Field Trip for the 5th Symposium of IGCP-632

Flagstaff AZ

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Field trip participants at Big Indian Rock, Lisbon Valley, Utah at the Chinle-Wingate contact close to the presumed level of the ETE.

Field trip participants are, from left to right and from back to front, Lê Thị Nghinh (Vietnam), Vivi Vajda (Sweden), Olsen Shevchuk (Ukraine), Igor Kosenko (Russia), Stephen McLoughlin (Sweden), CAI Chenyang (China), Andrew Milner (USA), Masayuki Ikeda (Japan), Petr Schnabl (Czcech Republic), Paul Olsen (USA), SHA Jingeng (China), Oleksander Shevchuk (Ukraine), Sean Kinney (USA). Photo by Sean Kinney and Paul Olsen.

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Introduction

During the Triassic and Jurassic an enormous blanket of largely continental strata, generally thickening, and passing into marine strata westward, formed in western North America. During this time, the supercontinent of Pangea was fragmenting, the Atlantic Ocean formed, and North American plate translated over 40° northward. While the main components of the modern land biota evolved, at least two major mass extinctions (end-Permian and end-Triassic), along with at least three major faunal reorganizations (mid-Norian, Toarcian, and Jurassic-Cretaceous events) transpired, filtering out what in hindsight we call archaic elements. Some of the most iconic of vertebrate fossils, such as *Coelophysis*, *Dilophosaurus*, and *Brontosaurus*, have been found within these strata.
The Colorado Plateau physiographic province (Fig. I.1) is a prominent upland with large expanses of badlands exposing these Early Mesozoic continental deposits providing a superb venue to stimulate discussions during our 5th IGCP 632 symposium on "Jurassic Tropical to Polar Biotic and Climatic Transects".

Our field trip takes along a three-day, 1962 km (1219 mi) loop on and adjacent to the Plateau (Fig. I.1) with the purpose of seeing some of the more accessible sites that illustrate some of the major features and problems of the western North American continental Early Mesozoic as they relate to global Earth System issues of climate, evolution, and tectonics.

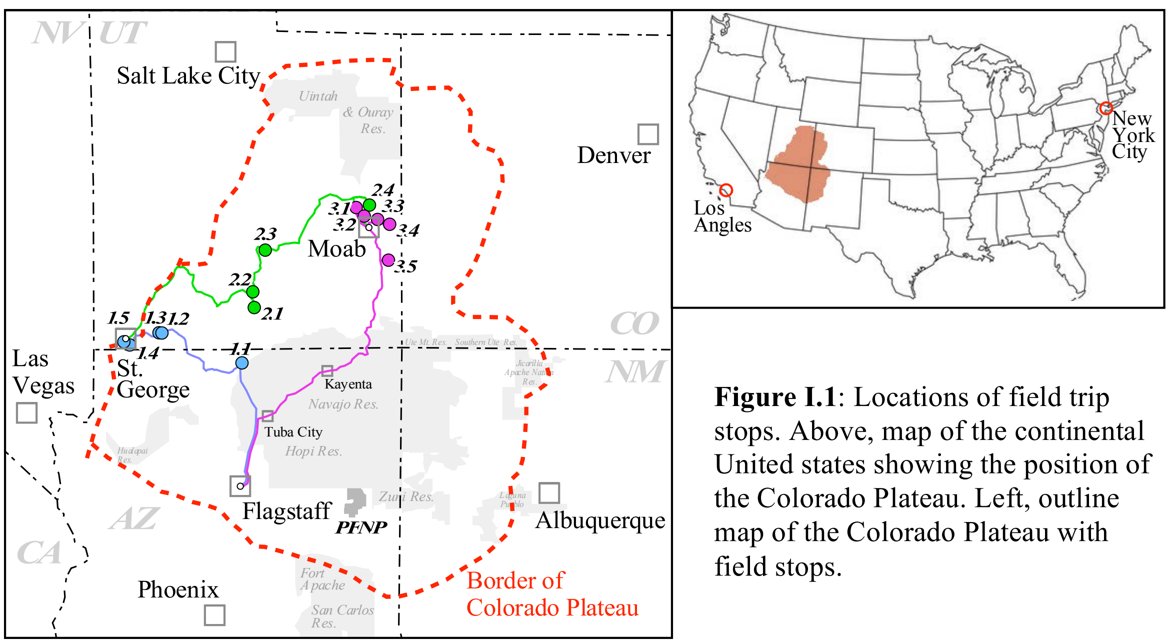

Figure I.1: Locations of field trip stops. Above, map of the continental United states showing the position of the Colorado Plateau. Left, outline map of the Colorado Plateau with field stops.

Geodynamic Context

Compared to relatively simple conceptual models of Early Mesozoic extension and continental rifting of central Pangea, including eastern Laurentia, models of western North America are extremely complex, involving exotic terranes, magmatic arcs, oceanic-plate subduction, and a lot of shortening deformation, with most of the pertinent tectonic geometry being so strongly deformed as to be inferable only by indirect means. Since the 1970s the leading theory for the tectonic context of the mostly continental Triassic-Jurassic sequences of the Colorado Plateau has been deposition in a back arc and/or foreland retroarc setting developed during Pacific oceanic-crust subduction beneath North America beginning during the Sonoma Orogeny (1, 2, 3), with a magmatic arc developing northward over the subducting slab and west of the backarc or foreland retroarc basins in which the Triassic-Jurassic deposits accumulated (4). Eastwardly directed subduction persisted though the Sevier and Laramide orogenies until development of the oblique strike-slip system that has characterized most of the US western margin since the Cenozoic. In the end members of this class of models the sea to the west of the Triassic-Jurassic continental strata was bound on its west by the relatively subaerial magmatic arc and the adjacent craton to the east was deformed by proximal active compressive and flexural forces controlling the depositional systems.

This model has been challenged more recently by radically different models based on geological (5) and geophysical (tomographic) (6) arguments postulating that western North America was a passive continental margin from the Paleozoic until the Cretaceous with westward-dipping subduction. In the end members of this class of models, Triassic-Jurassic continental strata sloped into the western sea deepening out to the trench and tectonic modification of the adjacent craton to the east and its overlying continental strata suffered little or no deformation, save those caused by interplate stresses.

In both models most of the sediment of the Triassic-Jurassic sequences was derived from northwesterly flowing fluvial systems (7), with a persistent slope from the interior of Pangea toward the Cordilleran margin. In both models there must be a southwestern source of silicic volcanic debris (e.g., 8) generally identified with the postulated Cordilleran arc.

A further consideration is that the southern and eastern edges of the western US Triassic / Jurassic sequences lie against the southwestern projection of the Central Atlantic rift system, generally ignored in discussions of the western Mesozoic. Changes in the uplift of the northwestern rift shoulders related to extensional pulses may be important factors in changing the rates of supply of sediments to western Triassic-Jurassic deposits (e.g., ref. 9) as well as far-field effects of activity along the African margin.

Thus, the geodynamic context of the Colorado Plateau Triassic-Jurassic strata is at best uncertain. While we cannot solve these issues directly with observations on this field trip, we should keep the alterative models in mind, because they are pertinent to the various unconformities and facies changes that we will see. These have been traditionally explained largely within the active-margin tectonic context, but not used to test any specific tectonic model. Specifically, one set of key features we will investigate is the dynamic relationship of the Early Mesozoic unconformities, facies and salt tectonics. Halokenesis might, in fact, prove more important than either basement-involved tectonics or eustasy in structuring much of the stratigraphy we will see as well as controlling the distribution of important fossil-bearing facies, all possibly consistent with a passive margin setting.

The Colorado Plateau itself remains geologically somewhat enigmatic. It is underlain by relatively undeformed crust, surrounded by strongly compressed and extended regions. Apparently, after the Cretaceous compressional formation of the Rocky Mountains, the region was relatively low-lying, but during the medial Cenozoic during the extension that formed the Basin and Range physiographic province, it was uplifted by at least a kilometer and streams and rivers deeply incised it producing the Grand Canyon of the Colorado River and associated erosional features. The combined effects of the compression and extension was a rotation of the Colorado Plateau about a vertical axis at least a net ~10° clockwise (10).

In the late Cenozoic, the volcanic landforms such as the San Francisco Peaks on the north side of Flagstaff, our meeting venue, formed, and the field as a whole is still active. The geodynamic origin and timing of the events shaping the Plateau remain hotly debated. Useful recent reviews of the history of the Plateau are presented by Flowers (11) and Liu & Gurnis (12).

Triassic-Jurassic Basic Stratigraphy and Climatic Context

We will focus on strata of Triassic and Jurassic age (Fig. I.2), mostly of continental origin. In the broadest sense, the sequence on and close to the Plateau remains continental to marginal marine through its entire Early Mesozoic history. The Plateau part of Laurentia was near the equator in the Early Triassic, moved north through the Triassic from more humid latitudes ~7° at 220 Ma into arid tropics at ~16° around 200 Ma (close to the Triassic-Jurassic boundary), continued into the arid sub-tropics at ~27° through the rest of the Early and Middle Jurassic, and then moved into the temperate latitudes ~47° by ~150-140 Ma (and the Jurassic-Cretaceous boundary) and roughly staying there for nearly 100 Myr. It then moved south to the present latitude of ~37°. Apart from the Moenkopi, which remains anomalous in being so arid-looking at the equator, the Late Triassic though Cretaceous climate-sensitive facies track latitude, assuming a simple zonal climate (e.g., ref. 13), with the giant sand sea of the Navajo Sandstone occurring in the sub tropics near 30° N, and much less arid facies developing during Morrison and Cedar Mountain time (Fig. I.3).

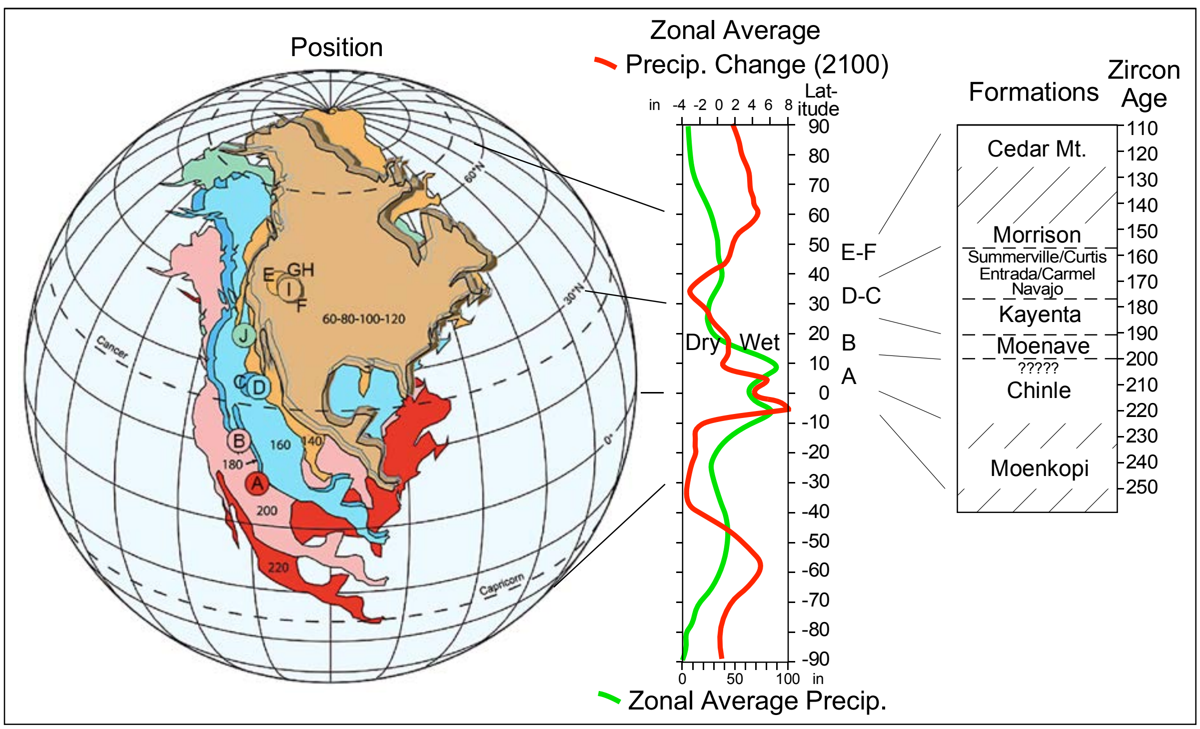

Figure I.2: Position of North America (modified from ref. 14) and the Colorado Plateau (circles) from 220 Ma to Present with comparison to zonally averaged precipitation for today (1950-2000, from ref. 15), change in precipitation for 2100 (from ref. 15), and the zircon ages for formations we will see in the field (see text).

The oldest Triassic we will see is nominally Early to Middle Triassic age Moenkopi Formation (Stops 1.1, 1.4, 1.5, 3.6), but in reality, as there are no fossils known from very low in the formation; the base could be as old as Late Permian. In addition, much of the formation is poorly known, and most of what is known is based on vertebrate fossils from east-central Arizona where the formation is thin with the much thicker western portions remaining relatively unstudied. The youngest Moenkopi is nominally middle Triassic in age, based on tetrapod biostratigraphy (16, 17), but parts could be as young as early Late Triassic (Carnian) based on admittedly sparse geochronology (18).

Most of the rest of Triassic time in the Colorado Plateau is recorded by the largely fluvial Chinle Formation (Stops 1.1, 1.3, 1.4, 3.3, 3.5, 3.6), the oldest dated strata of which is Early Norian in age (19,20) and the youngest Late, but perhaps not latest Rhaetian in age. Latest Rhaetian time and the level of the end Triassic extinction (ETE) may be represented in the basal Glen Canyon Group, possibly in the lower Moenave Formation (Stops 1.2, 1.3, 1.4) and more certainly in the Wingate Formation (Stops 3.3, 3.5) (21,22,23). The Chinle and lower Wingate formations have provided the richest Pangean tropical plant and vertebrate assemblages of Norian and Rhaetian. In addition, the Chinle has been recently been placed in a high-resolution geochronologic framework with many levels being dated in recent years by zircon U-Pb geochronology (20,24,25) and correlated globally with magnetic polarity stratigraphy (26).

