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Mesozoic Lakes of the Colorado Plateau

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ABSTRACT

The Upper Triassic Chinle Formation and the Upper Jurassic Morrison Formation preserve a record of lacustrine deposition along the western margin of tropical Pangaea and post-Pangaean North America. The lake deposits in these formations contain archives of sedimentary and geochemical paleoclimatic indicators, paleoecological data, and characteristic stratal architecture that provide glimpses into the evolution of basins linked to global- and continental-scale tectonic events and processes, and the establishment of a mosaic of continental paleoecosystems. This field trip highlights the lacustrine and associated fluvial deposits of the Monitor Butte Member of the Chinle Formation and the Tidwell and Brushy Basin Members of the Morrison Formation in the southern part of the Colorado Plateau region, with emphases on: (1) sedimentary facies analysis and paleogeography of the paleolakes; (2) stratal architecture and high-frequency sequence stratigraphy; (3) recognition of lake basin-fill types; and (4) paleontology and ichnology of lake strata and their paleoecologic, paleohydrological, and paleoclimatic interpretation.

Keywords: lakes, Chinle, Morrison, Colorado Plateau, paleoclimate, paleoenvironments, paleoecology.

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INTRODUCTION

This field trip highlights some of the Mesozoic fluvio-palustrine-lacustrine deposits of the Colorado Plateau region of southern Utah and examines the evolution of ancient lake systems and their associated paleoecosystems reconstructed from the sedimentary and paleontologic record. Data used in these reconstructions include stratal architecture, paleosols, continental ichnofossils, and a rich fossil fauna and flora. Primary themes of the trip include (1) Permian-Jurassic stratigraphy; (2) continental depositional systems; and (3) Pangaean to post-Pangaean tectonics, paleogeography, paleohydrology, and paleoclimate. Field stops examine fluvio-palustrine-lacustrine deposits formed under tropical monsoonal climatic conditions, including those of the Upper Triassic Chinle Formation in Glen Canyon National Recreation Area and Capitol Reef National Park, Utah (Fig. 1). Other stops examine palustrine-lacustrine deposits formed under tropical wet-dry climate conditions, including the Upper Jurassic Morrison Formation in Moab, Four Corners (Utah, Colorado, New Mexico, and Arizona), Henry Mountains, and Capitol Reef National Park areas, Utah (Fig. 1).

The continental succession of Mesozoic strata of the Western Interior of the United States provides a valuable basis for reconstructing the paleoenvironments through a critical interval of geologic time. The Morrison Formation is known worldwide to contain a large diversity of dinosaur fossils including some of the largest herbivores that ever roamed the planet (Dubiel, 1989a; Parrish, 1989). Since the great dinosaur-bone wars of the late 1800s, geologists and paleoecologists have been interested in the details of the numerous habitats of tropical western Pangaea. The most recent studies of the Morrison Formation interpret the distribution of environments and their associated biotic communities, describing the Late Jurassic extinct ecosystem as part of a complex landscape mosaic, the components of which have shifted through time (Carpenter et al., 1998; Gillette, 1999; Turner and Peterson, 2004).

The importance of interpreting continental paleoecological archives associated with the Mesozoic sedimentary succession of the Colorado Plateau is underscored in studies of the early diagenetic mineralogy (Turner and Fishman, 1991), geochemical isotopes (Dunagan and Turner, 2004), preserved invertebrate fauna (Schudack et al., 1998; Good, 2004), associated flora (Parrish et al., 2004), continental ichnofossils (Hasiotis, 2004), and paleosols (Demko et al., 2004) of lacustrine and related strata. The study of continental waterways in this succession of ancient landscapes—namely, its rivers, floodplains, wetlands, and lakes—are of particular interest, because water controls

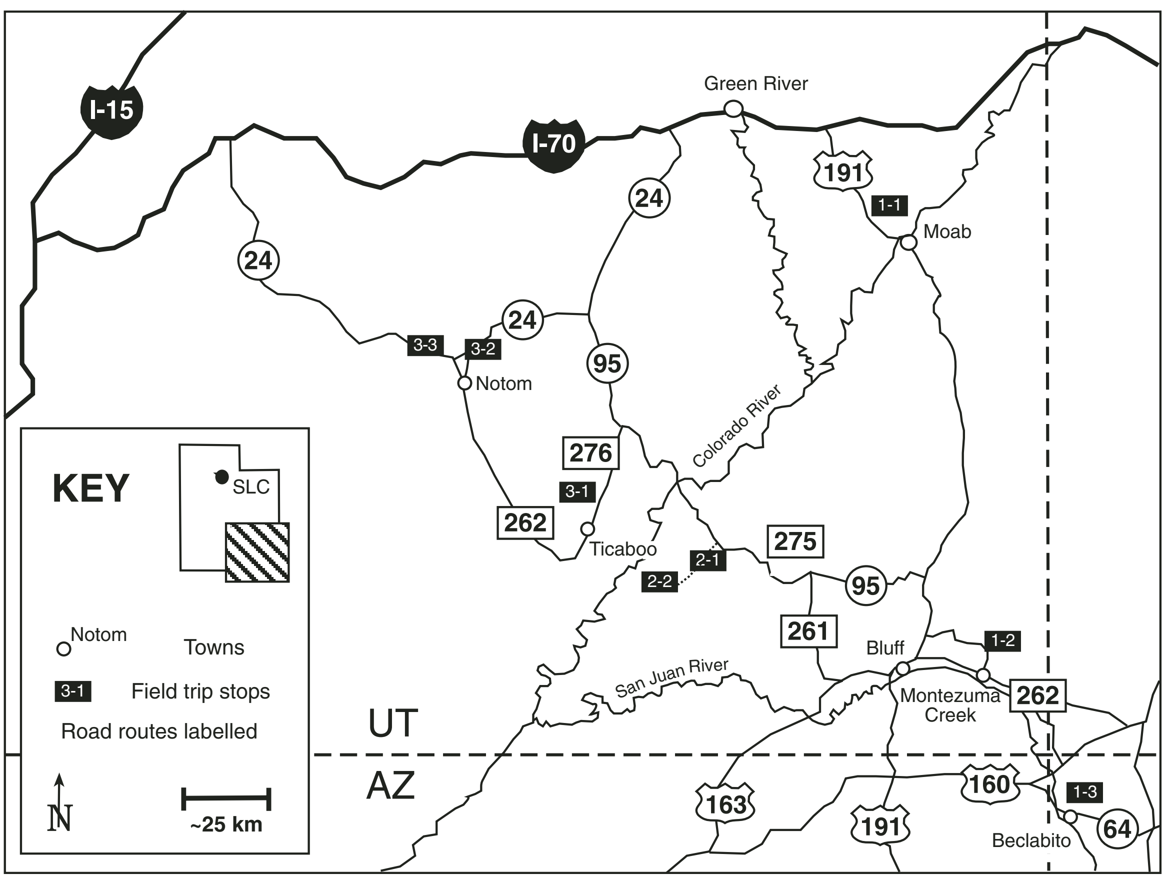

Figure 1. Location map of field trip stops.

the occurrence and distribution of organisms and their activities (e.g., Parrish, 1989; Fiorillo et al., 2000; Engelmann et al., 2004; Hasiotis, 2004). Understanding the significance of aquatic deposits and their associated physical, chemical, and biological components is particularly useful in reconstructing a conceptual paleohydroclimatic framework (the ancient hydrologic and climatic setting) for a particular depositional unit.

Current models of modern and ancient lacustrine depositional systems interpret strata in the context of three major facies associations at various scales from beds to members or parasequence to depositional sequence to sequence-set at the scale of meters to hundreds of meters. These facies associations exhibit a characteristic stacking pattern as lake basins fill (see Bohacs et al., 2000, and references therein). Three end-member lithofacies associations are recognized generally on objective physical, chemical, and biological criteria: fluvial-lacustrine, fluctuating profundal, and evaporative (Carroll and Bohacs, 1999). The fundamental controls on these lithofacies associations in space and time include lake morphometry and water depth. These controls are a function of the relative balance of rates of potential accommodation change (eustatically and tectonically forced) and sediment + water supply (hydroclimatically-forced) (Einsele and Hinderer, 1998). Models predicting lake occurrence, distribution, and character link the three most common facies associations with distinctive lake-basin types: overfilled, balanced-fill, and underfilled lake basins (Bohacs et al., 2000). The fluvio-lacustrine deposits examined on this field trip will be described and interpreted within this lake basin classification system.

PALEOGEOGRAPHIC SETTING AND STRATIGRAPHY

During the Triassic, the supercontinent Pangaea was positioned symmetrically across the equator, with exposed land extending from ~85°N to 90°S (Ziegler et al., 1983; Blakey et al., 1993) (Fig. 2A). Global sea level was low throughout the Permian and the Triassic (Vail et al., 1977), and Pangaea disrupted nearly every part of the zonal circulation due to its large size, resulting in a high degree of continentality of climate. The location of the large landmass in low latitudes and the presence of a warm seaway that acted as a moisture source maximized summer heating in the circum-Tethyan part of the continent (Parrish, 1993). The resultant Pangaean climate was likely seasonally wet-dry, or megamonsoonal (Parrish et al., 1986; Dubiel et al., 1991).

As Pangaea broke up and North America moved north, the exposed land area was distributed more evenly on either side of the equator. Seasonality intensified through the Triassic, and the equatorial regions and mid-latitude continental interiors became more arid when the monsoonal circulation was at its maximum (Parrish, 1993). Further breakup of Pangaea eventually disrupted the megamonsoonal circulation pattern, and global climate gradients became more latitudinal. However, global climate models (GCMs) (Moore et al., 1992; Valdes and Sellwood, 1992) also suggest that a semiarid to arid climate persisted in the Western Interior through the Late Jurassic. A high-pressure system dominated southwestern North America, with surface temperatures of 30–40 °C in the summer and 0–20 °C during the winter. Estimated rainfall amounts and precipitation-evapotranspiration (P/E) ratios from the GCMs (Moore et al., 1992; Valdes and Sellwood, 1992) suggest direct meteoric contribution may have been minimal.

Upper Triassic Chinle Formation

The Chinle Formation was deposited in a broad, fully continental, cratonic basin created by subsidence due to viscous flow in the mantle associated with the subduction of the Farallon plate and flexure due to supracrustal loading by the associated volcanic

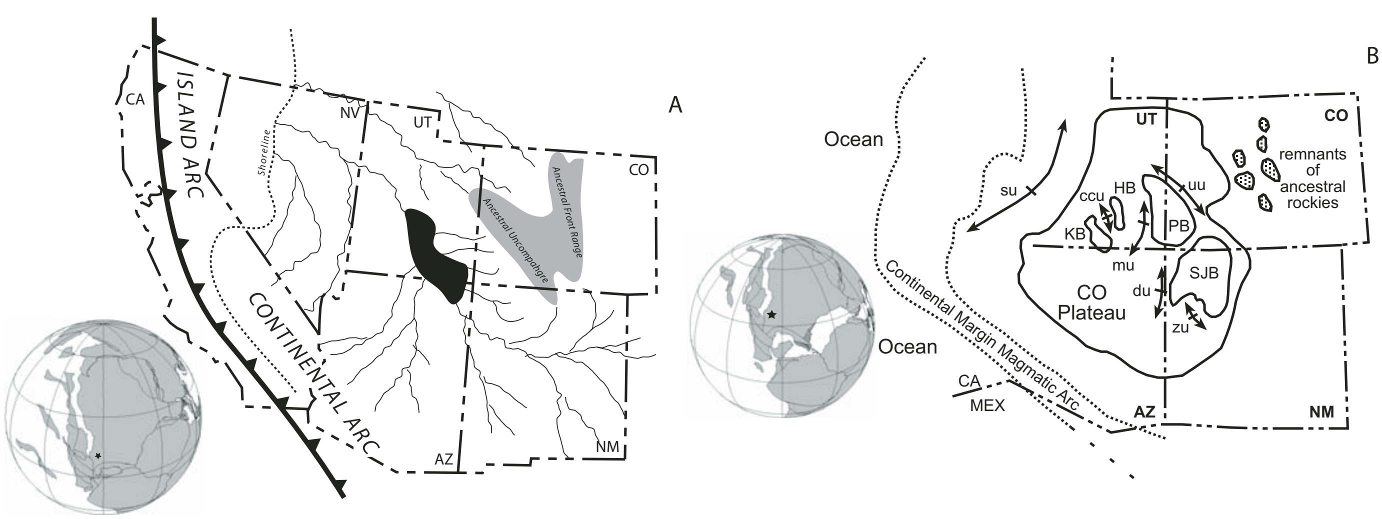

Figure 2. Paleogeographic maps of western North America during: (A) the Late Triassic and (B) the Late Jurassic. Position relative to global paleogeography noted on inset global plate reconstructions.

arc (Lawton, 1994). The vast, >2.5 million km^2 Chinle basin was along the tropical west coast of the supercontinent Pangaea between 5–15°N paleolatitude (Dubiel, 1994) (Fig. 2A). The Chinle Formation consists principally of fluvial, floodplain, palustrine, and lacustrine deposits with minor eolian and playa environments present at the close of Chinle time (Blakey and Gubitosa, 1984; Dubiel 1989b). Various petrographic, sedimentary isopach, stratigraphic, and paleontologic evidences suggest that the sediment sources were the Mogollon Highlands in Arizona and the Uncompahgre and Front Range highlands of the Ancestral Rocky Mountains in Colorado. The Mogollon Highlands and the adjacent magmatic arc system contributed both volcanic and sedimentary detritus to the lower part of the Chinle Formation in the southern part of the basin (Stewart et al., 1972; Riggs et al., 1996).

The lower part of the Chinle Formation (Shinarump, Monitor Butte, and Moss Back Members) was deposited in a succession of valley-fill sequences under monsoonal climatic conditions (Demko, 1995; Demko et al., 1998). The upper part of the Chinle Formation (Petrified Forest, Owl Rock, and Church Rock Members) was deposited in a regionally dynamic basin complex of alluvial-lacustrine systems (Stewart et al., 1972; Dubiel, 1989a, 1994) (Fig. 3). Vertic paleosols and cyclic lacustrine facies are among the sedimentologic and paleopedologic evidence that suggest the Chinle basin was characterized by strongly seasonal precipitation, with distinctive wet and dry seasons (Dubiel et al., 1991). The Chinle Formation is well known as one of the richest Late Triassic fossil plant–bearing units in the world (Ash, 1980; Demko et al., 1998), with over 70 plant taxa, including lycopods, ferns, cycads, conifers, bennettitaleans, seed ferns, and several other unclassified forms in the published literature. The fossil floral physiognomy (Ash 1967, 1972, 1980; Ziegler et al., 1993) and vertebrate paleoecology (e.g., Parrish et al., 1986; Parrish, 1989) are among the paleontologic evidence that contribute to a reconstruction of the Chinle paleoenvironment.

The Chinle Formation preserves an abundant and diverse continental ichnofauna upon which much of the paleohydrologic interpretations of Triassic tropical Pangaea have been made (Hasiotis and Dubiel, 1993, 1994, 1995a, 1995b; Hasiotis and Mitchell, 1993; Hasiotis et al., 1993, 2004). Trace-making organisms and trace fossils can be placed into behavioral categories that indicate the space, trophic associations, and groundwater moisture zones occupied by organisms (Hasiotis, 2000). The tiering of above- and below-ground trace-making organisms in Chinle deposits indicates that their distribution was controlled in part by annual and seasonal fluctuations of unsaturated (soil moisture) and saturated (water table and phreatic) zones, which in turn was controlled by regional climate (Hasiotis and Mitchell, 1993; Hasiotis and Dubiel, 1994) (Fig. 4). Traces of crayfish, bees, beetles, soil bugs, and plant roots are the preserved products of the water balance in paleosols that record the relation between annual precipitation inputs, solar radiation, evapotranspiration losses, and soil moisture. This information, combined with other paleontologic, sedimentologic, stratigraphic, isotopic, and paleogeographic data, suggests spatial and temporal variations associated with tropical monsoonal climates during deposition of the lower Chinle Formation to increasingly arid climate at the end of Chinle deposition (e.g., Dubiel and Hasiotis, 1994a, 1994b, 1995). For example, the great depth, wide distribution, and high abundance of crayfish burrows in the Shinarump, Temple Mountain, Petrified Forest, and Owl Rock Members suggest that influent rivers were fed by the local and regional saturated zone (Hasiotis and Mitchell, 1993; Hasiotis et al., 1993). Adhesive meniscate burrows (AMB), constructed by beetles (adults and larvae) or soil bugs, co-occur with rhizoliths and the upper parts of crayfish burrows, reinforcing the interpretation of moderate soil moisture levels in the unsaturated zone (Hasiotis and Dubiel, 1994, 1995b).

