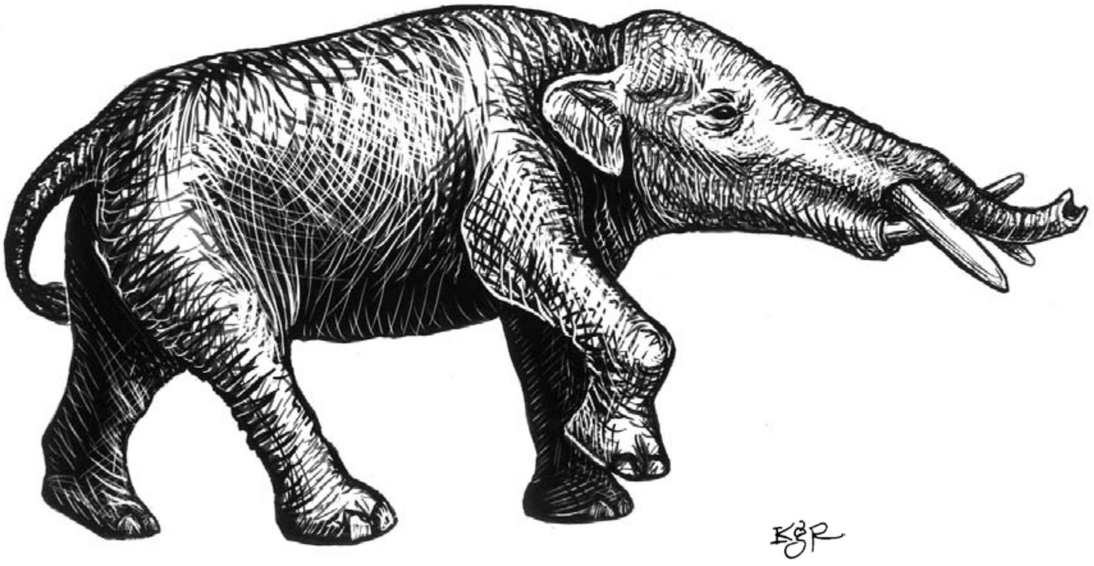
Making Tracks
Across the Southwest

Robert E. Reynolds, editor



Making tracks—the field trip guide

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Abstracts from the 2006 Desert Symposium

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Table of Contents

Front cover: The Spectrum Tracksite. R.E. Reynolds photograph.
Back cover: Track replication in the Barstow Fossil Beds. Robert Hilburn photograph.

Making Tracks Across the Southwest
The 2006 Desert Symposium Field Trip

Day 1

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What we will see: The day 1 route takes us north through the Soda Valley into southern Death Valley and ends in the valley of the Amargosa River. We pass Soda, Silver, Silurian and Dumont dry lakes that have been intermittently filled over the last 15,000 years by drainages from the south. At Shoshone, the Amargosa River has created exposures of Lake Tecopa sediments that were deposited between 2.5 Ma and .02 Ma. The Avawatz Mountains and the Silurian Hills to the east and west of Highway 127 contain Miocene sediments that filled extending basins. Tracks of artiodactyls, horses, elephants and carnivores were left in stream sands and playa margins. A similar assemblage of mammal tracks awaits us in Lake Tecopa.

0.0 (0.0) Convene at Zzyzx with a full tank of gas for the ~188 mile trip. Wear sturdy shoes and dress for the occasion; bring water, hats and sunscreen.

4.7 (4.7) ENTER Interstate Highway 15 (I-15) eastbound toward Baker.

11.0 (6.3) EXIT at Kelbaker Road in central Baker.

11.3 (0.3) Stop at Main Street; PROCEED NORTH on Highway 127.

11.4 (0.1) Pass a landing strip on the left (west).

16.4 (5.0) Silver Lake is on the left (west).

18.7 (2.3) Pass under a power line at elevation ~960 feet. Silver Lake filled to and overflowed this sill during late Pleistocene time (Reynolds, 2004). Building the Tonopah & Tidewater Railroad (T&T) across the flat dry lake surface was easy in 1906, but the railbed and the town of Silver Lake had to be relocated east to higher ground after the lake filled during storms of 1917. Storms in early 2005 refilled Silver Lake and water backed up into Soda Lake to the south.

25.9 (7.2) Continue past a right turn to the Silurian Hills and talc mines.

29.0 (3.1) Silurian Dry Lake is on the right (east).

30.7 (1.7) TURN RIGHT at the paved area with a gravel pile. This is the site of Renoville and the road to Kingston Wash, a historic shortcut to Stump Spring on the Old Spanish Trail.

30.9 (0.2) SLOW for a dip.

34.9 (4.0) This is the site of Valjean, a 1906 stop on the T&T railroad (Hereford and Webb, 2001; Mulqueen, 2001). PROCEED EAST on the road heading toward Kingston Wash and the Eastern Star Mine.

36.0 (1.1) Caution: dip.

39.8 (3.8) Reach a fork in the road with BLM directional signs. STAY RIGHT, continuing past the left fork to Kingston Wash.

40.3 (0.5) Caution: dip.

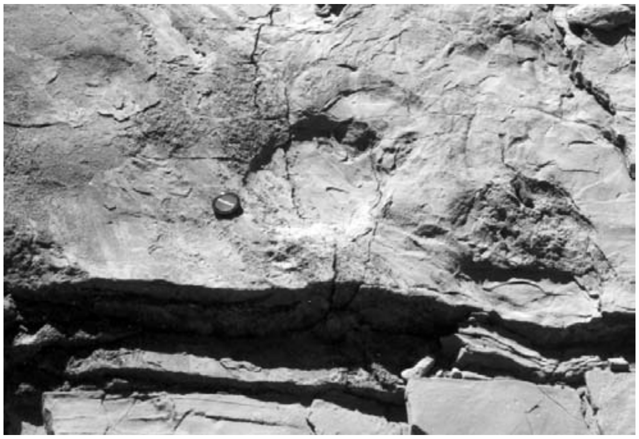
40.8 (0.5) The road runs across a late Pleistocene surface above a thick pedogenic carbonate equivalent to the Valjean Valley surface and possibly equivalent to the pedogenic carbonate along Excelsior Mine Road north of Interstate 15.

41.3 (0.5) Pass south of a drainage exposing thick Pleistocene pedogenic carbonate.

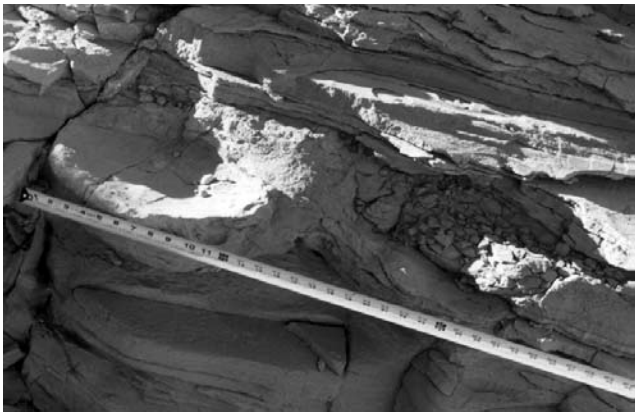
42.3 (1.0) We are driving on a terrace underlain by indurated pedogenic carbonate. In Eastern Star Wash, 20 feet below the pedogenic carbonates, an extremely mature, varnished desert pavement indicates a 15 Ky surface (Wells and others, 1990).

43.2 (0.9) The road drops into a wash.

43.3 (0.1) **STOP 1-1.** PARKand inspect the pedogenic carbonate and underlying red Miocene sediments that contain distinctive clasts of the late Proterozoic Tapeats Conglomerate that occur at only one source on the north side of Clark Mountain. Miocene sediments in the vicinity contain tracks of proboscideans, carnivores, camels, and pronghorn. The substrate that preserves the tracks is the coarse sand of a braided stream deposit. Each fluvial pulse fines upward into silty sands. Northeast are gray limestone



Plan view of Eastern Star Wash gomphothere tracks in coarse fluvial sandstone. These tracks are several inches deep, suggesting that the sandy substrate was moist, but not wet.



Exposed cross-section of gomphothere track impression showing the compression of underlying layers that form "ghost prints." Tracks approach 12 inches in diameter.

Gompothere track, exposed by erosion, was deeply impressed into wet, fluvial sand.

megabreccia sheets and dark volcanic rocks interbedded with the China Ranch beds (Wright, 1974). The China Ranch beds are a northwestern extension of the late Miocene basin filling sediments deposited during extensional tectonics.

RETRACE toward Highway 127.

46.8 (3.5) Continue past a fork in the road that leads northeast to Kingston Wash.

51.7 (4.9) Site of Valjean. TURN LEFT (south) and proceed along the east side of the T & T railbed to Railroad Valley. The intermittent ridge on the west (right) is called "The Islands" (Kupfer, 1960).

55.0 (3.3) **STOP 1-2**. Park in red sediments at the north end of the railroad cut. These red sediments filled the extending Miocene basin between 12 and 10 million years ago. The presence of Tapeats Sandstone in a red groundmass suggests a source from weathered sediments that occur at the only Tapeats locality on the north side of Clark Mountain. PROCEED SOUTH along the east side of the T&T grade.

55.4 (0.4) Intersection of T&T Railroad grade with an east-west road. TURN LEFT (east) and prepare to stop.

55.5 (0.1) **STOP 1-3**. Park and walk south 500 feet to look at weathered Teutonia Quartz Monzonite with leisingang weathering rings. This erosional surface exhibits concentric, red-brown limonite rings called leisingang weathering rings that indicate deep erosion over a long period of time. The deep erosion developed prior to the Miocene, and the soft gruess or arkosic sediments were stripped from the granitic surface during extensional tectonics, beginning locally around 12 Ma and continuing through 10 Ma. This is the pre-Miocene erosional surface that received chaotic deposition of metamorphosed carbonate gravity slide blocks thrust from the west around 9 Ma (Kupfer 1954, 1960: Reynolds and Calzia, 2001). These older limestone sheets sit on both the eroded quartz monzonite and on Miocene basin-filling sediments. Windows (fensters) in the limestone thrust sheets expose steeply-dipping, west striking Miocene silty sandstones that contain the tracks of wading birds. RETRACE to intersection with the T&T.

55.6 (0.1) Cross the intersection with the T&T railbed and PROCEED WEST across Silurian Dry Lake toward Highway 127.

55.8 (0.2) Pass between "The Islands" of Proterozoic carbonate rock.

58.5 (2.7). East edge of Silver Lake Playa.

59.0 (0.5). West edge of Silver Lake Playa.

59.2 (0.2) Stop at Highway 127, look for traffic, TURN RIGHT, and proceed north.

60.9 (1.7) Continue past the site of Renoville and the road to Kingston Wash.

66.8 (5.9) Pass through white and green lacustrine sediments of Lake Dumont. Stratigraphic relationships and radiocarbon ages suggest that the earliest-known Lake Dumont phase (30,000 BP) predated the earliest-known Lake Mojave phase (22,000 BP). Certain authors suggest that Mojave River waters probably did not contribute to lake-building events during this time, and that local precipitation draining from from Kingston Wash, Salt Creek, and the Avawatz Mountains was responsible for perennial Lake Dumont stands. However, Lowell Ford (p.c. 1999) reports carapace fragments from the Western Pond Turtle (*Clemmys marmorata*) weathering from a sandy silt in the middle of the stratigraphic section. Pond turtles are known from sediments of Manix Lake and the Mojave River, and their carapaces in Lake Dumont suggest a Pleistocene connection to the Mojave River system, no matter how brief.

138.1 (1.2) Continue past the Salt Spring Visitor Center. The view to the south shows scarps of the southern Death Valley fault zone and the Mule Springs Fault at the northern base of the Avawatz Mountains.

67.7 (0.9) Continue past the Wade Exit Monument. Harry Wade was a member of the "Sand Walking Company" that reached Salt Lake City in 1849 too late in the season to cross the Sierra Nevada into California. The company decided to break away from the Old Spanish Trail and other travelers led by Jefferson Hunt to take a supposed short cut through Death Valley. Wade abandoned the short cut and led his family and wagon out of Death Valley along the Amargosa River, rejoining the Old Spanish Trail at this point (Lingenfelter 1986).

69.9 (2.2) Cross the Amargosa River. The Amargosa River has not caused much incision into this shallowly-convex landform.

71.8 (1.9) Continue past the graded dirt road to the Dumont Dunes and head toward the Sperry Hills.

75.8 (4.0) Before reaching the left bend in the road, look to the right at 2:00 to a light gray limestone megabreccia sheet and dark volcanic rocks interbedded with the China Ranch beds (Wright, 1974).

77.6 (1.8) Continue past a left turn to a microwave station.

78.0 (0.4) Rocks of the Sperry Hills are light-colored because they consists of late Miocene granite boulders from the 12 Ma Kingston Peak pluton.

79.1 (1.1) Cross over Ibex Pass. We are entering Inyo County.

83.6 (4.5) Lake Tecopa sediments dip gently eastward. In 0.2 miles we will see the Lava Creek B Ash, dated at 0.62 Ma (Hillhouse 1987).

84.8 (1.2) Continue past Spanish Trail Mesa on the right.

85.3 (0.5) Continue past a right turn for Old Spanish Trail.

88.3 (3.0) Continue past a right turn to Tecopa Hot Springs (a pleasant place to end a day).

93.5 (5.2) SLOW, continue past Highway 178 (the Charles Brown Highway).

93.8 (0.3) **PARK** on the right at the Shoshone Museum. **STOP 1-4:** Exhibits display Pleistocene mammoth and mastodon remains, and replicas of Pleistocene mammal tracks from the mid-Pleistocene Lake Tecopa sediments that we have driven through. From the museum, we will walk to the Lava Creek B volcanic ash quarry to look at original tracks, examine the substrate containing tracks and overlying sediments, and discuss direct and indirect methods for dating fossil trackways.


Pleistocene Late Irvingtonian LMA horse tracks in the sediments near Lake Tecopa. These tracks show typical impression of hind foot on the imprint of the fore foot.

Pleistocene horse tracks near Shoshone are in mud-flow debris near Lake Tecopa. This track shows the impression of the "V" shaped frog at the rear margin of the foot.

RETRACE the day's route south along Highway 127 to Baker. Fill vehicles with gas and obtain supplies such as water, sunscreen and snacks.

DAY 2

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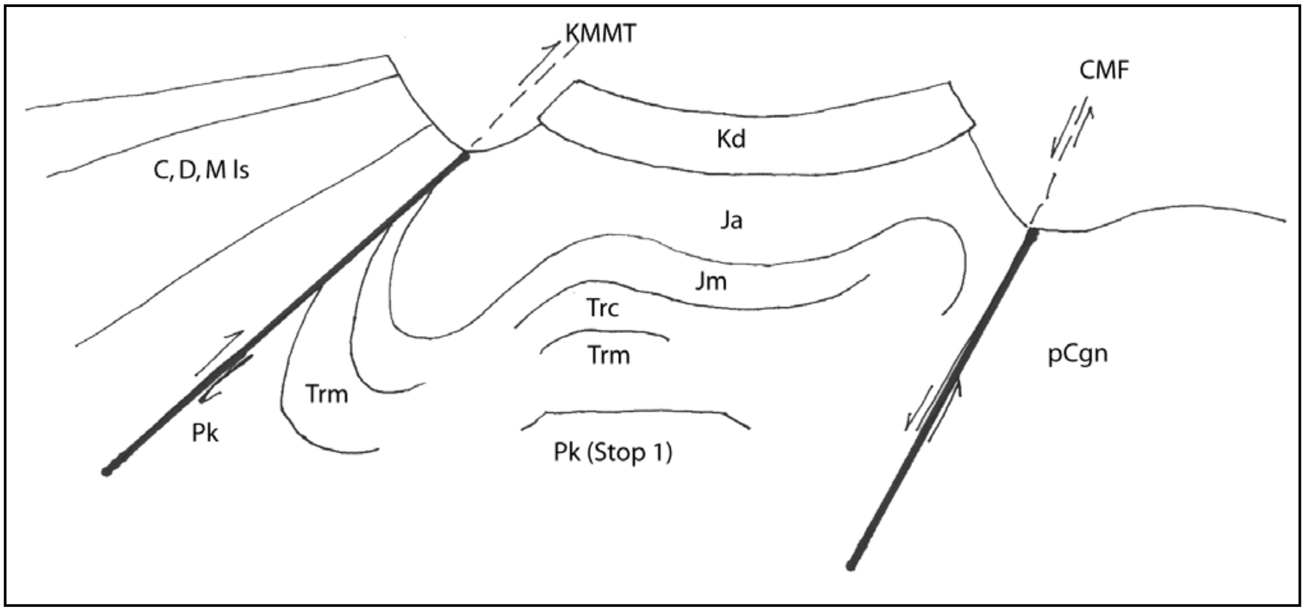
Dwight L. Schmidt, *U.S. Geological Survey*

Convene at CSU Desert Studies Center. Be sure your gas tank was filled and provisions were obtained the previous evening. Proceed north toward I-15 for the ~300 mile trip.

What we will see:

East of Las Vegas, our Day 2 route will be in the Basin and Range Province where we will see:

- low, fault-bounded mountain blocks that contain east-dipping sediments.
- marker beds of late Paleozoic to Middle Jurassic age. These include the prominent, resistant lower Permian Kaibab Limestone overlain by the colorful, easily-weathered clastic sequence that includes the Chinle Formation, the Moenave, Kayenta, Aztec and Navajo Sandstones. These will be somewhat abbreviated by thrust faults and erosional events.



View north from Stop 1 of south side of Mescal Range: depositional history. ***Kd****: Cretaceous Delfont Volcanics;* ***Ja****: Jurassic Aztec Sandstone;* ***Jm****: Jurassic Moenave–Kayenta Sandstone;* ***Trc****: Triassic Chinle Formation;* ***Trm****: Triassic Moenkopi Formation;* ***Pk****: Permian Kaibab Limestone;* ***C, D, M ls****: Cambrian–Mississippian limestone;* ***pCgn****: Proterozoic gneiss. Structural geology:* ***CMF****, Clark Mountain Fault (Cretaceous, <100 Ma, down-to-west);* ***KMMT****: Keaney–Mollusk Mine Thrust (older east over younger, <83 Ma).*

- California's only Mesozoic dinosaur tracks in the Jurassic Aztec Sandstone
- Miocene crustal thinning–extensional faults and the formation of basins related to these tectonics that contain sediments with trackways of birds and mammals of middle and Late Miocene time.

At the end of Day 2, we will enter the transition zone from the Basin and Range Province to the elevated, flat lying strata of the Colorado Plateau.

0.0 (0.0) Convene at Zzyzx CSUF Desert Studies Center with a full tank of gas

4.7 (4.7) Enter I-15 eastbound, toward Baker.

11.0 (6.3) Continue past Kelbaker Road, central Baker.

23.6 (12.6) Continue past the Halloran Spring exit. Petroglyphs in the vicinity are ichnites (tracks or traces) made by humans. Petroglyphs, pictographs, artifacts, and vertebrate fossils and their tracks and traces are non-renewable resources that must not be disturbed under penalty of fine or imprisonment.

29.6 (6.0) Continue past the Halloran Summit exit.

36.7 (7.1) Continue past the Cima Road exit.

45.1 (8.3) EXIT at Bailey Road at Mountain Pass.

45.4 (0.3) STOP at Bailey Road. TURN RIGHT (south) and immediately LEFT on frontage road. Proceed east.

46.1 (0.7) Pavement ends; the road turns right (south).

46.5 (0.4) Corral. TURN LEFT (east) and continue to the first summit.

47.2 (0.7) At the first summit, proceed downhill, then ascend to second summit.

48.3 (1.1) BEAR RIGHT at the summit at the east end of Piute Valley.

48.6 (0.3) BEAR RIGHT at the junction; follow the Kokoweef Cave sign.

49.4 (0.8) TURN LEFT (south) at the intersection marked with a sign to Kokoweef Cave.

49.8 (0.4) **STOP 2-1**. PARK at a gray limestone outcrop on the north side of the wash. Discuss Permian to Cretaceous sequence of sediments and volcanic rocks and the tectonic events that placed them in this sequence. Some of the formations here are similar to those in the Grand Canyon.

We can see:

> A depositional sequence that spans 150 Ma from the Permian Kaibab Limestone (underfoot) through Moenkopi (Trm), Chinle (Trc), Moenave (Jm), and Aztec (Ja), capped by the 100 Ma Delfont Volcanics (Kv)
>
> Cretaceous volcanics (Kv) are related to intrusion of the 100 Ma Teutonia Quartz Monzonite (Kt) batholith
>
> Thrust faults (Keaney-Mollusk Mine—KMM) and extensional faulting (Clark Mountain Fault—CM) dating between 100–83 Ma. Thrust faults place older rocks over younger rocks. In this case, the middle Paleozoic limestone sequence is thrust over the late Paleozoic–early Mesozoic clastic sequence

RETRACE NORTH to the intersection.

50.2 (0.4) Cross the intersection.

50.4 (0.2) **STOP 2-2**. PARK in the flat area. HIKE northwest toward California's only dinosaur tracks, located in the early Jurassic Aztec sandstone (see Reynolds, *Jurassic*, this volume). This is a BLM Area of Critical Environmental Concern (ACEC) and is patrolled regularly by BLM rangers, as well as by paleontologists doing monthly research. Specimens are "collected" by replication, which involves applying a release agent to prevent harm to the trackway panel, then making silicone replicas and restoring the surface of the trackway panel to its original condition. All research and replication require a BLM permit specifying a museum repository.

The Cowhole volcanics that intrude and interfinger with the Aztec Sandstone in the Cowhole Mountains date between 170 and 173 Ma, suggesting that the Aztec is younger than the Navajo Sandstone. Recent research (Reynolds, 2005) has recognized tracks left by quadrupeds which can be grouped by equidimensional (five ichnotaxa), elongate (two ichnotaxa), and gracile (one ichnotaxa), and secondarily by length/width ratios. Seventy percent of the tracks in the Mescal Range were left by quadrupeds; bipeds account for thirty percent. Size and symmetry of two bipeds compare with *Anchisauripus* and *Grallator*. A third, unnamed, bipedal track is symmetrical, with wide digit divarication. Conservatively, the Mescal Range Aztec Sandstone contains tracks representing three bipedal theropods and eight quadrupeds with *Navahopus*, *Brasilichnium,* and *Pteraichnus* previously recognized. Additional ichnites are attributed to *Octopodichnus* and *Skolithos*.

Compression rings around tracks show paleo-slope orientation. Cross-bedding, ripple marks and raindrops are present, cubic pseudomorphs suggest primary halite, and limonite concretions represent weathering profiles. Folded strata, secondary druzy quartz, and irregular goethite stains show a long weathering history.

Kokoweef Peak to the southeast consists of Paleozoic limestone cut by northwest-trending faults. Groundwater percolation along fault breccia zones has created fissures and caverns that were open to the surface during late Pleistocene time. These caves were filled with sand, packrat midden debris, and the remains of Pleistocene snails, fish, reptiles, birds, and mammals that lived at the top of the peak, or were brought to the peak by mammalian carnivores and avian raptors, and introduced into the cave by scavenging wood rats (Reynolds et al, 19991a).

RETRACE to the Bailey Road junction with I-15.

54.2 (3.6) TURN RIGHT at a corral.

55.3 (1.1) STOP at sign. TURN RIGHT.

55.4 (0.1) Enter I-15 eastbound at Bailey Road and head toward Las Vegas.

59.9 (4.5) Pass the Nipton Road exit.

69.2 (9.3) Pass the Yates Well Road exit.

74.6 (5.4) Pass the Primm exit (formerly Stateline) at the Nevada border.

86.4 (11.8) Pass the Jean/Goodsprings exit.

99.4 (13.0) Pass the Sloan exit. The mines at Sloan Hill to the north have produced limestone and dolomite from the Dawn and Bullion members of the Monte Cristo Limestone since 1910.

101.3 (1.9) Pass the Henderson exit (Highway 146).

107.1 (5.8) Pass the Blue Diamond exit (Highway 160 west to Pahrump).

108.1 (1.0) Pass the exit to Airport and Southern Beltway West.

112.6 (4.5) Pass the Tropicana exit.

117.1 (4.5) Pass the Charleston West exit.

117.7 (0.6) PROCEED THROUGH the Highway 95–515 interchange. Proceed northbound on I-15 toward Mesquite. Avoid the exits to Tonopah and to Henderson/Kingman.

121.4 (3.7) Pass the CHEYENNE exit. Gas and fast food are available east and west of I-15.

124.9 (3.5) Pass Lamb Blvd.

126.6 (1.7) Pass 215 Northern Beltway West.

128.2 (1.6) Pass the Speedway Blvd. exit.

132.9 (4.7) Pass the Apex exit to Nellis Air force Base.

133.1 (0.2) Note the yellow to orange sediments of the Muddy Creek Formation overlain by a gray conglomerate of cemented limestone clasts. Crustal thinning during the Miocene caused tectonic extension which created fault-bounded, east-tilted mountain ranges of Paleozoic rocks and early Miocene basin-filling debris. Drainages leaving the unextended Colorado Plateau to the east brought red-colored sediments to fill basins between the fault blocks. These flat-lying sediments are called the Muddy Creek Formation (Schmidt et al, 1996), which extends from Las Vegas, Nevada to Littlefield, Arizona. The Muddy Creek Formation does not extend past the local basins, since it was deposited before the formation of a cohesive Colorado River trough. All younger, overlying formations were deposited in drainage systems that emptied into the Colorado River system.

137.0 (3.9) The Apex Limestone mine to the north (Longwell and others, 1965) produces pure crystalline limestone from the Crystal Pass Member of the Sultan Limestone. PREPARE TO EXIT at Great Basin Highway (Highway 93).

138.8 (1.8) EXIT at Great Basin Highway (Highway 93 exit 64 to Pioche/Ely)

139.1 (0.3) STOP. TURN LEFT (north) under the freeway toward Caliente and Ely.

139.6 (0.5) The playa in Dry Lake Valley is to the east.

141.1 (1.5) Look to 10:00 at the distinctive scalloped layer cake of the Mississippian Bird Spring Formation.

146.6 (5.5) Enter Hidden Valley. We are in the Basin and Range geologic province. This province extends from eastern California north of the Garlock Fault, and southern Nevada to Yellowstone, Wyoming. The Mojave Desert Province (Day 1) is characterized by northwest-trending fault-bounded ranges (as well as east-west faults parallel to the Garlock Fault). In contrast, the Basin and Range Province is characterized by north-trending fault-bounded ranges with intervening basins. We will pass through fault-block ranges that have been tilted east, the west side being the retreating scarp, and the east slope being supported by the resistant bedding plane of underlying sediments. This east slope is called a "cuesta." At the end of Day 2 we will enter the transition zone from the Basin and Range Province to the Colorado Plateau geologic province where unextended flat-lying Paleozoic and Mesozoic rocks sit at high elevations.

The Las Vegas Range dips east; however, strata to the north are folded into anticlinal and synclinal folds with north-trending axes (Page and others, 2005).

155.4 (8.8) Pass between the Las Vegas Range to the west (Devonian–Mississippian) and the Arrow Canyon Range (Upper Cambrian–Silurian–Devonian–Ordovician–Mississippian) to the east.

160.1 (4.7) The east-dipping beds of limestone exposed in the retreating scarp to the east can be found in the east-dipping rocks of the Meadow Valley Mountains to the northeast. Hence, the brown, silicified limestones at 11:00 are the same bed we see at 2:00 (Page and others, 2005). The view north of repeated fans illustrates the concept of bajada. In Spanish, *bajada* means ladderway. Compound, coalescing alluvial fans compose a ladderway of undulating character, stretching into the distance like ladder rungs. The bajada surface of deposition contrasts with a pediment, a surface of erosion. When bajadas are carbonate-cemented, however, they may act as a pediment, and rock debris may be transported across them to the axial valley drainage.

163.1 (3.0) Enter Coyote Springs Valley. White groundwater discharge deposits can be seen at Starvation Flats to the northeast at 10:00. Basin-Range faulting tilts mountain blocks eastward. Follow the bands of black and brown limestone northeast as they repeat through mountain blocks as far northeast as the Meadow Valley Mountains (Page and others, 2005).

166.0 (2.9) TURN RIGHT (east) on Highway 168.

167.2 (1.2) Pass through white groundwater discharge deposits consisting of poorly consolidated calcareous mud, silt and sand. Here along Pahranagat Wash, these calcareous groundwater discharge deposits are characteristically deposited with the aid of evaporation as sulfate-bearing, carbonate precipitates in wetlands and marshy areas along the axial drainage of major basins. Fossils include ostracodes and gastropods, fragmentary remains of mammoth, camel, and horse (Quade and others, 1995, 1998) and a late Pleistocene age (in part) is suggested by fragmentary remains of bison, the late Pleistocene Rancholabrean Land Mammal Age indicator fossil (REF; and Woodburne and Swisher, 1999).

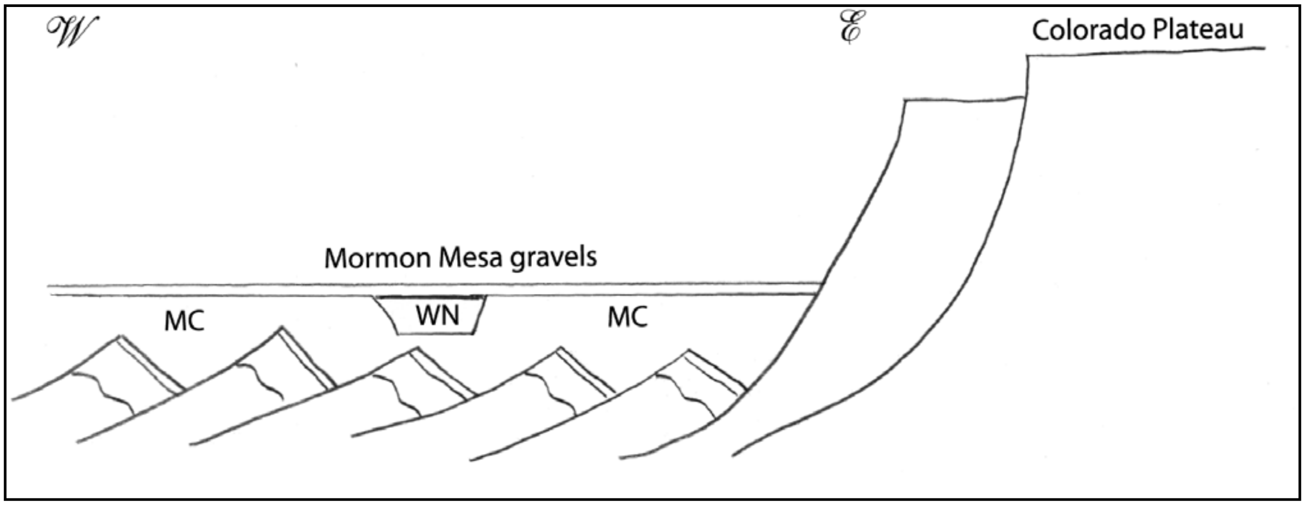
167.8 (0.6) View north at 10:00 shows terraces of white groundwater discharge deposits.

168.2 (0.4) Look ahead to the pale salmon-orange lower member of the Muddy Creek Formation.

168.7 (0.5) Pull to the right shoulder and PARK.

STOP 2-3. Starvation Flat. The lowland ahead was named for consistent but minor production of placer gold during the Great Depression years. The abrupt cliff above and east of the flood plain of the Pahranagat Wash is composed of the Aggradational Gravel of Whitmore Mesa (the type area is near Glendale, which we will see later in the day). At the top of the cliff, but below the gravel and in descending stratigraphic order are the thin basal Yellow Sand Member of the Aggradational Gravel, the thinner Green Claystone Member of the uppermost Muddy Creek Formation, and the underlying, thick, pale salmon-orange Mudstone Member of the Muddy Creek Formation. Of this four unit sequence, the three units below the cliff are poorly exposed at this site. This same sequence of four units will

View west of exposures of the Muddy Creek Formation showing the pale salmon-colored lower member and the greenish-gray upper member. The overlying bluffs contain the aggradational Yellow Sand of Whitmore Mesa.



Simplified cross section from west to east, showing the relatively unextended terrain of the Colorado Plateau to the east, the highly extended Basin and Range terrain to the west. Basins of the latter were subsequently filled with sediment of the Muddy Creek Formation and, in grabens, the White Narrows Formation.

be observed near Glendale. These latest Miocene to early Pliocene of Muddy Creek and Aggradational Gravel formations have relatively flat bedding planes, suggesting deposition was at a time when there was only minor extensional deformation.

During extensional tectonics in the Basin and Range Province, the relatively non-extended Colorado Plateau was left at high elevations to the east (for example, the high plateau terrain of the Grand Canyon area), whereas the Basin and Range fault blocks were subsided to lower elevations to the west (for example, our present area or the Great Basin region of Nevada). During most of the extensional deformation of the Basin-Range Province, range-scale blocks of the Paleozoic through Mesozoic strata were tilted either eastward or westward. Locally derived, pale-gray and brown or pale-greenish gray, Middle Miocene sediments, which comprised the Horse Spring Formation and filled the basins, were being similarly and continuously tilted during deposition. After major tilting, extensional deformation had greatly diminished by about 12-11 Ma and the mostly flattish-lying sediments of the Muddy Creek Formation continued to fill the basins until about 5 Ma. For the most part, these basin-fill sediments were locally eroded debris from adjoining ranges and after deposition, during subsurface deuteric alteration, were oxidized to their characteristic pale salmon-orange color. The sparsely preserved fossil mammals are consistent with a late Miocene, mid-Hemphillian Land Mammal Age (Reynolds and Lindsay, 1999).

By the end of Muddy Creek time, about 5 Ma, the individual basins of the Greater Lake Mead Depression were filled to a high level, such that a few individual, adjoining basins had become connected at a common fill level. An example is the coalescence of the Glendale basin (which we will see later today) to the California Wash basin, and the very near coalescence of the California basin to the Dry Lake basin, which we saw earlier today in the vicinity of the junction of I-15 and US Highway 93.

The Yellow Sand of Whitmore Mesa (Schmidt and others, 1996) is also the basal unit of the White Narrows Formation, which we will soon see at Moapa. The Yellow Sand stratigraphically is defined as the basal unit of the Aggradational Gravel of Whitmore Mesa, which is contemporaneous with the White Narrows Formation, and both overlie the Muddy Creek Formation (Schmidt and others, 1996).

At this stop looking at the cliff to east, the Yellow Sand lies conformably, directly on the Green Claystone of the top of the Muddy Creek Formation, but only sparse, small outcrops of the Green Claystone are exposed. The Yellow Sand, in part, represents a hiatus that was followed by the aggradational sands and gravels of the transgressive, aggradational gravel that originated from the north, mostly from upper Pahranagat Wash. This Yellow Sand contains the fossil vertebrae of large fish (Reynolds and Lindsay, 1999). These fish fossil in the Yellow Sand beg the question of the source of the fish because at this time this remote area was not connected to the proto-Colorado River. Integration of this area to the Colorado River drainage system may have been about a million years later and will be indicated by the top of the Aggradational Gravel of Whitmore Mesa (Tag), which is probably represented by the uppermost depositional surface on top of the cliff we are viewing.

About five million years ago, this stop would have been far and remote from the encroaching proto-Colorado River drainage about 80 km to the southeast and south in the Lake Mead area. By this time the newly forming Colorado River had traversed the Colorado Plateau above the future Grand Canyon course (as we know it today), had spilled at the Grand Wash Cliffs into the greater Lake Mead Depression, and was spilling above its present-day, Hoover Dam reach into the Lower Colorado River Corridor where no prior integrated river had previously existed. The new massive volume of proto-Colorado River water caused lakes to form in a string of closed basins between Hoover Dam and the then newly developing Gulf of California. Scabs and bodies of fossiliferous, nonmarine carbonate deposits of the Bouse Formation precipitated from these short-lived, evaporating lake waters, both north and south of Parker, AZ. Entrenchment across the several rock barriers between Grand Canyon the Gulf of California by roughly four million years ago finally established a through-flowing Colorado River at its maximum aggradation altitude about 4.2–3.6 Ma. Shortly thereafter, the Colorado River cut down to about its present-day level before 3.3 Ma (Atwater, 1992; Buising, 1992; Dorsey and others, 2005; House, 2005; McDougall, 2005; Spencer and others, 2005; House and others, 2005).

ENTER Hwy 168 and continue eastbound.

168.9 (0.2) Cross Pahranagat Wash.

171.6 (2.7) A resistant carbonate cap of the upper member of the Muddy Creek Formation is on the right.

173.1 (0.5) Pass through a saddle.

173.9 (0.8) Pass a gravel pile on the right. PREPARE for right turn.

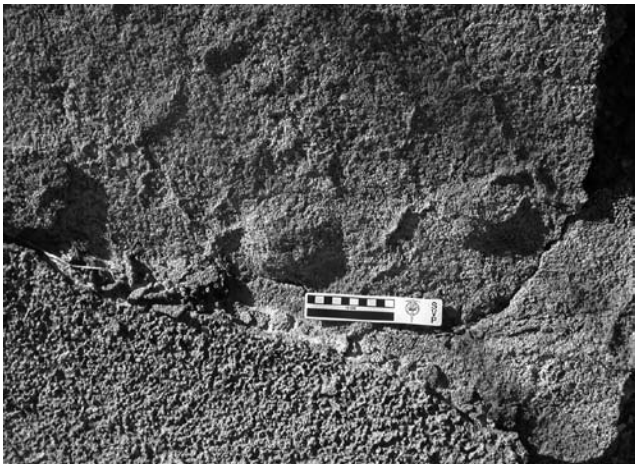
174.0 (0.1) TURN RIGHT (southwest) on the graded road down Dead Man Wash. Table Mountain is ahead.

174.3 (0.3) The road drops into Dead Man Wash heading along the east side of Table Mountain.

175.5 (1.2) **STOP 2-4**. PARK at Table Mountain. Table Mountain consists of white groundwater discharge deposits more than 200 feet thick at this stop. This white facies grades laterally into the normal pale salmon-orange mudstones of the upper Muddy Creek Formation with the top of the Muddy Creek about 200 feet above the top of Table Mountain. The local section consists of thin bedded, pale gray to pale greenish-gray, gypsiferous, carbonate-rich siltstone and mudstone. It is a mixture of locally derived fine-grained sediments and sulfate-bicarbonate aquifer water from which gypsum and carbonate were precipitated by evaporation. The depositional environment throughout was biogenic-rich marsh and swamp of which the carbonaceous parts have long since been oxidized and only trace fossil are found. Locally, in the vicinity of Table Mountain on exposed limestone bedding planes, preserved tracks of large birds, camels, and possibly proboscideans are found in abundance. Complex sedimentary structures also seen on slabs may represent trampling by herds of artiodactyls. These traces of animals indicate a late Miocene Hemphillian NALMA (as young as about 5 Ma). This general age range agrees with a specific well dated ash located about 2/3 of the way up the Table Mountain section, but the ash bed is difficult to see without detailed examination because the gray crystalline gypsiferous beds and the ash bed look alike.

However, the ash bed, about half a meter thick, is widely exposed throughout the Table Mountain basin and ready seen elsewhere by its contrasting pale gray ash bed in the characteristic pale salmon-orange mudstones of the Muddy Creek Formation.

Fallen blocks expose layered biogenic carbonate mats at Table Mountain. The carbonate mats contain tracks of large water birds and camels.



Carbonate mats at Table Mountain contain depressions from mammals that might have been the size of mastodons.

The ash at 5.6 Ma is the well dated and well known Wolverine Ash and Ignimbrite of the Snake River Plains in southern Idaho. The spring sources of the groundwater discharge were along the Range Front Fault about 2 km to the east of the parked cars. Ancient springs are found along this fault. However, the range-front is better represented by a wide fault zone that suggests that a much closer discharge site probably existed hidden within and beneath the Table Mountain deposit.

Return to vehicles and RETRACE to Highway 168.

177.0 (1.5) Stop at the pavement at Highway 168. Watch for oncoming traffic and TURN RIGHT (east southeast) onto the highway.

178.5 (1.5) Pass over a ridge into the drainage divide at the head of Upper Moapa Valley.

180.8 (2.3) Upper Moapa Valley, Muddy River Springs and White Narrows lie ahead (southeast). Muddy

River Springs, consisting of a half dozen major warm springs (35C; 95F), are located along north-south trending faults of a one-kilometer wide range-front fault zone along the east front of the Arrow Canyon Range. Together these springs discharge about 136 acre-feet/year of deep circulating, sulfate, bicarbonate aquifer groundwater. This spring discharge keeps the Muddy River flowing year around and it was once used entirely for agriculture and minor domestic use, mostly in the Lower Moapa Valley south of Glendale. Currently much of the discharge is intercepted in shallow wells for industrial and municipal use and the Muddy River perennial flow is accordingly much decreased. The groundwater of these springs flows from the huge, deep White River Aquifer System, a very wide, interbasin flow system in the very thick Paleozoic carbonate rocks that roughly parallels the White River (upstream part of the Pahranagat Wash we saw at STOP 2-3) north to the vicinity of Ely, NV.

An older version of the Arrow Canyon range-front fault zone is located 1 to 3 km farther east and well defines most of the graben structures wherein most of the White Narrows Formation of the local area was deposited. Likewise, older warm springs discharged the sulfate-carbonate, aquifer groundwater from this older fault system. This spring water precipitated the minerals (gypsum, calcite, etc.) that produce the characteristic white color of the local sediments filling the White Narrows graben structure. At least one small warm spring is currently still active on the fault-bounded west margin of the local fault and graben system, but otherwise all spring discharge had been long previously transferred to the west to the modern Muddy River Springs area.

181.9 (1.1) Continue past the westernmost turnoff to Warm Springs Road.

182.7 (0.8) Continue past the second turnoff to Warm Springs. Arrow Canyon is a spectacular gorge to the west.

183.5 (0.8) Continue past Hawthorn Road/Sinclair Road. Note the dense growth of Washingtonia palms along the fault seeps to west. Note also that regardless of the large carbonate-saturated groundwater discharge resulting in abundant wetlands, carbonate deposits are not present at the surface, presumably because of the strongly reduced (low pH) biogenic environment.

184.2 (0.7) Battleship Butte is at 2:00 to the southwest. A low silt and gravel terrace of Pleistocene age is at 9:00.

185.7 (1.5) Continue past the third right turn to Warm Springs. Outcrops of silty sandstone expose the salmon-colored red mudstone facies of the Muddy Creek Formation along the left side of the highway and ahead. In this area the red mudstone has been down-dropped and eroded many tens of meters below the green claystone of the uppermost Muddy Creek Formation. At more distance to the right and left can be seen the White Narrows Formation that occupies a fault-bounded graben complex and lateral channels (Schmidt and others, 1996). Photos 123, 122, 121.