Early Jurassic age strata include the vast majority of the Glen Canyon Group including all or nearly all of the Moenave Formation (Stops 1.2-1.5), and all of the Kayenta Formation (Stops 1.2-1.4), and probably all of the Navajo Formation (Stops 1.2-1.4,3.6). While, the age of these formations was debated for decades based purely on biostratigraphy (e.g., refs. 27,28), independent U-Pb geochronology confirms the Early Jurassic age (e.g., 29) and shown in fact that the Kayenta Formation is as young as Toarcian (30). Strata of the Navajo Formation giant sand sea could extend into the Middle Jurassic (Aalenian), although age-relevant data are completely lacking.

Middle Jurassic age strata comprise the bulk of the San Rafael Group. Formations we will see include the Temple Cap, Carmel, Entrada, and Summerville formations (Stops 2.1-2.3, 3.1, 3.2, 3.4). These strata include marine intercalations and invertebrates as well as large-scale dinosaur track sites, some of which we will visit. While age-relevant fossils are as yet unknown from the eolianite-dominated continental strata of the Temple Cap, Entrada, and Summerville formations, recent U-Pb and $^{40}Ar/^{39}Ar$ geochronology have refined the age of the eolian Temple Cap Formation to be Aalenian to Bajocian in Age (31, 32, 33). The marine and marginal marine (evaporitic) Carmel Formation has long been regarded as Bajocian through Callovian age based on marine invertebrates, including ammonites (e.g., ref. 34), and this is supported by $^{40}Ar/^{39}Ar$ geochronology on sanadine from ashes (e.g., 169.5±0.5 Ma, 170.2±0.5 Ma in its lower part; ref. 32). The eolian Entrada Formation, overlying the Carmel, is on $^{40}Ar/^{39}Ar$ dates on air fall ash beds in the Entrada Sandstone, with biotite ages ranging from 168.1 ± 0.2 Ma to 160.8 ± 0.2 Ma (35) consistent with a Middle Jurassic age. Like the Navajo Sandstone, it makes prominent cliffs in the Colorado Plateau at many locations. Summerville Formation and its equivalent, the Moab Tongue of the Curtis Formation, comprise the uppermost units in the San Rafael Group. It is marginal marine and is Late Jurassic, Early to Late Oxfordian (based on correlation to other, more open marine parts of the Curtis) (36).

The Late Jurassic continental Morrison Formation overlies the San Rafael Group, and is globally renowned for iconic dinosaur remains, including *Brontosaurus*, *Allosaurus*, and *Stegosaurus*. Recent U-Pb dates from the Morrison (Brushy Basin and Salt Wash members) in southern Utah and adjacent Colorado range in age from 149.0+2.5/-2.2 Ma to 152.18 ±0.29 Ma and 156.7 ± 1.0 Ma to 157.2 ± 1.9 Ma from the underlying Tidwell Member (37,38,39,40,41), suggesting an Oxfordian to Tithonian age for the Morrison.

The youngest formation we will examine is the continental, dinosaur-bearing Cedar Mountain Formation. It is Early Cretaceous in age with the dates ranging from 121.8 ± 2.2 Ma (42) to 139.7±2.2 Ma (40) (reviewed by ref. 43), making it plausibly Valanginian to Aptian in age. Thus far, the youngest Tithonian is missing From the Morrison and the Berriasian is missing from the Cedar Mountain Formation, and therefore the Jurassic-Cretaceous boundary is apparently in the Morrison-Cedar Mountain hiatus.

Big issues

The two most important aspects of the Triassic-Jurassic sequence in the Colorado Plateau and environs, is that several units have diverse tetrapod assemblages, several being among the best known in the world, and there is an abundance of apparently datable ashes and reworked ashes, which when combined with magnetic polarity stratigraphy have the potential to greatly refine the early Mesozoic timescale, in interval for which the marine magnetic anomaly record is deficient.

Intimately related to these properties of Colorado Plateau strata are several key issues that we will discuss during the fieldtrip. These are: 1, how are major events and transitions known from largely the marine realm reflected in the continental biota, including the end Permian mass extinction (EPE), the mid-Norian event possible related to the Manicouagan bolide impact, the end-Triassic mass extinction (ETE), the Toarcian Ocean Anoxic Event (T-OAE), and the Jurassic-Cretaceous boundary event; 2, to what extent are these continental sequences “complete”, that is lacking in internal significant regional gaps or unconformities; 3, to what extent are these continental sequence controlled by the underlying Paleozoic salt movement compared to basement involved tectonics and how does that relate to still poorly understood tectonic context – i.e., back arc vs passive margin; 3, what component of the obvious changes in climate relevant sedimentary facies are related to global climate change driven by CO_2 changes or other mechanisms vs. plate position.

Field Stops

Our stops are arranged geographically in a loop (Fig.I.1): beginning in Flagstaff, AZ, going to St. George, UT on Day 1; then onto Moab, UT on Day 2; and then returning to Flagstaff, on Day 3.

Day 1: Flagstaff to St. George

We begin our field trip in the lava flows and tephras of the San Francisco Peaks area resting on red beds Early to Middle Triassic Moenkopi Formation. As we head north on US-89 we will also drop down in elevation and stratigraphy through the Moenkopi and into the underlying marine Permian Kaibab Limestone in the vicinity of Gray Mountain. From there we will climb section again through the Moenkopi and into the Late Triassic Chinle Formation at Cameron, AZ. Around Cameron you can see the bluffs of Ward Terrace, Red Rock Cliffs, and Adeii Eechii Cliffs comprised of Triassic Chinle, and the Glen Canyon Group comprised of Early Jurassic age Moenave and Wingate formations overlain by Kayenta Formation and Navajo Sandstone on the right (east) and Paleozoic rocks to the left (west) towards the North Rim of the Grand Canyon. A sample of tetrapod-bearing sandstone from the middle third of the silty facies of the Kayenta Formation at Gold Spring Wash yielded a zircon LA-ICP-MS date of 183.7±2.7 Ma (late Pleinsbachian-Toarcian: ref. 30).

At the intersection of US 160 that we will pass again towards the close of Day 3, we can see that the Glen Canyon Group starts to form a distinct ridge comprising the Echo Cliffs monocline. We will follow US-89 north along the base of the Echo cliffs all the way to Marble Canyon close to the Moenkopi-Chinle contact. At Bitter Springs we keep left onto US 89A, and cross the Colorado River at Marble Canyon cut into the late Paleozoic limestone. Stop 1.1 is on the west side of the river.

Stop 1.1 Navajo Bridge, Marble Canyon (36.818136°, -111.634109°)

Main points

1) Basic Stratigraphy of Triassic and Early Jurassic
2) Search images for major units.

Park and walk out onto the pedestrian bridge over the Colorado River.
Looking North towards Lee's Ferry, we see the canyon cut into the Permian largely eolian Coconino Sandstone (tiny cliff at bottom), marine interbedded carbonate and marine siliciclastic Toroweap Formation (slope in middle), and limestone of the Kaibab Formation (big cliff). On the sides and forward in the distance are the largely clastic rocks of Triassic and Jurassic age.

The oldest Triassic units is the Moenkopi Formation, which in this region is divided into several members that are, in ascending order, the basal gray carbonate-bearing marginal marine Timpoweap Member, the red clastic "lower red member", the yellow-brown clastic and carbonate Virgin Limestone Member, the red clastic "middle red member", the evaporate-bearing gray-green Shnabkaib Member, and the "upper red member". They lie with an unconformity above the Paleozoic rocks. A striking difference between what we saw at 70 km around Cameron, AZ is how much grayer and thicker the Moenkopi from this area to the west. The Timpoweap is supposed to correlate to the Sinbad Member of the Moenkopi to the west and northwest (44), and the latter produces the Smithian ammonite *Meekoceras*, probably the best biostratigraphic tie for the Moenkopi. Paleomagnetic evidence (45) suggests that the lower three quarters of the Moenkopi, including all of the Timpoweap, "lower red" and Virgin Limestone members are lost by onlap onto Paleozoic rocks to the southeast towards Cameron. The Shnabkaib pinches out in the same direction with the fusion of the "middle red" and "upper red" members as seen at Lee's Ferry with the latter composite being equivalent to the Wapatki, Moqui, and Holbrook members as seen around Cameron where no marine fossils are present. In turn, going towards the northwest, the sequence progressively thickens, becoming more dominated by marine strata and passes into the Thaynes and Ankareh formations in Nevada and Idaho (46).

Moenkopi strata in the Moab area, evidently buck these trends, probably because of salt tectonics (see Day 3).

The Late Triassic age, multicolored Chinle Formation overlies the Moenkopi Formation with what is generally regarded as an unconformity, spanning most of the Middle and early (Carnian) Late Triassic. The base of the Chinle comprises a coarse clastic unit with variegated mudstone interbeds termed the Shinarump Member of the Chinle Formation. A broad channel, trending northwesterly, perhaps 20 m deep seems to be present in this area (47) and provides one example of the paleovalleys that have figured prominently in discussions of the Chinle, and is usually considered evidence of a major unconformity, which is supported in this area by paleomagnetic data (45) that suggests loss of the upper part of the formation in this area. Overlying the Shinarump is a finer, multicolored sequence. Correlation of this part of the Chinle to the classic sections at Petrified Forest National Park is presently obscure, but lithologically it resembles the Blue Mesa Member of the formation which is also highly variegated, but not the Petrified Forest Member, which is nearly completely red to which it is often equated. However, the upper part of the Chinle at Lee's Ferry consists of interbedded red and purple mudstone mudstones with multi-meter interbedded limestones resembling the Owl Rock Member. Going further northwest to Stops 1.3 and 1.4, these Owl Rock-like strata are missing, again suggesting the presence of an unconformity.

Overlying the Chinle are clastic red beds of the Moenave Formation. Elsewhere (see Stops 1.3 and 1.4) biostratigraphic data, U-Pb zircon geochronology, and paleomagnetic data suggest that the Moenave Formation is very latest Rhaetian, but post ETE and Early Jurassic (Hettangian-Sinemurian), although there is no data from the immediate Lee's Ferry Area. The Moenave is generally divided into two members – the red, sandy Dinosaur Canyon Member and the overlying variegated mudstone-dominated Whitmore Point Member. The former was deposited largely in a fluvial environment, with an eolian component, while the latter is characterized by thin-bedded lacustrine deposits (48). The Whitmore Point Member seems missing at Lee's Ferry, but appears not far to the northwest. It is unknown if the absence of the member is due to erosion beneath the overlying Kayenta Formation of lateral facies changes.

The Kayenta Formation overlies the Moenave and consists mostly of red sandstones and mudstones and subordinate purple and olive mudstones. The base of the Formation is the variegated Springdale Sandstone Member, which forms a prominent bench in this area, thinning and disappearing to the southeast. The Springdale is supposed to rest unconformably on the Moenave Formation, but in many places, especially where the underlying Whitmore Point Member is present, the transition seems more gradational (see Stops 1.3 and 1.4). The rest of the Kayenta consist of a lower siltier interval, gradually coarsening upward. The lower "silty facies" has laterally continuous purple mudstones and thin limestone intervals, which are clearly lacustrine, but upward, both fluvial sandstones and eolian sandstones become more common upward and the transition into the overlying Navajo Sandstone is usually described as transitional with inter-tonguing of the two formations. While only footprints have been found locally, they as well as all the other fossils and the one published U-Pb date (30), as previously mentioned, are consistent with a late Early Jurassic age (Pliensbachian-Toarcian) age.

The cliff-forming, mostly eolian sandstones of the Navajo Formation are the highest stratigraphic units we can see here. The age of the Navajo is poorly constrained but should be Toarcian to early Middle Jurassic in age.

Younger Mesozoic strata present in the area include the marginal marine Carmel and the eolian Entrada formations of the Middle Jurassic age San Rafael Group (see Stop 1.2 and Days 2 and 3), as well as some Early Cretaceous age strata of the Dakota Formation.

We will drive down section though the switchbacks along spectacular cliffs of Navajo Sandstone, exhibiting classic eolian cross stratification and then through the Kayenta, and Moenave formations.

Stop 1.2 Zion South Campground and Nature Center (37.204539, -112.983423).

Main Points:

1) Basic Stratigraphy
2) Navajo details
3) Temple Cap age and cap on age of Navajo
4) Theory of pigmentation and hydrocarbons in Navajo

Park and assemble to have an overview of the largely Jurassic strata of Zion National Park that we just drove through. A main purpose is again to get a search image for formations, basic orientation, and stratigraphic, geochronological, and paleoclimate issues.