Upper Jurassic Morrison Formation

This unit, famous for abundant dinosaur fossils, but also containing abundant and diverse plant, invertebrate, and trace fossils, was deposited throughout the Rocky Mountain region from New Mexico to Montana between 30 and 45°N paleolatitude (Peterson, 1994; Chure et al., 1998) (Fig. 2B). The Morrison Formation represents 7–8 m.y. of deposition from latest Oxfordian or early Kimmeridgian (ca. 155 Ma) to early Tithonian (ca. 148 Ma) (Kowallis et al., 1998; Litwin et al., 1998). The Morrison Formation includes the Tidwell, Salt Wash, and Brushy Basin Members in the Colorado Plateau area. The Tidwell Member interfingers with the Bluff Sandstone and Junction Creek Sandstone Members in the Four Corners region, whereas the lower Brushy Basin and Salt Wash Members grade into and interfinger with the Recapture and Westwater Canyon Members in the same area (Peterson and Turner-Peterson, 1987; Peterson, 1994) (Fig. 3).

The Morrison Formation consists of a succession of conglomerate, sandstone, siltstone, mudstone, limestone, and evaporites that were deposited in alluvial, lacustrine, palustrine, eolian, and continental-marine transitional environments (Brady, 1969; Peterson and Turner-Peterson, 1987; O'Sullivan, 1992; Peterson, 1994; Dunagan, 1998; Turner and Peterson, 1999). Many of the alluvial, lacustrine, palustrine, and eolian deposits within the Morrison Formation were modified by some degree of pedogenesis after deposition, producing a variety of immature to mature paleosols, some of which mark significant unconformities and can be correlated across the region (Demko et al., 2004).

Paleoclimatic interpretations for the Morrison ecosystem range from tropical wet-dry to arid, depending on the various indicators and the area and stratigraphic unit under study (see reviews by Dodson et al., 1980, and Demko and Parrish, 1998). Previous controversy over the paleoclimate of the Morrison Formation largely resulted from conflicting interpretations of the associated flora. Reevaluation of plant taphonomy and taxonomy led Parrish et al. (2004) to conclude that the paleoclimate was warm, seasonal, and semiarid, with the climate changing slightly from dry semiarid throughout most of Morrison deposition to humid-semiarid near the end of Morrison deposition. The semiarid climate in Morrison time probably exerted a primary

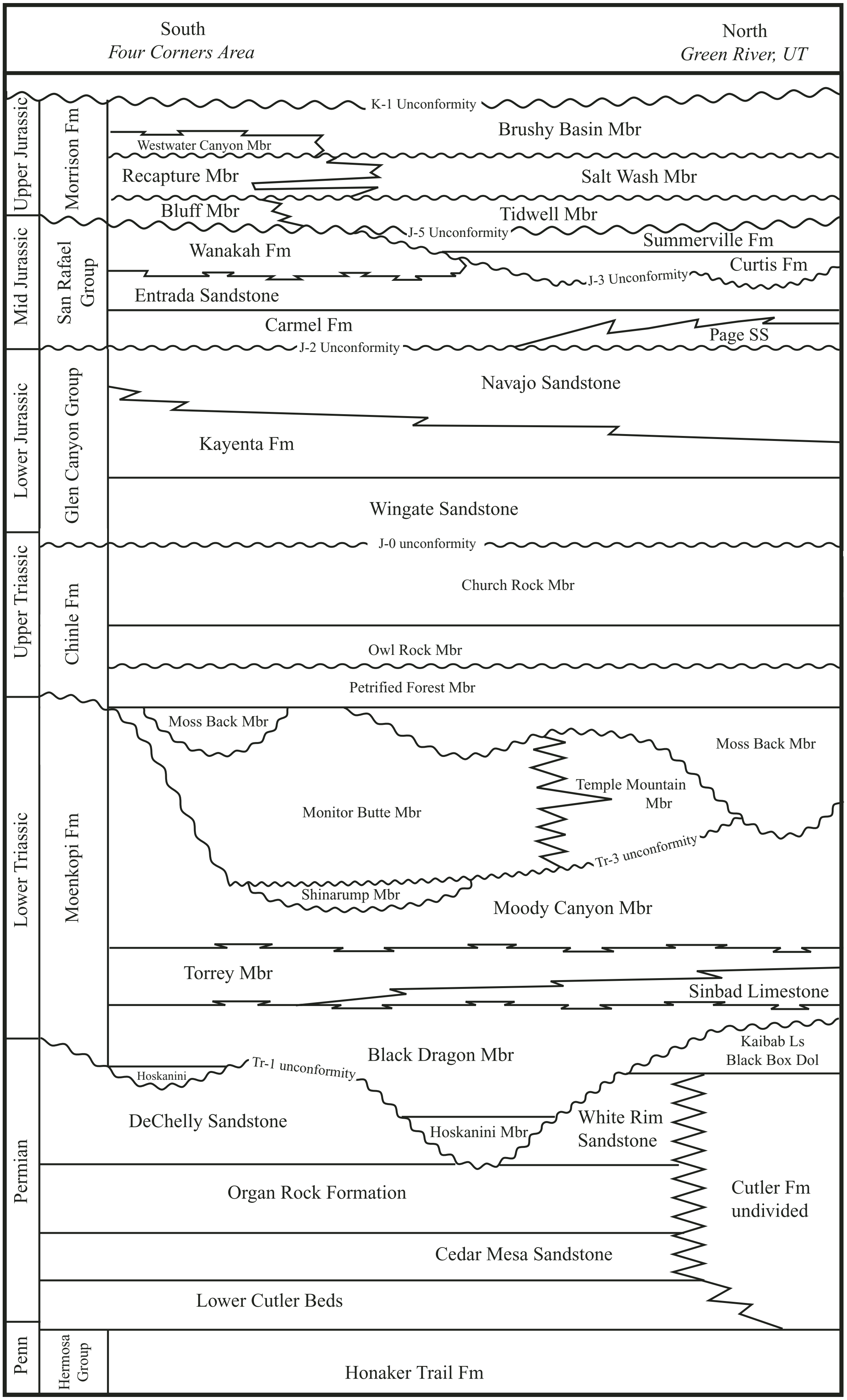

Figure 3. Upper Paleozoic through Upper Jurassic stratigraphy of the Colorado Plateau region. Regional unconformities from Pipiringos and O'Sullivan (1978).

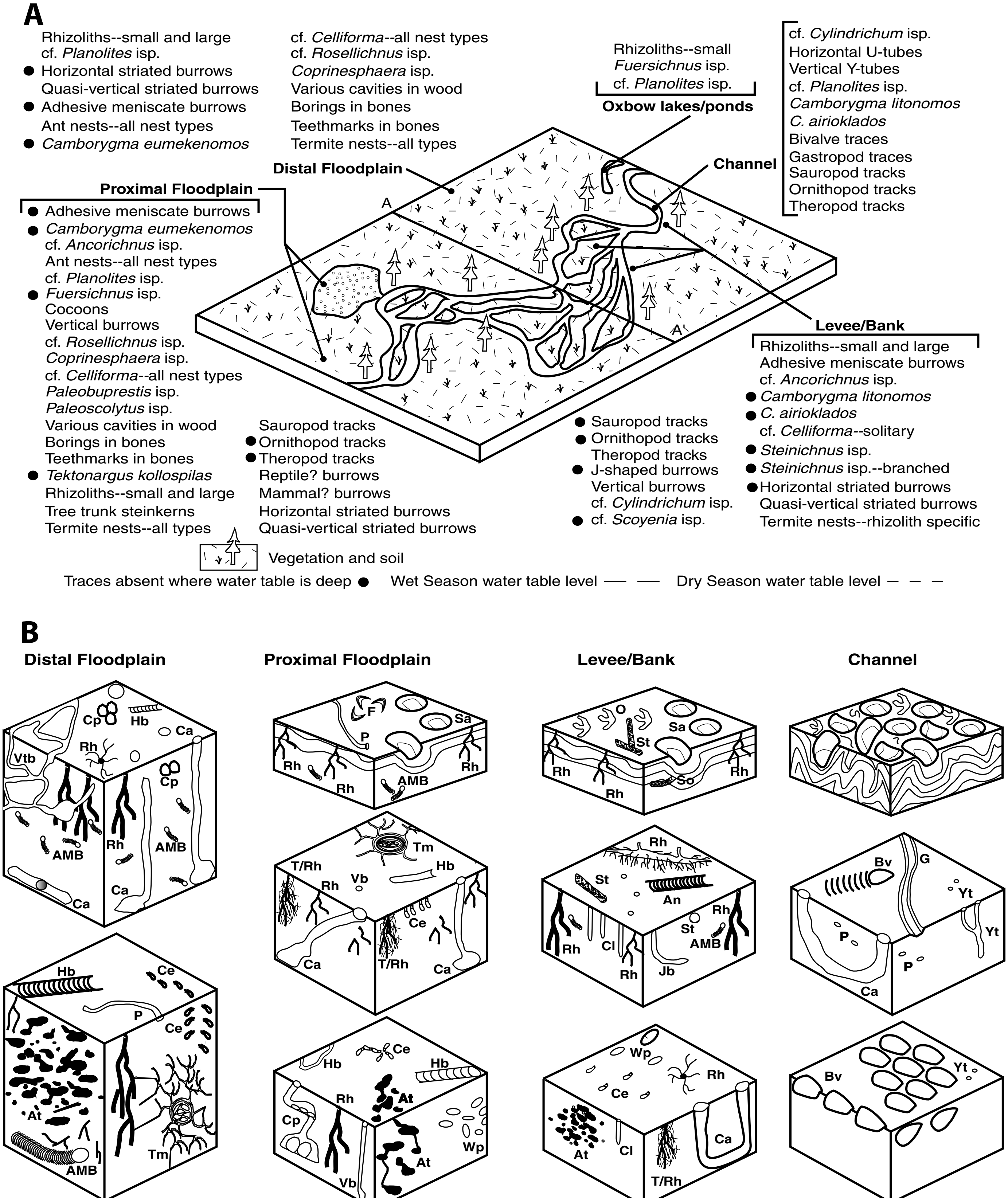

Figure 4. Trace fossils assemblages characteristic of proximal-to-distal alluvial deposits in typical Mesozoic continental settings. (A) Generalized spatial distribution of continental trace fossils in alluvial settings. (B) Trace fossil assemblages in alluvial deposits in relationship to sedimentation rate and hydrology in channel and overbank settings.

control on plant recruitment in the environment, which may have resembled a modern savannah. Ground cover in the floodplain regions was predominantly herbaceous, whereas woody vegetation was limited largely to riparian environments (Parrish et al., 2004). The distribution of rhizoliths, with larger ones limited to riparian environments and smaller ones locally present across the floodplain, is consistent with the plant taphonomic inferences drawn by Parrish et al. (2004).

The tiering of above- and below-ground trace-making organisms in Morrison deposits, in conjunction with other paleontologic, sedimentologic, stratigraphic, isotopic, and paleogeographic data, suggests spatial and temporal variations associated with tropical wet-dry to Mediterranean-type climates from the southern to the northern part of the Morrison basin (Hasiotis and Demko, 1996; Hasiotis, 2004). Traces of crayfish, termites, ants, bees, beetles, soil bugs, and plants are the preserved products of the water balance in paleosols that record the relation between annual precipitation inputs, solar radiation, evapotranspiration losses, and soil moisture changes during the Late Jurassic. For example, the limited depth, restricted distribution, and low abundance of crayfish burrows in the Salt Wash and Recapture Members suggest that rivers were effluent seasonally and fed the local saturated zone. Burrows with depths of 1–2 m are present close to paleochannels and in very proximal extra-channel environments that were weakly modified by pedogenesis. Termite nests, from <1 to >30 m in depth, indicate shallow to deep saturated zones in proximal to distal alluvial and eolian-derived deposits in the Salt Wash, Recapture, and Brushy Basin Members. Most nests occur in the shallow subsurface in well drained and oxygenated substrates (unsaturated zone) weakly modified by pedogenesis, with fewer and fewer galleries and chambers (fungal gardens, storage, and waste disposal) found deeper in the paleosols.

Seasonality of Morrison climate is further substantiated by analysis of annual growth bands in freshwater unionid bivalves from lacustrine beds and fluvial deposits (Good, 2004). Bivalve faunal associations suggest that some of the streams were perennial, although most of the streams in the depositional basin were intermittent. Extended periods of drought might account for some of the famous dinosaur death assemblages (e.g., Carnegie Quarry at Dinosaur National Monument); however, the ecosystem simultaneously sustained some of the most unusual life forms that ever roamed the planet. The semiarid climate interpreted for the Colorado Plateau raises issues about the availability of food and water resources for the large herbivorous dinosaurs (see Engelmann et al., 2004). To survive in such a resource-limited landscape, dinosaurs probably developed various adaptations. Engelmann et al. (2004) discuss how large size conferred an adaptive advantage to sauropods for traveling long distances, enabling the necessary migrations to resources across the landscape with a seasonally dry, semiarid climate. Similarly, scaling effects of large body size make large herbivores efficient relative to their size because they need proportionately less food, and food of lesser quality, than smaller herbivores (Engelmann et al., 2004). In sauropods, differences in dentition and range of neck movement have been used to infer styles of resource partitioning, a strategy suitable for survival in a resource-limited environment (Engelmann et al., 2004).

A viable alternative interpretation of available evidence suggests a tropical wet-dry climate in the southern part of the Morrison depositional basin and a transition to a Mediterranean-type climate in the northern part of the basin close to or at the edge of the Late Jurassic seaway (Hasiotis, 2004). Throughout Morrison time these paleoclimates fluctuated between seasonally drier and wetter years, similar to climates today (Lydolph, 1985). This fluctuation probably included extreme years with either extended periods of drought ($P/E < 1$) or precipitation ($P/E > 1$). The members of the Morrison Formation record high spatial heterogeneity produced by a mosaic of hydroclimates coupled with environments that included dune fields in transitional marine, alluvial, and lacustrine landscapes (Windy Hill, Tidwell, Bluff, and Recapture Members), rapidly aggraded to topographically dissected mixed alluvial landscapes (Salt Wash, Westwater Canyon, Brushy Basin Members), and freshwater to alkaline palustrine-lacustrine systems (Tidwell and Brushy Basin Members).

These Late Jurassic settings are analogous to modern climates that dominate the African savanna from ~14°N to 5°N latitude and 2°S to 22°S latitude. Modern environments in tropical wet-dry climates contain herds of megaherbivores (elephants, rhinoceros, wildebeests, zebra, and gazelle), predator-scavengers (several types of cats, hyenas, and wild dogs), groups of smaller vertebrates (various birds and rodents), perennial freshwater organisms (fish, crabs, clams, and snails), vast numbers of insects with varying degrees of eusocialism, as well as a variety of plants. This biodiversity is shaped by climate and supports the total biomass through a nutrient and energy cycle robust enough to maintain the ecosystem (e.g., Odum, 1971; Aber and Melillo, 1991; Martinez et al., 1999). Assuming that Jurassic plants, invertebrates, and vertebrate trophic groups such as herbivores, megaherbivores, and predators had water, temperature, and nutrient requirements with ranges of feeding behaviors proportional to their size and physiology comparable to those of extant African biota, then the diversity and distribution of Jurassic continental biota was likely similar to analogous environmental and ecologic settings in modern tropical wet-dry climates. Therefore, the ichnofossils, body fossils, sedimentary facies, paleosols, and geochemical and isotopic signatures of the deposits indicate spatial drier to wetter environmental, hydrologic, and climatic settings within a relatively short distance across the Morrison landscape from any one position at any given time (Hasiotis, 2004).

Mesozoic Lake Basin Types

Facies associations within members of the Upper Triassic Chinle Formation and Upper Jurassic Morrison Formation exhibit many of the characteristic stacking patterns of lake basin fill under different paleoclimatic settings. Lithofacies representative of fluvial-lacustrine, fluctuating profundal, and evaporative associations are recognized generally on objective physical, chemical and biological criteria in the Monitor Butte Member of the Chinle Formation, as well as in the Tidwell and Brushy Basin Members of the Morrison Formation. Hydroclimatic controls during the Late Triassic were dominated by a tropical monsoonal climate that produced varying amounts of sediment through time. Hydroclimatic controls during the Late Jurassic were dominated by a tropical wet-dry climate that experienced periods of seasonally greater and lesser amounts of precipitation through time.