186.0 (0.3) Ascend the slope rising above the valley floor and enter the graben filled with White Narrows Marl (Schmidt and others, 1996). PREPARE to turn right. This turn is about on a major graben fault with pale salmon-orange Muddy Creek to west (behind) and White Narrows Formation to east (ahead).

186.3 (0.3) TURN RIGHT onto a two lane graded road.

186.5 (0.2) PARK at the junction with a second graded road. Do not block traffic.

STOP 2-5. We are surrounded by white, marl-rich siltstone of the graben-filling White Narrows Formation. The relation between the orange Muddy Creek Formation and the infilling White Narrows Formation is very significant because it provides age constraints on the change in drainage systems (chiefly the Colorado River system) of southern Nevada and the southwestern United States. The White Narrows Formation represents unconformable deposition in a graben complex developed during early Pliocene time in the late Miocene Muddy Creek Formation. The White Narrows Formation consists of two contemporary units: a central gypsiferous, calcareous graben-fill unit, and a lateral channel-fill unit of similar composition that backfills the eroded Muddy Creek footwalls outside the graben. Fossil rodents found near the base of the White Narrows Formation at the Reid Gardner Generating Station at Moapa (the power plant can be seen 7 km to southeast) date to earliest Pliocene (latest Hemphillian or earliest Blancan NALMA at 4.7?4.5 Ma; Woodburne and Swisher, 1995; Schmidt and others, 1996; Reynolds and Lindsay, 1999)Photos 132 – 127.

Stromatolites are calcium carbonate layers or coatings precipitated by blue-green algae that cover water reeds and bushes. The woody interior subsequently decays, leaving a hollow. The stromatolites at this stop are indicative of deposition of the White Narrow Marl in a wet meadows environment that was shallow, choked with vegetation, and rich in calcium carbonate (calcite) as well as in calcium

Stromatolites (tufa) are calcite that coats underlying objects. At this locality, calcium carbonate was precipitated from shallow, sun-lit lake water and deposited around plants and water reeds. The plant material subsequently dissolved, leaving hollow tufa structures.

sulfate (gypsum), probably owing to discharge of carbonate-saturated groundwater, rich in calcium sulfate, warm springs discharging along the then active graben faults.

WALK WEST and climb up thick limestone beds of the White Narrows Formation to find stromatolites.

Return to vehicles and RETRACE to pavement.

187.1 (0.6) Stop at pavement. Watch for traffic and TURN RIGHT (south) toward Moapa.

187.4 (0.3) Continue past Ranch Road on right.

188.6 (1.2) Enter the Moapa Indian Reservation. The high surface we are driving on is the Late Pliocene regrade terrace underlain by its gravels (Trg) that represent the down cutting of all streams in the area after the Meadow Valley Wash integrated via the Overton Arm to the then well entrenched early Colorado River in the Lake Mead area. The regrade terrace represents the first preserved early Pliocene erosional step-down from the high Aggradational-Gravel terrace (Tag; to be seen soon at next stop).

The regrade gravel here beneath the highway is that of Meadow Valley Wash and has a well-developed, resistant calcrete soil cap commonly about 2 m thick (in contrast to the older, about 5-m thick calcrete on the high Aggradational Gravel).

188.9 (0.3) Continue past Lytle Lane.

189.3 (0.4) Continue past Reservation Road.

190.5 (1.2) Continue past Postal Road, cross over the railroad tracks, and continue past Hidden Valley Road.

191.2 (0.7) Ascend the terrace and PREPARE to turn left.

191.4 (0.2) WATCH FOR ONCOMMING TRAFFIC and TURN LEFT (north) onto a terrace with a white metal tank.

191.6 (0.2) At the tank, TURN RIGHT (east) and proceed along the power line road. The underlying terrace surface is the oldest Quaternary terrace preserved in the area and it is of early or middle Pleistocene age. The gravel is mainstream alluvium of an ancestral Meadow Valley Wash (The currently active Meadow Valley Wash can be seen immediately ahead).

192.0 (0.4) Cross a cattle guard and PARK at the edge of the bluff.

STOP 2-6 View to east perpendicular to Meadow Valley Wash and north of Glendale on I-15. The pale salmon-orange, siltstone-sandstone cliffs of the Muddy Creek Formation are cut by several conspicuous, high, gravel terrace remnants of the same early-middle Quaternary age as those on which we stand. The viewed terrace remnants consist of sidestream gravel, which slope steeply up to the east to a local source for the gravel. In contrast, we are standing on a low gradient, flat gravel terrace that has the low gradient of Meadow Valley Wash, indicating a source from the very large Meadow Valley Wash drainage basin.

From N45E to N on the right valley side of Meadow Valley Wash, the Aggradationl Gravel of Whitmore Mesa makes a striking caprock cliff high above a steep colluvial slope eroded in mudstones and claystones of the Muddy Creek Formation. In the vicinity, the late Miocene Muddy Creek bedding planes contain tracks of elephants, camels, birds, coyotes and small, three-toed, hipparion horses called *Nanippus* sp. (Reynolds, *Hoof Prints*, this volume).

The high Early Pliocene terrace gravel (Tag) here is only about 20-m thick and has a thick (about 3 m), middle-Pliocene calcrete soil top (Tak). This calcic paleosoil is a couple million years younger that the Mormon Mesa calcrete soil (about 5-m thick) of earliest Pliocene age, which we will see in road cuts along I-15 four miles east of this stop. The more distant high gravel cliff hardly seen to the north-northeast underlies Whitmore Mesa, the type locality for the Aggradational Gravel of Whitmore Mesa (located 16-20 km to the north-northeast). Many tens of miles farther north, the Aggradational Gravel is several hundreds of feet thick. The gravel in our near view to the northeast is the feathering edge of the deposit.

The Arrow Canyon Range is seen continuously from the southwest and west-northwest where it terminates at Highway 168. The Meadow Valley Mountains to the northwest continue to the north. These two ranges have cores of Paleozoic and Mesozoic sedimentary rocks that have been tilted eastward, whereas the Mormon Mountains to the north-northeast constitute a huge structural dome having a core of Precambrian and Paleozoic rock that tilts radially in all directions around the dome. Deformation by uplift and tilting was caused chiefly by extensional tectonics during the Late Miocene. The core rocks of the ranges act as basement for the early Late Miocene syntectonic basin fill (Horse Spring Formation) that was also tilted eastward (and tilted radially around the Mormon Mountains). The tilted rocks are covered by sediments of the Muddy Creek Formation that are generally flat-lying, suggesting that extensional deformation had greatly reduced in intensity by about 10 million years ago.

Our next stop (Stop 2.7) is a large Pleistocene spring mound that forms an obvious topographic dome about 3 km distant, slightly left of south (at about 1:00 relative to alignment of Highway 168). Only the upper part of the mound is seen in profile

Return to vehicles and PROCEED EAST on the continuation of the pipeline road, down a steep grade to Henry Road .

192.3 (0.3) STOP at pavement (Henry Road). Watch for cross traffic and TURN RIGHT (south).

192.7 (0.4) STOP at Highway 168. Perkins Elementary School is on the left. TURN LEFT (southeast) and proceed south toward Glendale. PREPARE to turn right after you cross the Muddy River.

193.7 (1.0) Cross the Muddy River.

193.8 (0.1) TURN RIGHT (west on frontage road) before you reach theInterstate15 onramp/overpass complex.

194.0 (0.2) Cross a railroad track and immediately TURN LEFT (south), proceed under the freeway bridge, and PARK.

STOP 2-7. WALK WEST to a very large, gypsum-rich carbonate spring mound. Subsurface aquifer water, flowing down-gradient and confined under hydrostatic pressure, discharges at the surface as springs where the aquifer meets barriers or impervious fractures. Moapa Valley from here northwest to Muddy River Springs has spring structures that date to earliest Pliocene time (Page and others, 2005; Schmidt and others, 1996). In general, spring mounds consist of poorly consolidated limestone (plus or minus gypsum) or travertine aprons developed around single or multiple fault-controlled spring vents discharging carbonate-saturated groundwater. At this mound, a single large vent is well exposed and bisected along I-15, 200 to 300 m west and high above us at this stop. The discharge aprons contain plant material, stem and root casts (Page and others, 2005), and uncommon mammoth and camel bones suggesting a late Pleistocene age (Illinoian) for the youngest growth cap on the mound (which is all we see at this stop). The source of the gypsum is a large content of sulfate ion in the discharged bicarbonate-sulfate aquifer water. Gypsum concentrations in this spring mound were mined for the production of wall plaster from 1919–23 (Papke, 1987). The mine was operated by the White Star Plaster Company using short adits underground and small open cuts on the surface; some of the ruins of its mill are seen in our parking area. RETRACE to vehicles at pavement.

Proceed north under freeway bridge

194.6 (0.1) Stop, TURN RIGHT across the railroad tracks.

194.8 (0.2) STOP at Highway 168. TURN RIGHT and then IMMEDIATELY LEFT before reaching the interstate. Proceed through Glendale to the eastbound onramp

195.0 (0.2) Cross the Muddy River.

195.5 (0.5) Stop at sign and PROCEED EAST.

195.7 (0.2) Turn right, under the interstate, then TURN LEFT and enter I-15 eastbound.

197.5 (1.8) EXIT I-15 (Exit #94) and TURN RIGHT toward Logandale on Highway 169.

197.8 (0.3) Slow, BEAR RIGHT (south) on Highway 169.

203.1 (5.3) Cross the Muddy River.

203.5 (0.4) TURN RIGHT (west) on Liston Road

203.7 (0.2) TURN RIGHT (north) on Mills Road.

203.9 (0.2) Cross the railroad tracks and PROCEED NORTH.

204.6 (0.7) At a complex intersection, TURN LEFT (west) at Tai-Arabian Lane toward Logandale Trails.

205.0 (0.4) The road reaches a saddle with a parking area.

205.9 (0.9) Continue past a second parking area.

206.1 (0.2) At the west end of parking area, TURN 45 degrees RIGHT (northwest) on a dirt track. Leave the main graded road. which drops down hill into gully

206.3 (0.2) Junction: BEAR LEFT at the fork.

206.4 (0.1) Junction: BEAR LEFT. Note the red Aztec Sandstone at 9:00.

207.0 (0.6) Continue past a reverse junction.

207.2 (0.2) PARK on the ridge.

STOP 2.8. Weiser Ridge, to the west, is supported by an overturned and repeated sequence of Permian sediments (Permian red-beds and Kaibab Limestone). Triassic and early Jurassic clastic sediments (Moenkopi, Chinle, Moenave, and Kayenta formations) are exposed below us in Anderson Wash, a tributary of the Muddy River. The overturned rocks on the ridge line are associated with the thrust fault due south that places older rocks, including the Aztec Sandstone, over Cretaceous sediments (Baseline Sandstone and Willow Tank Formation; Page and others, 2005; Longwell and others, 1965).

We can see:

> A depositional sequence that spans 150 Ma: from the Permian red-beds and Kaibab Limestone (on the ridge to the west), through clastic sediments of Triassic and Jurassic Moenkopi, Chinle, Moenave, Kayenta and Aztec formations.
>
> Thrust faulting that places older rocks over younger rocks. In this case, the overturned late Paleozoic Kaibab Limestone and early Mesozoic clastic sequence dating between 200–170 Ma is thrust over 100 Ma Cretaceous sandstones.

We are standing at 1,860 feet and Weiser Ridge reaches 2,260 AMSL, with intervening Anderson Wash at 1,630 feet. The “Plio-Pleistocene” gravels (east along our access route) consist primarily of clasts of Paleozoic limestone. Our elevation is higher than the divide between the Muddy River and Meadow Valley Drainage to the north at Moapa, so the Paleozoic clasts may have been derived from Kaibab-capped Weiser Ridge to the west. If these gravels are Pliocene or early Pleistocene in age, there have been significant drainage changes and down-cutting as the Muddy River reached the Virgin River arm of the Colorado River system. RETRACE to the two-lane graded road and OHV parking area.

208.2 (1.0) Junction with the two lane road. PROCEED EAST.

209.7 (1.5) TURN RIGHT (south) at Tai-Arabian Lane.

210.5 (0.8) Cross the railroad tracks and TURN LEFT on Liston Road.

210.7 (0.2) STOP at Moapa Valley Blvd. (Highway 169). Look for cross traffic, TURN LEFT (north) and Retrace to I-15.

211.1 (0.4) Cross the Muddy River.

216.3 (5.2) TURN RIGHT and enter I-15 eastbound toward Mesquite, Nevada and St. George, Utah.

217.0 (0.7) Ascend Mormon Mesa through orange, cross-bedded sands of the Muddy Creek Formation and white marls of the upper Muddy Creek to spectacular exposures of the capping Morman Mesa calcrete. This early Pliocene calcrete is a 5 m thick soil.

218.5 (1.5) Continue past truck turnout.

222.4 (5.4) Pass the Elgin/Carp exit.

232.2 (9.8) Pass a truck turnout.

232.5 (0.3) Descend through a road cut in the cemented cap of Pleistocene gravels (QTc–Pliocene and Pleistocene calcrete of Page and others, 2005) that caps the underlying red Muddy Creek Formation of late Miocene age. The Virgin River branch of the Colorado River system has cut this deep incision into the Pleistocene and Miocene sediments. Note the patches of the gravel cap on the northwest fanglomerate slopes of the Virgin Mountains to the southeast. Snow-covered Virgin Peak rises to 8,075 feet.

234.0 (1.5) Pass the exit to Riverside/Bunkerville, Nevada (Highway 170).

236.7 (2.7) Pass over Toquop Wash. Flat Top Mesa to the northeast consists of calcrete (QTc; Page and others, 2005) that caps the Muddy Creek Formation. San Bernardino County Museum excavations led by the author in 1996 (Howe, 1977) recovered skulls, jaws, and limbs of the late Miocene, Hemphillian Land Mammal Age camel Alforjas (Harrison, 1979). Resistant channel sands immediately overlying the camel bones contained tracks of a camel of similar size. Road cuts ahead expose a thick section of silty sandstone with alternating resistant channel sands and benches eroded above silt layers.

237.0 (0.3) The Virgin River branch of the Colorado River can be seen on the right (south).

241.3 (4.3) Pass the West Mesquite exit. Gas and food are available here.

243.9 (2.6) Pass the East Mesquite exit.

244.8 (0.9) Cross into Arizona at the Nevada border.

247.5 (2.7) Cross the freeway bridge at Sand Hollow Wash. The next bridge crosses Coon Creek. The Virgin River to the east meanders past the "Little Bend" and, upstream, the "Big Bend." Note that the Pleistocene calcrete (QTc; Pliocene - Pleistocene pedogenic carbonate of Page and others, 2005) in this area sits at an elevation of 2,120 feet northwest of the highway, and dips southeast to 1,700 feet at the Big Bend, substantiating tilting of Pleistocene sediments over a large area. East tilting of Pleistocene sediments may be the result of the Piedmont Fault along the western margin of the Virgin Mountains.

We are climbing through a sequence of Paleozoic and Mesozoic rocks in the transition zone between the Basin and Range geological province to the north and northwest onto the Colorado Plateau. The Basin and Range Province is characterized by north-trending, east tilted mountain ranges that sit at relatively low elevations due to structural collapse westward away from the Colorado Plateau. In contrast, the Colorado Plateau to the northeast contains flat lying Paleozoic and Mesozoic strata that sit at an elevated position much higher that the province to the west. The west-dropped fault blocks help form the St. George Basin.

255.4 (7.9). Pass the Littlefield (Highway 91) exit. At Littlefield, the Virgin River branch of the Colorado River cuts eastward through the Virgin River Gorge into the Colorado Plateau. This drainage system erodes red, clastic Triassic and Jurassic sediments that contribute to the color and sediment load of the Colorado River system. At Littlefield, Beaver Dam Wash runs north parallel to the Piedmont Fault along the western front of the Beaver Dam Mountains that locally represent the transition from the Basin and Range Province to the Colorado Plateau.

257.0 (1.6) Pass Exit 9 to Farm Road.

260.0 (3.0) Enter the Virgin River Gorge.

260.5 (0.5) A north-northwest-oriented fault separates the younger Monte Cristo Group from Lower Paleozoic rocks. Late and Middle Cambrian Bonanza King Dolomite, Dunderberg Shale, and Nopah Dolomite make up the Paleozoic sequence in this portion of the gorge. Thin interbeds of green shale and dolomite marking the Dunderberg Formation are clearly visible in road cuts between mileposts 13.9 and 16.8. Late Devonian Muddy Peak Limestone lies below the Dunderberg Formation. The Mississippian Monte Cristo Group makes up steep cliffs above the Dunderberg Formation.

261.4 (0.9) Late Mississippian and Pennsylvanian Callville Limestone is not exposed at the roadside, but can be seen above the Monte Cristo Group north and south of the highway from the lower end of the Narrows to MP 14.4.

264.2 (2.8) The Sullivan's Canyon Tear Fault and Cedar Wash Fault intersect and cross the highway here. We pass from Cambrian–Devonian rocks west of the fault into Mississippian Monte Cristo and Permian rocks east of the fault. Looking back toward the south-southwest, you can see the upward-turned Permian Toroweap Formation on the east side of the Sullivan's Canyon Fault, and the Monte Cristo Group steeply dipping in the opposite direction on the west side of the fault.

265.3 (1.1) Prepare to exit at Cedar Pocket. Just before the exit, a red sandstone outcrop on the right contains large amplitude cross-beds representing large sand dunes in the Permian Supai Group.

283.5 (18.2) (0.3) EXIT at Cedar Pocket Camp Ground. This open area takes advantage of the incised meanders of the Virgin River that have cut through the Permian Supai Group and the thin-bedded Coconino Sandstone. The campground rests on Quaternary terrace deposits. Surrounding high cliffs have Supai Group and Coconino Sandstone at the base, and are capped with Permian marine Toroweap and Kaibab formations.

STOP, TURN RIGHT to the group campground. Individual camps are to the left. Cedar Pocket Recreational Area is open all year with 33 day-use picnic tables and 75 campground sites with tables, charcoal grills, water, and flush toilets. Three group campsites are available by reservation. The recreation area is 20 miles southwest of St. George, Utah and about 20 miles northeast of Mesquite, Nevada. Fees are charged for overnight camping and group use. Your fees are returned to the recreation area for continued operation and maintenance. For additional information or reservations, contact the BLM Field Office at (435) 688-3200.

As Day 2 comes to a close, be sure that you fill your gas tank and obtain food and drink at either Mesquite Nevada, to the west, or St. George, Utah, to the east along Interstate Highway 15.

END OF DAY 2

DAY 3

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Convene at Cedar Pocket Campground in the Virgin River Gorge. Your gas tank and box of provisions are already full from last evening's visit to Mesquite, Nevada or St. George, Utah.

What we have seen:

On Day 1 trip we visited the Mojave Desert Province and saw tracks of proboscideans in Miocene extensional basin-filling sediments. We then explored lacustrine sediments filling the unextended Tecopa Basin, where footprints of mid-Pleistocene megafauna are preserved.

Our Day 2 route followed a sedimentary package deposited between Permian and early Mesozoic time. These units consist of Permian marine and early Mesozoic continental clastic units, the latter containing Early Jurassic tracks in dune deposits. We also explored late Miocene to early Pliocene basin-filling sediments of eastern Nevada which contain the tracks of horses, camels, elephants and birds. We crossed the southern Basin and Range Province and climbed onto the Colorado Plateau.

What we will see:

On Day 3 we will pass through Paleozoic marine sediments and Triassic and Early Jurassic continental clastic deposits that contain a rich variety of tracks left by dinosaurs, therapsids, lower vertebrates, and invertebrates.

START at Cedar Pocket Campground where the incised meanders of the Virgin River branch of the Colorado River have cut through a thick section of Permian Supai Group and Coconino Sandstone capped by the late Permian marine Toroweap and Kaibab formations.

0.0 (0.0) Enter I-15 eastbound toward St. George, Utah.

6.0 (6.0) Pass through the Permian Supai Group and Coconino Sandstone in the bottom of the gorge, covered with Permian Toroweap Formation and Permian Kaibab Formation. Around milepost 25.5, pass the contact with the Coconino Sandstone and overlying Toroweap Formation.

7.4 (1.4) Pass the contact between two Permian marine formations; the Toroweap below and the Kaibab above.

7.9 (0.5) Continue past the Black Rock Road exit.

8.0 (0.1) Pass over the covered contact between the underlying Kaibab Limestone and overlying Lower Red Member of the Moenkopi Formation. Open country at the top of the plateau reflects the transition from resistant Permian limestones to more easily weathered siltstones, mudstones, and sandstones of the Lower to Early Middle Triassic Moenkopi Formation. The Moenkopi in this area is divided into the Lower Red, Virgin Limestone, Middle Red, Shnabkaib, and Upper Red members. Above the Moenkopi is a prominent ridge-former called the Shinarump Formation, composed of conglomerates and sandstones. Petrified wood is common in the Shinarump, which is the basal formation of the Chinle Group (formation of some authors). These ridges can be clearly seen from the northwest toward the northeast. The Beaver Dam Mountains can be seen toward the northwest and the Pine Valley Mountains to the north.

8.1 (0.1) Buff-colored ridges and road cuts represent the Virgin Limestone Member of the Moenkopi Formation. This marine sequence contains common fossils (echinoids, crinoids, bivalves, brachiopods, gastropods, *Tirolites* ammonites and invertebrate trace fossils).

10.4 (2.3) Enter Utah at the Arizona border.

12.5 (2.1) Pass through the Moenkopi Middle Red Member capped by the lightly-colored sabkha (salt flat) deposits of the Shnabkaib Member. Look for light banding of gypsum veins in the Middle Red Member.

13.5 (1.0) Pass through the Moenkopi Shnabkaib Member to the east, which is overlain by the Upper Red Member. Reptile and amphibian tracks are locally abundant in the Late Early Triassic to Early Middle Triassic Upper Red Member of the Moenkopi Formation.

14.4 (0.9) Continue past Utah Exit 4 (Bloomington). Red cliffs of the Moenkopi Upper Red Member are capped by conglomerate and sandstone of the basal Shinarump Formation of the Chinle Group. In the St. George area, the Chinle Group is divided into, from oldest to youngest respectively, the Shinarump, Petrified Forest, Moss Back, Owl Rock and Rock Point Formations. Above this is the Glen Canyon Group. The Glen Canyon Group is subdivided into the Moenave, Kayenta and Navajo Sandstone formations in southwestern Utah. The Chinle and Glen Canyon groups are exclusively terrestrial deposits.

14.6 (0.2) Cross the Santa Clara River. Prepare to exit at Bluff Street.

16.1 (1.5) EXIT at Bluff Street (Utah Exit 6).

16.2 (0.1) STOP at intersection. PROCEED LEFT (northwest) on Bluff Street.

16.8 (0.6) Prepare for a left turn at 700 South Street.

16.9 (0.1) TURN LEFT at 700 South Street. PARK along both sides of this short street.

Stop 3-1 "Dixie Lube Site." This stop provides excellent exposures of the Early Jurassic (Hettangian) Whitmore Point Member of the Moenave Formation. Sedimentary structures and trace fossils are abundant, as are fish remains at this locality. The fine mudstones, shales, limestones, siltstones, and sandstones mostly represent cyclic freshwater lacustrine deposits from Early Jurassic Lake Dixie. Down slope is a thick sandstone bed with tracks. The stromatolite layer and bone-bearing layers in the cliff correlate this locality with outcrops to the east at the St. George Dinosaur Discovery Site (SGDS) at Johnson Farm (Stop 3-3). Many of the fish remains in the Whitmore Point Member belong to *Semionotus*; however freshwater sharks, giant coelacanths, lungfish, and rare palaeoniscoids have also been recorded. Theropod dinosaur remains have been found in the Whitmore Point member at the SGDS and at the north end of Warner Valley, approximately 10 miles to the east. Return to vehicles, Retrace to the intersection of 700 South Street and Bluff Street.

17.0 (0.1) Stop at intersection and TURN RIGHT (southeast) on Bluff Street.

17.6 (0.6) Proceed over I-15 bridge and TURN LEFT at traffic signals.

17.7 (0.1) Enter I-15 northbound (actually northeast). Proceed 7 miles to Washington Parkway.

19.6 (1.9) Continue past the St. George Boulevard exit (Utah Exit 8).

19.7 (0.1) Pass through road cut exposures of Middleton Black Ridge. The orange-brown sediments belong to the "Silty Facies" of the Early Jurassic lower Kayenta Formation. These sediments were deposited in fluvial and lacustrine settings. Channel sandstone beds from meandering streams can be seen in roadcuts on both sides of I-15. Caps of 1 million year old basalt above the Kayenta sandstone originated from a cinder cone to the north. These lavas actually flowed down Pleistocene stream channels, filling them with basalt. The resistant basalt remains capping prominent ridges, while the less resistant Jurassic sandstones have eroded away. Similar volcanic features are seen throughout southwestern Utah.

22.4 (2.7) Pass the Washington exit (Utah Exit 10). Our return trip south from this exit will take us to the SGDS museum. Remember to proceed south on Green Spring Drive for 2.1 miles to the museum.

25.3 (2.9) EXIT at Washington Parkway (Utah Exit 13).

25.4 (0.1) Stop, TURN RIGHT (east) onto Washington Parkway.

25.5 (0.1) Pass the traffic circle/round-about, and move to left lane.

25.6 (0.1) TURN LEFT (northeast) on the first dirt road after the traffic circle. Proceed northeast on this dirt road through construction. Watch for a gate on the right and drive up to it.

25.7 (0.1) PARK at the gate with a sign "Utah State Institutional Trust Land." Walk east, downhill, into Grapevine Wash. When in the wash, proceed north along the right (north-northeast) branch of the wash. This is an easy hike along flat wash bottom for about 0.2 miles.

Stop 3-2. Spectrum Tracksite. Approximately 200 tracks of bipedal dinosaurs are exposed in fine carbonate-rich sandstone exposed along the wash bottom (Hamblin, this volume). These tracks were left by theropod dinosaurs walking in a SSW direction, perhaps parallel to the margin of a body of water. The fine-grained sandstone is within the lower Kayenta Formation, which is Lower Jurassic (Sinemurian) in age. Return to vehicles. RETRACE to Washington Parkway and I-15.

25.9 (0.2) Stop at Washington Parkway. Watch cross-traffic. TURN RIGHT (northwest) on Washington Parkway and Retrace back to the I-15 on-ramp (Utah Exit 13). Cross over the I-15 bridge and TURN LEFT to on-ramp. ENTER I-15 (southwest) and proceed to the Washington exit (Utah Exit 10).

28.7 (2.8) Prepare to exit at the Washington exit (Utah Exit 10).

28.9 (0.2) EXIT at Washington Street (Utah Exit 10). BEAR LEFT through traffic lights. Pass under I-15 overpass and proceed straight (south-southeast) for 2.1 miles along Green Spring Drive.

31.0 (2.1) STOP for traffic lights at intersection of Green Spring Drive and Red Cliffs Parkway.

PROCEED on Green Spring Drive which turns into 3050 East Street (by the Costco store).

PROCEED through pronounced right curve where the street is renamed Riverside Drive and narrows from 4 lanes to 2 lanes.

32.9 (1.9) Look for 2200 East Street prior to turning into SGDS Museum. TURN IMMEDIATE LEFT (south) into St. George Dinosaur Discovery Site at Johnson Farm.

Stop 3-3. This museum preserves a one of the greatest records of early Jurassic trackways left by a diverse population of ichnogenera in North America (Milner and Lockley, this volume).

Reconvene in the parking lot after the tour. Return to vehicles. Be sure you have gas and provisions for your return trip. Watch for traffic, and enter Riverside Drive. Retrace to I-15 by way of Riverside Drive to 3050 East Street to Green Spring Drive.

35.0 (2.1) Pass under the interstate at Washington Exit 10. TURN LEFT and ENTER I-15 southbound for Arizona, Nevada and California. Fuel and provisions at Las Vegas are 116 miles (1.5 hours) to the southwest.

END OF DAY 3

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Jurassic Tracks in California

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ABSTRACT

The Aztec Sandstone (Early-Middle Jurassic age) crops out in the eastern Mojave Desert of southern California. This aeolian unit contains tracks (ichnites) of quadrupedal reptiles, therapsids, pterosaurs, and therapod dinosaurs. Conservatively, the Mescal Range Aztec Sandstone contains tracks representing three bipedal theropods and nine quadrupeds. Additional ichnites attributed to invertebrates include *Octopodichnus* and *Skolithos*. Quadrupeds are responsible for seventy percent of the vertebrate tracks in the Aztec dune sands, while bipedal theropods contributed thirty percent. Two of the three therapod track morphologies have been attributed to *Anchisauripus* and *Grallator*; the most common biped track is unnamed. Quadruped tracks can be grouped by low to high length:width ratios and morphology producing nine distinct groups. Three are recognized in published descriptions and five are apparently not described. Ichnotaxa *Navahopus* and *Brasilichnium* are measurably distinct in the Mescal Range. Trackways of three individuals are referred to *Pteraichnus*, tracks made by pterosaurs. *Pteraichnus* tracks in the 173–170 Ma Aztec Sandstone in the Mescal Range represent the westernmost known North American occurrence of this ichnogenus.

GEOLOGY

At its type section near Goodsprings, Nevada, the Aztec Sandstone is 2,100 feet thick. The Aztec section in the Mescal Range contains an abbreviated sequence of 1,000 feet, and differs from the Nevada section by becoming more silty up-section. The Aztec Sandstone also crops out west of the Mescal Range, in the Cowhole, Soda, and Ord Mountains between Baker and Victorville, California. The Cowhole Volcanics that interfinger and overlie the Aztec Sandstone in the Cowhole Mountains date between 173 and 170 Ma. (Ferriz, 2002; Busby-Spera and others, 1987), suggesting that the Aztec Sandstone is younger than the Navajo Sandstone (Barnes, 2004). In the Mescal Range, the Aztec sandstone is capped by the overlying Mountain Pass Rhyolite (100.5 Ma, Fleck and others, 1994; Fleck and Reynolds, 1996).

The abbreviated section of Aztec Sandstone in the Mescal Range conformably overlies the brick-red Moenave–Kayenta equivalent sandstone (Marzolf, 1982; Marzolf, and Dunne, 1983). The Aztec Sandstone includes yellowish-white resistant arenaceous sandstone, friable purplish-red sandstone, a second yellowish-white resistant arenite, red-brown friable sandstone, a dark brown to black volcaniclastic sandstone, brown friable bedded sandstones, and an upper section of tan and brown to greenish thin-bedded sandstones. Only the two layers of arenaceous sand in the Mescal Range show dunal cross bedding. The remainder of the section is silty, suggesting a poorly drained basin with silty, interdunal pans. The Aztec section farther west in the Cow Hole Mountains (Barca, 1966; Ferriz, 2002) also consists of silty sands, supporting the concept of a broad, poorly drained plain of silty sand southwest of the thick dune field of Aztec Sandstone at the type section.

Structure

The Triassic-Jurassic sedimentary sequence in the Mescal Range underlies the Keystone Thrust Plate (Burchfiel and Davis, 1971). Mesozoic sediments underlying the east-vergent Keystone Thrust have been overturned synclinally in western exposures. Drag along the right-lateral Kokoweef Fault (Burchfiel and Davis, 1971; "South Fault" of Evans, 1971) on eastern exposures has caused an anticlinal fold. The entire sequence of Triassic through Cretaceous clastic and volcanic rocks has been folded by an east –west trending syncline (Evans, 1958, 1971).

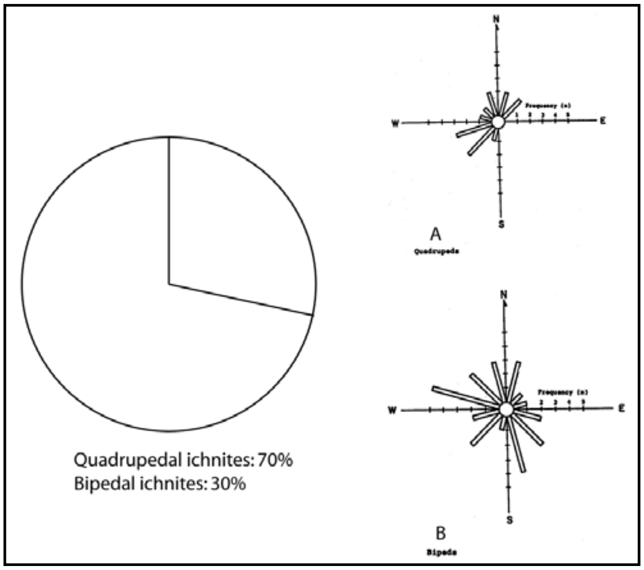

Figure 1. Quadrupedal ichnites make up 70 % of the tracks in the Mescal Range. Vectors of quadrupeds trend southwest and northeast, while vectors of bipeds appear to be random.

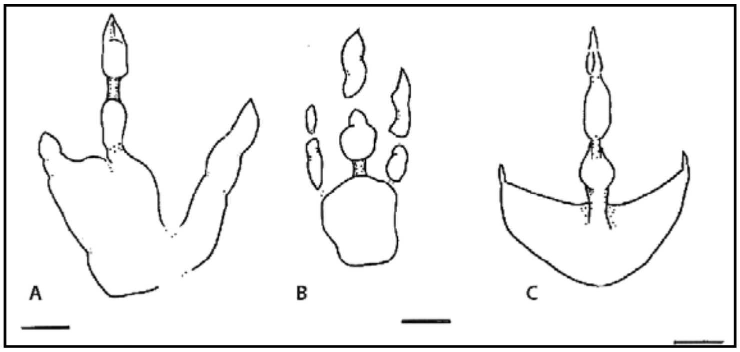

Figure 2. Tracks of bipedal therapod dinosaurs in the Mescal Range include a single Grallator *track (Fig. 2A), six tracks of* Anchisauripus *(Fig. 2B), and multiple tracks of an unnamed broad form (Fig. 2C) with a composite metatarsal pad where digits meet.*

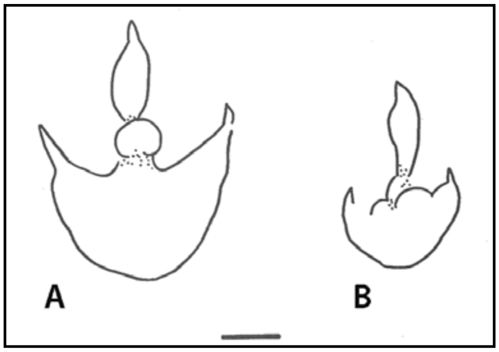

Figure 3. The most abundant biped in the Mescal Range left tracks of small individuals walking parallel to large individuals.

TRACKS

California's only known dinosaur tracks, the Jurassic ichnites in the Mescal Range, were noted in geologic mapping (Evans, 1958). They were studied in greater detail (Reynolds, 1989) and a comprehensive inventory (Reynolds and Weasma, 2002) showed that 70% of the inventoried tracks were from quadrupeds traveling in a northwest-southeast direction (Fig. 1). Current research focuses on identification of quadruped and biped populations.

During the inventory, trackway panels were assigned numbers and each locality was plotted using a Trimble GPS unit (Reynolds and Weasma, 2002). Return visits measured the length and width of each track or of individual tracks in a trackway. When possible, the manus and pes were differentiated. Measurements were used to develop length: width track ratios to compare tracks of multiple individuals, and to compare trackways made by a single individual. Theoretically, these ratios can be used to avoid creation of artificial ichnotaxa based on the varying ages of the popu-

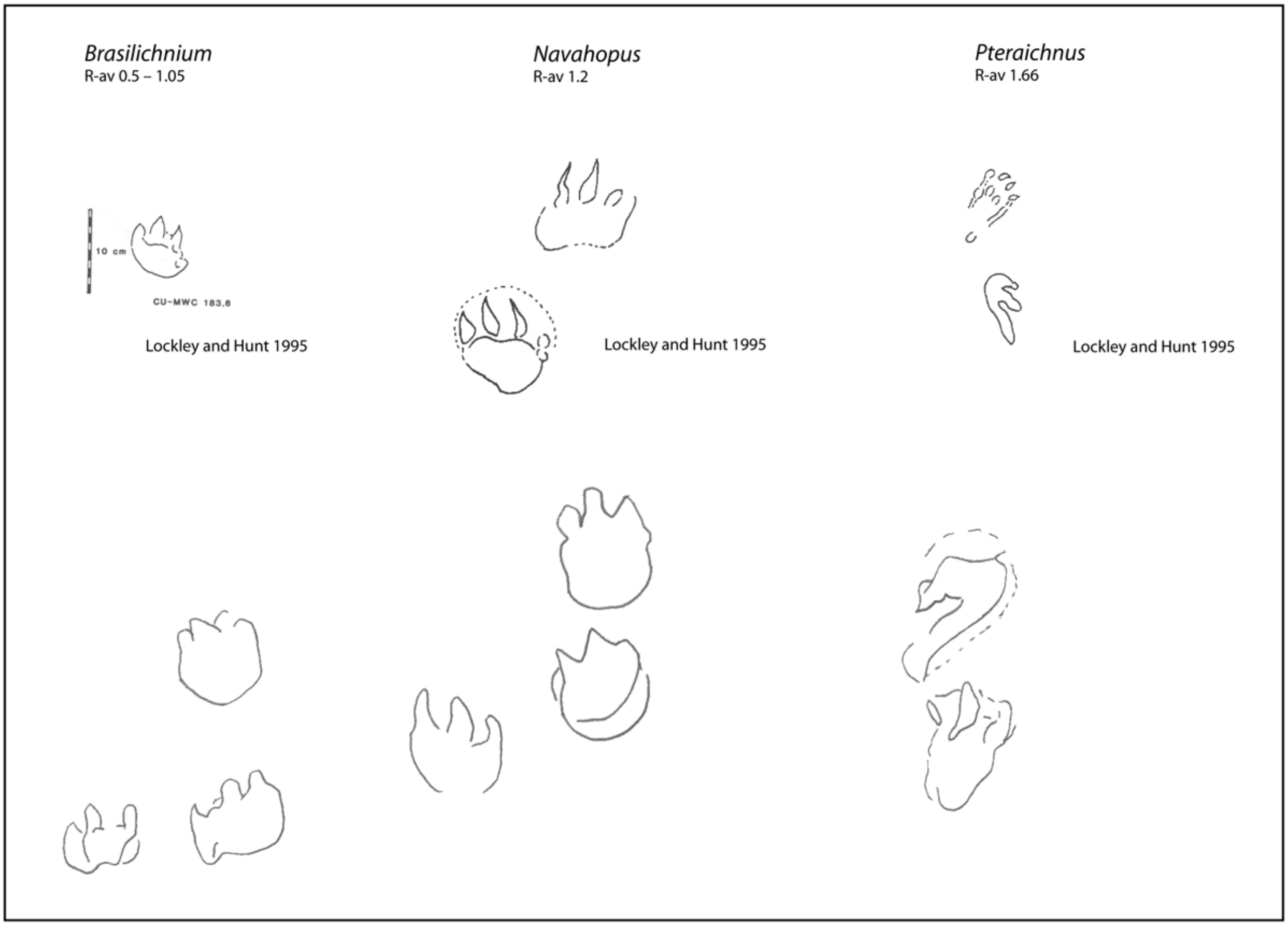

Figure 4. Ichnogenera in the Mescal Range Aztec Sandstone that are previously recognized in the literature include Brasilichnium, Navahopus, *and* Pteraichnus.

Figure 5. Brasilichnium *tracks.*

lation making the tracks. While not addressing the possibility of anisometric growth in these species, the ratios are the only quantitative measures available for grouping different age individuals of the same taxa. These metrics also provide a way of characterizing and comparing multiple tracks. They are not considered sensitive to trackway substrate because similar ratios result whether substrates are firm or loose, viscous or fluid.

Use of ratios alone allows comparison of tracks of all sizes, but these computations do not take into account the variations in the actual morphology of the pes and manus. Original drawings and measurements were reviewed to determine if morphological differences could be identified for tracks with a similar ratio. At Mescal Range outcrops, sorting large sizes from small sizes with the same ratio produced one additional ichnotaxonomic category 100% larger than smaller prints with the same ratio. Visible differences in morphology yielded an additional category.

Initial studies (Reynolds, 1983, 1989) focused on the bipedal dinosaur tracks noted by Evans (1958). Prelimi-

Figure 6. Navahopus *tracks.*

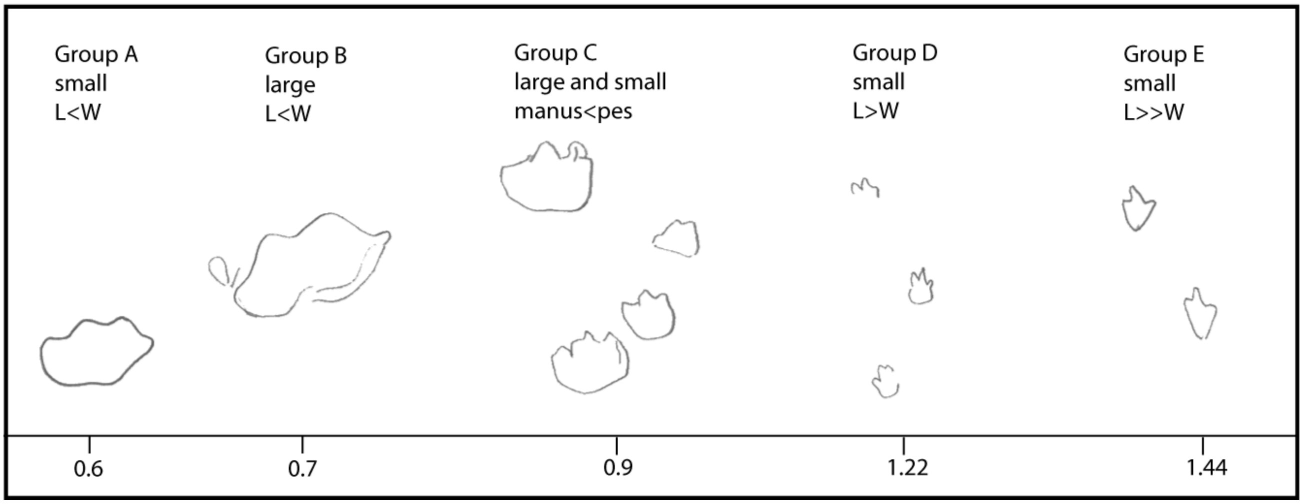

Figure 7. Mescal Range quadrupeds apparently not previously described differ in size as well as in ratios of length to width.

nary descriptions (Reynolds, 1989) identified three bipeds; two ichnites were assigned to named ichnogenera and another was left unnamed pending comparison. Tridactyal theropods leave distinct foot imprints that differ morphologically from quadrupeds at this locality. Tridactyl foot imprints are not the ideal shape for analysis by ratios, but they are included for the sake of consistency. A single large track (L 15.2 x W 15.2 cm; R 1:1, Fig. 2a) was assigned to *Grallator* (Reynolds, 1989) on the basis of digit asymmetry and divarication (30 degrees). However, Lockley and Hunt (1995) suggest that large tracks at this locality once referred to *Grallator* might be assigned instead to *Eubrontes*. A sequence of six narrow tracks (L 12.2 x W 7.1 cm; R = 1.72, Fig. 2b) was assigned to *Anchisauripus* on the basis of distinctly narrow digit divarication (14 degrees).