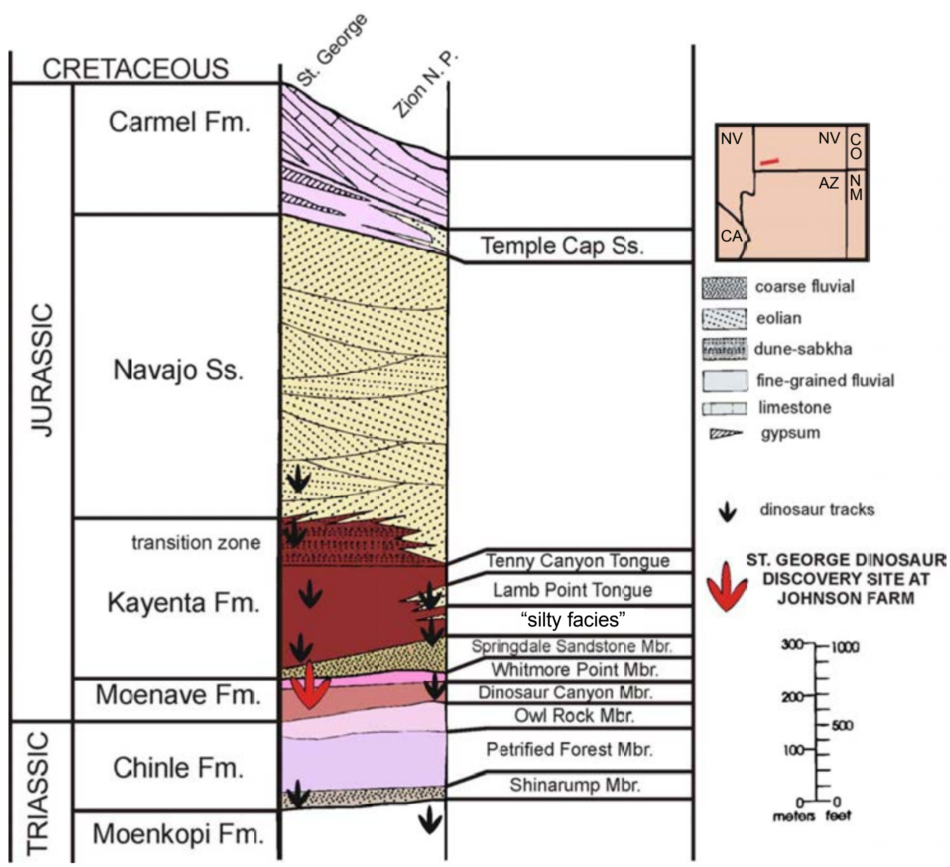

Figure 1.2.1: Basic stratigraphy in the Zion to St George area

Lunch: Springdale Town Park (37.195859, -112.998748)

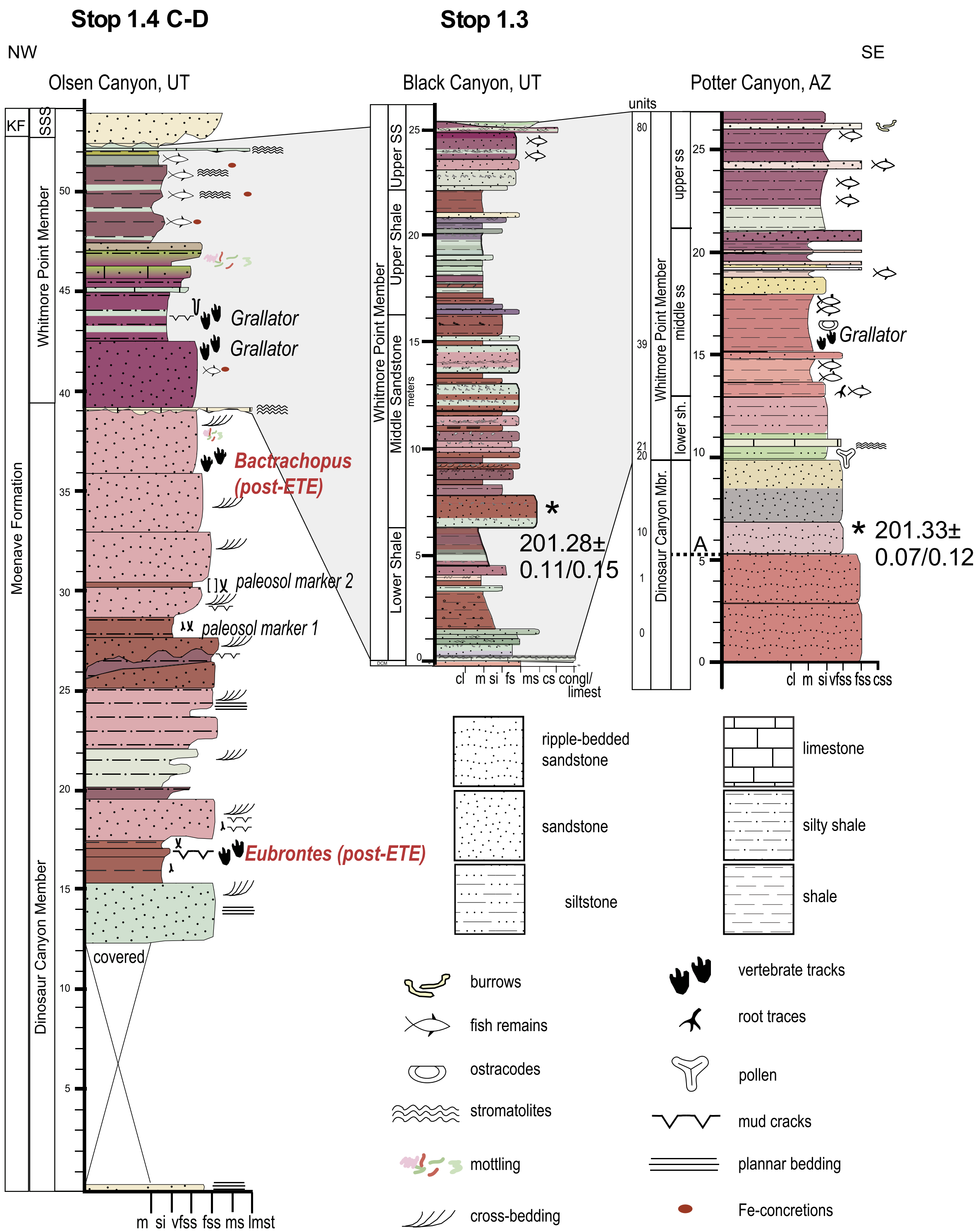

Figure1.3.1: Stratigraphic profiles of Black Canyon (Stop 1.3) and Olsen Canyon (Stop 1.4) slightly modified from Suarez et al. (29) Sections are organized from NW to SE and show the thickness changes of the Whitmore Point Member. Asterisks are zircon U-Pb dates also from Suarez et al. (29)

1.3: Black Canyon (37.199140°, -113.001415°)

Main Points:
1) Details of Moenave-Chinle contact
2) Magnetostratigraphy of Moenave
2) Zircon dates of Moenave and Glen Canyon Group in general.
3) Meaning of C isotope anomalies
4) Environments and environmental history
5) Relation to Wingate

The section is a very steep climb and we will not attempt to go up to it. However, this is a very important site and stands as a good introduction to the issues and prospectus. Important work on this section has been published by Donoho-Hurley et al. (49), Kirkland et al. (50), and most recently by Suarez et al. (22).
On our way to the next site we will drive off the Plateau, at Hurricane, UT and cross the eponymous fault, drop markedly in elevation thorough late Paleozoic strata into Early Mesozoic rocks capped by Quaternary lava flows and then travel along west side the fault and the escarpment to Warner Valley and Stop 1.4.

Stop 1.4: Warner Valley Entry (point at 37.058455, -113.306341°)

Main Points:
1) Stratigraphy of Early Jurassic age strata on the west side of the Colorado Plateau
2) unconformity at Moenave/Chile contact
2) Evidence of lack thereof of pre-ETE strata in Moenave
3) Lacustrine facies in the Moenave and Kayenta
4) Is there a diastem at the Sprindale-Moenave contact?
5) Post ETE track assemblages
6) Climate change or plate position??
7) Unconformity at the Chinle/Moenkopi contact
8) Cyclicity of the Moenkopi and its expansion to west.

This stop is divided into 5 stations A-E. A is a tracksite in the lower Kayenta Formation; B, is the Chinle-Moenave Contact; C, is a track locality in the lower Dinosaur Canyon Member of the Moenave; D, is a transect from the Dinosaur Canyon and Whitemore Point members of the Moenave, up into the Springdale Sandstone and "silty facies" members of the Kayenta Formation, E, is the contact between the Chinle and Moenkopi and Moenkopi cyclical strata.

Station 1.4 A (37.023111°, -113.367139°) Warner Valley Dinosaur Tracksite (parking)

The Warner Valley Dinosaur Tracksite was discovered in 1982 by Gary Delsignore of Cedar City, Utah. It has been described by Miller et al. (51), Birthisel et al. (52,53), and Milner et al. (54). The site covers about 700 m^2 area in an active wash. with consists of four, closely-spaced track-bearing horizons at and immediately above the contact between the

Springdale Sandstone Member and the overlying silty facies of the Kayenta Formation (52, 53).

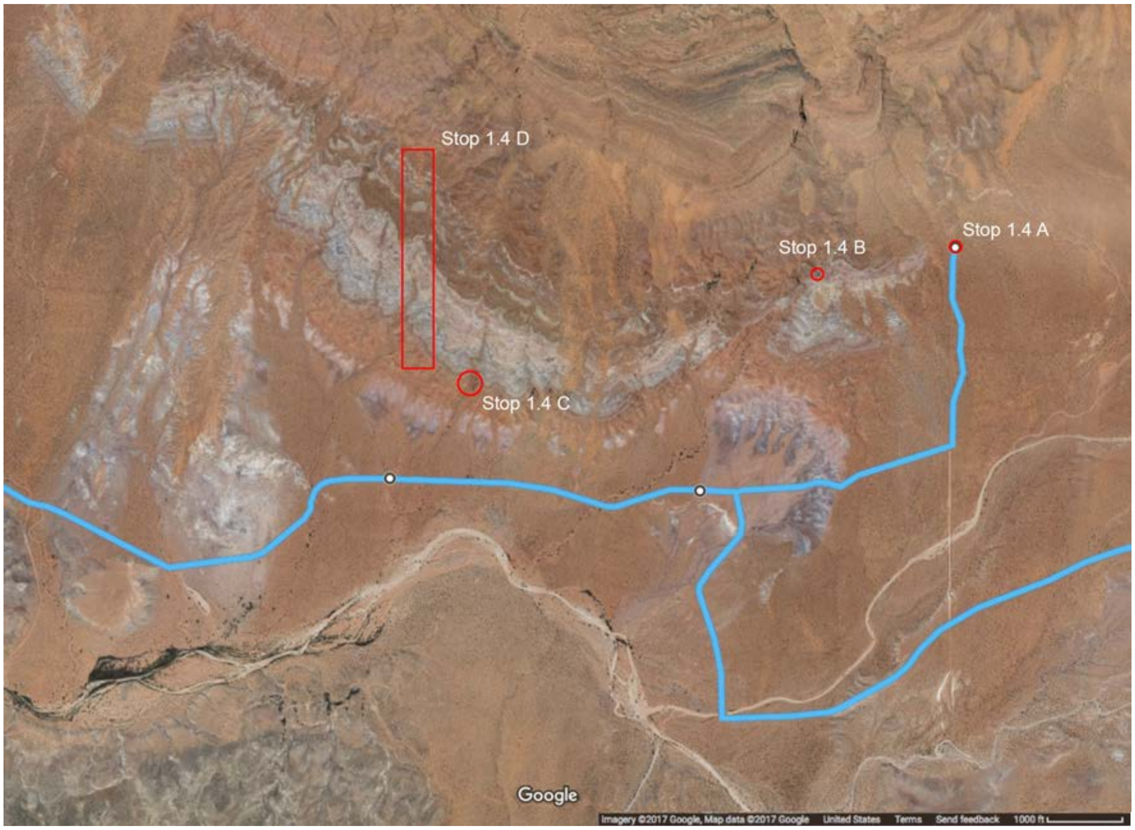

Figure 1.4.1: Stations at Stop 1.4, Warner Valley. White dots are places to park or turn off road. Strata tilt northwards (towards top of page). Lower purple colors are Chinle and upper big purple interval is Whitmore Point of the Moenave and Springdale Ss of the Kayenta. Thin upper purple layers are in the silty facies of the Kayenta.

By far the most abundant tracks at this site are brontozoids (55) [forms classically called *Grallator*, *Anchisauripus*, and *Eubrontes*, but forming an apparent morphological continuum from small to larger (56, 57, 58)]. Based on reconstructed osteology of the tracks, brontozoid footprints were made by small to large theropod dinosaurs as has been concluded by many (see review in ref. 58), although not all authors (e.g., 59). Specifically, the Kayenta theropods "*Megapnosaurus*" *kayentakatae* and *Dilphosaurus wetherelli*, make good contenders for the makers of medium and large tracks. Also present is a single trackway of small broader facultatively 3-toed tracks assigned to *Anomoepus*. Based on osteological reconstruction, the latter were made by small basal ornithischians (excluding heterodontosaurids), the Kayenta thyreophoran ornithischian *Scuttelosaurus lawleri* is a good match.

A striking feature of Early Jurassic, and post-ETE Late Triassic track sites is the abundance of brontozoids, particularly those assignable to *Eubrontes giganteus*, especially in contrast to pre-ETE Late Triassic assemblages. Why so many carnivores compared to herbivores – were the theropods primarily fish-eaters (e.g., 60); is this a reflection of the recovery period after the ETE (57,58); is it a facies bias, or all three?

Note the odd style of preservation on one surface, where the footprints seem to be inverted. Apparently, the mass of a trackmaker compacted the sediment within a track and after lithification, the slightly more resistant compacted areas weathered proud of the surrounding rock (54).