Continental trace fossils provide valuable insights into details of deposits interpreted as lake margin, lake plain, palustrine, fluvial, and floodplain paleoenvironments that are often excluded in conventional paleohydroclimate analyses (Hasiotis, 1998, 2004). Trace fossil analysis is especially useful when combined with broader-scale observations of stratal geometries, geochemistry, lithology, and pedogenic features in a lake-basin–type framework. Better integrated analyses of continental alluvial, palustrine, and lacustrine deposits provide more accurate paleoenvironmental reconstructions, including that of the paleohydrologic and paleoclimatic settings during deposition and pedogenic modification of sediments in the early and middle Mesozoic.

Please note: any persons wishing to conduct geologic field trips or investigations on the Navajo Reservation, including visiting some of the stops described in this guide, must first apply for and receive a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515, USA.

No samples of any kind may be collected while in the National Parks, Recreation Areas, or Navajo Nation Reservation lands without written permission. This includes rock, sediment, vegetation, and cultural materials. Any and all archaeological materials encountered must be left alone and left behind. You may take pictures and leave behind footprints.

IMPORTANCE AND GENERAL OVERVIEW OF FIELD TRIP

The Upper Triassic Chinle Formation and the Upper Jurassic Morrison Formation are unique in the Mesozoic succession of the Colorado Plateau in that they contain both rich records of continental paleoecosystems and abundant, diverse sedimentary paleoclimatic and paleoenvironmental indicators. Through interpretations of these sedimentary successions and paleontological assemblages, we know that a mosaic of hydrological, ecological, and edaphic conditions characterized both the ancient Chinle and Morrison landscapes. The record of these soils, streams, and lakes of Mesozoic tropical western Pangaea and North America give a glimpse into a dramatic period of Earth history, which included the continued recovery of the continental ecosystem from the Permian-Triassic mass extinction, the appearance and ascendancy of the dinosaurs, and the breakup of a supercontinent. Further evaluation of fluvial-lacustrine deposits in the Colorado Plateau region has enormous potential for further refining our understanding of Mesozoic paleoenvironments and hydroclimatic evolution of the Rocky Mountain orogen and its associated sedimentary basins. This field trip focuses on the lacustrine paleoenvironments within these landscape mosaics and the details of their sedimentary facies, stratal architecture, trace and body fossil assemblages, and regional paleogeography. However, these archives comprise only part of the rich and fascinating record of this scenic wonderland within the Colorado Plateau.

This trip may be initiated from Green River or Moab, Utah. The itinerary outlined here commences from Green River, Utah, and ends at Chimney Rock, located west of Capitol Reef National Park near Torrey, Utah. The general trip route is summarized in Figure 1, and GPS coordinates are provided for some specific landmarks useful for navigation and outcrops (UTM and latitude/longitude in degree decimal on the datum WGS 1984). Many of the stops are accessed via unpaved and unsigned roads. Access to the Day 2 stops, in particular, requires a high clearance and/or four-wheel drive vehicle and suitable weather conditions. As always, good judgment must be used in evaluating local road conditions.

FIELD TRIP STOPS

Day 1: Saline-Alkaline Lake, Wetland, and Sandy, Ephemeral Fluvial Channel Lake-Margin Deposits of the Brushy Basin Member of the Upper Jurassic Morrison Formation near Moab, Utah, and Four Corners Area

Introduction

Total mileage for Day 1: ~242 mi (389.5 km). Field stops for Day 1 focus on the upper Brushy Basin Member of the Morrison Formation, interpreted as an alkaline-saline evaporative wetland-lake deposit named Lake T'oo'dichi' (Navajo for "bitter water") (Turner-Peterson, 1987; Turner and Fishman, 1991). Lake T'oo'dichi' may be the largest and oldest alkaline-saline wetland-lake system described from the geologic record (Turner-Peterson, 1987; Turner and Fishman, 1991). During the Late Jurassic, the ancestral Uncompahgre Uplift imposed a barrier to rivers and shallow, eastward-flowing groundwater that discharged into the San Juan–Paradox Basin on the upstream side of the uplift (Fig. 5). This closed hydrologic setting was necessary for development of a sizeable palustrine-lacustrine environment that persisted for ~2 m.y., based on ^{40}Ar/^{39}Ar dates on minerals from altered ash beds intercalated with the lacustrine deposits (Kowallis et al., 1998).

The inputs of silicic volcanic ash were delivered by prevailing winds from a system of calderas located to the west and southwest of the basin. A distinctive lateral hydrogeochemical gradient, indicating increasing salinity and alkalinity in the pore waters, altered the ash to a variety of authigenic minerals in concentric zones defined within the basin (Fig. 6). The basinward progression of diagenetic mineral zones is smectite → clinoptilolite → analcime ± potassium feldspar → albite (Turner and Fishman, 1991). The groundwater-fed wetlands were shallow and evaporated frequently to dryness. Scarce laminated gray mudstone beds record distinct pulses of freshwater lacustrine deposition that resulted from intermittent streams carrying detritus into the basin (Dunagan and Turner 2004). The zeolites, evaporites, and authigenic mineral assemblages of Lake T'oo'dichi' are similar to such Holocene saline-alkaline wetland and lake environments as Lake Magadi, Kenya, and Teels Marsh, Nevada (Surdam and Sheppard, 1978) and Pleistocene Lake Tecopa, California (Sheppard and Gude, 1968, 1986).

Planned field stops examine facies of the Upper Brushy Basin Member across a western transect of Lake T'oo'dichi' (Figs. 5 and 6). Stop 1.1 is along the northern pinch-out, Stop 1.2 is within the clinoptilolite-dominated basin center, and Stop 1.3 is in the analcime zone of the lake, where it was influenced by flashy, ephemeral stream input.

Stop 1.1: Courthouse Draw

Route and location: After departure from Green River, take I-70 east to Crescent Junction, Utah, and then U.S.-191 (also signed as UT-163) south toward Moab, Utah. Stop 1.1 is off the left side of the road at ~12S 612702 E 4285394 N (38.71188°, −109.70377°).

The Brushy Basin Member of the Morrison Formation is characterized by major lateral facies changes from fluvial sandstone beds to low-energy lacustrine sediment and deposits of playa-lake environments containing thick intervals of volcanic tuffs and variegated silty and sandy mudstone overlain by well-sorted and strongly cemented sandstone beds (Turner-Peterson et al., 1986; Bell, 1986). A clinoptilolite-heulandite zeolite mineral assemblage occurs in these sediments deposited along the playa margin. The zeolites formed below the sediment-water interface in these saline-alkaline environments.

Near Moab, Utah, in the region northwest of Arches National Park, the contours of ancient Lake T'oo'dichi' apparently bend in a northward direction toward the area of the present-day Salt Valley anticline (Fig. 6). This suggests that a topographic depression existed in this same area during deposition of the lacustrine sediments during Morrison time.

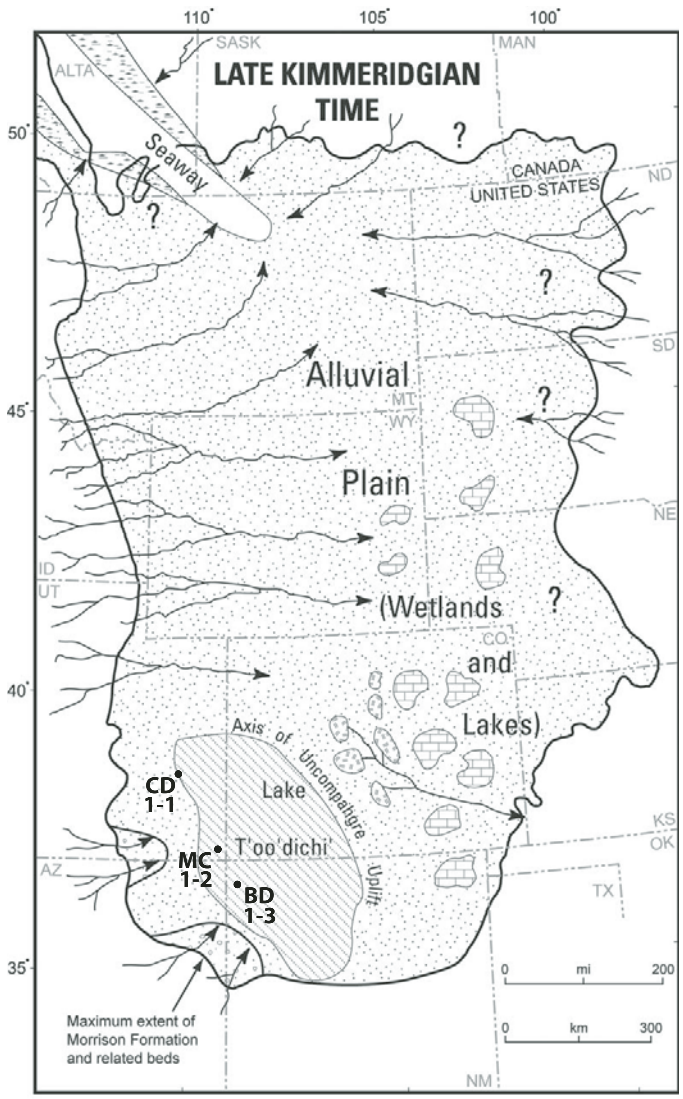

Figure 5. Paleogeographic map of the western United States during Kimmerigian time (from Turner and Peterson, 2004) showing relative locations of Stop 1.1 (Courthouse Draw [CD]), Stop 1.2 (Montezuma Creek [MC]), and Stop 1.3 (Beclabito Dome [BD]).

Stop 1.2: Montezuma Creek

Route and location: To reach the stops in the Four Corners region, take U.S.-191/UT-163 south toward Monticello and Blanding, Utah. South of Blanding, take UT-262 (turn off at 12S 634119 E 1413583 N; 37.42936°, −109.48344°) east and south to a dirt road turnoff to the right at 12S 648852 E 4132213 N (37.32468°, −109.31927°). The outcrop stops are ~0.5 mi east on this road at 12S 618157 E 4131900 N (37.3220°, −109.3279°).

This stop examines the upper part of the Brushy Basin Member in the Morrison Formation within the clinoptilolite diagenetic mineral zone of ancient Lake T'oo'dichi'. The observable ledge-forming units (2–50 cm thick) are tuffs, comprised of altered silicic volcanic ash, that contain a variety of authigenic minerals including mixed-layer illite-smectite, clinoptilolite, analcime, potassium feldspar, albite, quartz, chalcedony, chlorite, kaolinite, barite, calcite, and dolomite (Turner and Fishman, 1991) (Fig. 7). The "popcorn surface texture" results from the weathering of local smectite clays into bentonite (Fig. 8A) and creates the distinctive rounded slopes. The 105-m section of the Brushy Basin Member at Montezuma Creek has yielded Late Jurassic ages (149.4 ± 0.7–145.2 ± 1.2 Ma) based on $^{40}Ar/^{39}Ar$ ages on plagioclase and sanidine grains (Kowallis et al., 1991, 1998).

Locally, a brown fossiliferous interval is marked by a laminated, carbonaceous claystone and mudstone unit of palustrine origin and is interbedded with zeolitic tuffs. The laminated claystone preserves plant fossils, including the leaves of the ginkophyte *Czekanowskia* (Fig. 8B), ferns, and cycads, trunks and stems of conifers and horsetails, and a low-diversity invertebrate fauna including conchostracans (Ash, 1994; Ash and Tidwell, 1998) and is interpreted to be associated with an interval of freshwater lacustrine deposition. This unit grades upward into a clinoptilolite-bearing unit, signaling a return to alkaline-saline palustrine deposition.

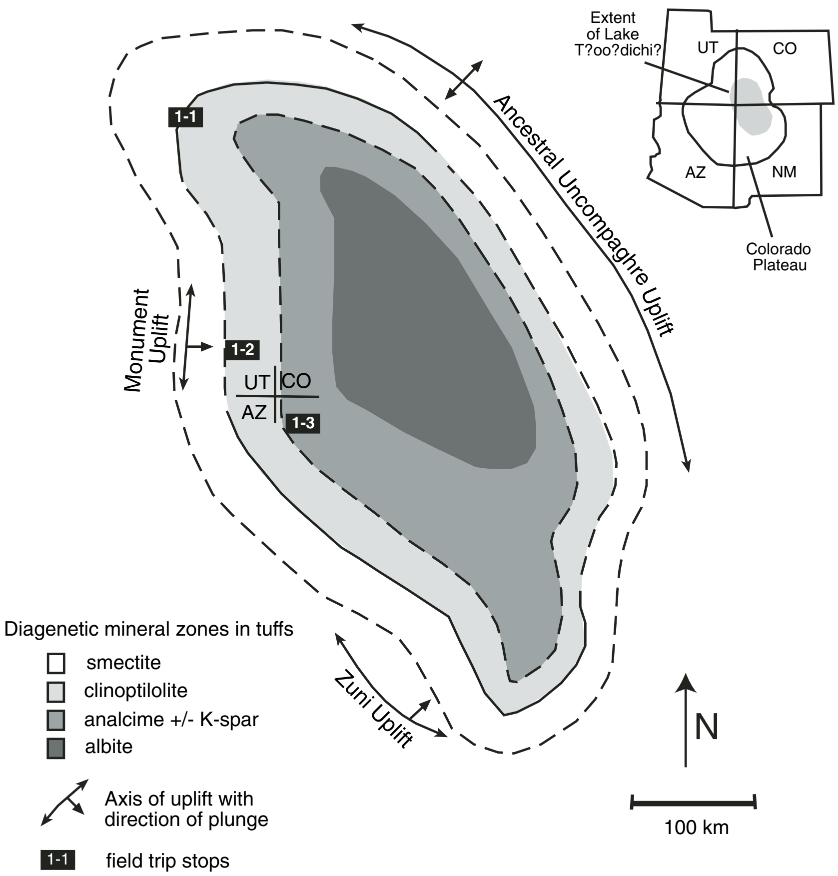

Figure 6. Paleogeographic map of Lake T'oo'dichi' (from Dunagan and Turner, 2004) showing locations of Day 1 stops relative to mapped diagenetic mineral zones.

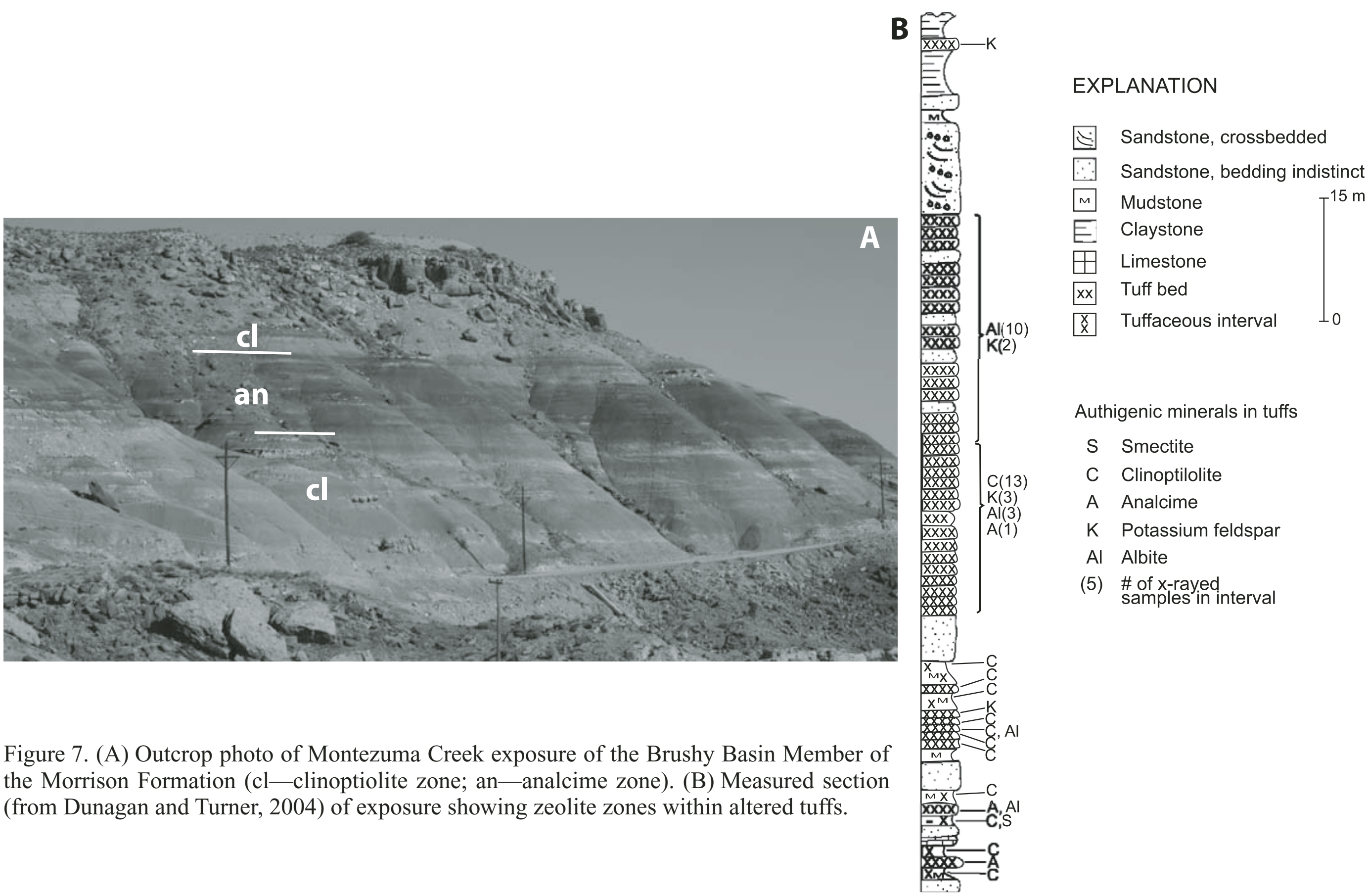

Figure 7. (A) Outcrop photo of Montezuma Creek exposure of the Brushy Basin Member of the Morrison Formation (cl—clinoptiolite zone; an—analcime zone). (B) Measured section (from Dunagan and Turner, 2004) of exposure showing zeolite zones within altered tuffs.

