Fieldtrip for the for the ICDP-EarthRates CPCP2/EMCT Workshop St. George Utah

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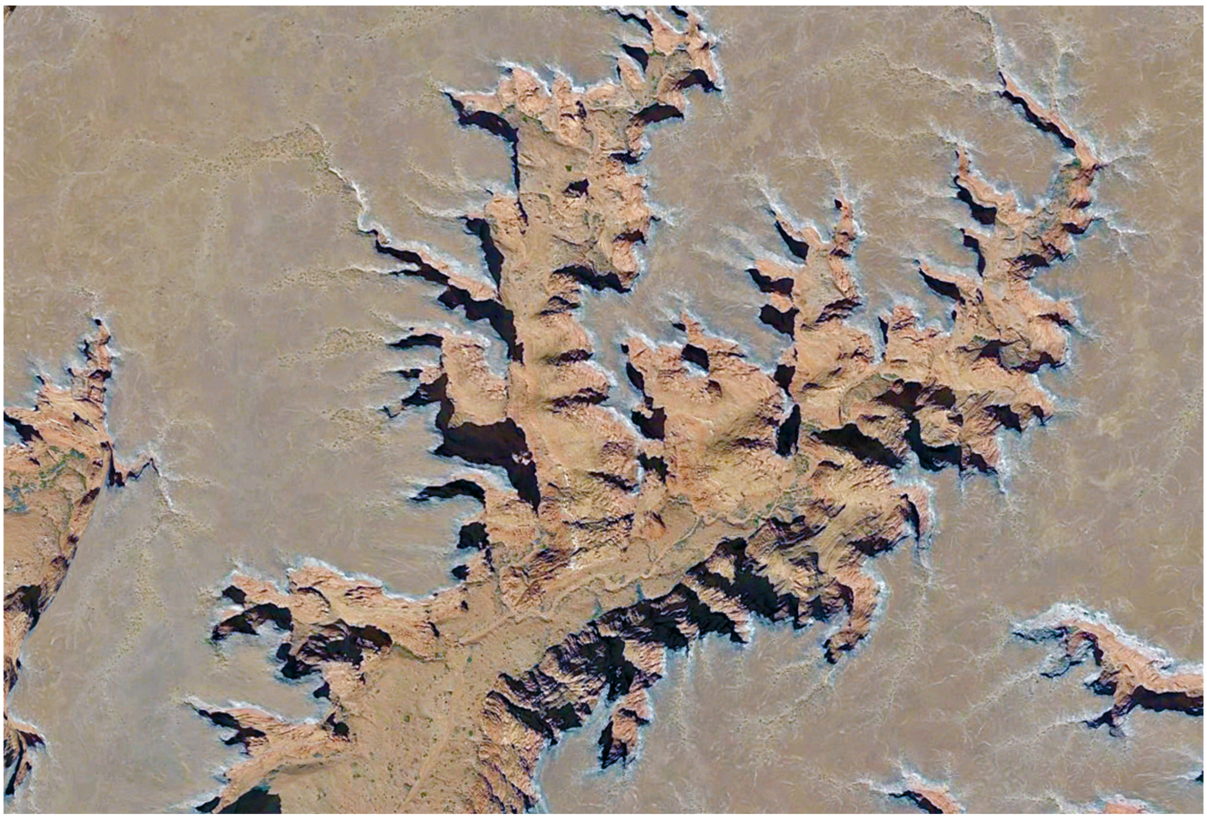

Canyons cutting the Moenave-Kayenta Contact at the Adeii Eechii Cliffs, Gold Spring, AZ area (35.745991°, -111.102613°), Navajo Nation. GoogleEarth image spans about 600 m.

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A. Introduction

One of the most iconic deposits of the Triassic and Jurassic is the enormous blanket of largely continental strata, generally thickening, and passing into marine strata westward that crops out in the Colorado Plateau and environs of western North America. This physiographic province (Fig. A.1) is a prominent upland with large expanses of badlands exposing these Early Mesozoic deposits, providing a superb venue to stimulate discussions following the workshop, as well as a target for study. These strata formed during the incipient fragmentation of Pangea, formation of the Atlantic Ocean, and translation of the North American plate over 40° northward. This time interval witnessed the evolution of the main components of the modern land biota and two major mass extinctions (end-Permian and end-Triassic), along with three major faunal reorganizations (mid-Norian, Toarcian, and Jurassic-Cretaceous events) that filtered out "archaic" elements. Some of the most famous of vertebrate fossils, such as *Coelophysis*, *Dilophosaurus*.

Our field trip takes along a two-day, 906 km (563 mi) loop on and adjacent to the Plateau (Fig. A.1) with the purpose of seeing some of the sites relevant to our workshop 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, as well as implications for Solar System Evolution.

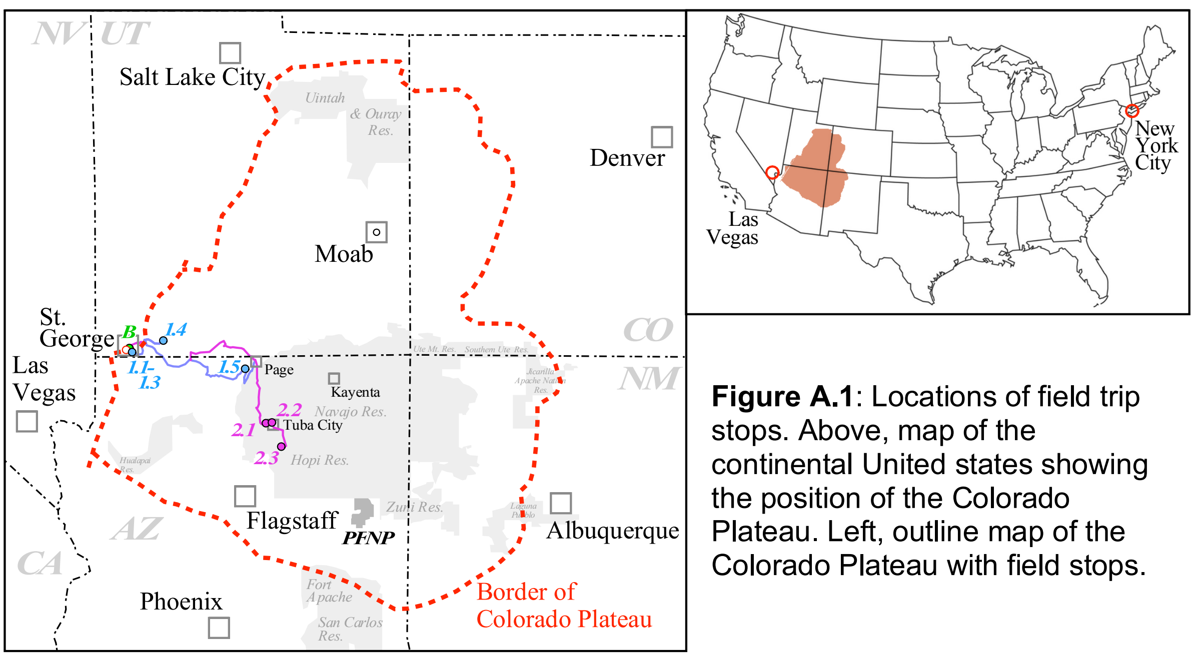

Figure A.1: Locations of field trip stops. Above, map of the continental United states showing the position of the Colorado Plateau. Left, outline map of the Colorado Plateau with field stops.

Goals

The three major goals of this fieldtrip are to:

1. Examine stratigraphy and facies related to goals of CPCP2/EMCT

2. *Observe and discuss the context of stratigraphy, climate, and environments, geochronological features and issues, and biotic and taphonomic patterns*

3. *Consider coring targets and locations in relation to future proposals*

We will channel these goals at each of the stops and we urge the participants to consider the largest context possible at the individual locals.

Geodynamic Context

Compared to simple conceptual models of Early Mesozoic extension and continental rifting of central Pangea, including eastern Laurentia, models of western North America are complex, involving exotic terranes, magmatic arcs, oceanic-plate subduction, and substantial 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 during the Sonoma Orogeny [1-3], 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, 10]) 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. Although we cannot solve these issues directly with observations on this fieldtrip, we should keep in mind the alterative models, 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. For instance, the dynamic relationship of the Early Mesozoic unconformities, facies and salt tectonics is demonstrating to be important in both facies development and the localization of fossiliferous facies for Triassic and Jurassic strata. Halokenesis might, in fact, be more important than either basement-involved tectonics or eustasy in structuring much of the stratigraphy 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 extension that formed the Basin and Range physiographic province, the Colorado Plateau 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 [11]. 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 [12] and Liu & Gurnis [13].

Triassic-Jurassic Basic Stratigraphy and Climatic Context

We will focus on strata of Triassic and Jurassic age (Fig. 1.2), 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 the arid tropics (~16° around 200 Ma; close to the Triassic-Jurassic boundary), continued into the arid sub-tropics (~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 remained roughly there for nearly 100 Myr. It then moved south to the present latitude of ~37°. These latitudinal changes were the primary drivers of apparent climate change in the Colorado Plateau [10]. Apart from the Moenkopi Formation, 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. [14]), with the giant sand sea of the

Navajo Sandstone occurring in the sub tropics near 30° N, and much less arid facies developing during deposition of the Morrison and Cedar Mountain formaations (Fig. 1.3).

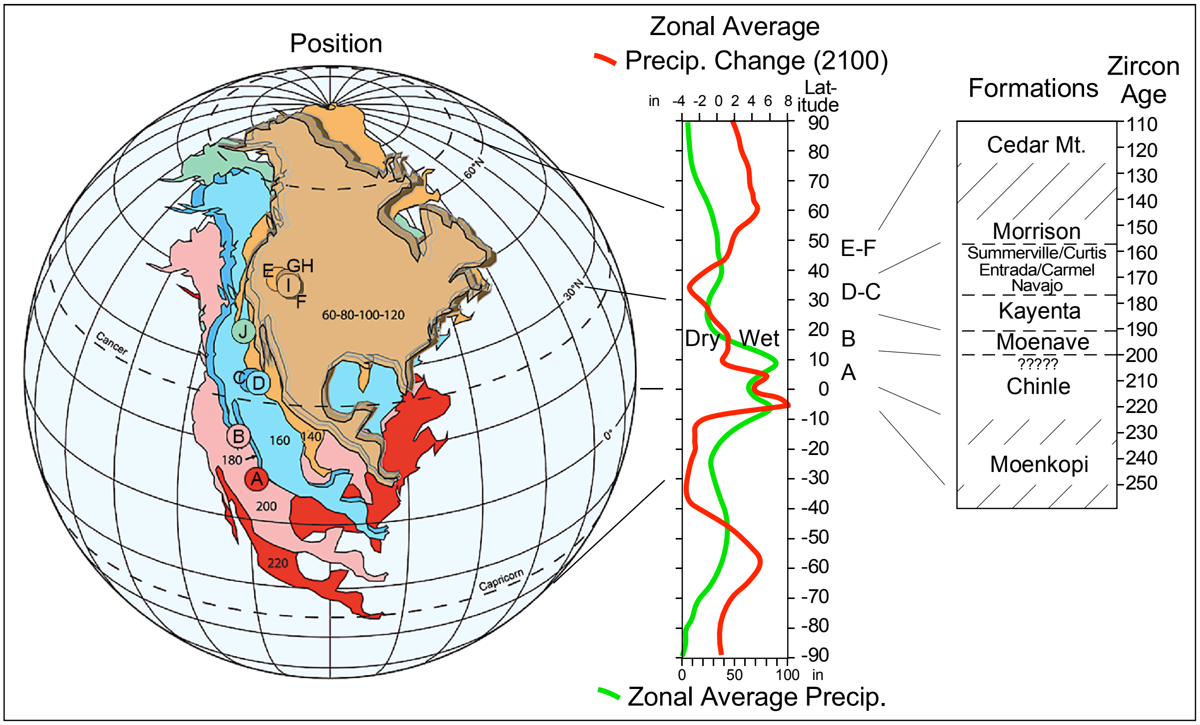

Figure A.2: Position of North America (modified from ref. [15]) and the Colorado Plateau (circles) from 220 Ma to Present with comparison to zonally averaged precipitation for today (1950-2000, from ref. [16]), change in precipitation for 2100 (from ref. [16]), and the zircon ages for formations we will see in the field (see text).

The oldest Triassic deposits we will see is the nominally Early to Middle Triassic age Moenkopi Formation (Stops 1.1, 1.4, 1.5, 3.6), but in reality, as there are few fossils known from very low in the formation; the base could be as old as Late Permian. 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; the much thicker western portions remaining relatively unstudied. The youngest Moenkopi is nominally middle Triassic in age, based on tetrapod biostratigraphy [17, 18], but parts could be as young as early Late Triassic (Carnian) based on sparse geochronology [19]. LA-ICP-MS and CA-ID-TIMS zircon results from the CPCP-1 cores [20] and future projects such as CPCP-2, along with developing magnetic polarity stratigraphy [21, 22] will help to resolve the age.

Most of the rest of the Triassic in the Colorado Plateau is recorded by the largely fluvial Chinle Formation (Stops 1.1, 1.2, 2.1), the oldest dated strata of which is Early Norian in age [23, 24] and the youngest Late, but perhaps not latest Rhaetian in age. The latest Rhaetian and the level of the end Triassic extinction (ETE) may be represented in the basal Glen Canyon Group, in the Wingate Formation [25-27] and possibly in the lower Moenave Formation (Stop 1.2). The Chinle and lower Wingate formations have provided the richest Pangean tropical plant and vertebrate assemblages of Norian and Rhaetian age. In addition, the Chinle has been recently been placed in a high-resolution geochronologic framework with many levels dated by zircon U-Pb geochronology [24, 28, 29] and correlated globally with magnetic polarity stratigraphy [30-34] incorporating the results of CPCP-1 [20, 35-37].

Early Jurassic age strata include the vast majority of the Glen Canyon Group including all or nearly all of the Moenave Formation (Stop 1.2), all of the Kayenta Formation (Stops 1.2-1.4), and probably all of the Navajo Formation (Stops 1.4, 2.3). Although, the age of these formations was debated for decades based on biostratigraphy (e.g., refs. [38-41]), independent U-Pb geochronology confirms the Early Jurassic age (e.g., [26]) and reveals that the Kayenta Formation is as young as late Pliensbachian or early Toarcian [34, 42, 43]. Strata of the sand sea of the Navajo Formation could extend into the Middle Jurassic (Aalenian), although age-relevant data are lacking. These Early Jurassic strata are overlain by the marine to non-marine San Rafael Group of middle Jurassic age, which, along with younger formations, we will see at a distance.

