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RISE OF THE ERG—PALEONTOLOGY AND PALEOENVIRONMENTS OF THE TRIASSIC-JURASSIC TRANSITION IN NORTHEASTERN UTAH

Brooks B. Britt, Daniel J. Chure, George F. Engelmann, and Jesse Dean Shumway

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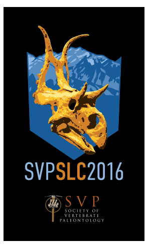

Cover

Three articulated sphenosuchians from the Saints & Sinners Quarry, which is Stop 5 of this field trip. The voids of various colors are weathered concretion sites.

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Rise of the Erg—Paleontology and Paleoenvironments of the Triassic-Jurassic Transition in Northeastern Utah

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ABSTRACT

This field trip focuses on the Late Triassic-Early Jurassic transition in northeastern Utah. This transition records one of the most striking terrestrial environmental transformations in the history of North America, wherein the fluvio-lacustrine Chinle Formation is transgressed by the vast erg system of the Nugget (Wingate+Navajo)/Navajo/Aztec Sandstones. Exposures in northeastern Utah are ideal for studying this transition as they are closely spaced and accessible. The uppermost Chinle Formation beds are lacustrine/fluvial fine-grained sediments which are overlain by increasingly drier, sandy, transitional beds. The non-eolian basal beds of the Nugget Sandstone preserve a Late Triassic ichnofauna, with some sites including *Brachychirotherium* tracks. Large-scale dune deposits comprise most of the Nugget Sandstone and contain vertebrate (*Brasilichnium*) tracks and a diverse invertebrate ichnofauna. Interdunal, carbonate, spring mounds, as much as 3 m tall, fed carbonate freshwater lake deposits containing gastropod body fossils and invertebrate ichnofossils.

Another lacustrine deposit, located at the Saints & Sinners Quarry, is on the shoreline of a non-carbonate interdunal lake/oasis. Over 11,500 bones have been collected from the site and represent two theropod dinosaur taxa, sphenodonts, sphenosuchians, a pterosaur, and drepanosaurs (with many complete, three-dimensional, articulated skeletons). In addition to bones, dinosaur trackways are also preserved in shoreline and other interdunal beds. The fauna shows that this interdunal area of the Nugget Sandstone was the site of intense biological activity. The drepanosaurs are chronologically significant in that they are restricted globally to the Late Triassic, indicating that at least the lower one-fourth to one-third of the formation is Late Triassic in age.

INTRODUCTION

The Chinle-Nugget formational transition records one of the most dramatic continental environmental changes in the Phanerozoic of North America, where a fluvial and lacustrine environment is gradually replaced by an eolian-dominated environment represented by a vast erg that covered much of the western U.S. for mil-

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lions of years (Blakey and Ranney, 2008).

These formations along the south flank of the Uinta Mountains have received less attention than equivalent exposures farther south on the Colorado Plateau. Over the last decade, however, intensive work in the Chinle Formation by Randall Irmis (Utah Museum of Natural History), and at the Nugget Sandstone area of Dinosaur National Monument (DINO) by Dan Chure (National Park Service), George Engelmann (University of Nebraska), and Brooks Britt (Brigham Young University) has shed new light on the Chinle-Nugget transition (Irmis and others, 2015) and the paleontology and paleoenvironments of the Nugget Sandstone (Chure and others, 2014a and 2014b).

This field trip focuses on recent paleontological discoveries in the Nugget Sandstone that provide insights into the rise of the erg, its biota, and paleoenvironments. We have selected sites for their significance and to minimize travel time so that more time can be spent on the outcrop and less time driving between stops.

Several different names and ranks, as summarized by Irmis and others (2015), have been applied to the stratigraphic unit referred to here as the Nugget Sandstone. Recently, this issue was addressed by Sprinkel and others (2011) and Irmis and others (2015), and both studies recommend the use of the Nugget Sandstone. The Nugget Sandstone correlates with the Glen Canyon Group, the Wingate/Moenave, Kayenta, and Navajo strata (see references in Doelger, 1987, and analyses in Sprinkel and others, 2011). Sprinkel and others (2011) propose using the term Nugget Sandstone in areas where the Kayenta Formation, a fluvial unit present between the Wingate and Navajo Sandstones farther south, is absent.

The Nugget Sandstone spans the Triassic-Jurassic boundary, but the position of this boundary is uncertain (see references and discussions in Sprinkel and others, 2011; Irmis and others, 2015). With a dearth of body fossils and the absence of volcanic units, including ash, that could be radiometrically dated, there are no calibrated ages for the Nugget. Consequently, dating is limited to stratigraphic bracketing and correlation using vertebrate trace fossils. The Nugget Sandstone rests conformably on the Late Triassic Chinle Formation (Irmis and others, 2015) whereas the marine Middle Jurassic Carmel Formation rests unconformably on top of the Nugget Sandstone. In the absence of age-specific invertebrate fossils, dating of the Nugget is based on vertebrate tracks, with a *Brachychirotherium* suite in the lower portions of the formation indicating a Late Triassic age (Lockley and others, 1992) and the Early Jurassic *Grallator*, *Otozoum*, *Eubrontes* assemblage near the top (Lockley and others, 1992; Lockley, 2011). These traces, however, do not help resolve the position of the Triassic-Jurassic boundary within the formation. The Saints & Sinners Quarry fauna sheds additional light on these issues by corroborating the ichnofossil-derived Early Triassic age for the lower portion of the formation with body fossils because the quarry contains a drepanosaur and a sphenosuchian with a rod-like posterior expansion of the coracoid. Drepanosaurs are known only from the Carnian to Norian (Renesto and Binelli, 2006; Renesto and others, 2010) and sphenosuchians with such expansions are known only from the Late Triassic (James Clark, George Washington University, personal communication, 2016). The Saints & Sinners Quarry horizon is 55 m above the base of the lowest contiguous eolian sandstone of the formation (figure 1A), indicating that at least the lower 25% of the formation locally is no younger than Late Triassic in age. It should be noted that Molina-Garza and others (2003) conducted a paleomagnetic study of the underlying Chinle Formation in our study area and concluded that the Gartra Member at the base of the Chinle was approximately 207–205 Ma (Rhaetian)—ages that are younger than indicated by vertebrate fossils from the lower one quarter of the Nugget Sandstone.

Recent summaries of studies of the Chinle Formation in, and adjacent to DINO can be found in Ericksson (2007) and Irmis and others (2015). In the study area, the Nugget Sandstone has received less attention than the Chinle Formation. Much of the work on the Nugget in this area has focused on nomenclature and correlation (Peterson, 1988, 1994; Sprinkel and others, 2011). Previously, little detailed work had been done on the paleontology and paleoenvironments throughout the Nugget, in part because it consists predominantly of eolian dunes, with a sparse fossil record composed primarily of dinosaur track sites (e.g., Lockley and others, 1992; Lockley and Hunt, 1995; Lockley, 2011). In 2006,

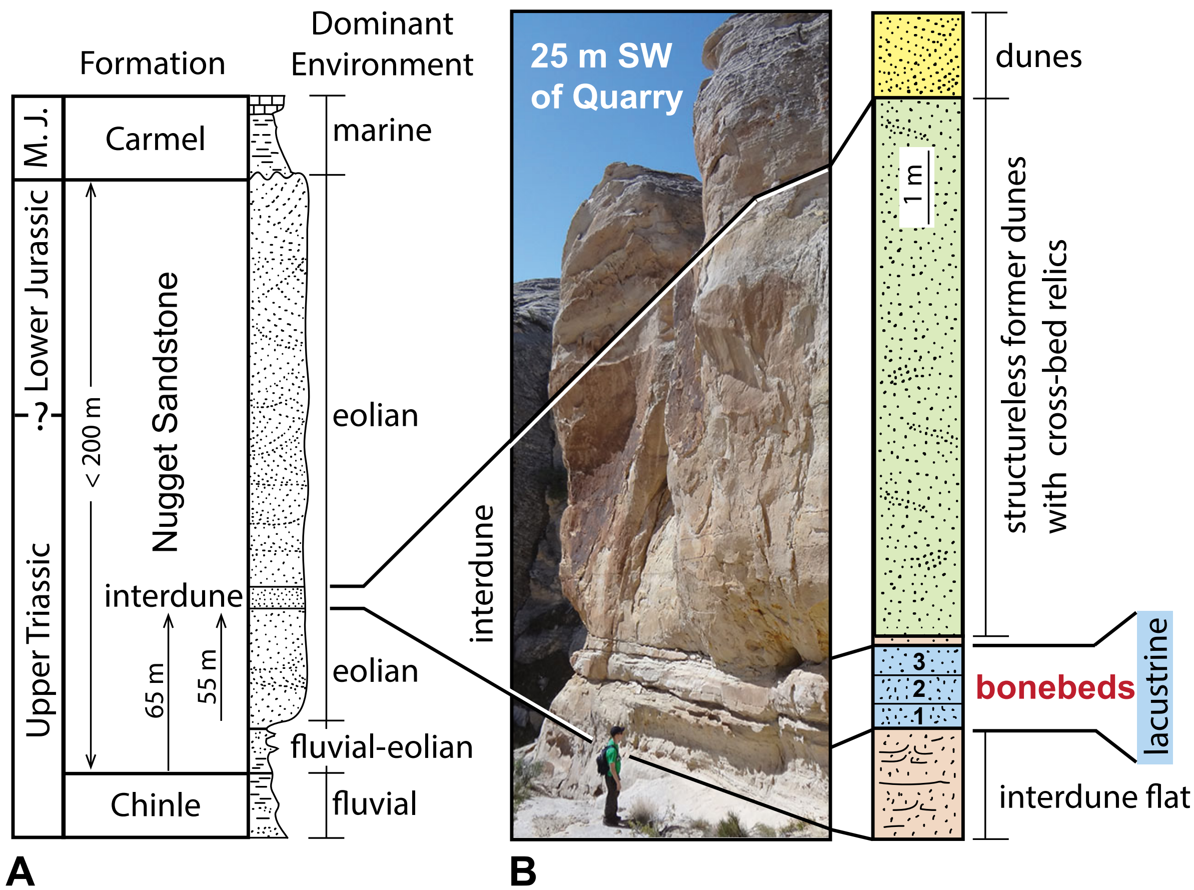

Figure 1. Nugget Sandstone stratigraphy and depositional environments in the vicinity of Saints & Sinners Quarry. (A) Section from the upper Chinle through the Carmel Formations showing the stratigraphic position of the interdune complex within the Nugget Sandstone and depositional environments. (B) Strata within the interdunal portion of the Nugget Sandstone. The lacustrine units, which contain the three bonebed layers of the quarry are located near the bottom of the interdune unit (see figure 18A).

Chure and Engelmann began a systematic inventory of the paleontology and paleoenvironments of the Nugget Sandstone in DINO. This intensive study was designed to provide basic information that could be used to establish baselines for resource protection, management, and research activities in the Monument (Chure and others, 2014a). This study yielded an unexpectedly rich fossil and paleoenvironmental record, including the discovery of the Saints & Sinners lagerstatten, providing an unprecedented view into the erg's biota.

Study Areas

There are two major study areas for the Chinle and Nugget Formations reported in the present work (figure 2). The first is in the western end of DINO around the nose of the Split Mountain anticline and adjacent lands managed by the Bureau of Land Management. The second is around Steinaker Reservoir north of Vernal, Utah, about 28 km northwest of the Quarry Visitor Center in DINO.

Localities

To protect the resources visited in the course of this field trip, we will not provide exact locality data for the sites in this publication, with the exception of field trip Stop 1 (the Cub Creek Petroglyph site) which is a designated stop (no. 14) on DINO's "Guide to the Tilted Rocks." This visitor stop is for viewing Fremont culture petroglyphs which feature a large lizard and Kokopelli (figure 3A), along with less defined rock art.