Stop 1.3: Beclabito Dome, New Mexico

Route and location: Departing Montezuma Creek for Stop 1.3, take UT-262 east ~17 mi (27.4 km). The route will be resigned CO-41. Continue to drive another 9.5 mi (15.3 km), and turn left on CO-60, then continue driving another 11.2 mi (18 km). Turn left on U.S.-64/AZ-504 another 6.7 mi (10.8 km) (note: the route becomes NM-504). Continue past the town of Beclabito, New Mexico, for Stop 1.3, ~1.4 mi (2.3 km) ahead, on a dirt road to the right at ~12S 67867 E 4077440 N (36.82597°, −108.99656°). The outcrops are located along the wash ~300 m SW of the parking area.

This stop along margins of underfilled lake T'oo'dichi' examines a crossbedded sandy facies derived from ephemeral streams that prograded into the playa system. To reach the outcrops exposed along the wash, head on foot southwest ~0.3 km. Shiprock, a distinctive, Tertiary-age volcanic diatreme, is visible in the distance to the south. Playa aggradational phases are marked by matrix-supported sheetflood deposits with rip-up clasts of tuffaceous material (Fig. 8C). The outcrop has a characteristic spotted texture due to alteration of analcime, other zeolites, and associated minerals. Another diagnostic lithofacies is characterized by an agglomeration of cm-scale iron-rich pellets (Fig. 8D).

Most of the palustrine-lacustrine deposits within the upper Brushy Basin Member do not preserve much macroscopic evidence of bioturbation, suggesting high rates of sedimentation, high alkalinity-salinity, anoxic bottom water conditions, or modification by authigenic mineral processes. Abundant but monospecific burrows are present in some thin beds, indicating the presence of only one type of burrowing organism (Hasiotis, 2004). This low diversity ichnofossil assemblage is consistent with harsh environments. Shallow rhizoliths and bioturbation are present in some of the tuffs, indicating that terrestrial vegetation grew locally as part of incipient soil formation during periods of subaerial exposure (Fig. 8E). This exposure was most likely associated with low water levels when the wetland-lake complex evaporated to dryness. The most striking ichnofossil assemblage at this locality includes subterranean termite nests preserved in sandstone deposited by fluvial processes (Fig. 9). The termite nests indicate that the substrates became unsaturated as the saturated zone moved downward and the fluvial deposits became well drained.

To return to Bluff, take U.S.-64/AZ-504/NM-504 west ~7 mi (11.3 km). This road will then become U.S.-160; proceed another 28.2 mi (45.4 km). Turn right onto U.S.-191/UT-163 and continue driving ~33 mi (53.1 km) to Bluff, Utah, for overnight lodging.

Day 2—Fluvio-lacustrine Deposits in the Upper Triassic Chinle Formation in Blue Notch Canyon and North Wash, Glen Canyon National Recreation Area

Note: High-clearance two-wheel drive vehicles or four-wheel drive vehicles AND good weather are required for safe access to the Day 2 sites.

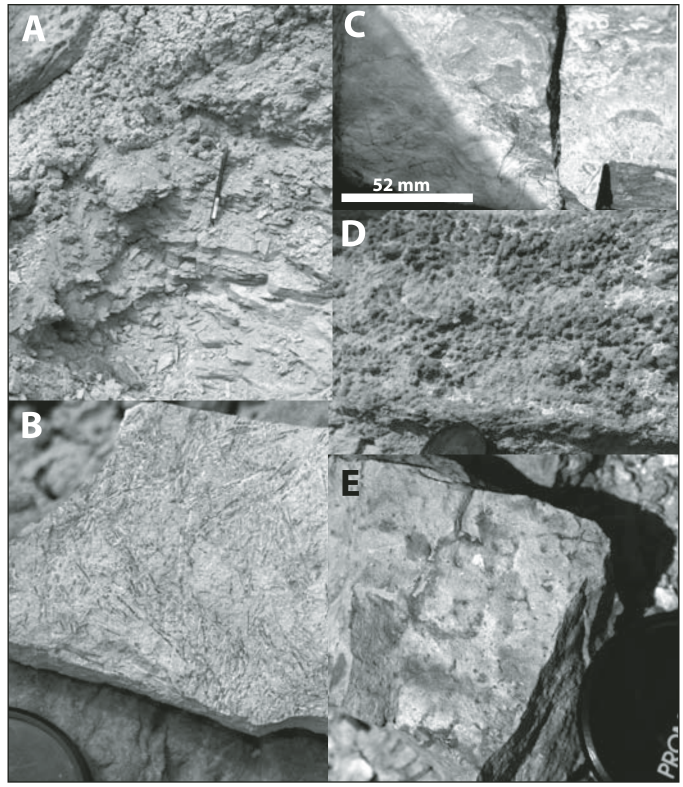

Figure 8. Features in the upper Brushy Basin Member at Montezuma Creek and Belcabito Dome: (A) "Popcorn" weathering of smectite-rich mudstone. (B) Fossil *Czekanowskia* leaves. (C) Analcime-rich mudstone rip-up clasts. (D) Iron-rich pellets in sandstone. (E) Rootlets within an immature paleosol. Lens cap in photos is 52 mm in diameter.

Introduction

Total mileage for Day 2: ~170 mi (273 km). Day 2 focuses on the fluvio-lacustrine deposits of the Upper Triassic Chinle Formation of Glen Canyon National Recreation Area. The majority of the day will be spent in Blue Notch Canyon, where the focus will be on the lacustrine facies preserved in the Monitor Butte Member. Panoramic views combined with excellent exposure permit the recognition and delineation of high-frequency sequences and parasequences from the fluvio-lacustrine successions. From Blue Notch, the route continues to North Wash to demonstrate the lateral variability of the Late Triassic landscape by correlating the Monitor Butte lacustrine sediments to chronostratigraphically equivalent paleosols.

Stop 2.1: Blue Notch Pass

Route and location: Morning departure from Bluff, taking UT-163 westbound to UT-261, and then northbound to UT-95. Travel northwest 32 mi (51.5 km) on UT-95. See Figure 10 for a detailed route map to the geologic stops. To access Blue Notch Canyon, look for the junction of UT-95 with an unpaved road (Bureau of Land Management [BLM] road 206A) on the left

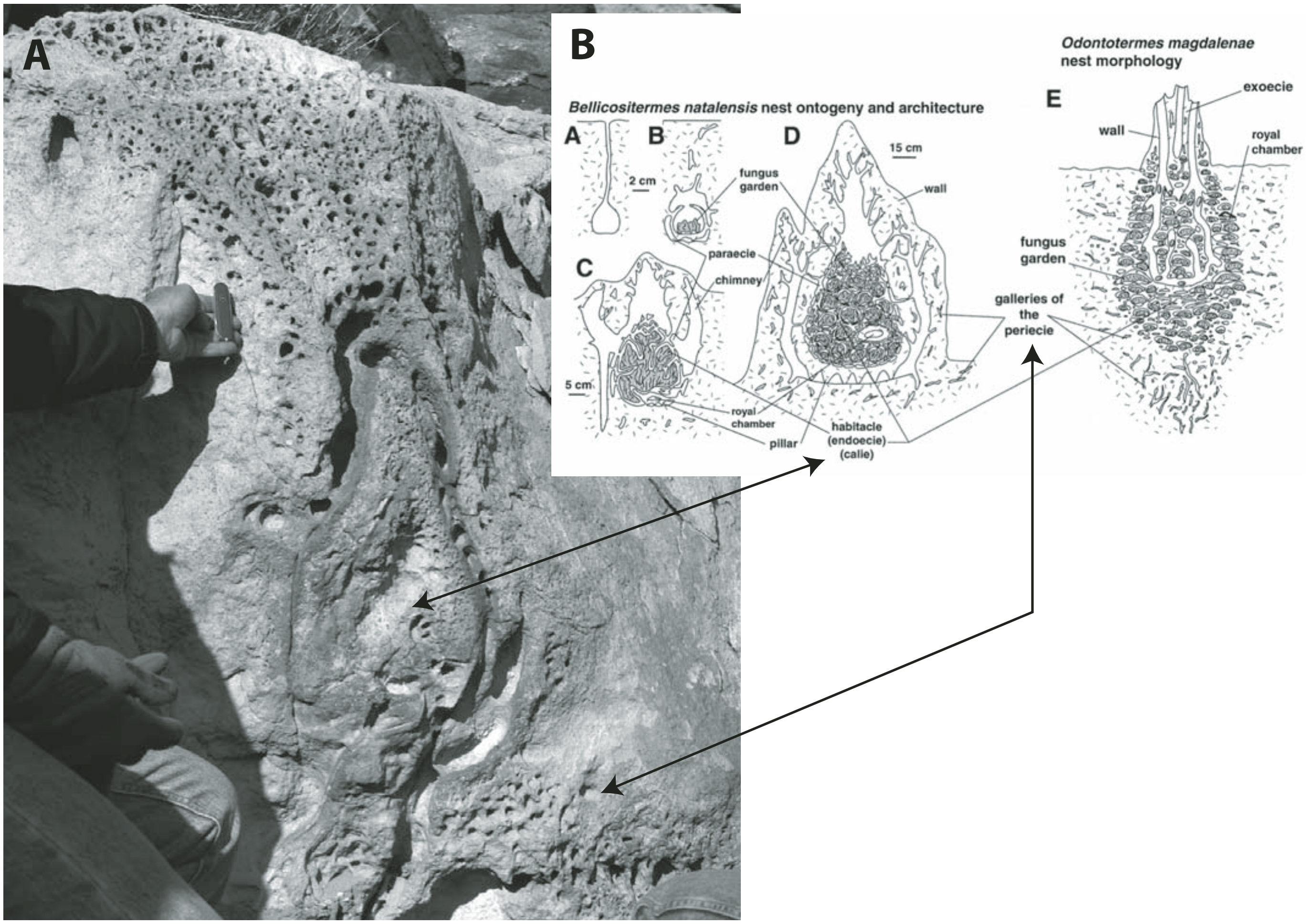

Figure 9. Comparison of ichnofossil termite nest (A) in the Brushy Basin Member at Beclabito Dome to modern termite nest architecture (B).

(12S 563021 E 4180252 N; 37.76742° −110.28444°); follow this road to the crest of the pass where there is a wide parking area (12S 561161 E 4180492 N; 37.76972°, −110.30556°).

This brief stop examines exposures of palustrine limestone and calcareous mudstone within the Petrified Forest Member of the Chinle Formation. These facies represent marginal lacustrine deposition associated with underfilled lake basins that overlie the Monitor Butte and Moss Back Members of the Chinle Formation, the main units that will be examined in the remainder of the stops during the day. The great exposures and spectacular view from the pass present an opportunity to spend some time introducing the stratigraphy of the Chinle Formation as well as contrasting these underfilled lake basin carbonate facies with the overfilled lake basin and fluvial clastic deposits beneath them.

Stops 2.2a through 2.2c: Blue Notch Canyon

Introduction: Stops 2.2a–2.2c are along BLM road 206A between the pass at Blue Notch and Lake Powell to the west. In Blue Notch Canyon, the stops focus on facies deposited in a fluctuating profundal lacustrine environment. Blue Notch Canyon exposes the Lower Triassic Moenkopi Formation, the Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock Members of the Upper Triassic Chinle Formation, the Lower Jurassic Wingate Sandstone, and Lower Jurassic Kayenta Formation. Stops highlight the lacustrine deposits of the Monitor Butte Member and the associated fluvial, paludal, and palustrine deposits and paleosols preserved in the lower part of the Chinle Formation (Fig. 11).

Within the lower part of the Chinle Formation, the top of the Shinarump Member is an extensive lacustrine flooding surface as well as, in some places, a sequence boundary that marks a previous surface of landscape degradation locally forming a flooding surface sequence boundary (FSSB). Greenish-gray mudstone and brown ripple cross-laminated sandstone of the Monitor Butte Member overlie the lacustrine flooding surface. The Monitor Butte Member locally contains abundant, well preserved plant fossils (Ash, 1975; Demko, 1995). Strata within the Monitor Butte Member are interpreted as a highstand systems tract, deposited as

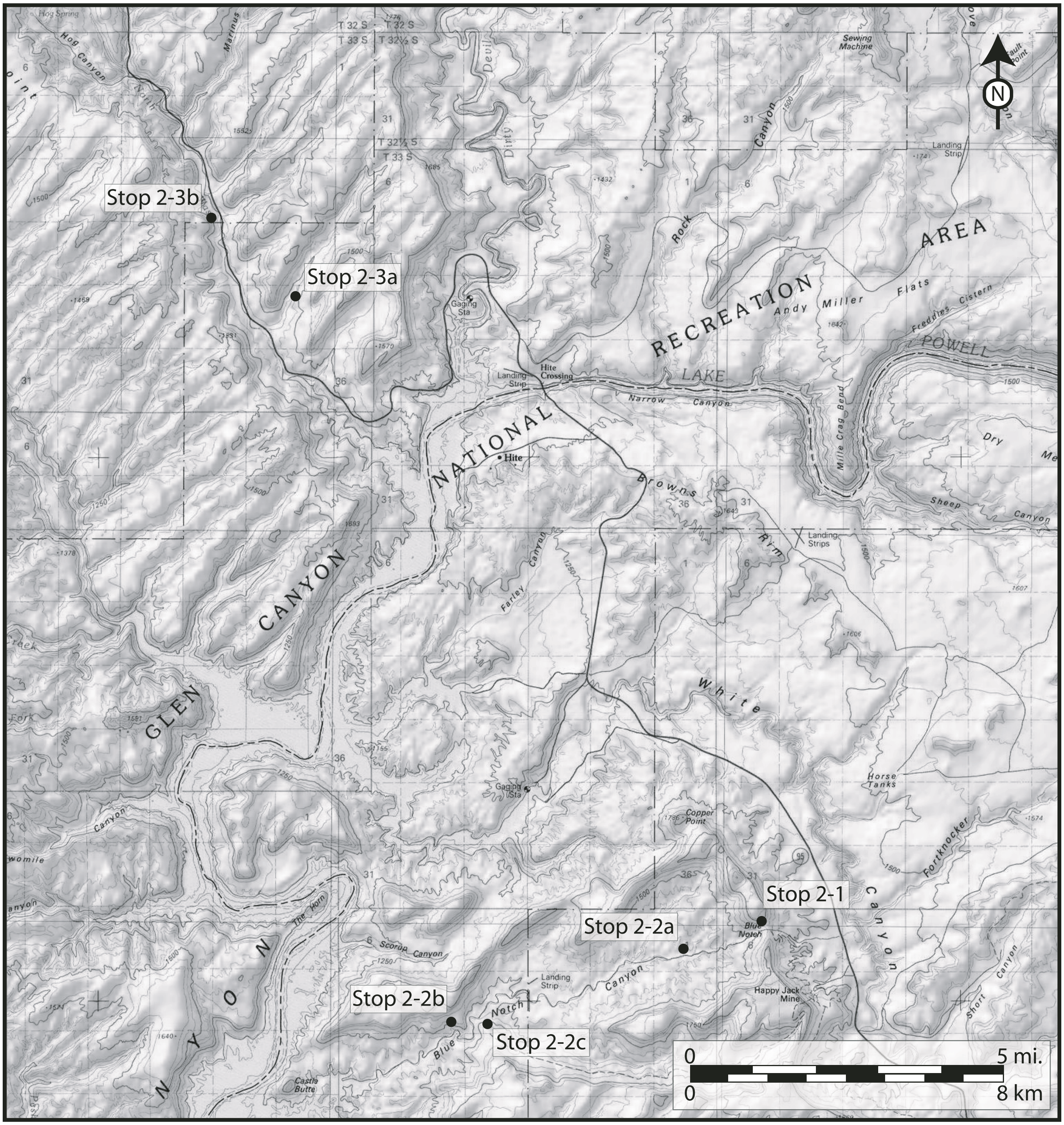

Figure 10. Detailed location map for geologic stops on Day 2 in the Monitor Butte and Moss Back Members of the Chinle Formation.