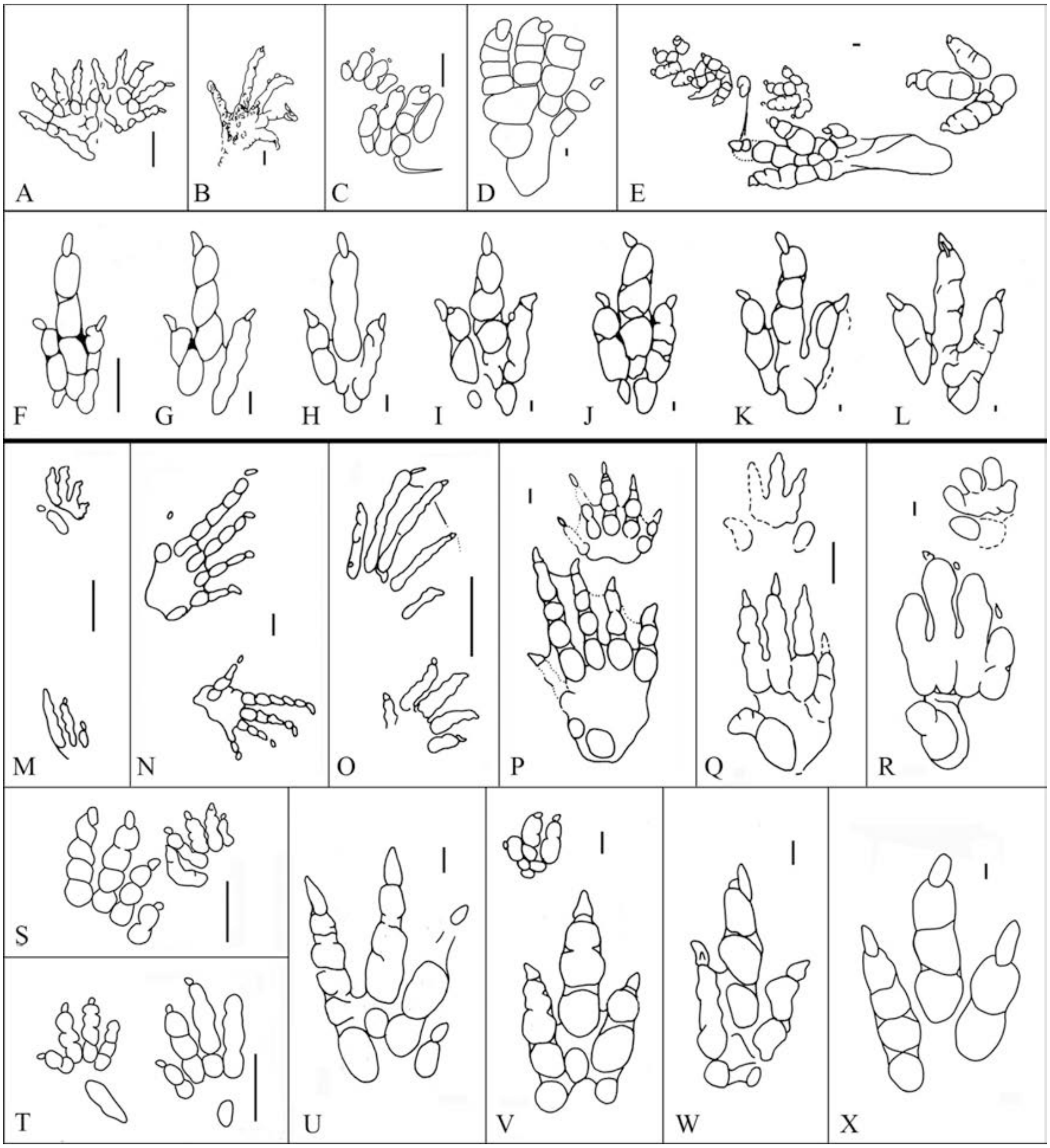

Figure 1.4.2: Post ETE taxa are A-L and pre-ETE forms are M-X. Taxa are A, *Ameghinichnus* n,sp.; B, *Rhynchosauroides* n.sp.; C, *Batrachopus deweyii*; D, *Otozoum moodii*; E, *Anomoepus scambus*; F-G, different sizes of brontozoid with *Grallator* spp.. on the left, *Anchisauripus* in the middle and *Eubrontes giganteus* on the right; M, *Rhynchosauroides brunswickii*; N, *Rhynchosauroides hyperbates*; O, *Gwyneddichnium* sp.; P, *Apatopus lineatus*; Q, *Chirotherium lulli*; R, *Brachichirotherium parvum*; S, "new taxon B"; T, "*Batrachopus*" *gracilis*; U, *Evozoum* n.sp.; V, *Atreipus milforensis*; W, small brontozoid, *Grallator* sp.; X medium sized brontozoid *Anchisauripus* c.f. *tuberatus*.

Station 1.4 B (37.022612°, -113.372823°) Chinle-Moenave contact

This is an unusually well-exposed contact between the Chinle and overlying Moenave formations and hence of the J-0/Tr-5 unconformity of ref.61. A chert-anhydrite pebble conglomerate is at the base of the Moenave Formation, as across all of southwestern Utah (54). In most areas, it is only observed by trenching the section as it is generally uncemented (Kirkland and Milner, 2006). At this stop, the conglomerate is well-cemented and thus readily examined (Fig. 64).

The Chinle here has nodules and secondary veins of gypsum within it. Are these nodules primary? Are they compatible with the overall facies context? Could they be derived from the paleo-weathering of pyrite prior to the deposition of the Moenave?
What part of the Chinle is this? Its color scheme and pedogenic fabrics (exclusive of the gypsum) is similar to the Blue Mesa Member as seen in Petrified Forest National Park, but some authors have called this Owl Rock Member (e.g., 62, which is much higher in the section at Petrified Forest. It does matter, given the implications for the magnitude of the unconformity.

Station 1.4 C (37.018068°, -113.389254°) Dinosaur Canyon Member of the Moenave and End Triassic Extinction (Olsen Canyon)

This site is a highly track-rich outcrop of the fluvial Dinosaur Canyon Formation comprises the lower Moenave Formation. Only track have been found here so far. Thus far, the ichnotaxa found here include the large (>30 cm) brontozoid *Eubrontes giganteus*, *Anomoepus* sp., and abundant *Batrachopus*, the latter attributed to protosuchian crocodilomorphs, based on reconstructed track osteology (63) and skeletal material of protosuchians, are known from this member of the Moenave and in fact include the type of *Protosuchus richarsoni* from the Moenave of Arizona at Dinosaur Canyon (64). This is the stratigraphically lowest track assemblage from the Moenave. The assemblage is indistinguishable from post-ETE assemblages from Eastern North America and the presence of *Anomoepus* suggests it post-dates the ETE by minimally 40 ky. There are no ichnotaxa from this site or elsewhere in the Moenave that are limited to pre-ETE strata.

The concepts of the ETE and Triassic-Jurassic boundary have become horribly conflated in the literature. The presumed mass extinction level, ETE, is not the same as the Triassic boundary, by definition since the establishment of the GSSP for the base Hettangian. The latter is an aggregate phenomenon based on the disappearance of a relatively large suite of taxa, that for continental environments is best seen in eastern North America where it is associated with U-Pb dates, paleomagnetic polarity stratigraphy, astrochronology, pollen and spores, footprints and some bones. However, the GSSP for the base Hettangian is defined by the first-appearance of an endemic(?) ammonite, *Psiloceras spelae* tirolicum in a marine section in the Austrian Alps lacking geochronology of any sort, with the level of the ETE being substantially lower in the section. The one continental proxy taxon for the Triassic-Jurassic boundary from the GSSP is *Cerebropollenites thiegartii* (65), which has yet to be found in the Moenave (65, 66,67). Conchostracans, or more properly spinocaudatans, have been used to infer that latest Rhaetian age strata are present in the Whitmore Point Member (68), but the putatively Rhaetian taxon identified from the Moenave is *Euestheria broderiana*

that extends ABOVE the ETE in the UK and Eastern North America (). Identification of the Triassic-Jurassic boundary is of much less interest than trying to figure out what actually happened at the ETE and identification the Triassic-Jurassic boundary, if even possible (!) in these continental strata will help us understand the recover, but not the extinction.
Pollen taxa, of supposed pre-ETE affinities, *Patinasporites* and *Vallasporites* (which may have been produced by the same plant) have been reported from the Whitmore Point Member (67), but the figured material is indeterminate. Thus, the complete absence of track taxa, otherwise limited to pre-ETE strata, such as *Brachychirotherium*, *Apatopus*, *Atreipus*, *Evozoum*, and *Gwyneddichnium* anywhere in the Moenave Formation, including Olsen Canyon, so common in the Rhaetian Church Rock-Rock Point Members of the Chinle Formation and lower Wingate Sandstone (summarized in 50,54). Body-fossils of taxa limited to pre-ETE strata, such as phytosaurs are also absent ftom the Moenave. Thus, if the ETE is represented by sedimentary strata in the Moenave, it would be in the lowest few meters of the member. This is not impossible, in as much as Donohoo-Hurley et al. (49) has found a possible candidate for the minute polarity zone E23r in the lower 7 m of the member (although not at this section). The arguments are summarized in Fig, 1.4.2.

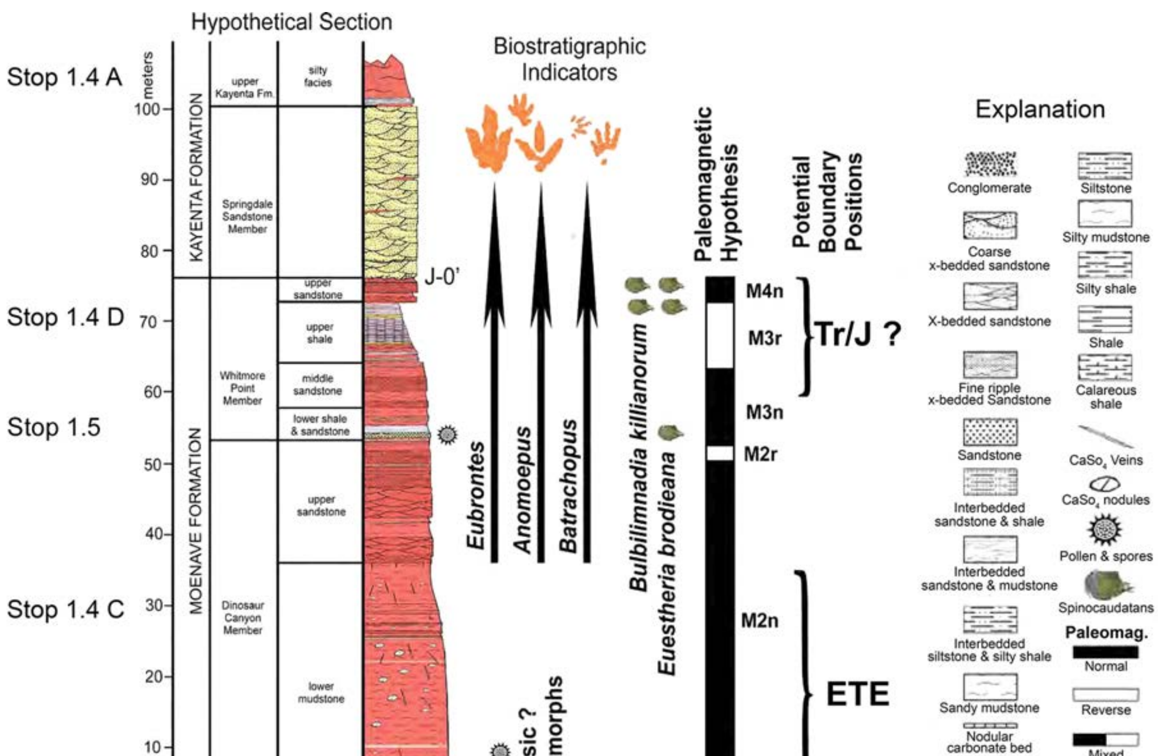

Figure 1.4.3: Synthetic section for the Moenave and basal Kayenta formations i Washing County showing the positions of the field stops. Slightly modified from ref. 50.

Station 1.4 E (~37.018117°, -113.392687° to 37.025251°, -113.391136°) Dinosaur Canyon and Whitmore Point Members of the Moenave to Springdale Sandstone and Silty Facies of the Kayenta Formation

This is an accessible and fossil-rich section of the Moenave Formation and one of the few places you can access virtually the compete member. We will traverse up section from the Chinle to the siltstone member of the Kayenta Formation. The main questions we want address at this stop are: 1) how can we correlate section to section. 2) what are the environments represented at this section; 3) what kind of climate(s) does it represent; 4) what is the relationship between the Springdale Sandstone and the Moenave Formation – unconformity or gradational; 5) how can we figure out where the ETE and Triassic Jurassic boundary are?

Figure 1.4.4: Location of Stop 1.4 E.

Station 1.4 E 37.056611°, -113.474833°) Overlook of basal Chinle and Upper Moenkopi

Looking north (Fig. 1.5.1) we can see the Shinarump Conglomerate of the Chjinle Formation resting on the Moenkopi, here with the "upper red", Shanbkaib, and "middle red" members exposed. The upper red has produced a few chirotheroid tracks as well a *Rhynchosauroides*. The rest of this section is practically unexamined.

Questions include: 1) what do the mottled finer grained strata of the Shinarump mean; 2) what is the age of the upper red of the Moenkopi? 3) what is the origin of the apparently cyclicity in the Moenkopi here?

Stop 1.5: St. George Dinosaur Discovery Site (SGDS) at Johnson Farm (37.101299°, -113.534799°).

Main Points:

1) Spectacular dinosaur tracks in the lower lacustrine sequence of the Moenave
2) Meaning to continental communities during recovery from ETE – where are the herbivores?
3) Theropod locomotion
4) Lake margin environments and dinosaurs

The St. George Dinosaur Discovery Site at Johnson Farm (SGDS) was discovered on private land by Sheldon B. Johnson in 2000, within the city limits of St. George, Washington County, Utah. The Johnson family donated the tracks that had been found and arranged for the land to be cared for by the City of St. George and set up the foundation that continues to preserve this site as a museum. The site has trackways preserved in situ indoors within the Museum as well as many slabs collected at the site and from elsewhere in the southwest. It is a major focus of continuing research in the region.