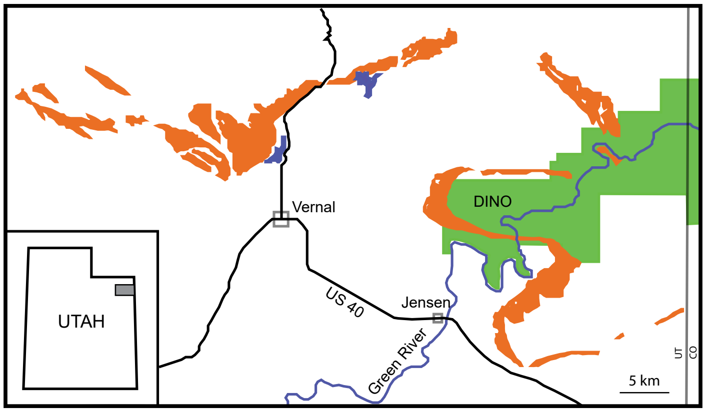

Figure 2. Nugget Sandstone exposures in the vicinity of Dinosaur National Monument. Mapped area indicated by the shaded area in the inset map of the state of Utah. Orange = Nugget Sandstone exposures. Green = Utah portion of Dinosaur National Monument. Modified from Irmis and others (2015).

Safety Issues

The stops on this trip are fairly safe to visit. Those acclimated to lower elevations may find hiking difficult and breathing labored due to the relatively high elevation (~1.5 km/5000 ft). Temperatures in late October are comfortable, and heat should not be a problem. Characteristics of the stops are described briefly below.

Stop 1. Cub Creek Petroglyphs: Elevation gain of ~50 m over 0.2 km (one way) hike, following, from road to exposure, the established trail at stop 14 of the Tour of the Tilted Rocks route in DINO. The steepest parts of the trail have rock steps.

Stop 2. Cub Creek Chirothere Site: Negligible elevation change. 0.7 km hike (one way) following a drainage floor.

Stop 3. Josie's Cabin: lunch stop.

Stop 4. Big Mounds: Negligible elevation change. Hike approximately 0.7 km one-way across several drainages. Some mounds are near the sloping rim of a deep canyon and caution should be exercised.

Stop 5. Saints & Sinners Quarry: Short easy hike with approximately 30 m of elevation loss from parking stop to quarry. The quarry is situated at the edge of a canyon and some drops are quite long. Observe caution and do not go to the edge of quarry as the sandstone is often slippery due to loose sand grains and especially lichens that are extremely slick when wet.

Stop 6. The Museum of Paleontology at Brigham Young University (BYU), Provo, Utah.

STOP 1. CUB CREEK PETROGLYPH SITE: THE CHINLE FORMATION – NUGGET SANDSTONE TRANSITION

Stop 1 (figure 3) offers a close look at the base of the Nugget Sandstone, the contact with the underlying Chinle Formation, and transitional environments that here form the lower few meters of the Nugget. The Chinle is characterized by mudstone, siltstone, and sandstone deposited in fluvial-lacustrine environments (e.g., Irmis and others, 2015). Elsewhere in the western U.S., the Chinle is often fossiliferous, but body fossils are rare in northeastern Utah and most are fragmentary (Irmis and others, 2015). The overlying Nugget is dominated by approximately 200 m of eolian sandstone but includes an interval of a few meters of non-eolian sandstone and mudstone, and occasional, small eolian dunes at its base (figure 1). The thickness and lithologic characteristics of this interval vary from one location to another, even within the study area, so no single site can be considered as typical (Irmis and others, 2015). At the Cub Creek petroglyph site these non-eolian beds are visible and easily accessible.

The petroglyphs (figure 3A) were pecked into desert varnish on sandstone cliff faces low in the eolian portion of the Nugget Sandstone. Following the trail northward along the base of the cliff leads to the fluvial unit of the basal Nugget, which consists of alternating tan sandstone and brown-red mudstone beds (figure 3B and C).

The slope at this locality is the purple interval at the top of the Chinle Formation (figure 3C, bottom right), which here is largely covered by colluvium. The uppermost Chinle is marked by an informally named "purple interval" that includes a distinctive, striped sandstone and grayish-red siltstone/mudstone layers that are ex-

Figure 3. Nugget Sandstone exposures at Stop 1, Cub Creek petroglyph site. (A) Petroglyphs chipped into desert varnish on the Nugget Sandstone cliff face. (B) Exposures as seen from the road at the petroglyph site. The lower slope is the upper Chinle Formation. The cliff is the lower part of the Nugget Sandstone. (C) Cliff base. This is the location of a measured section described in detail in Irmis and others (2015). The white dashed line marks the boundary between the Chinle and Nugget Formations as interpreted by Irmis and others (2015).

posed at its top at Stop 1; Irmis and others (2015) place the boundary between the Chinle and Nugget at the top of these beds (figure 3B and C), just above the colluvium. The formation boundary is at the base of a channel sandstone that overlies the grayish-red mudstone, just above Irmis and others' (2015) "red stripe sandstone" (figures 3C and 4). Branching, horizontally oriented, hemicylindrical features (downward-protruding ridges approximately 10 cm wide) stand out on the sole of the sandstone. These may be burrows or large, rounded, desiccation cracks. Close inspection of the sole of the sandstone, especially of the branching features, reveals many cylindrical burrows 5 to 8 mm in diameter that groove, or penetrate the surface (figure 5). These small traces can also be seen penetrating the sandstone in cross section. This lowest sandstone in the Nugget Sandstone varies in thickness over the extent of its outcrop at Stop 1, from as much as 0.5 m to as little as 10 cm. A thin to almost absent mudstone separates the basal sandstone from a thicker sandstone above. The mudstone has well-developed mudcracks, and the overlying sandstone contains rip-up clasts of this mudstone.

Above the mudstone in the Nugget is an interval of fluvial sandstones and red mudstones/siltstones approximately 2 m thick. At the southern end of the outcrop, this interval consists of massive to cross-bedded sandstone beds 0.5 m or less in thickness, alternating with red, laminated mudstones and siltstones. Tracing

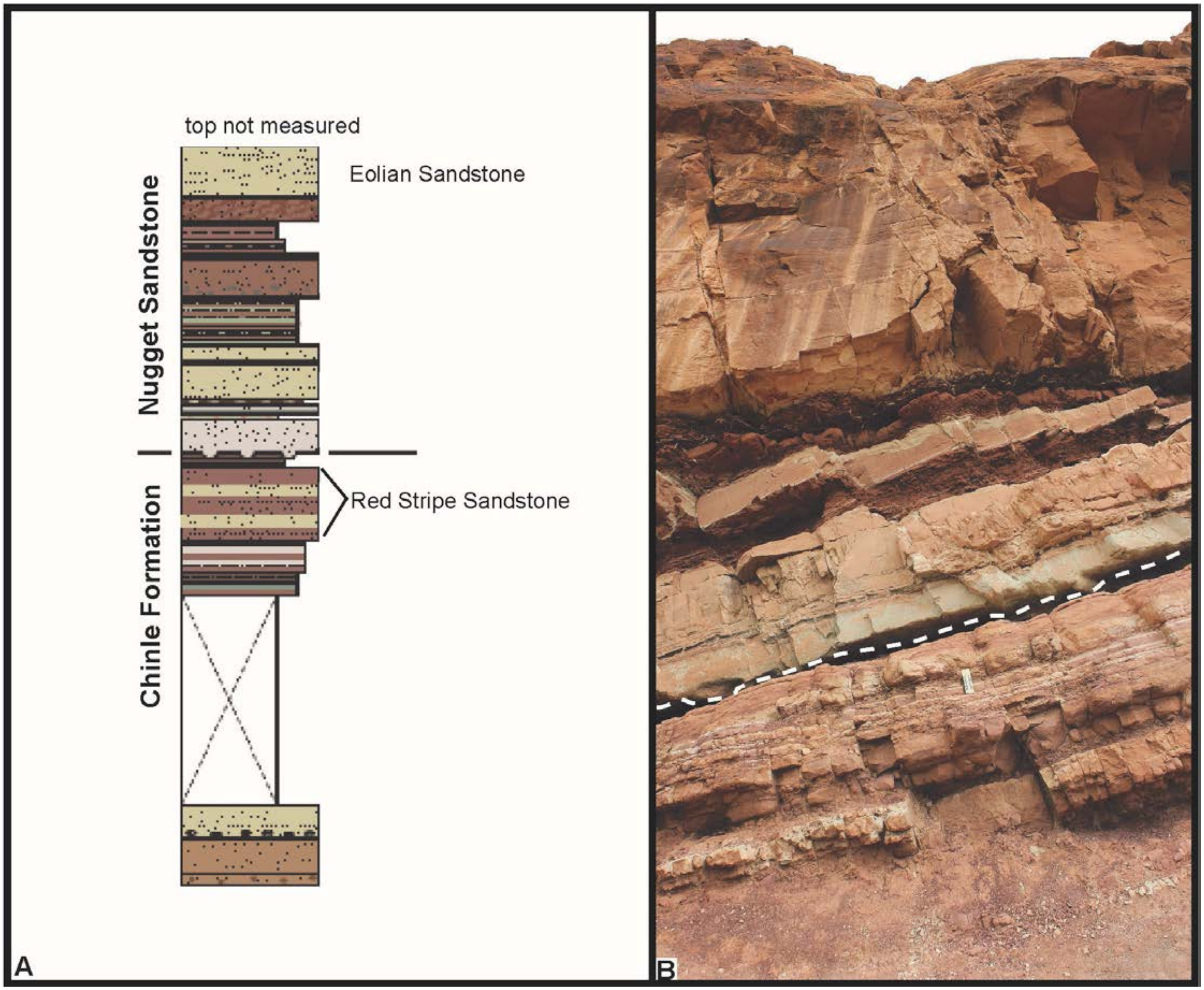

Figure 4. Full section at Stop 1, Cub Creek petroglyph site. (A) Measured section including the top of the Chinle Formation and the base of the Nugget Sandstone (modified from Irmis and others, 2015). (B) Exposure where the section in (A) was measured. The white dashed line marks the formation boundary. The scale is 18 cm long.

this interval along the outcrop to the north, the sandstones and mudstones of the upper part thin and pinch out, whereas the basal sandstone of the interval thickens. At the northernmost end of the outcrop, this interval consists almost entirely of sandstone with only thin partings of mudstone.

Above the fluvial interval just described, the cliff continues upward as uninterrupted sandstone. The lower 1 to 2 m thick interval of the sandstone is fluvial, as indicated by small, low-angle cross-beds. This interval is overlain by the large-scale, high angle cross-beds of eolian sandstone that are typical of most of the overlying portions of the Nugget Sandstone. The contact between these two facies is not pronounced, although the lowest 1 to 2 m of the eolian sandstone is marked by soft-sediment-deformation features. Based on sorting and grain size, it is likely that the fluvial sandstone beds were reworked from eolian dunes.