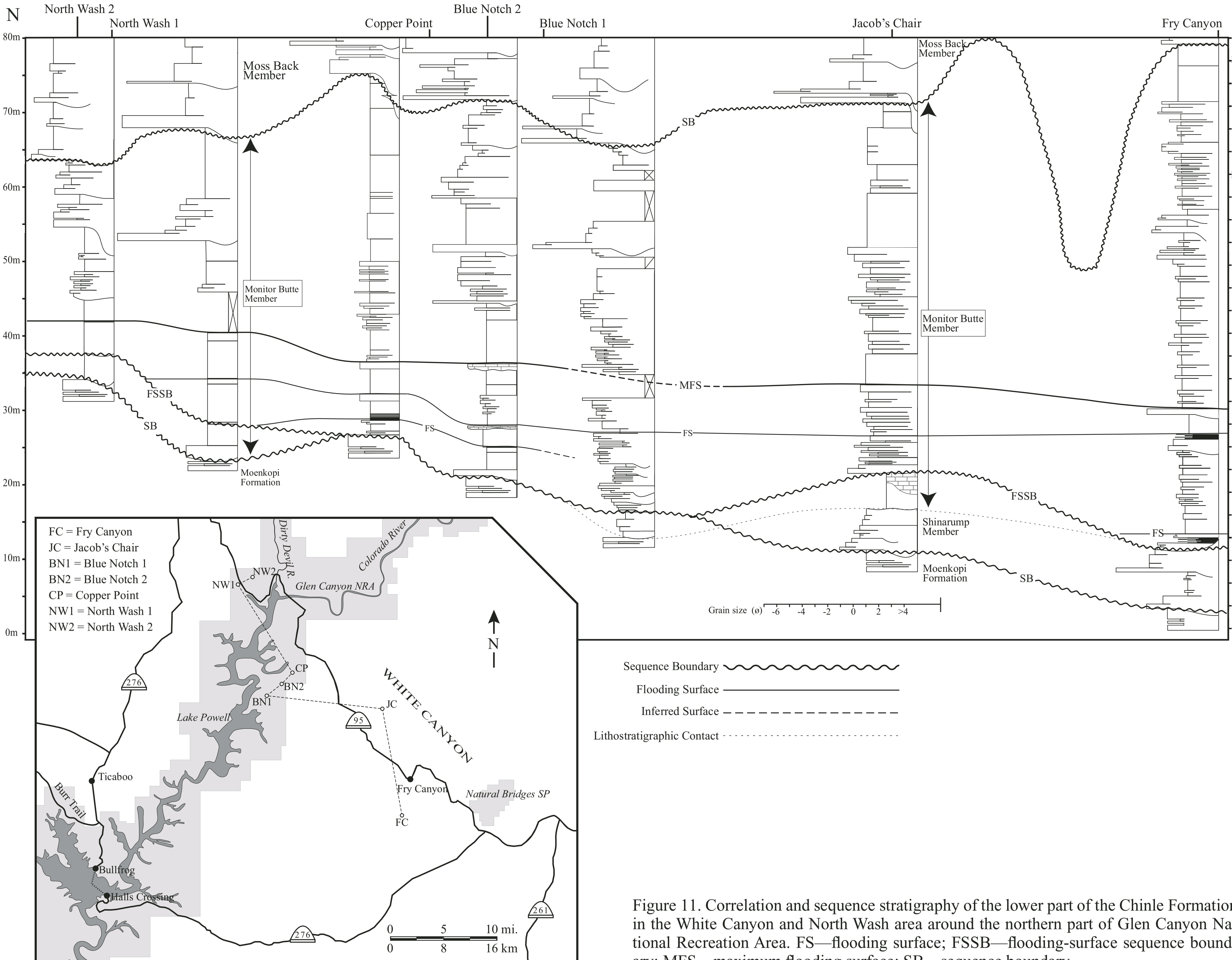

Figure 11. Correlation and sequence stratigraphy of the lower part of the Chinle Formation in the White Canyon and North Wash area around the northern part of Glen Canyon National Recreation Area. FS—flooding surface; FSSB—flooding-surface sequence boundary; MFS—maximum flooding surface; SB—sequence boundary.

a prograding lacustrine delta complex that was fed by a rapidly aggrading fluvial system. The top of the Monitor Butte Member is a sequence boundary, marked either by an erosional surface at the base of the discontinuous Moss Back Member sandstone (where present), or a well developed paleosol characterized by distinctive red coloration and carbonate nodules. The Moss Back Member is a trough crossbedded sandstone characterized by large-scale lateral accretion beds. It represents a smaller, inset incised valley cut into the underlying Monitor Butte lacustrine valley fill. The tripartite fluvial-lacustrine-fluvial succession in the lower Chinle valley fill is reminiscent of other such documented lacustrine basin fills as those in rift basins of the Newark Supergroup (Lambiase, 1990; Olsen, 1990; Carroll and Bohacs, 1999).

Stop 2.2a: Coals in the Lower Part of the Monitor Butte Member of the Upper Triassic Chinle Formation

Route and location: Continue westbound from the pass into Blue Notch Canyon on BLM road 206a. The road levels off after a relatively steep descent, and parking is available near the stop at a wide switchback (12 S, 559938 E, 4180432 N; 37.76925°, −110.31944°).

This short stop examines unique organic-rich lacustrine facies preserved in the Monitor Butte Member (Fig. 12). The Monitor Butte Member unconformably overlies the Shinarump Member and is composed predominantly of olive-gray to greenish gray smectitic mudstone and siltstone, but also contains fine-grained, tuffaceous sandstone, laminated carbonaceous mudstone and shale (Stewart et al., 1972). The Monitor Butte Member ranges from >80 m thick to zero where it onlaps the paleovalley margins (Stewart et al., 1972). Distinctive sedimentary features in the Monitor Butte include (1) delta foreset beds (Fig. 13); (2) thin, broad distributary channels; and (3) contorted and slumped strata (Stewart et al., 1972; Dubiel et al., 1993). The Monitor Butte Member represents deposition in fluvial, lacustrine, lacustrine delta, and paludal environments (Stewart et al., 1972; Dubiel, 1987; Demko, 2003).

In the White Canyon area of southeastern Utah, the Monitor Butte Member also contains thin limestones and coal seams (Dubiel, 1983, 1989a) (Fig. 12). The thin coal seams indicate two distinct sedimentary environments: (1) allochthonous, detrital peat deposited in lacustrine delta-front environments; and (2) autochthonous peat interbedded with fine-grained siliciclastic deposits associated with hydric paleosols developed on transgressive lacustrine margins. Stop 2.2a provides a look at the first type of these organic-rich facies preserved in a lacustrine delta.

Stop 2.2b: Clinoform Delta Foresets in the Monitor Butte Member of the Upper Triassic Chinle Formation

Route and location: Continue driving west on BLM road 206a ~0.3 mi (0.5 km) west-northwest of Stop 2.2c. Pull off at a wide spot on the road near 12 S, 553148 E, 4177523 N.

This stop features an excellent exposure of a well-developed paleosol characterized by intense bioturbation, color mottling, and vertic features that mark a regional unconformity (Tr-3 of Pipiringos and O'Sullivan, 1978). Lacustrine deltaic deposits of the Monitor Butte Member sharply overlie the paleosol, indicating this surface represents a combined FSSB (Fig. 13). The deltaic deposits at the base of the Monitor Butte Member consist of thinly bedded, coarsening upward, fine-grained sandstones that exhibit a complex cut-and-fill architecture. These deposits grade upward to coarser-grained trough crossbedded lacustrine shoreline facies. Two major stages of progradation can be identified by tracing the sharp transition from these shoreline deposits, and a laterally equivalent minor paleosol exposed elsewhere in the canyon, back to fluvial-deltaic deposits. The upper portion of the Monitor Butte Member is truncated by a surface of erosion at the base of the Moss Back Member (Fig. 14A), the focus of the next stop.

Stop 2.2c: Moss Back Member of the Chinle Formation Incised Valley

Route and location: Turn around, and head east on BLM road 206a. Park on a wide spot on the road at 12 S, 553596 E, 4178048 N.

The Moss Back Member overlies the Monitor Butte Member, or overlies older rocks where the Monitor Butte or Shinarump Members are not present, in a belt ~80–120 km wide (Blakey and Gubitosa, 1983) from northern New Mexico and southwestern Colorado to southeastern Utah. The Moss Back Member ranges from 50 m thick in the White Canyon area of southern Utah and pinches out along the margins of the paleovalley (Stewart et al., 1972). The lower part of the Moss Back Member is characterized by large-scale trough and planar crossbedded, medium-grained sandstone with interbedded carbonate nodule and extrabasinal

Figure 12. Coal bed in the lower part of the Monitor Butte Member of the Chinle Formation in Blue Notch Canyon, Glen Canyon National Recreation Area.

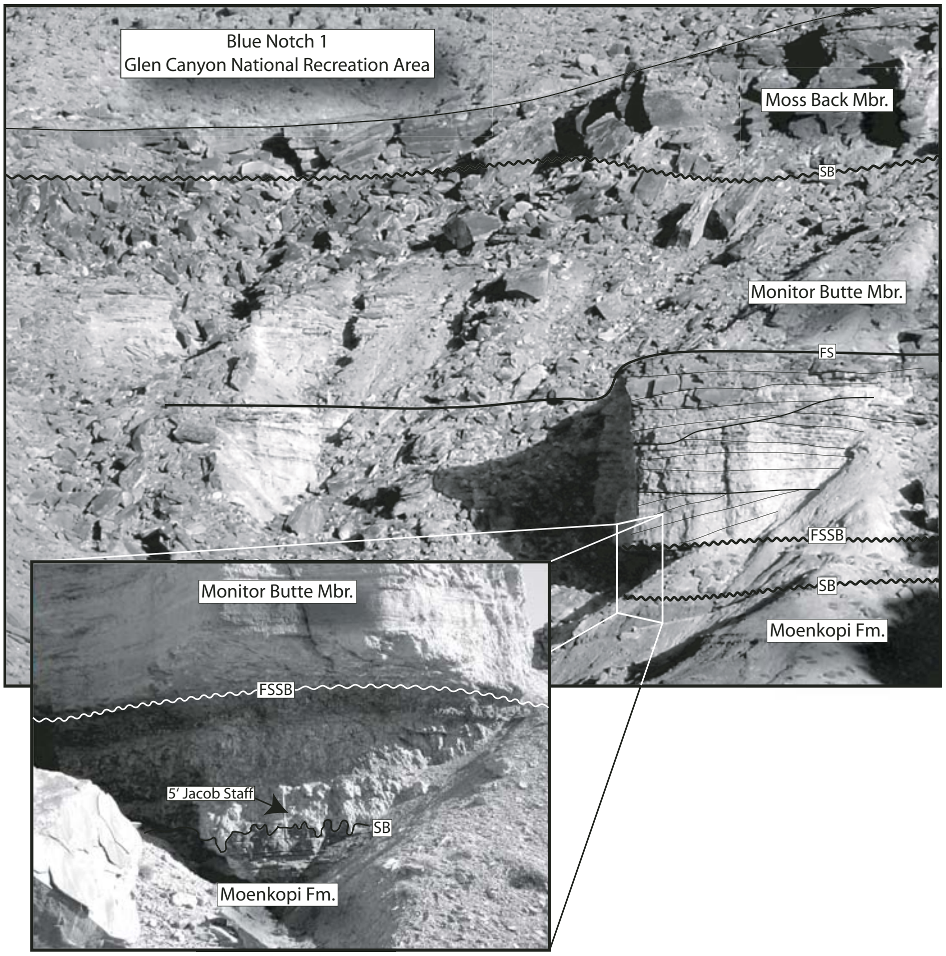

Figure 13. Delta front foresets (highlighted by black lines) in the Monitor Butte Member of the Chinle Formation in Blue Notch Canyon, Glen Canyon National Recreation Area. Inset: unconformity paleosol developed on the Moenkopi Formation underlying the Monitor Butte Member of the Chinle Formation, interpreted as a flooding-surface sequence boundary (FSSB) and unconformity. FS—flooding surface; SB—sequence boundary.

pebble conglomerate near the base of the unit. The upper part of the Moss Back Member is characterized by small- and large-scale trough and planar crossbedded, medium- to fine-grained sandstone (Stewart et al., 1972). The Moss Back Member is interpreted to have been deposited in high- and low-sinuosity stream environments. Blakey and Gubitosa (1984) interpreted the sandstones in this unit as low-sinuosity, braided stream deposits, whereas Dubiel (1987), noting the large-scale lateral accretion elements that dominate the internal architecture of the sandstone, viewed them as having been deposited by high-sinuosity, meandering streams.

The Moss Back Member outcrops along the southern wall of Blue Notch Canyon and is >30 m thick in the southwestern portion of the canyon near Stop 2.2c and pinches out to the east (Fig. 15). The base of the Moss Back Member is marked by erosional truncation of the underlying Monitor Butte Member. This surface, interpreted as a sequence boundary based on the truncation of underlying strata and a significant basinward shift in facies, can be traced laterally to a well-developed paleosol formed along the Moss Back interfluve. Paleocurrent measurements taken in the canyon (Fig. 14A) suggest the Moss Back trunk stream flowed westward nearly parallel to the modern canyon wall.

After viewing the geologic stops in Blue Notch Canyon, retrace the route east on BLM road 206a back to the paved road, UT-95. Turn left and drive north 20 mi (32.2 km) on UT-95 to Stop 2.3a.

Stops 2.3a through 2.3b: North Wash

Introduction: These stops demonstrate the stratal architecture and facies relationships within the paleovalley fill. Compared to Blue Notch, the section at North Wash is markedly thinner, and lacustrine facies are absent. Despite the differences between these two sections, spatio-temporal correlations can be made on the basis of paleohydrologic soil indicators. These correlations provide some basis to constrain the facies relationships within the paleovalley (Beer, 2005) (Fig. 11).