Outstanding issues

The three most important aspects of the Triassic-Jurassic sequence in the Colorado Plateau and environs is that: 1) several units have diverse continental tetrapod assemblages, including among the best known in the world; 2) there is an abundance of datable and reworked ashes that, in concert with magnetic polarity stratigraphy, have the potential to refine the early Mesozoic timescale for an interval with a deficient marine magnetic anomaly record; and 3) there are abundant soil carbonates amenable for use as the pedogenic carbonate $p\mathrm{CO_2}$ proxy.

Intimately related to these properties of Colorado Plateau strata are several key issues related to CPCP-2/EMCT that we will discuss during the fieldtrip. These include: 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 (possibly related to the Manicouagan bolide impact), the end-Triassic mass extinction (ETE), and the Toarcian Ocean Anoxic Event (T-OAE)? 2) To what extent are these continental sequences “complete”, that is, without significant regional gaps or unconformities? 3) Can we extract a meaningful and exportable U-Pb-calibrated paleomagnetic polarity timescale from these strata? 4) What component of the marked changes in sedimentary facies relate to global climate change driven by CO_2 variations or other mechanisms vs. plate position?

CPCP-1

Phase 1 of the Colorado Plateau Coring Project (CPCP-I) recovered > 850 m of stratigraphically overlapping core from three coreholes at two sites in the Moenkopi and Chinle formations in Petrified Forest National Park (PFNP), northeastern Arizona, USA [20]. This project was an outcome of the 1999 US NSF- and ICDP-funded “International Workshop for a Climatic, Biotic, and Tectonic, Pole-to-Pole Coring Transect of Triassic-Jurassic Pangea” (http://www.ldeo.columbia.edu/

~polsen/nbcp/westpangea.html) that recognized “Western Equatorial Pangea (Colorado Plateau)” as a key coring target. Subsequent CPCP workshops held in 2007 and 2009 (funded by the US NSF, ICDP, and DOSECC) focused on identifying key issues outlined above and narrowed down the optimal site for the first phase of the CPCP to Petrified Forest National Park, in northern Arizona. Coring took place during November and December of 2013 and the project is now in its post-drilling science phase.

The CPCP cores have abundant detrital zircon-producing layers (with survey LA-ICP-MS dates selectively resampled for CA-ID-TIMS U-Pb ages ranging in age from at least 210 to 241 Ma), which together with their magnetic polarity stratigraphy demonstrate that a globally exportable timescale can be produced from these continental sequences and in the process show that a prominent gap in the calibrated Phanerozoic record can be filled. The portion of core CPCP-PFNP13-1A for which the polarity stratigraphy has been completed thus far spans ~215 to 209 Ma of the Late Triassic age, and strongly validates the longer Newark-Hartford Astrochronostratigraphic-calibrated magnetic Polarity Time-Scale (APTS) [44] based on cores recovered in the 1990s during the Newark Basin Coring Project (NBCP) [35], which in turn shows that the values for Solar System chaotic evolution based on the NBCP are accurate [36]. We are hopeful that CPCP-2/EMCT projects will greatly extend the exportable paleomagnetic and U-Pb calibrated time scale well into the Jurassic.

Field Stops

Our stops are arranged geographically in a partial loop (Fig.1.1): beginning in St. George, UT on the last day of the workshop; going to Page, AZ on Day 1; then on to the Tuba City, AZ area on Day 2; returning that evening to St. George.

B. Visit During Workshop: St. George Dinosaur Discovery Site (SGDS) at Johnson Farm (37.101299°, -113.534799°).

Main Points:

1) Lacustrine facies of Glen Canyon Group
2) Spectacular dinosaur tracks in the lower lacustrine sequence of the Moenave Formation
2) Meaning to continental communities during recovery from ETE – where are the herbivores?
4) Lake margin environments, arboreal stromatolites, and fishing 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 [45]. The Johnson family donated the tracks, 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 Museum has trackways preserved *in situ* indoors as well as many slabs collected from the site and from elsewhere in the southwest. It is a major focus of continuing research in the region.

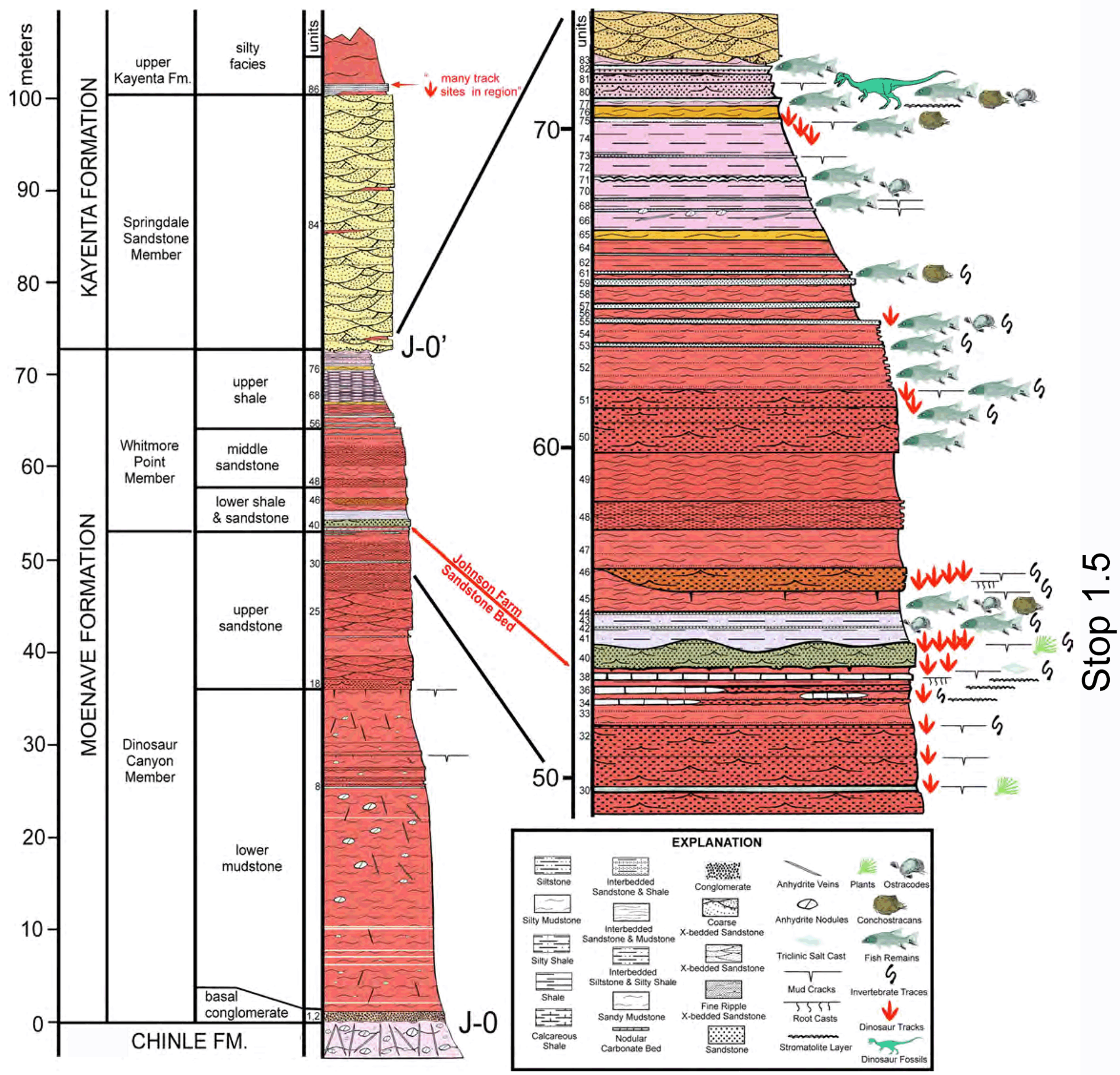

Figure B.1: Stratigraphic section as measured at SGDS (from ref. [46]). J-0 and J-0' are positions of supposed regional unconformities.

The stratigraphic position of the SGDS is in the “lower shale and sandstone” of the lower Whitmore Point Member of the upper Moenave Formation [46] (Figure B.1). Thin suspension dominated lacustrine beds alternate with traction and wave deposited coarser units that alternate with more fluvially dominated units and eolian strata typical of much of the Glen Canyon Group in the southern and western parts of the Colorado Plateau. Neither magnetostratigraphy nor U-Pb dates are available for this area, however, the stratigraphy here is very similar to that of Potter Canyon, 66 km to the east southeast (at 36.88100, -112.84315) (Figure B.2), where there are both forms of age-relevant data. In both sections, there are two intervals dominated by lacustrine strata which Kirkland et al. [46]. interpreted as correlative. The lower interval contains the SGDS track and fish-bearing facies at St George, UT, and the pollen-bearing interval [47] with an $\delta^{13}C_{org}$ isotopic excursion [26] at Potter Canyon (Figure B.2). About 4 m below the pollen-bearing interval Suarez at al. [26] reports a zircon CA-ID-TIMS age of 201.33 ± 0.07/0.12 Ma, which is within error of the estimated age of the Triassic-Jurassic boundary at 201.36 ±0.17 Ma in ammonite-bearing marine strata [48] but significantly younger than the estimated age of the end-Triassic extinction at 201.564 ± 0.016 Ma in the continental eastern US [49] and 201.51 ± 0.15 Ma in marine strata [48].

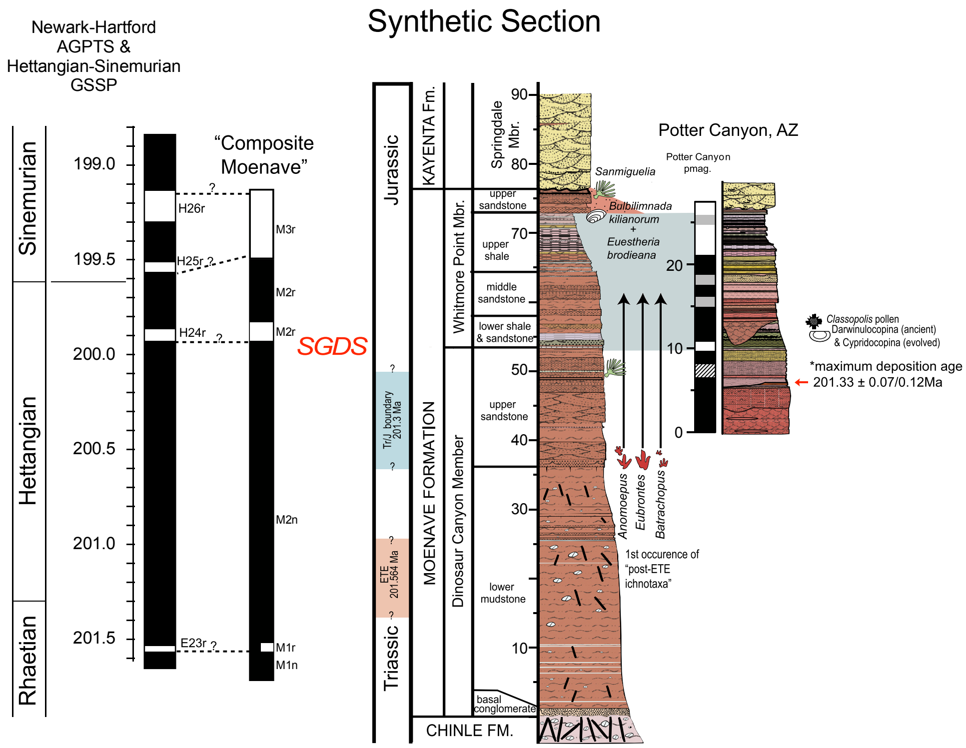

Figure B.2: Correlation between synthetic section of Moenave Formation representative of the SGDS and Warner Valley and Potter Canyon. Modified from Suarez et al. [26] with Newark-Hartford AGPTS from [44, 50] and GSSP ages and correlation to Newark-Hartford AGPTS from [51, 52].

The Potter Canyon section also has a magnetic polarity stratigraphy [25]. The upper Dinosaur Canyon Member is of normal polarity as is most of the Whitmore Point Member. The lower shale and sandstone interval is of reverse polarity as is most of the upper shale and sandstone interval (Figure B.2). As synthesized by Donohoo-Hurley et al. [25] and Kirkland et al. [46], three reverse polarity intervals occur in the Moenave, one near the base, M1r (represented by only one sample), and two, M2r and M3r, in the upper part of the formation. A simple correlation of this polarity stratigraphy to the Newark-Hartford astrochronology [50] is shown in Figure B.2 (modified from Suarez et al. [26]), although this correlation requires extremely variable accumulation rates or that the detrital zircon date does not accurately represent the depositional age.

Nonetheless, if the physical correlation between the SGDS and Potter Canyon is correct, then both data can be exported to SGDS (Figure B.2), to provide some constraints amenable to further testing. Using the data from Potter Canyon, the SGDS levels appears to be either within or next to reverse polarity zone M2r. SGDS also appears to be above the level of the detrital zircon date from Potter Canyon of 201.33 ± 0.07/0.12. Thus, the SGDS should have an age between 199 Ma from Newark-Hartford H24r that tentatively correlates to Moenave M2r and 201.33 Ma from the detrital zircons at Potter Canyon. Its age would late Hettangian. These constraints, however, actually span nearly the entire Hettangian (201.3 – 199.4 [53, 54]). That said, the correlation can be tested by recovering the magnetic polarity at the SGDS itself as well finding additional and local detrital zircon samples.

The fossil assemblages and geology of the site have been well documented in a series of papers by Milner et al. (e.g. [55-58]) and Kirkland et al. (e.g., [59]). Highlights include: 1) abundant and exceptionally good brontozoid [60] footprints (putative from theropod dinosaurs) 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.

A presumably shoreline feature seen here is the presence of stems and roots encrusted by stromatolites (Figure B.4). In many muddy and sandy aquatic environments, trees, bushes, and roots provide the only stable substrate for encrusting microbial communities. These "arboreal" stromatolites, are known globally, often in lacustrine shoreline environments especially during transgressive phases, when plant communities were drowned by the rising waters based on the interpretations of Whiteside [61].