The fossil assemblages and geology of the site have been well documented in a series of papers by Milner et al. (e.g. 69, 70) and Kirkland et al. (e.g. 54, 71), two of which are appended to this field guide. Highlights include: 1) abundant and exceptionally good brontozoid tracks ranging in size from small *Grallator* to large *Eubrontes*; 2) various different track implantation and preservation modes; 3) different postures and locomotory modalities – walking, running, and swimming brontozoid tracks; 4) associated fragmentary skeletal material; 5) associated fish, plant material, and stromatolites; 6) unusual high-relief track-bearing surface; 7) super abundance of sedimentary structures 8, tracks and many other fossil from Triassic and Jurassic localities.

Both the style of preservation and the composition of the assemblages is very similar to the just-post-ETE assemblages from the uppermost Passaic Formation of the Newark basin (72). However, a critical difference, is that the ornithischian dinosaur ichnite *Anomoepus* is present at SGDS and is absent, thus far in the upper Passaic. No evidence, ichnological or otherwise, of dinosaurian herbivores are known from the tropics of Pangea until a few tens of thousands of years after the ETE, including in the Chinle Fomration where skeletal remains are otherwise relatively abundant. In addition, the uppermost Passaic sites produce a distinctive species of Rhynchosauroides and that genus is thus far lacking from the SGDS, and the entire Glen Canyon Group for that matter. Based on the relative position of the SGDS section (Fig. 1.5.2) within the Moenave Formation and associated data, it is probably about 50 to 100 ky younger than the ETE.

A particularly important aspect of the SGDS brontozoids is their association with theropod teeth that have similar form to those of spinosaurid dinosaurs. Combined with the morphology of Glen Canyon Group theropod snouts and the swim tracks at SGDS, a plausible case has been made that both small and large SGDS theropods were fisheaters (60), and a similar argument has been put forward for the eastern pot-ETE US theropods (58).

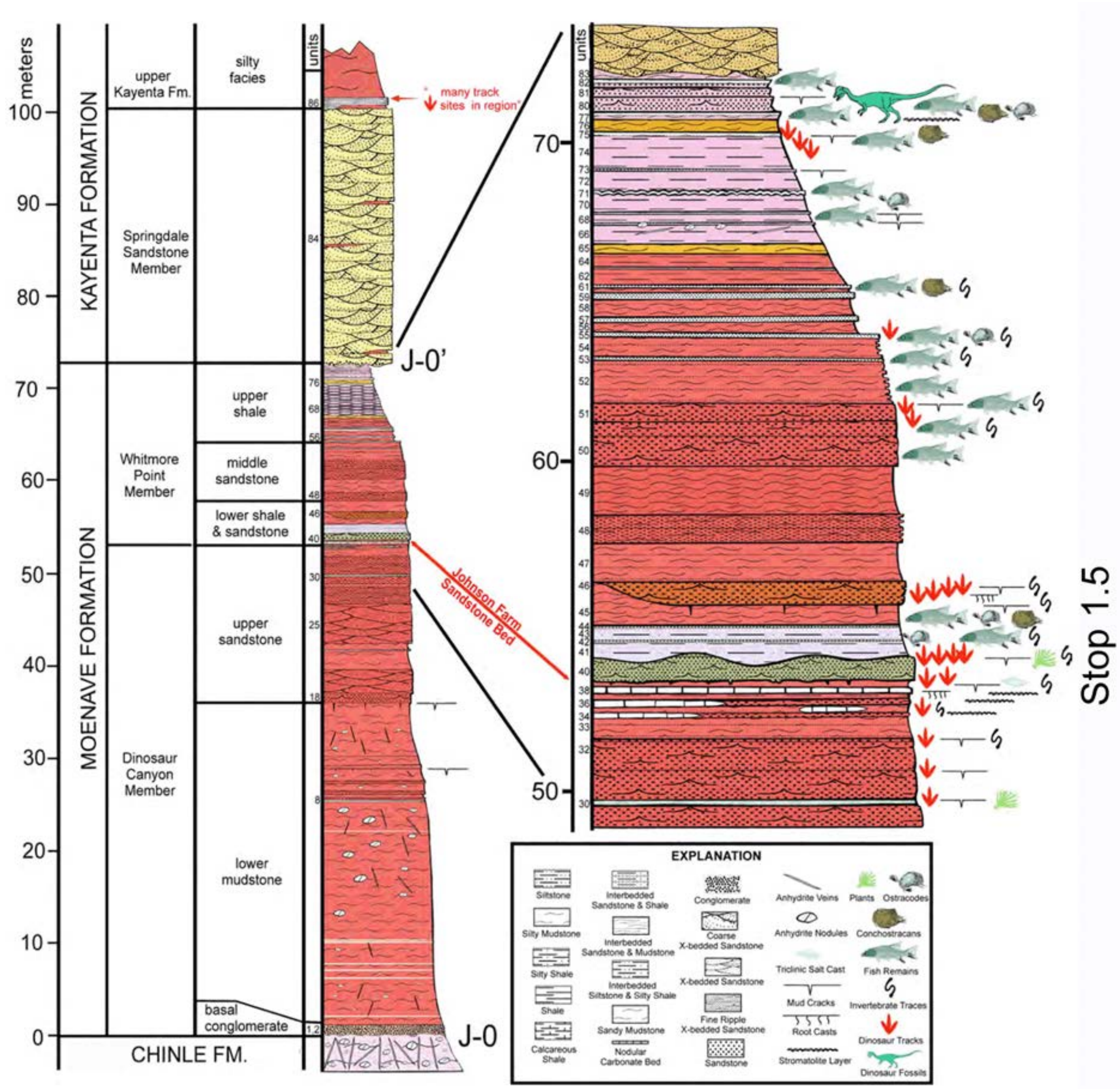

Figure 1.5.2: Stratigraphic section as measured at SGDS (from ref. 54). J-0 and J-0' are positions of supposed regional unconformities.

Leave SGDS and drive to Hotel in Washington, UT, nestled amongst the red cliffs of the Glen Canyon Group.

Day 2: St. George Washington to Moab, Utah

From Washington we head north along I-15 passing just to the west of the escarpment of the Colorado Plateau, first through Early Mesozoic strata, mostly red strata of the Glen Canyon Group and Quaternary lava flows, and long stretches of Quaternary alluvium.

Elevation increases towards Cedar City pass along a complex of Cenozoic igneous rocks while staying largely on high-flat Quarternary alluvium. At Paragonah we turn right at exit 95 and join UT-20 heading largely east climbing again onto the Colorado Plateau and

Miocene silicic volcanic rocks of Showalter Mountain flatter areas of Quarternary alluvium and more Cenozoic igneous rocks and Quarternary alluvium. We turn right onto US-89 on Quarternary alluvium and stop briefly at Panguich, UT for a pit stop. As we continue on to Bryce Canyon, we enter a sedimentary basin with early Cenozoic, Eocene and US-89 south and east and turn left onto UT-12. UT-12 is one of the most geologically spectacular highways in the US. At Black Mountain (peak at 2400 m) we pass briefly through some Quaternary igneous rocks and then into the incredibly bright red-orange, largely lacustrine strata of the Paleogene Claron Formation that make of the walls of the nearby Bryce Canyon to the southeast. Between the town of Bryce and Tropic we pass into Cretaceous sandstones of the marginal marine Mesa Verde Group and drop down into dark Late Cretaceous marine mudstones of the Tropic Shale that is broadly equivalent to the hugely extensive Mancos Group shale, unsurprising an important source rock for hydrocarbons. We are on the Kaiparowits Plateau and drop down off of thorough the Straight Cliffs entering early Mesozoic rocks. Just before the town of Escalante, we turn left onto Reservoir Road for Stop 2.1 and Lunch.

Stop 2.1 and Lunch: Escalante Petrified Forest State Park and Morrison Formation (37.786008°, -111.630904°).

Main Points:

1) Drab colors of clastics compared with older earl Mesozoic strata
2) More humid conditions on average consistent with higher latitude passion into temperate zone
3) Classic formation for abundant dinosaurs
4) Silicified trees attest to more humid conditions

Escalante Petrified Forest of the local Kaiparowits Basin preserved silicified trees, some large, in the Brushy Basin Member of the Morrison Formation of Oxfordian-Tithonian, around 150 Ma. The largely fluvial to lacustrine (73) Brushy Basin Member is in the upper part of the Morrison and tends to have more red strata at its base tending to become drabber upward.

Return to UT-12 eastbound to BLM 201 (Hole in the Rock Road; unpaved) and turn right heading south passing largely through San Rafael Group marine and marginal marine rocks. At BLM 230 we turn right and park Left Hand Collet Canyon in Twentymile Wash and Stop 2.2 at the foot of the Straight Cliffs. We are in Escalante-Grand Staircase National Monument.

Stop 2.2: Twentymile Wash Tracksite, Entrada Formation (37.551315, -111.422558°).

Main Points:

1) Extreme aridity represented by Entrada sand sea
2) Transition into overlying Morrison Formation
3) Middle Jurassic – Callovian?
4) Dinosaur tracks on multiple layers, mostly in non-aeolian – "megatracksite"
5) Oldest evidence of sauropods?
5) Recognizing deep tracks

Park vehicles and walk up to beautifully cross-bedded sandstones of the local "upper sandy member" or Escalante Member (=Moab Member" of the Entrada Formation (74). These white eolian strata pass upward into tabular beds of ripple-laminated sandstone in which most sedimentary features are hard to see perhaps because of bioturbation. Walk up the eolian cross-stratified bluff to the flat top and the tabular white sandstones. The ripple bedding may be oscillatory, consistent with the very tabular beds. This interval has been variously referred to as at the transition between the Entrada and Morrison, Curtis, or Summerville formations, depending on the author.

Foster et al. (75) describe the Twentymile Wash tracksite is as being in in the upper 16 m of the upper sandy member. Foster notes that the main tracksite is on a on a 400 m bench about 400 m long. This has been described as part of the Moab "megatracksite" (76, reviewed in refs. 7778). Supposedly, this is supposed to be the same surface covering a vast area of at least hundreds of square kilometers. Most of the track-bearing sequence is comprised of wave reworked sandstone as and Lockley et al. (78) point out it seems to part of the overlying transgression of the Sundance seaway associated with the Summerville and Curtis Formation. We will see that is regarded as the same surface at Stop 3.4 at the Bull Canyon Track Site. However, this assertion has not been tested, and the surface could easily be a time-transgressive aggregate of surfaces associates with a pulsed transgression. The presence of the tracks is related, not doubt to the specific cohesive, water saturated, facies and need not represent a specific time.

Figure 2.2.1: Tracks at Twentymile Wash, Stop 2.1. Left, one of the more distinct "*Megalosauripus"* – type 3-toed tracks tracks; note concentric infilling. Right, cross-section of track, note paleo-erroded upper surface down-warped laminae on sides of track (most easily seen just above right side of hammer head) and down-warped fill. Hammer is 30 cm long.

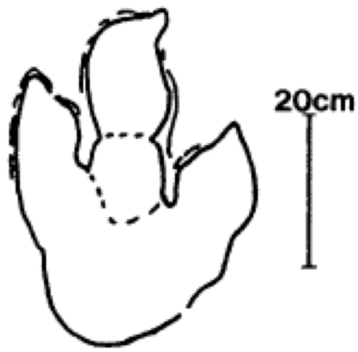

Figure 2.2.2: Drawing of *Megalosauripus* – type track (left pes), probabaly the same one as Fig. 2.1, left. From Foster et al. (75).

Tracks at this site are poorly defined, penetrating in some cases 20 cm or more, and filled with thinbedded sandstone. Most of the tracks seems to be 3-toed but several quadrupeds trackways are present. The larger three-toed tracks are referred to the ichnogenera *Megalosauripus* and *Therangospodus* (78). *Megalosauripus* (see 79) is a large facultatively tridactyl track and *Therangospodus* (80) is another facultatively tridactyl track, both assigned to theropod dinosaurs. In as much as the tracks are so poorly defined and dominated by extramorphological variation caused by the substrate interaction with the feet, the paleorerosion of the track bearing surface, and modern erosion, placing names on such tracks seems unnecessary, perhaps obscuring meaning as opposed to clarifying. In fact, the more distant track appear indistinguishable from similarly preserved *Eubrontes giganteus* track as we saw at SGDS (Stop 1.5) yesterday.

The apparent quadrupedal trackways have a tail trace and a manus that is smaller than the pes. These are supposed to be the oldest evidence for sauropods in North America. Unfortunately the absence of morphological detail makes this hypothesis difficult to explore. Could these be large crocodilomorph tracks for example, which often have trail traces, while sauropods trackways very rarely do? The resemblance to sauropod tracks is superficial although plausible, but the deep tail trace is suspicious. What would the apomophic sauropod features be?

Footprints here, while of questionable phylogenetic affinities, do offer examples of what to look for while searching for tracks in cross section (Fig. 2.1, right). The deformation associated with tracks, especially penetrative tends to be overlooked as non-biological "soft sediment deformation". But the style of deformation is distinctive and the presence of footprints is a very important environmental indicator.

Drive back the way we came to UT-12 and head east.

Stop 2.3: Head of the Rocks Overlook: (37.746908°, -111.454295°).

