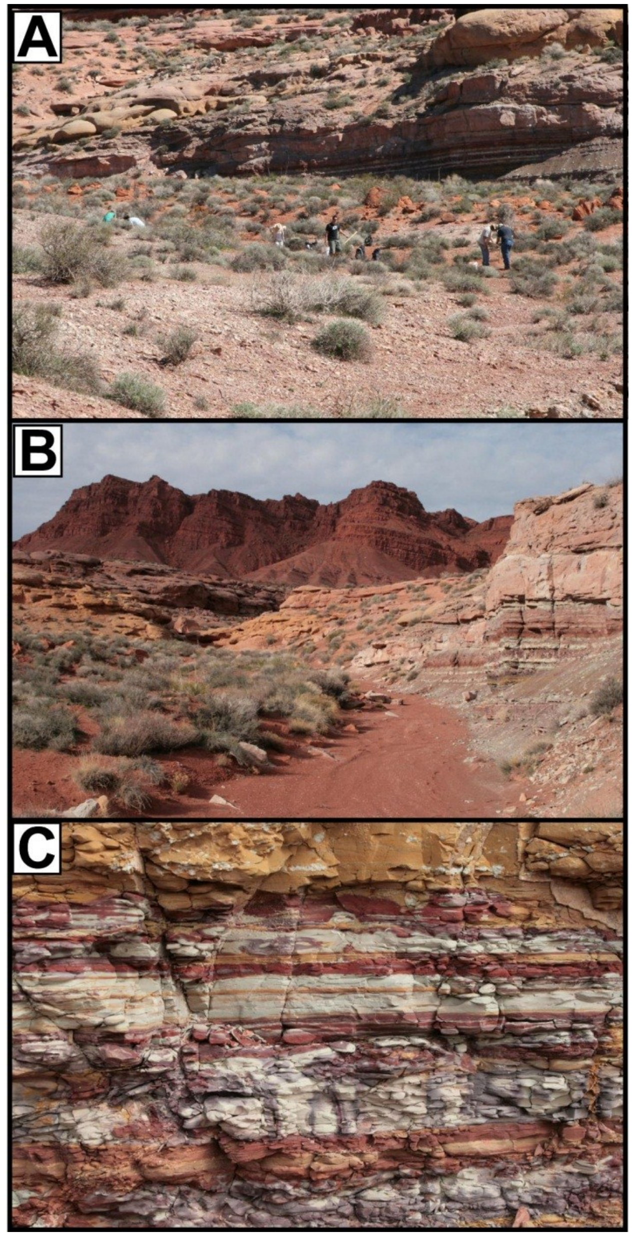

Figure 69. Excellent exposures of the upper Whitmore Point Member of the Moenave Formation at the unconformity and below the Springdale Sandstone Member of the Kayenta Formation. A, Excavation of a coelacanth skull in the upper Whitmore Point Member. B, View of Whitmore Point and Springdale members. C, Close-up of lacustrine beds in upper Whitmore Point Member. Photos by Dan Whalen.

Point Member, along with invertebrate traces, stromatolites, conchostracans, ostracods, and rare dinosaur remains (only theropod teeth have been found in this area to-date).

The lightly colored outcrops of the Springdale Sandstone Member, the lowermost member of the Kayenta Formation, were deposited in large braided river systems mostly flowing from the southeast toward the northwest. For the most part this member is unfossiliferous, although well-preserved trees are more common in the upper 10 meters or so. Rare vertebrate fossils have been found in the uppermost Springdale, generally as water-worn bone fragments in dark brown conglomerate beds that pinch in and out laterally throughout the region. Semionotid fish scales are the only identified vertebrate fossils from this part of the formation so far.

The very top of the Springdale Sandstone Member and lowermost silty facies is considered a megatracksite (see above). Within a meter above the top of the Springdale in the silty facies are thin limestone beds (stromatolitic in places) that do contain locally abundant fish remains. So far in these beds, fragmentary and articulated semionotids have been found, a braincase belonging to a new species of coelacanth (Fig. 70), among other isolated coelacanth bones, and partial palaeoniscoid fishes. We call these limestone layer "Sarah's Fish Beds" because the first fishes were discovered by Sarah Gibson (formerly Spears) while employed with the SGDS. A future quarry site (the "Fossil Chum Site") is located near here.


Figure 70. Partial coelacanth braincase on the right and two pieces of associated skull roof bones on left and center. From the lower silty facies, Kayenta Formation (UMNH VP number pending).

Recently, the first crocodylomorph bones including vertebrae and scutes were discovered in the lower red beds of this area. Dinosaur and other vertebrate tracks are locally common in many of the sandstone and siltstone ledges throughout the silty facies and up into the Kayenta-Navajo transition zone (Fig. 71).

Figure 71. The Kayenta Formation in Warner Valley. The light-colored sandstone ledge in the foreground marks the top of the Springdale Sandstone Member. Above this are the silty facies capped by the steep cliffs of the Kayenta–Navajo transition and lower Navajo Sandstone Formation.

Common, small (10-40 cm in diameter) petrified logs are present, closely associated with track levels at the top of the Springdale Sandstone Member and lowermost silty facies.

The occurrence of large fish in the lower silty facies suggests that the region had reverted to a large lacustrine system like that preserved in the Whitmore Point Member of the Moenave Formation, at least periodically. Blakey and Ranney (2008) have likened the earliest Jurassic on the Colorado Plateau to an inland delta like the modern Okavango Delta in Botswana. We agree with the Okavango model, but would center it on Lake Dixie with the delta being inundated by Lake Dixie with possible increased subsidence of the northern Zuni Sag (Figs. 8, 50B, 52). Following the tectonic and/or depositional hiatus represented by the regional J-0' unconformity represented by the Springdale Sandstone Member, we would extend the Okavango model up into the overlying Kayenta Formation. Following the renewed development of Lake Dixie in the lower silty facies, lacustrine conditions returned. Eventually increased aridity lead to fluctuation of fluvial, saline playa, and eolian environments in the upper Kayenta Formation before it was finally buried by the Navajo erg (Fig. 72; Blakey and Ranney 2008).