The most common bipedal track in the Aztec Sandstone of the Mescal Range is currently unnamed. These tracks are distinct from the other Mescal Range bipedsbecause digit III extends much farther anteriorly past the termination of the lateral digits. Digit III extends approximately 49% of the length of the entire foot, suggesting that the central digit makes up almost half the length of the foot imprint. In contrast, digit III of *Grallator* extends approximately 37 % of the foot length past lateral digits, while digit III of *Anchisauripus* extends approximately 27 % past lateral digits. In addition, the unnamed tridactyl ichnogenera has broad digital symmetry with angle of divarication very wide (greater than 40 degrees), no apparent hallux, and the presence of a composite metatarsal pad that creates the appearance of webbing between digits. The tracks are roughly equidimensional (L11.4 x W 10.9 cm; Fig 2c), smaller than *Grallator,* and much wider than the *Anchisauripus* from this locality. Although most tracks of this ichnogenus are similar in size, one is larger (L 14 x W 10 cm) and at two sites, trackways of smaller individuals (L 8.9 x W 5.1 cm, Fig. 3) are parallel to tracks of larger individuals, suggesting animals moving in a group as has been described elsewhere (Lockley and Hunt, 1995; Chapters 4 & 5). These tracks are distinct from *Kayentapus*, which is larger, retains a hallux, and has narrower digit divarication (less than 40 degrees; Lockley and Hunt, 1995).

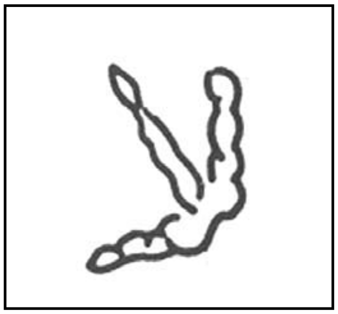

Figure 8. A small quadruped with slender digits may be from a lizard-like animal.

Tracks of quadrupeds comprise 70 % of the ichnofauna in the Mescal Range. *Brasilichnium*, *Navahopus,* and *Pteraichnus* can be recognized in the Aztec Sandstone (Fig. 4). *Brasilichnium* (Fig. 5), the most common quadruped track in the Mescal Range, has tracks of relatively equal length and width (ratio 0.8–1.05) and great size diversity. The range of ratios for *Brasilichnium* (0.8–1.05) may be due

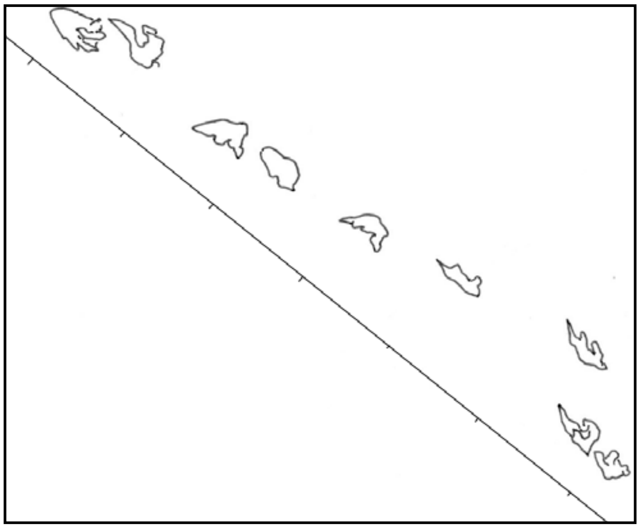

Figure 9. Manus tracks of Pteraichnus *are more common than the pes since the weight of the body was apparently carried on the forelimbs.*

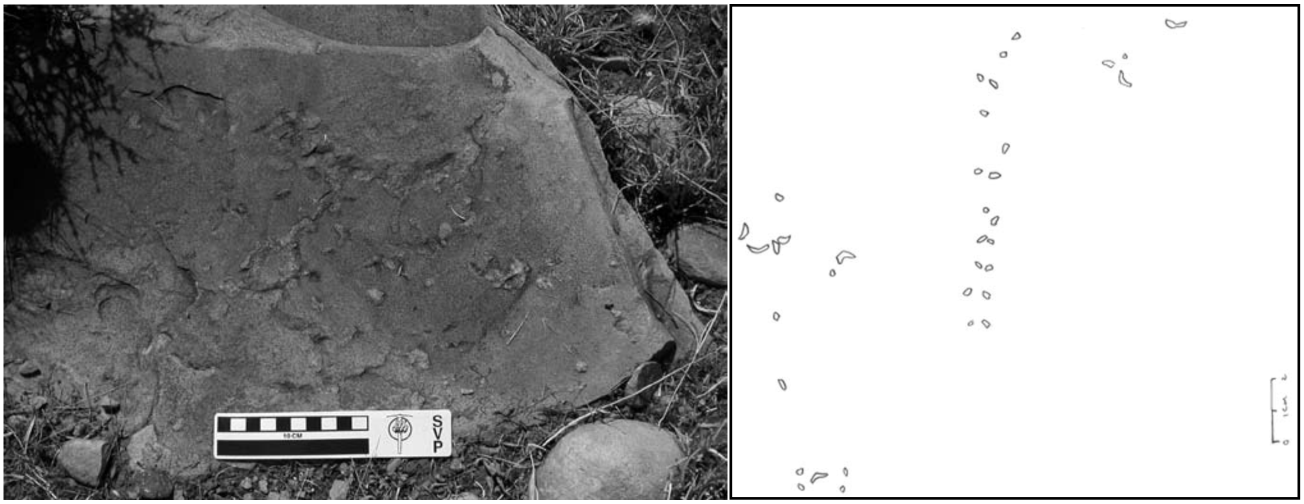

Figure 10. Octopodichnus *ichnites suggest the presence of large arachnids during deposition of the early middle Jurassic Aztec Sandstone.*

to a mix of young, old, or sexually dimorphic groups. The span of ratios might also be due to the mixing of manus and pes measurements or to differences in substrate. *Navahopus* (Fig. 6) is uncommon, larger than *Brasilichnium*, and the tracks are longer (ratio 1.20). *Pteraichnus* is recognized by its distinctive morphology and the slender track produces a high ratio (1.66). Since this study is ongoing, and the range of ratios has not been compared to that at other outcrops of different ages, this paper continues to use the "range of ratios" instead of reporting a mean +/- standard deviation.

As yet undescribed tracks (Fig. 7) from the Mescal Range include:

Group A: Small tracks (L=1.8 cm) with a low ratio (0.6, L<W) and manus equal to pes.

Group B: Large tracks (L=3.6 cm) with a low ratio (0.7, L<W) and manus equal to pes.

Group C: Small tracks with a low ratio (0.75–0.8) and manus size, and ratio smaller than pes.

Group D: Small tracks with length greater than width (ratio 1.22)

Group E: Small tracks with length much greater than width (ratio 1.44).

Group F: Slender lacertoid tracks (Reynolds, 1989) (Fig. 8).

The Mescal Range *Pteraichnus*, the ichnogenus named for tracks of pterosaurs, represents one of the oldest and the most westerly occurrence of pterosaur tracks on the North American continent. Differential preservation favoring the manus has been noted elsewhere (Mickelson and others, 2004: Lockley and Hunt, 1995, P. 160, Fig. 4.43) and impressions of the manus outnumber those of the pes in the Mescal Range. Length:width of manus and pes (ratio 1.66) from the Mescal Range *Pteraichnus* (Fig. 2) are approximately equal (Figs 4, 9). Regardless, this early-Middle Jurassic *Pteraichnus* is smaller than all *Pteraichnus* tracks from later and stratigraphically higher occurrences. The only older record of *Pteraichnus* is from the Navajo Formation (late-Lower Jurassic) of Utah (Stokes and Madsen, 1979).

North American localities that have produced tracks of pterosaurs include, from oldest to youngest:

- Navajo Formation (late-Lower Jurassic) of Utah (oldest record of the genus)
- Aztec Sandstone (early Middle Jurassic) of California
- Summerville Formation (late-Middle to early-Upper Jurassic) of Utah
- Stump/Windyhill Formations (early-Upper Jurassic) of Utah, Wyoming, and Colorado
- Tidwell/Recapture/Lower Morrison (Undifferentiated Members) Formations (early-Upper Jurassic) of Arizona, Colorado, Utah, and Oklahoma.

ASSOCIATED FEATURES

The Aztec Sandstone commonly produces invertebrate trace fossils left by burrowing annelid worms (*Skolithos*) and arachnids (*Octopodichnus*, Fig 10), often in association with *Brasilichnium*. In addition, compression rings around tracks show paleo-slope orientation (Reynolds, 1989, Fig. 30.3; Lockley and Hunt, 1995, Fig. 4.14; Lockley, 1991, Fig. 10.10). In the Mescal Range their orientation changes, suggesting that animals walked over crests of low dunes (Reynolds, 1989, Fig. 30.3). Cross-bedding, ripple marks, and raindrop marks are present. Cubic pseudomorphs suggest primary halite and limonite concretions represent weathering profiles. Folded strata, secondary druzy quartz, irregular goethite stains, and leisingang weathering rings attest to a long sequence of deformation and weathering. Ichnites appear only on the dune surface of the cross-bedded dune sands that now appear as bedding planes. The fact that any tracks remain in a deposit constantly undergoing aeolian recycling suggests that special conditions of preservation existed. This author speculates that aeolian silt was dropped on the dune surface daily by a moist (fog) marine layer. Aeolian silt settling on the sand trapped moisture that would preserve the shape of the impressed footprint. Silt acted as a sealant to hold sand in place during mild winds. During Pleistocene and Holocene weathering, the silt might have served as a parting layer that allowed the silica-cemented orthoquartzite to part along bedding planes where tracks were preserved.

ENVIRONMENT OF DEPOSITION

The thin (30 m) dune fields of Aztec Sandstone in the Mescal Range migrated across surfaces stabilized by silt, moisture, or soil development. Interdunal pans might have contained silty sands, interstitial moisture, and perhaps supported low growths of vegetation. The tracks of twelve vertebrate taxa and several invertebrates suggest that there was ample vegetation to support a food chain of herbivores and carnivores. A horsetail impression found in the greenish, bedded sandstones high in the section implies a moist or riparian environment (Reynolds, 1989).

ONGOING RESOURCE MANAGEMENT

Resource management in the Mescal Range by volunteers, BLM, and NPS personnel has resulted in the location by UTM coordinates of 116 outcrops, panels, and slabs. BLM rangers patrol weekly and researchers conduct inventory four times a year.

SUMMARY

California's only terrestrial Jurassic trackways are a robust ichnofauna consisting of three tridactyl bipeds, nine quadrupeds, and tracks from invertebrates. *Grallator* and *Anchisauripus* are bipeds previously reported in literature, as are the quadrupeds *Brasilichnium*, *Navahopus* and *Pteraichnus*. *Skolithos* (burrows) and *Octopodichnus* (arachnid tracks) and the imprint of a water reed are present. Described but unnamed ichnogenera include one broad tridactyl bipedal track and six quadrupedal tracks distinguished by length:width ratios as well as size and morphology.

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Horse Hoof Prints in the Fossil Record

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ABSTRACT

Two localities, Prosperity Canyon in the Calico Mountains, California, and Meadow Valley Wash, Moapa, Nevada, contain previously undescribed equid-like tracks that prompted a review of horse tracks from localities in both states. Measurements of horse tracks were compared to determine if the hoof wall thickness increases with geologic age and phylogenitic time, to see if the surface area of the hoof track (surface displacement) increases accordingly, and to see if such increases are related. The presence of a "V" shaped frog in equid-like track impression is first noted in one of three ichnomorphs from Copper Canyon, Death Valley, that date to early Blancan time.

Although tracks and trackways are not uncommon in late Quaternary stratigraphy, the occurrence of horse tracks is relatively rare (Sarjeant and Reynolds, 1999). The six trackway localities addressed in this paper by no means represent all horse tribes known in the fossil record (MacFadden, 1992) but are the only examples known for this study. Previously undescribed horse-like tracks prompted a review of track morphology. One of the "new" track localities is from early Miocene, late Hemingfordian (He2) North American Land Mammal Age (NALMA) sediments described as part of the Barstow Formation (Dibblee, 1970) in Prosperity Canyon, western Calico Mountains (Fig. 1). Small horse tracks (Fig. 2) have also been located in the late Miocene, late Hemphillian (Hh4) NALMA sediments of the Muddy Creek Formation near Moapa, Nevada (Reynolds, 2004; Schmidt and others, 1996). Also used in this study are imprints from the Barstow Formation in the Mud Hills northwest of Barstow (Sarjeant and Reynolds, 1999; Woodburne, 1991; Pagnac and Reynolds, this volume), tracks from Shadow Valley Basin northeast of Baker (Friedmann, 1996; Sarjeant and Reynolds, 1999), Copper Canyon Formation tracks in Death Valley (Scrivner and Bottjer, 1986; Sarjeant and Reynolds, 1999; Nyborg, and Buchheim, 2005), and mid-Pleistocene tracks at Shoshone (Reynolds, 1999; Hillhouse, 1987), all in California.

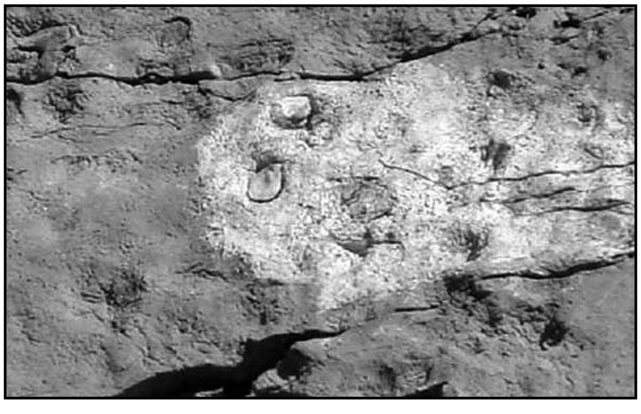


Figure 1. Horse and camel tracks from coarse sandstone of the Barstow Formation in Prosperity Canyon, western Calico Mountains, Barstow, California.

Morphometric studies of fossil footprints (ichnites) representing horse tracks have been the subject of study by the "Trackways through Time" program of the Mojave River Valley Museum. Horse ichnomorphs have been measured and replicated from early to mid-Barstovian NALMA sediments in the Barstow Formation, from early Blancan NALMA sediments of the Copper Canyon Formation of

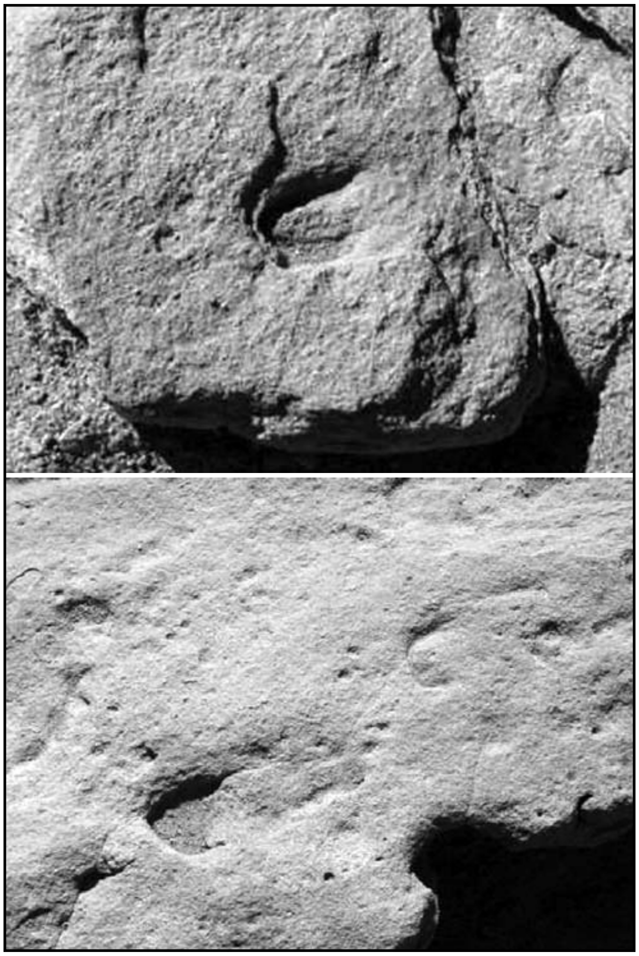


Figure 2. Small horse tracks in channel sands were probably left by Nannippus. *These tracks are preserved in red silty sandstone of the late Miocene Muddy Creek Formation along Meadow Valley Wash at Moapa, Nevada.*

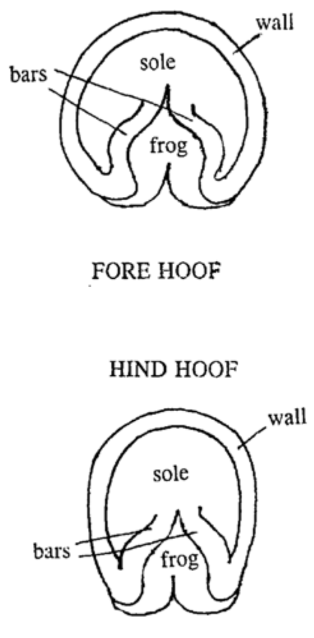


Figure 3. Morphology of horse tracks (from Sarjeant and Reynolds, 1999). The hoof wall is sometimes referred to as the ungual sheath since it surrounds the ungual digit (distal phalange) of the horse. The fore hoof of modern horses is generally more equidimensional than the hind hoof, and a similar relationship can be seen in the measurements for the Barstovian Hippipeda araiochelata *(Sarjeant and Reynolds, 1999).*

Death Valley, from late Hemphillian NALMA Muddy Creek Formation, southern Nevada, and from mid-Pleistocene sediments of Lake Tecopa.

This preliminary research helps quantify the record of equid foot morphology and shock absorbing mechanisms in the Neogene trackway record of the southwest. Fossil horse tracks often show distinct hoof walls (Fig. 3) and rarely a frog (Fig. 3) both of which are shock-absorbing mechanisms in the horse foot. This study looks at the thickness of the hoof wall impression (Fig. 4) to determine if hoof wall thickness increases through geologic time and

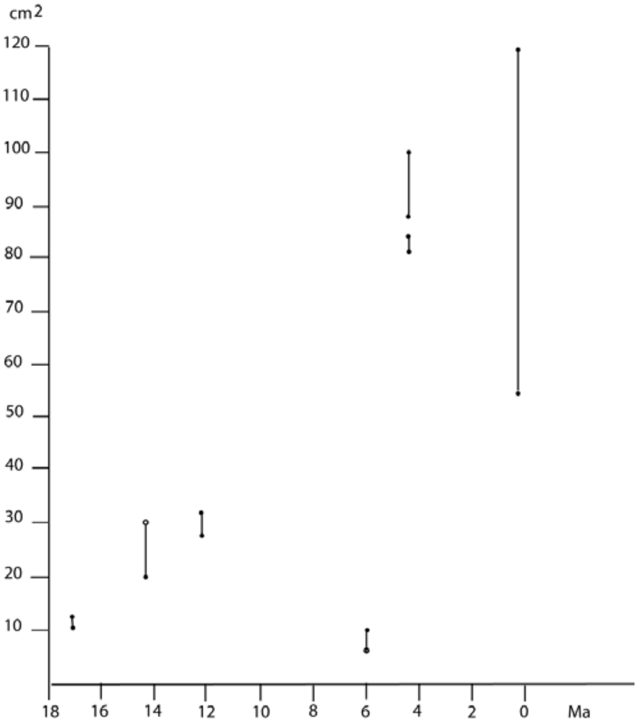


Figure 5. Hoof imprint area through the last 18 Ma. There does not appear to be a consistent trend showing increased area of displaced substrate, probably in part due to the limited size of the sample under study. Note that the tracks between 6–4 Ma vary most greatly in substrate area displaced. The adults in the single herd of Pleistocene Equus *sp. (right at 0.6 Ma) show an extremely broad range of area displaced. Including juveniles in the sample (Sarjeant and Reynolds, 1999) extends the range of area farther.*

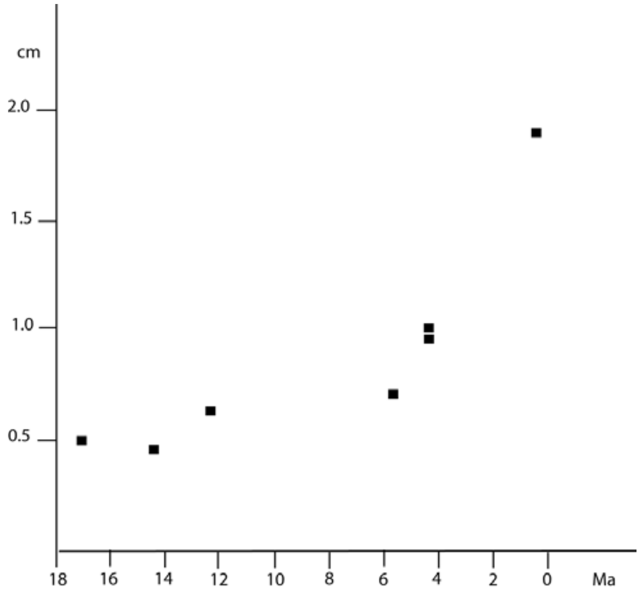


Figure 4. Hoof wall thickness through the last 18 Ma. The subjects between 18–12 Ma are probably tridactyl "Merychippine" horses. Those between 6 – 4 Ma may be a mix of hipparionine and protohippine tribes. Fossil Equus *sp. is at 0.6 Ma.*

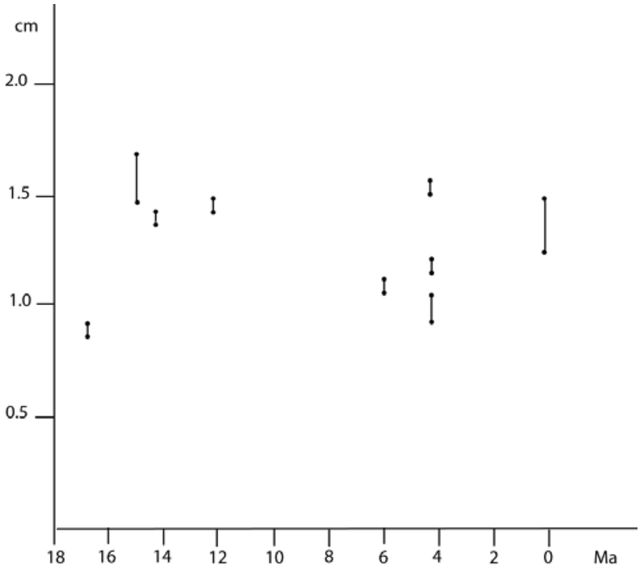
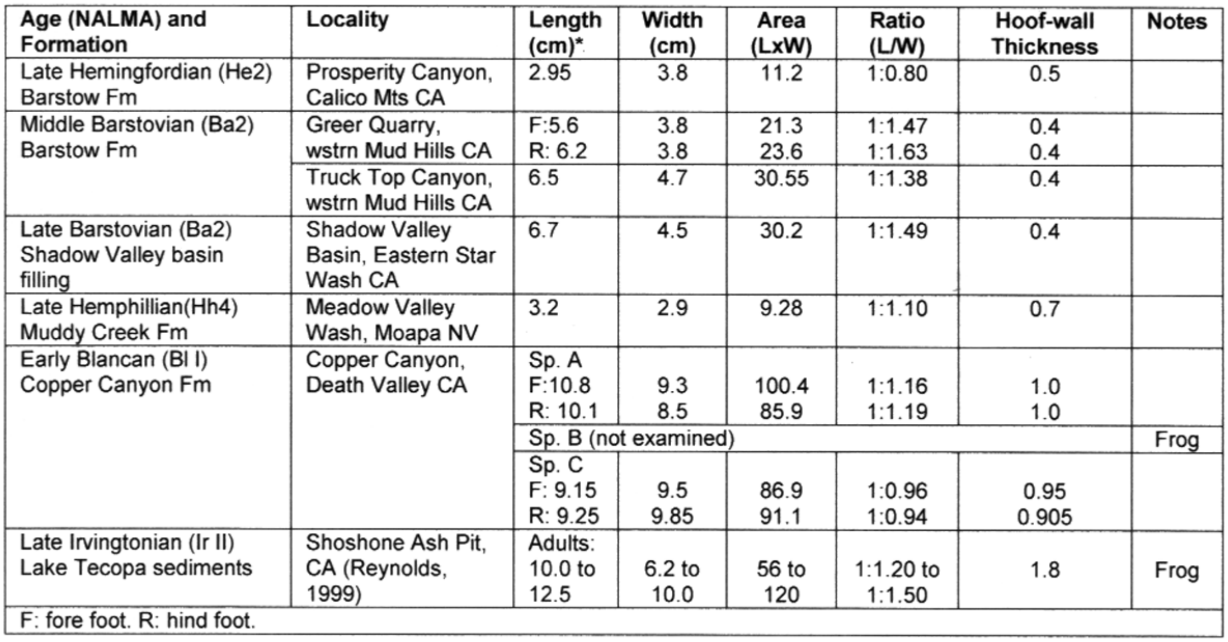


Figure 6. Hoof (L/W) ratio through the last 18 Ma. Note the sharp increase in imprint ratio between 18 and 15 Ma. Note also the different ratios (0.94–1.58) preserved at 4.3 Ma in the sample from Copper Canyon Formation. The range of ratio of Barstovian "Merychippine" prints and one ichnomorph of early Blancan prints fall within the same range of ratios (1.25 – 1.5) as the herd of adult Pleistocene Equus *sp. from the Lake Tecopa sediments.*

Table I. Measurements of equine ichnites from southern California and Nevada



Age (NALMA) and Formation	Locality	Length (cm)*	Width (cm)	Area (LxW)	Ratio (L/W)	Hoof-wall Thickness	Notes
Late Hemingfordian (He2) Barstow Fm	Prosperity Canyon, Calico Mts CA	2.95	3.8	11.2	1:0.80	0.5	
Middle Barstovian (Ba2) Barstow Fm	Greer Quarry, wstrn Mud Hills CA	F:5.6 R: 6.2	3.8 3.8	21.3 23.6	1:1.47 1:1.63	0.4 0.4	
	Truck Top Canyon, wstrn Mud Hills CA	6.5	4.7	30.55	1:1.38	0.4	
Late Barstovian (Ba2) Shadow Valley basin filling	Shadow Valley Basin, Eastern Star Wash CA	6.7	4.5	30.2	1:1.49	0.4	
Late Hemphillian(Hh4) Muddy Creek Fm	Meadow Valley Wash, Moapa NV	3.2	2.9	9.28	1:1.10	0.7	
Early Blancan (Bl I) Copper Canyon Fm	Copper Canyon, Death Valley CA	Sp. A F:10.8 R: 10.1	9.3 8.5	100.4 85.9	1:1.16 1:1.19	1.0 1.0	
		Sp. B (not examined)					Frog
		Sp. C F: 9.15 R: 9.25	9.5 9.85	86.9 91.1	1:0.96 1:0.94	0.95 0.905	
Late Irvingtonian (Ir II) Lake Tecopa sediments	Shoshone Ash Pit, CA (Reynolds, 1999)	Adults: 10.0 to 12.5	6.2 to 10.0	56 to 120	1:1.20 to 1:1.50	1.8	Frog

F: fore foot. R: hind foot.

phylogenitic time. Hoof wall thickness was also compared with area of the imprint (Fig. 5). The ratio (length to width) of the horse tracks was computed to separate elongate from equant tracks (Fig. 6).

Equid ichnites under study from southern California and Nevada are from sediments deposited in Miocene to Pleistocene basins during the late Hemingfordian, Barstovian, Hemphillian, Blancan, and late Irvingtonian NALMA. These localities and track dimensions are given in Table I.

Tridactyl Barstovian merychippine and later hipparionine horses (MacFadden, 1992; p. 256, Fig. 11.16) leave tracks that appear to show functional monodactyly. The impression of the central digit of "*Merychippus*" (Fig. 4) is relatively narrow, which perhaps reflects the persistence of lateral digits. All fossil horses in the Barstow Formation retain lateral digits next to a large, weight-supporting, central digit. However, prints of the central digit two centimeters deep in silt do not show impressions of lateral digits. When a horse with lateral digits becomes larger and more weight is born on the central digit, the area of support expands lengthwise. Ahorse foot without lateral digits would expand equally in two dimensions, producing an equant hoof area and a print with a low ratio (approaching 1:1). In Copper Canyon, two horse ichnomorphs are equidimensional, while the third is longer than wide, suggesting the presence of two monodactyl (pliohippine) forms and one tridactyl (hipparionine) form. Outcrops of the late Miocene Muddy Creek Formation near Moapa, Nevada, contain tracks of a small horse taxon. In the late Hemphillian LMA, small, slender tracks that are approximately one inch wide and two inches long may be attributable to *Calippus* or *Nannippus*. The narrow width of the Moapa tracks may represent a tridactyl form, which suggests the latter genus. This study did not produce data that differentiates tridactyl equids with feet that functional like monodactyls from foot imprints of true monodactyl horses. The distinction may be moot, since certain herds of *Dinohippus* (Voorhies, 1981) have been shown to contain individuals of the same species that were either monodactyl or tridactyl.

Measurements of available fossil horse foot imprints from southern California and Nevada show an increase through time in hoof wall thickness (Fig. 2) from the late Hemingfordian NALMA through the middle Irvingtonian NALMA, suggesting an evolutionary trend toward thicker hoof walls. The frog structure within the margin of the hoof wall first appears in the southwestern fossil record in one of three ichnogenera found in the Copper Canyon sediments that are younger than 4.33 Ma (Nyborg and Buchheim, 2005).

The area of substrate displaced by the horse foot is variable through time (Fig. 3) and the variability may show habitat preference by certain ichnogenera. The ratio (L/W; Fig. 4) of the horse tracks increases in the Barstovian LMA, but that ratio remains within certain limits (1.0 – 1.6) in available specimens through the late Cenozoic. Although it is tempting to suggest that this constant ratio reflects habitat preference, all of the tracks inventoried were preserved in playa or lake margin sediments where theoretically all animals might go to find water.

Acknowledgements

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Spectrum Tracksite—also known as the Grapevine Pass Wash Tracksite

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INTRODUCTION

The Spectrum Tracksite is located in the east branch of Grapevine Pass Wash, 1-1/2 miles northwest of Washington City, ¾ mile south of Grapevine Pass and Interstate 15, in SW1/4, NW1/4, Section 7, T 42 S, R 14 W. The Spectrum Tracksite has been known locally for some time and visited often by the public. The tracksite is on property owned by the Utah School and Institutional Lands Administration (SITLA) and is managed by its Southwestern Area Office. The Southwestern Area Office of SITLA funded the original study of the Grapevine Pass Wash Tracksite, here called the Spectrum Tracksite.

SITE DESCRIPTION

The sandstone exposure containing the tracks occurs in the lower part of the Kayenta Formation (Figure 1). The track layer dips 13 degrees north, with a dip direction of north 35 degrees west. According to Beik (2003), the Kayenta is early Jurassic in age (from Imlay, 1980) and 925 feet (282 m) to 935 feet (285 m) thick northwest of the study area. Kayenta exposures are seen as "a thick, monotonous sequence of interbedded, thin-to medium-bedded, moderate-reddish-brown siltstone, fine-grained sandstone, and mudstone". Beik further states that "Kayenta strata generally weather to poorly exposed slopes, except in the upper part of the formation where ledges and small cliffs are common" (Beik, 2003).

The Kayenta layer containing the tracks is about ½ meter (18 to20 inches) thick. It is 5 meters (15 feet) above the Kayenta base and is "a very pale-orange, medium-bedded, very fine-to fine-grained sandstone that is overlain by thin-bedded, reddish-brown mudstone and siltstone" (Beik, 2003). The tracks on the track layer were exposed as the mudstone and siltstone above was removed by erosion. Erosion also wears away the tracks on the track layer, but this process has been slowed by a dam ¼ mile north of the site. Currently, slope wash from the mudstone and siltstone slope above the site covers 1.80 to 3.10 meters (6 to 10 feet) of the bed that was at one time exposed. Prior to the dam this material would have been washed away; so much of this slope wash has accumulated since the dam was installed upstream. Approximately 20 additional square meters were cleared from the track layer next to the slope. This exposed additional tracks, but all had been weathered to some extent.

The exposed track layer covers over 500 square meters and measures approximately 44 meters (144 ft.) by 12 meters (39 ft.). Not all of this rock exposure contains tracks, many tracks likely having been eroded away years ago. Most tracks occur down slope near the contact with the overlying layer. Some of the deepest and best tracks also occur in the area. Some of the tracks are quite shallow and hard to distinguish. Others are distorted by erosion of the dipping sandstone bed.

Meter by meter mapping produced a long narrow map of the track site. This map has been reproduced in 6 separate page sized maps, Maps 1 through 6. A somewhat one directional trend can be seen when standing on the site and this is readily apparent on the map. Ninety six percent

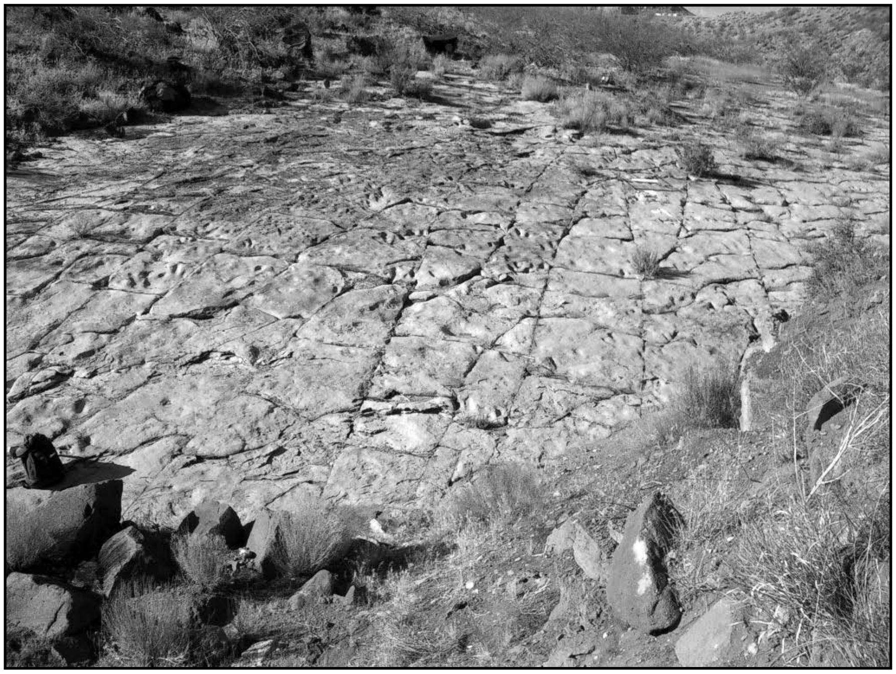
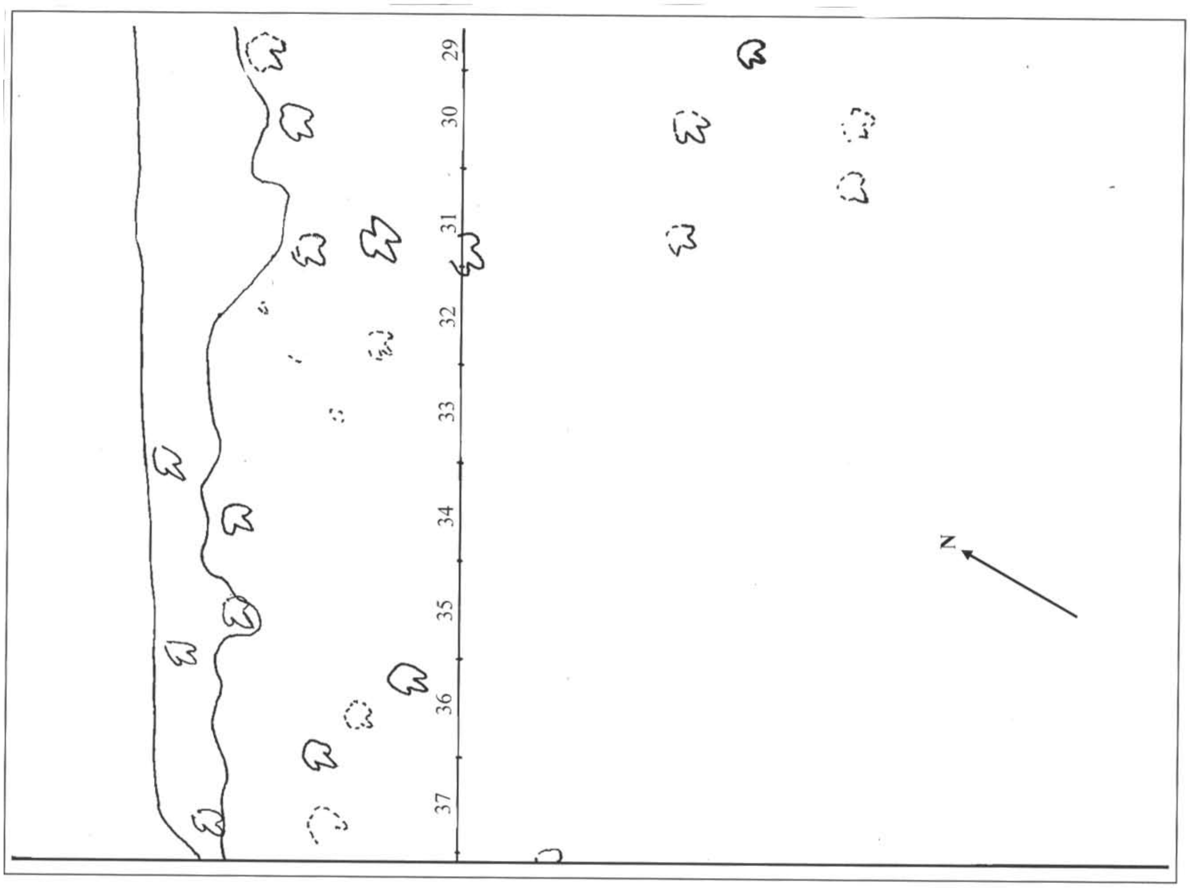
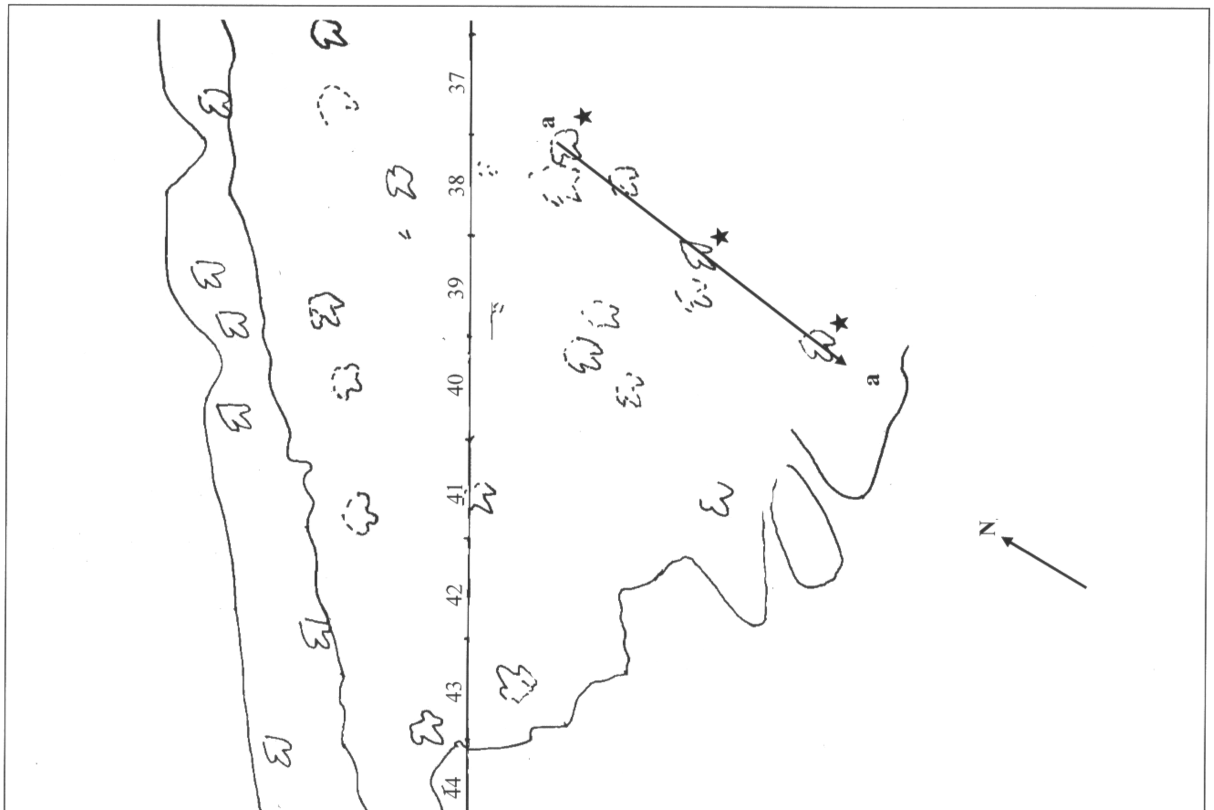


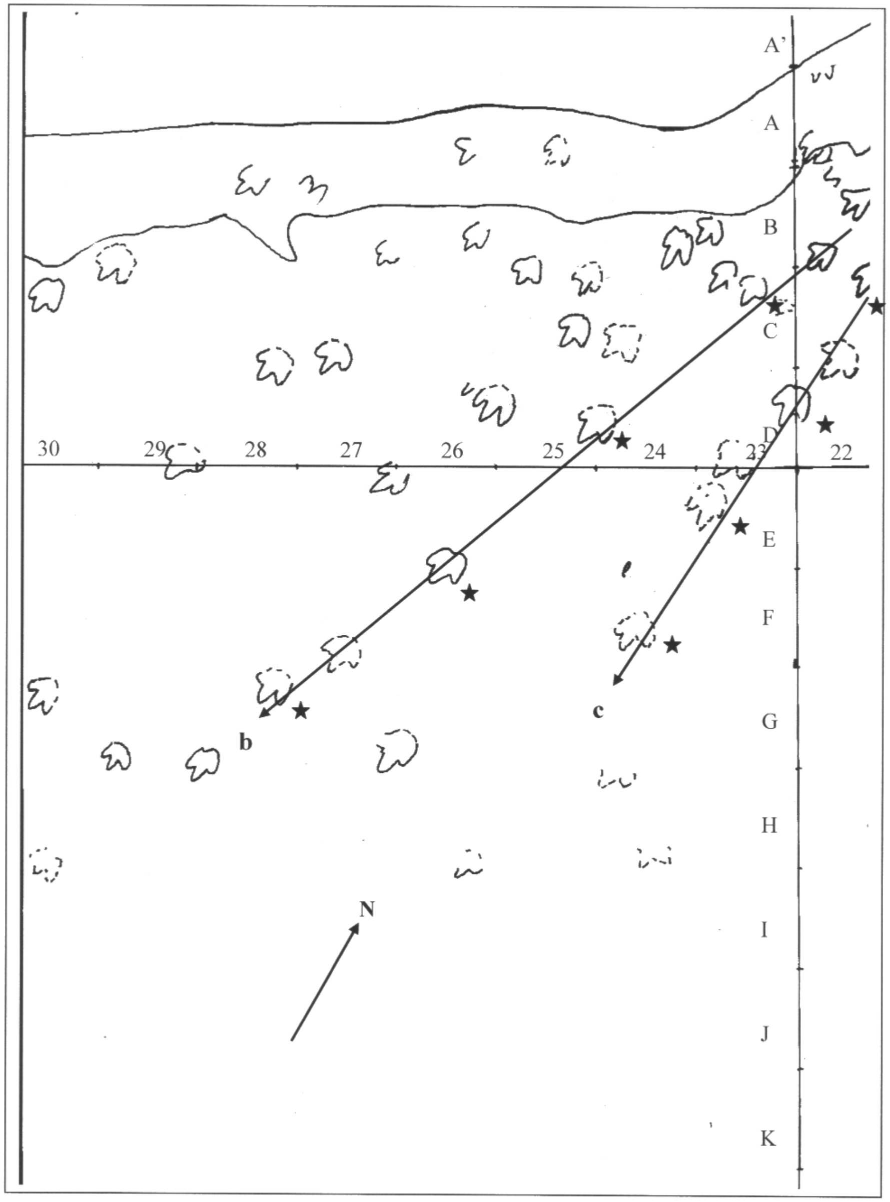
Figure 1. Spectrum Tracksite. View is looking south. Track surface is 5 meters (15 feet) above the base of the Kayenta Formation (Lower Jurassic) and dips 13 degrees north, with a direction of north 35 degrees west.