This is an overview of the stratigraphy into the Escalante River canyon. Most noticeable are the white eolian cross strata

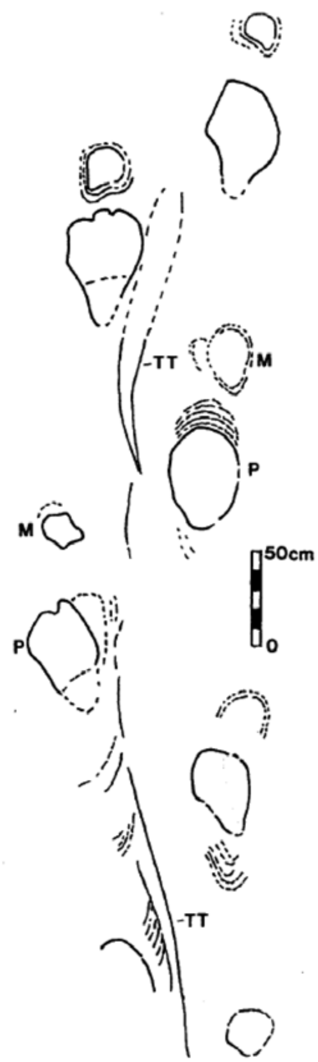

Figure 2.2.3: Possible sauropod trackway at Stop 2.2. From Foster et al. (75)

of the Navajo Sandstone, but at least Kayenta Formation is also visible along our route to the north.

As we head north along UT 12, we will continue to pass through early Mesozoic strata until we get to Boulder Mountain underlain by medial Cenozoic igneous rocks, where we ascend to nearly 3000 m and look at a brief scenic overlook before dropping back down into early Mesozoic and Late Paleozoic strata again. In Capitol Reef National Park we will see extraordinary outcrops of Moekkopi, Chinle (without a basal Shinarump Conglomerate, and overlying Wingate Sandstone, prior to the next stop near the Fruita Schoolhouse.

Stop 2.4: Stop near Fruita Schoolhouse – Chinle-Wingate Contact: (38.288125°, -111.242570°).

Main Point:
1) View of Chinle – Wingate contact: unconformity or gradational contact?
2) Petroglyphs

This is a brief overview of the Clinle Wingate contact. What features should we look for to discern if it represents a major hiatus or if the ETE level might actually be preserved here. We will see a very similar section at our last Stop 3.5 tomorrow.

We will keep driving east and pass up section though the Glen Canyon and the San Rafael groups, Morrison and into Cretaceous marine rocks, again of the Mancos Group. Just before Hanksville we pass back down into the Jurassic Morrison, marginal marine Summerville and Curtis formations deposited in the Sundance Sea . At Hanksville we will have a short rest stop and head north along UT-24 though more San Rafael Group and Morrison Formation to I-40 East towards Green River, UT. We drive up section into the Mancos Group again heading east. At Exit 193 – Yellow Cat, we exit south on BLM 163 to the Yellow Cat Section and Stop 2.5. On the way we will drop down section thought the Late Cretaceous (Cenomanian) Naturita Formation (=Dakota) into the Cedar Mountain Formation.

Stop 2.5: Yellow Cat – Cedar Mountain Formation: (38.854917, -109.544344 to 38.877552, -109445015).

Main Points:
1) Jurassic – Cretaceous "boundary"
2) Early Cretaceous Cedar Mountain Formation.
3) Paleozoic salt withdrawal mini basin influencing Early Cretaceous sedimentation.
4) Early Cretaceous lacustrine deposition.

This is the Yellow Cat to Poison Strip section described by Kirkland et al. (43) that will attach and therefore not describe in detail here. The larger picture, however, that salt tectonics, rather than basement-involved tectonics seems to have been critical in the development of local sub basins and particular members. Specifically, the Yellow Cat Member of the Cedar Mountain Formation, seen here, owes its development to the last effects of salt diapirism in the northern Paradox Basin around Arches National Park (43, 81, 82). Evacuation of salt and migration to higher structural levels creates extremely rapid growth of sub-basins that have a major influence on sedimentation. This is a relatively recently recognized phenomenon, which we will explore in more detail tomorrow

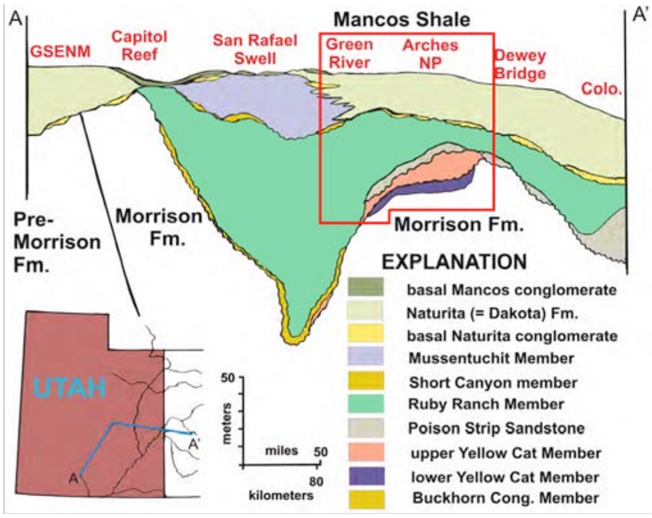

Figure 2.5.1: Simplified cross section of Cedar Mountain Formation across eastern Utah showing the relationship of its various members, select dinosaur sites, and adjacent stratigraphic units. The red box shows the position of Fig. 2.5.2. Most of the section shown, especially its eastern half lies above the Paradox Basin Modified from ref. 43.

The Paradox Basin an asymmetric basin located mostly in southeast Utah and southwest Colorado and to a lesser extent into northeast Arizona and northwest New Mexico. It covers about 85470 km^2 and contain locally over 4600 m of Paleozoic strata. A major feature of the basin is the presence of thick halite deposits and associated potash of the Middle Pennsylvanian Paradox Member of the Hermosa Formation (83), and it has long been understood that the salt migrates and is major feature in controlling the structure over large areas (e.g., Shoemaker et al., 1958; ref. 84). Much more recently, its effects on Mesozoic facies are becoming clear. In the case of the Cedar Mountain Formation the effects seem to be most clear for the Yellow Cat member that we will see at this stop (Fig. 2.5.1).

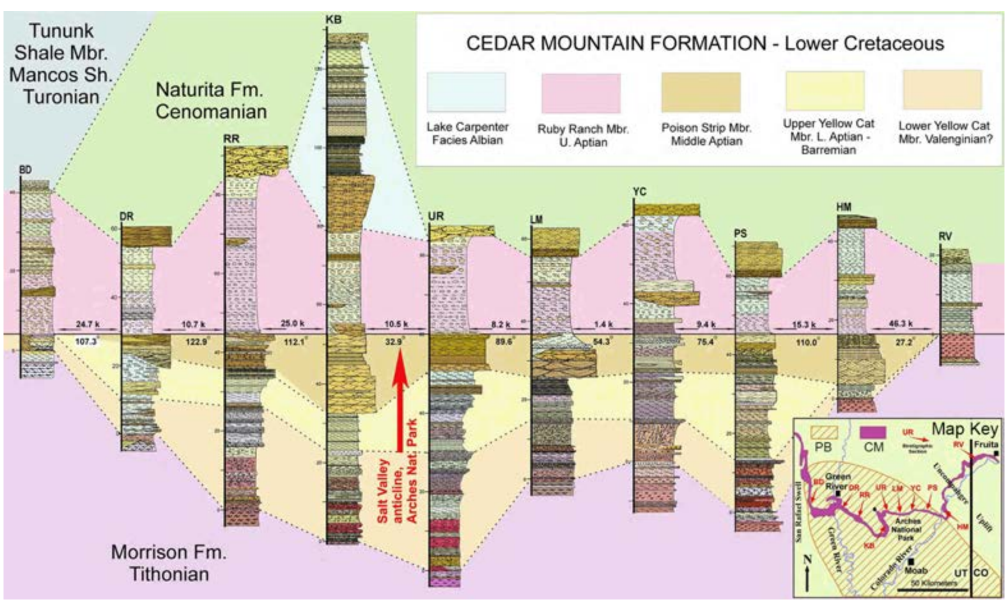

Figure 2.5.2: Cross section of Cedar Mountain formation across the north end of the Paradox Basin, Grand County, Utah (from ref. 43). Sections YC = Yellow Cat, and PS=Poison strip are at Stop 2.5. In Map Key, PB refers to Paradox Basin and CM to map outcrop of Cedar Mountain Formation.

Fossil assemblages, including many dinosaurs from these outcrops, are described in Kirkland et al. 2017 (ref. 43). The relations between accumulation rates and fossil preservation and their relationship to salt tectonics will be discussed.
Nominally, the Jurassic Cretaceous boundary occurs between the Cedar Mountain and the under lying Morrison. That a significant hiatus is present is supported by available geochronology with 121.8±2.2 to Ma 139.7±2.2 Ma for the former as opposed to 149.0+2.5/-2.2 to 157.2±1.9 for the Morrison (reviewed in 43). However, those dates are not found in superposition, and it is possible that salt tectonics might give more complete sections in aerially limited basins, that we are as yet unaware of.

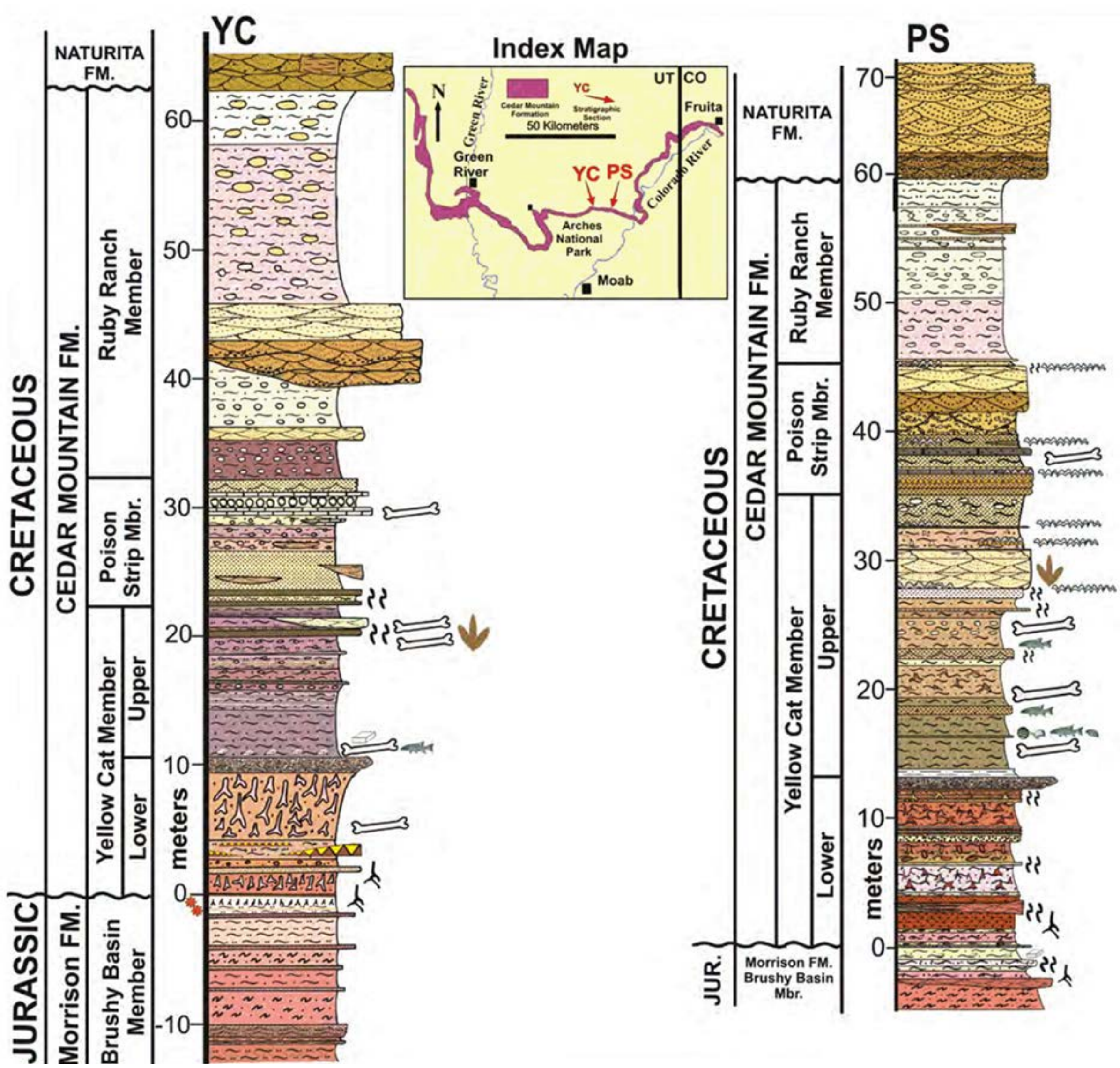

Figure 2.5.3: Comparison of the Yellow Cat Road section (YC) with the Poison Strip (PS) sections (38.854917, -109.544344 and 38.877552, -109445015). (from ref. 43).

Return to I-40 and head westbound, turning left at exit 182 for US-191 South towards Moab. This route takes us right into the Moab Salt Valley, directly on top of one of the Paradox Basin salt tongues. We will pass though the early Mesozoic section, starting in the Cedar Mountain Formation and passing all the way down into Permian age formations.