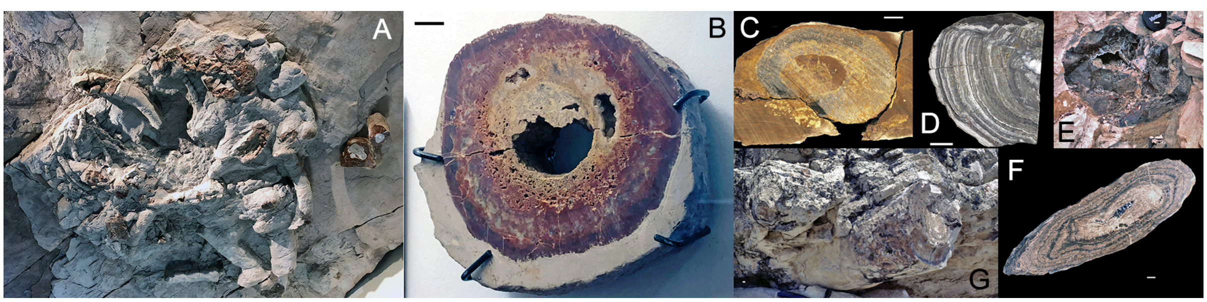

Figure B.4: Lacustrine arboreal stromatolites from the Mesozoic and Cenozoic. A, *in situ* mass of stromatolites around stems and roots, SGDS (compare broken examples to B for scale); B, cross section of stromatolite around stem or root – note geopedal fill and orientation upside down - SGDS; C, stromatolite around stem or root, Lockatong Formation, Newark Basin. New Jersey, Late Triassic (Early Norian); D, stromatolite around stem or root. Passaic Formation, Newark Basin. Pennsylvania, Late Triassic (Middle Norian); E, stromatolite around tree, Scots Bay Formation, Fundy Basin, Nova Scotia, Late Triassic (latest Rhaetian); F, stromatolite around tree, Towaco Formation, Newark Basin, New Jersey, Early Jurassic (Hettangian); G, stromatolite around tree, Green River Formation, Green River Basin, Wyoming, Eocene. Scale bar in B-G is 1 cm (approximate for B and G). After [61].

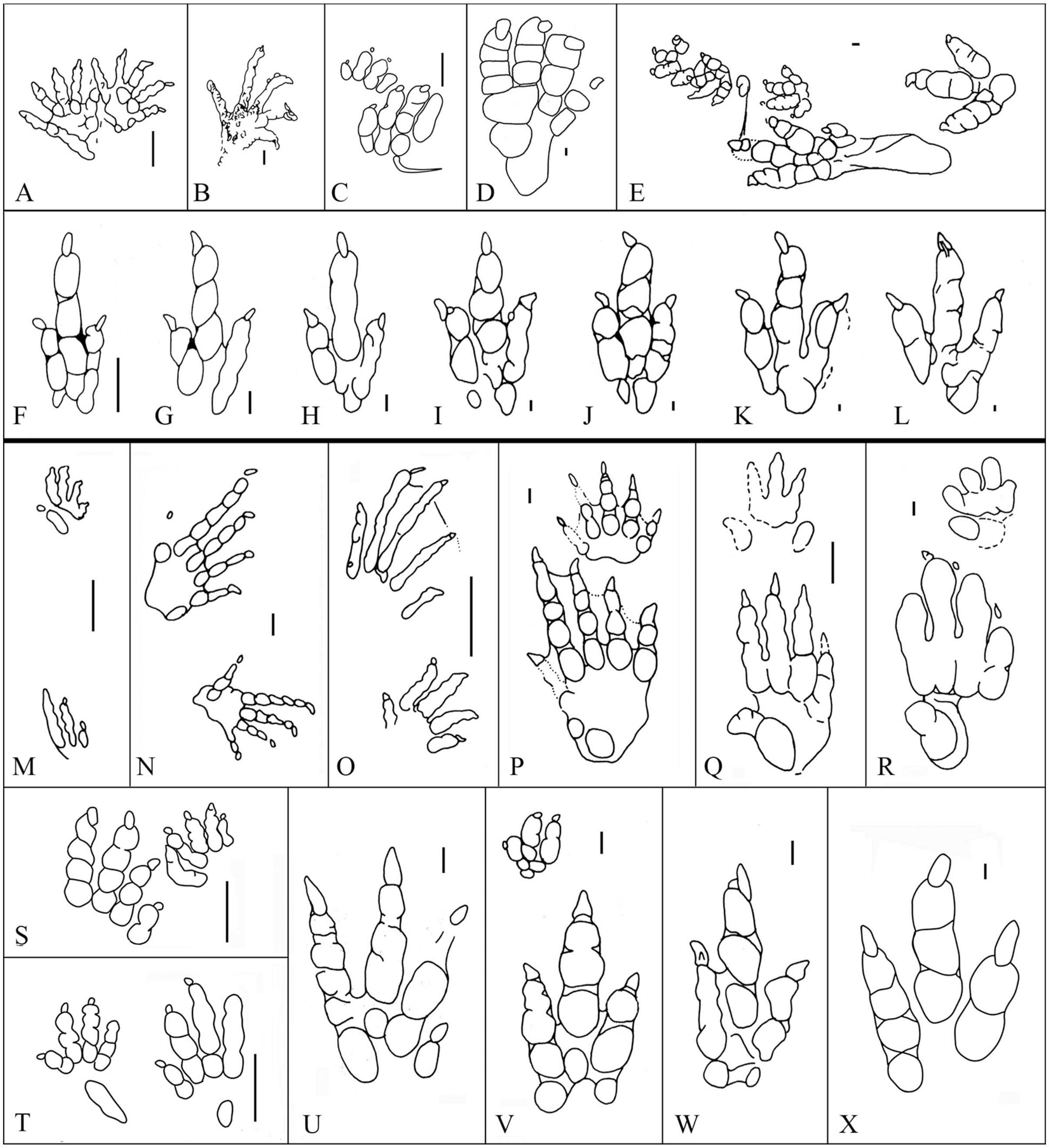

Figure 1.6: Post ETE taxa are A-L and pre-ETE forms are M-X exam\mples of most of which are at SGDS as exhibits or for F-L, in situ. Taxa are A, *Ameghinichnus* n,sp.; B, *Rhynchosauroides* n.sp.; C, *Batrachopus deweyii*; D, *Otozoum moodii*; E, *Anomoepus scambus*; F-G, different sizes of brontozoid 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*.

By far the most abundant tracks at this site are the brontozoids [60]. These are forms classically called *Grallator*, *Anchisauripus*, and *Eubrontes*, but forming an apparent morphological continuum from small to larger [62-64]. 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. [62]), although not all, authors (e.g., [65, 66]). Specifically, the Kayenta theropods "*Megapnosaurus*" *kayentakatae* and *Dilphosaurus wetherelli*, make good contenders for the makers of medium and large tracks.

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 are there so many carnivores compared to herbivores – were the theropods primarily fish-eaters (e.g., [56]); is this a reflection of the recovery period after the ETE [62, 63]; is it a facies bias, or all three?

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 fish-eaters [56], and a similar argument has been put forward for the eastern post-ETE US theropods [62, 63].

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 [67, 68]. However, a critical difference is that the ornithischian dinosaur ichnite *Anomoepus* is present at SGDS and is absent 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 Formation where skeletal remains are otherwise relatively abundant. In addition, the uppermost Passaic sites produce a distinctive species of *Rhynchosauroides* and that genus is absent from the SGDS, and the entire Glen Canyon Group.

C. Fieldtrip stops

Day 1: St. George Utah to Page AZ

Stop 1.1 *Warner Valley (37.056611°, -113.474833°) Overlook of basal Chinle and Moenkopi formations and stratigraphic context of Warner Valley.*

Main Points:

1) Lowest Mesozoic strata in region
2) Cyclicity of the Moenkopi and its expansion to west.
3) Unconformity at the Chinle/Moenkopi contact
4) Possible secondary drilling target

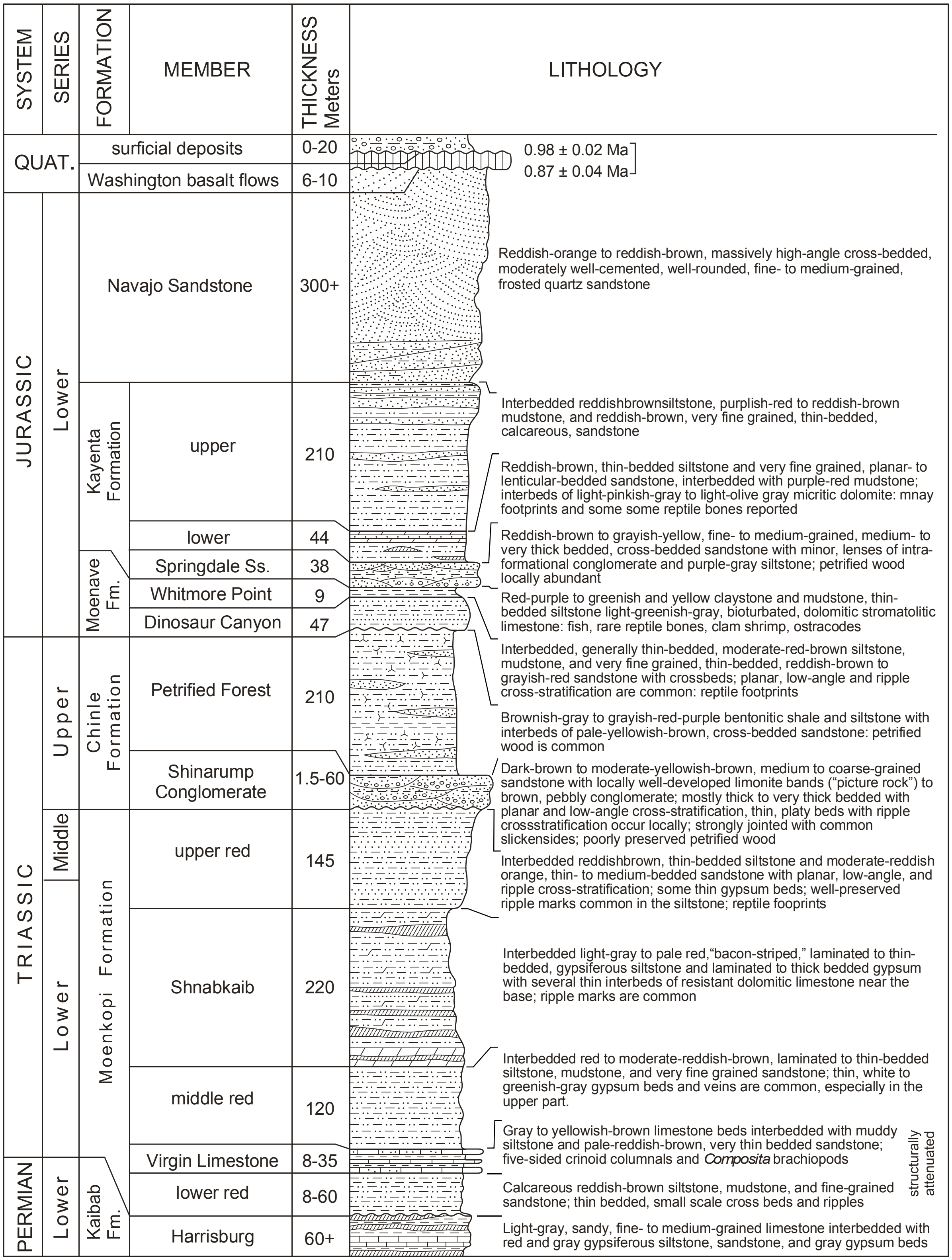

Figure 1.1: Stratigraphic units at Warner Valley, stops 1.1-1.3; adapted from [69].

This stop is an overview of the geology of the lower parts of the section at Warner Valley (Figures 1.1, 1.2). This area is just off the Colorado Plateau, separated from it by the Hurricane Fault which we will pass later in the day and upon our return. The Paleozoic and Mesozoic stratigraphy, however, is the same as on the Plateau on the other side of the fault.

Figure 1.2: Location of Stop 1.1.

Moenkopi

Looking to the north from this spot, we see on the right the cuesta of the local expression of Shinarump Conglomerate member (227-222 Ma) of the Late Triassic age Chinle Formation overlying with a gentle angular unconformity the Early to Middle Triassic age Moenkopi Formation in front of us and to the immediate left. The rest of the Chinle Formation, nominally Petrified Forest Member, is mostly covered in Warner Valley until the base of the ridge of overlying Moenave Formation of ?Latest Triassic-Jurassic (~202-199? Ma), Early Jurassic Kayenta Formation (199-180? Ma), and Early Jurassic Navajo Sandstone (~180-175? Ma), which supports its own large cuesta called Sand Mountain (Figure 1.1). Moenkopi Formation strata on the left are truncated by a fault.

The oldest strata we can see are the "middle red member" of the Moenkopi Formation. It overlies the Virgin Limestone of the Moenkopi which was deposited during a significant marine incursion during the early Spathian of the Olenekian latest Early Triassic, based on ammonoids [70, 71] and strontium isotopes [72] and is regarded at a tongue of the marine Thaynes Group [73, 74]. This places an older bound on the age of the Triassic strata in Warner Valley, although the Moenkopi Formation gets even older elsewhere, although how old is yet to be determined. It could even cross into the Permian.

Very little is known about the “middle red member” or the succeeding, dramatically cyclical Shnabkaib Member, the latter with its “bacon striping” related to alternating siltstone and gypsum-bearing beds. From this member, poorly preserved mollusks are reported, including an ammonoid; most workers have accepted that the Columbites zone characteristic of the Spathian is present [75] despite the lack of evidence.

The overlying red “upper red member” consists of ripple cross-laminated fine sandstone and mudstones. Reptile footprints occur at a locality near Warner Valley, about 14 km west of Hurricane, UT that produced the type specimen of *Rotodactylus mckeei* [76] (synonymized with *R. cursorius* [77]) (Figure 1.3 A). PEO found footprints in Warner Valley under a bench in a ravine not far from the overlook point (Figure 1.3 B, C). These appear to be an incompletely impressed *Chirotherium ?barthii* trackway that superficially looks like a set of tridactyl tracks that might be mistaken for dinosaurian (as have similar trackways) [78].

The “upper red member” has been traditionally correlated with the Holbrook Member of the Moenkopi Formation in northern Arizona, based largely on similar facies with no independent geochronological data. As a correlative of the Holbrook, it would be of Anisian age (early Middle Triassic), based largely on a correlation using amphibians [18].