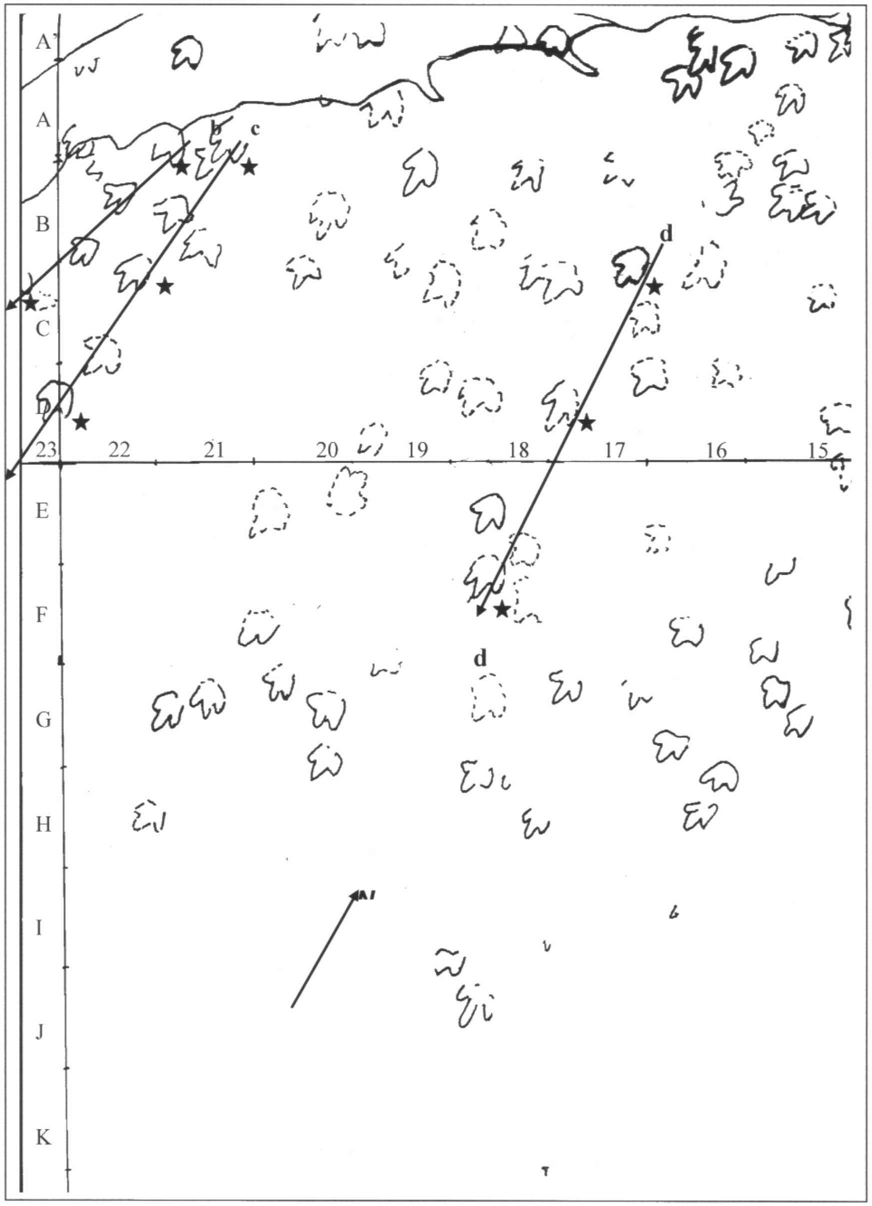
MAP 2. SPECTRUM TRACKSITE, Paleontology Locality 42Ws201T
[----------] Scale = 1 meter



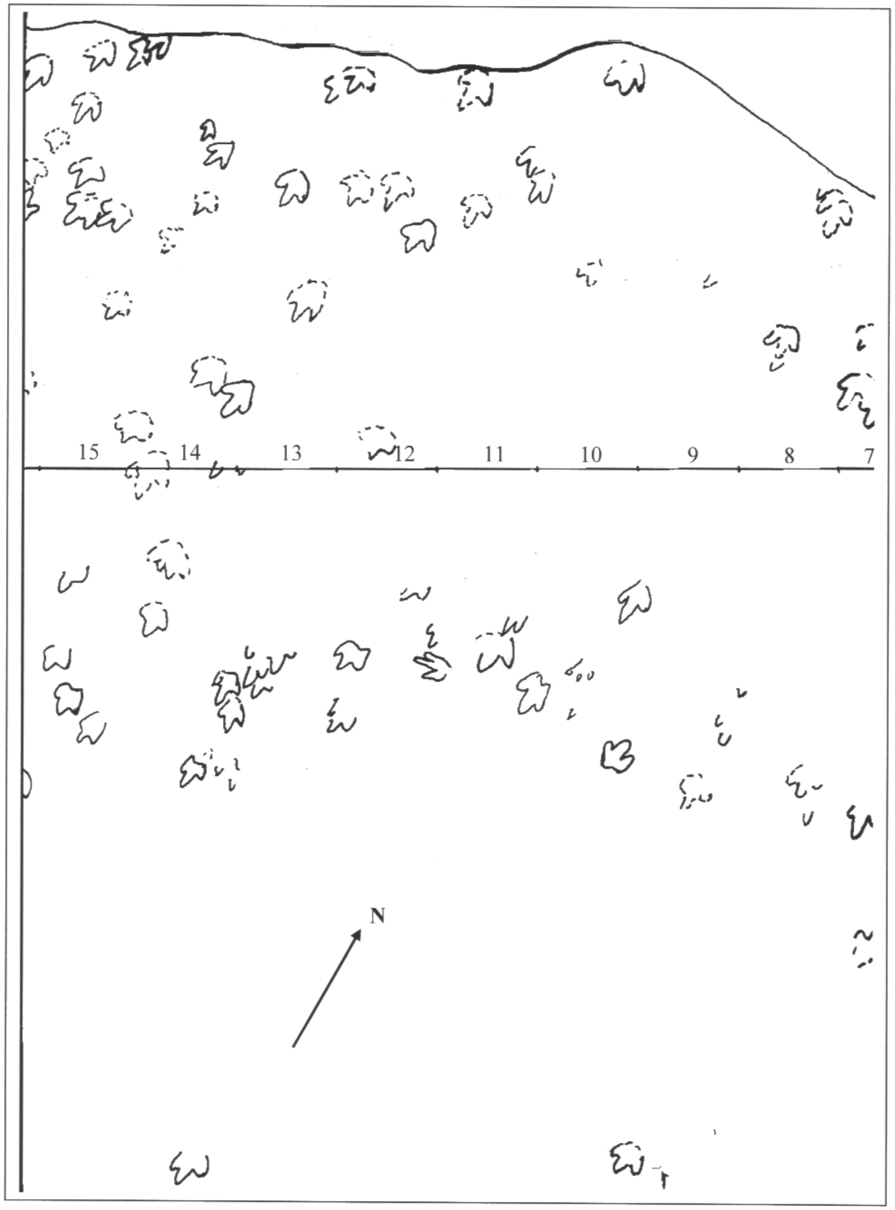
MAP 1. SPECTRUM TRACKSITE, Paleontology Locality 42Ws201T
★——▶ **= Possible trackway**
[----------] Scale = 1 meter



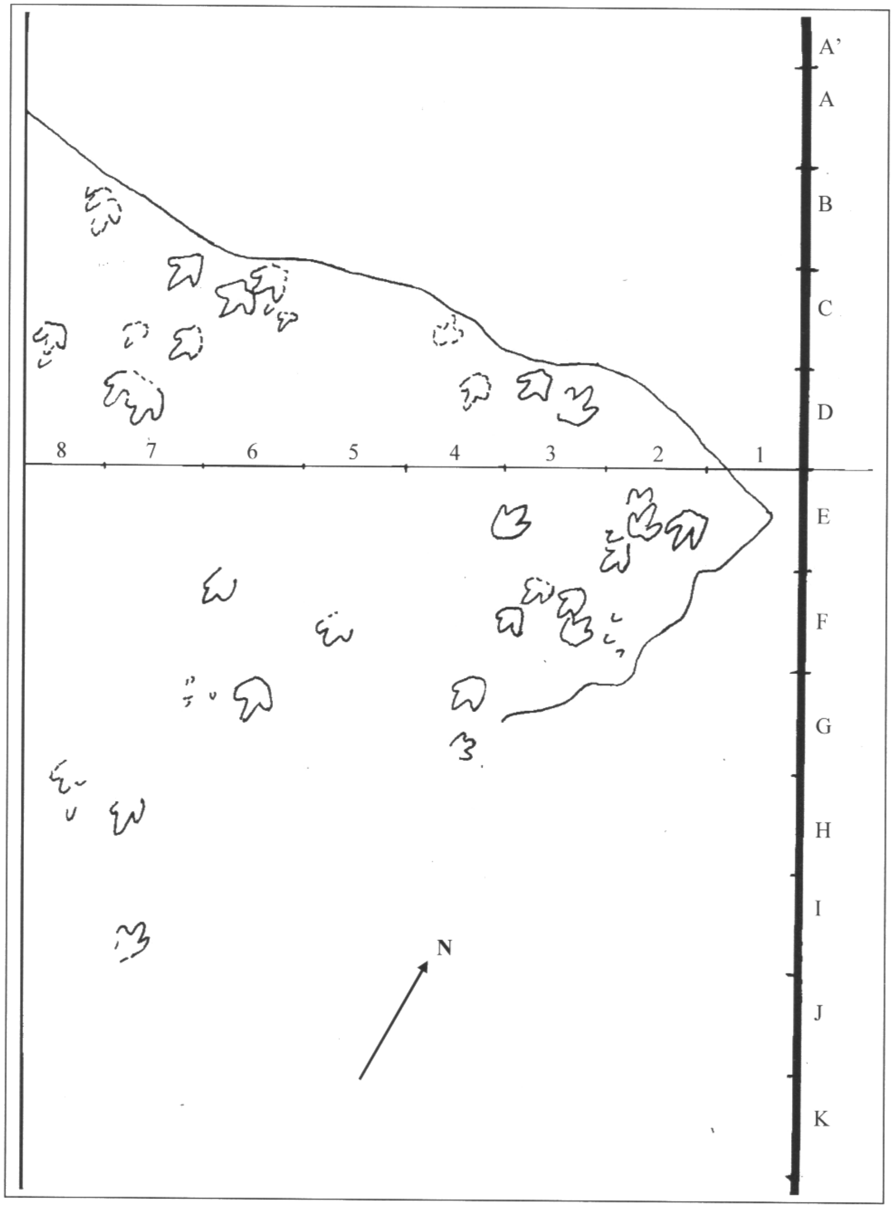
MAP 3. SPECTRUM TRACKSITE, Paleontology Locality 42Ws201T
★→ **= Possible trackways, continued on MAP 4** [-----------] Scale = 1 meter



MAP 4. SPECTRUM TRACKSITE, Paleontology Locality 42Ws201T
★→ **= Possible trackways, continued on MAP 3** [-----------] Scale = 1 meter



MAP 5. SPECTRUM TRACKSITE, Paleontology Locality 42Ws201T
[-----------] Scale = 1 meter



MAP 6. SPECTRUM TRACKSITE, Paleontology Locality 42Ws201T
[-----------] Scale = 1 meter

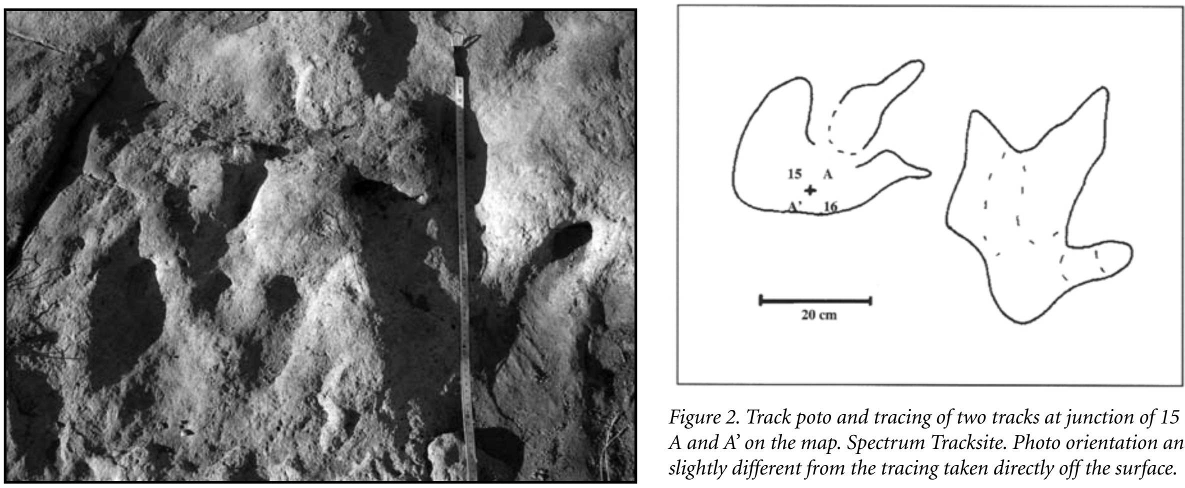


Figure 2. Track poto and tracing of two tracks at junction of 15 and 16, A and A' on the map. Spectrum Tracksite. Photo orientation and angle is slightly different from the tracing taken directly off the surface.

of the tracks are going roughly south-southwest. There are, however, a few tracks (4%) going in the exact opposite direct.

TRACKS

In his report on the Geologic Map of the Harrisburg Junction Quadrangle, Beik (2003) describes the tracks at the Spectrum site as "about seven sets of parallel tracks" and that "the tracks are up to 16 inches 40cm long, 12 inches (30cm) wide, and 2 inches deep."

A casual inspection of the track-bearing surface shows 50 or so tracks. However, detailed mapping of the site revealed approximately 200 tracks. Detail of the tracks varies with some showing good form and up to 5cm (2 inches) deep. Others are quite shallow with little detail and only visible under certain light conditions. In some cases, only toe points were map able. All tracks appear to have been made by the same species of animal, a tridactyl, bipedal theropod dinosaur. They are very similar in shape and size. Most fit in the size range of 30 to 46cm (12 to 18 inches) in length and 25 to 37cm (10 to 15 inches) wide. The smallest track observed measured 25cm (10 inches) long and 18cm (7 inches) wide. No small tracks of *Gallator* size

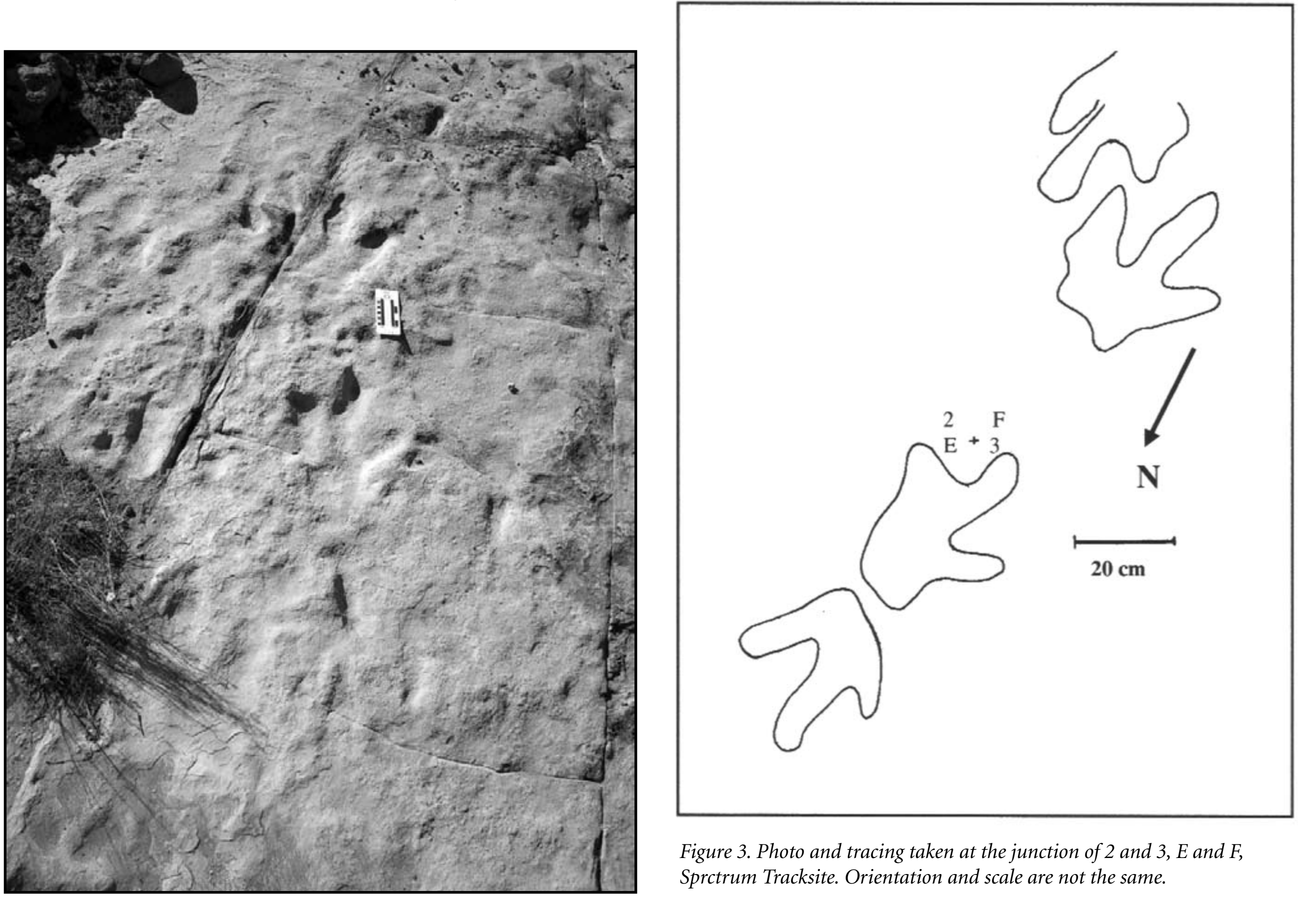


Figure 3. Photo and tracing taken at the junction of 2 and 3, E and F, Sprctrum Tracksite. Orientation and scale are not the same.

and type (as are also common in the Kayenta Formation) were observed at this site. These small track makers may have been absent at the time the other tracks were made and preserved or being much smaller, eroded away from the surface more quickly. Perhaps smaller tracks would be found if new material were to be exposed by removing the overlying siltstone and mudstone beds where no erosion has occurred.

The tracks are most likely referable to the ichnogenus *Eubrontes*, the most common large track in the Kayenta Formation. Although many tracks are distorted by erosion, those that do show good form compare well with *Eubrontes* type tracks (Lull, 1953). (Figures 2 and 3.)

TRACKWAYS

Trackways (a set of three or more tracks demonstrating steps by one individual) at the site are sometimes hard to distinguish because of eroded and missing tracks, or mixing with other tracks. Although trackways are difficult to distinguish, there may be as many as 8 or 9 trackways at the site. Four examples are noted on the track site Maps, numbers 1, 3, and 4. These vary in direction of motion from South 10 degrees east to south 17 degrees west with. Measured steps (measured toe tip to toe tip) of these trackways are as follows (see Maps 1, 3, and 4):

a - Tracks 1 to 2 = 1.70 m, tracks 2 to 3 = 1.45 m in a south 6 degrees west direction.

b – Tracks1 to 2 = 2.10 m, tracks 2 to 3 = 2.10 m, 3tracks 3 to 4 = 2.10 m, tracks 4 to 5 = 2.05 m in a south 17 degrees west direction.

c – Tracks 1 to 2 = 1.75 m, tracks 2 to 3 = 1.50 m, tracks 3 to 4 = 1.40 m, and tracks 4 to 5= 1.45 m in a south 2 degrees west direction.

d – Tracks 1 to 2 = 1.30 m, and tracks 2 to 3 = 1.30 m.

ENVIRONMENT, POSSIBLE TRACKMAKER, AND BEHAVIOR

Referencing Sansom (1992), Blakey (1994), and Peterson (1994), Beik (2003) describes the depositional environment of the Kayenta as fluvial, distal fluvial/playa, and minor lacustrine. The sandstone track-bearing layer may represent the shoreline of a small lake.

Over the years several types of dinosaurs have been proposed as track-makers for *Eubrontes* tracks. Miller, Britt and Stadtman (1989) suggested a prosauropod for the track-makers at the Warner Valley tracksite. However, others consider *Eubrontes* tracks to be those of theropod (meat-eating) dinosaurs (Olsen, 1980; Thulborn, 1989; and Lockley and Hunt, 1995; and Hamblin and Bilbey, 1999). Kirkland, Lockley and Milner (2002), in discussing the new tracksite at Johnson Farm, suggest the *Eubrontes* tracks were made by the crested, meat eating dinosaur *Dilophosaurus* or some similar animal known from the Kayenta Formation following the interpretation of others (Lockley and Hunt, 1995.

With a few exceptions, tracks at the Spectrum site show large (for early Jurassic times) theropod dinosaurs moving in a south-southwest direction. Numerous parallel tracks and trackways are often interpreted as indicating animal movement next to a lake shore, stream, or seaway (Lockley, 1987). It may also indicate gregarious behavior (Lockley, 1986). Trackway "b" is of particular interest because of the length of the step, over two meters. If this is a correctly measured trackway without missing tracks, this possibly represents a dinosaur moving faster than a walking gait.

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History, Geology and Paleontology: St. George Dinosaur Discovery Site at Johnson Farm, Utah

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ABSTRACT

A spectacular dinosaur tracksite discovered in early 2000 is now the home of a museum that opened in April 2005 named the St. George Dinosaur Discovery Site at Johnson Farm (SGDS), St. George in southwestern Utah. A variety of abundant and very well-preserved vertebrate tracks, mostly belong to dinosaurs and crocodylomorphs, have been found within the Lower Jurassic Moenave Formation of the Glen Canyon Group (approximately 198–195 million years old). Trace fossils unique to SGDS include an enormous collection of dinosaur swim tracks, tail drag marks, skin impressions, and a very rare theropod resting trace. At least 25 track horizons have thus far been recognized within a 1 km^2 area in and around SGDS, in association with plants and the body fossils of ostracods, conchostracans, a variety of fishes, and dinosaur bones and teeth. Along with these fossils, there are a wide variety of sedimentary structures including stromatolites, mudcracks, ripple marks, salt crystal casts, flute casts, rill marks, scours, load casts, tool marks, groove casts, and raindrop impressions. Fossils and sedimentary structures provide a unique view of an Early Jurassic lacustrine shoreline—now coined Lake Dixie.

INTRODUCTION AND HISTORY

On February 26th, 2000, Dr. Sheldon Johnson was leveling a hill on his property when he accidentally discovered an incredible dinosaur tracksite within St. George city limits, Washington County, Utah (Fig. 1 and 2). A couple of months following this discovery, paleontologists making initial investigations of the tracksite recognized fish fossils and bones on an undisturbed hill located north-northwest of Riverside Drive, and the present location of the St. George Dinosaur Discovery Site at Johnson Farm (SGDS) (Fig. 1).

Within two months of the original discovery, the site had received much public and media attention, and by late June had already been visited by more than 50,000 visitors. This interest was only heightened by further discoveries in nearby, stratigraphically contiguous outcrops (provisionally referred to as the Darcy Stewart site (DS), Washington County School District property (WCSD), and the Church of Jesus Christ of Latter Day Saints property (LDS)). Many of these discoveries, including the traces of a crouching theropod dinosaur, also attracted national media attention.

From 2000 through 2004, representatives of the Utah Geological Survey (UGS), the University of Colorado at Denver Dinosaur Trackers Research Group (CU), and many other professional paleontologists worked closely with the City of St. George, which appointed the author as City Paleontologist, to map more than 1000 *in situ* tracks, and preserve, prepare, and document those already excavated, through tracings, measurements, photography and casting (Kirkland et al., 2002). A significant result of this scientific activity was the scheduling of a March 2005 international symposium called "Tracking Dinosaur Origins: the Triassic-Jurassic Terrestrial Transition." This symposium attracted paleontologists and geologists from all over the world, some of whom are now actively involved in research at the SGDS and surrounding areas.

The site is further increased in its significance by the discovery of plants, enormous collections of fossil fishes, invertebrate body fossils, and theropodan dinosaur remains, all found in close association with the tracks.

The prime objective of this paper is to provide introductory descriptions of the tracks, traces, plants, body fossils, and sedimentary structures. Track assemblages of this age in the eastern United States (Hitchcock, 1858, Lull, 1953) provide a global standard for Lower Jurassic track classification (taxonomy) despite many specialized, complex historical problems of terminology. We try to avoid unnecessary specialist terminology in describing the tracks, fossils and geology, and stress that the St. George tracksites collectively provide a window into an Early Jurassic ecosystem associated with the shores of a large lake or and lake system now dubbed "Lake Dixie".

GEOLOGY, STRATIGRAPHY AND SEDIMENTOLOGY

Dinosaur tracks and other fossil footprints are well known in the Lower Jurassic of the southwestern United States (Lockley and Hunt, 1995), though skeletal remains are rare in the region. However, until the discovery of the SGDS only a relatively small number of tracksites had been documented in this part of southwestern Utah or 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 a number of additional sites in the region, including multiple track and bone localities in the Late Triassic Chinle Group, and at many new sites in the overlying Lower Jurassic Moenave and Kayenta formations (Figs. 1 and 3).

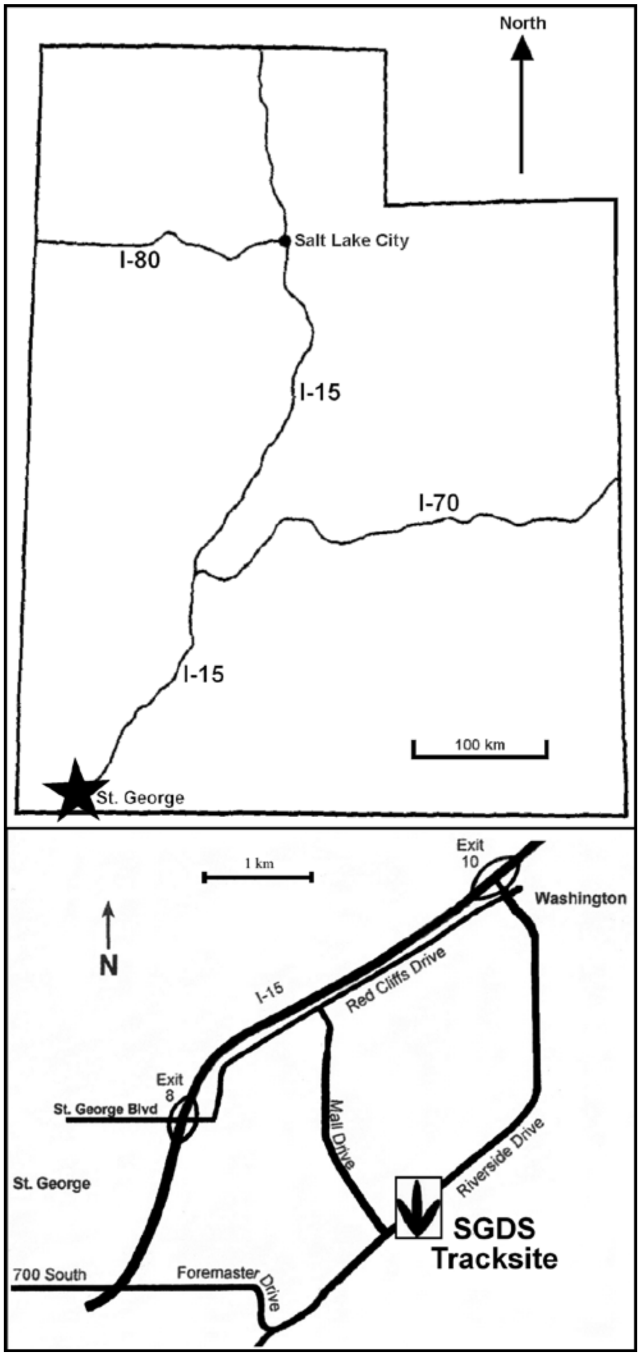

Figure 1. Locality map of the St. George Dinosaur Discovery Site at Johnson Farm, St. George, Washington County, Utah.

Figure 2. Dr. Sheldon Johnson with Eubrontes *track specimen, SGDS.9. Photograph by James I. Kirkland (Utah Geological Survey, 2000).*

At the SGDS, the Moenave Formation is about 73 meters thick; consisting of the underlying Dinosaur Canyon Member (about 48 meters thick) and the Whitmore Point Member (about 25 m thick) above (see Fig. 3). The Moenave unconformably overlies the Late Triassic Chinle Group. The Moenave is overlain by the Springdale Sandstone Member of the Lower Jurassic Kayenta Formation, separated by an angular unconformity. The Triassic-Jurassic boundary is located somewhere within the Dinosaur Canyon Member. This study focuses on fossils from the uppermost part of the Dinosaur Canyon to the top of the Whitmore Point. Based on the track types and body fossils found, the age of the upper portion of the Moenave is interpreted as Early Jurassic (Hettangian—the earliest stage of the Jurassic Period, from 199.6 to 196.5 million years ago).

Tracks have been identified on 25 stratigraphic levels in the immediate vicinity of the SGDS (Fig. 3), and many of these layers have been mapped *in situ*. The first-discovered horizon, called the "Main Tracklayer" at the SGDS, reveals tracks and associated mudcracks preserved as robust sandstone casts (negative relief) at the base of a thick (30–70 cm) well-sorted, fine-grained sandstone bed, located about 53 meters above the formation base (Figs. 2, 3, 4A). The casts, which have up to 10–20 cm of relief, can only be seen after the "Main Tracklayer" sandstone bed has been turned over. This process requires heavy equipment, and necessitated removing blocks from their original *in situ* location.

Excellent dinosaur track-bearing horizons are located on top of the "Main Tracklayer" sandstone, termed the "Top Surface," an enormous portion of which still remains *in situ* within the first phase museum at the SGDS. These

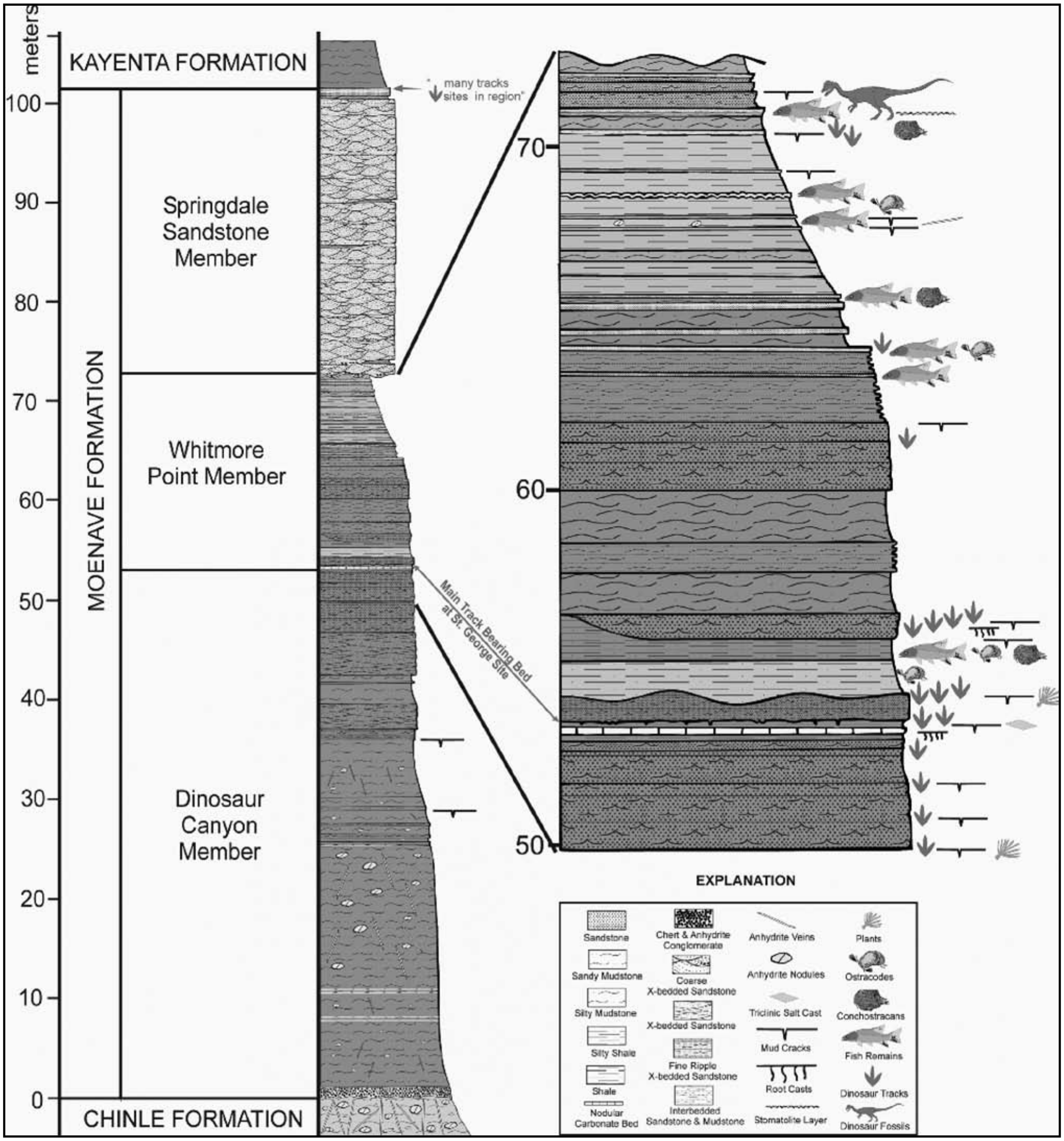

Figure 3. Stratigraphic section measured at the SGDS. Fossil types and sedimentary structures are indicated by the appropriate symbols and are keyed in the accompanying legend. Thickness measurements are in meters.

important and complex undulating surfaces reveal several laterally variable layers in a thin stratigraphic interval, and display a complex of irregular current ripples (Fig. 4B), regular oscillation ripples, ridges, swales, mudcracks (Fig. 4A), scour and depositional features, in addition to tracks and/or under-tracks with variable preservation.

One of the striking features of the SGDS is the relationship between trackways, topography, and the local paleogeography. We cannot map the paleogeography at every track level, as surfaces are only exposed sporadically, and the cost of additional excavation would be prohibitive. However, it is possible to map the "Main Tracklayer" where most of the trackways were made by animals walking on an undulating surface. By contrast to this "onshore" location, an extensive track-bearing surface discovered to the northwest on WCSD and DS properties is a continuation of the "Main Tracklayer", and shows abundant dinosaur swim tracks (*Characichnos*–see below) representing an "offshore" loca-

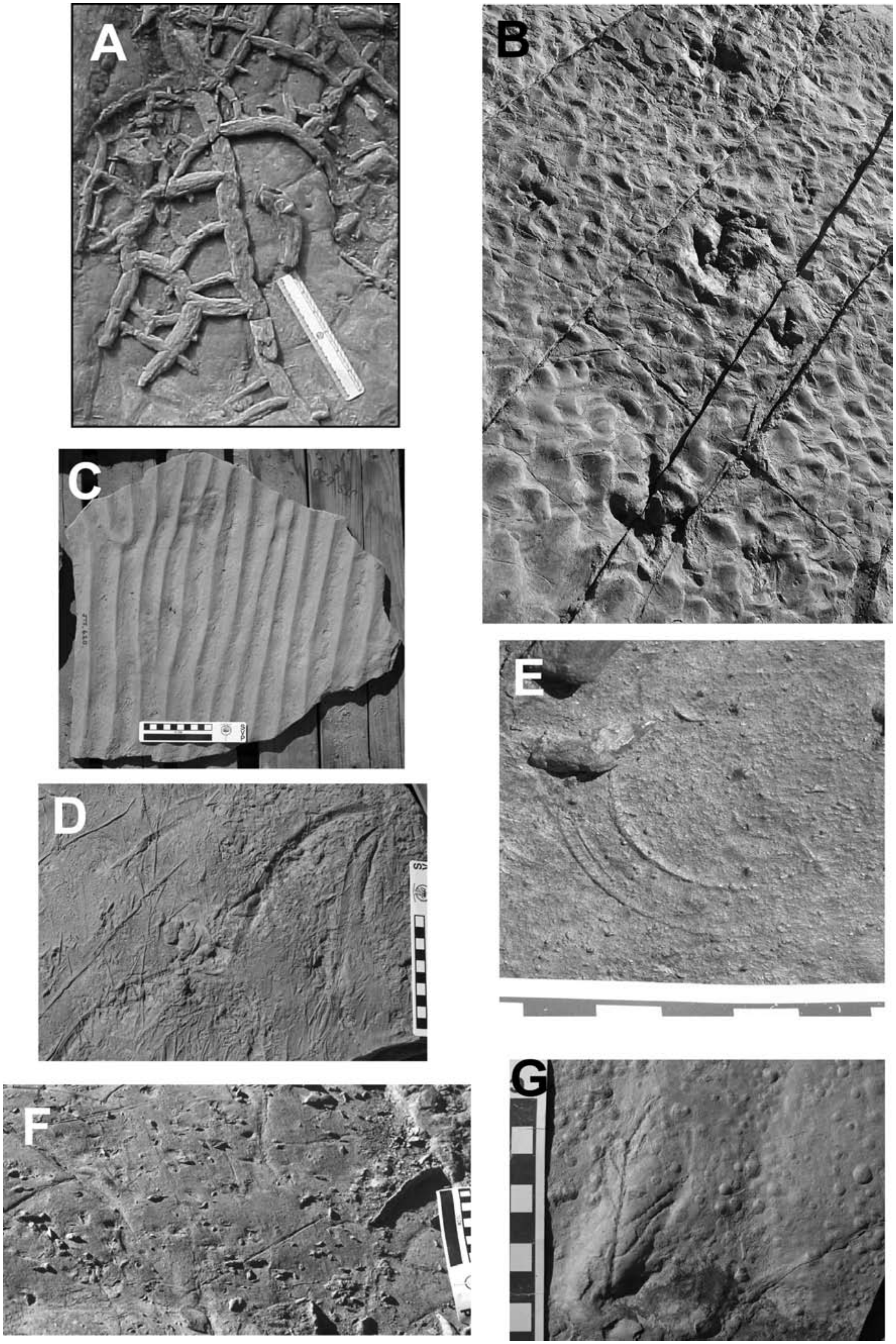

Figure 4. Representations of some of the more common and significant sedimentary structures from and around the SGDS. A, natural casts of mudcracks, SGDS.10.; B, Eubrontes *and* Grallator *trackways with current ripples and joints, SGDS.18.T1.; C, symmetrical wave-formed ripples, SGDS.620.; C,.; D, tool marks, SGDS.262; E, scratch circles; F, sulfate salt crystal casts; and G, raindrop impressions around a* Pagiophyllum *conifer branch, SGDS.491.*

tion equivalent to the "onshore" surface marked by well-preserved *Eubrontes* tracks.

This same kind of pattern can be seen in sedimentary structures, showing evidence of being formed on-shore and off-shore. Off- or near-shore submerged sedimentary structures include a variety of current and symmetrical ripples (Figs. 4B, C), tool marks (Fig. 4D), flute casts, and scratch circles (Fig. 4E). Likewise, certain kinds of sedimentary structures can only be formed on land, such as mudcracks (Fig. 4A), salt crystal casts through evaporation (Fig. 4F), and rain drop impressions (Fig. 4G).

Many fish remains have been recovered from areas to the north and northwest of the SGDS museum site on DS, WCSD and LDS properties, especially from higher stratigraphic levels in younger Whitmore Point sediments (Fig. 3). This gives us an indication that at the time the "Top Surface" layers were deposited the lake shoreline probably ran somewhere between the SGDS and DS sites, probably with a NNE–SSW trend. Recently, fish scales have been found in the mudstones deposited directly on to the "Top Surface" tracksite, suggesting lake level rise (transgression) soon after track formation.