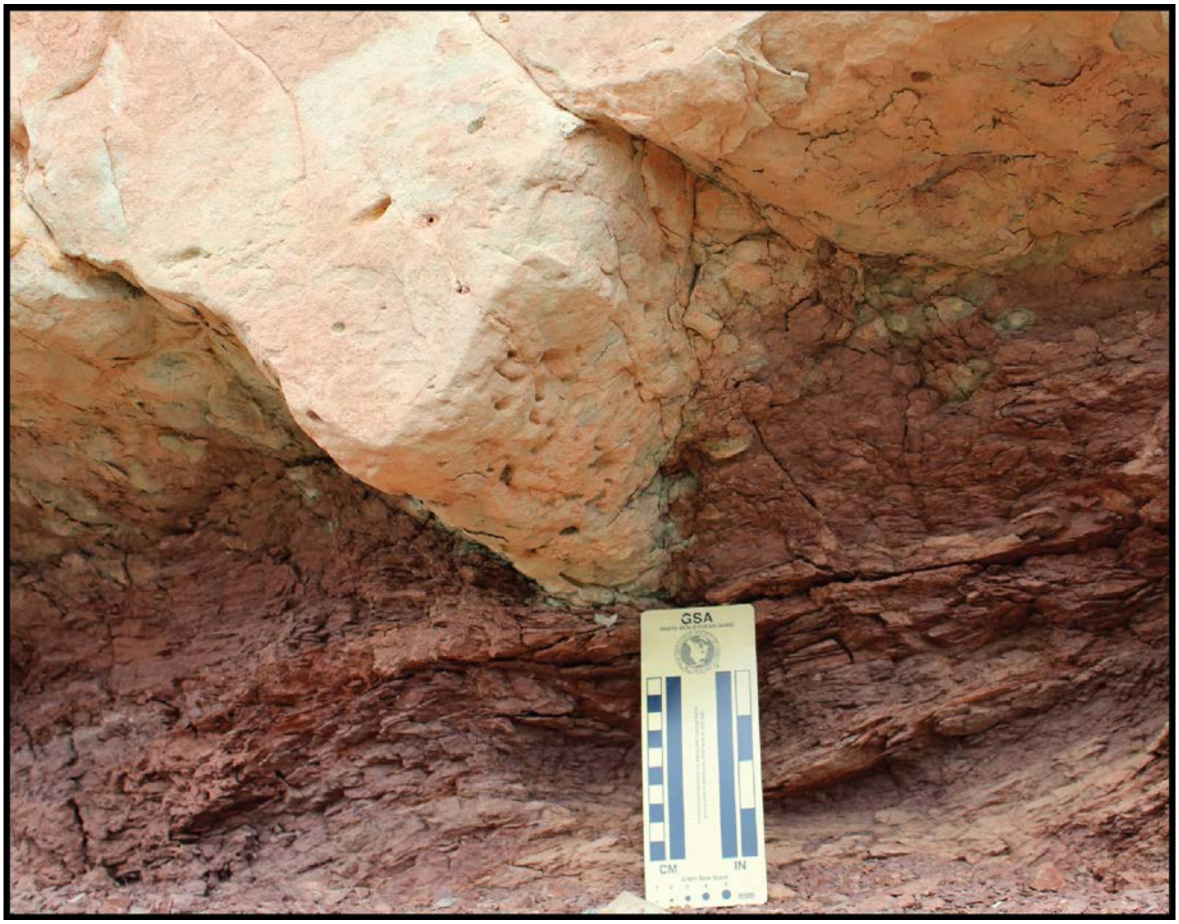

Figure 5. Partially bioturbated, large-scale desiccation crack, or possible burrow, at the base of the Nugget Sandstone, extending into the underlying mudstone. The feature contains numerous small burrow traces in various orientations. Small divisions on left side of the scale equal 1 cm.

Nowhere in the Chinle-Nugget section exposed at Stop 1, or elsewhere in the study area, is there evidence for an unconformity (Irmis and others, 2015). The transition from the fluvial-lacustrine environments of the Chinle to the dominantly eolian environments of the Nugget is gradual. In accord with Walther's Law, stacked, conformable facies were also coeval within the depositional basin. Thus, the purple interval of the top of the Chinle Formation, the interbedded sandstones and mudstones of the basal Nugget Sandstone, and the eolianites of the balance of the formation represent different depositional facies that were laterally adjacent and graded into one another on a regional scale. The relatively wetter fluvial-lacustrine facies of the Chinle Formation graded laterally into the semi-arid fluvial system with intermittent, small dunes (not preserved at this stop) of the basal Nugget Sandstone which in turn graded downslope into the dune fields of the Nugget (May, 2014).

STOP 2. CUB CREEK CHIROTHERE SITE: NON-EOLIAN ENVIRONMENTS IN THE BASAL NUGGET SANDSTONE

Although generally thought of as an eolian unit, the basal part of the Nugget Sandstone was deposited primarily in fluvial environments (Sprinkel and others, 2011; May, 2014; Irmis and others, 2015). We have not measured a section at Stop 2, but here the fluvial base of the Nugget is approximately 10 m thick (figure 6), consisting of fine- to medium-grained, moderately well-sorted sandstone with small-scale cross-beds (figure 7). Elsewhere, this same interval includes small eo-

Figure 6. Horizontally bedded, non-eolian basal beds of the Nugget Sandstone at Stop 2. The overlying cliff faces are composed of thick, large-scale cross-bedded eolianites.

lian dunes (May, 2014).

At Cub Creek, vertebrate tracks occur on two bedding planes separated vertically by about 10 cm (Anderson and others, 2011; Anderson, 2013). The tracks occur over a total of 123 m^2 of exposed bedding surface, with track density as high as 4.4 tracks/m^2. Tracks occur as manus-pes pairs (hand-foot), but because of the density of the tracks and their poor preservation, few trackways can be identified. Most or all tracks are undertracks, often poorly preserved with little morphological detail. Pes impressions are longer (as much as 30 cm) than wide and manus impressions wider than long (figure 8). Asymmetrical push-up rims are rare.

Only one type of track is present at Stop 2, and poor preservation of the tracks makes assignment to an ichnotaxon problematic. The fact that all tracks are manus-pes pairs indicates that the track-maker was a likely obligate quadruped. Lockley and Hunt (1995) identified well-preserved *Brachychirotherium* isp. from the base of the Nugget at the nearby Bourdette Draw tracksite (figure 9). This occurrence is significant because *Brachychirotherium* is regarded as diagnostic of Triassic age (Lucas and others, 2006). The pedal claw impressions in the tracks at Stop 2 show five digits of unequal length (figure 10). This is unlike the tridactyl pedal impressions of ornithopods and theropods. These cannot be prosauropod pedal impressions, which consist of four, elongate digits as opposed to five (Lockley and other, 1992). We feel confident that the Stop 2 tracks are chirothere tracks, but a more specific ichnotaxon assignment is not warranted. In addition to Stop 2, there are two other chirothere sites within the monument with similarly

Figure 7. Small-scale cross-beds in the basal non-eolian section of the Nugget Sandstone. Scale bar in cm.

preserved tracks. Both sites are within the fluvial beds in the lower, non-eolian portions of the Nugget Sandstone.

STOP 3: LUNCH AT HISTORIC JOSIE MORRIS SETTLER CABIN, DINOSAUR NATIONAL MONUMENT

Josie Morris was born in the latter part of the 19th century and raised in remote Browns Park, Utah, north of present-day DINO. This rugged upbringing gave her a strong sense of independence and resourcefulness. In 1913, Josie decided to homestead in the Cub Creek area where she built her own cabin and lived until she died of complications from a broken hip in 1963. She married five husbands and divorced four. She was a colorful character, a friend of outlaws such as Butch Cassidy, and was tried and acquitted for cattle rustling when she was in her 60s (McClure, 1985). We will lunch at Josie's homestead, which includes her cabin, chicken coop, cattle pond, fences, orchards, and shade trees. Her cabin is open to the public, so wander in and step back for a few moments into the life of a pioneer and colorful character.

STOP 4. LARGE CARBONATE MOUNDS: INTERDUNAL LAKES OF THE ERG SYSTEM

Stop 4 shows some of the features of the interdunal carbonates that occur within the Nugget Sandstone in the study area.

Nugget Carbonate Beds

Carbonate beds make up part of interdunal facies at

Figure 8. (A) Overview of chirothere trackway site at Stop 2. (B) Chirothere manus-pes pair showing proportions of impressions. Scale bar in cm.

three different areas (figure 11) in the overall study area. These carbonate localities include exposures at Stop 4, as well as other nearby outcrops (figure 11, Area 1), a larger occurrence consisting of a layer along the rim of a mesa west of Steinaker Reservoir north of Vernal (figure 11, Area 2), and exposures in a Nugget Sandstone hogback on the south flank of the Blue Mountain anticline cut by Cocklebur Draw (figure 11, Area 3).

All the carbonate beds in the study area are of limited lateral extent (<0.5 km along strike). Some of the beds include mound structures. All are dolomitic and incorporate sand-sized quartz grains. There are calcite infills within post-lithification fractures and cavities.

Carbonate layers are exposed south of Cub Creek (figure 11, Area 1), along the rims and walls of canyons cut by a small drainage that flows into the Green River near where the Cub Creek Road (State Route 149) crosses the drainage. The carbonate layers are exposed along the rim on the north and south sides of the main, west-draining canyon, in the east and west walls of the westernmost tributary canyon that drains northward into the main canyon, and high on the divide between the tributary canyon just mentioned and the next canyon to the east. The carbonate beds are not vertically stacked, that is, we have not observed carbonates repeated through a significant vertical thickness of section.

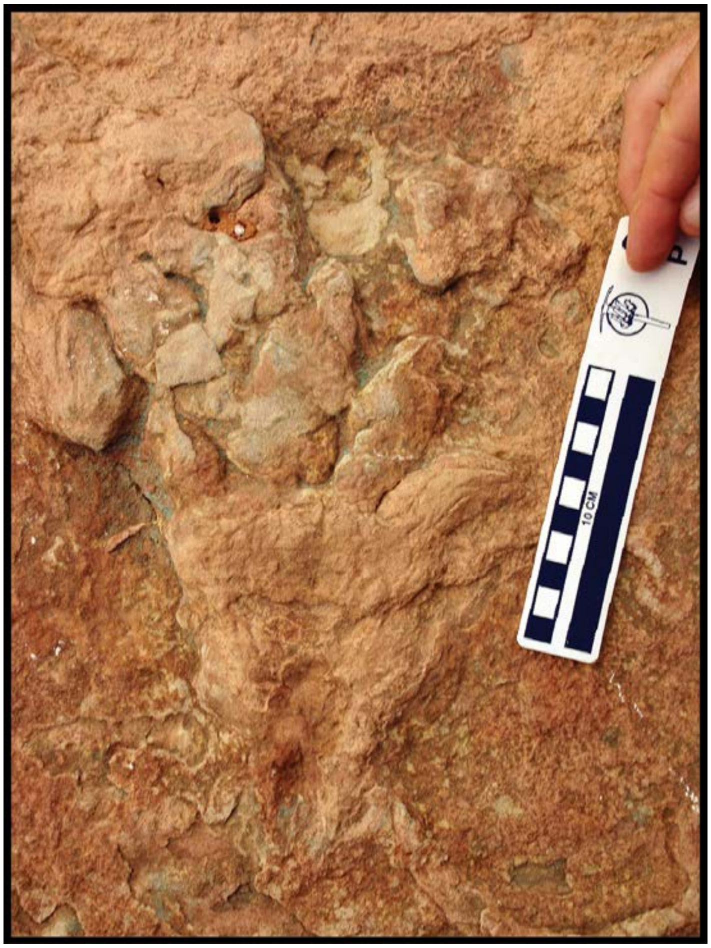

Figure 9. *Brachychirotherium* pes print from basal beds of Nugget Sandstone in Bourdette Draw. Scale bar in cm.

The single exception consists of two carbonate horizons separated by < 2 m of sandstone. In the absence of horizontal marker beds and the laterally discontinuous nature of interdune horizons in the Nugget Sandstone, we cannot tell whether carbonates occur within a preferential horizon within the Nugget or are distributed through a greater portion of the section. This is true between and even within the carbonate exposure areas noted above.

Carbonate beds exposed in the canyons south of Cub Creek occur as horizontal layers and as several mound structures. The carbonate layers vary in thickness from 10 to almost 100 cm. Beds within the carbonate horizons range in thickness from 1 to 10 cm and are usually massive, but some contain fine, wavy laminae. At Stop 4, the carbonate mounds occur on both the north and south rims of the main canyon directly opposite each other.

Large Mounds

Carbonate beds are exposed along the north rim of the main canyon. The most prominent features of these carbonate units are mound structures, which are preserved and dissected to varying degrees (figure 12). There are at least five mounds. These mounds are relatively large, the largest being at least 10 m across

Figure 10. Deep chirothere pes impression at Stop 2 showing differing lengths of toes. Scale bar in cm.