Cyclicity

In Utah, the Moenkopi Formation tends to be strongly cyclical, especially the Shnabkaib Member as was noted by McKee [79]. This cyclicity is expressed as alternating more and less evaporitic beds. A larger-scale, pronounced cyclicity is expressed as alternating more marine (more gray) vs more continental (more red strata) demarcating the members of the formation. McKee did not speculate on the origin of these cycles; with the exception of repeated suggestions of tidal deposition, and sea level, the origin of this stratigraphic architecture remains virtually unexplored. With essentially no geochronological calibration and incomplete sections, this is hardly surprising. However, should the cyclicity prove to be of Milankovitch origin, it could be another useful interval complimentary to the plausibly contemporaneous section of the Buntsandstein in the Central European basin that has a well-developed magnetostratigraphy [80, 81] and astrochronology [82, 83], and nearly identical footprints [76].

Footprints

The Moenkopi Formation is famous for its reptile footprints, best known from northern Arizona especially near Holbrook, Winslow, and Cameron, AZ[76, 77]. The most iconic forms are the chirotheroid footprints, generally regarded as having been made by cursorial pseudosuchians and archosauriforms (crocodile relatives), excluding the Avimetarsalia (pterosaurs plus dinosauromorphs). One common chirotheroid footprint in the Moenkopi Formation is *Chirotherium barthii*, which we may have at Warner Valley. Indistinguishable footprints are known from Europe, including Germany, France, and the UK in strata argued to be of Anisian age [77].

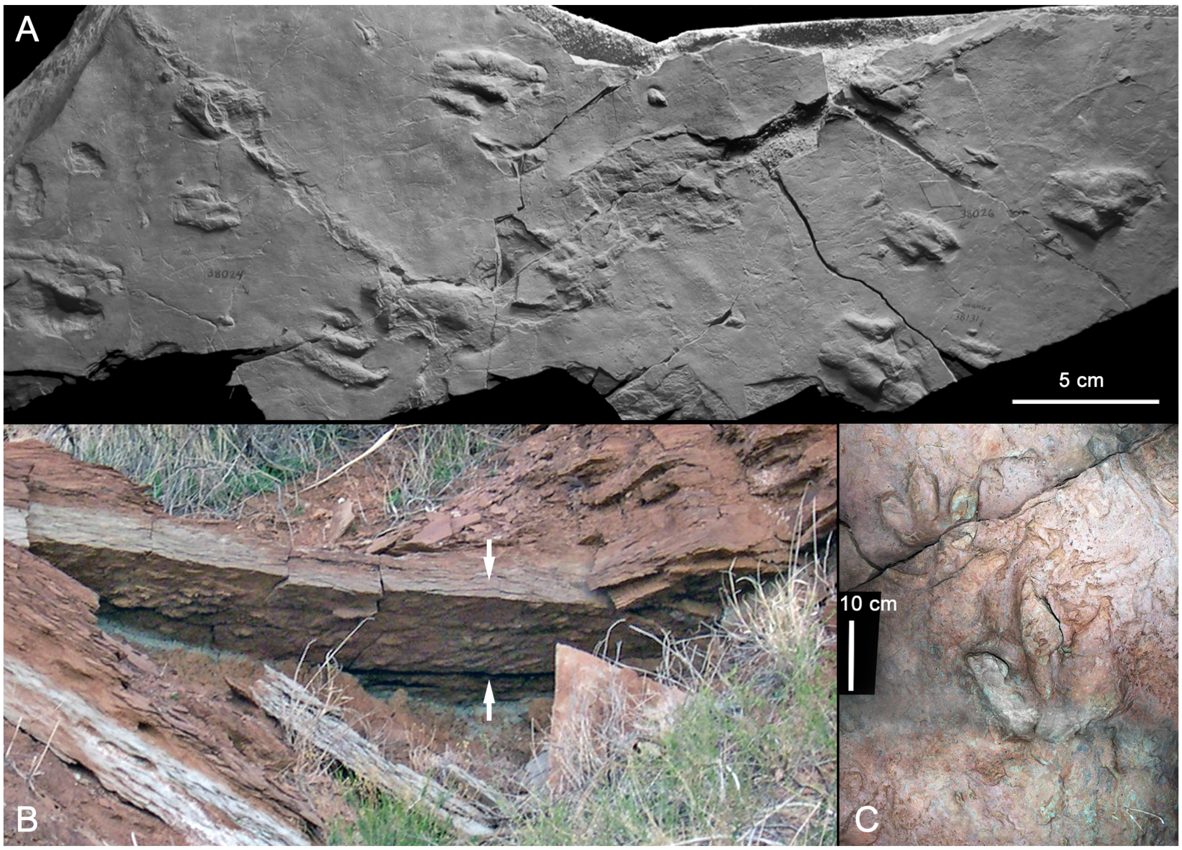

Figure 1.3: Footprints from Warner Valley and the vicinity. A, holotype of *Rotodactylus. mckeei*, from 14 km west of Hurricane, UT, about 13 km north, north east of Stop 1.1 (from [77]). B and C, *Chirotherium ?barthii* from Warner Valley, just north of stop 1.1, showing position of trackway (between arrows) with detail (a composite of 3 photos because of photographic difficulties under ledge)(scale is approximate).

Rotodactylus, such as the form from near Warner Valley*,* is asserted to have been made by a non-dinosaurian dinosauromorph [84], which would mean that it is more closely related to dinosaurs than any other reptile group. However, *Rotodactylus* lacks key specializations seen in not only dinosaurs but also in archosaurs and even Archosauriformes, most notably the trackmaker retained a manus with essentially the same proportions as the pes, only generally smaller, and in both the manus and pes, digit IV projects the furthest forward. In the archosauriformes the manus diverges greatly in form from the pes with apomorphies shared with the Dinosauromorpha. This is important because this track taxon and a similar form *Prorotodactylus*, has been used as evidence to project the origins of the

Dinosauria into the Early Triassic, as part of a rapid recovery and adaptive radiation after the end-Permian mass extinction [85], for which no other evidence exists.

Secondary Drilling Target

The Moenkopi Formation is an interesting secondary target for coring in this region. It is well known that the formation thickens dramatically from east to west and grades laterally in the same direction into marine strata, the Thaynes group. In the area around St. George and Warner Valley (Virgin River), Shoemaker et al. [86] produced a magnetic polarity stratigraphy that was never fully published and appears only as a column in a figure by Steiner et al. [87] which we have redrafted here for clarity (Figure 1.4). It is unclear how this correlation was achieved or what the evidence is for the asserted hiatuses shown in the various correlation summary figures. Continuous core through this sequence in the Warner Valley area could allow direct comparison with the results from CPCP-1 and other areas as well as contribute to astrochronology of the Early to middle Triassic.

Analyses of detrital zircons from the Moenkopi Formation show that young populations of grains are present [88, 89] and could provide valuable calibration for the paleomagnetic record and chronology of the Early to Middle Triassic and recovery from the end-Permian mass extinction. Some of these zircon ages have hints that the youngest strata of the Moenkopi might be Ladinian in age [19].

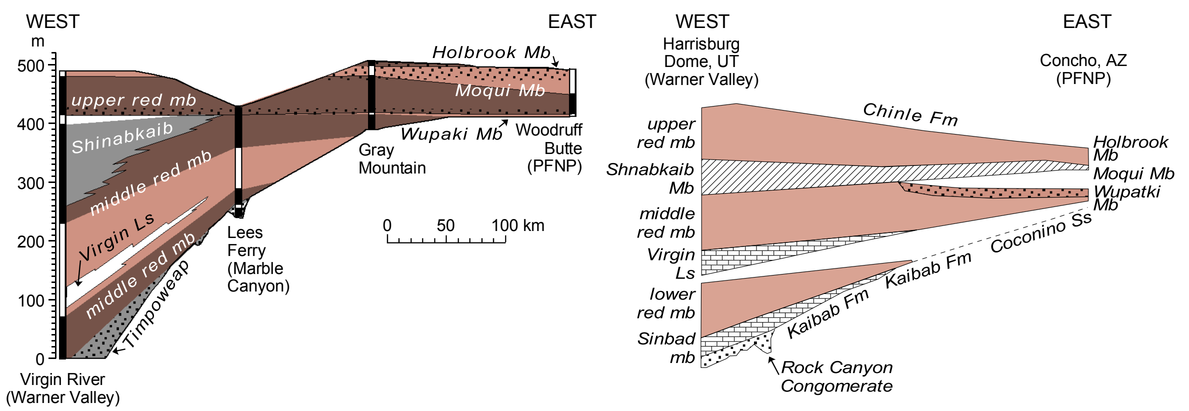

Figure 1.4: Correlation panels for the Moenkopi Formation in Arizona and Utah: PNFP denotes Petrified Forest National Park where the CPCP-1 cores were recovered [20], but the paleomagnetic record or stratigraphy depicted is from the cited authors not the cores. Reddish colors depict red clastic facies; gray and white depict gray clastic or limestone facies. Left, correlation of paleomagnetic polarity and litho-stratigraphies from four outcrop sections based on Shoemaker et al. [86] as figured in Steiner et al. [87]; darker bands depict strata with normal polarity, lighter indicated reverse polarity Right, Wheeler Diagram from Klein and Lucas [77] based on McKee [73].

Chinle Formation and Younger Strata

A gentle angular unconformity separates the Early to Middle Triassic Moenkopi Formation from the overlying Late Triassic Chinle strata. Although not obvious while staring at the outcrop from this vantage, a longer view enhanced in GoogleEarth makes the angular unconformity clear (Figure 1.5). This is the Tr-3 unconformity of Piperingos and O'Sullivan [90] which is they argue is. "…one of the most widespread, conspicuous and widely recognized unconformities…", recognized in the southwest Mesozoic.

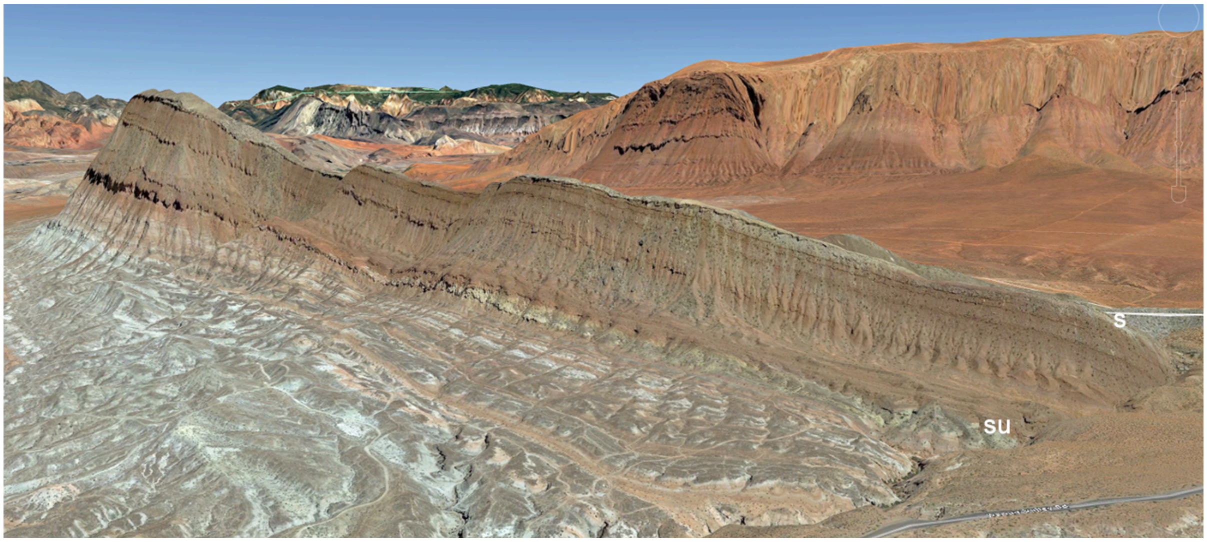

Figure 1.5: GoogleEarth image (vertical exaggeration is 200%) of the position of Stop 1.1 (lower right) looking northeast towards the Moenkopi-Shinarump cuesta. The Moenave-Kayenta-Navajo cuesta is in back of that, with the valley in between being underlain by poorly exposed Chinle Formation. Note how the uppermost beds of the Moenkopi are progressively cut out by the Shinarump ("s"), going north along the cuesta crest. The Shnabkaib-upper red member contact is at "su".

From oldest to youngest, units above the Moenkopi are Shinarump Member of the Chinle (Late Triassic), a resistant, white, yellow and grey conglomeratic sandstone with large cross beds and some horizontal laminations, irregularly interbedded with funky multi-colored mudstones called "mottled" strata in Chinle Formation parlance. This is a intensely developed paleosol sequence which where thicker finer-grained in eastern Arizona is called the Mesa Redondo Formation. It need not be the same age. The Shinarump can be seen forming cap-rock throughout these badlands. A gradational contact exists between Shinarump and the overlying rest of the Chinle grouped nominally in the Petrified Forest Member, which is characterized by broadly banded pastel colors.

Over most of Warner Valley, the Chinle Formation is very poorly exposed and is overlain by what looks like an unconformity. We will be walking on this formation at the next stop on the way to see the Moenave and basal Kayenta formations.

The Moenave Formation consists of generally well-bedded (at the meter scale) layers of reddish-brown sandstone, siltstone, and varicoloured mudstone deposited in lakes, floodplains and streams. We saw the Moenave at the SGDS yesterday, and it is the focus of the next stop. The Moenave, Kayenta, and overlying Navajo formations comprise the cuesta of Sand Mountain in the background.

Looking due north, we see mountains underlain by Oligocene to Miocene age intrusive Quartz monzonite and granite underlying Signal Peak (3159 m, 1367 m above the surroundings) bordered by metamorphosed continental Claron Formation of Paleocene to Early Oligocene age, and progressively towards us, Cretaceous and Jurassic sediments of progressively lesser degrees of metamorphism.

The Kayenta Formation is similar to the Moenave, and consists of layers of red-brown and pink sandstone with variegated mudstone and siltstone deposited in river floodplains and lakes with fluvial sandstones. Sandstone becomes more abundant upwards and the eolian sandstone beds become common and eventually dominant into the overlying Navajo Sandstone. The environment is traditionally described as arid. Dinosaur tracks are found within these layers, as well as disarticulated fish remains. We will look at the basal part of the Kayenta at Stop 1.2 and lower part of the formation at Stop 1.3.