Support for this interpretation of the shoreline trend comes from the orientation of trackways, symmetrical wave-form and current ripple marks, and other sedimentary structures (Figs. 4B, C, D). For example, there is a series of large ridges and swales (or troughs) with a WNW–ESE trend. The troughs contain current ripples that suggest consistent flow patterns towards the WNW: i.e., towards the lake. These features may represent remnants of bars and associated sedimentary structures that formed during high runoff in the direction of the lake. Locally, this topography has been eroded or reworked by small-scale water action. Furthermore, we find symmetrical wave-form ripples with a NNE–SSW trend suggesting the lapping of waves parallel to the paleo-shoreline, but perpendicular to the ridge and swale topography. Many of the dinosaur trackways follow lake shore-parallel or shore-perpendicular trends, as noted at other sites in the area and elsewhere (Lockley and Hunt, 1995). This means that shore-perpendicular trackways follow the ridge and swale trend. There also seems to be a concentration of *Batrachopus* tracks on the ridges (i.e. shore-perpendicular), therefore walking across higher terrain.

Tracks are also exposed immediately to the northwest of the SGDS museum and Riverside Drive (NE–SW road orientation). This tracksite is called the "Stewart-Walker Tracksite", having approximately 60 mapped tracks that occur on four different stratigraphic levels separated by about 50 cm (Fig. 3). These beds are about 1.5 meters above the SGDS "Top Surface" track horizons. In August 2005, the first undisputable plant-eating dinosaur tracks were discovered on one of the track horizons. These tracks are called *Anomoepus*, and were produced by small bipedal ornithischian dinosaurs.

Other sites at various stratigraphic levels above the "Stewart-Walker Tracksite" have also been mapped, or at least recognized. Together the mapped areas place about 3000 tracks (not including about 2000 dinosaur swim tracks) in their *in situ* orientations and stratigraphic context. A similar or larger number of additional tracks are preserved on isolated blocks from the "Main Tracklayer" and other outcrops on the northwest side of Riverside Drive. Thousands of additional tracks and body fossils have yet to be excavated.

VERTEBRATE ICHNOLOGY

Traditionally, the study of track and traces (ichnology: from the Greek *ichnos* meaning trace) involves the use of a specialized naming or classification system or taxonomy. Thus, rather than species and genera, ichnologists or "trackers" refer to ichnospecies and ichnogenera, which name the track—not the animal that made them. This parallel classification system is called ichnotaxonomy.

In the case of three-toed (or tridactyl) tracks from the Early Jurassic (or Liassic) such as *Grallator* and *Eubrontes*, the traditions of naming or classification traces dates back to the origins of the science founded by Reverend Edward Hitchcock in the 1830s. His life's work, summarized in Hitchcock (1858), was revised by Richard Swann Lull culminating in his best-known track monograph (Lull, 1953).

These classic Liassic tracks, including the *Grallator*-like ichnogenus *Anchisauripus*, and the larger track *Eubrontes* were recently re-examined by Olsen et al. (1998). We use their evaluations and illustrations of the holotypes as a point of reference for comparison with the tracks from St. George.

Tracks from St. George assigned to *Grallator* and *Eubrontes*, as well as crocodylomorph tracks of *Batrachopus* (Lockley et al, 2004), are all remarkably similar to those described by Hitchcock (1858) and Lull (1953) from the Early Jurassic of New England, and strata of this same age from elsewhere around the world, including the western United States (Lockley and Hunt, 1995). Traditional studies of the ichnogenera *Grallator*, *Anchisauripus* and *Eubrontes* (sometimes referred to as the G-A-E plexus) have drawn attention to the large number of very similar ichnospecies. In fact, these kinds of tracks are considered so similar by some workers (Olsen, 1980; Olsen et al., 1998) that they have suggested that all may belong to the same species, and size differences probably reflect growth changes from juveniles to adults. As discussed below, some authors including us do not fully agree with this interpretation; however it is convenient to describe the tracks in order of increasing size.

The size range of tracks from the SGDS is remarkable. The smallest tracks are only about 2–3 cm long, but several comprise trackways with exceptionally long steps. In fact, the smallest trackmaker with footprint length of 2 cm has a step length of 23-36 cm. Another trackmaker with a footprint length of 5 cm has a step of 57 cm. Some, although small (footprint length 8 cm including heel trace), have short steps and show traces of the "heel" (metatarsal, or lower leg impression) and hallux (digit I).

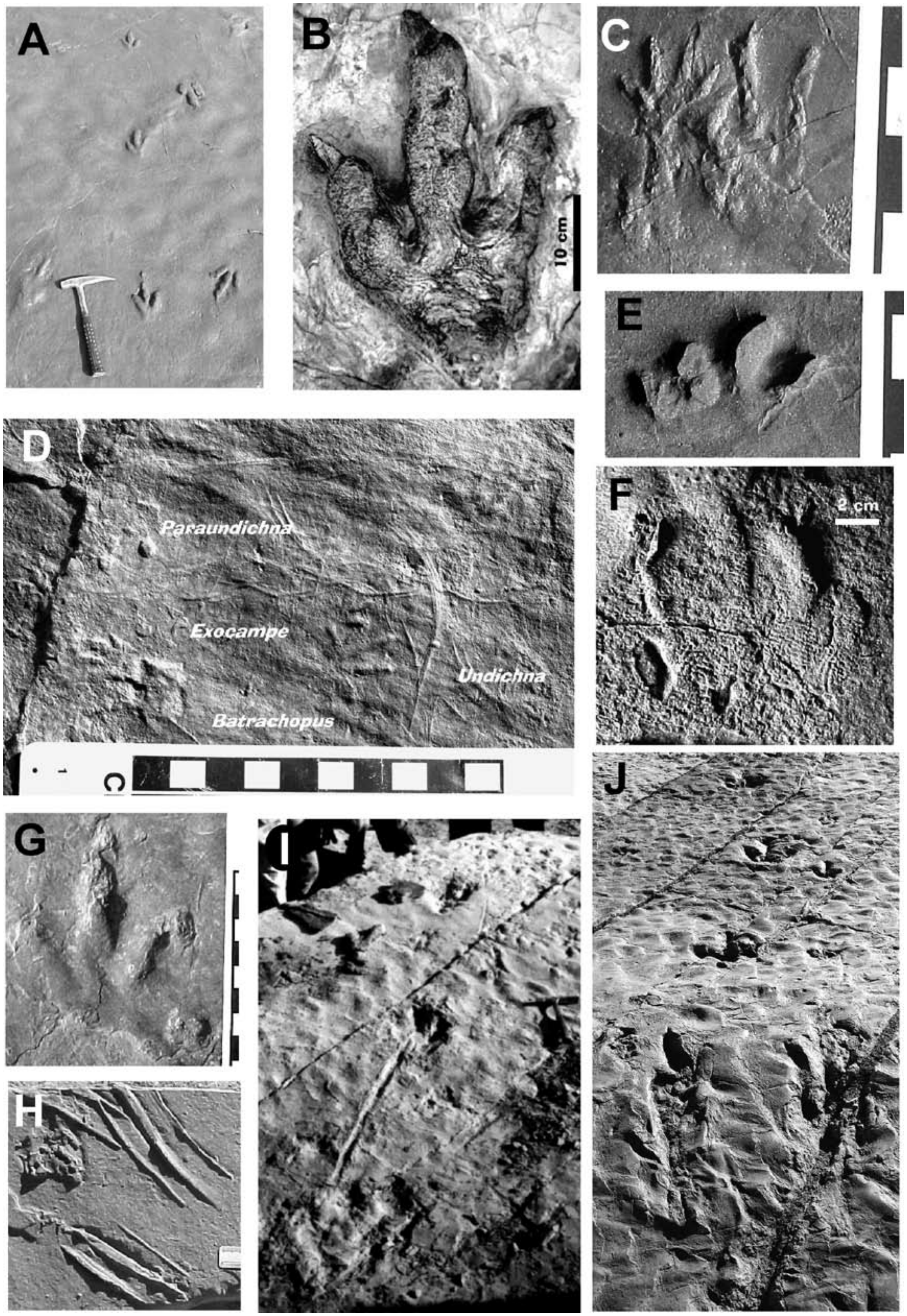

Figure 5. Vertebrate tracks from the SGDS and nearby localities. A, small coelophysoid theropod trackways, Grallator, *SGDS.568.; B, large ceratosaurian theropod track,* Eubrontes, *SGDS.9.; C, manual and pedal tracks of* Batrachopus, *produced by a small crocodylomorph reptile, SGDS.170.; D, elongate digits on manual and pedal tracks of a sphenodontian reptile track, possible* Exocampe, *associated with a potential coelacanth fish swim trace similar to* Paraundichna *SGDS.509.; E, small and unidentified synapsid-like track, SGDS.190.; F, large and potential synapsid track showing five digits, claw marks and skin impressions, SGDS.176.; G, small bipedal ornithischian dinosaur track,* Anomoepus*; H,* Grallator*-type dinosaur swim tracks (*Characichnos*), SGDS.47.; I,* Eubrontes *trackway with tail drag marks, SGDS.18.T1.; J, set of two crouching* Eubrontes *traces with associated manus impressions, ischial callosities, and tail drag marks, SGDS.18.T1.*

Small tracks identified as *Grallator* (Figure 5A) have been identified on all but two track layers at SGDS. By contrast to the *Eubrontes* tracks (foot length >32 cm – Fig. 5B), the size of the *Grallator* tracks ranges from 10-25 cm long and 8-11 cm wide. There appear to be few intermediate track sizes in the range of foot length 25-32 cm, and few *Grallator* tracks exceed 20 cm in length. Well-preserved *Grallator* or *Grallator*-like tracks from the SGDS are hard to distinguish from similar tracks from the Hitchcock collection in New England (Hitchcock, 1958).

Some *Grallator* tracks from the "Top Surface" indicate that the track maker dragged or pushed its claws through wet mud before firmly planting the foot. These kinds of tracks give insight into theropod dinosaur behavior in the context of local topography in this marginal lake setting.

Many small, non-dinosaurian tracks have been found at the SGDS. Most resemble the well–known Early Jurassic ichnogenus *Batrachopus* (Olsen and Padian, 1986), which is usually attributed to a small crocodylomorph (Fig. 5C). Tracks of this type typically fall in the size range of 1–5 cm in length, though maximum lengths of about 8 cm are known. The hind footprint, which is most commonly preserved, is larger than the front footprint. In fact, the hind footprint may cover the front footprint on occasion, known as overprinting. *Batrachopus* trackways are hard to follow in detail though several have been recorded, including one that traveled for several meters paralleling the top of a ridge on the "Top Surface" track site within the SGDS museum.

Various other incomplete tracks may suggest the presence of lizard-like sphenodont animals (*Exocampe* tracks; Fig. 5D) and synapsids reptiles (Figs. 5E and F). Such tracks are known from other Triassic–Jurassic boundary sequences in the western USA, but especially in the case of the protomammals, they tended to prefer dry habitats.

As mentioned above, *Anomoepus* tracks were discovered at the SGDS by the author during excavation for further development near the museum (Fig. 5G). Early Jurassic *Anomoepus* tracks are quite common in New England, and are attributed to small bipedal ornithischian dinosaurs, possibly an animal like *Scutellosaurus*. Although poorly preserved, all of the characteristics are met for a positive identification of the SGDS specimens as *Anomoepus*.

Two very important associations of dinosaur tracks preserved at the SGDS make the Moenave Formation in this area of tremendous significance. First is the world's largest and best preserved collection of dinosaur swim tracks (Milner et al., 2004, 2005b), which subsequently ended all 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 out at each end, with the longer digit III leaving a more elongate and deeper scrape mark as compared to shorter digits II and IV (Fig. 5H). Dinosaur swim tracks from the Middle Jurassic of England were described and given the name *Characichnos* by Whyte and Romano (2003).

Finally, an interesting 22.3 m long *Eubrontes* trackway (SGDS.18.T1.) preserved on the "Top Surface within the SGDS museum displays very rare tail drag marks along much of its length (Fig. 5I). Near the beginning of this same trackway are squatting marks from the animal sitting down on the substrate, then shuffling forward and squatting second time to create two overlapping crouch impressions (Fig. 5J). This very unique trace fossil shows associated hand impressions left behind during the first squat (Milner et al., 2004). Both tail drag marks and crouching marks of theropod dinosaurs are extremely rare! To make this particular trackway even more unique, ischial boot marks, hallux impressions, and scale scratch lines are also preserved!

INVERTEBRATE TRACKS

A low diversity invertebrate ichnofauna in addition to the tetrapod tracks has been recognized at the SGDS and surrounding sites (Lucas et al, 2005). Horizontal burrows of the ichnogenus *Scoyenia* (Fig. 6A) are the only invertebrate traces found in the Dinosaur Canyon Member at the SGDS to date, and they occur in the upper 3 meters of the member. *Scoyenia* burrows also occur in local abundance on at least four horizons in the basal Whitmore Point Member which represents marginal lacustrine deposits. Two of these levels include the "Main Tracklayer" and the "Top Surface." Very well preserved horseshoe crab (*Kouphichnium*, Fig. 6B), insect (Fig. 6C), and beetle (Fig. 6D) trackways occur commonly on the "Split Layer" and "Top Surface" at the SGDS. Protovirgularia trails, probably produced by dragonfly larvae (Metz, 2002), also occur on the "Top Surface" leaving chevron-shaped trails (Fig. 6E). Abundant *Skolithos* burrows (Fig. 6F) cover enormous areas in association with mudcracks and hundreds of *in situ* dinosaur tracks and semionotid fish remains on LDS property. One of the best *Skolithos* layers is called the "Slauf burrow bed", with less common dinosaur tracks and fish fossils. Another bed of *Skolithos* burrows, called "Sally's burrow bed," is located directly above this. These beds are named after David Slauf and Sally Stephenson, both dedicated volunteers at the SGDS and members of the Utah Friends of Paleontology (UFOP). Extensive surfaces of *Palaeophycus* burrows (Fig. 6G) occur at the base of a heavily bioturbated, green sandstone bed containing abundant fish bones, coprolites, and conchostracans.

The overall diversity of invertebrate trace fossils is low, although many surfaces (more than dinosaur track-bearing layers) occur in the very top of the Dinosaur Canyon Member and throughout the entire Whitmore Point Member. Inferred trace makers include annelids, snails, insects and chelicerates. The invertebrate trace fossils at the SGDS represent those of marginal lacustrine to shallow lacustrine environments. This goes hand-in-hand with what vertebrate traces, body fossils and the sedimentology display.

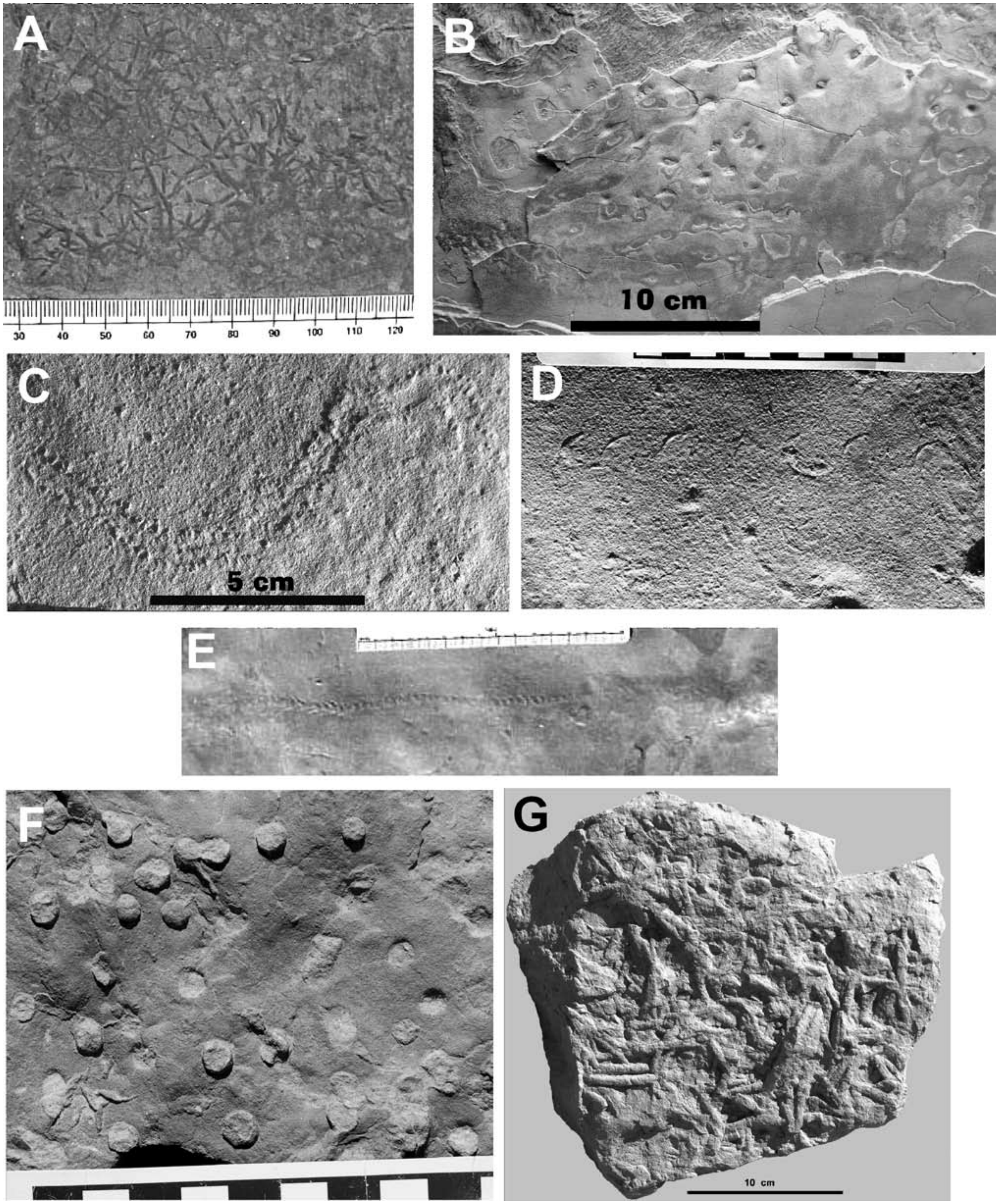

Figure 6. Invertebrate trace fossils found at and around the SGDS. A, Scoyenia *traces; B,* Kouphichnium *horseshoe crab trackway, SGDS.452.; C, insect trackway, SGDS.197.; D, beetle trackway, SGDS.197.; E,* Protovirgularia*, possible larval dragonfly trails, SGDS.38; F,* Skolithos *burrows, SGDS.453.; and G,* Palaeophycus *burrows preserved as natural casts, SGDS.191.*

BODY FOSSILS

Another unusual and quite unique feature of the SGDS is the rare occurrence of traces found in association with body fossils in the Whitmore Point Member of the Moenave. Invertebrate body fossils include ostracod and conchostracan arthropods. A growing diversity of fishes is being studied by the author at and near the SGDS. Two new species are described by Milner et al. (in press) and several additional new taxa will eventually follow as specimens are prepared, studied in detail, and compared with other fishes (Milner et al., 2005a). Of further interest are tetrapod remains from the SGDS and surrounding area, all of which belong to theropod dinosaurs thus far (Kirkland et al., 2005).

Invertebrate Body Fossils

A very low diversity invertebrate body fossil fauna has been found in multiple layers, all within the Whitmore Point Member (see Fig. 3). Bivalved shells of very small crustacean arthropods called ostracods and conchostracans are all that have been found so far. As mentioned above, invertebrate trace fossils are of low diversity, but they do show many more invertebrate types not represented by body fossils, such as insects (including beetle and possible dragonflies), worms, clams, snails, and horseshoe crabs.

Michael Schudack (in press) has reported *Darwinula* ostracods from the Moenave at the SGDS. *Darwinula* is a long-ranged freshwater genus and is extremely abundant. Other ostracod carapaces are attributed to forms from the Superfamily Cypridoidea, and all ostracods taxa combined represent shallow, freshwater lacustrine forms (Schudack, in press).

Conchostracans appear to be monospecific in and around the SGDS, most of which are quite small compared to other well-known conchostracan localities in the southwestern United States. The St. George conchostracans, like the ostracods, represent a freshwater, shallow lake paleoenvironment. They will be described in detail in the near future.

Fish Fossils

A moderately diverse fish fauna known as the "Lake Dixie Assemblage" is restricted to marginal-lake and exclusively lacustrine deposits of the Whitmore Point Member, Moenave Formation (Milner et al., 2005a, in press).

Two rice-shaped and -sized teeth of a new species of freshwater hybodont shark, along with several dorsal fin spines, have been discovered from WCSD property near the SGDS in the upper Whitmore Point Member (Milner et al., 2005a, in press) (Fig. 7A, B). Based on tooth shape and fin spine morphology, this new species belongs to the genus *Lissodus*, and probably would have measured over a meter in length.

A nearly complete palaeoniscoid fish was discovered by the author and awaits preparation. This specimen will most likely be a new taxon, since no know palaeoniscoid fishes of Early Jurassic age have been found in the southwestern United States.

Only two lungfish specimens, both represented by tooth plates of the "garbage-can" taxon *Ceratodus*, have been found in Early Jurassic rocks of the southwestern United States. The first specimen discovered is from the "Silty Facies" of the Kayenta Formation in northeastern Arizona (Kirkland, 1987, 1998). On October 2, 2004, SGDS volunteer and UFOP member Sally Stephenson discovered the second Early Jurassic specimen in the northwestern portion of Warner Valley near St. George (Fig. 7C). It was found in the Whitmore Point Member and is being described as a new species elsewhere (Milner et al., in press).

A huge and undescribed coelacanth from the near the SGDS is by far the largest recorded coelacanth from the Early Jurassic, and most likely the largest known freshwater coelacanth on record (Fig. 7D). No coelacanths have been found in the Early Jurassic of the southwestern United States. Preliminary examination of the specimens thus far prepared shows similarities to the Late Triassic Chinle Group coelacanth, *Chinlea sorenseni* (Schaeffer, 1967; Elliott, 1987).

The St. George fish fauna is dominated by remains of semionotid fishes. So far, all specimens can be attributed to the genus *Semionotus*. Several specimens clearly represent *Semionotus kanabensis* at the SGDS. *Semionotus kanabensis* was first described by Schaeffer and Dunkle (1950) from three-dimensional specimens they misinterpreted as coming from nearby Upper Triassic Chinle Group in Zion National Park. The fish fossils they described actually came from the Lower Jurassic Whitmore Point Member of the Moenave Formation. Enormous collections of semionotid fish have been assembled at the SGDS, and at least one new species can be determined thus far (Milner et al., 2005a, in press) (Fig.7E).

Aside from body fossils, the SGDS localities also produce an abundance of fish swim trails and coprolites. Fish swimming traces include fine examples of *Undichnia* (Fig. 7F), formed by the caudal fin of the fish scraping the submerged substrate as the fish swam along the lake bottom.

Another type of fish swimming trace from the SGDS resembles the ichnogenus *Paraundichnia* from the Middle Triassic (Ladinian) Lower Keuper of Rot am See, Baden-Württemberg, Germany (Simon et al, 2003). *Paraundichnia*, as well as the St. George specimen (Fig. 5D), were probably made by the pectoral and pelvic fins of a coelacanth scraping along a muddy substrate.

Theropod Dinosaur Remains

The best known Late Triassic-Early Jurassic theropods that are most often suggested as the probable producers of *Grallator* tracks are *Coelophysis* (from the Late Triassic Chinle Group) and *Megapnosaurus* (formerly *Syntarsus*). *Megapnosaurus* has been found in the Early Jurassic of Southern Africa (Raath, 1977, 1990) and from the Moenave (Lucas and Heckert, 2001) and Kayenta (Rowe, 1989) formations of Arizona. Both of these primitive theropods

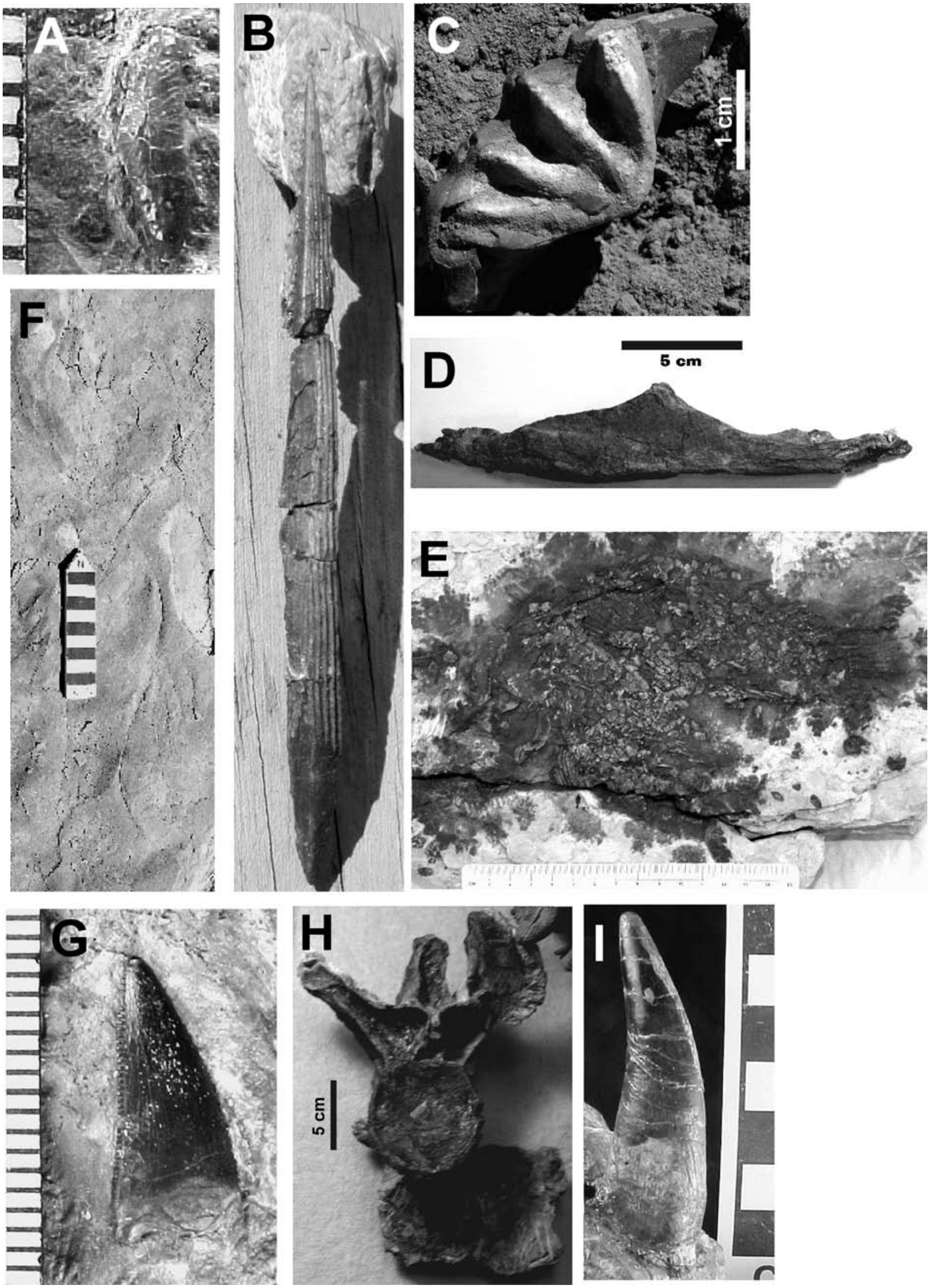

Figure 7. Vertebrate body fossils and a fish swim trail all found close to the SGDS. A, tooth from a new species of Lissodus *hybodont shark, SGDS.820; B, dorsal fin spine from a new species of Lissodus hybodont shark, SGDS.828; C, new species of* Ceratodus *lungfish tooth plate; D, angular bone from the lower jaw of new taxa of coelacanth fish; E, new species of* Semionotus *fish; F,* Undichnia *fish swim trail; G, coelophysoid theropod tooth possibly belonging to* Megapnosaurus*; I, mid-dorsal vertebra from a coelophysoid theropod dinosaur; and H, tooth from an undescribed theropod dinosaur.*

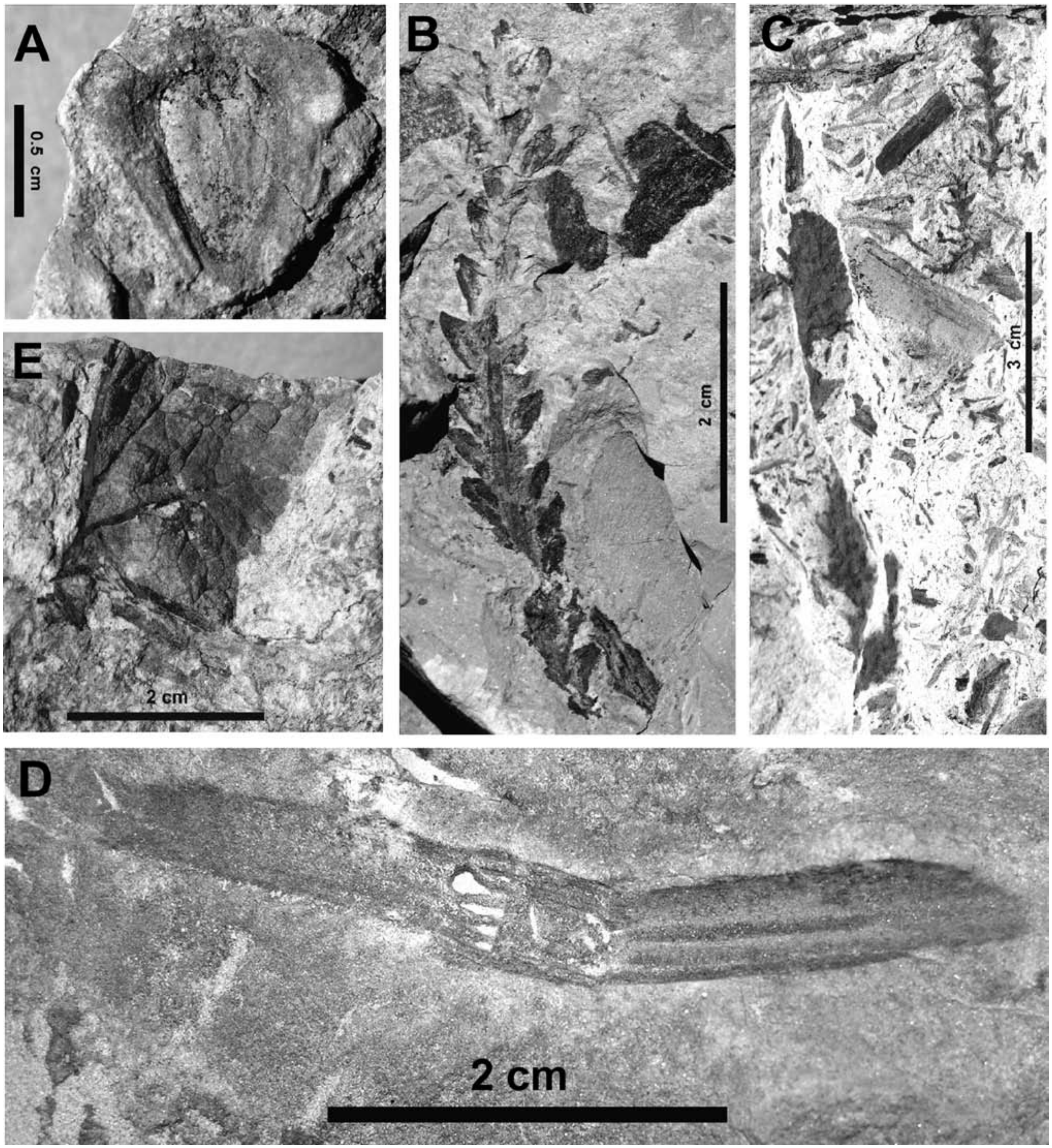

Figure 8. Plants from the upper Dinosaur Canyon Member in the vicinity of the SGDS. A, new species Araucarites *conifer cone scale, SGDS.515.; B, new species of conifer branch, SGDS.513.; C, new species of conifer branch with cones attached, SGDS.517.; D,* Equisetum *horsetail stem section, SGDS.569. and E, a partial leaf of the fern* Clathopteris, *SGDS.465.*

(coelophysoid ceratosaurs) are known from well-preserved skeletal remains, and their foot skeletons also provide close matches to *Grallator* tracks. We should note, however; that *Coelophysis* only occurs in the Upper Triassic Chinle Group and therefore predates the Moenave Formation. *Megapnosaurus* has been found in the Early Jurassic Dinosaur Canyon Member of the Moenave Formation (Lucas and Heckert, 2001) and the overlying Kayenta Formation (Rowe, 1989), both in northeastern Arizona. The possibility that *Megapnosaurus* made the SGDS *Grallator* tracks is further supported by the discovery of a possible *Megapnosaurus* tooth (Fig. 7G) from "Freeman Quarry" on WCSD property. A mid-dorsal vertebra of an unknown ceratosaur could also belong to *Megapnosaurus* (Fig. 7H). This specimen is currently under preparation and still requires detailed study.

Eubrontes tracks are often attributed to the genus *Dilophosaurus*, a well-known crested ceratosaur from the Kayenta Formation of Arizona. This correlation is almost inevitably given to *Dilophosaurus* because it is the only large theropod from this epoch that is well known from complete skeletal remains in North America. For this reason, *Dilophosaurus* has been used as a model of the track maker at Dinosaur State Park in Connecticut, where a surface with abundant *Eubrontes* tracks is on display, and this trend is now being followed at the SGDS. The correlation between *Eubrontes* and *Dilophosaurus* was further strengthened when Welles (1971) coined the name *Dilophosauripus* for a *Eubrontes*-like track from the Kayenta Formation of northern Arizona. Many authors agree that *Dilophosauripus* could be a synonym of *Eubrontes* (Lockley and Hunt, 1995; Irby, 1995; and Lockley, 2000).

This does not imply that *Dilophosaurus* made the large *Eubrontes*-like tracks at St. George. In fact *Dilophosaurus* is somewhat younger than the SGDS tracks since it occurs in the overlying Kayenta Formation. Moreover, several of the well-preserved dinosaur teeth found in Freeman Quarry on WCSD property (Figure 7I) resemble those of the early Cretaceous fish-eating dinosaur, *Spinosaurus* (Kirkland et al., 2005). More extensive remains of this new SGDS dinosaur are needed before it can be properly named. Thus far, there are several specimens of these distinctive teeth and possibly the above mentioned dorsal vertebra (Fig. 7H).

PLANTS

Two localities preserved in the upper part of the Dinosaur Canyon Member on DS and Paul Jensen properties (formerly owned by the late Layton Ott), and plant impressions preserved on the "Top Surface" within the SGDS museum display a low diversity flora. This flora contains poorly preserved impressions that represent seven species of conifers, ferns and horsetails (Tidwell and Ash, in press). All of the plant localities were discovered by the author.

Conifer fossils consist mainly of branches and twigs showing small needles (leaves) equally spaced along the branches. A new species of conifer cone and cone scales belongs to the genus *Araucarites* (Tidwell and Ash, in press) (Fig. 8A). Three distinct conifer branch types have been found at these sites: one is identified as *Pagiophyllum* sp. (Fig. 4G); the remaining two will be described as new genera and species (Tidwell and Ash, in press) (Figs. 8B, C). One of these new conifers is spectacular in that it not only preserves branches, but cones and shoots still attached (Fig. 8C).

Tidwell and Ash (in press) also suggest fragments of cycad leaves, possibly belong to *Podozamites*. Several horsetail stem impressions have been found on the "Top Surface" and are assigned to *Equisetum* (Tidwell and Ash, in press) (Fig. 8D). Four specimens of partial fern leaves show distinct characteristics placing them in genus *Clathropteris* sp. (Tidwell and Ash, in press) (Fig. 8E).

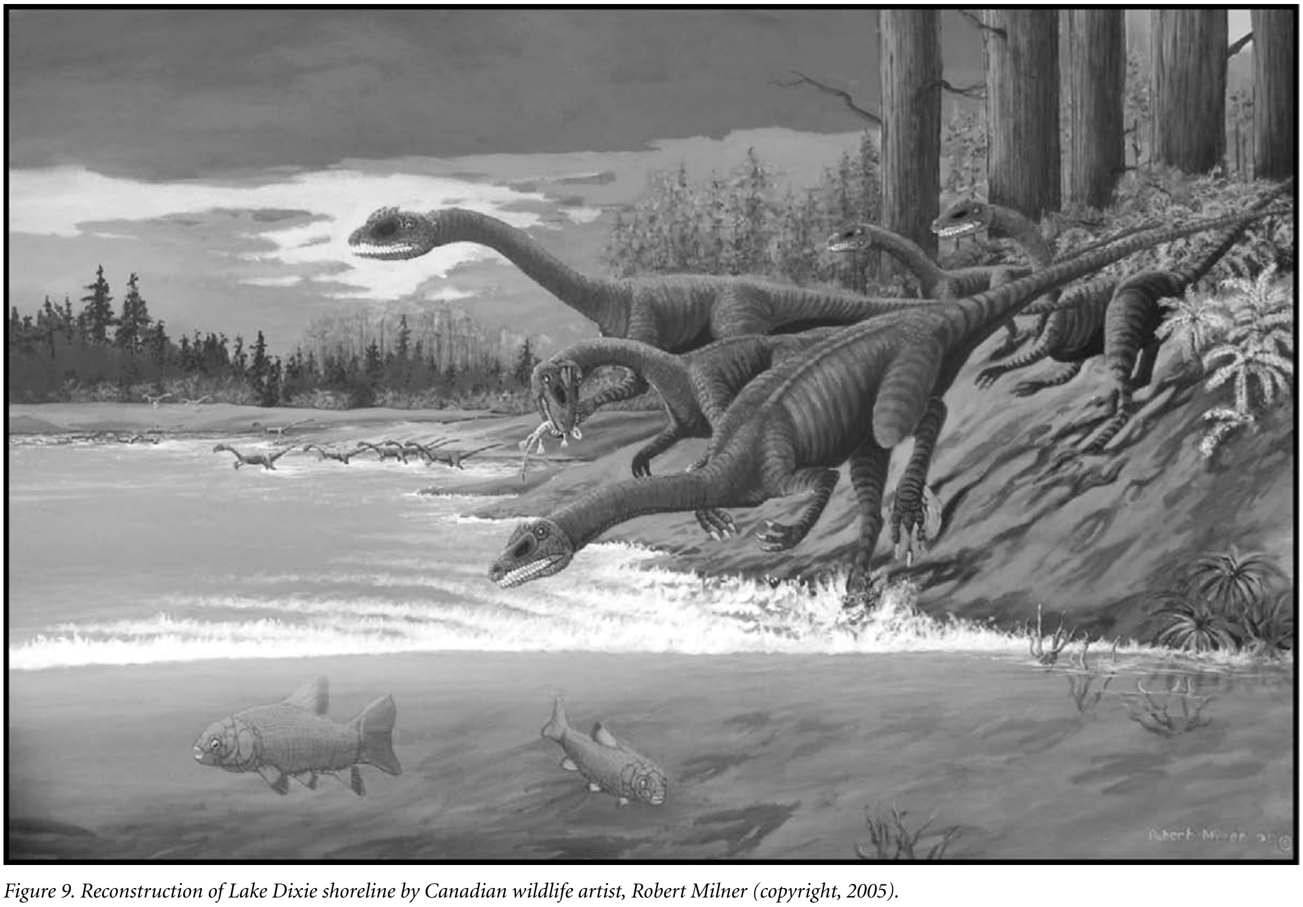

Figure 9. Reconstruction of Lake Dixie shoreline by Canadian wildlife artist, Robert Milner (copyright, 2005).

Identifiable plants from these localities are hard work to obtain and not very common among abundant unidentifiable plant debris. The DS locality is completely excavated away and presently under development. The second locality on Jensen property remains undisturbed at this time, but the entire property is planned for development.

Plant fossils from the SGDS and surrounding area were probably washed into debris piles on mudflats, or into topographic depressions in lake-margin or submerged lake deposits. A fluvial origin of these rocks containing the plants is not out of the question based on data to be published elsewhere by the author. No other localities containing identifiable plants from the Early Jurassic are known in western North America, making these specimens and localities very significant, particularly relative to associated fossils and geology at the SGDS.

CONCLUSION

The SGDS is now considered by many to be one of the most significant Early Jurassic tracksites in the world for the following reasons:

A "snapshot" of an Early Jurassic lake ecosystem at a time when the supercontinent of Pangaea was in its initial phase of break-up and dinosaurs were beginning their ascendancy to becoming the predominant land vertebrates of the Mesozoic Era (Fig. 9).

A rare concentration of trace fossils preserving incredible details of an Early Jurassic biota (fauna, flora, bacteria, and array of other organisms).

A rare association of trace fossils made by vertebrates and invertebrates, along with plants and body fossils of invertebrates, fish, and theropod dinosaurs.

The SGDS is considered a lagerstätte, or a site with an unusually high quality of preservation, including skin impressions and other fine details of reptilian foot morphology.

The SGDS has been ranked as one of the ten best dinosaur tracksites in the world because of the enormous number of tracks preserved in such a small area.

An unusual and rare collection of paleoenvironments represented laterally on single bedding surfaces and multiple track-bearing levels.

A great diversity of vertebrate locomotory traces representing animals walking, running, slipping, swimming, and sitting. Also represented are a variety of different organisms interacting in the same environment.

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Trace Fossils and Paleoenvironments of the Early Jurassic Kayenta Formation, Washington County, Utah

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INTRODUCTION

The Early Jurassic Kayenta Formation of southern Utah contains dinosaur and other fossils (Wilson, 1958; Loewen et al., 2005), especially tracks (Hamblin & Foster, 2000; Foster et al., 2001; DeBlieux et al., 2005; Hamblin, 2005; Vice et al., 2005), but little is known of its other ichnotaxa.

This is the first report of invertebrate and plant trace fossils in the Kayenta Formation near St. George, Washington County, Utah. Because of highway construction in the area, many of the described specimens and outcrops no longer exist. The study area is stratigraphically and areally restricted to the construction site at the Interstate 15 Exit 13. Both sides of the interstate are included in an area of just under 1 square km. Observations and descriptions of trace fossils and other primary sedimentary structures in unweathered, freshly exposed mudrock facies, which is normally difficult to achieve, were made possible by the construction excavation.