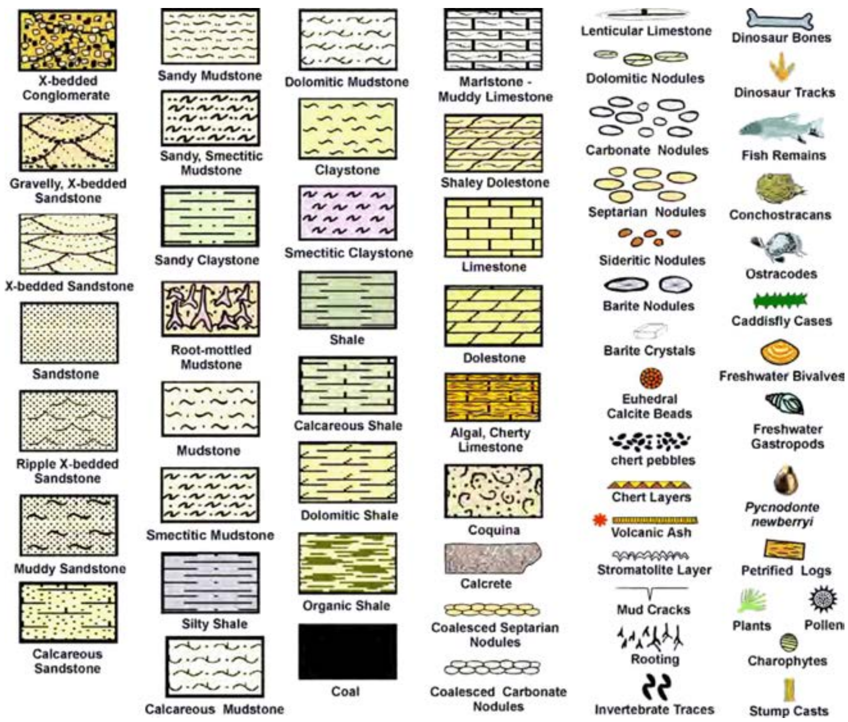

Figure 2.5.4: key for stratigraphic sections presented in Figs. 2.5.2 ands 2.5.3. From ref. 43

Day 3: Moab, Utah to Flagstaff, AZ

We begin by retracing our trip north along US-191 to the right turn exit for Arches National Park. The park lies along the Moab Valley salt wall.

Stop 3.1: Arches National Park: Navajo, Dewey Bridge, and Entrada: (38.616451°, -109.620715° and 38.688061°, -109.537191°).

Main Points:

1) Middle Jurassic arid facies – dunes and sabkas
2) Deformation due to asteroid impact shock wave, or penecontemporaneous salt dissolution?
3) Relationship to underlying Paradox Basin salt?

Arches National Park has truly exceptional outcrops of the quintessential arid facies of the Middle Jurassic. Strata exposed in the areas we will be examining are the top of the Navajo, the Dewey Bridge Member of the Carmel Formation and the Entrada Sandstone. The arches themselves are developed in Entrada largely eolian sandstone, but the main unit of interest is the underlying, very peculiar Dewey Bridge Member of the Carmel Formation.

After parking at the Visitor’s Center (38.616451°, -109.620715°), walk to the south side of the parking area and observe the road leading up to the main part of the park. Note the highly deformed looking interlayered sandstone and mudstone sandwiched between the overlying cliffs of Entrada and underlying much lighter colored Navajo Sandstone. Note that the Navajo does not partake in the deformation and the Entrada hardly does (try to test these observations as we drive along). While these specific outcrops are quite close to the Moab Fault (related to underlying Paradox Basin salt), the deformation of the Dewey Bridge is typical of the member over its entire area covering hundred of square kilometers. While generally attributed to slumping loading of the overlying Entrada another explanation has been offered by Alvarez et al. (1998: ref. 85), that is seismic deformation cause by an impact at nearby Upheaval Dome.

Figure 3.1.1: GoogleEarth image of Upheaval Dome.

Upheaval Dome is a concentric crater-shaped topographic structure in Canyonlands National Park about 34 km south west of the entrance to Arches. It is about 3 km in diameter and about 300 m deep. In terms of structure it is a deeply eroded dome surrounded by relatively undeformed rock. The youngest strata deformed within it are Navajo Sandstone, so it must postdate that and therefore it must be Middle Jurassic or younger. The two radically different but plausible hypothesis for its formation are: 1, it is a salt diapir (86); 2, it is an impact crater (87). From the observations by PEO of unquestioned eroded salt diapirs, it does resemble one in considerable detail. On the other hand, shocked quartz has been reported from the structure as well as purported shatter cones (a rather weak example that could be pedogenic vertisol silickensides), and a majority of people who have worked on the structure seem to favor an impact origin. We won't solve this puzzle here, however, it has been directly implicated as the cause of the deformation of the Dewey Bridge (85).

Figure 3.1.2: Dewey Bridge Member of the Carmel Formation overlain by Slick Rock Member of the Entrada Formation. Note the diaper-like, yellowish feature and the wedging sequence to the right in the Dewey Bridge Member.

We will discuss the pros and cons of the various arguments for this deformation (Fig, 3.2.1). PEO favors the arguments of Kocureek & Dott (1983: ref. 88) that the deformation is a result of the dissolution of Carmel evaporates. The Dewey Bridge deformation in fact closely resembles both context and in detail penecontemporaneous halite dissolution documented in detail in the Late Triassic age Blomidon Formation of the Fundy Basin in Nova Scotia (89, 90). The key hypothesis is that the deformation is a result of the progressive dissolution of salt beds during clastic and mixed deposition. The key observations is the prevalence of growth structures formed as dissolution took place replacing the salt. By the end of the process, no salt is left, but there is a decipherable historical sequence of depositional, that results in the production of folds and pipes and dikes and breccias. The breccias are particularly indicative because they are often sourced from overlying units, seemingly defying supposition. In fact, the pattern of superposition more closely resembles that illustrated by Steno himself (91) to explain the complexities of karst formation and deposition that that applied by modern texts. The growth structures described are a consequence of salt karstification. In terms of the overall context like the Blomidon, the

Dewey Bridge and Slickrock members, are comprised of sand patch cycles. These are produced by deposition of primarily eolian dust and sand on an efflorescent salt crust that undergoes frequent dissolution (92,93) (Fig. 3.1.3). The cycles are produced by varying amounts of salt deposition and dissolution caused by climatic variations and ground water levels. This is a very common but underappreciated facies formed in saline playas with high-saline water tables and sabkha environmnents. The cyclical sequences within the Dewey Bridge and Slick Rock members appear to be examples of mud-rich and sand-rich sand patch cycles. We will discuss the observations in the field.

Proceed to the "The Windows" area (38.688061°, -109.537191°) and park. Here we can walk up to and examine the sand patch cycles as well the deformation features and see if we can identify growth feature. A firm identification of growth features as a major feature of the deformation which falsifies the hypothesis of seismic disruption. Note, however, that a seismic interpretation was also applied to the Blomidon features as well (94), in that case ascribed to the Manicouagan impact, despite the fact that the intervals are demonstrably millions years different in age.

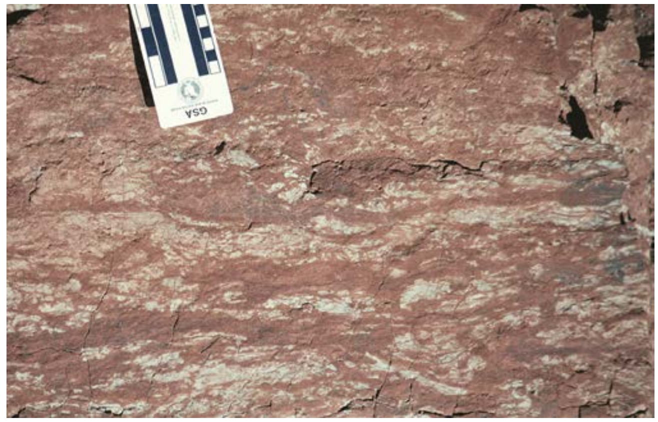

Figure 3.1.3: Sand patch fabric in Blomidon Formation, Fundy Basin

Return to US-191 and turn north to right hand turn for BLM 143 and drive along unpaved road to the east to the Copper Ridge Dinosaur Track site. Note along the way that many mudstones in the Chinle, Morrison, and Cedar Mountain along this rout have a very peculiar intense sea to emerald green color. That this is so intense and in multiple formations in the same area suggests it owes its origin to the underlying salt. What might the mechanism be?

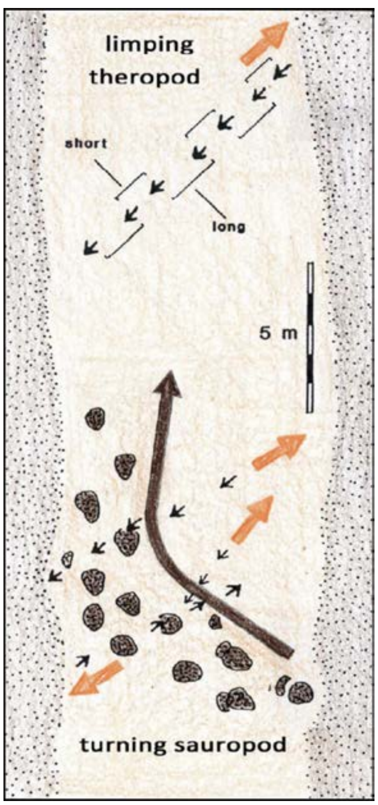

Figure 3.2.1: Above, map of Copper Ridge tracksite , Stop 3.1 from ref. 95 after Lockley & Hunt (96).

Stop 3.2: Copper Ridge Track Site: (38.288125°, -111.242570°).

Main Points:
1) Sauropod and theropod tracks in Salt Wash Member of Morrison
2) Track-bearing facies
3) Green mudstones – what do they mean?

Discovered in the the Copper Ridge Tracksite is in the upper Salt Wash Member of the Morrison Formation. According to Hunt-Foster (95) the tracks occur on on a current-ripple-marked surface of sandstone of a sand bar lateral to a fluvial channel. The ichnogenera *Brontopodus* and *Hispanosauropus* have been attributed to a sauropod and theropod, respectively with the sairopod making a nearly 90-degree right turn and the theropod progressing with a limp (Fig. 3.2.1: ref: 96). The tracks are not especially well defined and puncture a sandstone layer into underlying mudstone. The assignment of the quadrupedal track way to *Brontopodus* is plausible, but what are the characters visible in the trackway, except its large size and lack of clearly defined digits that allow it to be placed in a biologically meaningful ichnogenus and assigned to the Sauropoda? The assignment of the limping theropod trackway to *Hispanosauropus* is more suspect.

There are many new methods employing digital imaging technology that can render the three-dimensional structure of objects more clearly and in three dimensions (Fig. 3.2.2). The tracks are clearly tridactyl, but aprart from that, what characters define this trackway as anything but a probable brontozoid?

There are a number of theropods that could have made tracks such as these know from skeletal material from the Morrison. These include *Allosaurus, Torvosaurus, Epanterias, Saurophagan, Certatosaurus, Torovosaurus, and Marshosaurus*. It is not known if there are characters that would allow the skeletons of the feet to be recognized let alone footprints.

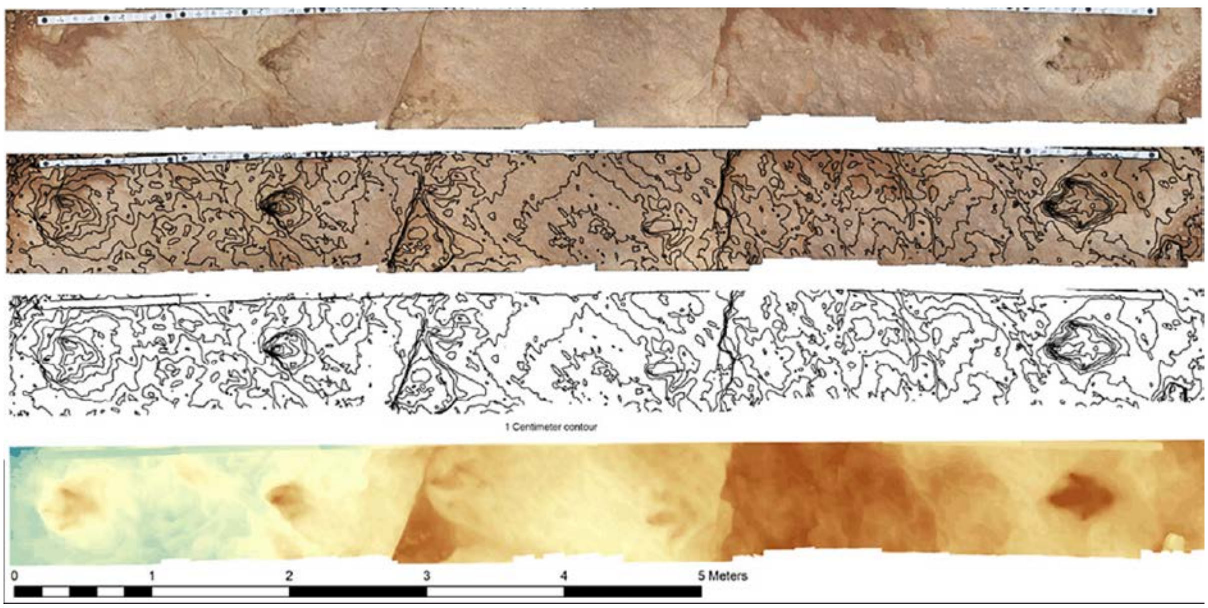

Figure 3.2.2: Examples of photogrammetric model of the Copper Ridge Hispanosauropus trackway (from Matthews in ref. 96).

Proceed back west along BLM 143 and turn left back onto US-191 towards Moab. Turn left onto UT-128 that parallels the south side of the Colorado River. Drive to turnout for Stop 3.3 A.

Stop 3.3 A and B: Syn-Chinle "Unconformity" and Salt Tectonics. (A 38.669895°, -109.498375° and B 38.684850°, -109.461622°).

Main Points:

1) Apparent unconformity in Chinle Formation
2) Growth structure related to salt withdrawal
3) Special environments created by local subsidence

This is the western side of spectacular exposures of an apparent unconformity within Chinle Formation apparent on the north side of river. This is one side of one of the better-documented salt tectonic growth structures. The structure is in the form of a syncline the other side of which is at "B" at 38.684850°, -109.461622°. Spend time looking closely at the strata. Note that at the apparent unconformity surface many beds tend to fan out away from the surface expanding in thickness down dip. This is NOT what would be expected of and erosional unconformity. Instead it is consistent with offlap during synsedimenatry subsidence.