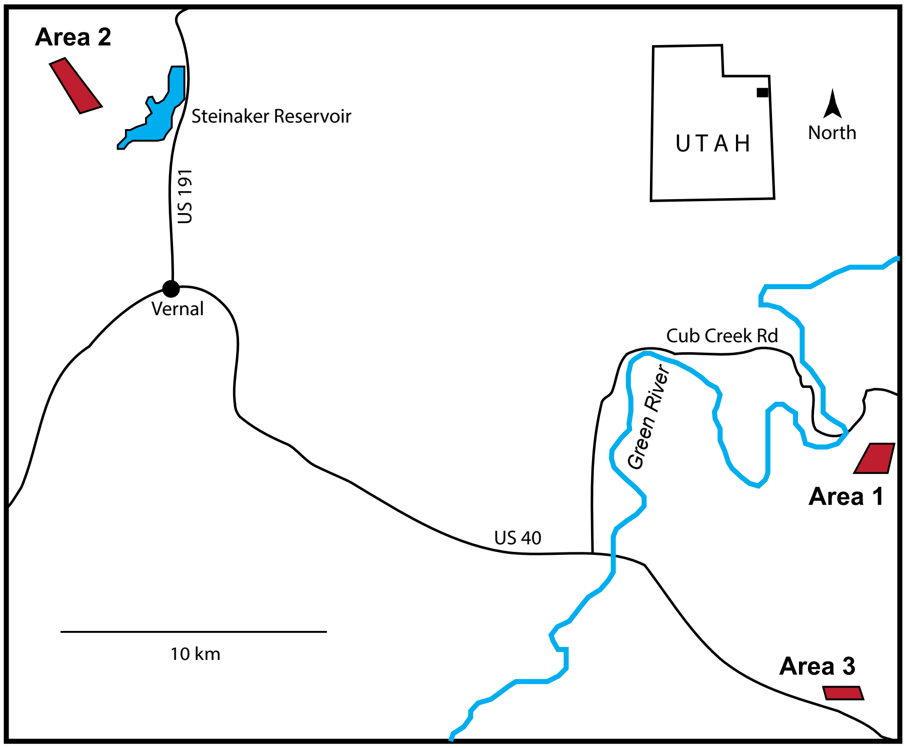

Figure 11. Interdune carbonate occurrences in the study area. The small polygons labeled Areas 1, 2, and 3 indicate where carbonates are exposed. Area 1 includes Stop 4 on this field trip.

at its greatest preserved extent. They are approximately aligned, with a nearly west-northwest trend. These mounds and intervening horizontal layers extend more than 110 m along the canyon rim.

The mounds are hemispherical in shape, and their peripheries merge contiguously with a horizontal carbonate layer that continues to the next mound (figure 13). Where erosion has exposed the core of a mound, laminae are inclined away from the center. The core can also be seen as an area where the carbonate laminae are brecciated and separated by intruded sand and the underlying sand units rise up in the center of the mound (figure13B and C).

Also visible in the area of the large mounds is the sandstone underlying the mound structures. The easternmost and largest of the mounds is perched on the canyon rim in such a way that it and the underlying sandstone are exposed in cross section through the mound core (figure 13B). This reveals soft-sediment deformation in the sandstone below the mound, in which reddish sandstone has intruded upward through light-colored, partly-consolidated sandstone into the base of the mound core. Soft-sediment deformation in the sandstone beneath the carbonate layer is also visible to a depth of 10 m or more in the wall of a small, south-draining canyon that cuts across the trend of the mounds. The deformation consists of contorted beds and fractured and offset, partly consolidated sandstone layers.

Parrish and Falcon-Lang (2007), Parrish and Dorney (2009), Parrish and others (2016) have described similar mound structures in the Navajo Sandstone near Moab, Utah. They interpret them as the result of upwelling of groundwater beneath the mounds, and this hypothesis fits the characteristics of mounds in Cub Creek Canyon equally well.

Associated with the large mounds at Cub Creek are abundant *Taenidium* isp. invertebrate traces in the sandstone immediately beneath the carbonate layer (Good, 2013, 2014). They are particularly well represented in exposures on the eastern periphery of the largest mound (figure 14). Here they consist of numerous, randomly

Figure 12. Carbonate exposures at Stop 4. (A) View is to the south of carbonate mounds exposed along the north rim of a canyon beyond (not visible). Arrows indicate carbonate mounds. (B) View to the east of the same area showing the same mounds.

oriented, tubular traces typically 1 to 2 mm in diameter. There are several larger meandering burrows, 10 to 12 mm in diameter, with meniscoid backfills.

Carbonate beds extend 200 m eastward along the north rim. At the level of the mound structures, erosion has stripped away any in situ carbonate, but there are some large (~0.5 m), loose carbonate blocks and several smaller pieces that indicate it was present; at least as a layer and possibly including additional mound structures. Over part of this same interval, a thin (10 to 20 cm) layer of horizontally bedded carbonate is present perhaps 2 to 3 m stratigraphically lower than the level of the mounds. These horizontal beds often exhibit fine, wavy laminae and there is a single, small mound structure about 30 cm across and about 20 cm thick. Crinkled laminae in this small mound suggest that it is stromatolitic in origin.

Small Mounds

South and west across the main canyon from the large mounds there are carbonate beds at what is probably the same stratigraphic level, including four mound structures (figure 15). These mounds are similar in morphology to those to the north, but are significantly smaller, the largest being about 2 m across. As with the mounds across the canyon to the north, these mounds are in line, oriented northwest-southeast, and about equally spaced, spanning a distance of about 8 m. The carbonate mounds pinch out or are lost to erosion to the east, but a horizontally bedded carbonate layer connects

Figure 13. Large carbonate mound structures at Stop 4. (A) Gray-weathering carbonates of mound draped over white and red sandstone that is higher at the center of the mound. The inclination and thinning of the carbonates away from the center is also apparent. (B) Mound dissected by erosion, viewed from below. The cross section exposes apparent soft-sediment deformation in the underlying red and white sandstones. (C) Carbonate in the core of a dissected mound structure separated and surrounded by sandstone. Divisions on left of scale equal 1 cm.

to the mound structures along a persistent outcrop to the north and west where it is usually 10 to 25 cm thick. Gastropods occur as external molds within the horizontally bedded carbonate layer, along exposures 20 to 40 m north and west of the mound structures (figure 16). These fossils occur at a wide range of angles to bedding. Patchy exposures and float show that the carbonate layer extended farther north and west to, and a short distance along, the south rim of the main canyon (figure 17). These last exposures along the rim are nearly 1 m thick in places, and show evidence of disturbance and brecciation.

Carbonates are also exposed in the walls of the westernmost canyon that empties northward into the main canyon of this small drainage system. They occur as horizontal layers 10 to 20 cm thick within associated interdunal facies that are as much as 2 m thick.

STOP 5. THE SAINTS & SINNERS QUARRY—A LAGERSTATTEN IN THE ERG

The Saints & Sinners locality (figures 1 and 18) preserves a wealth of bones, tridactyl theropod tracks, and an isolated vertebrate burrow, all about 55 m above the base of the eolian portion of the Nugget Sandstone. This site is BYU locality 1442, and coordinates are in the files of the BYU Museum of Paleontology. This is the most

Figure 14. Trace fossils in sandstone immediately beneath a carbonate layer peripheral to one of the large mound structures at Stop 4. Traces of varying size and orientation include burrows that exhibit meniscoid backfill structure and other possible burrows or root traces. Divisions on the scale equal 1 cm.

Figure 15. Small mounds (arrows) in carbonate bed exposed along the rim on the south side of a canyon at Stop 4. Although smaller in scale, these features are similar in all respects to the large mounds on the north side of the canyon.

Figure 16. Gastropods preserved as external molds in carbonates on the south rim of the canyon a short distance from the small carbonate mounds at Stop 4. (A) Carbonate slab with numerous gastropod molds of varied size and orientation. (B) Silicone rubber cast of a gastropod (mold of a natural external mold) from carbonates along the south rim of the canyon. Most of the gastropods have this high-spired morphology.

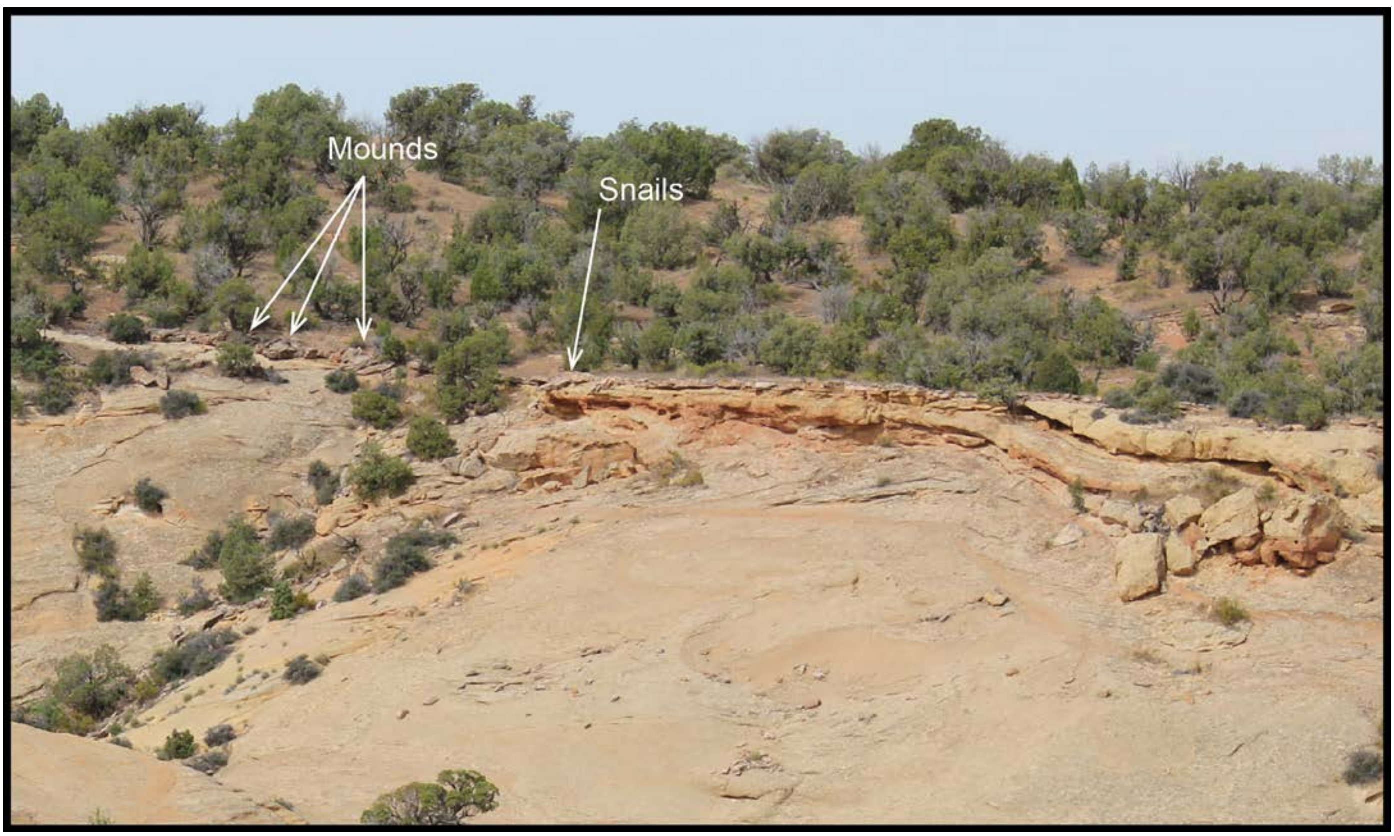

Figure 17. Carbonate exposures along the south rim of the canyon as seen from Stop 4. The small carbonate mounds and the location of gastropod fossils are indicated by arrows.

prolific body-fossil-producing site of any of the Late Triassic to Early Jurassic sand ergs in terms of number of bones, number of individuals, and taxonomic diversity. The site was first excavated in 2009 and continues to be actively worked. To date, over 11,500 specimens (articulated skeletons, bones, and partial bones) have been prepared with thousands more awaiting preparation. All preparation is done by BYU students at the university's Museum of Paleontology, which will be the last stop of our trip.

The vertebrate fauna (table 1) consists of two sphenosuchian genera, a drepanosaur, two theropod genera (a coelophysoid and a medium-sized taxon of unknown affinity), and a dimorphodontid pterosaur. An informal tally (many specimens are not yet in the database) indicates there are at least 76 individuals, 41 of the smaller sphenosuchian and 20 of the coelophysoid.