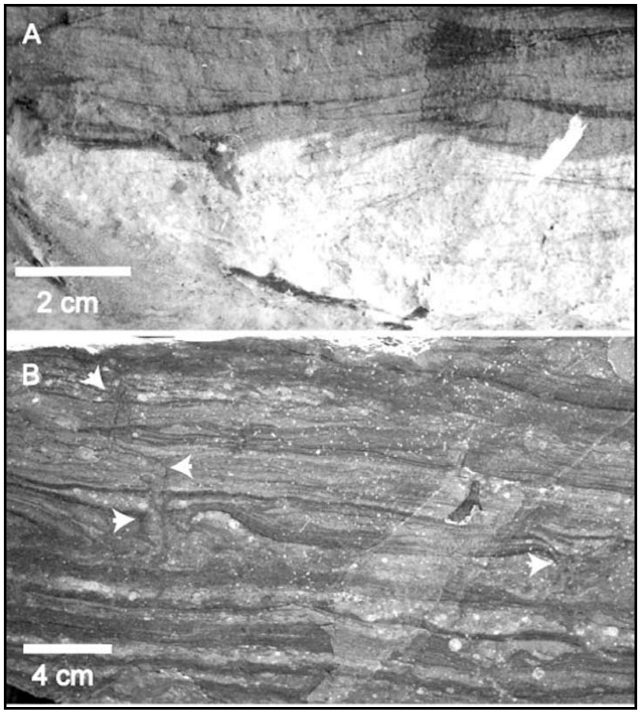

Figure 1. Primary sedimentary structures in freshly excavated clayey siltstones. A. The ripple cross lamination in the upper dark portion of the bed is unaltered. The chalky white zone (pale green in outcrop) in the lower light portion of the bed obscures most of the primary structures, which fade out downward. B. Parallel, wavy and lensoid laminae exhibit white spots where reduced iron has been leached out. Vertical and subvertical burrows are indicated by arrows.

GEOLOGY

The Kayenta is up to 282 meters thick in the study area (Biek, 2003), and the formation is divided into two informal members for this study. Investigated ichnotaxa were observed and collected in the upper part of the lower member as both float samples and *in situ* specimens from a 72-meter section, which did not extend to the base of the formation due to construction limitations. The lower member correlates with the lower two members (undifferentiated) of Hintze (1988; stratigraphic column #94) about 24 kilometers to the west.

The lower member is generally more than 72 m thick, and it consists mostly of banded, dark brownish red and pale green, variably resistant, commonly slope-forming claystones and siltstones with variable sand content, minor thin silty sandstone lenses, and localized carbonate rock. Diagenetic alteration of the red mudrock to pale green is suggested by irregular mottling, which does not always follow bedding planes. The color mottling cross-cuts, obscures or erases primary sedimentary structures (Fig. 1A), although at times the alteration appears to follow the biogenic structure outlines. Diagenetic alteration and weathering of mudrock surfaces obscure the trace fossils and make them difficult to study.

Mudrocks are often structureless with localized, small, crystal-lined vugs (possibly containing gypsum). However, some display delicate cross beds (~1 cm thick) and thin-bedded to finely laminated wavy (Fig. 1B), flaser, lenticular and micro-scour-and-fill beds. Sandstones and sandy mudrocks display rib and furrow structures and uncommon parting lineations. Mudcracks and ripple marks (some very wide and symmetrical) appear in very low relief in the finer grained mudrock (Fig. 2).

The 33 meter-thick upper member of the Kayenta Formation consists of interbedded sandstone and siltstone. The sandstone facies in this member of the Kayenta appears to be similar in character to the sandstone facies in the lowermost part of the overlying Navajo Sandstone.

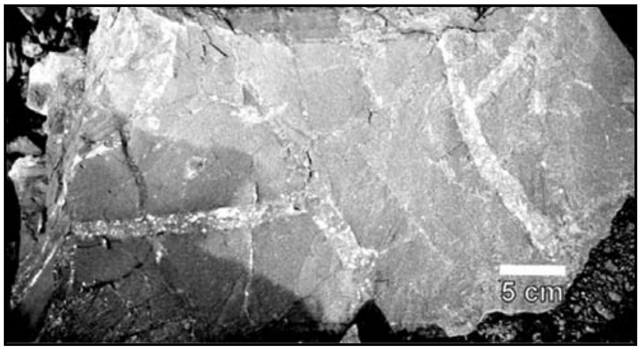

Figure 2. Freshly excavated pale reddish brown claystone with reduction-spotted, polygonal desiccation cracks.

TRACE FOSSILS

Sparse vertical, horizontal and obliquely oriented invertebrate traces were observed chiefly north of the interstate in the interval between 33 and 56 meters below the Kayenta/ Navajo contact. They include *Skolithos*, *Planolites* and *Taenidium* (up to 1 cm across and several cms long). They are preserved in claystones, siltstones (Fig. 3) and sandstones (Fig. 4). Carbonized and ferruginized traces of plant roots (2 cm wide) penetrate mudrocks to depths of up to 20 centimeters. Calcareous rhizocretions occur locally in three dimensions in red mudrock. They are cylindrical, tapering, hollow, tufa-like root encrustations (up to 4 cm across with hollows up to 2.5 cm across; Fig. 5).

South of the interstate, fossil wood and dinosaur tracks occur at about 98 and 83 meters, respectively, below the Kayenta/ Navajo contact. Fossil tree limb segments (up to 6.5 cm across), which exhibit cavities that resemble possible insect borings, weather out from some mudrock layers (Fig. 6). A restricted exposure of slightly displaced, incomplete dinosaur tracks appears in weathered relief in red-mottled, muddy sandstone (Fig. 7). The tracks are interpreted as push structures, slip traces and partial toe impressions with lengthwise striae. The toe impressions were shallow to deep, pointed and rounded, and up to 5 cm across with preserved lengths up to 15 cm.

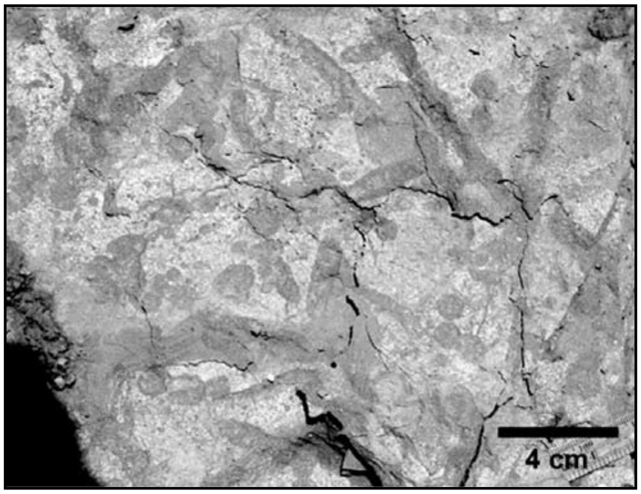

Figure 3. Freshly excavated, bioturbated, silty claystone containing horizontal and subhorizontal Planolites. *A broken part of the slab (lower left) shows the three-dimensional arrangement of the burrows.*

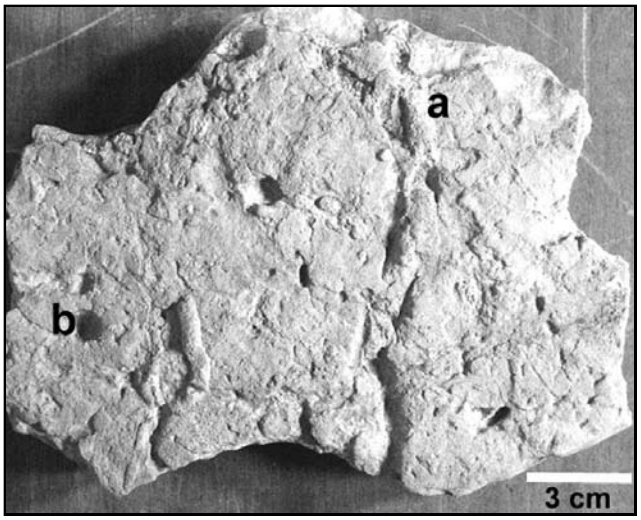

Figure 4. Silty, fine-grained sandstone (in plan view) containing burrows of different sizes, including Taenidium *(a) and* Skolithos *(b).*

PALEOENVIRONMENTS

Three-dimensional rib-and-furrow structures, small-scale cross beds, flaser, lenticular and wavy structures demonstrate variable current directions in fluvial and lacustrine settings (Boggs, 1987). The dominance of fine-grained mudrocks with variable sand content, small-scale sedimentary structures and claystones suggest variable (but usually low energy) situations. Mudcracks, symmetric ripple marks, fine laminations and other delicate structures in siltstones and claystones might have formed in mudflats around the periphery of small, shallow, ephemeral lakes (Wilson, 1958). Thin, silty, bioturbated sandstone lenses may represent deposition in small associated streams.

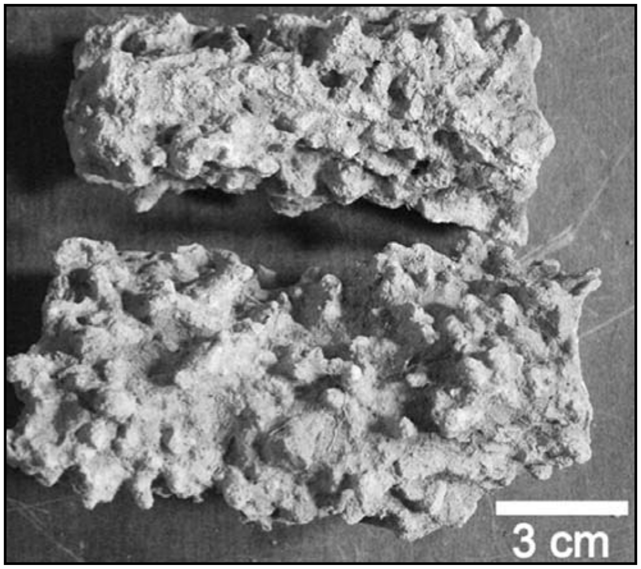

Figure 5. Rhizocretions resulted from paleosol calcification or from paleokarst enlargement surrounding large roots with hair roots.

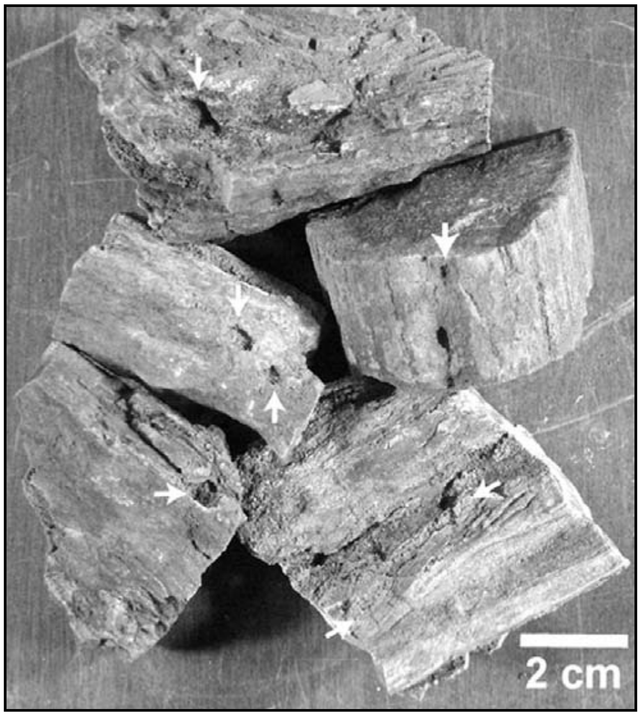

Figure 6. Silicified wood commonly contains cavities that probably were ancient insect borings (arrows). Some of these cavities are subparallel to the limb axis and have a single aperture.

Fossil tree limbs may reflect a floodplain setting. *Skolithos* and *Planolites* also may have been produced in a fluvial floodplain (Frey et al., 1984). *Taenidium* suggests an alternately submerged and exposed transitional environment in a stream or lake (Squires & Advocate, 1984; Buatois & Mangano, 1998). The red colors suggest subaerial exposure. Rhizocretions found in red mudrocks indicate paleokarst enlargement around roots. They also may indicate root growth above the water table in an arid, shallow playa environment, especially when they are associated with localized carbonate rocks and/or gypsum crystals (Rodriguez-Aranda & Calvo, 1998). Dinosaur tracks may have been emplaced in the edges of the playas.

The entire suite of trace fossils and sedimentary structures in the lower member of the Kayenta Formation in this area suggest that these layers may have been deposited in a fluvial floodplain with associated mudflats and playas.

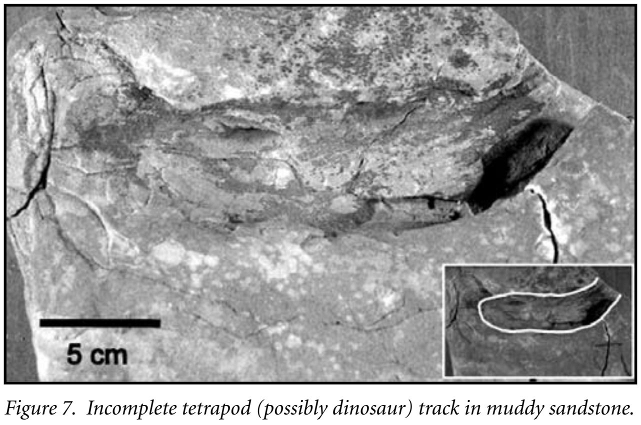

Figure 7. Incomplete tetrapod (possibly dinosaur) track in muddy sandstone. This is interpreted as the trace of a single toe with a push structure on its lower and left margins (see inset).

Acknowledgments

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Footprints on the Sands of Time: Fossil Tracks at the Raymond Alf Museum of Paleontology

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ABSTRACT

The Raymond M. Alf Museum of Paleontology, located on the campus of The Webb Schools, houses one of the greatest fossil footprint collections in the world. This collection is a testament to the work of museum founder Raymond Alf, whose interest in trace fossils translated into a decades-long search for fossil footprints throughout the Western United States. Webb students and faculty assisted Alf in this endeavor which spanned nearly four decades (late 1930's to early 1970's). The Alf Museum track collection consists of about 800 specimens from the Coconino, Moenkopi, Moenave, Wasatch, Barstow, Avawatz, Tecopa, and Muddy Creek formations. The largest holding is from the Barstow Formation (322 specimens) and the smallest from the Tecopa Formation (13 specimens). The collection includes 21 holotype, syntype, or paratype specimens representing 14 ichnotaxa. Forty four specimens are currently on exhibit, 8 in the Hall of Life and 36 in the Hall of Footprints. The stratigraphic utility of the collection is limited by the lack of precise locality data for many specimens. However, excellent photographs of Alf's collecting sites are housed in the museum archives and have been used in a few cases to tie specimens to specific sites. This work needs to be extended to all museum track sites.

INTRODUCTION

The Raymond M. Alf Museum of Paleontology is the only large museum in the world devoted solely to paleontology located on a secondary school campus (The Webb Schools). The museum is named for its creator, Raymond Alf, a teacher who eventually became intensely devoted to the study of paleontology. After establishing himself as a track star at Doane College in Nebraska, Alf served as first alternate on the 1928 United States Olympic Track Team. In 1929 Alf moved west to run for the Los Angeles Athletic Club and later that year joined the faculty at Webb School of California, a private high school on the outskirts of Los Angeles. In 1935, inspired by seeing a fossil horse jaw from the Barstow Formation on display in a local shop, Alf took Webb students to the Mojave Desert in search of fossils. In 1936, Alf and student Bill Webb found a skull and jaw fragments of a Miocene peccary in the Barstow Formation. They took the specimen to Chester Stock at Cal-Tech who described it as the new genus and species *Dyseohyus fricki* (Stock 1937). Inspired by their Barstow success, Alf, Webb and another student went to Nebraska and South Dakota in the summer of 1937 to expand their search for fossils. In South Dakota, Alf met John Clark, a paleontologist from the University of Colorado who was studying the Chadron Formation (Clark 1937). The discovery of *Dyseohyus fricki* combined with the meeting with Clark inspired Alf to pursue a career in paleontology. Alf took a sabbatical from Webb and studied under Clarks' tutelage at the University of Colorado, earning a masters degree in a single year (includes 2 summer sessions). He then returned to Webb and launched the Peccary Society, an innovative melding of paleontology into secondary school education where Webb students were active participants in all aspects of paleontological collecting and research. Alf inspired some Webb students to pursue paleontology careers, including Dwight Taylor, Malcolm McKenna, David Webb, Daniel Fisher, and the late Donald Kron, who all earned doctorates and became academic paleontologists.

From the late 1930's through the early 1970's Alf took students on collecting trips, called peccary trips, traveling to sites in California, Utah, Wyoming, South Dakota, Nebraska, and Arizona. Alf concentrated on recovery of fossil vertebrates, and by the 1960's had amassed a large regional collection (45,000 specimens). Alf was especially interested in collecting tracks and trackways and obtained 800 specimens from the Avawatz, Barstow, Coconino, Moenkopi, Moenave, Muddy Creek, Tecopa, and Wasatch formations (Figure 1); the largest collection in the western United States. By the 1960's the incredible amount of material Alf and his students had collected overwhelmed the small museum that Alf had established in the basement of a library on the Webb campus. By 1966, funds were raised for "Ray's Museum" and a new facility was built and dedicated to Alf in 1968.

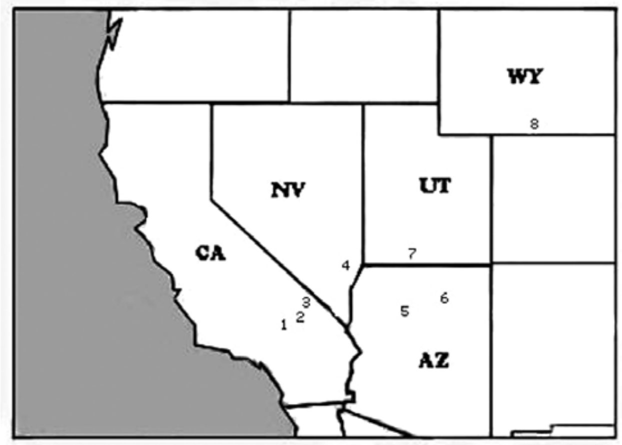

Figure 1. Map of the southwest United States showing the location of the Alf Museum's fossil footprint collecting areas: (1) Barstow Formation; (2) Avawatz Formation; (3) Tecopa Formation; (4) Muddy Creek Formation; (5) Coconino Formation; (6) Moenkopi Formation; (7) Moenave Formation; (8) Wasatch Formation.

The new Raymond M. Alf Museum included two large round exhibit halls: 1) the Hall of Life, where specimens were ordered by geologic time with the theme of showing the history of life; and 2) the Hall of Footprints, which displayed an overview of the museum's extensive track collection including some very large slabs with multiple tracks. The Hall of Footprints, renovated in 2002, is the largest, most diverse collection of fossils tracks and trackways on display in North America. One enormous slab from the Coconino Formation with multiple trackways, which Alf called "Footprints on the Sands of Time," had to be lowered into the building by crane before the roof was completed. It dominates the foyer of the Hall of Life and is the first specimen seen when a visitor enters the museum.

The fossil track and trackway collection at the Alf Museum contains many type specimens and other specimens of significant scientific importance, but the entire collection has never been discussed as a unit and most specimens have not been assigned to an ichnotaxon. Here we review the museum's extensive track collection organized by formation and presented in ascending geologic age. Each formation section includes an overview of field activities and/or general locality information, a brief discussion of the collection, including types and other significant specimens, and a description of specimens currently on exhibit.

ABBREVIATIONS

cm: centimeter

km: kilometer

m: meter

NALMA: North American Land Mammal Age

RAM: Raymond M. Alf Museum of Paleontology; RAM records each vertebrate locality using a V followed by numbers (e.g. V94005).

COCONINO FORMATION

(Late Permian)

Locality: all specimens are from a single site; RAM locality V94004, approximately 4 miles north of Seligman, Arizona.

The Coconino Formation is comprised primarily of cliff-forming, cross-stratified sandstone exposed over a wide area of northern Arizona. In the Grand Canyon, the Coconino Formation is about 350 feet thick, but it can be up to 900 feet thick elsewhere (Middleton et al. 1990). In

Figure 2. Ray Alf (kneeling on left) and students collecting the huge slab (RAM 244) now on display in the museum's foyer from the Coconino Formation near Seligman.

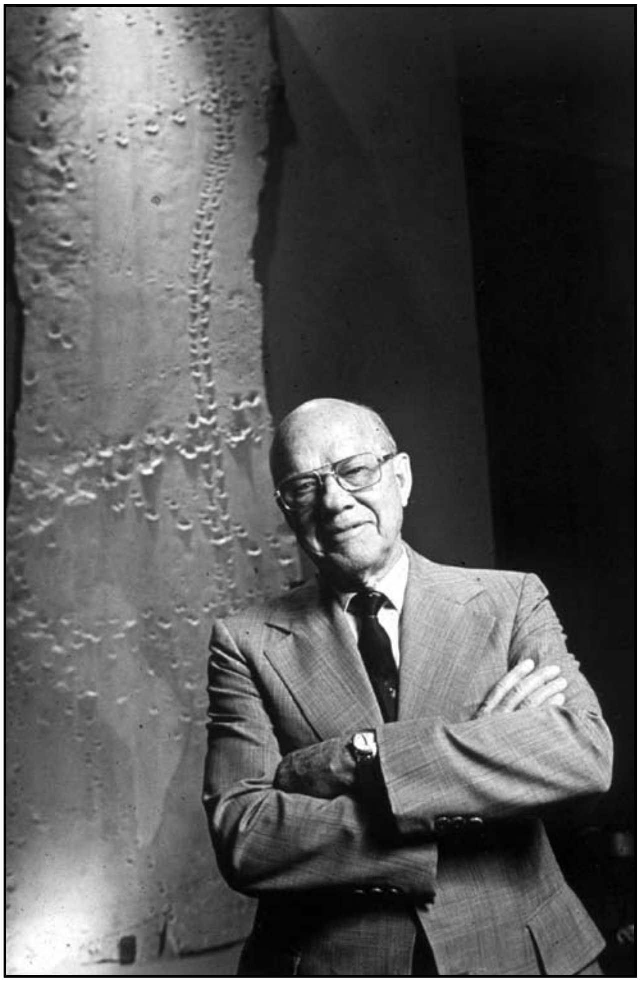

Figure 3. Ray Alf standing beside RAM 244 in the museum's foyer.

the late 1930's Ray Alf went to the Grand Canyon at least twice with Webb students to hike the Kaibab and Bright Angel trails and got his first glimpse of the Coconino Formation. On one of these trips he met Edwin McKee, who was in the beginning stages of his decades-long study of the geology of Grand Canyon National Park. McKee was investigating the canyon's Paleozoic formations (McKee 1937, 1939) and was developing a particular interest in the numerous trackways of vertebrates and invertebrates found in the Coconino Formation (McKee 1933, 1944, 1947). McKee told Alf about a site near Seligman, Arizona, where he could collect specimens of Coconino tracks. Shortly thereafter, Alf began to lead trips to Seligman on an annual basis until the early 1970's. Alf and students collected in a canyon in or near Chino Wash a few miles north of Seligman (Figure 2); the precise site has not been relocated but easily could be using the many excellent photos of the site housed in the museum's archives.

Alf and Webb students collected 142 track specimens that include the ichnogenera *Laoporus* (over 120 specimens), *Agostopus* (RAM 128), *Octopodichnus* (RAM 139), and *Paleohelcura* (RAM 142). Over 90% of Coconino specimens exhibit one or multiple tracks of the vertebrate represented by *Laoporus.* Many large slabs have unidentified and poorly preserved invertebrate tracks on them in addition to *Laoporus.* Specimens range in size from 10 cm square, up to the massive slab (RAM 244) displayed in the museum's foyer (Figure 3), which is about 5 m in length, 1.3 m in width, and 20 cm thick. The only Alf Museum Coconino holotype is RAM 139 (Figure 4) representing *Octopodichnus raymondi* (Sadler 1993; original specimen number JF 5905 was recatalogued as RAM 139). Alf compared modern spider tracks with RAM 139 and concluded the tracks preserved on RAM 139 represented a spider, but did not name it (Alf 1968). Sadler's (1993) more extensive study supported Alf's original hypothesis and the species *O. raymondi* was named in his honor.

For many years it was generally accepted that the large scale and abundant cross stratified sandstones of the Coconino Formation that often preserve vertebrate and invertebrate tracks represented eolian deposits. However, a relatively recent challenge was presented by Brand and Tang (1991). They argued for a subaqueous origin of the tracks. Using slabs on display at the Alf Museum (RAM 244 is figure 2A and 2F, RAM 235 is figure 2G, and RAM 132 is figure 2E in Brand and Tang 1991) and other specimens, Brand and Tang (1991) noted that many *Laoporus* trackways displayed odd characteristics, such as abrupt starts and ends of track sets on undisturbed bedding planes and that individual tracks are often oriented perpendicular to the trend of the trackway. Tests performed with modern newts in shallow flowing water created tracks similar to those made in the Coconino Formation and formed the basis of the underwater hypothesis (Brand and Tang 1991). However, the geology of the Coconino Formation supports an eolian hypothesis because the large scale bedforms, low

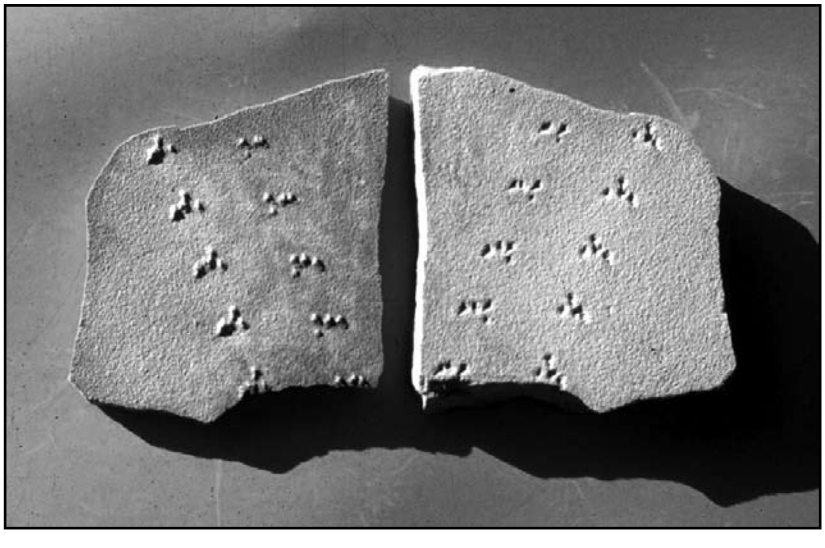

Figure 4. Holotype of Octopodichnus raymondi *(RAM 139) from the Coconino Formation.*

Figure 5. Ray Alf (standing far right) and students with trackway slabs from the Coconino Sandstone (RAM 245 on left, RAM 238 on right).

angled cross stratification, abundance of well sorted quartz sandstone, and the absence of ripple marks all indicate the probability of eolian deposition (for further discussion of this controversy see Brand 1992; Lockley 1992; Loope 1992; Lockley and Hunt 1995).

Exhibited Specimens: The Hall of Life has many tracks of *Laoporus* including three small specimens in the Grand Canyon Geology display case, a large slab (RAM 127), and two sets (RAM 245 and 247) of matched bedding plane slabs (Figure 5) that each show the mold and cast of a single trackway (Ray Alf referred to mold-cast pairs as "books of life"). Also, many exceptionally well preserved trackways of *Laoporus* are evident on the huge slab (RAM 244) in the museum's foyer. A set of large tracks (RAM 128) referred to *Agostopus* is also on exhibit in the Hall of Life.

The Hall of Footprints has two large slabs (RAM 132 and 214) with multiple *Laoporus* tracks and a relatively small mold-cast pair (RAM 238, Figure 5) displaying a set of the tracks of this very common ichnotaxon. Of special note is RAM 235, which exhibits a unique *Laoporus* trackway ("S" in overall shape, but with individual prints all in a single direction) which figured prominently in development of the subaqueous origin hypothesis of Coconino trackways (see figures 2G and 4I in Brand and Tang 1991); the eolian versus subaqueous origin controversy is highlighted in text and graphics that accompany the display featuring RAM 235. Also on exhibit are small specimens showing the scorpion *Paleohelcura* (RAM 142) and the holotype of the spider *Octopodichnus raymondi* (RAM 139, Figure 4), which is a mold-cast pair or "book".

MOENKOPI FORMATION

(Early-Middle Triassic)

Locality: all specimens from a single site, RAM V94005, 5 miles southwest of Cameron, Arizona, and 1/2 mile west of US Highway 89.

The Moenkopi Formation is composed of sandstones, siltstones, and mudstones of fluvial origin (McKee 1954). As Alf became more interested in collecting fossil tracks, he developed an annual Webb spring break trip which was organized into a general Arizona-Utah-Nevada loop route with stops at Seligman, Grand Canyon National Park, Cameron Junction (where he encountered the Moenkopi Formation), Kanab, and Zion Canyon National Park. Alf and students collected track specimens at Seligman (Coconino Formation) and Kanab (Moenave Formation) in addition to those from the Moenkopi near Cameron Junction. These spring break trips ran for nearly 35 years and collections were made in the Moenkopi from around 1950 to 1970. As with many Alf Museum track localities, V94005 has not yet been precisely relocated. There are only a few photos in the museum's archives showing collecting activities in the Moenkopi Formation, but they probably would provide adequate information for site relocation.

The Alf Museum collection from the Moenkopi consists of 25 specimens, each in red siltstones with one or two tracks (usually one), which vary from moderately distinct to very faint. Ten specimens are referred to *Chirotherium* in the Alf Museum catalog, with the remaining 15 unidentified. However, all tracks are of similar size and shape and thus appear to represent a single ichnotaxon. *Chirotherium* has distinctive 5 digit impressions that superficially resemble human hand prints, with the 5th digit on the pes remarkably similar to a thumb imprint (Lockley and Hunt 1995). *Chirotherium* tracks from the Moenkopi Formation show a wide variety of sizes and probably represent various types of quadrapedal archosaurs (Lockley and Hunt 1995).

Exhibited Specimens: No specimens from the Moenkopi Formation are currently on exhibit.

Figure 6. Webb students with Eubrontes *track (RAM 239) from the Moenave Formation.*

MOENAVE FORMATION

(Early Jurassic)

Locality: all specimens from a single site, RAM V94277, in a canyon 5 miles north of Kanab, Utah.

The Moenave Formation, confined mainly to northern Arizona and southern Utah, is composed of the Dinosaur Canyon Member, the Whitmore Point Member, and the Springdale Sandstone Member (Harshbarger et al. 1957; Miller et al. 1989). On Webb spring break trips, Alf and students would often collect along Kanab Creek north of Kanab in the Dinosaur Canyon Member of the formation; in contrast to most other track sites, V94277 has been precisely located (Figure 6). These trips yielded 69 specimens of small to large 3 toed tracks attributed to bipedal dinosaurs. The Alf Museum catalog lists 22 specimens of *Eubrontes*, 15 of *Grallator*, and 13 of *Anchisauripus*. These identifications, made by Webb students, are based on size and may not be entirely accurate, as according to Lockley and Hunt (1995), *Anchisauripus* has not been identified in the Western United States. The Alf Museum has 19 other specimens identified only as dinosaur tracks. Of the 69 Moenave specimens, only one (RAM 176) has more than 2 tracks. RAM 176, catalogued as *Grallator*, has 11 full or partial tracks oriented in various directions (Figure 7). Thus, the tracks appear to represent more than one individual.

Exhibited Specimens: There are 7 specimens from the Moenave Formation on display in the Hall of Footprints. Six are single tracks, 3 of which are identified as *Eubrontes* (RAM 109, 240, 122) and 3 as *Grallator* (RAM 169, 173, 479). The 7th specimen is RAM 176, a large (1 m x .6 m) slab exhibiting multiple tracks of *Grallator* as noted above.

WASATCH FORMATION

(Early Eocene; Wasatchian NALMA).

Locality: all specimens from a single site, RAM V94207, located in Carbon County, Wyoming, and from poorly exposed outcrops along a dirt road adjacent to Muddy Creek.

The exact location of V94207 is uncertain as field notes that document the site do not exist. However, excellent photos of the site are present in the museum archives and presumably the site could be relocated without great difficulty. What is known is that the site occurs north of Baggs in outcrops adjacent to Muddy Creek, which parallels State Highway 789 in south central Wyoming. Based on this general location, the site is probably within the main body of the Wasatch Formation, which would indicate that the Early Eocene-Wasatchian age determination is probably correct.

In 1969 and/or 1970, Raymond Alf, Webb faculty members Ken Monroe and Al Korber, Webb alumni Blake Brown and Dan Fisher (now a paleontology professor at the University of Michigan), and others collected 24 specimens, 7 of which represent birds of very small size that remain undescribed. The other 17 appear to represent tracks of a single mammalian taxon (some slabs with mammal tracks have very small and faint bird tracks on them as well). Based on these 17 specimens, Sarjeant et al. (2002) described and named the ichnogenus and species *Quiritipes*

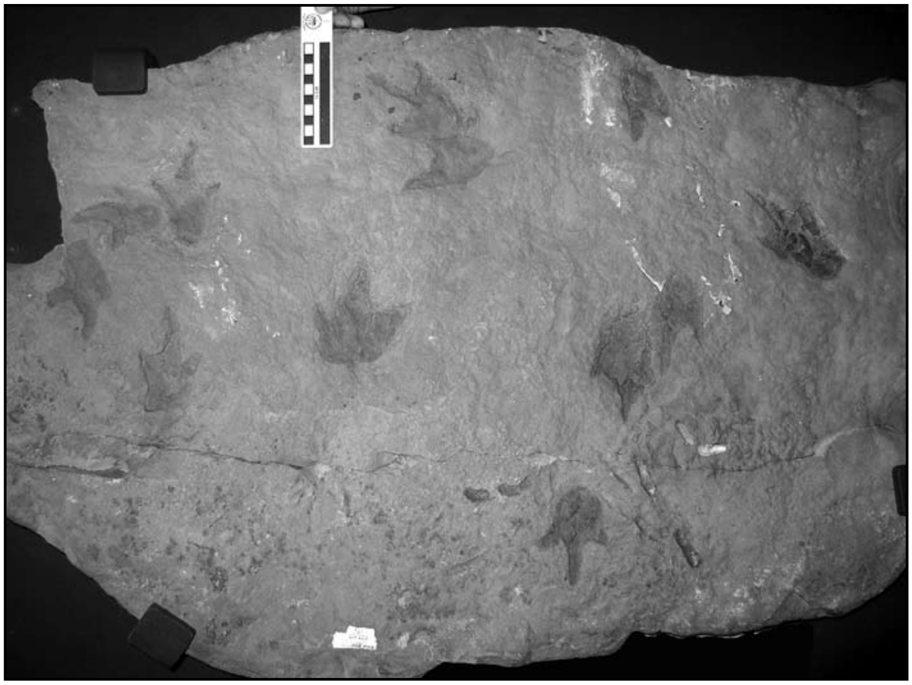

Figure 7. Multiple Grallator *imprints (RAM 176), common smaller tracks from the Moenave Formation.*

impendens. The type is RAM 154, a set of tracks reconstructed from 9 individual slabs arranged in their presumably original position, and then set in cement. The paratype is RAM 267, a left pes. Sarjeant et al. (2002) thought the tracks of *Quiritipes impendens* belonged to a carnivore and noted the lack of claw impressions which could indicate they represented a feloid. But their overall morphology was unlike any known feloid (Sarjeant et al. 2002) and the Early Eocene age of the site virtually precluded any alliance with the much younger feloid clade. Based on their age and morphology, Sarjeant et al. (2002) surmised that the tracks were probably made by a creodont. In any case, the tracks of *Quiritipes impendens* housed at the Alf Museum represent a taxon not found in any other museum collection.

Exhibited Specimens: There are 3 specimens of *Quiritipes impendens* on display in the Hall of Footprints. The holotype (RAM 154), which has 13 full or partial tracks, is exhibited adjacent to 2 smaller slabs, RAM 150 with 2 tracks and RAM 152 with 4 tracks (some partially overprinted). RAM 154 was partially figured by Lockley and Hunt (1995, see figure 6.4).

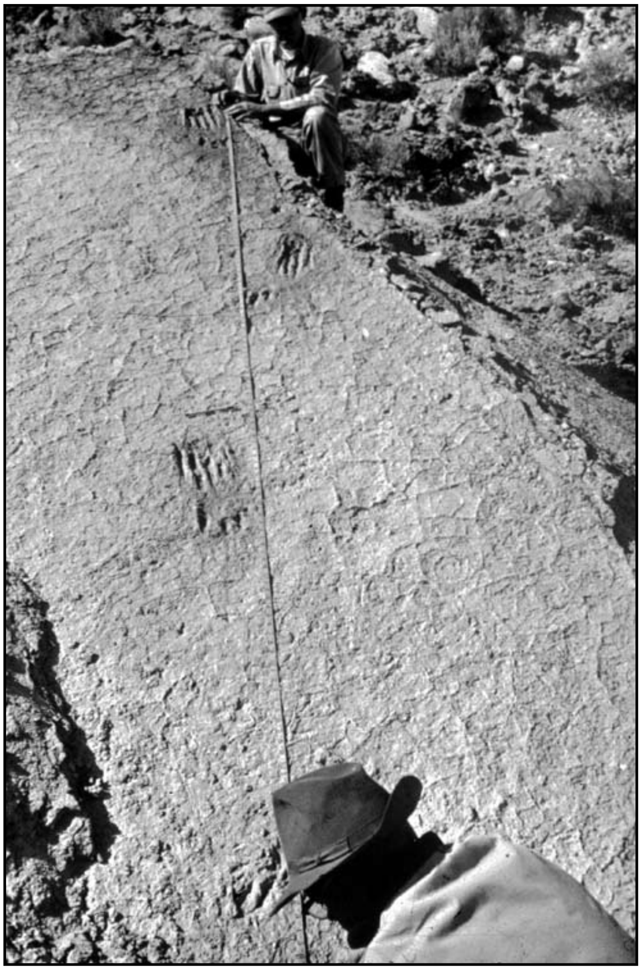

Figure 8. Ray Alf (bottom) and Richard Tedford (top) measure the bear-dog trackway (RAM 100, holotype of Hirpexipes alfi*) prior to its excavation from the Barstow Formation.*

BARSTOW FORMATION

(Middle Miocene, Barstovian NALMA).

Locality: from various RAM sites (V94064, V94065, V94176, V94272, V94281, V94283, V94284, V94293) in the Mud Hills about 15 km northwest of Barstow, San Bernardino County, California.

The Barstow Formation is about 1000 m thick and is composed of a sequence of fluviatile and lacustrine sediments and air-fall tuffs (Woodburne et al. 1990). The formation is subdivided into the Owl Conglomerate, Middle, and Upper members (Woodburne et al. 1990). All the Barstow Formation tracks at the Alf Museum were collected in the Middle and Upper members. Alf first prospected for fossils in the Barstow Formation in 1935. After the discovery and publication of the new genus and species of peccary, *Dyseohyus fricki* by Stock (1937), Alf realized Barstow's great potential as a paleontological resource and the Barstow Formation became Alf's main collecting area for the next 40 years. When Alf collected his first track from the Barstow Formation is unknown. But it must have been after 1959 as in that year he described mammal tracks from the Avawatz Formation and claimed they were the first ever reported from the Mojave Desert (Alf 1959). It is documented that the Barstow bear-dog trackway (described below) was found in 1960 by Webb teacher Lach MacDonald and collected in 1964. It is reasonable to assume that the success of finding tracks in the Avawatz Formation inspired Alf to expand his search to the Barstow Formation. Unfortunately, locality data for nearly the entire Alf Museum track collection from the Barstow Formation is very poor and stratigraphically unreliable. The only exceptions are the bear-dog (RAM 100, V94272, Figure 8) and proboscidean (RAM 187, V94176, Figure 9) trackways which were relocated in 1994 using photos in the museum's archives.

The Barstow Formation has yielded more track specimens, about 322, than any other formation from which Alf and Webb students collected. The majority of these specimens were collected in the 1960's and early 1970's and include 295 tracks/trackways of camels, 22 of felids, one set of canid prints (RAM 183), an *Amphicyon* trackway (RAM 100), and a proboscidean trackway (RAM 187). There are 7 holotype, syntype, or paratype specimens from the Barstow Formation in the Alf Museum collection.

One of the most important Barstow specimens is the bear-dog or *Amphicyon* trackway (Figure 8) which Alf (1966) briefly described and identified as representing an amphicyonid. The trackway was collected in 1964 using a gasoline powered saw where 5 manus-pes track sets were removed in sections along with all intervening rock and then placed in storage on the Webb campus. Once the new museum building was dedicated in 1968, the trackway was reconstructed and displayed in the Hall of Footprints (see figure 6.21 in Lockley and Hunt 1995). This specimen (RAM 100) is the holotype of *Hirpexipes alfi* (Sarjeant et al. 2002). The large size, 5 digits, and rake-like claw marks strongly support the interpretation that the tracks represent an amphicyonid (Alf 1966; Sarjeant et al. 2002). Their

Figure 9. Webb students pose with the partially excavated proboscidean trackway (RAM 187).

very large size and stratigraphic position in the Middle Member of the Barstow Formation suggest they were made by *Amphicyon ingens* (Sarjeant et al. 2002). Based on RAM 100, *A. ingens* had a stride of 245 cm and a pace of 120 cm (Sarjeant et al. 2002).

The Alf Museum collection includes two other reconstructed trackways from the Barstow Formation both of which are on display in the Hall of Footprints. One is a set of 4 proboscidean tracks (RAM 187, Figure 9) from the Upper Member which were removed in large slabs (around 1969) using a gasoline powered saw and reconstructed back at the museum. The other is a large slab (RAM 166, Figure 10) containing 2 sets of camel prints (see figure 6.20 in Lockley and Hunt 1995) that were broken into blocks (date unknown) and later reconstructed in the museum. The camel prints preserved on RAM 166 were designated as a syntype of *Lamaichnum alfi* by Sarjeant and Reynolds (1999). The other syntypes were RAM 159 (a right pes) and RAM 182 (a right manus). RAM 166 is particularly important because it clearly shows the gaits of at least 2 camels. The majority of Barstow camel prints in the Alf Museum collection are similar in morphology to *L. alfi* (Sarjeant and Reynolds 1999).

Other types in the Alf Museum collection from Barstow include the felids *Felipeda bottjeri* and *Felipeda scriverni* described by Sarjeant et al. (2002). The holotype of *F. bottjeri* is RAM103 (right pes?) and the paratype is RAM 104 (right manus?); figured specimens of *F. bottjeri* also include RAM 181 and RAM 275 (Sarjeant et al 2002). The holotype of *F. scriverni* is RAM 242 (now part of the collections at Death Valley National Park) and the paratype is RAM 105 (left manus?).