Drive along unpaved Warner Valley Road to southeast on poorly exposed Chinle Formation. On left you have the Moenave Formation and on the right small outcrops of Chinle overlain by Moenave, Kayenta, and Navajo formations. Pass road heading to Fort Pierce Historic Landmark, then outcrops of Chinle Formation are on the left. Keep an eye out for free-range animals.

Take first dirt road (the big one) on left after big Chinle outcrop close to road at 37.013931°, -113.396442° follow dirt trail 0.3 mi (0.54 km) to north northwest and park.

Stop 1.2 *Warner Valley (37.018242°, -113.395177° to 37.022069°, -113.391927°) Uppermost Chinle to Kayenta Formation – excellent outcrop of Moenave, "Olsen Canyon".*

Main Points:

1) Stratigraphy of Early Jurassic strata on the west side of the Colorado Plateau
2) Unconformity at base of Moenave
3) Evidence or lack thereof of pre-ETE strata in Moenave and location of ETE
5) Lacustrine facies in the Moenave and Kayenta
6) Is there a diastem or unconformity at the Sprindale-Moenave contact?
7) Post-ETE track assemblages
8) Part of primary coring target

This is an accessible and fossil-rich section of the Moenave and basal Kayenta formations. We will traverse up section from the Chinle to the siltstone member of the Kayenta Formation. The main questions we want to 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?

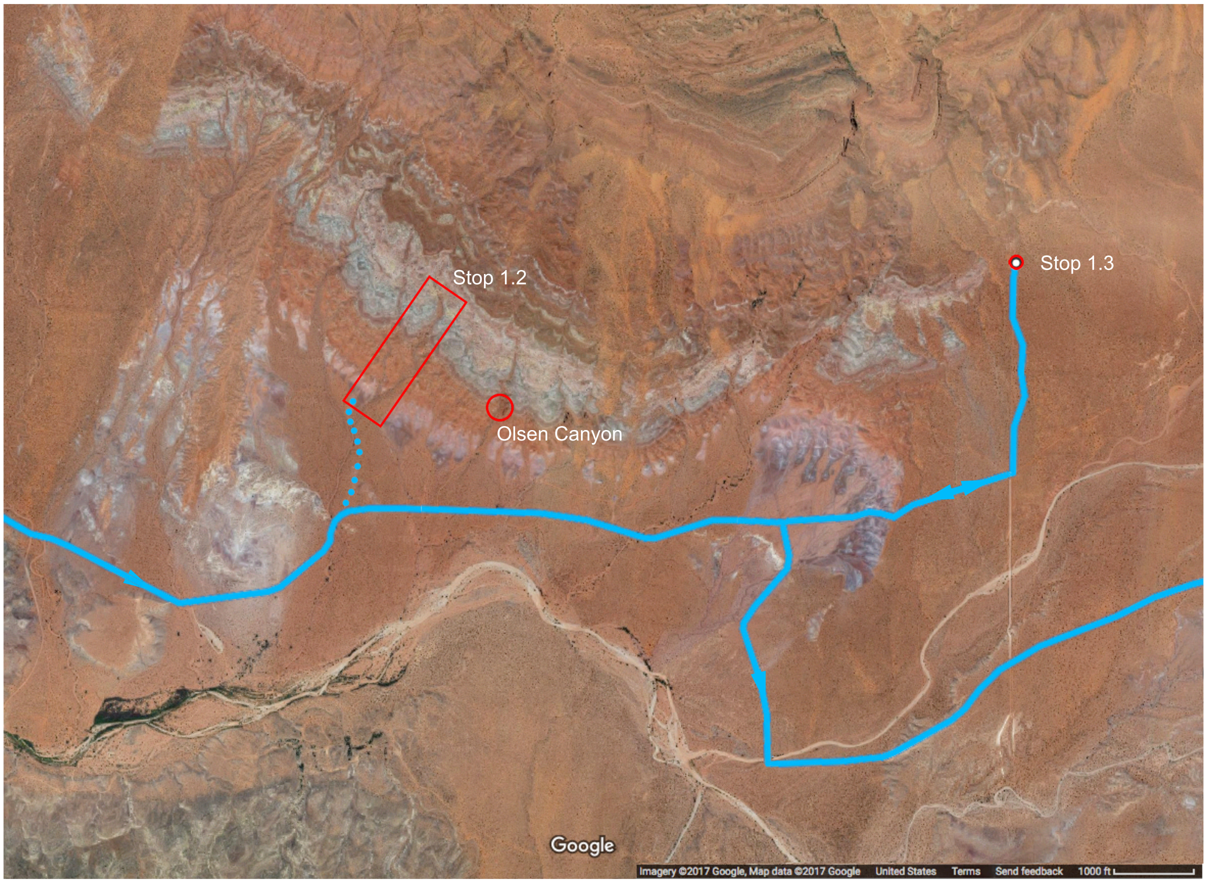

Figure 1.6: Stations at Stop 1.4, Warner Valley. White dots are places to park or turn off road. Strata tilt northwards (towards top of page). Lower purple colors are Chinle and upper big purple interval is Whitmore Point of the Moenave and Springdale Ss of the Kayenta. Thin upper purple layers are in the silty facies of the Kayenta.

The main focus of this stop is the Whitmore Point Member of the Moenave Formation however we will also discuss the underlying Dinosaur Canyon Member and its contact with the Chinle. Note the various lithologies we are walking on as we go about 0.5 km northeast to a wall of Whitmore Point Member at 37.022069°, -113.391927°. This is the “Olsen Canyon” section of Suarez et al. [26] that actually consists of this section plus a more steep-sided valley about 0.4 km southeast (at 37.018336°, -113.389096°) of this stop (section beginning at 37.01728, -113.38951 in [26]).

Contact with the Chinle

Olsen Canyon (at 37.017417°, -113.389678°) has a well-exposed contact between the Chinle and overlying Moenave formations and hence of the J-0/Tr-5 unconformity of Piperingos and O’Sullivan [90]. A chert-anhydrite pebble conglomerate is at the base of the Moenave Formation, which has been reported as occurring across all of southwestern Utah [57]. 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 (Figure 1.7).

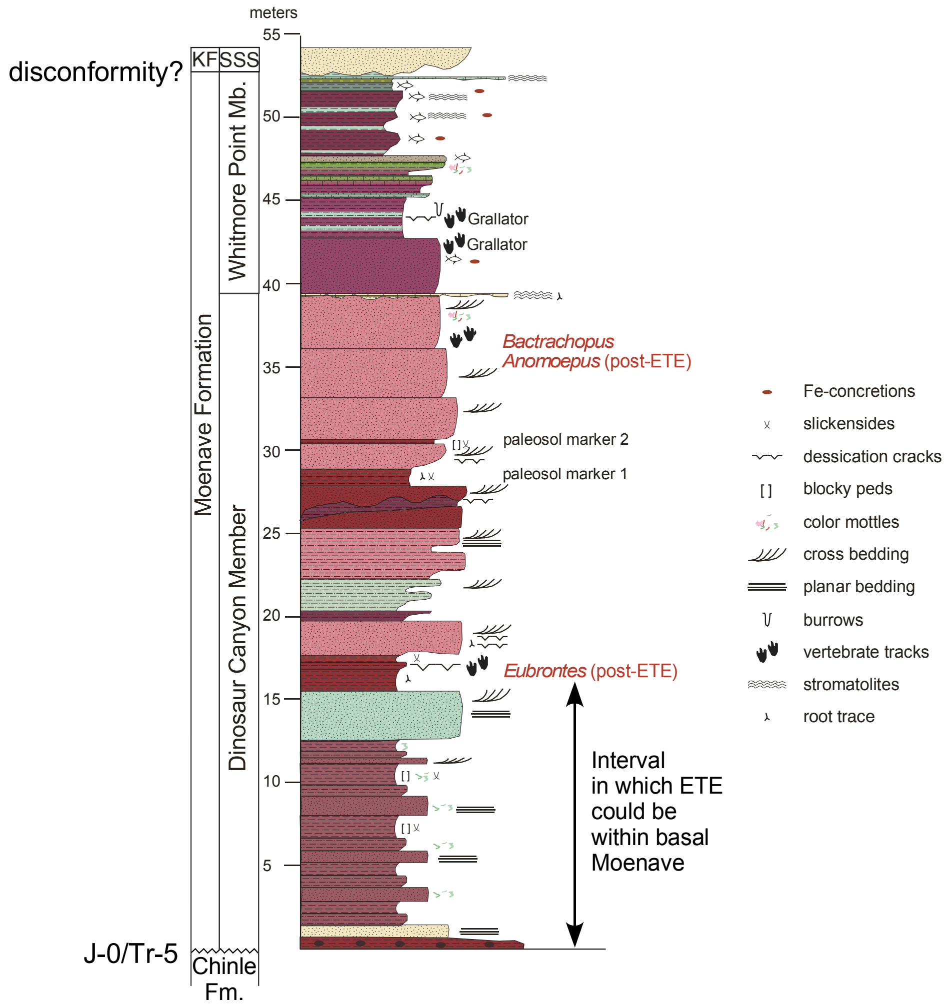

Figure 1.7: Measured section of entire Moenave Formation at Olsen Canyon from 37.017417°, -113.389678° to 37.021408°, -113.391617°.

The Chinle Formation here has nodules and secondary veins of gypsum that might not be primary and do not seem compatible with the overall facies context? Could they be derived from the paleo-weathering of Chinle pyrite prior to the deposition of the Moenave?

We have walked over the Chinle Formation but, apart from being the upper Chinle locally, what part of the greater 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., [91]) or Petrified Forest Member [69] which is mostly red at its type section much higher in the section at the national park. It does matter, given the implications for the magnitude of the unconformity. It does matter, given the implications for the magnitude of the unconformity. Continuous core and its consequent magnetostratigraphic polarity stratigraphy through this Chinle in this region would solve this problem and yield insights into the regional dynamic stratigraphy and tectonics.

Figure 1.8: Left, J-0/Tr-5 unconformity (at hammer head) between Dinosaur Canyon Member of the Moenave Formation of the Glen Canyon Group and the underlying Chinle Formation at Olsen Canyon. Note numerous gypsum veins. Right, *Eubrontes giganteus*, a typical post-ETE form from Olsen Canyon (see Figure 1.7).

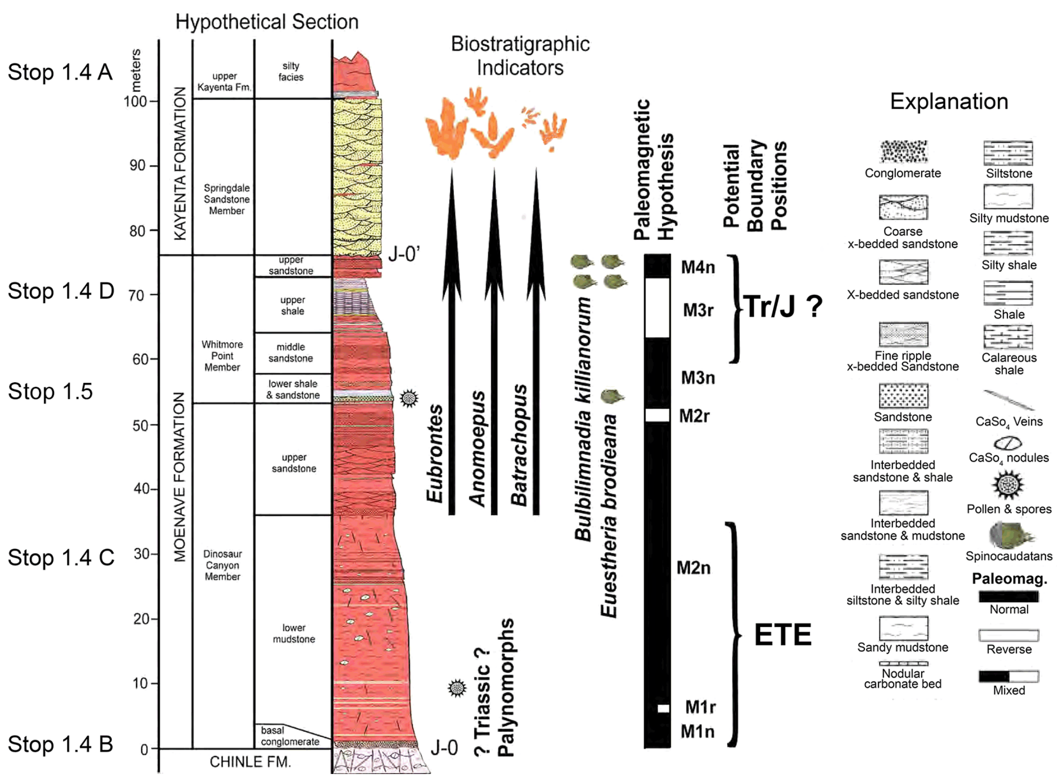

Figure 1.9: Synthetic section for the Moenave and basal Kayenta formations, Washington County showing the positions of the field stops. Slightly modified from ref. [46].

Position of the ETE

Olsen Canyon exposes the highly track-rich outcrop of the fluvial Dinosaur Canyon Member that comprises the lower Moenave Formation and has produced biostratigraphically important material relevant to the position of the end-Triassic mass extinction (ETE). Only ichnotaxa have been found here so far. These include ichnotaxa found here include the large (>30 cm) brontozoid [60] *Eubrontes giganteus* (Fig. 1.8*)*, *Anomoepus* sp., and abundant *Batrachopus* [46], the latter attributed to protosuchian crocodilomorphs, based on reconstructed track osteology [92] and skeletal material of protosuchians, is known from this member of the Moenave, including the type of *Protosuchus richarsoni* from the Moenave of Arizona at Dinosaur Canyon [93] along the base of the Adeii Eechii Cliffs near which *Batrachopus* has been recovered [92]. 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 Formation 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-Jurassic boundary, by definition since the establishment of the GSSP for the basal Hettangian [94]. The latter is in aggregate a 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, and carbon isotopes. 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* ([94, 95], which has yet to be found in the Moenave [47, 96, 97]. Conchostracans, or more properly spinocaudatans, have been used to infer that latest Rhaetian age strata are present in the Whitmore Point Member [98], 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 recovery, 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 [97], 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 [57]). Body-fossils of taxa limited to pre-ETE strata, such as phytosaurs are also absent from 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. [25] 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. 1.9.