The Saints & Sinners Quarry, BYU locality 1442 (figures 1 and 18A), is located along a flank of the Section Ridge anticline, a Laramide structure that strikes southwest to northeast in northeastern Utah, along the south flank of the Uinta Mountains uplift. The anticline deforms and exposes Paleozoic to Cretaceous strata. The resistant Nugget Sandstone forms a marked cuesta above the strike valley of the Chinle and Moenkopi Formations. A series of small canyons, developed in fault zones, breach the cliff-forming Nugget cuesta, which locally dips about 20° to the southwest. The Saints & Sinners Quarry is on about a 4 by 10 m shelf at the top of the cliff wall of one of these canyons (figure 18A). All of the shelf is bone bearing, but only 19 m^2 have been excavated (figure 19A). This stratigraphic interval is traceable to the southwest of the quarry into a small alcove bounded by small cliffs (figure 18A). Although no bones are present in those cliffs, they provide exposures crucial to understanding the depositional environment of the quarry and our detailed stratigraphic section (figure 1) was measured in the alcove (figure 18A). From our vehicles we will walk to the rim of the cuesta to look down at the Chinle Formation and the lower Nugget Sandstone at the base of the cliff that conformably overlies the Chinle Formation. From the overlook we will walk into the quarry to observe its various units, then down into the alcove to put the bone-bearing unit into context with under- and overlying strata.

The Quarry

Discovery

The site of what is now known as the Saints & Sinners Quarry was first seen by two of us (Dan and George) on July 8, 2007. We were wrapping up a long, hot day of prospecting for fossils and interdunal deposits in the Nugget Sandstone. Looking north across a canyon, we spied a vertical outcrop on the opposing canyon wall containing well-defined interdunal deposits (figure 18A, alcove). As it was the last day of the field season, we decided to visit the outcrop the following year. In

Table 1. Faunal and floral list from the Saints & Sinners Quarry (mm = millimeters, cm = centimeters, and m = meters).

	Taxon, high	Taxon, mid	Taxon, low	Size, approx.	Common name	Notes	# Individuals
Body fossils							
Plantae							
	Gymnospermophyta						
		Cycadeoidophyta	cycadeoid		bennettitalian "cycad"	isolated frond, rhachi, petioles	
Animalia							
	Sauroposida "Reptilia"						
		incerta sedis	drepanosaurid	40-cm-long	bird-like head, digging arms	articulated/associated/disarticulated	>5
		Lepidosauromorpha	sphenodontian A, normal-jawed	30-cm-long	tuatara-like "lizard"	isolated jaw elements	7
		Lepidosauromorpha	sphenodontian B, slender-jawed	30-cm-long	tuatara-like "lizard"	isolated jaw elements	
		Crocodylomorpha	sphenosuchian A, primitive	20 to 50-cm-long	crocodylomorph, terrestrial	articulated/associated/disarticulated	>41
		Crocodylomorpha	sphenosuchian B, large	1.5-m-long	crocodylomorph, terrestrial	braincase, dermal ossicles	1
		Pterosauria	dimorphodontid	1.5-m-wingspan	pterosaur	single individual, partial skull + phalanx	1
		Dinosauria, Theropoda,	coelophysoid	1.5 to 3-m-long	predatory dinosaur	disarticulated	20
		Dinosauria, Theropoda,	medium-sized	7-m-long	predatory dinosaur	teeth, partial vertebrae	1
Trace fossils							
	Invertebrata		*Skolithos*	< 8 mm diameter	invertebrate burrows	in dune facies	
			Planolites	< 8 mm diameter	invertebrate burrows	in dune facies	
	Vertebrata		*Grallator*	~15-cm-long	small tridactyle tracks	only in/on crinkly beds?	
			Burrow at toe of dune to beach	15 cm diameter x 1.5 m	vertebrate burrow	single occurrence	

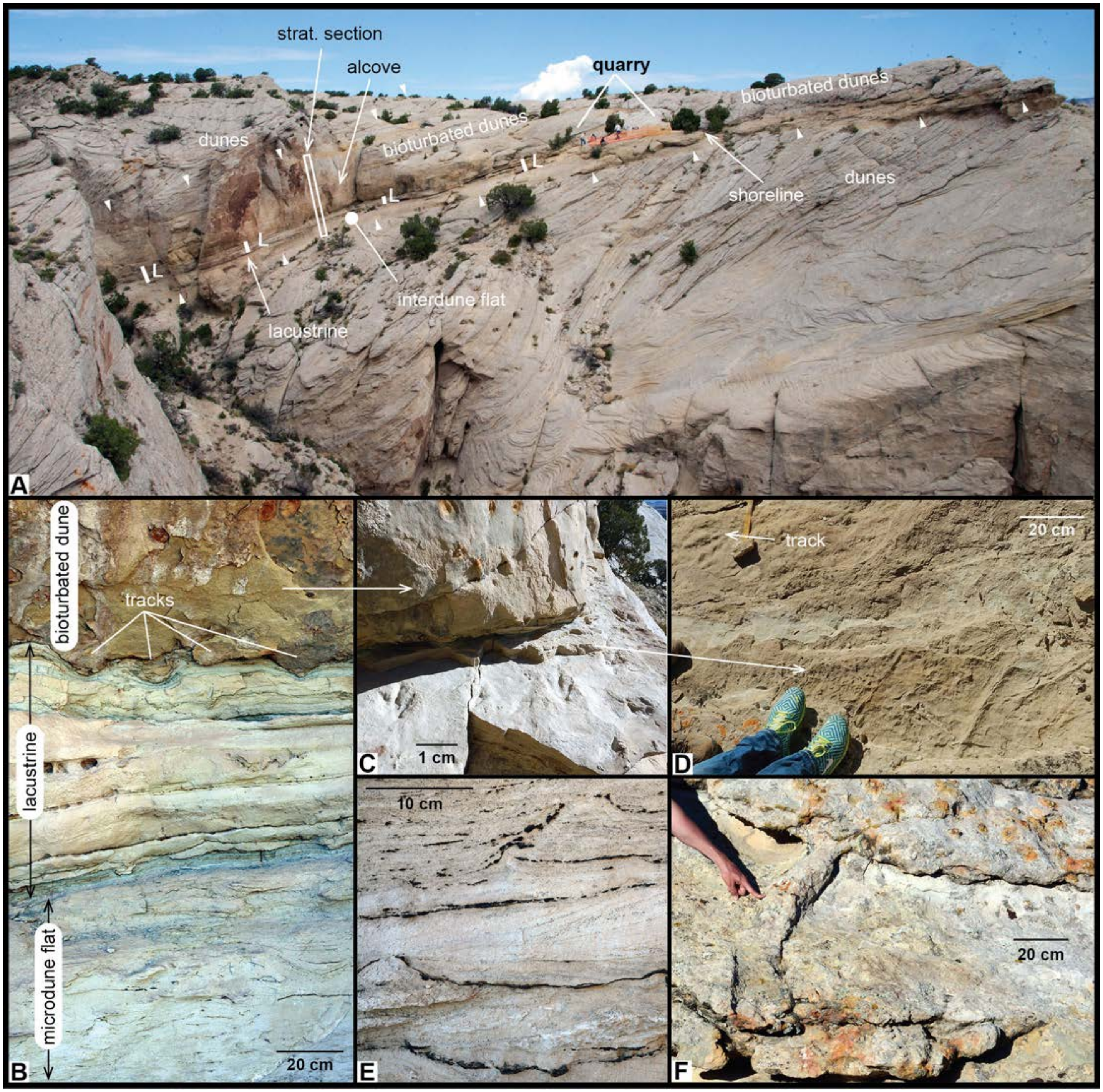

Figure 18 caption on following page.

June 2008, we, along with intern, Josh Finkelstein, hiked back to the location and worked our way around the upper canyon to get to the interdunal facies in the vertical wall of the alcove. As we crossed what is now the western part of the Saints & Sinners Quarry, George spied grooves in the sandstone and called out to Dan, who was farther ahead, that it looked like there were tool marks similar to those we had seen at the Cub Creek petroglyph site. At Cub Creek, grooves in the sandstone at the base of the cliff had been made by native Amer-

Figure 18 (on previous page). Saints & Sinners area overview, depositional environments, and facies. (A) Overview of quarry area with interdune strata bounded by solid arrowheads, sandwiched between prominently cross-bedded sandstones representing dunes. Bars with "L" = lacustrine bed, which pinch out to the right (east) at the shoreline arrow and to the north, but the latter terminus is covered. The lacustrine beds are underlain by interdune flat deposits, indicated with a ball and bar, consisting primarily of cm-scale dune and ripple sandstone (B, E). The position of the measured section (figure 1) is indicated by elongate rectangle in the upper left. (B) Site-typical interdunal flat, lacustrine, and bioturbated dune facies sequence. The lacustrine facies consists of stacks of couplets of structureless sandstones overlain by green silty clays. Tracks are common on the top of the lacustrine facies. Individual digits (toe infillings) are sometimes visible when the undersurface of the tracks are exposed, confirming these are tracks. (C) Oblique view of *Grallator* isp. Tracks on the upper surface of a lacustrine couplet. The mm-thick clay at the top of the couplet has been eroded, but the clay provided the parting plane between the two bounding sandy beds. The 3-cm-thick bed overlying the tracks is a typical wrinkly facies bed, interpreted as a silty sand interdune flat layer that was once covered by a biofilm. (D) Several interdune flat wrinkly units exposed in plan view showing a *Grallator* track in the upper left and ridges in bottom right. The ridges are interpreted as pressure ridges developed as evaporites accumulated just below the surface in the Triassic interdune. (E) Detail of microdune playa flat deposit in cross section. The thin trough cross-bed sets are interpreted as microdunes (large sand ripples) migrating across the interdune. The teepee structure (upper right) may be related to curled biofilm edges and/or evaporite-related pressure ridges (Pakzad and Kulke, 2007). (F) Possible vertebrate burrow, 15 cm in diameter in the toe of a dune along the shoreline of the lake. Moderate bioturbation has destroyed all trough cross-bedding in the dune except the larger, cm-scale trough cross-bed sets.

icans sharpening tools on the sandstone. In the alcove we examined the interdunal layers, and Dan found a tridactyl track. On our way out of the alcove, we checked out the groove and noticed it didn't look right. Dan recognized it as the external mold of a small tibia. Looking around, we found more external molds of bones, some with traces of bone still in them, and saw short strings of small vertebrae nearby. We followed that surface to the east, continuing to see scattered bone. When we got to the main surface where the quarry is, there was abundant and identifiable bone everywhere (figure 19B). We were elated with the discovery, and our excitement was obvious as we tried to assess what we had found. Josh, not being familiar with paleontologists, thought we were putting him on, on his first day in the field. In fact, it turned out to be the find of our (DJC and GFE) lives.

Collecting

Following the discovery of bones in 2008, Chure and Engelmann contacted the BYU Museum of Paleontology to see if it was interested in collaborating with collecting and researching the site. After a visit to the site by Rodney Scheetz, BYU agreed. A permit was applied for and obtained for the 2009 season. The site is unusual compared to other areas we have worked, with numerous, small, fragile bones on the surface embedded in structureless sandstone, largely lacking fractures. The bones are three-dimensional, with no crushing, which we attribute to burial in clean sands (now sandstone) that does not compress because of grain-to-grain contact. The sandstone matrix is generally poorly cemented. The bones are not permineralized, and many can be scratched or pulverized with a fingernail. The softness of the bones is evident from the many external molds on the tops of the bonebed; the bone is usually more easily eroded than the sandstone. Fragile bones were stabilized with Vinac B-17 (polyvinyl acetate) in a low-viscosity acetone solution.

Because the bone-bearing layers are low in relief, we created a grid of 1-m squares with spray paint (figure 19A). Painted lines are short-lived, however, so the intersections of the easting and northing lines were marked with large washers engraved with grid coordinates and affixed with concrete nails (figure 19B to F).