Felipeda bottjeri differs from *F. scriverni* in its more elongate shape and lesser digital span (Sarjeant et al. 2002). Specimens of *F. bottjeri* are more numerous in the Alf Museum collection than *F. scriverni*. These felid tracks may represent those of *Pseudaelurus* (Alf 1966; Sarjeant and et al. 2002).

Other specimens of particular interest include RAM 183, a small canid print referred to *Canipeda* species A that may represent the track of *Tomarctus* (Sarjeant et al. 2002), and a bird print on the beardog trackway slab (RAM 100)

Figure 10. Multiple camel trackways (RAM 166, syntype of Lamaichnum alfi*) from the Barstow Formation on display with a camel skeleton mounted above.*

that was used to emend the diagnosis of *Gruipeda becassi* (Sarjeant and Reynolds 2001).

Exhibited Specimens: There are many specimens from the Barstow Formation on display (all in the Hall of Footprints) including the 3 spectacular reconstructed trackway slabs described above. The proboscidean slab preserves 4 tracks and is 4.5 m long and 1.5 m wide, the bear-dog slab has 5 manus-pes sets and is 5 m by 1 m, and the camel slab preserves 2 sets of tracks and is 6 m by 1.2 m. A skeletal cast of a bear-dog is mounted directly over RAM 100 and a recent camel skeleton is mounted over RAM 166 (Figure 10). The bird print on the beardog trackway that was used to emend the diagnosis of *Gruipeda becassi* is faint and very difficult to locate.

Other specimens on display are 5 cat tracks of *Felipeda*, including the holotype and paratype of *F. bottjeri* (RAM 103 and RAM 104 respectively) and the paratype of *F. scriverni* (RAM 105). The other 2 Barstow specimens on exhibit are RAM 161, a mid sized camel track, and RAM 163, a very small (3 cm by 4 cm) track that may represent a newborn camel or some other type of small artiodactyl.

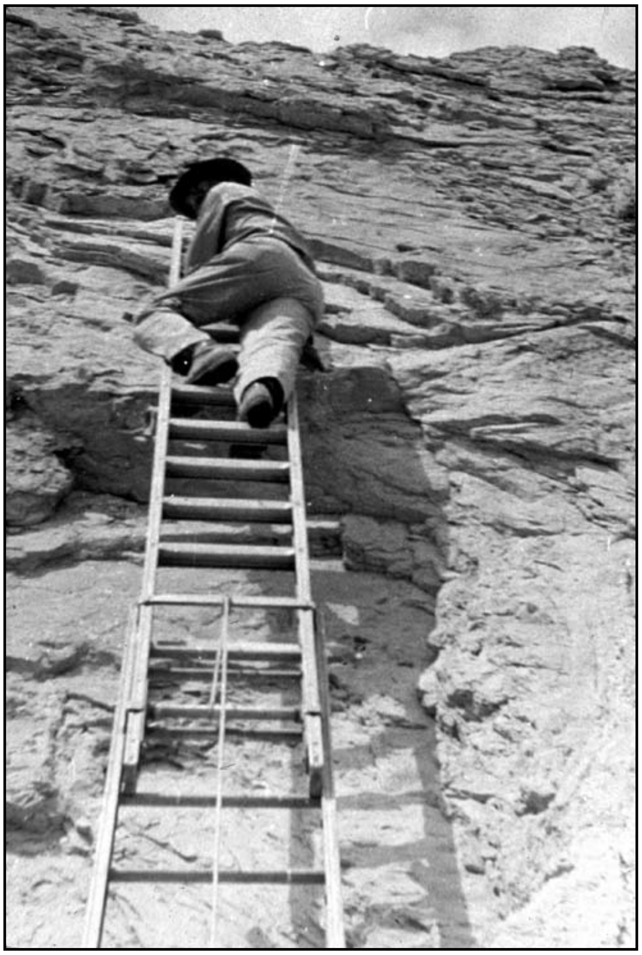

Figure 11. Ray Alf on ladder collecting trackway slabs (RAM 215 and 216) from the Avawatz Formation.

AVAWATZ FORMATION

(Late Miocene, Clarendonian NALMA).

Locality: from various RAM sites (V94021, V94134, V94135, V94136) in the southeastern part of the Avawatz Mountains, north of Baker, California.

The upper part of the Avawatz Formation yields vertebrate fossils and is composed of coarse to fine grained tuffaceous sedimentary rocks interbedded with distinct white to buff colored volcanic ashes that can be over a meter thick (Henshaw 1939; Alf 1959). While on a trip with Alf in February of 1957, Webb student Robert Baum discovered mammal footprints on steeply dipping bedding planes, high on the side of a steep canyon in the Avawatz Formation. Two more trips were made soon thereafter to remove the tracks, which had to be excavated while standing on a ladder (Figure 11). These were the first mammal tracks described from the Mojave Desert (Alf 1959). The Avawatz Formation proved to be an untapped treasure trove of tracks as nearly 140 specimens were collected by Alf and Webb students following Baum's original discovery. These Avawatz specimens include 81 bird, 49 camel, 4 felid, and 7 unidentified vertebrate tracks. All of these specimens were assigned to the general Avawatz locality V94021 because the locations of the 3 main Avawatz collecting sites (V94134, V94135, V94136) were unknown. In 1994 Robert Baum led an Alf Museum crew back to the Avawatz Formation and precisely relocated 2 (V94134 and V94135) of the 3 original collecting sites. Reassignment of specimens from V94021 to V94134 and V94135 has yet to be completed.

Eight holotype, syntype, or paratype specimens from the Avawatz Formation are housed at the Alf Museum. The birds, all described by Sarjeant and Reynolds (2001), include: RAM 110, the holotype of *Avipeda gryponyx,* a series of 7 prints with partial impressions of others that probably represent a small wading bird (Sarjeant and Reynolds 2001); the holotype (RAM 115, left pes) and paratype (RAM 269, right pes) of *Anatipeda californica*, webbed footprints of small to moderate size with 3 digits directed forward and a 4th backwards; the holotype (RAM 111, right and left pedes) of *Anatipeda alfi*, a web-footed species named in honor of Raymond Alf (figured specimens also include RAM 113, Figure 12, a left pes and RAM 112, left

Figure 12. Left pes of Anaipeda alfi *(RAM 113) from the Avawatz Formation.*

Figure 13. Print of Lamaichnum macropodum *(RAM 165) from the Tecopa Formation made by a very large camel.*

and right pedes); and ?*Anatipeda* sp. based on RAM 274, a left pes, which is like others of the genus but is larger in size. Footprints of *Anatipeda* were probably made by pelicans, flamingos, ducks, geese, swan or another similar bird (Sarjeant and Reynolds 2001). Also, Sarjeant and Reynolds (2001) used RAM 272 and 278 to emend the diagnosis of *Aviadactyla vialovi,* and RAM 270 to emend the diagnosis of *Charadriipeda recurvirostrioidea*.

Other important specimens include: RAM 205, a small slab with 2 cat prints (right manus and left pes?) that was described as the holotype of a new genus and species, *Pycnodactylopus achras*, by Sarjeant et al. (2002); RAM 197 (manus) and RAM 209 (pes), the syntypes of *Dizyogopodium dorydium*, a camel of moderate size (Sarjeant and Reynolds 1999); and RAM 216 (slab with left manus and right pes), the syntype of *Dizygopodium quadracordatum,* a camel of moderate size (Sarjeant and Reynolds 1999).

Exhibited Specimens: There are 8 specimens from the Avawatz Formation on display in the Hall of Footprints. Two fairly large slabs from Baum's original discovery site (V94134, Figure 11) are RAM 215 (1.4 m x. 6 m), which has 2 manus-pes sets of cat tracks (each partially overprinted), and RAM 216 (.8 m x 1 m), which has 3 cat tracks and 3 short sets of camel prints (two medium sized, the other very small). RAM 216 is the syntype of *Dizygopodium quadracordatum* (camel).

Other specimens include: RAM 112 and 113 (Figure 12) medium sized bird prints of *Anatipeda alfi* figured by Sarjeant and Reynolds (2001); RAM 158, smaller sized camel tracks; RAM 160, 4 mid-sized camel tracks with one showing a camel slipping on wet substrate; and 2 uncataloged specimens, one with a single medium-sized bird track and the other with many very small bird prints.

TECOPA FORMATION or "CHINA WASH BEDS"

(Late Miocene, Clarendonian NALMA).

Locality: all specimens from a single site, RAM V94215, from outcrops along the Amargosa River in Sperry Hills, approximately 5 miles south of Tecopa, California.

The Tecopa Formation is comprised of a series of tuffaceous sedimentary rocks that outcrop south of Tecopa in the Sperry Hills; these same rocks are informally referred to as the "China Wash Beds" by Sarjeant and Reynolds (1999). This collecting area was only visited by Alf and Webb students a few times between 1967 and 1970. Photos of locality V94215 are housed in the museum's archives, showing excavation of track slabs on the bank of a dry and apparently broad creek bed. Based on general descriptions of V95215, this dry creek could be Sperry Wash or the Amargosa River. Thus, the site could presumably be relocated without great difficulty.

Thirteen specimens were recovered from locality V94215, all of which represent camels. Most slabs preserve the tracks of a very large camel. Sarjeant and Reynolds (1999) assigned these specimens to *Lamaichnum macropodum* and designated RAM 146 (manus) and RAM 165 (pes, Figure 13) as syntypes. These tracks measure about 20 cm in length and width and probably were made by either *Aepycamelus* or *Megatylopus* (Sarjeant and Reynolds 1999), the largest known camels of the late Miocene.

Exhibited Specimens: Two specimens from V94215 are on display in the Hall of Footprints. One is RAM 165 (Figure 13), the syntype of *Lamaichnum macropodum*. The other is RAM 135, a .9 meter long and .6 meter wide slab of sandstone exhibiting 6 very large tracks (some partially overprinted) that probably can be referred to *Lamaichnum macropodum.*

MUDDY CREEK FORMATION

(Late Miocene, Hemphillian NALMA).

Locality: from various RAM sites (V94163, V94164, V94286) located within a few miles north of Interstate 15, near Glendale, Clark County, Nevada.

The Muddy Creek Formation is comprised of a thick series of sandstone, siltstone, and mudstone with lesser amounts of conglomerate and tuff (Stock 1921) that were deposited in a series of small basins in southern Nevada that coalesced into a single large basin (Reynolds and Lindsay 1999). There are 3 recorded Alf Museum track sites in the Muddy Creek Formation. However, all 3 have not been relocated and the few photos of these sites are not labeled as to which site they represent. Thus, it is doubtful that the Alf Museum specimens could be assigned to a specific locality even if the 3 Muddy Creek Formation sites could be relocated.

In the late 1960s Alf and Webb students collected about 53 track specimens and one large trackway slab from the Muddy Creek Formation. They represent camels and 2 types of carnivores, an ursid and a canid. This ursid formed the basis of the new genus and species, *Platykopus ilycalcator*, which was described by Sarjeant et al. (2002). RAM 277 (manus) was designated as the holotype and RAM 232 (pes) the paratype. Because of its large size and the presence of 5 digits, *P. ilycalcator* was interpreted to represent a large bear (Sarjeant et al. 2002). There are other specimens of this large ursid in the Alf Museum collection including a large trackway (RAM 218) comprised of multiple slabs preserving 10 tracks which were numbered in the field and then reconstructed for display at the museum. RAM 218 was removed from exhibit when the Hall of Footprints was renovated in 2002. Another example of this large ursid is RAM 327 which has 2 tracks.

Exhibited Specimens: No specimens from the Muddy Creek Formation are currently on exhibit.

SUMMARY

The fossil footprint collection at the Raymond M. Alf Museum of Paleontology Alf Museum on the campus of The Webb Schools, consists of approximately 800 specimens and is one of the best in the world. These tracks and trackways were recovered from 8 formations, with those from the Barstow (322 specimens), Coconino (142 specimens), and Avawatz (141 specimens) formations comprising the largest holdings. Forty four specimens are currently on exhibit, all but 8 in the recently renovated Hall of Footprints. The collection includes 21 holotype, syntype, or paratype specimens representing 14 ichnotaxa (Sadler 1993; Sarjeant and Reynolds 1999, 2001; Sarjeant et al. 2002). The Alf Museum once housed 12 specimens from Tertiary rocks in Death Valley National Park, some of which represent the holotypes or syntypes of 4 ichnotaxa: 1) *Hippipeda gyripeza* (equid), holotype RAM 204; 2) *Lamaichnum etoromorphum* (camel), syntypes RAM 203 and RAM 200 (Sarjeant and Reynolds 1999); 3) *Alaripeda lofgreni* (bird), holotype RAM 201(Sarjeant and Reynolds 2001); and 4) *Felipeda scrivneri* (felid), holotype RAM 242 (Sarjeant et al. 2002). These specimens were returned to the National Park Service in the late 1990's and presumably have been recatalogued.

The great track collection at the Alf Museum is a testament to the life's work of museum founder Raymond Alf whose early interest in trace fossils translated into a career-long search for fossil footprints throughout the Western United States. Students and faculty at The Webb Schools assisted Alf in this endeavor which spanned nearly four decades (late 1930's to early 1970's).

The stratigraphic utility of parts of the collection is limited by the lack of precise locality data for many specimens. Also, many specimens cannot be assigned to a specific site as field notes linking sites with specimens do not exist. However, there are many excellent photographs of Alf's collecting sites and field activities housed in the museum archives. These photos have been taken to the field and used to relocate specific sites in the Barstow, Avawatz, Moenave formations. This work needs to be expanded to all other museum track sites.

ACKNOWLEDGMENTS

Thanks are extended to: recent Webb students Benjamin Scherer and Michael Greene for helping identify tracks from the Coconino and Moenave formations; Webb alumni Robert Baum for information on early collecting activities in the Avawatz Formation, Blake Brown for information on the Tecopa Formation site, and Richard "Dick" Lynas for helping document the track collection; former assistant curator Judy Mercer for sorting track specimens and assigning them to specific sites in the early 1990's; Malcolm McKenna for inspiration and support; Robert Reynolds and the late William A. S. Sarjeant for their efforts to describe the museum's track collection from Tertiary rocks in California, Nevada, and Wyoming; John Rogers and the Mary Stuart Rogers Foundation for financial support; and especially Raymond Alf and numerous Webb faculty and students who collected the specimens that make the museum's track collection one of the best in the world.

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Miocene Invertebrate Trackways in the Owl Canyon area, Barstow, California

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Miocene invertebrate tracks (Figs 1, 2) were discovered in the process of inventorying and replicating vertebrate trackways in the Owl Canyon area of the Mud Hills, north of Barstow, California. The trackways north of Owl Canyon Campground are preserved in a medium grained tuffaceous limestone that may represent a freshwater lacustrine environment with stream input or possibly a closed lake system with little circulation. The trackways are associated with fossils of plants (Fig. 3) and other organic materials.

The Miocene Barstow Formation in the Mud Hills is the type locality for mammals that represent the Barstovian Land Mammal Age of North America that spans a period of time from 16 Ma to 12 Ma (Woodburne, 1991) The invertebrate trackways are situated below outcrops of the Skyline volcanic tuff (14.8 Ma) in Owl Canyon, suggesting that they may approach 15 million years in age (Woodburne, 1991).

Figure 1 (above). Crustacean tracks on the upper surface of silty ash beds in Owl Canyon. Figure 2 (right): detail of tracks.

The trackways are significantly different from Permian arthropod (tarantula) trackways (Alf, 1968) described from the Coconino Formation. Abundant invertebrate fossils have been described from the Barstow Formation in the Calico Mountains (Jenkins, 1986: Palmer, 1957; Pierce, 1958, 1962, Pierce and Gibron, 1962), however, none of these arthropods appear large enough to have made the 2cm wide row of tracks from Owl Canyon.

Although the track maker is undefined, the trackways appear similar to those made by arthropods such as crayfish, (add graphic) (Clarkson, 1998; Lane, 2006). Repeated imprints left by arthropods represent the distance between consecutive impressions made by the same appendage. The frequency of the respective Owl Canyon appendage imprints is 3 tracks per 1 cm. Each trackway is made up of left and right appendage imprints, with a central, non-cancellated drag mark totaling approximately 2 cm in width. The footfalls have two aspects composed of a back stroke and forward stroke making up the step cycle and this in turn can tell us about the arthropod's specific gait and obstacles such as vegetation or terrain that they may be dealing with. Due to the fluid texture of the sediment during the track maker's activity, the trackways are poorly defined. Mud cracks indicate periods of dryness and

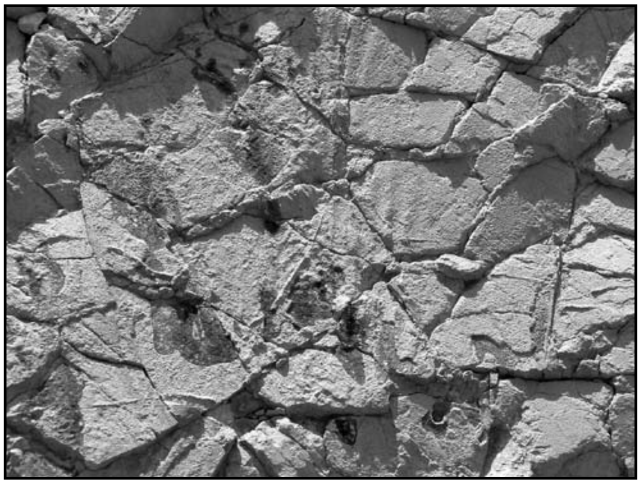

Figure 3. Plant material associated with crustacean tracks.

it is likely that the trackways were made in alternating moist/dry sediments representing a repeatedly inundated lacustrine shoreline environment.

In summary, ichnofossils represent potential data in regard to more detailed interpretation of depositional environment. Because trackways occur where animals lived, variations in the trail of tracks may illustrate specific shoreline features and conditions of depositional environment.

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The Fossil Mammals of the Barstow Formation

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ABSTRACT

The Barstow Formation, roughly 10 miles north of the town of Barstow, has a long and rich history of study involving its fossil mammals. Several institutions have collected thousands of specimens providing paleontologists with a detailed picture of life from roughly nineteen to thirteen million years ago. The Barstow Formation was deposited in alluvial fans, riverbeds, or lakebeds in a wooded savanna environment similar to modern east Africa. A diverse array of herbivores has been recovered, including abundant horses, rhinos, peccaries, camels, antelope, and proboscideans. Predatory animals include a wide variety of dogs, "running bears," "bear-dogs," and felids. Two major evolutionary events are recorded in the Barstow Formation. The first represents the introduction of a number of new taxa that demarcate the boundary between two important time intervals. The second is an extinction event interpreted to be the result of changes in vegetation across the western United States.

INTRODUCTION

The Barstow Formation crops out in the Mud Hills and Rainbow Basin areas of the Mojave Desert north of the town of Barstow. It consists of several thousand feet of alluvial fan, riverbed, and lake bed sediments that were deposited in a restricted basin by runoff from highlands to the north, west and south. Radiometric dating of several volcanic ash beds throughout the formation suggest that the oldest sediments are roughly nineteen million years old, and the youngest around thirteen million years old (Woodburne *et al.*, 1990; MacFadden *et al.*, 1990). Thus, the Barstow Formation was deposited during the medial portion of the Miocene epoch.

The Barstow Formation is renowned for its abundant and diverse fossil assemblages. From as early as 1911, paleontologists have focused their efforts on describing the Barstow Formation's fossil mammals (Baker, 1911). In the early part of the century, the majority of investigations were conducted by two entities. The first was the University of California Museum of Paleontology at Berkeley, where efforts were headed by J.C. Merriam from 1911 to 1919. Merriam produced the first papers to comprehensively describe the fossils from the Barstow Formation (Merriam, 1913; 1915; 1919). The second thrust of research was conducted by several researchers under the direction of Childs Frick. Throughout the 1920s and 1930s, the Frick Labs excavated massive amounts of fossil material which, upon Frick's death, were bequeathed to the American Museum of Natural History in New York. The Frick Collections today represent the largest collection of Barstow Formation fossils in the world.

Since the pioneering work of these first researchers, several other institutions have conducted smaller-scale collection programs of their own. The Los Angeles County Museum had a modest collection program at Barstow in the 1960s. The University of California, Riverside, had always taken an interest in the fossils of the Barstow Formation and conducted collection programs at the same time as the L.A. County Museum. The San Bernardino County Museum collected extensively as well, particularly from Robbins Quarry, high in the stratigraphic section. Finally, work continues through the Raymond Alf Museum in Claremont, where high school students regularly make weekend trips to prospect the Mud Hills for the abundant fossil material.

As a result of the collections programs, our knowledge of the mammalian fauna of the Barstow Formation is quite extensive. The Barstow Formation fossils allow us a unique opportunity to paint a detailed picture of life during the medial Miocene in the western United States. What follows is a brief overview of the megafaunal (larger than rabbit-sized) mammalian taxa commonly found throughout the Barstow Formation. Additional comments are made on the environment these animals lived in, as well as major evolutionary events which are recorded in the Barstow Formation deposits.

ENVIRONMENT OF DEPOSITION

Examination of the sediments from the Barstow Formation shows three major depositional trends (Woodburne, 1990). The oldest sediments of the Owl Conglomerate member consist of large clasts in a sandstone matrix that were deposited in an alluvial fan. Some input from this fan came from uplands to the north; another significant source area was from the south. The middle member of the Barstow Formation consists primarily of fluvial (stream and river bed) deposition with some alluvial fan input. The system of rivers which deposited the sediments of the middle member appears to have originated in areas of higher elevation to the west and spread northward and eastward. Finally, the uppermost member of the Barstow Formation consists of lacustrine (lake bed) clays deposited in a very low energy environment. Because the upper member was deposited more continuously and under less turbid waters these sediments contain far more abundant and better preserved fossil remains than the lower members. Deposition changed through time from alluvial fan-dominated, to riverbed deposition, to calm deposition at the bottom of a lake.

Scattered throughout these sediments are several layers of volcanic ash. These ash beds allow stratigraphers to correlate sedimentary layers from throughout the Mud Hills area by providing important landmarks in the stratigraphic sequence. These ash beds also contain the minerals necessary to obtain radiometric dates at several levels throughout the depositional sequence.

ENVIRONMENT

The climate and environment that existed in the Mojave Desert fifteen million years ago was markedly different than that which exists there today. Overall, the climate was not as arid as it is today, was slightly cooler, and seasonal variation in precipitation likely created a distinct rainy season. The environment would have closely resembled certain parts of eastern Africa, with wooded savanna dominating the landscape. Areas directly adjacent to rivers would have been covered with several types of deciduous trees, as well as shrubs like poison oak (Alf, 1970). The areas of higher elevation in between river beds would have been slightly more open, with small areas of grassland, chaparral associations, or meadows dotted with small copses of coniferous trees. The environment produced a wide variety of vegetation types which in turn supported a diverse mammalian community.

THE HERBIVORES

The wide variety of plant types present in the Mojave Desert around fifteen million years ago supported a diverse assemblage of herbivorous mammals. By far the most abundant herbivorous mammals were horses. Several different types of horses are found at Barstow, the most common being *Scaphohippus* (Pagnac, 2006) (Figure 1). *Scaphohippus* was ancestral to modern horses, was about three feet tall at the shoulder, and still retained three toes, although the two lateral digits were vestigial and did not touch the ground. *Scaphohippus* had relatively high crowned teeth that were suited to process tough vegetation such as chaparral or possibly grasses. The thick, durable nature of these teeth makes them easily preserved and, thus, the most common fossil found in the Barstow Formation. Another type of horse from Barstow is *Megahippus*. Literally meaning, "large horse", *Megahippus* was only slightly smaller than modern horses. However, its teeth were much lower crowned and most likely suited to processing softer vegetation from shrubs or low hanging trees.

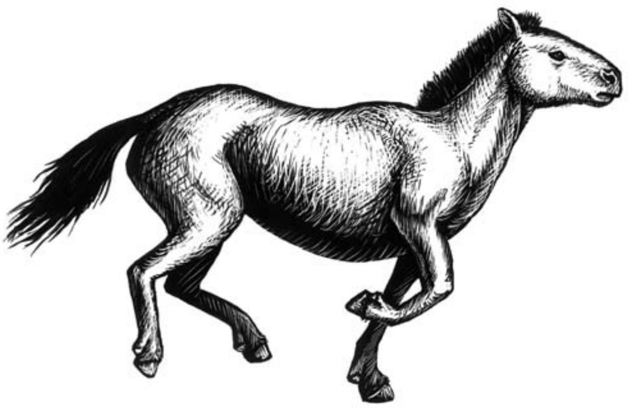

Figure 1: Reconstruction of the three-toed horse Scaphohippus *(drawing by Katura Reynolds).*

A single taxon of rhinoceros is known from Barstow, *Aphelops*. *Aphelops* was slightly smaller and more slender than a modern Sumatran rhino. Its more slender legs suggest that it was more active than modern rhinos and capable of running a greater speeds. It is uncertain whether *Aphelops* had horns. A bulbous protrusion on its snout suggests a strong anchor point for such a structure, but no fossil evidence confirming the presence of a horn has been found.

A number of peccaries are known from the Barstow Formation, the most notable being *Dyseohyus*. Discovered by students from the Webb School in 1936 (Stock, 1937), *Dyseohyus* has since been adopted as the official symbol of the Raymond Alf Museum. In overall appearance and habits, the peccaries from the Barstow Formation were probably very similar to the modern javelina found throughout the southwestern United States.

Oreodonts are a group of sheep-like herbivores that are extremely abundant in faunas from the Oligocene (one can literally trip over oreodont skulls in the White River badlands of South Dakota). However, by the Miocene these animals had diminished in numbers and were on the way

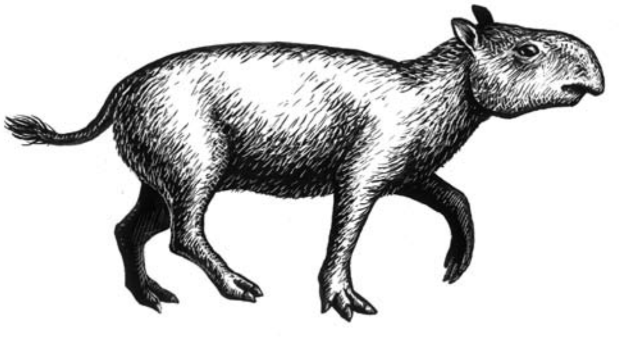

Figure 2: Reconstruction of the oreodont, Brachycrus *(drawing by Katura Reynolds)*

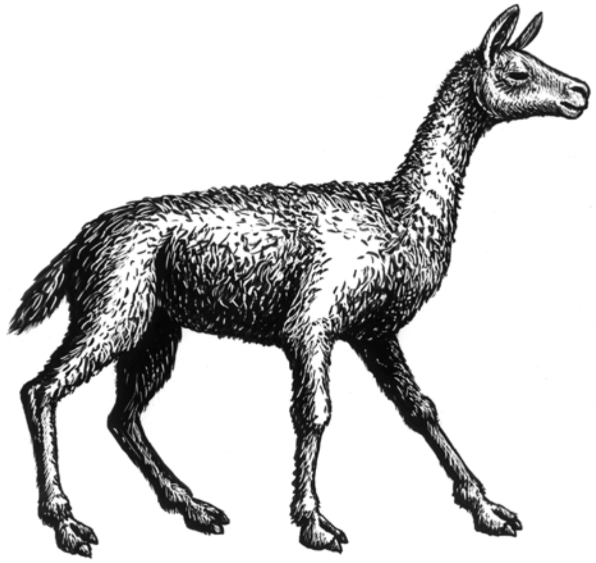

Figure 3: Reconstruction of the medium-sized camel, Protolabis *(drawing by Katura Reynolds)*

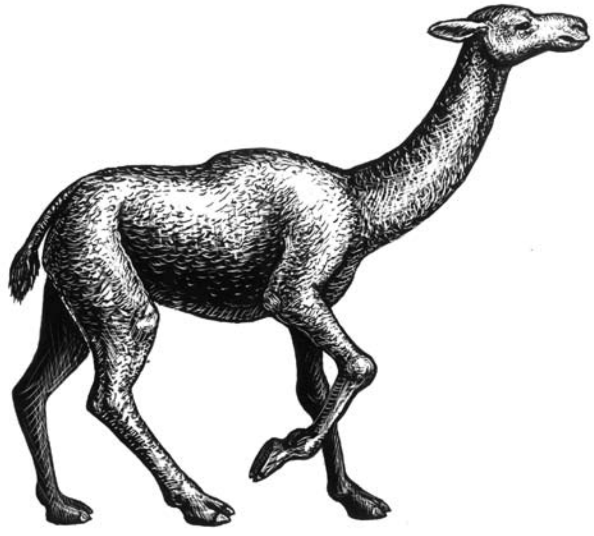

Figure 4: Reconstruction of the large camel, Aepycamelus *(drawing by Katura Reynolds)*

to extinction. A tapir-like oreodont, *Brachycrus* (Figure 2), is known from older sediments in the Barstow Formation. *Brachycrus* was about the size of a modern pig. The similarity of the skull of *Brachycrus* to that of modern tapirs suggests that it may have had a short proboscis or at least a prehensile upper lip. The teeth of *Brachycrus* were suited to processing soft vegetation and this animal likely congregated in the deciduous forests near river beds.

Aside from horses, the most abundant fossil mammal remains from Barstow are those of camels. The camels from Barstow assumed a wide variety of shapes and sizes. The smallest, *Paramiolabis minutus*, was only about two feet tall at the shoulder and probably resembled modern species of small deer (Pagnac, 2005). Several types of medium sized camels were present, including *Protolabis* (Figure 3), which in appearance, size, and lifestyle more closely resembled a modern deer than a camel. Finally, one of the largest members of the fauna was *Aepycamelus* (Figure 4), a long-legged, long-necked camel which had assumed the size and lifestyle of a giraffe, feeding on vegetation high in the wooded canopy.

A number of small, horned animals were present at this time. *Rakomeryx* (Figure 5) had curved horns resembling those of many types of African antelope and was about the size of an impala or similar African antelope. Some of the earliest ancestors of modern pronghorn antelope are found from the Barstow Formation as well. The most common is *Merycodus* (Figure 6), which had a pair of forked horns. Several other types of antelope with different shaped horns are known from Barstow, such as *Merriamoceros*, with small, moose shaped horns, and *Ramoceros*, with tripod shaped horns. All of the antelope taxa from Barstow were quite small, not much larger than a modern fawn.

Proboscideans (elephants and mastodons) first appeared in North America around fifteen million years ago.

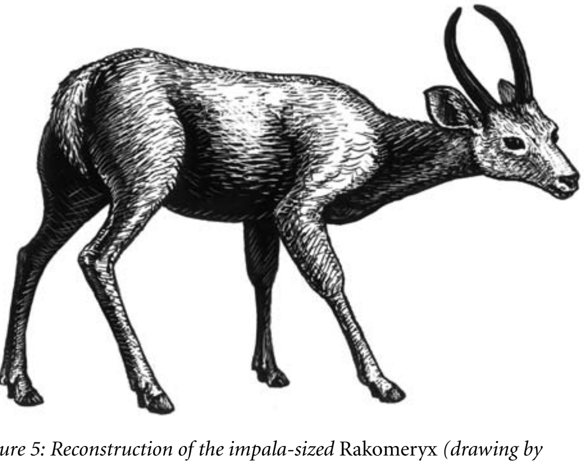

Figure 5: Reconstruction of the impala-sized Rakomeryx *(drawing by Katura Reynolds)*

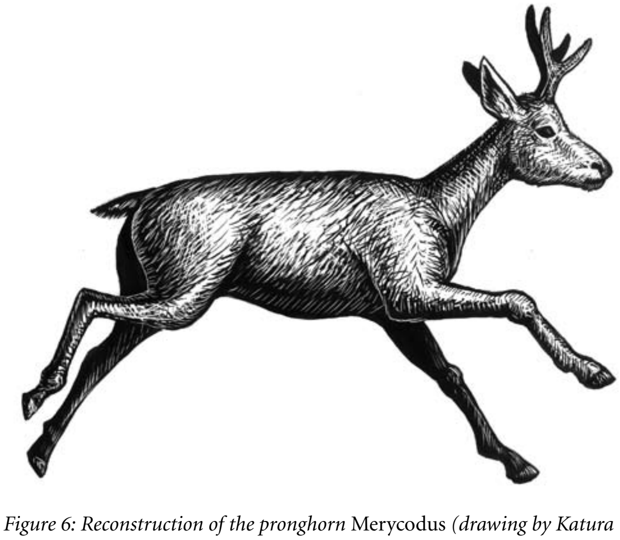

Figure 6: Reconstruction of the pronghorn Merycodus *(drawing by Katura Reynolds)*

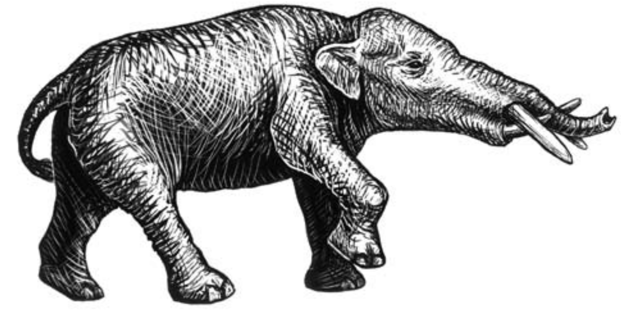

Figure 7: Reconstruction o the elephant,f Gomphotherium *(drawing by Katura Reynolds)*

Figure 9: Reconstruction of the bear-dog, Amphicyon *(drawing by Katura Reynolds)*

The most recognizable of these animals is *Gomphotherium*, which differs from modern elephants in having both an upper and lower set of tusks (Figure 7). *Gomphotherium* was slightly smaller than a modern African elephant. In addition to skeletal remains, proboscidean tracks from the Barstow Formation have provided paleontologists with some of the earliest evidence of these animals' appearance in North America (Woodburne and Reynolds, 2001). Additionally, the tracks of Miocene horses, camels and pronghorn from the Barstow formation show how the animals acted while alive (Serjeant and Reynolds, 1999).

THE CARNIVORES

Where there is an abundance of prey, one will always find predators, and the fauna from the Barstow Formation is no exception. The Barstow Formation yields an extremely high diversity of carnivorous taxa. The wide variety of predators adds credence to the hypothesis that the environment was very similar to modern east Africa, as this is the only modern environment with comparable predator diversity.

The most common group of predatory mammals from the Barstow Formation is the dog subfamily. Unlike modern canids of the subfamily Caninae, the dogs from the Barstow Formation belong to the subfamily Borophaginae. The relationship between these two groups is comparable to that of modern humans and chimpanzees. The borophagine canids assumed a wide variety of shapes and sizes that correspond to a number of lifestyles exhibited in the modern family of dogs. *Cynarctus* was similar to a modern fox; *Tomarctus*, resembled a coyote, and *Aelurodon* was nearly identical to a gray wolf. However, other taxa had morphology quite unlike modern canids. *Cynarctoides* was about the size of a modern mink or fisher and had remarkably similar morphology. *Protepicyon* (Figure 8) had evolved a shortened muzzle and likely assumed a lifestyle similar to a modern hyena, scavenging carcasses and crushing bones for the nutritious marrow inside.

Dogs were by no means the only predatory mammals of the time. The "reigning king" of predatory mammals from the Barstow Formation was *Amphicyon* (Figure 9). *Amphicyon* is often referred to as a "bear-dog" as this family of carnivores occupies an evolutionary position between modern bears and dogs. *Amphicyon* resembled a modern grizzly bear in many respects, but it was not as bulky and had slightly longer legs, suggesting it was capable of greater speed. *Amphicyon* probably had a very similar lifestyle to modern bears, but its diet was most likely more carnivorous with less fish and plant input. *Amphicyon* trackways suggest an agile animal capable of running down many of the larger prey available.

A single taxon of bear, *Hemicyon* (Figure 10), was also present at this time. However, it was not at all like its modern counterparts. *Hemicyon* morphology was much more similar to a modern dog than a bear. Slightly larger than a gray wolf, its skull was slightly lighter than that of modern bears, its body less robust, although stockier than even the largest wolf, and it walked on its toes rather than flat-footed. *Hemicyon* is from a family of "running bears" common

Figure 8: Reconstruction of the carnivore Protepicyon *(drawing by Katura Reynolds)*

Figure 10: Reconstruction of the running bear, Hemicyon *(drawing by Katura Reynolds)*

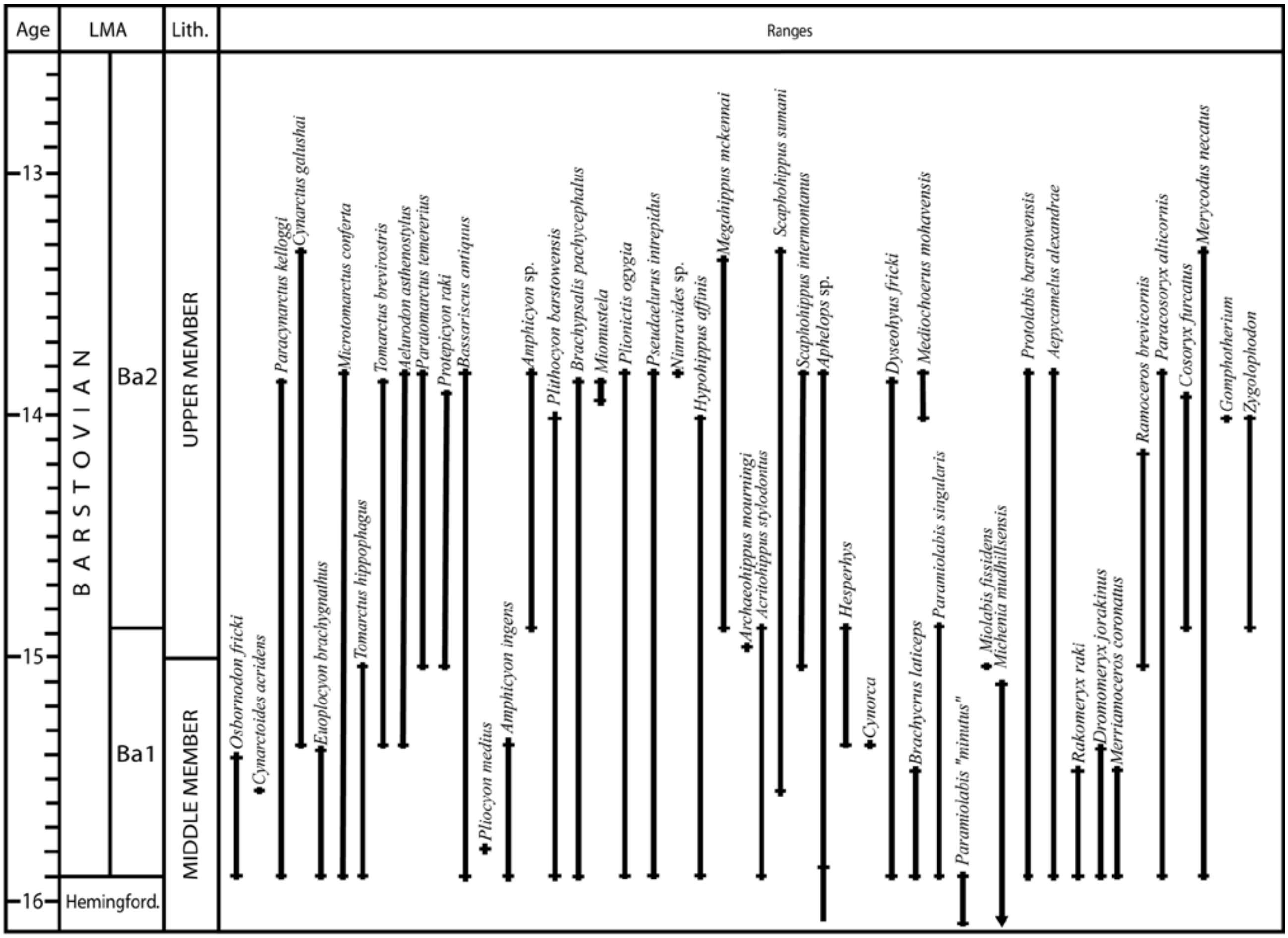

Figure 11: Stratigraphic and temporal ranges of megafaunal taxa from the Barstow Formation. Left hand portion includes Land Mammal Ages and Subdivisions, as lithostratigraphic subdivisions of the upper portion of the Barstow Formation.

throughout the Miocene of Eurasia and first appears in North America around fifteen million years ago.

A number of mustelids (weasels, badgers, wolverines, and the like) are known from the Barstow Formation. Two of these, *Miomustella* and *Plionictis,* are virtually identical to minks or weasels. However, a third taxon, *Brachypsalis*, was quite large, rivaling a wolverine in size and likely assuming a similar lifestyle.

Finally, the cats of the Barstow Formation are of special note. Although cat-like animals are common in older sediments, these animals were not true cats of the family Felidae, but relatives from the family Nimravidae (again similar to humans versus chimpanzees). However, about fifteen million years ago we see the first evidence of truly modern cats. The most common of these animals is *Pseudaelurus*. *Pseudaelurus* was not a saber-toothed cat, but had morphological characteristics nearly identical to a modern cougar. Only one saber-toothed cat is known from the Barstow Formation, *Nimravides*. *Nimravides* was not a large cat, somewhere in size between a lynx and a small cougar, but it had the flattened, elongate canines typical of all saber toothed taxa. It is unclear how it would have used these weapons, however, as its small size would have prevented it from taking large prey.

MAJOR EVOLUTIONARY EVENTS

The Barstow Formation was deposited over a time span of almost seven million years. As a result, an extended record of evolutionary events is preserved within these sediments. As paleontologists, it is important for us to identify these evolutionary events as they give insight into faunal response to factors such as climate shift, tectonic activities, or changes in vegetation.

Mammalian paleontologists divide the Cenozoic into time segments based on characteristic mammalian faunas. These time divisions, or Land Mammal Ages, are often based on the first appearances of key taxa. Figure 11 shows the stratigraphic ranges of all large mammalian taxa from the Barstow Formation. A notable change in the fauna of the Barstow Formation occurred at around sixteen million years ago. This time represents a boundary between two of these Land Mammal Ages, the Hemingfordian (nineteen to sixteen million years ago) and the Barstovian (sixteen to twelve million years ago). This point in time is characterized by several notable changes in the fauna across North America. Most importantly, a number of animals make their first appearance at this time, including *Hemicyon*, *Aphelops*, *Rakomeryx*, essentially modern subfamilies of horses, pronghorn antelope, and some proboscideans.