Whitmore Point Member (Lake Dixie)

Thin bedded to laminated mudstones and minor carbonates of variegated color along with tabular sandstones comprise the Whitmore Point Member of the Moenave (at 37.021408°, -113.391617°). This is one of the most accessible outcrops of the lacustrine portion of the member. Thin bedded to laminated mudstones of this member have produced ostracodes [99, 100], spinocaudatans (clam shrimp) [98], semionotid, paleonisciform, and coelacanth fishes [101-105], and scraps of theropods [101], including a theropod tooth found at this locality in a nodule. However, these beds still remain under-collected, and given how widespread they are, would seem to have great promise.

The style of bedding and lamination with abundant pinch and swell and oscillatory ripples, a lack of microlamination, and the overall very low organic content suggests relatively shallow water at maximum lake depth, although “shallow water” could be 80 m with such a large potential fetch (~200 km) so that wave base would still be intersecting bottom at normal storm wind speeds (25 m/sec) [106]. There are mudcracked layers in the section but there is as yet no cyclicity or periodicity recognized, although presumably the some version of the climate cyclicity observed in contemporaneous strata in eastern North America [50] would have been expressed here.

As we will see at Stop 2.2, thin lacustrine intervals persist in the upper Moenave well beyond the mapped extent of the Whitmore Point Member. Is it possible that the mud-dominated portions of the Whitmore Point have simply been divided up by fluvial deltaic sandstones outside where “Lake Dixie” strata have been traditionally been recognized? These thinner intervals might be important lithostratigraphic markers. Based both on the correlation by polarity stratigraphy (see Figs. B.2 and 1.9) the age of these lacustrine strata should be Early Sinemurian. This age assessment is in conflict with the Hettangian age based on palynomorphs [47, 96] and needs testing by further, more detailed, magnetostratigraphic analysis, and zircon U-Pb dates as would be obtained by coring, with the main benefit being further calibration of the polarity time scale.

Springdale Sandstone of the Kayenta Formation

At the top of the thin bedded mudstone sequence of the Whitmore Point there is a rapid transition into the sandstones and conglomeritic sandstones of the Springdale Sandstone. Lucas and Tanner [107] review the nomenclatural placement of this mappable unit, which extends from at least the Warner Valley region to the Echo Cliffs north of Moenave, AZ (Stop 2.2), with the unit currently regarded as part of the Kayenta Formation. Lucas and Tanner [107] argue that the Springdale Member rests disconformably on the Moenave Formation and the contact has even been termed the “J-sub-Kay” unconformity [108]. However, as we can see at this stop and Stop 1.4, wedge shaped sandstone beds pinch out into mudstones of the Whitmore point in advance of the main body of the Springdale suggesting deltaic progradation. This suggests that Springdale Member is a progradational fluvial-deltaic sequence filling topography of the “Lake Dixie” which attains a maximum thicknesses of 67 m [107].

The Springdale Sandstone is conformably overlain by interbedded tabular sandstones and laterally continuous lacustrine mudstones of the Kayenta Formation making a return to conditions similar to the Whitmore Point Member as we shall see at Stops 1.3 and 2.2.

Stop 1.3 (37.023111°, -113.367139°) Warner Valley Dinosaur Tracksite *(coordinates for parking area)*

Main Points:
1) Basal Kayenta Formation
2) ?Megatracksite?
3) Continuation of episodic lacustrine deposition from Moenave
4) Part of primary coring objective

The Warner Valley Dinosaur Tracksite was discovered in 1982 by Gary Delsignore of Cedar City, Utah. It has been described by Miller et al. [109], Birthisel et al. [110, 111], and Milner et al. [57]. The site covers ~ 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 [57].

As at SGDS, brontozoid tracks dominate, with *Eubrontes giganteus* being the most common form. The forms here seem indistinguishable from forms from eastern North America referred to as *Eubrontes giganteus* (Fig. 1.10). This Kayenta form most closely resembles C in Figure 1.10 and is typical of *Eubrontes giganteous* impressed in firm mud that resisted deep impressions. Deep impressions tend to have toes slimmer in appearance because the pads did not compress as much.

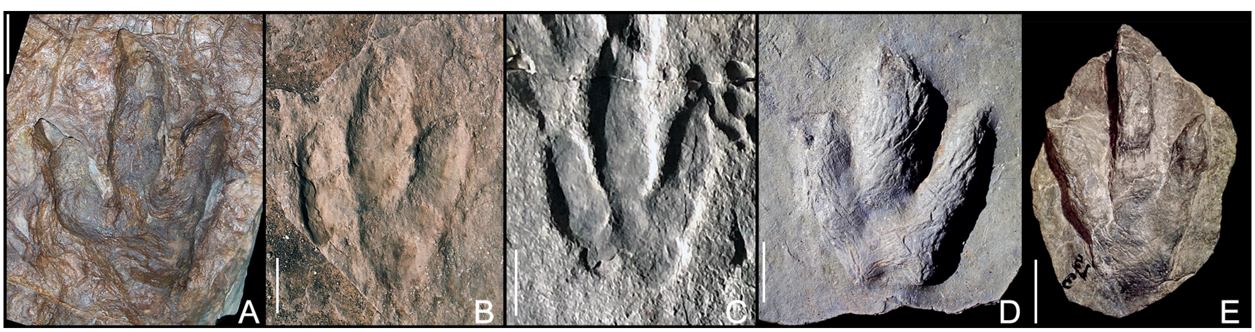

Figure 1.10: *Eubrontes giganteus* from the Glen Canyon Group and Newark Supergroup, figured as though impressions of right pes (scale bars 10 cm): A, deep natural cast from SGDS, Moenave Fm. (Hettangian); B, an example from the Warner Valley Dinosaur track site (Stop 1.3), Kayenta Fm. (Sinemurian); C, Beneski Museum, Hitchcock Ichnological Collection AC 45/1, from Turners Falls Ss., Deerfield Basin, Newark Supergroup (?Hettangian?); D, natural cast of specimen from Dinosaur State Park, East Berlin Fm., Hartford Basin, Newark Supergroup (Hettangian) (flipped); E, natural cast, type specimen of *Eubrontes giganteus* Beneski Museum Hitchcock Ichnology Collection AC 15/3, Portland Fm., Hartford Basin (Hettangian) (flipped) [64].

Also present is a single trackway of small yet broader, facultatively three-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.

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 around the surrounding rock [57]. We will see a very similar style of preservation at Stop 2.2.

The track-bearing surfaces are sandstones overlain by mudstones and appear to be deposited during lake transgression with relatively shallow water lake strata filling the track surfaces. The precise depositional environment of the sandstones is unclear, although wave transport would seem a simple mechanism for producing such tabular bodies. One interbedded fine sandstone bed, below the main track bearing surface, has footprints within it and dish fragments on its upper surface in contact with a purplish mudstone. The entire sequence is reminiscent of the Whitmore Point Member of the Moenave and also what has been termed basal Kayenta Formation at the Moenave dinosaur tracksite at Stop 2.2. Because of the similarity in facies to multiple sites in the region around St. George, Zion, and Tuba City, AZ, and its position above the Springdale Sandstone (and supposed equivalents), the main track bearing surface has been termed a megatracksite, or mega-tracksite (from Lockley [112]) by Lucas et al. [113] with the explicit interpretation that it is a single-surface tracksite. However, there are clearly multiple track bearing surfaces separated by mudstone and given the slow average accumulation rates in these strata, the surfaces could be separated by tens of thousands of years.

Lunch: Springdale Town Park (37.195859, -112.998748)

1.4: Black Canyon (37.199140, -113.001415) Glen Canyon Group

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 Formation

The section is a steep climb and we will not attempt to ascend. However, this is an important site as it has yielded a U-Pb date (Suarez et al. [26]), a magnetostratigraphy (Donoho-Hurley et al. [25]), detailed palynostratigraphy (Kürschner et al. [47]), and other stratigraphic information [46]. The section is overall very similar to that at Warner Valley (Stop 1.2) (Figure 1.11).

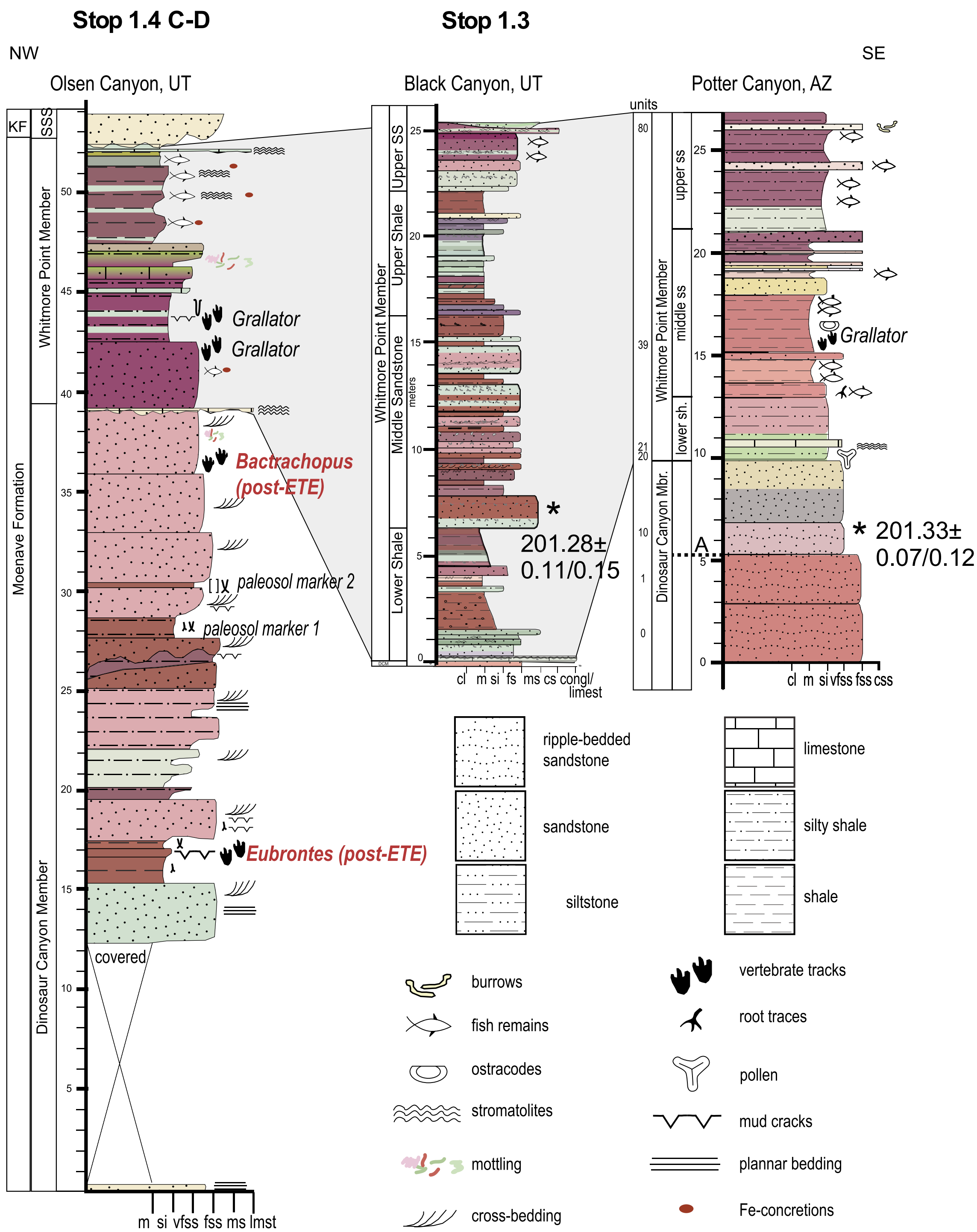

Figure1.11: Stratigraphic profiles of Black Canyon (Stop 1.2) slightly modified from Suarez et al. [26] Sections are organized from NW to SE and show the thickness changes of the Whitmore Point Member. Asterisks are zircon U-Pb dates also from Suarez et al. [26].

As at Warner Valley (Stop 1.2) the transition between the Whitmore Point and the Springdale Sandstone appears gradational with bedforms suggestive of deltas interbedded with mudstones, followed by fluvial facies. This suggests there is not a hiatus between the two units with significant erosion seemingly being ruled out by the lack of large scale relief on the Whitmore Point Member.

Looking further up the slope we can see the rest of the Early Jurassic section. The Kayenta Formation grades upward through a series of interbedded fluvial and eolian beds culminating in the spectacular cliffs of Navajo Sandstone that make Zion National Park so famous. The Navajo Sandstone is capped by the eolian Temple Cap Sandstone and the marine and marginal marine (evaporitic) Carmel Formation. 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 [114-116] thus placing a cap on the Early Jurassic part of the record.

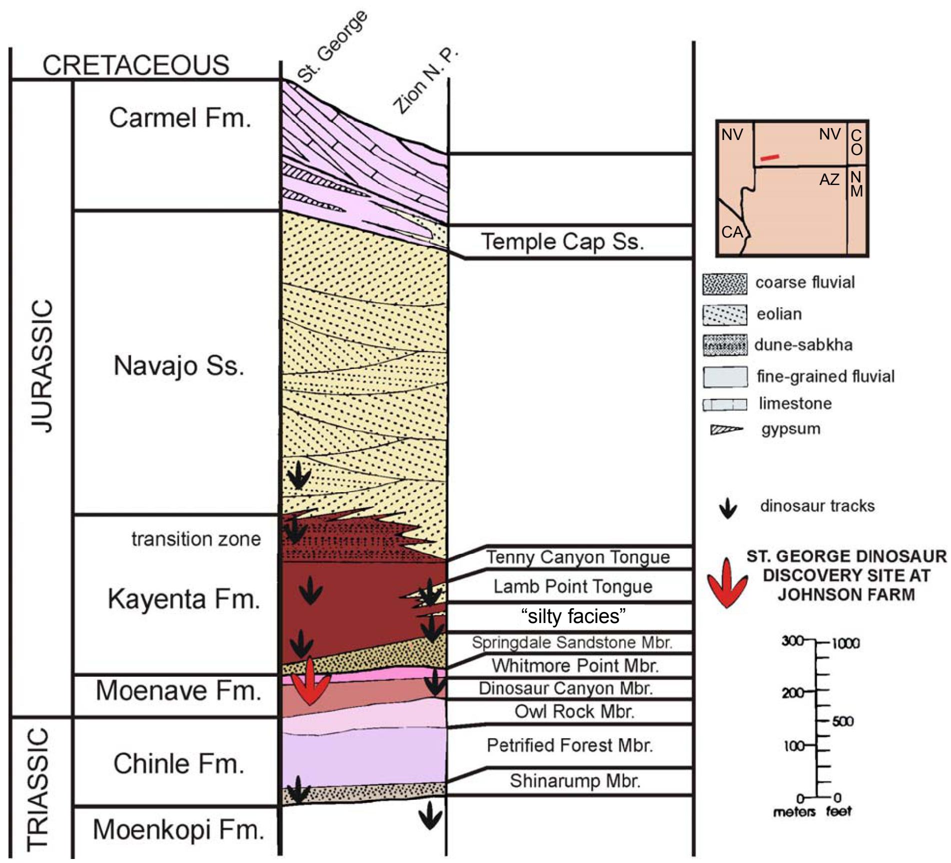

Figure 1.12: Basic stratigraphy in the Zion to St George area (from [57]).