Initially, not knowing how abundant the bones were, we made silicone rubber casts in the external molds. Our first season of collecting involved recovery of cobble-to-small-boulder-sized fragments of the bone-bearing units that had fallen downslope, and loose blocks of in situ sandstone. We also used air scribes to remove individual bones (figure 20A). Working in the field with air scribes is painfully slow, expensive to employ, and

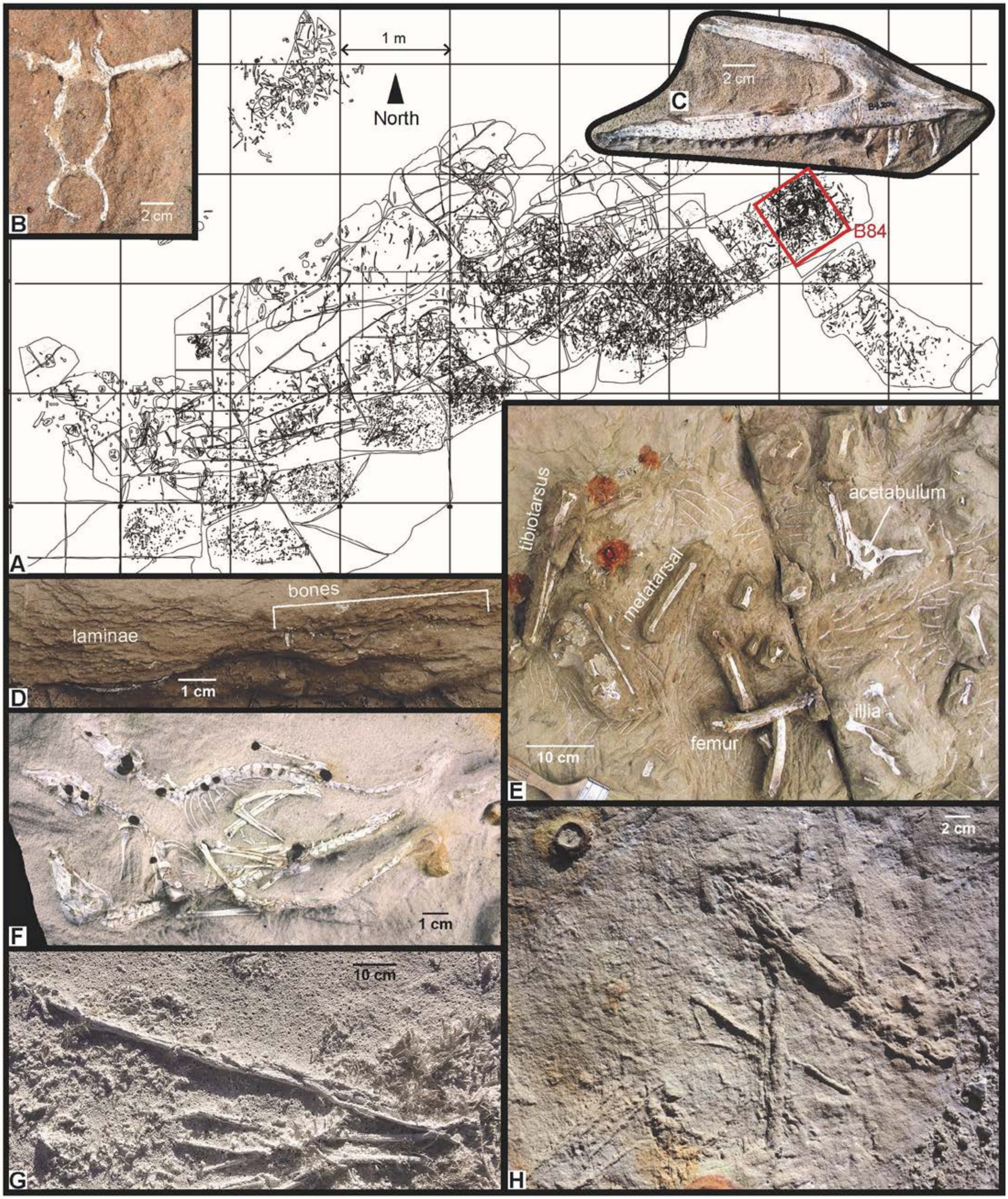

Figure 19 caption on following page.

Figure 19 (on previous page). Saints & Sinners Quarry map and fossils. (A) Most of the quarry map as of mid-2016 showing the positions of over 11,500 bones. For numerical perspective, the upper right block (B84 outlined by a red rectangle) alone yielded 827 bones from the uppermost horizon, bonebed 3. Horizontal bone distribution is non-uniform, as exemplified by B84. Blocks with no bone have not been prepared. Although there are three superimposed bone layers, each approximately 25 cm thick, at the time this map was made only one layer had been prepared for most areas of the quarry. (B) Coelophysoid theropod dorsal vertebra in transverse section exemplifying how bones look as exposed by erosion. (C) Coelophysoid left maxilla in medial view after preparation showing the excellent, uncrushed nature of bones from the locality. (D) Naturally eroding bones (white) of a small, articulated sphenosuchian near the bottom of bonebed 2 horizon. Weathering reveals sub-mm-thick, irregular laminae not apparent in fresh exposures. (E) Associated and somewhat broken pelvis and hind limbs of one of the smaller coelophysoids from the top of bonebed 2. These were the only bones preserved in this area of the quarry, making it clear that they pertain to a single individual. In other areas bones of multiple individuals are mixed together, making it difficult to discern individuals. (F) Three articulated sphenosuchians from middle to top of bonebed 2. This cluster suggests they died in a burrow during estivation but at least five other specimens of the same size were found in the same area in different orientations and there was no evidence of a burrow. The voids of various colors are weathered concretion sites. (G) Plant debris covered with efflorescent, puffy evaporites on modern playa flat bordered by, and overlain by dunes in Utah's West Desert. (H) Top of bonebed 2 with what appear to be sandstone casts of plant debris based on their straightness and bundled morphology. Compare with G, to the left.

too dependent on weather. This quickly necessitated a shift to creating moderate-sized blocks that could be prepared in the lab.

The bones occur in three massive sandstone beds separated from each other by parting planes developed along mm-thick silty clay layers (figure 20E). At first we and the crew leader, Jeff Higgerson, worked slowly to enhance the few natural cracks to break out individual blocks from each bonebed stratum. However, cracks were few and some blocks defined by natural cracks were very large. Later, a demolition saw (figure 20C) was employed to cut out blocks, but the bonebeds are 25 cm thick, which was too thick to cut through with the diamond blade. We experimented with a standard pressure washer (figure 20B) and succeeded in cutting through 30 cm of sandstone, but the process was messy and the cut relatively thick and uneven. The most effective cutting tool has proven to be a concrete-cutting chain saw, which can penetrate up to 60 cm in a single cut (figure 20D). The extraction system we have settled on is as follows. A block is outlined with a timber crayon, the initial guide cut made with a demolition saw (figure 20C), and the ultimate cut made with a concrete-cutting chainsaw (figure 20D). We have honed this method to the degree that several workers can cut, extract, and load 544 kg of sandstone blocks in a few hours by either winching the blocks upslope to a lift-gate truck (figure 20G) or driving a truck with a bed-mounted crane into the quarry.

Quarry Geology

Stratigraphy

In the vicinity of the quarry, the true thickness of the Nugget Sandstone is difficult to measure because of the dip of the beds and the fact that it is an incomplete section. We estimate the thickness in the area to be no more, and probably substantially less, than 200 m, with the quarry being about 55 m from the base of the upper, eolian part of the formation (figure 1A).

The quarry is positioned near the bottom of a large wedge-shaped unit (figure 18A, with the upper and lower boundaries indicated by solid arrowheads) dominated by structureless sandstone along with a stratum consisting of cm-scale sandstone layers separated by mm-scale mud drapes, all related to the interdunal environment (figure 18B). The maximum area within which the wedge is exposed is 320 m north-to-south and 50 m east-to-west. The wedge becomes untraceable at its north and south ends in canyons developed along faults. To the west it is obscured where it dips into the subsurface and the eastern boundary has been lost to erosion. The maximum thickness of this wedge is 10 m at its south end and it gradually thins to less than 1 m

Figure 20. Collecting methods. (A) Air scribes were used for the first season before we realized the bones were abundant and often closely spaced. (B) A high pressure washer with a stream nozzle was used successfully to cut to depths of over 30 cm but the cut was wide (15 mm) and rough. (C) A demolition saw is used to make the guide cuts after block locations are demarcated with timber crayons and the block numbers marked on the sandstone. We often followed pre-existing joints for the cuts. (D) A concrete chain saw with a potential cut depth of 60 cm is used to cut through up to two bonebeds simultaneously. Water to cool the chain is sourced from standard barrel equipped with a gas-powered pump. (E) Cut blocks ready to collect showing the three discreet bonebeds separated by mm-thick silty clay beds. Quarry grid lines marked in orange spray paint. (F) Grid coordinates are engraved on washers at grid intersections held in place by concrete nails. (G) A truck-mounted crane is used to lift and load larger blocks.

thick over some 200 m to the north. The wedge continues another 120 m in that direction before being terminated by a fault. The wedge also thins eastward. Above and below this wedge-shaped stratum is sandstone with high-angle cross-beds, a facies that overwhelmingly dominates the Nugget Sandstone and represents dune fields (figure 18A).

Interdune Strata

The three bone-bearing strata (figure 20E) constitute only part of a complex of strata deposited in an interdunal flat that at times included a lake (Shumway and Britt, 2015, 2016).

The base of the interdunal wedge is marked by a planar deflation surface on which there are centimeter-scale, cross-bedded and convolute sandstone beds, whose contacts are accentuated by post-depositional hematite laminae (figure 18E). These sandstones represent alternately dry to damp (Kocurek and Fielder, 1982) interdunal flats, sometimes with biofilm-covered surfaces (Hagadorn and Bottjer, 1993; Eisenberg, 2003). The small-scale, trough cross-bedding represents small dunes (Ahlbrandt and Fryberger, 1981). This interdunal flat stratum extends across the entire base of the interdunal wedge, and to the north, it is the only facies of the wedge preserved. Largely structureless sandstone beds cm to dm thick and overlain by green, silty mudstones (figure 18B) are indicative of a flooded interdune (Ryang and Chough, 1997), and were deposited in a small lake. The lacustrine units pinch out only 30 m north of the southern end of the wedge. It is on the northeastern shoreline of this lake that the bones are preserved.

At the north end of the lake, cm-scale beds exhibiting wavy textures in cross section, a wrinkly surface, and pressure ridges in plan view (figure 18D) sometimes overlie lacustrine, clay-sand couplets. Some of these wrinkly beds preserve *Grallator* tracks. Often, these beds exhibit pressure ridges, and alternate with the finer lacustrine beds (figure 18). These beds represent short-lived interdune flats sometimes blanketed with biofilms or biomats that developed as the lake level dropped (Hagadorn and Bottjer, 1993; Eisenberg, 2003). These organic-rich beds are thought to play a role in the preservation of vertebrate tracks (Carvalho and others, 2013). The pressure ridges formed as the surface dried and growth of evaporite crystals increased the surface area of the bed surface (Pakzad and Kulke, 2007).

Overlying the uppermost lacustrine unit are structureless sandstone beds with some relict cross-bedding and sporadic deflation surfaces (figure 18A, 18B, and 18C) that are now accentuated by post-depositional hematite. This unit is as much as 7 m thick and represents eolian dunes that migrated across the flats, covering the shoreline and what was left of the lake. These dune sands were often wetted by a high water table. The moist sands encouraged vegetation and burrowing invertebrates, ultimately resulting in the structureless texture (Thomas, 1984; Loope and Rowe, 2003). The intense burrowing all but destroyed the trough cross-bedding. On top of these structureless sandstone beds rest thick, high-angle, trough cross-bedded sandstone representing structurally intact (not bioturbated) dunes, marking the end of the local interdunal phase (figure 18A).

The interdune story is summed up as follows: (1) deflation and development of an interdunal flat with deflation being controlled by the water table – specifically by the capillary zone above the water table, (2) deposition of ~1 m of sand and silt on the interdunal flat in the form of thin layers of sand via microdunes/sand ripples (some trapped by moist ground) with minor development of biofilms, (3) flooding of the southern part of the interdunal flat, and development of a lake, with fluctuating lake and shoreline levels, (4) development of cm-scale sand/biofilm layers along the lake shoreline resulting in the preservation of theropod tracks, (5) partial drying of the lake and dune migration across the interdunal flat (these dunes are bioturbated by invertebrates during damp phases), and (6) complete burial of the interdunal flat by large dunes. The bonebeds are part of the lacustrine phase and are described and interpreted below.