These faunal changes are not limited to the Barstow Formation, but occurred across all of North America. The exact causes of these faunal changes are still unknown, but may include first immigrations from other continents, and changes in animal form and function caused by floral changes induced by climatic shifts.

Yet another change is evident when examining the fossils of the Barstow Formation. Figure 11 shows this change between fifteen and a half and fifteen million years ago when a number of taxa become extinct: *Brachycrus*, several kinds of camels such as *Paramiolabis* and *Michenia*, the deer-like *Rakomeryx*, and the pronghorn antelope *Merriamoceros*. Examination of floral patterns throughout the western United States during this time reveals the cause of this faunal extinction event. Prior to fifteen million years ago, the vegetation of the western United States consisted of forests of deciduous hardwood trees and shrubs. Warming and a decrease in yearly precipitation caused deciduous hardwoods to be replaced by plants which are much more familiar to the western United States today. Chaparral, sagebrush, and small coniferous trees became much more common (Axelrod and Schorn, 1994; Graham, 1999). These types of vegetation have much tougher foliage than the deciduous trees and shrubs they replaced. A common factor among all the mammals that disappeared at this time is teeth adapted to processing soft vegetation.

SUMMARY

The Barstow Formation represents a depositional sequence which occurred from about nineteen to thirteen million years ago. These sediments contain a rich and diverse assemblage of fossil mammals preserved in depositional environments such as alluvial fans, rivers, or lake beds.

A diverse array of herbivorous animals are found in the Barstow Formation, including abundant horses and camels, antelope, deer-like taxa, rhinos, and proboscideans. Feeding on these animals were a wide variety of carnivorous forms, including abundant dogs, large bear-like predators, a “running bear”, several mustelids, and two species of cat.

Two major evolutionary changes are preserved in the Barstow Formation. The first, from about sixteen million years ago, represents the boundary between the Hemingfordian and Barstovian Land Mammal Ages. At this point a number of new taxa appear throughout North America, including *Hemicyon, Rakomeryx*, pronghorn antelope, and proboscideans. An additional faunal turnover is observed at roughly fifteen million years ago. At this time, animals with low-crowned teeth adapted for processing soft vegetation became extinct due to the increased occurrence of chaparral and coniferous vegetation common to the American west today.

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Abstracts from the 2006 Desert Symposium

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Groundwater sampling strategies: selenium and sulfate enrichment along a shallow groundwater flowpath, Orange County, California

Rachel Andrus, Barry Hibbs, and Mercedes Merino, *Center For Environmental Analysis (CEA-CREST), California State University, Los Angeles*

Weepholes and water wells oriented along a shallow groundwater (<3 meters) flowpath in San Diego Creek Watershed of Orange County, California were sampled for selenium, chloride, sulfate, and sulfate isotopes. The data indicate that selenium increased significantly along the flowpath from a low value of 20 ìg/L to a high value of 178 ìg/L. Sulfate increased simultaneously from a low value of 458 mg/L to a high value of 1430 mg/L as groundwater flowed down the hydraulic gradient. Chloride concentrations did not increase proportionately to sulfate and selenium concentrations along the hydraulic gradient. Chloride varied from a low of 189 mg/L to a high of 251 mg/L in the other wells and weepholes. The changes in ion concentration along the flowpath means that groundwater evaporation alone cannot explain selenium and sulfate enrichment in groundwater, otherwise, the chloride (the most conservative of the three ions) in groundwater would become similarly enriched. This suggests a geologic source of selenium and sulfate in shallow groundwater. The greatest increase in selenium and sulfate in groundwater corresponds with the boundaries of a large, historic marsh that was drained in 1890. Selenium and sulfur are immobile in anoxic waters of marshes, but are soluble in oxidizing environments, such as the shallow groundwater environment that exists in San Diego Creek Watershed today. To test this hypothesis, sulfate isotopes were sampled in groundwater along the same groundwater flowpath. Sulfate isotopes become increasingly negative along the groundwater flowpath. Once groundwater enters the historic marsh region, the sulfate isotope signatures decrease from -0.6 to -15.9 ä^{34}S[SO$_4^{2-}$]. This is a very significant change in the sulfur isotope signature that points to a local geologic source of sulfate, and by association, a geologic source of selenium.

The Amargosa River—a rare desert resource

Brian Brown, *The Amargosa Conservency. dates@china-ranch.com*

Although most people interested in the Mojave Desert know of the Amargosa River, few are familiar with the river in its entirety. This program will give a visual tour of the Amargosa from the headwaters in Nevada to the endpoint at Badwater in Death Valley. Along the way, it will catalogue the major springs that contribute to the flow, look at some of the unique flora and fauna, and consider some of the possible threats to maintaining a surface flow in critical areas along the rivers course.

As with all areas of the southwest facing increased demands on the water supply, the Amargosa water course has limits of sustainability, but where that point may be is unknown at this point in time. Increasing populations, commercial dairies, and large scale real estate speculation in the area all add to the urgency of finding out some of this critical information and making allowances to preserve existing sensitive and unique areas.

The Amargosa Conservancy is a newly formed non-profit organization that has a primary interest in preserving special areas and critical surface water flows in the Amargosa drainage. Throughout this presentation, we will explore the purpose of this organization and the goals it hopes to accomplish. Contact information for the audience will also be offered.

Refining the "Protohistoric Period": analysis of chipped glass tools

David Brunzell, M.A., R.P.A., *Cultural Resources Manager, LSA Associates, 1650 Spruce Street, 5th Floor, Riverside, CA 92507, dave.brunzell@lsa-assoc.com*

Traditionally, most Cultural Resource Practitioners/Contract Archaeologists (including myself) record and categorize archaeological sites and resources as either historic or prehistoric. *The Protohistoric Period* has been used to characterize California Native American populations after ca. 1200 through the historic period. Within this period, an intermediate category has been useful in the analysis of artifacts left behind by Native Americans, specifically those which have been traditionally constructed using historic materials (i.e. amethyst color glass made into a projectile point). These so called protohistoric artifacts occur in a narrower time frame than their defined period:

after European contact, but before integration. This paper will introduce and address several research questions with regard to the post-contact protohistoric components of sites in the Mojave Desert Region. How old are the earliest post-contact protohistoric artifacts, and when do they occur in relationship to actual contact? Do any of these finds alter known contact dates? Were post-contact protohistoric materials traded along traditional prehistoric trade routes? To what extent should historic glass scatters be recorded as lithic scatters in the field? Are historic glass sourcing and dating methods adequate to address protohistoric chipped glass tools and debitage, or should traditional lithic analysis be employed? Is there a causal relationship between quality (i.e. grain size) of prehistoric locally available lithic source materials and the predilection for using glass as a lithic source? In addition to characterizing transition from the prehistoric to the historic era, these questions can help organize a framework for enhanced analyses of ethnic, technological and chronological dimensions of development of this little studied, but increasingly important facet of archaeological inquiry.

Be-10 cosmogenic radionuclide surface exposure dating Of alluvial fan deposits at the Calico Site, Mojave Desert, California

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The Calico site in the Mojave Desert is one of the most famous and controversial archaeological sites in North America. In addition to the controversy centered on the authenticity of the artifacts, the ages of the deposits within which the artifacts are buried or have been derived is poorly defined. The deposits comprise of fanglomerates (the Yermo Deposits) that have been highly dissected to form hills, which rise between 100 to 130 m above the surrounding landscape and contain box-shaped arroyos. These are collectively known as the Calico Hills. Previous attempts to date these deposits have included soil, thermoluminescence and uranium series methods. These attempts, however, have met with little success. We, therefore, have applied newly developing cosmogenic radionuclide surface exposures methods to attempt to define the ages of the topographically highest deposits and topographically lowest deposits. The master archaeological pits are within the lower deposits. Dating these two successions of deposits will provide minimum ages for the deposits. Furthermore, the dating may allow us to resolve a long standing controversy over whether the two sets of deposits have a simple stratigraphy, with the higher deposits simply overlying the topographically lower and therefore are younger in age, or the succession represents a more complex cut-fill history, with the topographically lower deposits being younger and inset into the topographically higher deposits.

Sediment samples where collected from 2 m-deep pits excavated into each surface to produce depth profiles for the Be-10 cosmogenic radionuclide surface exposure dating. The initial data for the topographically higher pit show a clear exponential decrease of Be-10 concentration with depth (as expected in an ideal situation) with an inheritance of about 10-15 ka. Correcting for this, the surface age is about 45 ka. The data for the topographically lower pit was disappointing. The Be-10 concentrations did not show an exponential decrease with depth. This could be due to errors, such as spurious results as a consequence of a few pebbles being derived within one of the horizons and/or an analytical error.

The young age of the upper most surface is surprising given the high degree of dissection and the semi-lithified nature of sediment within the archeological pits. This suggests that the surfaces have undergone significant deflation and erosion to provide young surface exposure ages. Be-10 dating of boulders on the topographically higher surface that we are currently undertaking will help test whether the surface has undergone significant deflation. In addition, Be-10/Al-26 burial ages dating of deposits in the deepest part of the archaeological excavations will provide further a test. Furthermore, we will apply luminescence dating to test the initial ages on sediments at the site. Supplementary insights into the depositional and denudational history will be provided by diffusion modeling of the erosion in the Calico Hills.

Rapid demise of giant Joshua trees

James W. Cornett, *Joshua Tree National Park Association, 74485 National Park Drive, Twentynine Palms, CA 92277*

In 1997, I reported at this symposium on the existence and location of the largest known Joshua trees (*Yucca brevifolia*). At that time, the largest Joshua tree stood 12.7 meters in height, had a crown width of 10.4 meters and a trunk circumference of 2.64 meters. Known as Emily's Tree, it was located in Queen Valley in Joshua Tree National Park (Cornett, 1999). The other two trees described in the 1997 symposium abstracts were Champion (9.9 meters in height) on U.S. Forest Service-managed land in the San Bernardino Mountains and Giant (9.8 m) located on Upper Covington Flat in Joshua Tree National Park.

By 2005, all three of these trees had died. Though Champion and Giant were noted as declining during site visits in 1996, Emily's Tree was recorded as viable and enlarging as late as 1998.

Based upon questions received from the public, there seems a popular belief that Joshua trees survive to great antiquity, for hundreds if not thousands of years. Unfortunately, Joshua trees do not produce annual growth rings as do conifer and dicot trees and there appear to be no rings to count for age determination. At this time, age and longevity can only be surmised through historical documents, observations over time and repeat photography projects (Cornett, 1998). These kinds of evidence suggest that even very large Joshua trees do not attain great ages. Average lifespan appears to be less than 150 years with a maximum age of perhaps 200 years.

Acknowledgements: This research has been supported through a grant from the Garden Club of The Desert.

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Invertebrate and plant ichnofossils of the Early Jurassic Kayenta Formation, Washington County, Utah

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The Early Jurassic Kayenta Formation of southern Utah contains dinosaur fossils, especially tracks, but little is known of its other ichnotaxa. This is the first report of invertebrate and plant trace fossils from this formation near St. George, Washington County, Utah.

The 94-meter thick Kayenta has two members. Investigated ichnotaxa were observed or collected from the lower member as float and *in situ* in a freeway construction site where many of the described specimens and outcrops no longer exist.

Vertical, horizontal and obliquely oriented invertebrate traces (up to ~ 1 cm across by up to several cm long) include *Skolithos*, *Planolites* and *Taenidium*. They are preserved in claystones, siltstones and sandstones. Root traces (2 cm wide) penetrate mudrocks to depths of up to 20 centimeters. Three-dimensional rhizoliths including cylindrical and tapering hollow, tufa-like root encrustations (up to ~4 cm across with hollows up to 2.5 cm across) also occur.

The lower member consists of banded, dark brownish red and pale green, variably resistant, but commonly slope-forming claystones and siltstones with variable sand content and minor thin silty sandstone lenses. Secondary alteration of the red mudrock to pale green is suggested by irregular mottling, which does not always follow bedding planes. The color mottling cross-cuts, obscures or erases primary sedimentary structures, although at times the alteration appears to follow the biogenic structure outlines. Secondary alteration and weathering of mudrock surfaces obscure the trace fossils and make them difficult to study.

Mudrocks display delicate cross beds (~1 cm thick) and thin-bedded to finely laminated wavy, flaser and micro-scour-and-fill beds. Sandstones and sandy mudrocks display rib and furrow structures and, less often, parting lineations. Mudcracks and ripple marks (some wide & symmetric), appear in very low relief in the finer grained mudrock.

In the same area, fossil wood and dinosaur tracks occur. Tapering fossil tree limb segments (up to 6.5 cm across) exhibiting possible paleoborings, weather from some mudrock horizons. A restricted exposure of slightly displaced, incomplete dinosaur tracks appears in weathered relief in red reduction-spotted mudrock. The tracks are interpreted as push structures, slip traces and partial toe impressions with lengthwise striae. The toe impressions were shallow to deep, pointed and rounded and up to about 5 cm across with preserved lengths up to about 15 cm.

Small-scale cross beds, flaser and wavy structures demonstrate variable current directions. The dominance of fine-grained mudrocks with variable sand content, small-scale sedimentary structures and claystones suggest variable (but usually low energy) situations. Mudcracks, symmetric ripple marks, fine laminations and other delicate structures in siltstones and claystones, apparently formed on mudflats around small, shallow, ephemeral lakes. Thin, silty, bioturbated sandstone lenses may represent deposition in small associated streams. The red colors and secondary alteration features in the fine grained rocks, rhizoliths and fossil tree limbs probably reflect a floodplain setting with paleosol development and possible paleo-groundwater influence.

Evidence in Utah of an eastward-moving energy wave that originated in the Permian/Triassic Panthalassa Sea: the Black Dragon Breccia and Hoskininni Connection

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The Black Dragon Breccia lies unconformably upon the Permian Kaibab Limestone and appears to be unconformable with the overlying remainder of the Triassic age Black Dragon member of the Moenkopi Formation in the San Rafael Swell of east-central Utah. This breccia grades southeastward into the Hoskininni member of the Moenkopi Fm, approximately 115 miles to the southeast of the San Rafael Swell in the White Canyon area located between Bridges National Monument and Hite, Utah.

Eastward trending off-set depositional patterns observed in the Black Dragon Breccia along with eastward thinning breccias and eastward thrusting recumbent folds present within the Hoskininni suggest an extremely potent energy regime that originated in the Panthalassa Sea west of Pangaea. Soft-sediment deformation features in the Hoskininni and deposits of chert breccia derived from the Kaibab (exposed only several miles west of the White Canyon area) are represented in a generally north-south belt measuring approximately five by fifteen miles and are herein considered to be the result of a major tsunami.

Population status of the endangered Mohave tui chub at Lake Tuendae

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The endangered Mohave tui chub (Siphatele*s bicolor mohavensis)* historically inhabited the Mojave River system in the Mojave Desert of California. These fish were eliminated from the Mojave River by competition and hybridization with the introduced arroyo chub (*Gila orcutti)*. A small population survived displacement from the river and has been used to stock recovery populations, of which three persist to date. These occur at Camp Cady Wildlife Area (San Bernardino County), China Lake (Kern County) and Lake Tuendae (San Bernardino County). This research focuses on the current status of the Lake Tuendae population. Lake Tuendae has experienced a perennial plankton bloom beginning in 2003, following a dredging project, and an unauthorized introduction of mosquito fish (*Gambusia affinis*). In addition, fish are infected with the introduced Asian tapeworm (*Bothriocephalus achelognathii*). This research documents current population size, structure, and trends; to aid in continuing monitoring plans and recovery efforts for this endangered fish. In April and October of 2004 and October 2005 a mark and recapture survey was conducted at Lake Tuendae. The population of Mohave tui chub at Lake Tuendae was estimated, using the Schnabel method, to be 2,241 (95% C.I.: 2416-2090) in April 2004, 3,708 (95% C.I.: 3894-3539) in October 2004, and 3,354 (95% C.I.: 3509-3213) in October 2005. Length frequency histograms also indicate successful juvenile recruitment to this population. In addition, lengths and weights were compared to populations at Camp Cady and China Lake. While data indicate the population at Lake Tuendae is not rapidly depleting, further studies are needed to determine the long-term effects these introduced species and habitat conditions will have on this endangered fish.

Hydrochemical and isotope studies to determine source flows at Soda Springs, California

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The Mojave tui chub is a listed endangered species that survives in Mojave Chub (MC) Spring and in the nearby artificial pond, "Lake Tuendae" at Zzyzx, California. Identifying source flows at MC Spring provides an opportunity to help managers protect the spring and the chub. MC Spring is located at an alluvial fan/playa margin interface between Soda Lake and the Soda Mountains. An alluvial fan formed on the flanks of the Soda Mountains is the likely source of recharge for a *relatively* dilute (2200 mg/L TDS) groundwater lense that provides water to production wells at the Zzyzx/Desert Studies Center. Other groundwaters around the Desert Studies Center are strongly mineralized, with salinities ranging from about 3500 mg/L to 30,000 mg/L TDS. Limestone Hill is an isolated carbonate outcrop located between the alluvial fan at Soda Mountains and the phreatic playa at Soda Lake. MC Spring flows from the opposite side of Limestone Hill, and is separated from Soda Mountains and the alluvial fan by Limestone Hill. Analysis of groundwater samples for standard inorganic constituents, chloride/bromide ratios, sulfur isotopes, stable O-H isotopes, and radioisotopes indicates that the waters in MC Spring are almost identical to the dilute groundwaters sampled from production wells near Soda Mountains. This implies a common source. On the basis of these data, our conceptual model for the source flows at MC Spring is as follows: (1) runoff from Soda Mountains and percolation at the alluvial fan to create the dilute groundwaters along the Soda Mountains; (2) flow of dilute groundwaters from the alluvial fan through permeability conduits (fractures/fault) at Limestone Hill; (3) flow through the conduits at Limestone Hill and discharge at MC Spring; and (4) overflow and interstitial leakage of water from MC Spring to the Soda Lake phreatic playa located downgradient from the spring.

Dinosaurs and other Mesozoic reptiles of California

Richard (Dick) Hilton, *author of "Dinosaurs and Other Mesozoic Reptiles of California," University of California Press, 2003*

This presentation is about dinosaurs and other fossil Mesozoic reptiles found in California and the people involved in their science. Bones, teeth, and trace fossils, originally deposited in sediments between 210 and 65 million years ago, have been discovered in the rocks of the hills, mountains and deserts of California. While most of these fossil reptiles lived in the sea (thalattosaurs, ichthyosaurs, mosasaurs, plesiosaurs and turtles), some, like the birds and the pterosaurs, soared above it. Others like tortoises and dinosaurs came from terrestrial habitats or died and were washed into the sea. Of particular interest here are the tracks of small dinosaurs and even pterosaurs locked in the Jurassic Aztec Sandstone of the Mojave Desert.

Perhaps just as interesting as these prehistoric creatures is the rich story of the work and adventure involved in the discovery, preparation and publishing of the finds. Here we find scientists, teachers, students, ranchers, weekend fossil hunters, and even a dog that found a fossil bone. There are folks from all walks of life and all levels of education. This talk chronicles the first 100 years of fossil Mesozoic reptile discovery in California.

Fossils of Anza-Borrego Desert State Park®, California: a continuous Plio-Pleistocene vertebrate record

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The Anza-Borrego Desert State Park® fossil record spans approximately 10 Ma, with no recognized breaks from the late Miocene through the late Pleistocene. Marine, freshwater, and terrestrial assemblages include over 550 taxa, ranging from plant pollen and colonial corals, to walrus and mammoths. Combined with long and complete sedimentary depositional sequences, these ecologically diverse fossil assemblages are an unparalleled North American paleontological resource.

The Park's unique geologic setting along the western margin of the Salton Trough rift provides a 25 Ma history of plate collisions and continental crustal rifting and faulting. These events, together with the cutting of the Grand Canyon and deposition of a delta across the Trough by the ancestral Colorado River, and uplifting of the California Peninsular Ranges, have transformed the region from a northern extension of the ancient Sea of Cortez to a habitat of estuarine and brackish waters, to a landscape with large fresh water lakes, stream banks, woodlands and savannah-like brush lands, to the present arid Colorado Desert.

The recovered 249 species of marine organisms include carbonate platform, outer and inner shelf, and near shore tropical sea invertebrates and vertebrates which predate the closing of the Isthmus of Panama. Spanning the Plio-Pleistocene boundary and the Blancan-Irvingtonian boundary in a 3.5 Ma conformable terrestrial stratigraphic sequence are the Park's richest and most significant fossil assemblages: 214 taxa of fresh water invertebrates, fish, amphibians, reptiles, birds, and mammals are represented. Of these, the early assemblages reflect neotropic origins, and later, holartic affinities. The over 6 km-thick stratigraphic section contains several tephra and is temporally calibrated by paleomagnetic transects.

Ethnographic analogy and the Mesquite Regional Landfill project: can the DTC tell us something about aboriginal occupation, and vice versa?

Frederick W. Lange, PhD, RPA, *Senior Cultural Resource Manager, LSA Associates,Riverside, CA 92507*

Beginning thousands of years ago, aboriginal populations utilized the lithic resources and meager seasonal plant resources of the southern Colorado desert. Their utilization of the area was either as a seasonal expansion from the Colorado River Valley or as they hurried from the river to Lake Cahuilla, or beyond to the Pacific coast, and back. Despite identified trail segments, pot drops, and lithic chipping debitage throughout the region, the prehispanic inhabitants are largely invisible.

From 1942 to 1945, many thousands, if not hundreds of thousands, of the 1.5 million member Armed Forces of the United States who were trained in the Desert Training Center (DTC) preparing for the North African campaign of World War II utilized the same landscape. Despite tank tracks, tent "shadows", occasional discarded equipment, and rifle and tank practice facilities, General Patton's soldiers are likewise almost invisible.

Both the prehistoric and the World War II eras were important periods in the history of the area encompassed now by the United States. This paper focuses on what the study of each might tell us about the other.

Obsidian hydration for Newberry Cave

Amy Leska

The archaeological site of Newberry Cave, located in San Bernardino County, is significant to the understanding of California's prehistory due to its unique rock art and artifact assemblage. The site was excavated in the 1950s and many of its artifacts have been housed at the San Bernardino County Museum, both on display and in the archives. Of special note, relatively few obsidian artifacts were found in a collection dominated by chert. Why so little? Where did it come from?

Within the assemblage of obsidian, at least three artifacts appeared to be from a non-local source. Obsidian hydration and X-ray fluorescence (XRF) were used to determine age and source location for the three samples. Trace elements in obsidian make it unique to one source and therefore possible to trace back. XRF analyses the "fingerprint" of each artifact. We can then compare the provenience of the artifact with the original quarry, if known, and learn more about travel and trade of prehistoric peoples.

When obsidian fractures during the tool-making process, the surface is exposed and a new hydration rind forms. The thickness of this rind gradually grows and when this is analyzed using obsidian hydration, an approximate age can be determined. Developed in the mid-1960s by JR Weaver and Fred H Stross, obsidian hydration has proven to be reliable in the Great Basin and California. However, inaccurate results from Mesoamerica have tainted its reliability and therefore it is mainly used to supplement other chronologies. Used independently, obsidian hydration is viewed as a fairly inaccurate means to establish chronology. On the other hand, it is more cost effective than other tests and does not destroy the sample.

Newberry Cave probably has so little obsidian because the Mojave Desert lacks a major source, forcing prehistoric people to make do with the "Apache tear" nodules that pop out of volcanic tuff. These are difficult to fashion into anything other than small cutting type tools due to their size. The results of obsidian hydration testing from Newberry Cave show that one sample appears to be from central Nevada. The obsidian for both the Elko corner notched point and the third sample comes from West Sugarloaf in the Coso Range, a major prehistoric source for southern California, and indicates a "later prehistoric" age. This comfortably vague term would fit ages established for the Newberry Cave assemblage via radiocarbon dating (3500BP).

Communicating natural science to the general public: a case study

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Fossil Treasures of the Anza-Borrego Desert has been a book five years in development and presents the collaborative work of some twenty-five scientists, researchers, and graphic artists. After publication, the task will be to disseminate the work to its intended audiences, which include readers who are interested in natural science or desert studies but who may not have the technical background to access available literature and scholarship. For this general science-oriented but non-technical audience the following themes have been presented:

1. A unique scientific resource- Combined with a long and complete sedimentary depositional sequence, the diverse fossil assemblages of the region are an unparalleled North American paleontological resource.

2. A window on the past- Geologic and paleontologic evidence from the last seven million years in the Salton Trough enables reconstruction of past climates and environments with possible predictive value for the future.

3. A project in science education- Multiple media, including text, full-color graphics, and new exhibits in the State Park Visitor Center, explore the twinned concepts of evolution and ecology in the Anza-Borrego Desert region.

This provides an overview of a study that will measure the success of disseminating this work over certain intervals of time as well as analyzing qualitative response from reviewers, readers, and the professional publication media.

Dinosaur collections at the Raymond M. Alf Museum of Paleontology

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The Raymond M. Alf Museum of Paleontology in Claremont, California was established in 1936 by Raymond Alf. Alf was very interested in the study of Tertiary mammals, Permian–Miocene vertebrate tracks, and Precambrian fossils of any type. Other than tracks collected from the Early Jurassic Moenave Formation, dinosaur paleontology was not a topic of great interest to Alf. However, donations of skull and skeletal casts along with the Moenave tracks allowed the Alf Museum to display a few dinosaur specimens in the Hall of Life exhibit area. Since 1992 the museum has directed more attention to both collecting and exhibiting dinosaurs. The Mesozoic Era section of the Hall of Life displays replicas of several types of dinosaurs including *Allosaurus, Ankylosaurus, Camarasaurus, Centrosaurus (Monoclonius), Coelophysis, Stegosaurus, Tyrannosaurus rex*, and *Velociraptor*, along with fossils from the Hell Creek and Kaiparowits formations. Also on display are dinosaur eggs. The Alf Museum collection houses a sizable collection of specimens from the Hell Creek, Kaiparowits, and Moenave formations. Specimens from the Hell Creek and Kaiparowits formations were collected by Webb students and museum staff over the past 15 years.

Mitigation of non-native Sahara Mustard (Brassica tournefortii) in the Lake Mead National Recreation Area

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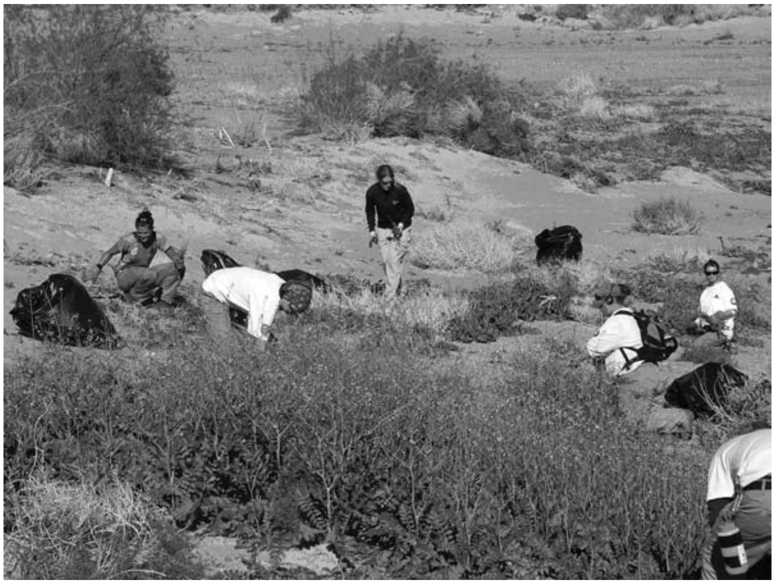
An examination of the efforts used in LMNRA to deal with this aggressive plant in terms of mitigation and expanding range, and invasion into rare plant habitats. Adequate funding for large scale control is difficult to obtain, therefore strategies must be designed and implemented that best address the particular invasive species at hand and will vary per site depending on the sensitivity of the site and the size of the infestation. Research and monitoring are vital in order to understand the biology of the plant and how it interacts with its environment. Designing strategies that address different habitats and different stages of invasion as well as cooperation with private, state, federal and county agencies in support of aggressive weed management is vital to control this invasive plant.



Americorp Crew pulling Brassica tournefortii *in sandy habitat at LMNRA, 2005.*

Nitrogen deposition effects on native and non-native desert plants

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Urban sources, largely automobiles, have elevated N deposition to up to 8 Kg/ha/year in desert areas such as Joshua Tree National Park (JTNP). Preliminary observations suggest that exotic grass invasions may be related to higher than normal levels of N. It is therefore hypothesized that desert native annuals grown in low soil N will not be subject to high densities of invasion by non-native species. This experiment will test individual growth response of six annual species to different levels of N on two different types of desert soils. Seeds of two nonnative species (*Schismus barbatus* and *Brassica tournefortii*) and four native species (*Salvia columbariae, Lepidium densiflorum, Cryptantha angustifolia* and *Phacelia distans*) were collected at JTNP. Seeds were planted in native soil found under-shrubs (US) where invasive species are abundant and in soil collected from shrub inter-spaces (IS) where invasive species are scarce. Two levels of nitrogen, 20 and 40-ppm N solutions, were added to eight replicate pots bimonthly. After sixty days plants were dried and weighted. *Schismus* growth was N-saturated in US soil, but was limited by N in IS soil. All species, except *Salvia columbariae.,* had greater growth in US soil than in IS soil. This suggests that elevated N deposition will allow all species, with the exception of *Salvia columbariae,* to thrive in the interspaces. However, field observations show that only *Schismus* is invading the interspaces, which suggest that there may be competitive interactions between native and invasive species that need to be investigated further.

Paleogeographic interpretation and archaeological site prediction in widely different present environments

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Though some archaeological sites defy any geographic logic in their occurrence, many sites are closely related to the geographic conditions pertaining at the time of occupation. Interpreting those former geographic conditions from present evidence, and building a site prediction model based upon them, is a tool that can be used in any present environment if suitable information is available. The technique is particularly successful where sites are closely related to such features as river mouths, shorelines, oases and springs, sites that are typically associated with a source of water, fishing or hunting small game. In former glaciated regions, predictive models associated with shoreline/river mouth sites have to take into account the degree of isostatic uplift that has occurred since occupation, since sites of a similar age may occur at varying elevations across a region according to the history of uplift. Indeed, water level changes can create archaeological discontinuities and raise issues of inheritance of older features. Glacio-isostatic uplift is generally predictable, but isostatic changes due to sediment loading or changes in elevation due to tectonic forces, such as occur in the Salton Sea region, presents a much more complex set of conditions to account for, unless working within very limited geographic areas. Examples drawn from Minnesota and the Mojave Desert regions will be used to illustrate these principles.

Monitoring populations of fringed-toed lizard, Uma scoparia, on lands administered by the Bureau Of Land Management and the National Park Service In the East Mojave Desert

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The Final Environmental Impact Report and Statement for the West Mojave Plan rendered in January, 2005 includes the establishment of large conservation areas for wildlife. Within these areas, Habitat Conservation Plans (HCPs) must be provided for the protection of unique and declining wildlife. One such species recognized in the plan is the Mojave fringed-toed lizard. This species is restricted to isolated wind blown sand dunes. The animal is highly specialized for living in the dune systems and is under pressure due to recreational activities and human population growth.

This study, funded by the Bureau of Land Management with cooperation of the National Park Service, seeks to establish population parameters for the fringed-toed lizard within the sand dune habitats of the east Mojave Desert – Ibex Dunes in Death Valley National Park, Dumont Dunes, Afton Canyon, West Cornese Dry Lake, Rasor Open area, and Devil's Playground and Kelso Dune systems, the latter two systems in the Mojave National Preserve.

The five year study will examine the presence or absence of suitable habitat and estimate the population size, age classes and activity patterns for the lizards. In addition plants associated with lizard sightings will be identified. Soil samples will be taken to classify soil type and particle size. All lizard sightings will be provided with GPS coordinates and weather data will be collected (Temperature; air, surface sand: Wind; speed and direction: Cloud cover, etc).

Using these data a management prescription will be identified for direct and indirect impacts with the goal of managing the species for recovery and conservation. Conservation requires protection of the dunes, hummocks and sand sheets occupied by the species as well as the sand source and sand transport system.

Similar studies are in progress in Riverside and Imperial counties for this species.

This presentation will report on the current progress of the study and discuss the current protocol and science used to obtain the data.

Categorization of California's Jurassic quadruped tracks

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Research on tracks and trackway panels in the early Middle Jurassic (170 Ma) Aztec Sandstone in the Mescal Range of California has resulted in the recognition of tracks from nine different quadrupeds in addition to tracks of three previously identified, tridactyl bipedal, therapod dinosaurs. Seventy percent of the identified trackways are from quadrupeds with bipeds accounting for the remaining thirty percent. Additional ichnites are attributed to the invertebrates *Octopodichnus* sp. and *Skolithos* sp

As part of this study, all Mescal Range quadruped tracks were measured, and their length divided by width (L/W). This calculation produced a ratio that was used to compare and categorize ichnite categories. Where multiple tracks were present within a trackway, the ratio was averaged. (R-av). Using ratios to compare ichnospecies may avoid creating artificial ichnite categories. Measurement ratios of the same ichnospecies plot at approximately the same point, although actual dimensions might differ because of size or age of the individual. Ratio comparisons also take into account changes in track size caused by substrate differences. These ratios are not considered to be sensitive to trackway substrates because similar ratios result whether substrates are firm or loose, viscous or fluid.

It is important to note that large and small tracks of equal ratio plot at the same point. Therefore, original track morphology and measurements were used to determine if there are noticeable differences. Two methods of sorting were employed: size, and different ratios between manus and pes. Sorting by size of ichnites with the same ratio produced one additional category. Sorting by visible differences in size and morphology between manus and pes provided an additional category. Graphing results produced five groups where L<W, L=W, L>W, L>>W, L>>>W; the lacertoid track has not been relocated or measured. Further evaluation of track and trackway morphology added groups where manus is not equal to pes and where there is a significant size difference, resulting recognition of nine total groups in the Mescal Range.

Ichnites previously described in the literature include:

- *Brasilichnium,* (R-av 0.8 – 1.05), tracks with manus size and ratio smaller than pes.
- *Navahopus,* (R-av 1.20), manus equal to pes
- *Pteraichnus.* (R-av 1.66), length significantly greater than width; distinctive morphology.

Six additional ichnomorphs are represented in:

- Group A: small tracks with a low ratio (0.6, L<W) and manus equal to pes.
- Group B: large tracks with a low ratio (0.7, L<W) and manus equal to pes.
- Group C: small tracks with length greater than width (R-av 1.22)
- Group D: Small tracks with length greater than width (ratio 1.22)
- Group E: small tracks with length much greater than width (R-av 1.44).
- Group F: gracile lacertoid ichnite.

The Mescal Range *Navahopus* (L>W) differs morphometrically from associated *Brasilichnium* (L<W). The Mescal Range trackway panels demonstrate fluctuation of *Brasilichnium* morphometrics (L<W to L=W). Fluctuating size suggests different ages and sexes of track makers along with changes in the consistency of the substrate. *Pteraichnus* imprints have the highest R-av (1.66) of quadruped tracks from the Mescal Range. These pterosaur tracks are the westernmost on the North American Continent.

Come look: Mojave River mammoths

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The City of Victorville is undergoing rapid urban development. Development in California is required to conform to guidelines of the California Environmental Quality Act (CEQA). Therefore, nonrenewable paleontological resources must be protected from impacts during construction excavation. Protection involves trained paleontological monitors checking the cuts made by excavation equipment. When large or small fossils are located, they are flagged for avoidance, stabilized with preservatives, wrapped in a protective plaster jacket, and removed to a safe repository.

In February 2006, paleontologic monitors from LSA Associates, Inc. (LSA) located a white powdered bone in a bulldozer cut at a construction site in Victorville. Excavation to determine the limits of the bone proved that it was the tusk of an Ice Age mammoth. Near this seven foot long tusk was a three-foot long section of the other tusk, and a three-foot section of mammoth rib. These mammoth tusks were deposited in white carbonaceous siltstones that indicate groundwater discharge deposits that were probably located in the marshy, central valley area north of the rising San Gabriel Mountains. Mammoths first arrived on the North American continent 1.9 million years ago. Previous dates on sediments along the ancestral Mojave River in the Victorville area suggest that this mammoth is less than 500,000 years old. Ice Age mammoths, camels, and horse have been discovered previously in Victorville. This very well preserved mammoth tusk and associated material were taken to the Mojave River Valley Museum for cleaning, and stabilization. Come to the museum on Barstow Road, two blocks north of the I-10 Freeway, and see the seven foot long tusk of an Ice Age mammoth that lived along the Mojave River.

Coyote Dry Lake meteorites: what can Holocene meteorite falls tell us about the recent drainage history of the Coyote basin?

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The Coyote Dry Lake meteorites are named after the California dry lake on which they were found, a large playa 20 miles NE of Barstow in San Bernardino County. For the past 10 years, over 250 chondritic stone fragments and individuals (meteorites) have been found at this locality. Every known find has been recorded, to include its date-of-find, weight in grams, and GPS coordinates. This information was reported to the Nomenclature Committee of the Meteoritical Society and provisional numbers have been assigned to each these 250 finds.

The first known find from this locality was made by the author in 1995, but it wasn't classified until 1999. It was characterized as being "H5 S2 W3", as are the majority of the finds from this locality. But, over the years as finds were continually made (by over a dozen field workers), each would be closely scrutinized, and every specimen that was deemed "out of character" (from the original H5 S2 W3 stones) would be turned in for classification. Presently, there are nearly 50 of these specimens that have been classified. Although a proper pairing study has yet to be done, Table I shows the breakdown of the current classifications.

The recovery information for each of these classified stones were tabulated, and that table was submitted to the Nomenclature Committee. The name "Coyote Dry Lake" was approved by the Committee for these classified stones, as well as for the remaining 200 "provisionally numbered" finds. The name "Coyote Dry Lake" appeared for the first time in print when the Meteoritical Bulletin #89 (2005) was published in the "Supplement" to the Meteoritics & Planetary Science – Journal of the Meteoritical Society (Volume 40).

Based upon the pairing scheme in the above table, it can be reasoned that there have been at least 10 separate events, called "meteorite falls", which have occurred over time. But this begs the question, "Over how much time?" It is this question that is now at the center of the discussion about Coyote Dry Lake meteorites. If it can be shown that these various meteorites accumulated over geologic time, and that their recovery was fortuitous due to recent exhumation by accelerated deflation/erosion of this lakebed, then 10 separate fall events is not an unusually high number. But, the consensus among geomorphologists is that late Quaternary drainage into this Mojave River system of basins has been intermittent, and with a deposition/deflation rate that is relatively static (Meek, 1994). Only at nearby West Cronese Basin has there been a study that has measured a significant (> 1 m) erosion of sediment which has occurred in just the past 250 +/-70 years (Clark, 1994).

Table 1. Current classifications of finds.

Number of classified finds (stones)	Classification (UCLA)	Pairing determination
21	H5 S2	most are "probably paired"
10	H4	1 group of whole individuals are "probably paired" and at least 2 other groups of "possibly paired" stones
5	H6	1 group of whole, fresh stones are "probably paired" and another group of weathered stones are "possibly paired"
2	H5-6 S2 breccia	"probably paired"
1	H5-6 S4 breccia	(unpaired)
1	H3	
2	L5-6 S2-3 W1	("probably paired")
2	L6 S4 W5	("probably paired")
1	LL6	

Only a handful of Coyote Dry Lake meteorites have undergone testing to determine their terrestrial residence age. Researchers conducted thermoluminescence (TL) testing to determine this age. Their results (which are still to be published) indicates an average terrestrial residence age of 5000 years for the Coyote Dry Lake H-chondrites.

Coyote Dry Lake meteorites have garnered attention recently, albeit for the large number of meteorites found upon the lakebed (more than 250 stony fragments and individuals), yet, if the number of separate fall events can not be shown to have occurred over geologic time, and are accepted as having occurred recently, this will be of great interest to those researchers studying the rate of influx for meteorites falling upon this planet.

Reconciling the number of Coyote Dry Lake meteorite falls with the Recent drainage history of the Coyote Basin is an endeavor that will require more in depth study by various, cross-disciplined researchers in order to resolve. It is to this end that the findings of the Coyote Dry Lake meteorites are being presented to this workshop.

Presentations from a workshop held in April 2005 at the Desert Studies Center in Zzyzx, California, are now published. Key issues addressed in the workshop included: (1) To conduct additional studies of the Mojave River "drainage history based on the physical record and seeking explanations for major discrepancies." (2) And for researchers of various disciplines "to interact to develop a broader perspective on the types of research that are being conducted to address issues of regional drainage history". The convenors of that workshop hoped that the successful interaction among those scientists of different disciplines would lead to future proposals for collaborative studies.

In keeping with the above perspectives, this abstract endeavors to promote a more in depth study of the Recent drainage history of the Coyote basin and to petition fellow researchers at this workshop to collaborate in a future "cross-disciplined" study.

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Surface emulsion impacts on seed germination, winter annual vital rates, soil seed banks and soil hydraulic conductivity in a Sonoran desert wash community

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Containment of depleted uranium contaminated soils due to ballistics testing for military purposes can be accomplished with surface soil application of emulsions of mixtures of asphalt, water and specific chemical chelating agents. However, the impacts of the emulsion application on soil hydraulic properties and native desert plants communities have not been evaluated. Our study site was located on the Yuma Proving Grounds in southwest Arizona in a native Sonoran Desert wash community. We applied a fuel oil-like by-product of the paper industry (produced by Encapco Technologies LLC) diluted with water at a 4:1 ratio at the rate of 1 liter m^{-2} to 4 (5 x 25 m) plots the first week of December 2004. Several weeks prior to spraying the emulsion on the soil surface, germination of native and introduced winter annual plants had occurred. Before spraying, two of the plots were seeded with 9 species of native trees, shrubs, forbs and grasses. Seed germination rates and winter annual density, diversity, growth and phenology data were collected 2, 6 and 10 weeks after application of the emulsion. Saturated soil hydraulic conductivity was measured before emulsion application and 1, 6 and 12 months post application. Winter annual soil seed bank samples were collected in October 2005 and germination densities and diversities were determined in February 2006. There was significant heterogeneity of soil resources within each plot and winter annual densities varied from less than 100 to more than 1000 plants m^{-2}. Mean density of winter annuals in the plots with the emulsion was not significantly different than the untreated plots, 415 versus 370 respectively, while annual diversity was significantly less on the plots with the emulsion, 8.6 versus 6.7 species m^{-2}. The emulsion significantly reduced seed germination from 5.8 to 0.2 plants m^{-2}. The impact of the emulsion on post-emergent winter annual survival, growth and reproductive allocation was minimal for an exceptionally wet and high net primary productivity year. The impacts of the emulsion on soil hydraulic properties and soil seed bank diversity and density will be presented.