This model also explains the distribution of vertebrate fossil remains in the Kayenta Formation. The fluvial and floodplain environments dominating the Kayenta Formation on Ward Terrace has yielded a high diversity of Early Jurassic primitive mammals, dinosaurs, and other reptiles, but very few fish (Clark and Fastovsky 1986; Sues et al. 1994; Lucas et al. 2005a) (Fig. 73). Further to the north along the Zuni Sag, the lacustrine paleoenvironments dominated in the lower silty facies of the Kayenta Formation, and has yielded large fish and few dinosaurs, whereas up-section in the saline playas and eolian units, few body fossils of any kind are encountered.

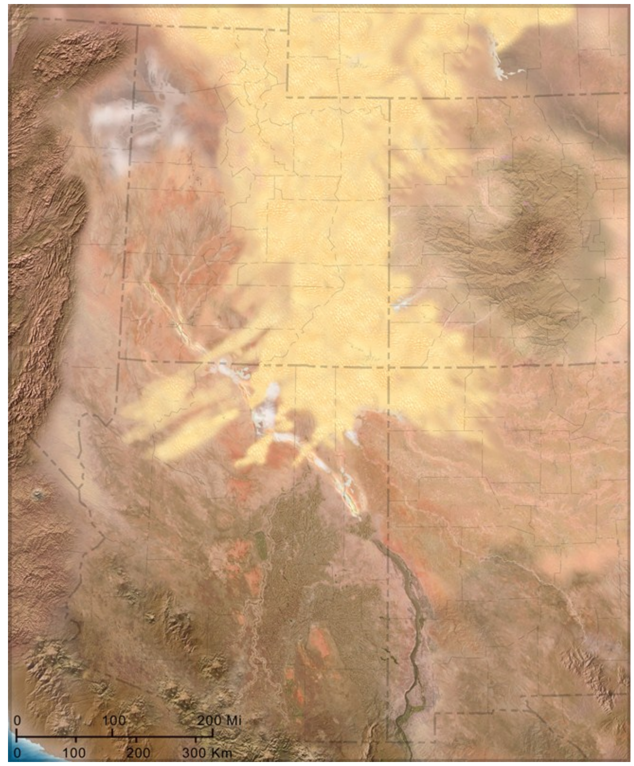

Figure 72. Paleogeographic map showing the American Southwest during the time of the Kayenta–Navajo transition. Map courtesy of Ron Blakey (Blakey and Ranney 2008).

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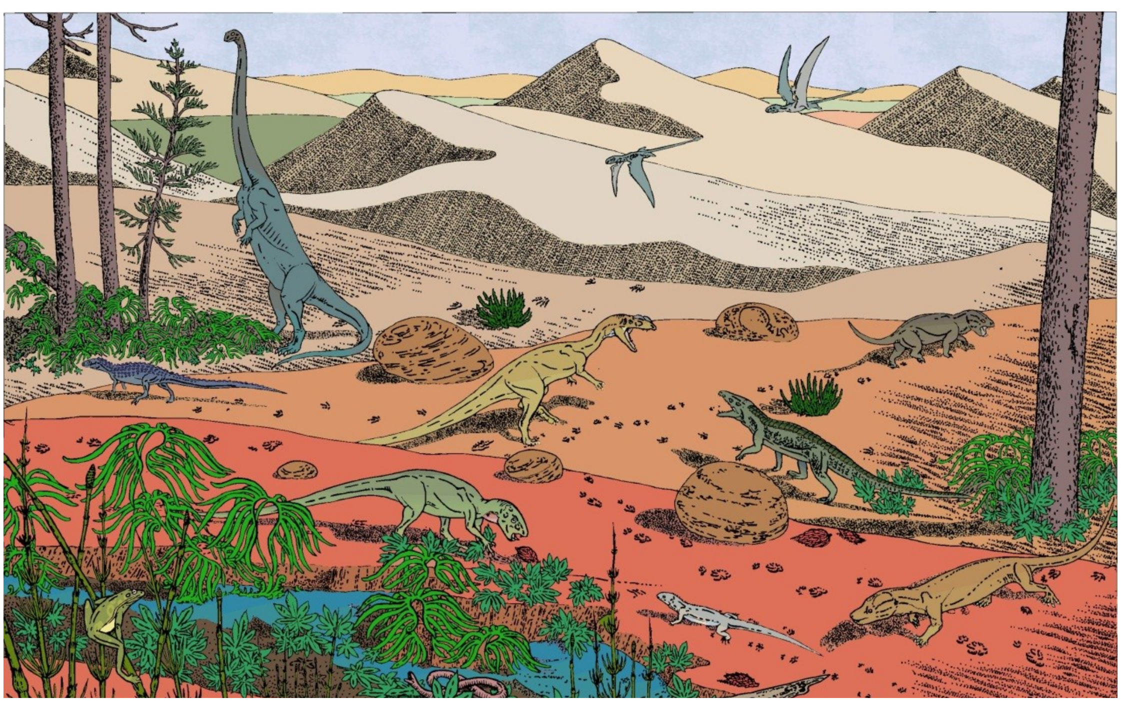

Figure 73. Reconstruction of life during late Kayenta time with the encroaching Navajo erg. Courtesy of Russell Hawley.

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