The Quarry Bonebeds

Description

The quarry is small, with only 19 m^2 (figure 19A) excavated to date, and in most areas only one of the three bone-bearing layers has been collected. The quarry is located in the lacustrine facies, along the paleoshoreline, which consists of generally structureless sandstones separated by green silty clays as described above. In the main area of the quarry, there are three superposed bone-bearing strata (figures 1B and 20E). The sediments are often mottled, with light, off-white blebs among a more pervasive tan matrix. This mottling may be a function of invertebrate bioturbation. All three layers are sandstone that appear to be essentially devoid of sedimentary structure, except for sub-mm-thick green clay layers. Deep weathering, however, reveals thin, irregular sandstone laminae that may represent relict ripple laminae, near the bases of bonebeds 2 and 3 (figure 19D). It is the thicker or closely spaced mud drapes that on weathering separate the three layers and permit their extraction (figure 20E). Bones in the quarry are not evenly distributed, neither vertically nor horizontally (figure 19A). Vertically, there is a high predictive value from the level of occurrence to both the size of bones and degree of articulation. The articulated small skeletons are found on the very top of bonebed 1 (the lowest bone layer) and the bottom to middle of bonebed 2. Bones of larger taxa are common upward from the middle of bonebed 2 and abundant in bonebed 3 (figure 19A). The orientation of bones/skeletons ranges from roughly random, from the bottom of bonebed 1 to bonebed 2 (figure 20E), to substantially oriented in bonebed 3 (Britt and others, 2011; Chambers and others, 2011).

Interpretation

The three nearly structureless sandstone beds that contain bone are interpreted to represent sand blown into standing water during haboobs or local wind storms. The capping green clay laminae on top of each sandstone bed marks a quiescence that allowed silt and clays to settle. The large number of animals and the taxonomic diversity of the fauna suggest a mass die-off, likely during drought. The animals may have gathered from across the interdunal flat to the last oasis and died because the waters were not potable, or the oasis completely dried up. In the drought, the carcasses may have dried and littered the landscape. Then when the lake level rose, the small carcasses of the drepanosaurs and sphenosuchians were buried by wave action or by sands blown in during a haboob. Larger carcasses were not immediately buried, and macerated in the shallows, where wave action reworked them, oriented them, and finally largely buried them. The increased orientation of bones in the uppermost bonebed, which consists of the disarticulated bones of the coelophysoid, suggests substantial reworking but only very minor transport by wave action.

The Quarry Flora and Fauna

Flora

The only plant fossils identifiable to a reasonable degree are extremely faint external molds of compressed cycadeoid fronds (William Tidwell, BYU, personal communication, 2012). Usually only the rachis or petiole is found but one specimen preserves pinnae (leaflets) that extend at right angles from the rachis.

We attribute the dearth of plants to postdepositional oxidizing groundwaters and/or alkaline waters. The latter is common in desert environments and can break down plant tissues before or soon after burial (Retallack, 2001). Despite the rarity of plant fossils, it is likely that the interdune supported a substantial floral mass and that growing conditions were favorable for relatively long periods. The same conditions that destroyed the plants could have destroyed organic components of the bones, resulting in their "bleached" white color. The absence of relic organics explains, in part, the friable condition of the bones.

Fauna

Invertebrate: No invertebrate body fossils have been observed within the quarry nor in the vicinity of the quarry. Whereas this could be a preservational bias, the absence of invertebrate trace fossils in the lacustrine deposits suggests that no complex invertebrates of any size resided in sediments at the bottom of the lake. The abundance of small vertebrates that were probably at least partly insectivorous, along with the occurrence of *Skolithos* and *Planolites* traces throughout the dune sands where slipface surfaces are well exposed, indicate that invertebrates were common. The near complete disruption of sedimentary structure by bioturbation of dunes above and lateral to the lake indicates that invertebrates thrived in such environments in the interdune area. The mottled sediments in the bonebeds is best interpreted as evidence of moderate bioturbation by invertebrates.

Vertebrate: Aside from the sheer number of individuals (>76), the most surprising aspect of the site is the faunal diversity. The minimum number of individuals (MNI) presented here is a conservative estimate because of a backlog of about 9000 specimens that have yet to be entered into the database. The estimates for MNI are most accurate for the larger taxa, the bones of which were the first recovered and entered into the database. We recognize eight vertebrate taxa at Saints & Sinners, which are enumerated in table 1 and briefly described here. This diversity is far greater than at any other site in the Triassic to Jurassic ergs of the American Southwest. Most, if not all, of these taxa are new and most are now in various stages of study, preparatory to their formal descriptions.

Sphenosuchians – The most common taxon in the quarry is a crocodylomorph, sphenosuchian A. Over 41 individuals are present based on articulated and associated skeletons. The taxon is represented by a range of sizes, with skulls ranging from 25 to >50 mm and body lengths to >500 mm. Many, if not all, are juveniles. Articulated, complete and partial skeletons are apparently randomly distributed between bonebeds 1 and 2, and about halfway up into bonebed 2 (figure 20E). Some skeletons occur in discrete clusters, with one cluster consisting of three overlapping skeletons all facing the same direction (figure 19F), suggesting they may have died in an estivation burrow. The armor is simple, limited to the parasagittal region, and dermal plates are unornamented save for a single ridge. The greatly elongated legs (figure 19F), a common feature in sphenosuchians, indicate it was fleet of foot, an advantage in the open spaces of the desert environs.

A second crocodylomorph, sphenosuchian B, is represented solely by a partial braincase and a couple of scutes of a 1.5-m-long individual(s). This may simply be an adult of sphenosuchian A but the morphology of the skull differs more than we expect for a single taxon.

Sphenodonts – Based solely on mandibular rami, there are two sphenodontian genera, one form with a mandible more typical for the group, and one other with a more gracile mandible, both similar in size. Unlike the other small taxa in the fauna, no articulated specimens have been recovered. Counting both forms, only six individuals have been recovered.

Drepanosaur – Numerous individuals are present including at least six articulated individuals of varying degrees of completeness plus numerous other partial skeletons (Engelmann and others, 2012, 2013; Chure and others, 2013, 2015). All portions of the skeletons save for the last half of the tail are known. The head is bird-like with large orbits and an expanded braincase; the arms and shoulder are adapted to scratch digging with a hypertrophied ungual on digit II (Chure and others, 2015); the chest is barrel-like; and proximal caudal vertebrae have bifid chevrons. There appear to be two morphs, distinguished primarily by differences of the pes, which we attribute to sexual dimorphism. The teeth are rectangular in cross section and high-crowned. The Saints & Sinners taxon differs from *Drepanosaurus* in a number of characters, including elongate straight unguals on digits III, IV, V of the manus; slender and thin digit I; an opposable hallux on the male morph; unexpanded distal end of the scapula; and more.

Theropods – There are two distinct theropods, a coelophysoid and much larger taxon. The larger taxon is represented only by few shed, robust, tooth crowns up to 40 mm long, suggesting a body length of approximately 7 m. The coelophysoid MNI is 20, with skulls ranging from 100 to 350 mm long and an estimated maximum body length of 3 m. Overall the taxon is similar to *Coelophysis* in build and morphology (Britt and others, 2010). A diagnostic difference is seen in that the shaft of metatarsal II is reduced to a splint, but with a functional distal articulation. No specimen is articulated, aside from short strings of vertebrae and partial limbs, but the skulls are typically closely associated and the skeletons of several individuals can be discerned based on related elements of bone pertaining to exceptionally large or small individuals. The large number of bones of intermediate sizes are not easily differentiated into individuals because the bones are so common and closely spaced.

Pterosaur – A dimorphodontid pterosaur is represented by a single individual consisting of a partially articulated and closely associated skull and a single postcranial element, the distalmost wing phalanx (Britt and other, 2015a, 2015b). Most of the skull is known, and it shares a number of diagnostic characters with *Dimorphodon* (e.g., supernumerary small teeth in the mandible along with two rostral fangs, needle-like nasal process in lateral view), but there are substantial differences in the Saints & Sinners taxon (e.g., large and bladiform maxillary teeth and a small orbit). Triassic pterosaurs are extraordinarily rare, with only 27 reported finds worldwide, and the majority of the finds consist of isolated elements, all of which are from marine or lacustrine deposits. The discovery of a desert-dwelling, Triassic pterosaur was quite unexpected.

Vertebrate trace fossils: The quarry horizon is bordered by a ledge that protrudes from a ledge/cliff along one side and sandstone hills or ledges on the other three sides. On one of these sides, erosion has been sufficient to show the toe of a dune interfingered with the shoreline lacustrine facies of the bonebeds. Thus, at least on one side of the lake, dunes migrated into the lake. The toe of this dune preserves several relics of larger slip-face laminae, but is otherwise nearly structureless. A gently curved, cylindrical trace (figure 18F), about 15 cm in diameter and about 1.5 m long, follows the slope of the slipface down toward the lake margin. There are no positively discernable scratch or other marks nor branches on the surface of the trace, and it does not branch. Similar burrows in other parts of the erg have been interpreted to have been made by reptiles or synapsids (Odier and others, 2004, 2007; Hasiotis and others, 2007). Such burrows indicate the sand was moist when burrowed (Loope, 2006). Wilkens (2008), however, argued that the branching traces described by those authors were made by plant roots, not vertebrates. The 15-cm-diameter trace at Saints & Sinners does not branch, and we attribute it to a relatively small, unknown vertebrate.

Interpretation of Fossils

The diversity of fossils at Saints & Sinners Quarry is unexpectedly diverse for a desert-dwelling biota. Elsewhere in the Nugget Sandstone, and at most fossil localities in the balance of the Late Triassic to Early Jurassic sand erg, ichnofossils are the only fossils, with body fossils being extraordinarily rare, and those occurring as isolated specimens (Engelmann and others, 2016). Happily, the Saints & Sinners, where bones are abundant and well preserved, representing eight taxa, is an exception to this general characterization.

Little can be said about the flora as it contains only poorly preserved compressions, molds, and casts. However, the presence of a cycadeoid and the sizes of the molds and casts of unknown plant parts indicate the area provided adequate growing conditions for at least years to decades. In addition to vascular plants, the biofilm covering wet to damp interdune surfaces likely consisted of photosynthesizing and non-photosynthesizing microbes, and played a role in vertebrate track preservation.

Invertebrates are represented only by trace fossils assignable to *Skolithos* and *Planolites*, and these are only discernible immediately below and in the lightly bioturbated dune sands east of the lake, overlying the interdune wedge. Intense bioturbation by invertebrates, however, is responsible for the structureless sandstones, indicating favorable conditions for a number of invertebrates.

The diversity of the vertebrate fauna indicates habitable conditions (abundant food in the form of arthropods/plants and fresh water) were stable for some time, allowing the area to become populated with a number of taxa, ranging from small, lizard-sized reptiles up to a medium-sized theropod. The presence of vertebrates with low vagility, such as drepanosaurs and sphenodontids, supports the idea of the lake/oasis being a permanent feature of long duration. The taxonomic diversity and large number of individuals seems too large for the size of the preserved portion of the interdune, suggesting either that the interdune area was much more expansive or that animals from other interdunes migrated to this area in response to drought or other conditions.

One of the great mysteries of the Saints & Sinners fauna is that is it composed entirely or almost entirely of carnivorous and insectivorous taxa. Were insects the dominant primary consumers? Through continuing research, we will be able to paint a better picture of this rare desert biota as we determine the taxonomy/phylogeny and taphonomy of this spectacular site in the near future.

Summary

The Saints & Sinners Quarry, including sphenosuchians, drepanosaurs, theropods, and a pterosaur, represents the most diverse vertebrate assemblage known from the Late Triassic-Early Jurassic erg of North America. It provides insights into the diversity and adaptations of vertebrates early in the age of dinosaurs. The bones are uncrushed and reveal previously unknown osteological details of pterosaurs and drepanosaurs that have been obscured by crushing at other Triassic localities. The drepanosaur and basal sphenosuchian indicate that much more of the Nugget Sandstone is Triassic than previously suspected.