Figure 3.3.1: Syn-Chinle salt withdrawal basin with apparent unconformity that is actually an offlap surface (with some erosion). This is the "Big Bend minibasin" of ref. 98, see Fig. 3.3.2.

The role in salt tectonic forming such Chinle (and Moenkopi) features has been described since the 1990s (e.g., 97). More recently models have been developed that explain the features dynamically (98, 99) and successfully explain observations not described in the papers themselves, such as the distribution of fish localities (see Stop 3.5).

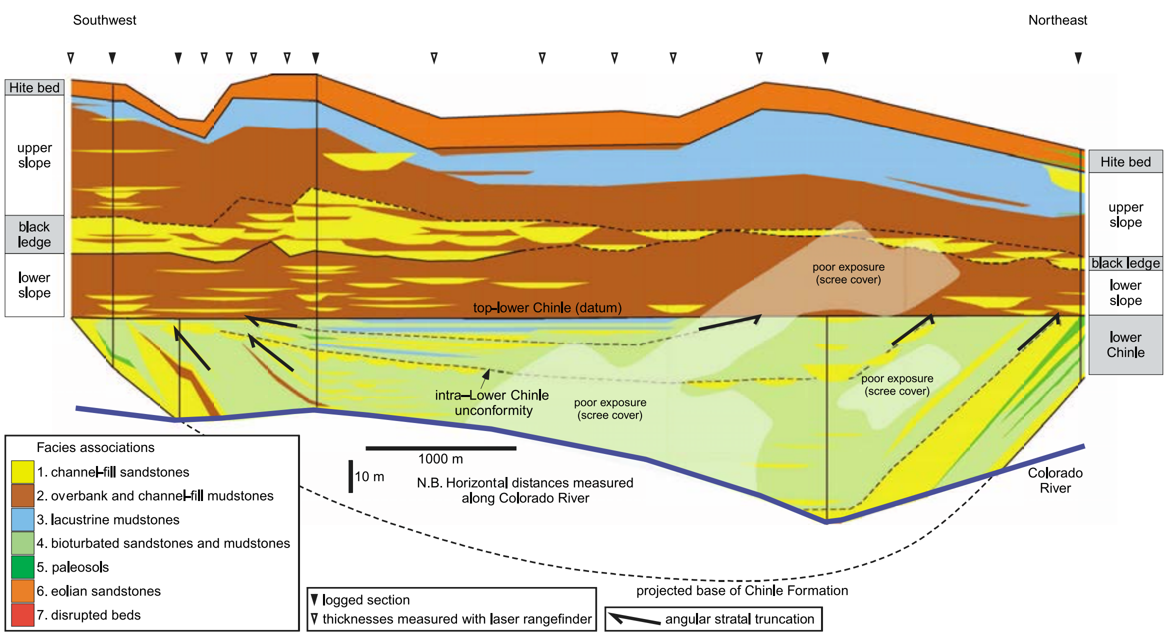

Figure 3.3.2: Facies architecture panel along the northern side of the Colorado River across the Big Bend minibasin (modified from ref. 98). The panel depicts the surface along the southeastern margin of the minibasin.

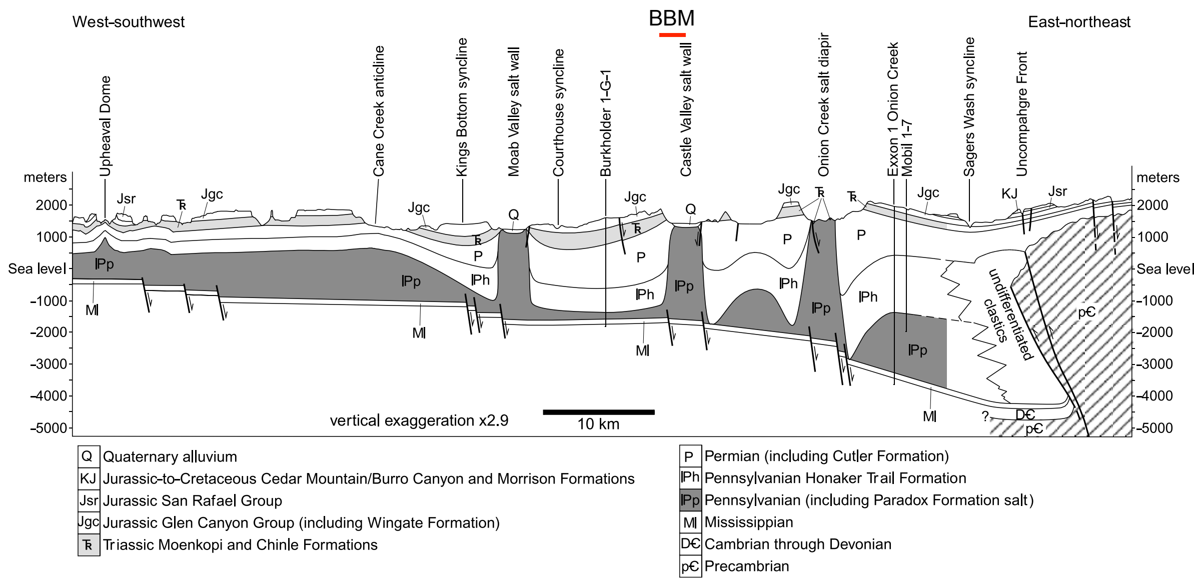

Figure 3.3.3: Regional cross section across the northeastern Paradox Basin showing present-day stratal architecture across major salt structures (from ref. 98). BBM (added by PEO) is the projected position of the Big Bend minibasin.

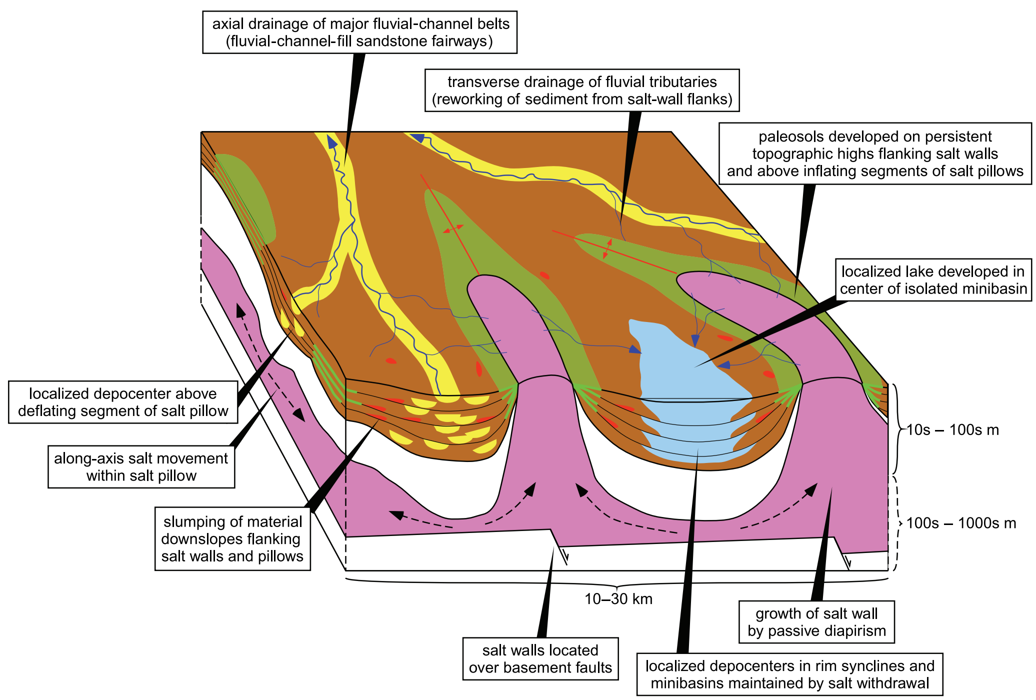

Figure 3.3.4: Conceptual model of facies distributions, stratal geometries, and thickness variations in fluviolacustrine strata based on the Chinle Formation, northeastern Paradox Basin for a high-accommodation system between salt walls (from ref. 98).

Return to vehicles and head east on UT-128 until turning south on the La Salle Loop Road and turn left on the Dolores Triangle Safari Route heading northeast until the Fischer Valley Overlook and Bull Canyon Dinosaur track site, Stop 3.4. We will have passed along the north side of the La Salle Mountains, consisting of Oligocene intrusive rocks that have metamorphosed the adjacent Jurassic strata.

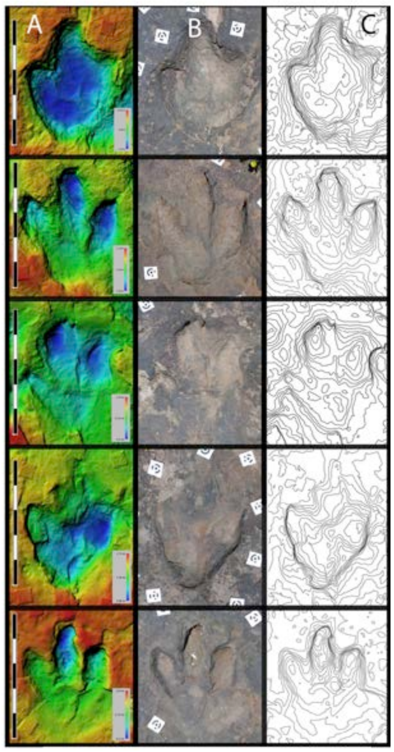

Figure 3.4.1: Photogrammetric documentation of tracks at the Bull Canyon tracksite: (A) Color depth maps, (B) Orthographic images, and (C) Topographic contour maps (5 mm [0.2 in] contours). From ref. 95.

Stop 3.4 Bull Canyon Track Site – Entrada Formation (38.615833°, -109.223333°) and Lunch.

Main Points:
1) Megatracksite in metamorphosed sandstone.

The Bull Canyon Tracksite in metamorphosed sandstone reported to be at the top of the Curtis Formation (95) but yet still part of the same surface as at the upper Entrada Twentymile Canyon site at Stop 2.2. As at the latter site *Megalosauripus* and *Therangospodus* are reported. We will discuss both the meaning of these ichnotaxa and the megatracksite concept.
Follow roads back to UT-128 and take it west toward Moab. Take US-191 south to Big Indian Road (Co. 106) and take that east to Big Indian Rock.

Stop 3.5 Big Indian Rock – the ETE and the Last Phytosaur (38.1554806°, -109.2415553°).

Main Points:
1) Fossiliferous transition from Chinle into Wingate may record ETE
2) Is transition an unconformity?
3) Major fossil fish localities related to salt tectonics.

In the 1960s Bob Schaeffer and crews from the American Museum of Natural History found a series of fossil fish localities in the Lisbon Valley area of eastern Utah (100) triggered by the discovery of fossil fishes in the search for Uranium. After a hiatus of some half century the area has proved to be one of the most important in the south west for understanding the Triassic Jurassic transition. We will examine the section around Big Indian Rock focusing on the nature of the Chinle –Glen Canyon Group transition. In particular we will look at the “last phytosaur” a natural mould of the skull roof of *Machaeroprosopus*. There are also abundant footprints from this area. Those in the lower strata of the Wingate are typically Triassic in aspect, while those in the upper strata are typical of post ETE time (Fig. 3.5.1).

The fish localities, show a particularly interesting pattern (Fig. 3.5.2), The localities line up with the distribution of the salt wall, strongly suggesting a genetic link between them and salt tectonics. What observations can we make in the field to examine this possible relationship?

Figure 3.5.1: *Brachychirotherium* tracks (typical pre-ETE form from the Redd Ridge area of Lisbon Valley. From ref. 95.

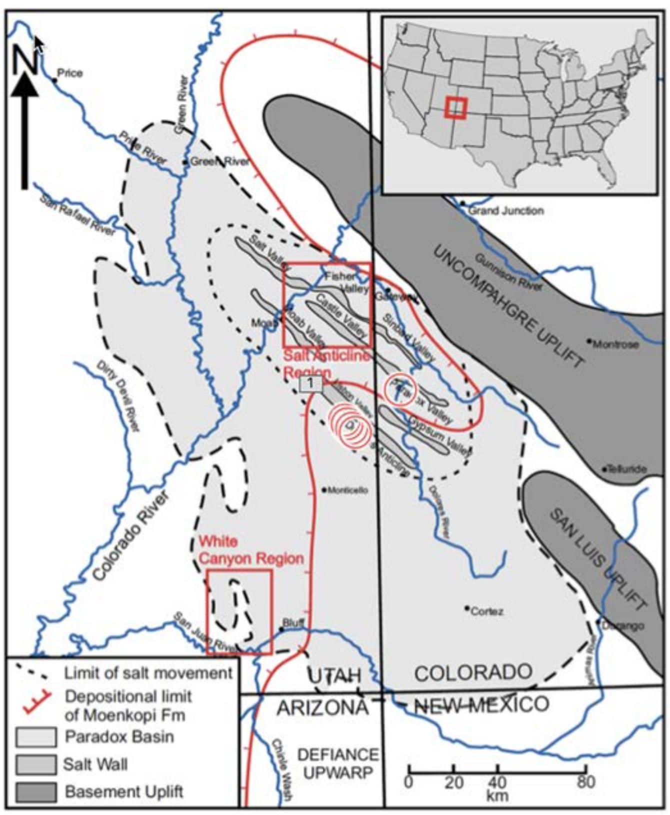

Figure 3.5.2: Distribution of fish localities (from Schaeffer (ref. 100) compared to the salt walls in the Paradox Basin (from ref . 99).

Follow roads back to US-191 and take it south to US-160 at Mexican Hat, turning west and south to Tuba City and then to intersection with US-189, turning right back to Flagstaff. Along the way we will bass through the Navajo Nation and the Triassic Jurassic section.

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