Stop 1.5 Navajo Bridge, Marble Canyon (36.818136, -111.634109)

Main point

1) Charismatic overview and review of the basic stratigraphy of Triassic and Early Jurassic

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 age, 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 unit 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". The Timpoweap is supposed to correlate to the Sinbad Member of the Moenkopi to the west and northwest [117], and the latter produces the Smithian ammonite *Meekoceras*, probably the best biostratigraphic tie for the Moenkopi. Paleomagnetic evidence reviewed at Stop 1.1 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. Moenkopi strata in the Moab area, evidently go against these trends, probably because of salt tectonics.

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. As at Stop 1.1, the base of the Chinle Formation comprises a coarse clastic unit with variegated mudstone interbeds termed the Shinarump Member of the Chinle Formation. A broad channel (perhaps 20 m deep), trending northwesterly, seems to be present in this area [118] and provides one example of the paleovalleys that have figured prominently in discussions of the Chinle. This channel is typically considered evidence of a major unconformity that is supported in this area by paleomagnetic data suggesting a regional loss of the upper part of the formation [87]. 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, the sequence resembles the Blue Mesa Member of the formation which is also highly variegated. (The nearly completely red Petrified Forest Member, to which it is often equated, is an exception). However, the upper part of the Chinle Formation at Lee's Ferry consists of interbedded red and purple mudstone mudstones with multi-meter interbedded limestones resembling the Owl Rock Member.

Overlying the Chinle are clastic red beds of the Moenave Formation (see Stop 1.2). As we have seen, 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. The Whitmore Point Member seems missing at Lee's Ferry, but appears not far to the northwest, and it might be represented by beds mapped as upper Dinosaur Canyon Member.

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 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. Going to the southeast, the silty facies of the Kayenta expands at the expense of the Navajo as we will see at Stop 2.3.

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

Day 2: Page, AZ to Tuba City, AZ and return to St. George, UT

From Page, AZ we head south along AZ 98 (Indian Road 20/Coppermine Road) staying in the Glen Canyon Group until "The Gap" where we cut down section into the Chinle Formation and join US Route 89. We then follow the Chinle Formation south along the west side of the Echo Cliffs and turn left onto US Route 160 towards Tuba City, AZ where we climb section onto the northern part of Ward Terrace to Stop 2.1 (Figure A.1).

Stop 2.1 (36.091282°, -111.365808°) Overlook of Chinle and Glen Canyon Group

Main Points:

1) Overview of Geology
2) Cyclical Owl Rock Member of Chinle Formation.
3) Contact with Moenave and Glen Canyon Group
4) Adeii Eechii Cliffs and transition from Moenave Formation to Wingate Sandstone.
5) Where is the ETE?
6) Major coring objective?

Park at turnout and climb the low hill on the east side of highway US 160. Here, we have a panoramic view of upper Chinle Formation and a 360º vista of Ward Terrace up to Adeei Ecchi Cliffs. Chinle Formation is exposed underfoot and visible to the west in badlands. Chinle exposed underfoot and visible to the west in badlands. To the north and west we see the Glen Canyon Group comprised in ascending order of Moenave Formation and Wingate Sandstone (to the east), Kayenta Formation (Silty Facies Member), and capped by Navajo Sandstone forming a large plateau that we will drive over to reach Stop 2.3.

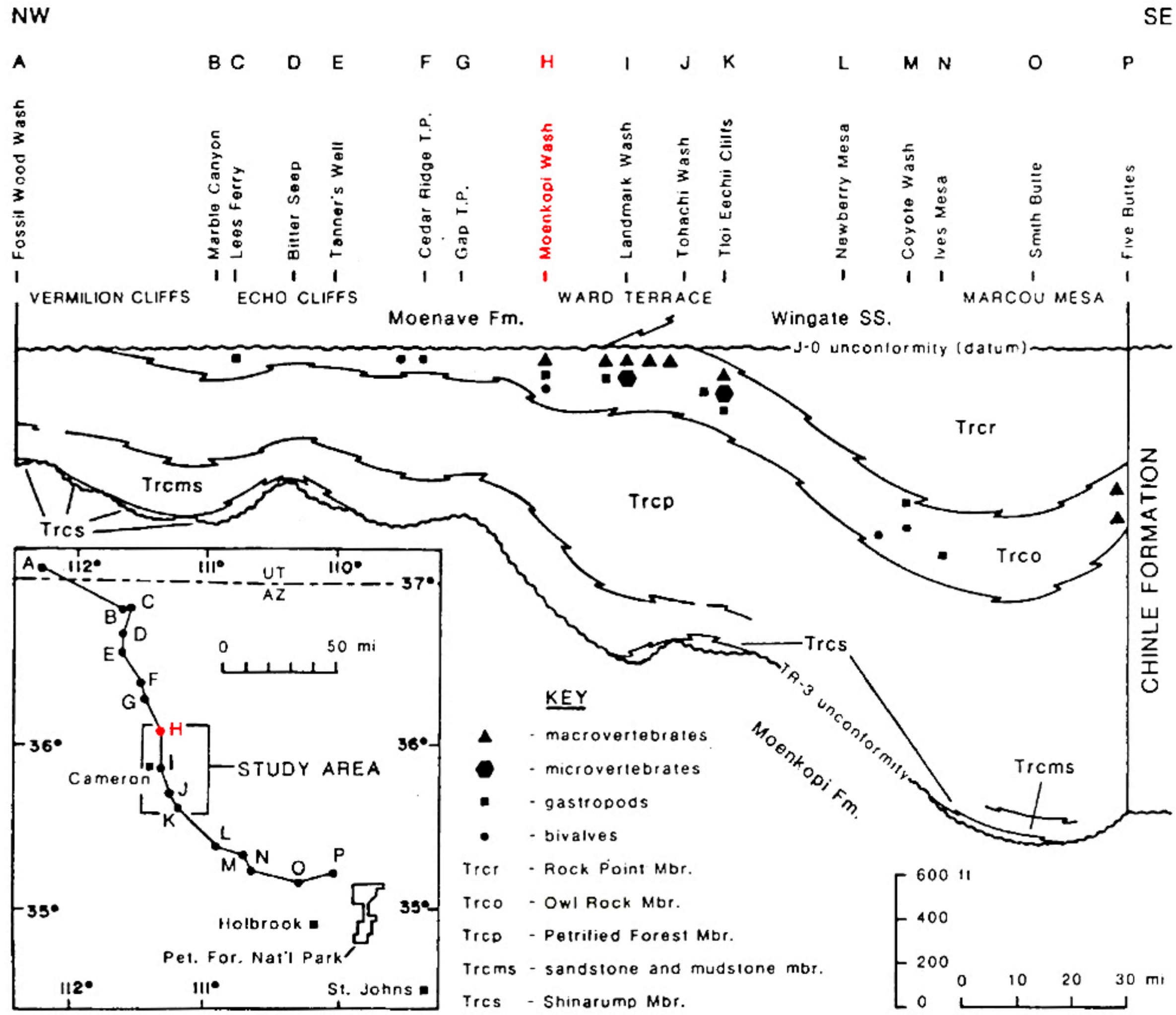

Figure 2.1: Cross section along Vermillion, Echo and Adeii Eechii cliffs to near Petrified Forest National Park (from Kirby [119]). Stop 2.1 is a Moenkopi Wash area (in red).

Chinle Formation: Owl Rock Member

We are standing on the Owl Rock Member, the uppermost member of the Chinle Formation in this area. It is strikingly banded lavender, yellow, red and orange siltstone with abundant benches of carbonate. These are a mixture of lacustrine, pedogenicly modified lacustrine and pedogenic carbonates that exhibit a cyclicity of unknown origin [120]. Unlike much of the Chinle Formation, individual beds of carbonate and mudstone can be traced for kilometers in the Owl Rock Member.

The Owl Rock Member rests conformably and gradationally upon the Petrified Forest Member, which we passed through as we headed north to this stop. It is a distinctly lighter red than at its type section in Petrified Forest National Park. The Dinosaur Canyon Member of the Moenave Formation overlies the Chinle Formation here separated by what is supposed to be the Tr-3 regional unconformity. We can make some estimates of the duration of the of the Owl Rock in this area and assess the duration of what if anything might be missing.

According to Kirby [119] the Owl Rock Member is ~96 m thick in this area (Moenkopi Wash). Assuming the accumulation rate is the same here as it is for the Petrified Forest Member at Petrified Forest (~34.6 m/Myr [35]) and the base of the Owl Rock Member is the same as at Petrified Forest, the duration of the Owl Rock Member would be only 2.8 Myr, and the top of the member would be at ~206.5 Ma (209.6 - 2.8 = 206.5 Myr, where 209.6 is age of the basal Owl Rock Member extrapolated from the CPCP-1 1A core [35]) This late Norian age seems incompatible with the ≤207.8 Ma [24] age in the lower Owl Rock from the Park, suggesting a hiatus of ~5 Myr. However, the Owl Rock Member thickens to the southeast toward Petrified Forest, and the sandy Rock Point Member of the Chinle appears between the Owl Rock and Moenave members and thickens dramatically in the same direction (Fig. 2.1). We do not know if the Rock Point Member is a lateral facies equivalent of the Rock Point or if the combined members decrease in thickness by erosion or by a lower accumulation rate. Nonetheless, in the vicinity of Petrified Forest, 350 m of combined Rock Point and Owl Rock are exposed. At the accumulation rate at Petrified Forest, this spans ~10.1 Myr, and when added to the age of the top of the Petrified Forest Member, suggests a date of ~199.5 Ma which means there is ample rock thickness to span the rest of the Triassic, given these loose constraints.

Looking north we can see the area of the next stop (2.2) in the Kayenta and Moenave formations. The boundary with the Moenave Formation is marked by a transition to more orange hues and the boundary with the Kayenta by a return to more pastel colors.

Stop 2.2 (36.111392°, -111.327692° to 36.103131°, -111.318135°) Tracksite and Stratigraphy – Moenave and Kayenta Formations

Main Points:

1) Stratigraphy of upper Moenave Formation and transition into lower Kayenta Formation in 1.3 km transect of 6 stations.
2) Continuation of episodic lacustrine deposition from Moenave Formation
3) Appearance of eolian sequences
4) ?Megatracksite?

Indian Route 23 closely follows the east side of the Moenave-Kayenta contact, on the basal Kayenta Formation as currently identified starting at its intersection with US, Route 160. These outcrops are unusual because not only did they produce the first skeletons of the iconic dinosaur *Dilophosaurus wetherelli*, but they are also host to a huge and famous track site with abundant *Eubrontes giganteus*. These tracks were plausibly made by that species or ones like it and other tracks and traces, and provide very important context for the regional geology and environmental interpretation.

Our stop is divided into six stations; we pass by the main track site (Station F), which we will return to, and proceed to station A where we will have an overview of the sequence. We will then go as far north and up section as we can (station B), given our time constraints, and then proceed back south to stations C, D, E and F.

Station A: (36.105549°, -111.318794°) overview of Moenave-Kayenta Transition

Park vehicles off dirt roads and proceed down the wash (south east) to the first distinctly purple mudstone (36.104535°, -111.320281°). As designated in the literature, we are in the Dinosaur Canyon Member of the Moenave Formation [113]. This purple mudstone is one of several discrete beds of lacustrine mudstones that occur in this area. These beds have yielded fish fragments and coprolites thus far. The occurrence of these laterally traceable units recalls the Whitmore Point Member which is not reported here.

Walking up section, there are several more mudstone levels and interbedded sandstone (up to 5-meter-thick) that Lucas et al. [107, 113] identifies as the Springdale Sandstone. It is not unusually thick for sandstones in the Moenave or Kayenta formations and this particular sequence disappears to the south towards Moenkopi Wash. *Eubrontes* footprints are present on the upper surface of this sandstone sequence and appear contiguous with the main surface at station F. The footprint surface is overlain by a few centimeters of heavily bioturbated siltstone and then red mudstones with darwinulid ostracodes and spinocaudatans. Further up section we see the cyclically alternating lacustrine mudstones and tabular sandstones designated basal Kayenta Formation. Higher in the section and in the distance, we can see eolian lenses within the Kayenta Formation. A plausible hypothesis is that the proportion of sandstones in the Whitmore Point Member increases in this direction and becomes very similar to the Silty Facies Member of the Kayenta Formation. This can be tested with paleomagnetic polarity stratigraphy. Looking directly ahead to the west/northwest is the possible locality of the type specimen of *Dilophosaurus* (Adam Marsh, pers. comm.) [39, 121].

Station B: (36.111392°, -111.327692°) lower Moevave and eolian strata

Proceed to the north until we are opposite several low rounded hills of rock. The large scale planer crossbedding is characteristic of eolian dunes. The base of the eolian sandstone rests on purplish silty sandstone with large white possible burrow about 5.6 m above the projected track position. The *Dilophosaurus* level seems to project to between the top of the eolian sand in the foreground (+3 m) and the base of the fluvial sandstone, 5 meters higher. There is a discontinuous purple mudstone below the aforementioned fluvial sandstone that has coprolites and bone fragments at this locality. Lacustrine strata continue at these levels and higher in the silty facies of the Kayenta.

Station D: (36.109132°, -111.323565°) distant confirmed main track layer

The sandstone bench on the east side of the road on the small wash has *Eubrontes* tracks on its upper surface as well as the characteristic bioturbated bed above. This is the furthest confirmed northern extent of the main track bed surface.

Station C: (36.109489°, -111.325303°) inverted theropod footprints of ?main surface?