Stop 2.3a: Depositional Facies Preserved on Paleovalley Margins

Route and location: Drive 20 mi (32.2 km) north of the Blue Notch canyon turnoff on UT-95. Take a left into a gravel parking

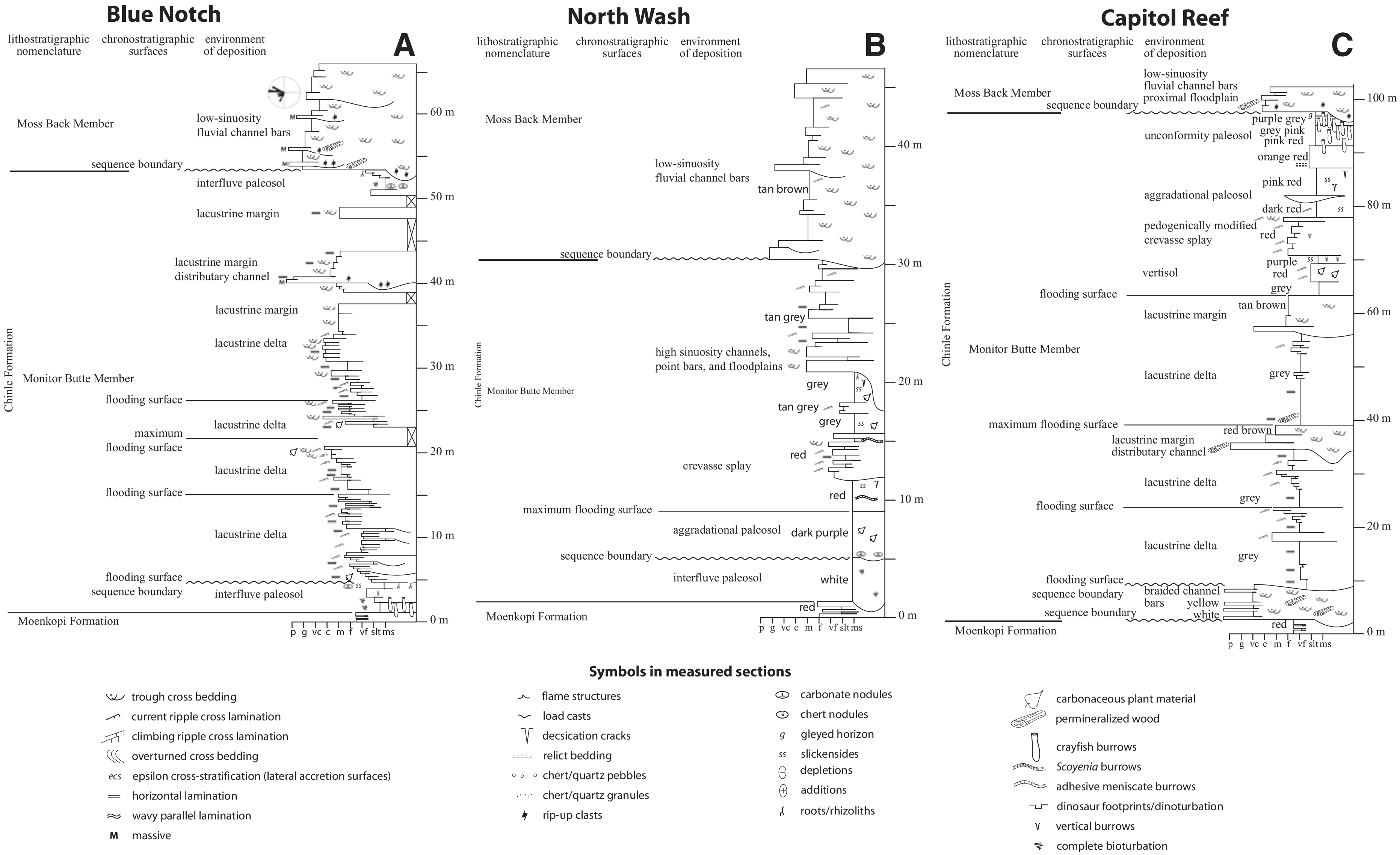

Figure 14. Measured section of the lower part of the Chinle Formation. (A) Blue Notch Canyon, Glen Canyon National Recreation area at Stop 2.2b; note paleocurrent rose diagram for Moss Back Member sandstone. (B) Stop-2.3a, North Wash, Glen Canyon National Recreation Area. (C) Chimney Rock in Capitol Reef National Park at Stop 3.4b.

lot. To reach the outcrop, hike along the road south (back toward Hite) and up the first major side canyon on the east side of the highway (with luck, you can walk directly up the wash starting at the culvert that passes under the highway). The outcrops are at 12 S, 548704 E 4195924 N (37.909555°, −110.445944°).

A 20 min hike up the side canyon ends at the outcrop in Figure 16, where a major erosional unconformity marks the base of the Chinle Formation. Access to a nearly complete exposure of the Monitor Butte and Moss Back Members provides a look at high-sinuosity fluvial, palustrine, and paludal deposits, along with paleosols associated with both landscape aggradation and degradation (Fig. 14B).

Stop 2.3b: North Wash—High-Sinuosity Lateral Accretion Deposits

Route and location: Continue north on UT-95 2.3 mi (3.7 km) to a safe place to pull off the road near the entrance sign for Glen Canyon National Recreation Area. The outcrop is a short distance off the west side of the highway.

High-sinuosity fluvial deposits and associated paleosols comprising the top of the Monitor Butte Member are apparent below the Moss Back Member (Fig. 17). These deposits are similar to those found elsewhere in the basin marking the final basinward progradation of the Monitor Butte fluvio-lacustrine system. These depositional and pedogenic facies can be correlated 50 mi (80.5 km) northward to the closest exposures of the Chinle Formation in the San Rafael Swell. Chinle strata below these high-sinuosity deposits onlap the margin of the master paleovalley over this distance, and the lithostratigraphic nomenclature of these units changes from Monitor Butte Member in the Glen Canyon area to the Temple Mountain Member in the San Rafael Swell area.

This ends the stops for Day 2. After Stop 2.3, continue north on UT-95. Go left on UT-276, westbound to Ticaboo, Utah, for overnight lodging.

Day 3—Balanced-Fill Lake Deposits in the Tidwell Member of the Upper Jurassic Morrison Formation and High-Frequency Sequence Stratigraphy of Fluvio-Lacustrine Deposits in the Lower Part of the Upper Triassic Chinle Formation

Introduction

Total mileage for Day 3: ~117 mi (188 km). Stops on the morning of Day 3 will examine outcrops of the Tidwell Member of the Upper Jurassic Morrison Formation interpreted as fluctuating-profundal and palustrine deposits in balanced-fill lakes in the Henry Mountains, Waterpocket Fold, and Capitol Reef National Park areas (Fig. 18). Stops in the afternoon of Day 3 will demonstrate the correlation of parasequences, parasequence sets, and high-frequency sequences within overfilled lakes and associated fluvial deposits the lower part of the Upper Triassic Chinle Formation (Shinarump, Monitor Butte, and Moss Back Members) in the Capitol Reef National Park area (Fig. 18).

Stop 3.1: Tidwell Member of the Morrison Formation, Photo Panorama Interpretation

Route and location: After a morning departure from lodging at Ticaboo, Utah, drive north on UT-276 7.5 mi (12.1 km) to a pullout on the east side of the road at 12S 530703 E 4179594 N (37.76314°, −110.65142°).

This stop will introduce the stratigraphy of the Middle and Upper Jurassic strata of the Henry Mountains, Waterpocket Fold, and Capitol Reef areas, including recognition of the boundaries between the Middle Jurassic Summerville and Upper Jurassic Morrison Formations, and the stratal architecture of the basal Tidwell and overlying Salt Wash Members of the Morrison Formation (Fig. 19).

Stop 3.2: Tidwell Member of the Morrison Formation, Measured Section

Route and location: Turn around and head back south on UT-276 3.4 mi (5.5 km) and turn right onto an unpaved road at 12S 527593 E 4174751 N (37.71961°, −110.68692°). Continue driving ~5.7 mi (9.2 km), past the uranium mill facilities (but not onto their access road), into Shootaring Canyon to Stop 3.2, near the Tony M Mine (12S 526105 E 4175302 N; 37.72461°, −110.70378°).

Shootaring Canyon is also spelled Shootering, and on some older maps it is also known as Shitamaring Canyon. This area was intensely prospected and mined for uranium ore bodies hosted in sandstones in the Salt Wash Member of the Morrison Formation.

Outcrops in Shootaring Canyon preserve vertebrate tracks, trackways, and burrows in the Salt Wash Member. In the canyon, floodplain paleosols interpreted as stacked argillisols and entisols, are intercalated with crevasse-splay deposits, levee sandstones, and channel and bar macroforms.

This stop is located at a well-exposed interval of the upper part of the Middle Jurassic Summerville Formation and the lower part of the Upper Jurassic Morrison Formation (Fig. 20A), near the recently active (ca. 2001) Tony M uranium mine. Here, the basal Tidwell Member overlies the J-5 regional unconformity (Pipiringos and O'Sullivan, 1978) cut into the Summerville Formation and is marked by a sandstone bed containing a lag deposit of chert granules and pebbles. This unit is a regional marker bed informally called "Bed A." Here in the Henry Mountains area, Bed A is interpreted as a unit that was deposited in a desert environment characterized by ephemeral streams and low-relief, eolian sand sheets (zibars). A progradational, coarsening-upward succession of mudstone, siltstone, and silty limestone immediately overlies Bed A (Fig. 20A), marking a lacustrine flooding surface and subsequent deposition of fluctuating-profundal lake facies in a balance-filled basin (Fig. 21).

Lacustrine trace fossil assemblages preserved in the Tidwell Member vary in composition areally due to the hydrologic conditions, with greatest benthic ichnodiversity in proximal settings (Fig. 22). These results are consistent with benthic diversity data

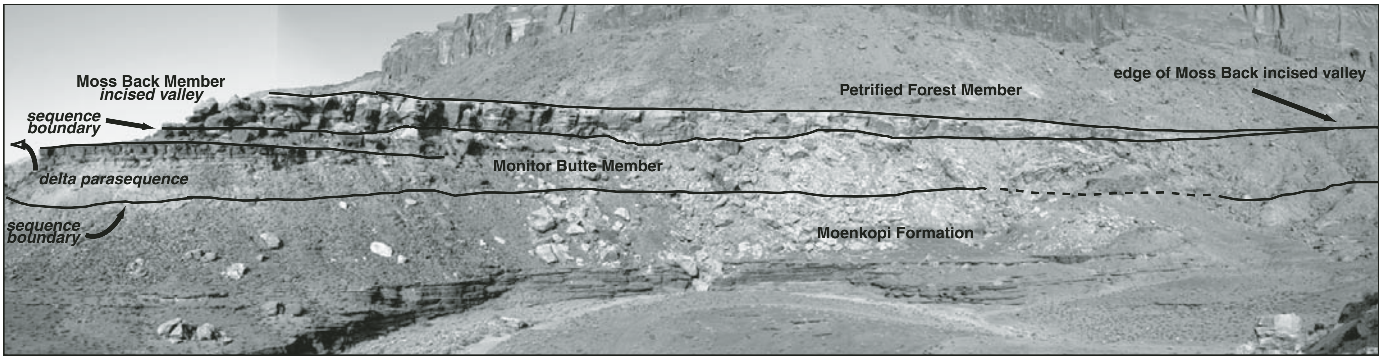

Figure 15. Interpreted photo panorama of the edge of the Moss Back paleovalley in Blue Notch Canyon, Glen Canyon National Recreation Area. Note coarsening-upward succession of the deltaic parasequence below the Moss Back unconformity.

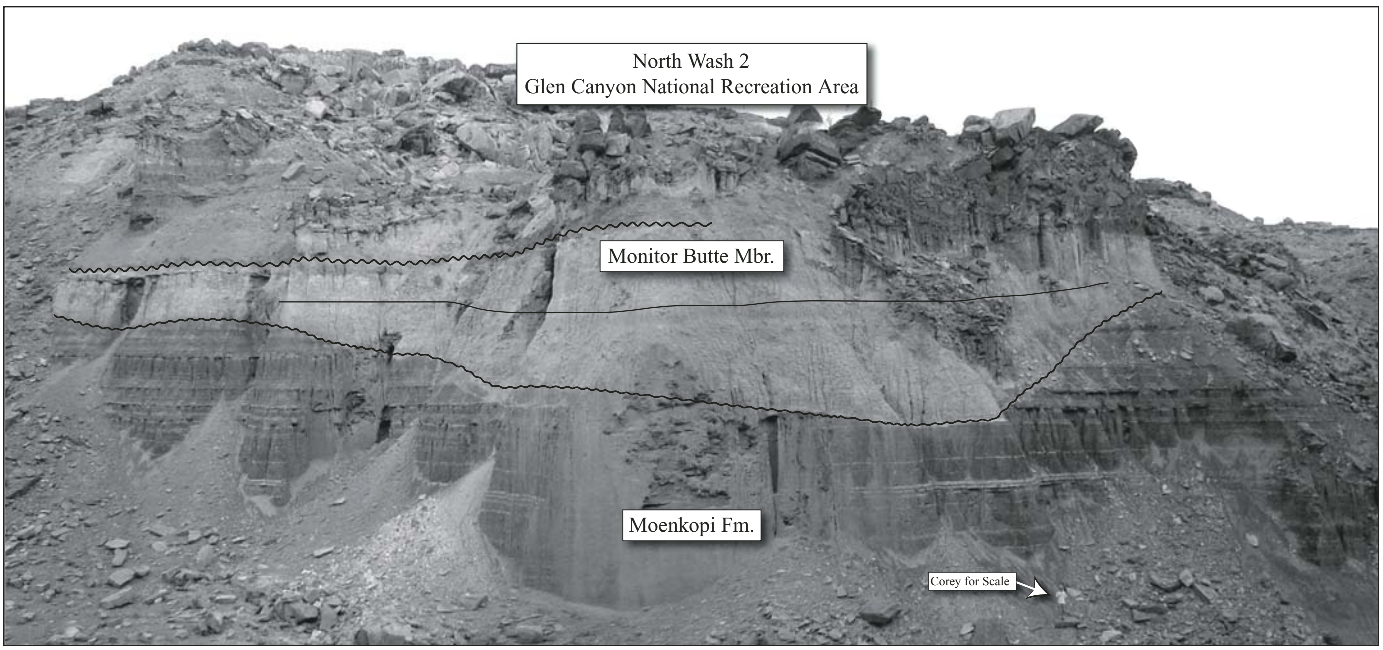

Figure 16. Interpreted photo panorama of Monitor Butte lacustrine facies filling the paleovalley cut into the underlying Moenkopi Formation in North Wash, Glen Canyon National Recreation Area. Note person for scale.

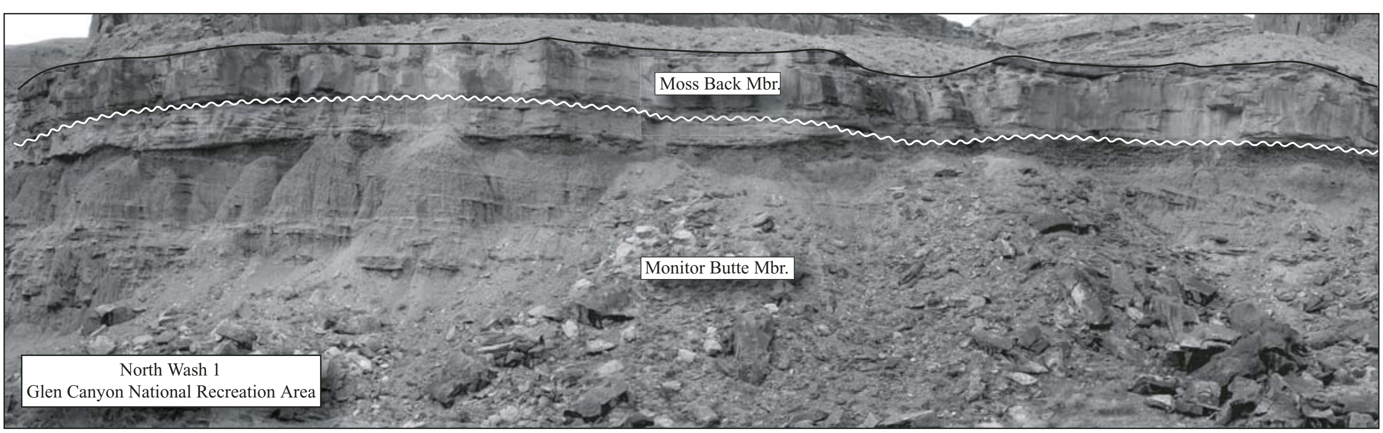

Figure 17. Interpreted photo panorama of high-sinuosity fluvial facies at the top of the Monitor Butte Member of the Chinle Formation at Stop 2.3b. Note lateral accretion surfaces dipping to the right.