The bones preserved at the Saint & Sinners Quarry represent part of a biocoenosis inhabiting an interdune flat and perhaps the surrounding dunes during a climatic wet phase, when the interdune hosted a long-lived playa lake abutted by sand dunes. There was likely a moderately developed plant community that included cycadeoids. The plants and the diversity of the small vertebrates indicate that, although no body fossils are preserved, invertebrates were common.

The diversity of the vertebrate thanatocoenosis suggests that the death assemblage is the result of a single drought, perhaps as the lake dried out and animals gathered at the last standing water. Carcasses accumulated in the lowest portion of the interdune. As the lake rose, the smaller carcasses were buried by wind-blown sands settling into the shallow margins of the lake. Larger carcasses were later entombed as the waters continued to rise, macerating the carcasses and facilitating disarticulation. The remainder of the bones were buried after slight-to-moderate reworking by wave action along the shoreline combined with silt and sand blown into the waters from nearby dunes. Ultimately, the interdune was buried by continued or renewed migration of the dunes.

Unlike the other interdune sites visited on this field trip, there are no carbonates at the Saints & Sinners locality. Even though the dominant cement in the sandstones is calcite, cementation is weak. It is clear that the lakes in the carbonate mound area and the lake at Saints & Sinners differed substantially. This implies a different source of water, or different positions of the interdunes relative to the water source as a result of geographic or temporal variation.

STOP 6. THE MUSEUM OF PALEONTOLOGY, BRIGHAM YOUNG UNIVERSITY

Specimens from the Saints & Sinners Quarry are housed at the BYU Museum of Paleontology. BYU is a private research university owned and operated by the Church of Jesus Christ of Latter-day Saints. With about 30,000 students, the campus is located in Provo, Utah, along the eastern boundary of the Basin and Range Province. It is nestled against the Wasatch Range, which is part of the Cordilleran thrust belt west of the Colorado Plateau.

On the edge of campus, we will visit the BYU Museum of Paleontology. This museum began as a small geology department museum that housed a collection primarily of minerals and invertebrates. It started to thrive in 1960 when James A. Jensen was hired as the new curator. Prior to coming to BYU, Jensen worked as one of Al Romer's preparators at Harvard's Museum of Comparative of Zoology. Jensen's lack of academic degrees was made up for by his uncanny artistic and tradesman skills. His earlier careers as a card-carrying machinist, welder, and longshoreman came in handy when collecting giant sauropods, where hands-on knowledge was more valuable than academic experience. His ability to gain the trust of rockhounds, however, was his skill that paid the highest dividends. With the added input of rockhounds combing the Upper Jurassic Morrison Formation of the intermountain region, many significant finds were discovered that were passed on to Jensen. Jensen then often used heavy equipment, such as bulldozers, to open large quarries, many of which produced thousands of bones (e.g., Dry Mesa, Dalton Wells, Cactus Park). Some of these specimens represented new taxa, ranging from the diminutive, a pterosaur, *Mesadactylus*, or two small ornithopods such as *Othneliasaurus*, to giant sauropods including *Supersaurus* and the massive theropod *Torvosaurus*.

In the 1960s and most of the 1970s, there were very few dinosaur workers. But in a little more than a decade after Jensen's arrival at BYU, the museum began growing exponentially. In 1972, with his opening (by bulldozer) of the Dry Mesa Quarry, BYU's dinosaur program received world-wide coverage in the media and the collections grew rapidly. Largely because of the Dry Mesa collection and its giant sauropods, the university spun the museum off from the Geology Department and a new museum was built specifically for vertebrate paleontology. The museum was completed in 1976. Jensen was awarded an honorary doctorate (perhaps his greatest source of pride), and became known world-wide as "Dinosaur Jim."

The collections now consist of over 20,000 cataloged specimens, primarily dinosaurs. The collections are housed in three buildings: (1) one for fossil mammals (primarily amassed by Wade E. Miller (retired BYU vertebrate paleontologist) between the 1970s and the end of the millennium), (2) one for unprepared specimens (with pallet racking and a forklift), and (3) the main museum with exhibit halls, an 167-m^2 preparation lab with a 5-ton ceiling crane, and two collections areas, one with two forklifts. The crane, forklifts, and 6-m-high pallet racking are crucial in the handling and storage of the many sauropod bones.

The field trip will begin with a quick tour of the museum's main buildings and dinosaur collections. The focus, however, is the Saints & Sinners Quarry collection, which currently consists of over 11,500 mapped specimens. These specimens range from broken bones, to isolated and associated bones, to dozens of articulated skeletons of drepanosaurs and sphenosuchians. We will lay out some of the most spectacular specimens for examination by participants.

In the lab, we will watch as students use a combination of several sizes of pneumatic scribes to conduct the gross preparation. Moderate-level preparation is done with sharpened carbide rods and the preparation of small bones is conducted with a needle under a microscope.

We will demonstrate how specimens are mapped in the lab. This begins with marking blocks with a 10 or 20-cm grid system using permanent markers. Then each bone is labeled with the block and field number and photographed. The bones in the photographs are traced using Wacom pen-on-screen monitors and digitally mapped using Avenza System's Map Publisher, a geographic information system (GIS) package that runs in Adobe Illustrator. With so many bones in a single quarry (one sandstone block 0.75 m^2 and 25 cm thick yielded 834 bones), a link between field and specimen databases is crucial. Using the special database analysis features of GIS we have been able to discover an associated skeleton in what appears to the eye to be an incoherent mass of bones.

The wide size range of the bones, from a few mm to about 400 mm, requires different storage methods. Few bones are fully extracted from the matrix; most are prepared in bas-relief. Both are stored in standard specimen drawers. Some bones are left in blocks of sandstone to preserved taphonomic and geologic information and are stored on pallets such that the blocks can be reassembled on the floor.

The bone is soft, sometimes not much harder than graham crackers, and only rarely can bones be completely extracted from the matrix. Important bones prepared only in bas relief have been scanned using a micro CT (micro Computed Tomography), segmented, and printed on high resolution 3D printers. All the bones of the Saints & Sinners dimorphodontid pterosaur have been printed. Holding the printed bones to the light allows one to peer inside and discern, for example, how the bones of the mandible articulate and how they are pneumatized. This can be done on a computer using 3D images, but it is infinitely more satisfying to hold in your hand printed bones of bizarre Late Triassic creatures.

Following the visit to the BYU Museum of Paleontology, we head 45 minutes north to the host hotel where the field trip ends.

THE DUNE DEPOSITS

Not unexpectedly, an erg deposit such as the Nugget Sandstone is dominated by dune sediments. These beds can contain significant fossils, all in the form of trace fossils. Although ichnofossils are generally rare, they can be locally abundant. The only vertebrate trace fossils found in the dune deposits themselves are assignable to *Brasilichnium*, which is a track believed to have been made by an advanced non-mammalian synapsid such as a tritylodont (Engelmann and Chure, in press). Engelmann and others (2010) reported a site with approximately 400 *Brasilichnium* footprints on a 10 m^2 surface (figure 21).

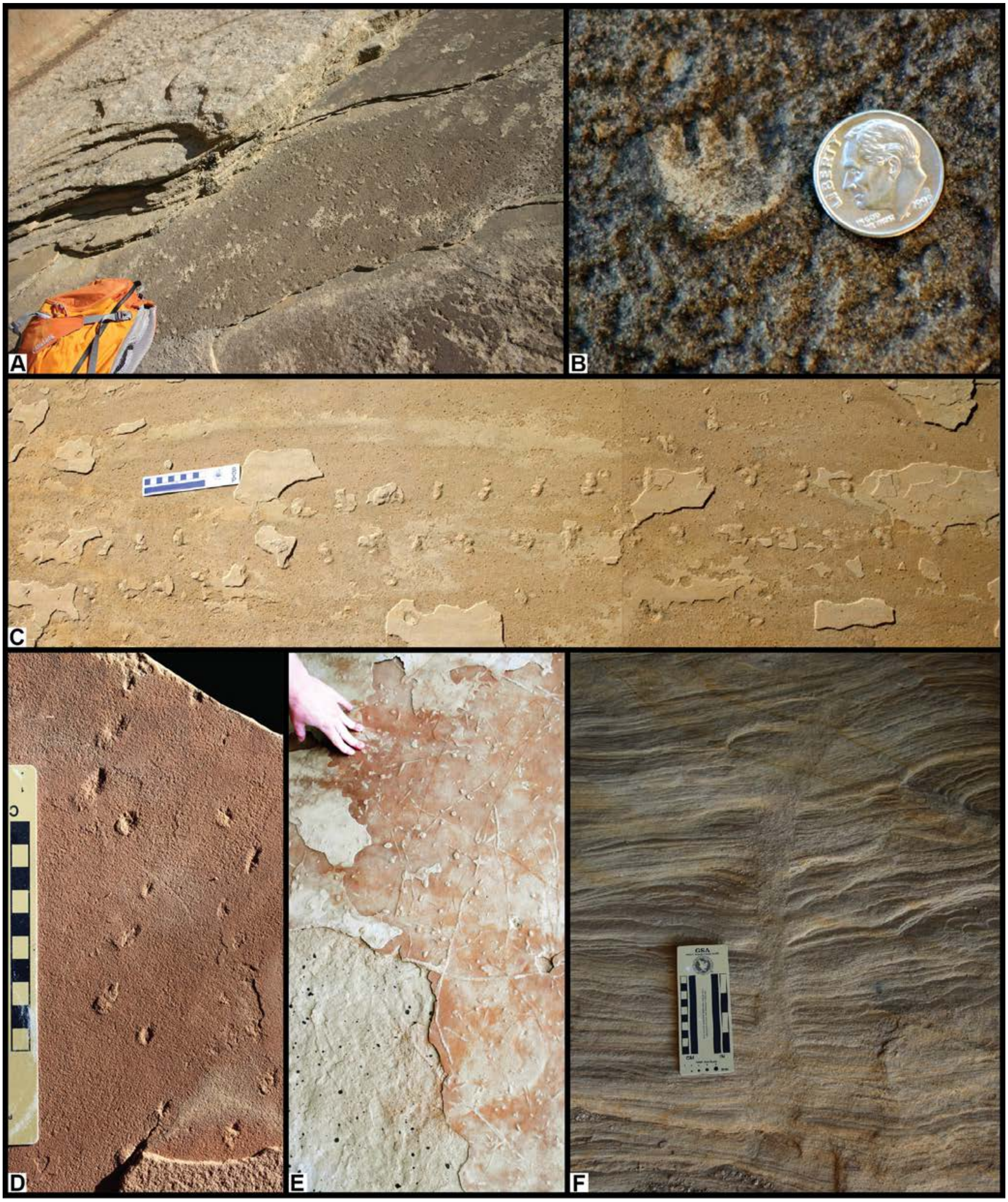

Figure 21. Ichnofossils in the dune deposits of the Nugget Sandstone in and around Dinosaur National Monument. (A) Dune slip surface with hundreds of *Brasilichnium* isp. tracks traveling upslope. (B) Close up of single *Brasilichnium* isp. pes track from (A). (C) *Paleohelcura* isp. trackway. (D) *Octopodichnus* isp. trackway. (E) Dune slip surface with abundant *Planolites beverleyensis*. (F) Possible small vertebrate burrow. Scale bar in cm.

Invertebrate traces are more widespread and diverse than vertebrate ichnofossils in the dune sediments. *Paleohelcura* and *Octopodichnus* are trackways made by scorpions and spiders (figure 21C and D). *Entradichnus*, *Planolites*, and *Taenidium* are invertebrate burrows and trails both parallel and perpendicular to the bedding surfaces of the dune slip face (figure 21E). In modern dune environments, such traces are made by larval dipterans and coleopterans. In addition, there are a number of unnamed forms that are of uncertain affinities and/or behavior (Good, 2013, 2014). Large burrows far out on the toe of the dune face (figure 21F) may have been made by large scorpions or small vertebrates (Engelmann and others, 2014).

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