What is either the same surface as the main track-bearing plane at station F or one stratigraphically adjacent to it, crops out on the west side of the roadbed. Topographically inverted *Eubrontes* tracks occur here, showing a surprising amount of detail. Lesser distinct smaller brontozoids are present as well.

Figure 2.2: (Left) Inverted (stand-alone) natural cast of left pes impression of *Eubrontes giganteus* resembling "*Anchisauripus minusculus*".

Station E: (36.108515°, -111.322858°) enigmatic but spectacular ?tracks?, cyclical lower Kayenta and cyclical lacustrine strata.

Figure 2.3: Left, Enigmatic traces resembling small sauropod footprints at stop 2.2, Station E (hammer is 30 cm long). Right, sauropod tracks from the Cretaceous Cal Orcko site Boliva (larger tracks are ~70 cm long) from [122].

Numerous large (>30 cm) and smaller (~3 cm), semicircular indentations with rims appear as if they were squeezed up around the depressions (Fig. 2.3). Superficially, they resemble sauropod trackways such as those at Cal Orcko, Bolivia [123]. These could be footprints, however, in the absence of clear toes or trackway patterns, we remain skeptical. An alternate possibility is that they are inorganic features. That said, they really look like tracks!

This bed, like the underlying main trackway surface, is part of a cyclical sequence of apparent transgressive-regressive cycles with the sandstone beds being part of the transgressive sequence. The cycles are so thin (~0.70 – 1.00 m) that they show up best cut obliquely in the road bed (Fig. 2.4). The bundling suggests a precessional cycle control, but the apparent subdivisions suggest a short-eccentricity regulator, if they are orbitally paced at all.

Figure 2.4: Meter-scale transgressive-regressive cycles obvious in road bed in basal Kayenta Formation at Station E. White bands are sandstone beds, the lowest of which (on left) is the main track surface of station F. GoogleEarth image.

Station F: (36.103131°, -111.318135°) main track layer, ?Megatracksite?

This is the famous Moenave or Moenkopi track site in the basal part of the Silty Facies Member of the Kayenta Formation. At this location, the Kayenta Formation yields brontozoid footprints that are predominantly assigned to the ichnogenera *Eubrontes* sp. and *Grallator* sp. [124]. Of particular import is the relatively thin (≤ 5 m thick) sandstone capped by the main track surface. This narrow interval yields tracks (mostly of *Eubrontes*) from St. George, Utah to Tuba City, Arizona, and has been referred to as the Springdale megatracksite [113].

This site also contains the holotype specimens of *Dilophosauripus* and *Kayentapus* that PEO regards as extramorphological variants of *Eubrontes giganteus* – that is they look different from *Eubrontes* for reasons having nothing to do with species or generic differences among track makers, but rather with substrate. Among ichnologists (footprint workers) this would seem to be a minority view [125], although *Dilophosauripus* has received much less attention. These are important as they bear on the diversity of theropod dinosaurs during the recovery from the ETE.

Eubrontes itself has foot morphology consistent with the feet of *Dilophosaurus* (Fig. 2.5), when the bones are properly reconstructed [62, 63], although as mentioned there are different opinions [65, 66]. However, the osteology of the feet of Triassic-Jurassic theropods tends to be so conservative it is doubtful the feet of the different taxa could be differentiated, not to mention their tracks. The superabundance of theropod dinosaur tracks seems to be part of the syndrome of the recovery from the ETE and may reflect fish-eating and opportunistic foraging, as discussed for SGDS.

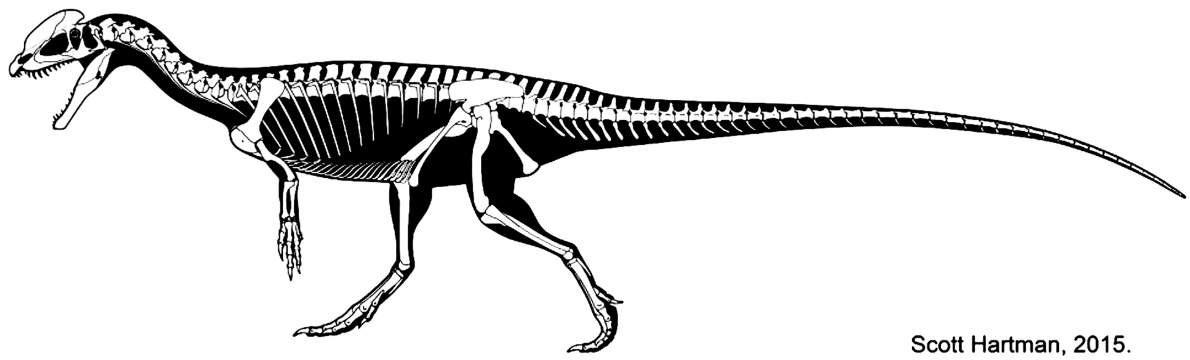

Figure 2.5: Reconstruction of *Dilophosaurus* based on 37302 and 43646 from [126]

The exact sequence of lithologies for this transgressive-regressive couplet seems specific for each cycle. In this case, there is a distinctive, highly bioturbated siltstone comprised of burrow fills that falls apart on weathering, looking like small plastic packing peanuts (Fig. 2.6). We can trace these thin beds for at least 2.5 km, from station C to the canyon for Moenkopi wash where the mudstone overlying the bioturbated unit becomes coarser and the underlying thin sandstone disappears. The track itself is separated from the underlying fluvial sandstones by siltstones and is not part of the same depositional unit what is identified here as “Springdale Sandstones”; this is the case for all of the track sites supposedly part of the Springdale megatracksite. It remains unclear how large each of these lakes were, but that will be important for linking cores and outcrops by lithostratigraphy.

Figure 2.6: Attenuated track surface (below hammer) with overlying bioturbated siltstone with burrow fills and succeeding lacustrine mudstone making a sequence specific (at least locally) to that cycle. Outcrop is at 36.097758°, -111.310438° about 1 km southeast of station F. Within 200 m south east of this spot the pattern fades out. Hammer is 30 cm long.

Stop 2.3 (35.775047°, -111.072362° - parking spot) Gold Spring Transect of Navajo, Kayenta, and Moenave Formations of Glen Canyon Group

Main Points:

1) Entire Kayenta Formation exposed – all silty facies
2) Zircon-bearing siltstones
3) Lacustrine mudstones common – cyclical?
4) Tetrapod-bearing lacustrine sequences
5) Contact with Moenave Formation and Springdale Sandstone is absent
6) Primary coring objective

This difficult to access site at Gold Spring on the Adeii Eechii Cliffs is one of the classic Kayenta localities. The entire formation is exposed along with the lower Navajo and Moenave formations. We will walk down from this point into the Navajo and Kayenta formations, and if time permits, reach the contact with the Moenave Formation.

Navajo Formation

The Navajo Formation is the classic western Mesozoic erg, reported to represent Earth's largest sand sea [127]. We saw some of this immense unit at Stop 1.4, but here we will get a close up look. There is a vast literature on the Navajo, which cannot be reviewed here; instead, we will focus a few salient points. The first is that as we descend though the formation note the cyclical repetition of white, tan and yellow large-scale cross-stratified sandstone with beds of brown-weathering carbonate beds.

The Navajo Formation is thought to have been originally red-brown (from hematite) in color with the drab and yellow colors seen here attributed to secondary "bleaching" by the reducing action of natural gas, implying that these units were originally a hydrocarbon reservoir – in fact a major reservoir [128]. The yellow staining that we see looks like it might be a product of pyrite weathering, although this is speculation. If the iron in the Navajo is secondarily reduced, this of course has implications for recovering a meaningful magnetic polarity record from this sandstone, although that might be doubtful in any case. The former (or present) presence of natural gas is also a concern for coring.

The interbedded carbonates are particularly interesting as they have remnants of the interdune (spatially and temporally) biota. Here we can see possible examples of "arboreal" stromatolites. Various plant remains and burrows have also been found in these beds and other interdune clastic strata in the Navajo Formation elsewhere [129], although these beds have not been recently prospected. They have also been described as analogs for Martian habitable areas [130].

A plausible hypothesis for their formation is that they represent clastic-starved lacustrine deposits in low areas formed by ground water seepage that both stabilized the dune deposits and filled the low spots. As such, they may be equivalent to muddy lacustrine deposits outside of the dune areas, forming in topographically higher areas bypassed by the fluvial systems of the Kayenta Formation. Presumably they would not have formed in the same climate regime as the dunes themselves and could mark out times of precessional variance maxima. These carbonates might also be an excellent place to look for depositional-age zircons, in as much as they received so little clastic input.

Kayenta Formation

As we descend into the Kayenta Formation, note the tongues of the Navajo Formation (Fig. 2.7) and surrounding lake carbonates. This is the expected pattern if the carbonates of the Navajo Formation represent lake high stands in elevated areas where the clastic systems could not reach. Some of these clastic interbeds are gray and may be palynologically productive.

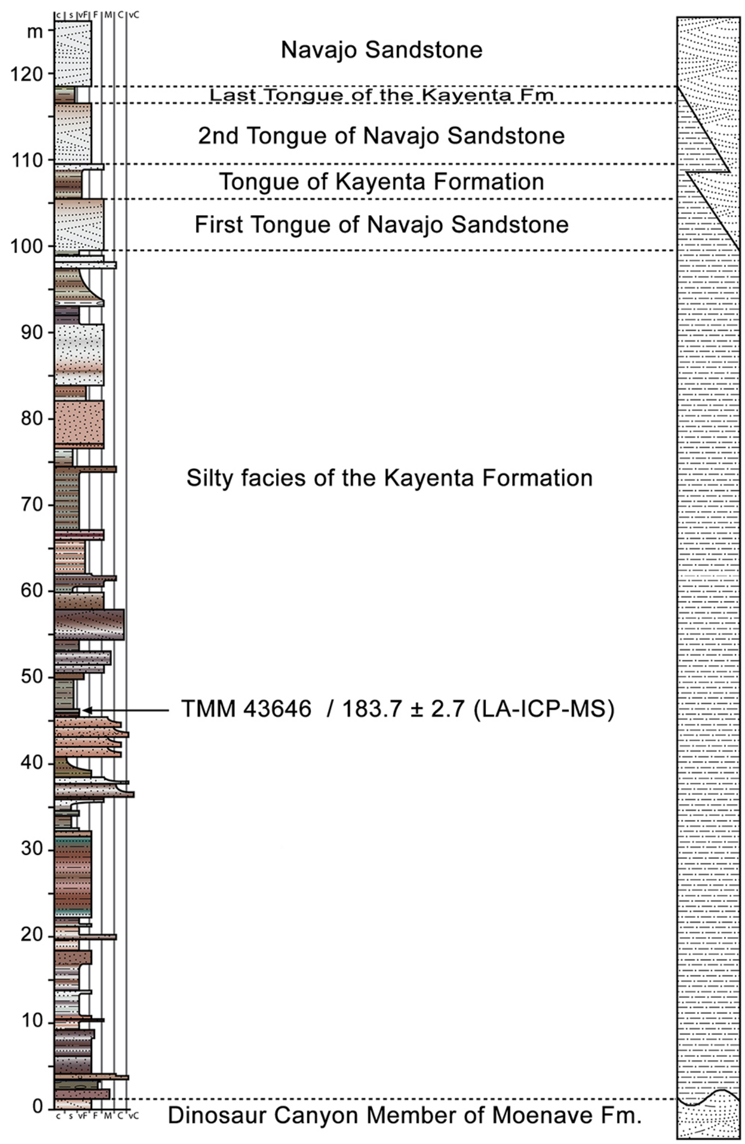

Figure 2.7: Measured section of Kayenta Formation at Gold Spring, Stop 2.3. Figure is from Marsh and Rowe [43] and is slightly reformatted. Date is added from [42].

Siltstones of this facies produce zircons that yield potential depositional ages. Marsh et al. [42] recovered zircons form the matrix of the sauropodomorph dinosaur *Sarahsaurus* (TMM 43646) [43] that yielded a zircon age of 183.7 ± 2.7 Ma which is a Late Pliensbachian or early Toarcian age. Other levels in the Kayenta Formation have produced zircons with ages (unpublished) consistent with this time of deposition and hold great promise for detailed temporal calibration of the Glen Canyon Group. In addition, although no paleomagnetic polarity stratigraphy has been published for this section, existing data [131] are consistent with polarity sequences from elsewhere in the Kayenta Formation [34], also consistent with a Sinemurian to Toarcian age, and show that a polarity sequence could be recovered here. These features make the silty facies of the Kayenta Formation a primary coring target.

The Kayenta Formation has produced a rich and varied fauna [43, 121, 132-146], much of which hails from these outcrops. We do not report locality details to protect the *in situ* resources, but these are available upon request for appropriate parties. Although the the age of the formation was long considered Triassic or Triassic-Jurassic, the Kayenta Formation was determined to be Jurassic on the basis of comparisons of footprint, faunal, and palynomorph assemblages in the late 1970s and early 1980s [40, 41, 133] with most authors agreeing on a Sinemurian-Pliensbachian age [132]. This fauna is strikingly modern in appearance, especially in the aquatic environments, with turtles, frogs, and modern-aspect crocodiles, many of which occur in the lacustrine mudstones seen here. These mudstones appear cyclical, although the origin of the cycles and possible periodicity remains unexplored.

Figure 2.9: Contact between the Moenave and overlying Kayenta formations at Gold Spring (35.748633°, -111.096894°). Here the basal Kayenta formation is partly silicified.

The contact with the Moenave Formation in this area lacks any sign of the Springdale Sandstone, and unlike at Stop 2.2 there are no lacustrine mudstones below the contact (Fig. 2.8). The contact does, however, mark a dramatic break in slope, with the basal Kayenta Formation partly silicified. Is this silicification related to an overlying lacustrine unit? Is the basal Kayenta Formation here correlative to the basal Whitmore Point Member of the Moenave Formation? How can we test these competing hypotheses – or if a significant hiatus exists at the contact, as suggested by Lucas and Tanner [107]?

End of Field Trip

Acknowledgements

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Author Contributions

PEO, designed the field trip, ran the pre-trip, contributed data and interpretations, wrote the guidebook and produced the figures; JHW, designed the field trip, contributed data and interpretations, ran the pre-trip, and wrote the guidebook; STK, edited the guidebook, organized the field logistics; ARCM, contributed data and interpretations and contributed figures; CAS, contributed data and interpretations and contributed figures; ADM, contributed data and interpretations and contributed figures.

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