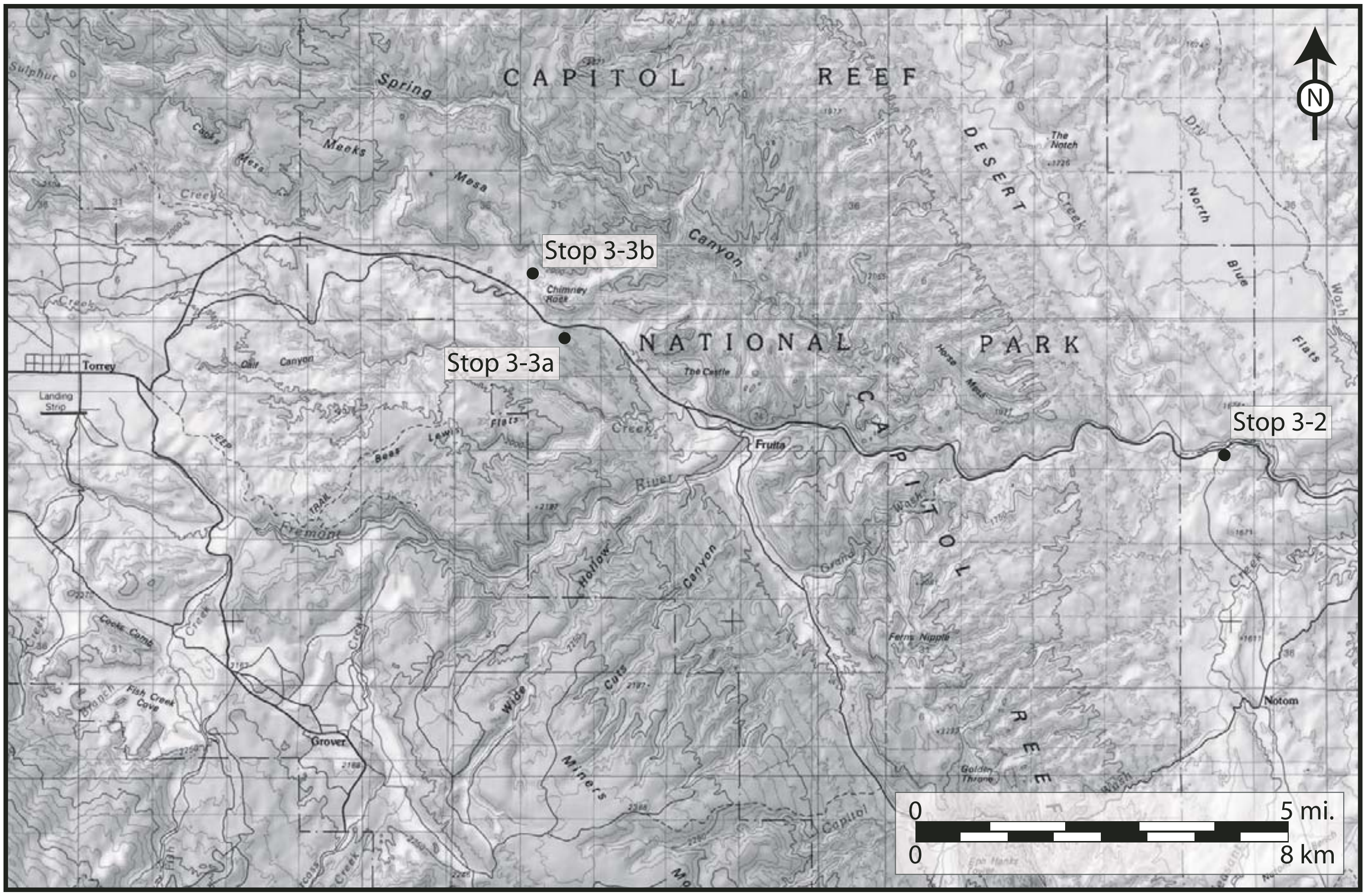

Figure 18. Detailed location map of geologic stops in the Chinle Formation for Day 3.

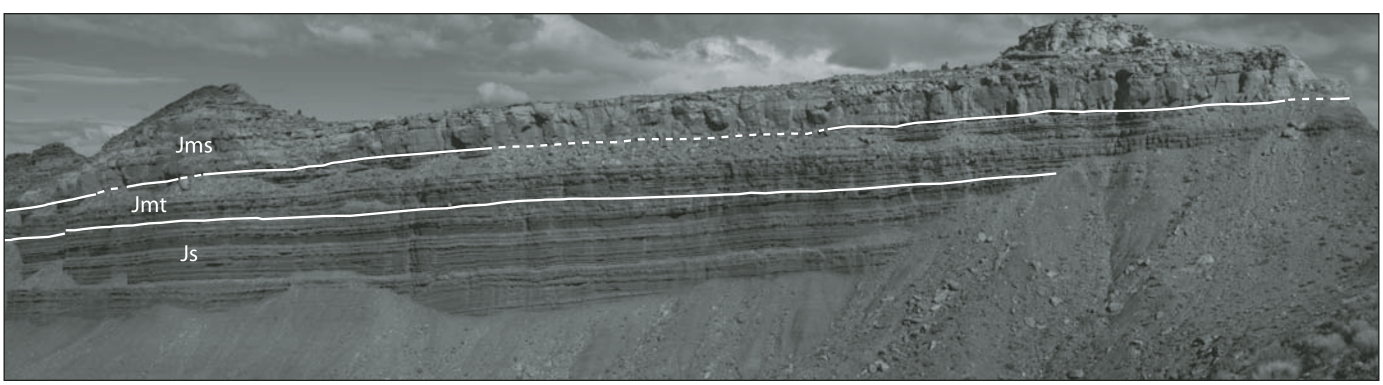

Figure 19. Interpreted photo panorama of the upper part of the Middle Jurassic Summerville Formation (Js) and the Tidwell Member (Jmt) and lower part of the Salt Wash Member (Jms) of the Upper Jurassic Morrison Formation at Stop 3.1. Note person for scale.

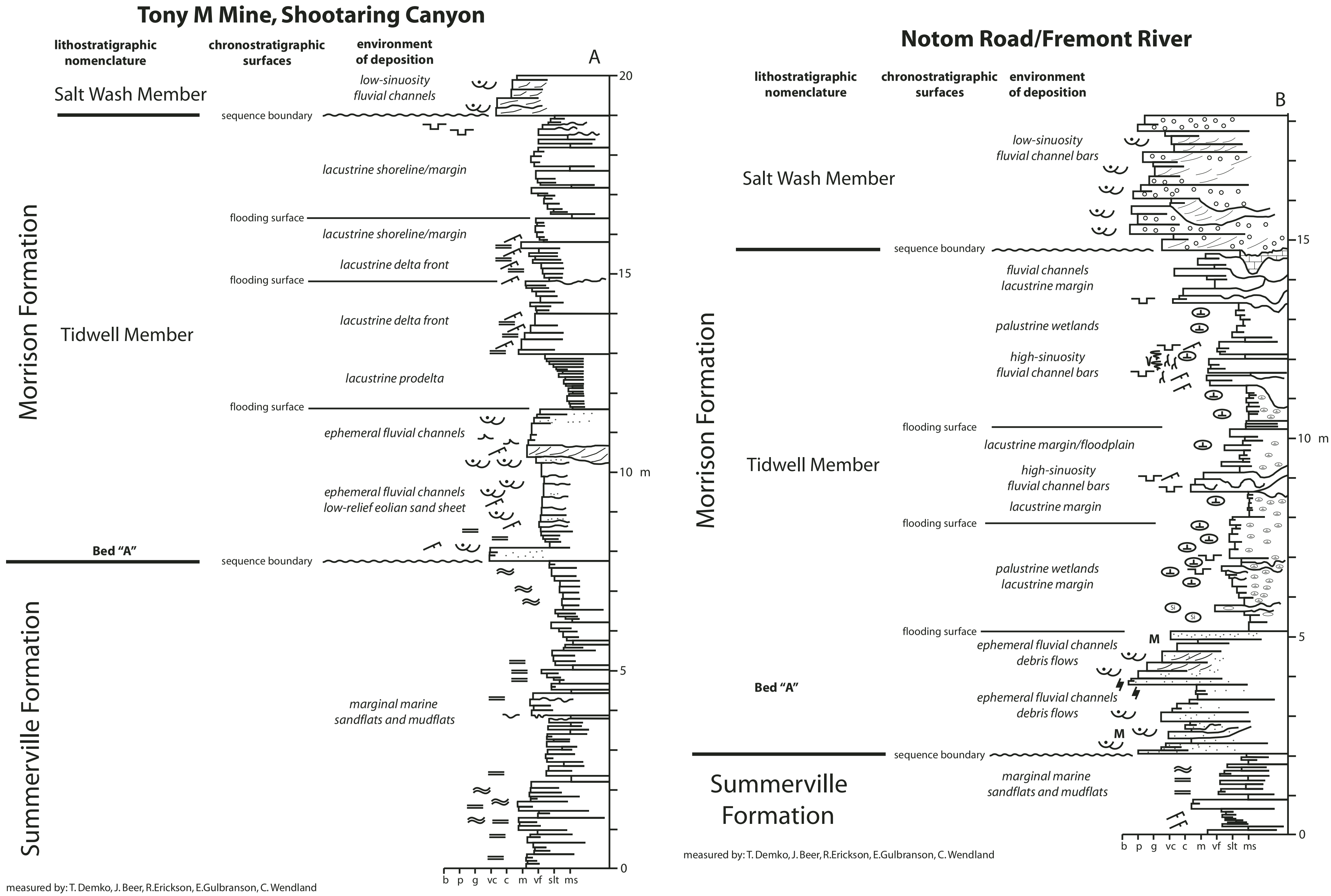

Figure 20. Measured sections of the upper part of the Middle Jurassic Summerville Formation and the Tidwell Member and lower part of the Salt Wash Member of the Upper Jurassic Morrison Formation. (A) Stop 3.2 in Shootaring Canyon near the Tony M uranium mine. (B) Stop 3.3 off the Notom Road and UT-24 near the Fremont River. See symbol key in Figure 14.

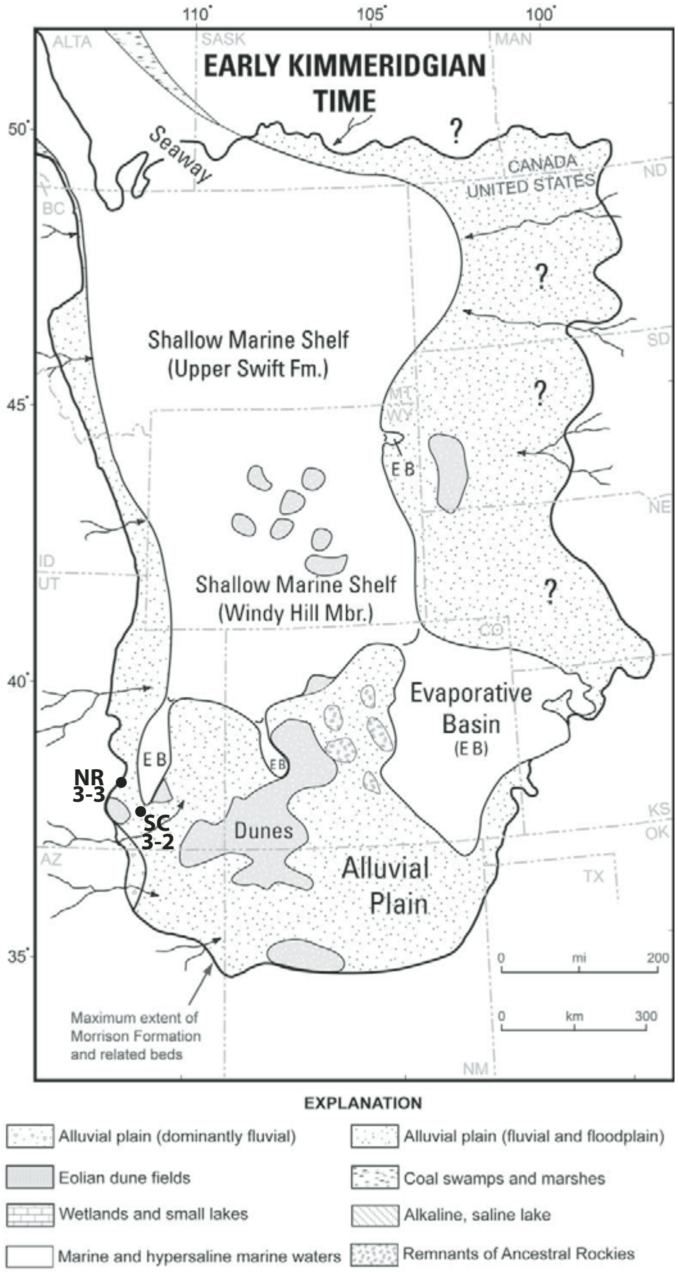

Figure 21. Paleogeography of the western United States during early Kimmerigian time (from Turner and Peterson, 2004) showing relative locations of Stop 3.2 (Shootaring Canyon [SC]) and Stop 3.3 (Notom Road [NR]) in the Tidwell Member of the Morrison Formation.

from modern lakes (Ward, 1992) such that the profundal zone contains mostly ichnofossils interpreted as those constructed by tubificid annelids and chironomid larvae. In general, tiering in lacustrine environments is quite shallow and can be subtle, dominated by hydrophilic traces no greater than 20 cm in depth below the sediment-water interface, with the majority within 5 cm of the paleolake bottom (Fig. 22).

Morrison lacustrine trace fossils do not fit into the *Mermia* ichnofacies as defined by Buatois and Mángano (1995) and Buatois et al. (1998) to characterize bioturbation in lake deposits. Many of the Morrison trace fossils indicate firm substrates in shallow water with intermittent subaerial exposure. Environments in deeper water settings do not show any of the diversity expected for the purported *Mermia* ichnofacies; only *Planolites* and simple ghost U-tubes are present in Morrison sublittoral deposits. Many characteristic ichnotaxa of the *Mermia* ichnofacies are absent from Morrison lacustrine deposits, with the exception of *Cochlichnus* and cf. *Planolites*, which are found in littoral environments. Such simple horizontal, vertical, and U-shaped feeding and burrowing traces as *Planolites*, *Palaeophycus*, *Arenicolites*, and *Skolithos* are likely to be present in lacustrine ichnocoenoses because similar forms can be made in any environmental conditions. The paleoenvironmental and paleoecological significance of such structures, however, would be different due to the different conditions found in lacustrine deposited strata.

The thick sandstone of the overlying Salt Wash Member sits on a sequence boundary, marked by regional truncation of strata, a significant basinward shift in facies, and an increase in grain size. If time permits, an optional stop will be made further up the main part of the canyon to examine dinosaur footprints and trackways, along with other ichnofossils, in floodplain deposits of the overlying Salt Wash Member of the Morrison Formation (Fig. 23).

Stop 3.3: Tidwell Member of the Morrison Formation along the Fremont River

Route and location: To proceed toward Stop 3.3, take UT-276 west ~11.7 mi (18.2 km) to UT-262 (Burr Trail). Continue on UT-262 north for another 55 mi (88.5 km). At Notom, take the left fork (Notom Road) toward UT-24. It is 3.4 mi (5.5 km) from the junction of Burr Trail (UT-262) and Notom Road to UT-24. Stop 3.3 is at outcrop directly east of the intersection of Notom Road and UT-24, on the south side of UT-24 at 12S 498923 E 4190134 N (37.85867°, −111.01235°).

Here the Tidwell Member of the Morrison Formation is dominated by marginal lacustrine and palustrine deposits, including rooted and trampled (dinoturbated) calcareous mudstone and calcrete layers and nodules (Fig. 20B). At this locality "Bed A" is much coarser than at the previous stop in Shootering Canyon and is characterized by massive to crude bedding, poor sorting, and a matrix-supported fabric and texture. "Bed A" here is interpreted to have been deposited in an ephemeral stream environment characterized by significant debris flow deposition and eolian modification.

Stops 3.4a through 3.4b: Capitol Reef National Park

Introduction: Traveling west from Stop 3.2, state highway UT-24 cuts through the Waterpocket Fold into the Mesozoic section. Here, all three sequence-bounding unconformities in the lower portion of the Chinle (Shinarump, Monitor Butte, Temple Mountain, and Moss Back Members), which define three periods

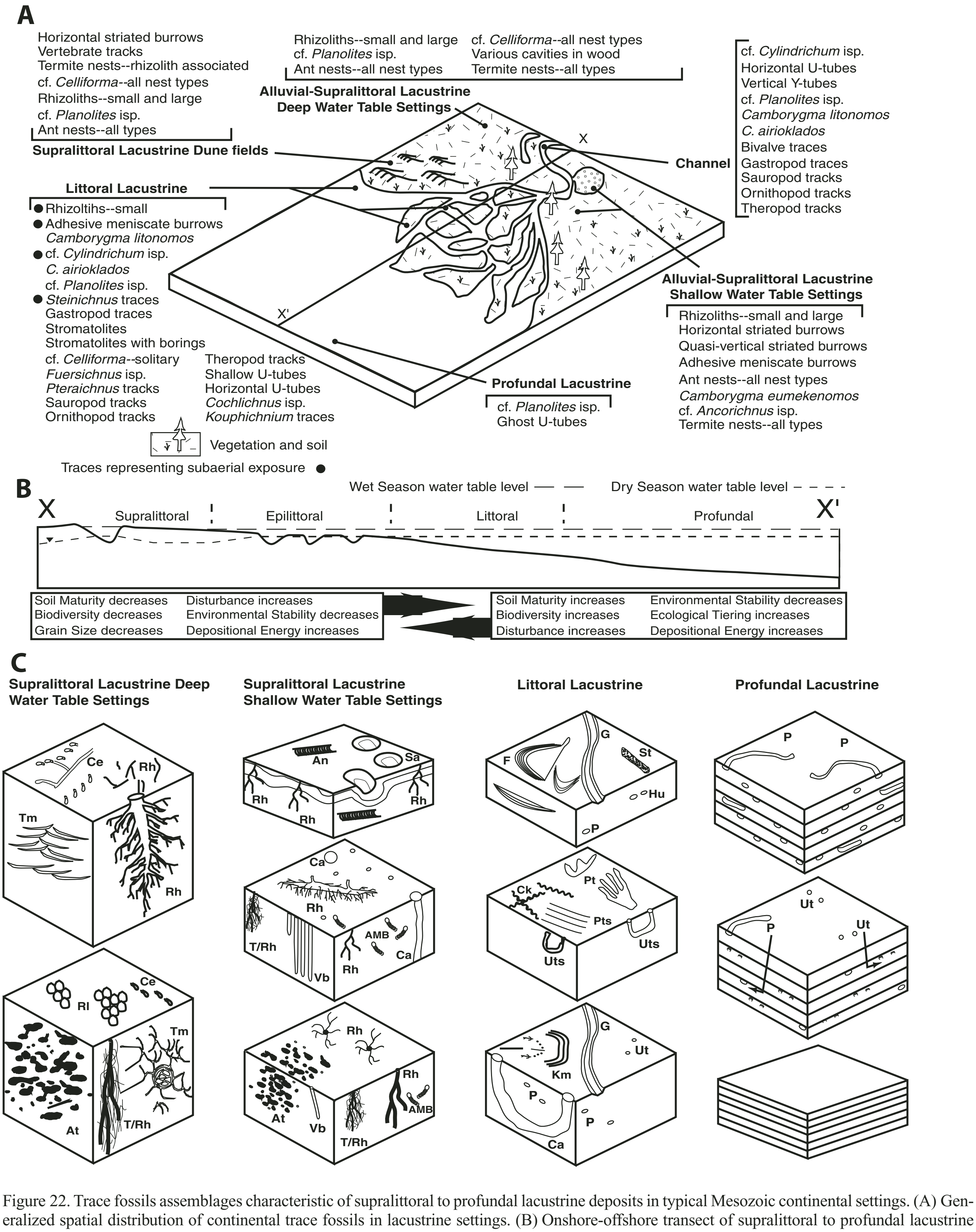

Figure 22. Trace fossils assemblages characteristic of supralittoral to profundal lacustrine deposits in typical Mesozoic continental settings. (A) Generalized spatial distribution of continental trace fossils in lacustrine settings. (B) Onshore-offshore transect of supralittoral to profundal lacustrine systems showing environmental gradients. C. Trace fossil assemblages characteristic of lacustrine subenvironments. At—ant nest; An—*Anchorichnus*; Ca—*Cambroygma*; Ce—*Celliforma*; F—*Fuersichnus*; G—gastropod trail; Hu—horizontal u-tubes; Km—*Kouphichnium*; P—*Planolites*; Pts—pterosaur scratch marks; Rh—rhizoliths; Rl—*Rosellichnus*; Sa—sauropods tracks; T/Rh—termite/rhizolith nest; Tm—termite nest; Ut—u-shaped tubes; Uts—shallow u-shaped tubes; Vb—vertebrate burrows. Trace fossil illustrations and box diagrams are schematic and not to scale.

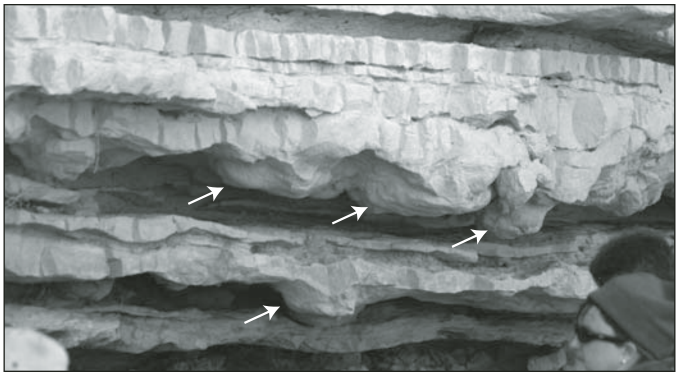

Figure 23. Sauropod footprints (marked by arrows) in alluvial facies of the Salt Wash Member of the Upper Jurassic Morrison Formation, Shootaring Canyon.

of incision and subsequent valley fill, can be seen (Fig. 24). The initial period of landscape degradation is marked by interfluve paleosols and truncation of the underlying Moenkopi Formation, creating a paleovalley that constrains the deposition of these four members, and defining the basal sequence-bounding unconformity (Demko, 2003; Beer, 2005). The first paleovalley fill, represented by the Shinarump Member, is interpreted as a confined, sandy, low-sinuosity river system. A second period of incision is marked by truncation of the Shinarump and correlative paleosols and pedogenically modified strata (Demko, 2003; Beer, 2005). These features define the second sequence-bounding unconformity. Above this unconformity, mudstones and sandstones of the Monitor Butte and correlative Temple Mountain Members were deposited, representing fluvio-lacustrine deposition and vertisol development in a high-sinuosity river system (Beer, 2005). Truncation of the Monitor Butte and Temple Mountain Members and the Moenkopi Formation, along with interfluve pedogenesis, mark the final cut-and-fill sequence occupying the master paleovalley. The high- and low-sinuosity fluvial deposits of the Moss Back Member overlie the surface of landscape degradation.

The first complete section of Chinle Formation is exposed across from "Guy Smith's Place" in historic Fruita, where a white-weathering paleosol developed at the top of the Lower Triassic Moenkopi Formation marks the base of the Monitor Butte Member. Compared to the deposits in Blue Notch Canyon, the lower part of the Chinle Formation (i.e., the Shinarump, Monitor Butte, and Moss Back Members) is significantly thicker in Capitol Reef National Park. These sediments were deposited closer to the center of the master paleovalley, and as a result a significant thickness of Shinarump basal valley-fill has been preserved (Fig. 25).

Stop 3.4a: Panorama Point—Capitol Reef National Park

Route and location: After Stop 3.3, head west 8.7 mi (14 km) on UT-24 toward Torrey, Utah. See Figure 18 for a detailed map of the next geologic stops. Turn left off UT-24 and follow the signs for Panorama Point at signed pulloff; 12S 0474148 E 4239944 N (38.30722°, −111.29569°).

From the vantage point at the Goosenecks overlook 1.7 mi west of the Capitol Reef National Park Visitor Center, we clearly see the nature of the surfaces bounding the Shinarump Member, as well as the stratal architecture of Monitor Butte Member deltaic clinoforms. The Shinarump Member is bounded above and below by regionally extensive unconformities. These surfaces are often marked by well-developed paleosols or by erosional truncation of underlying strata. Erosional truncation of the underlying Moenkopi Formation marking the Tr-3 unconformity can be seen at outcrop scale in many places on the Colorado Plateau; however, truncation of the upper part of the Shinarump Member of the Chinle Formation is often much more subtle. At the Goosenecks Overlook, several meters of truncation is clearly visible and the surface is overlain by Monitor Butte Member fluvio-lacustrine deposits (Fig. 25). This surface is interpreted as a FSSB.

Stop 3.4b: Chimney Rock—Capitol Reef National Park

Route and location: To reach Stop 3.4b, return to UT-24 and continue west 0.5 mi (0.8 km). Turn right following a sign for the Chimney Rock Trailhead. At 0.5 mi (0.8 km) west of Panorama Point, turn right into the parking lot just north of the highway.

A short hike heading northwest from the parking lot at Chimney Rock provides access to the Shinarump, Monitor Butte, and Moss Back Members of the Chinle Formation (Figs. 14C, 25, and 26). The lower two-thirds of the Monitor Butte Member consist of two distinct phases of lacustrine progradation separated by a distinctive flooding surface. The overlying portion of the Monitor Butte is characterized by paleosols associated with landscape aggradation, pedogenically modified crevasse splay deposits, and lateral accretion sets. These depositional facies represent a high-sinuosity fluvial system that prograded into the lake. The contact between the Monitor Butte and Moss Back Members is marked by a well-developed paleosol, which forms a resistant red-orange cliff in the outcrop.

This stop ends the geologic field guide. To continue to Salt Lake City, Utah, continue west and then north on UT-24 to Salina, Utah, and then take either U.S.-50 or UT-28 to I-15N. It is ~220 mi (354 km) to Salt Lake City.

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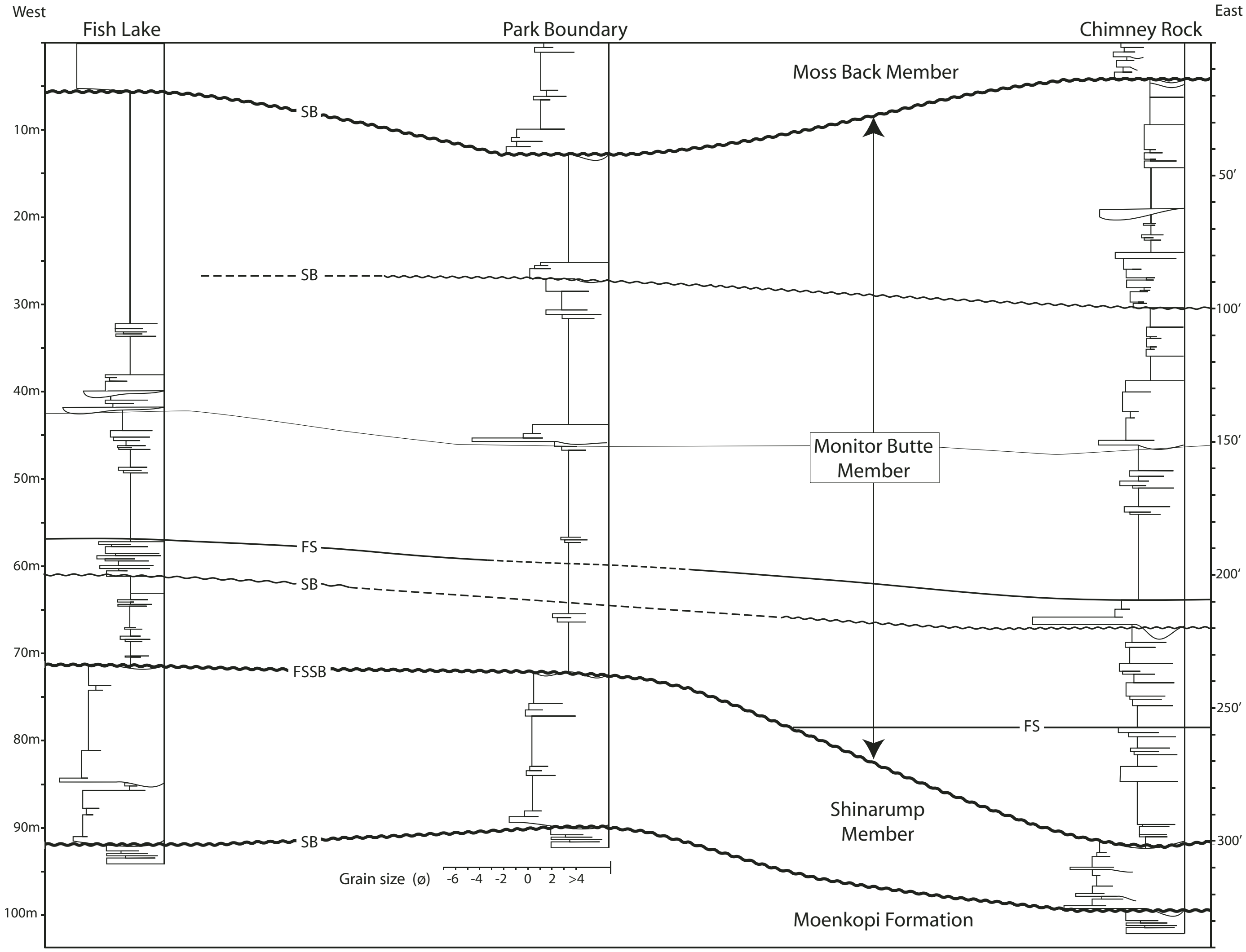

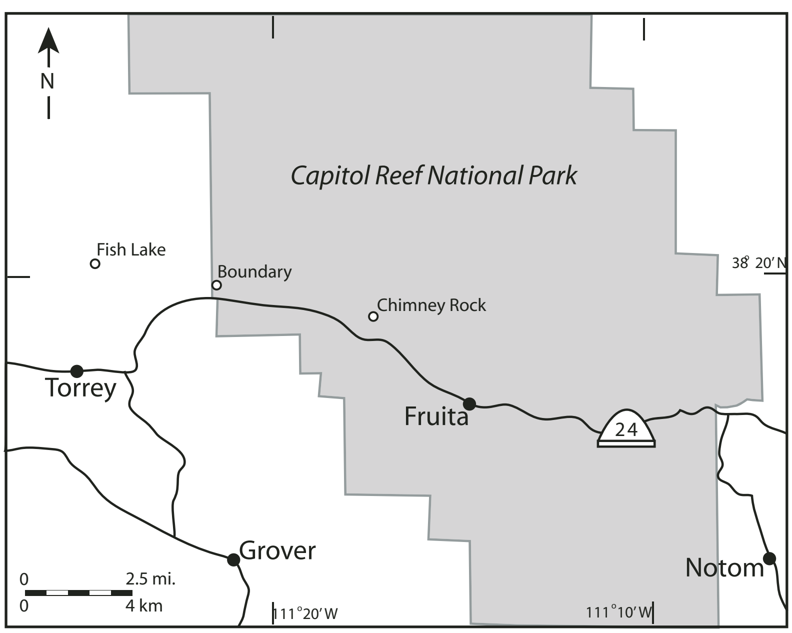

Figure 24. Correlation and sequence stratigraphy of the lower part of the Chinle Formation in and around the central part of Capitol Reef National Park. FS—flooding surface; FSSB—flooding-surface sequence boundary; SB—sequence boundary.

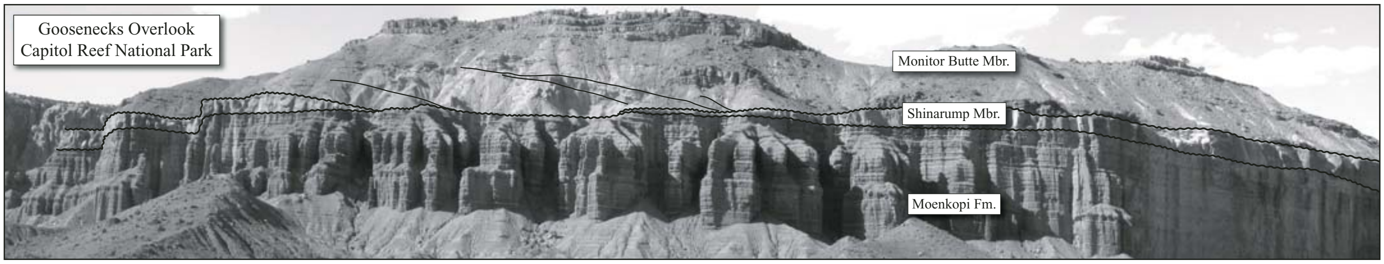

Figure 25. Interpreted photo panorama of the lower part of the Chinle Formation from Panorama Point in Capitol Reef National Park (Stop 3.4a). Note incision of the top of the Shinarump Member and clinoforms of delta foresets in the Monitor Butte Member.

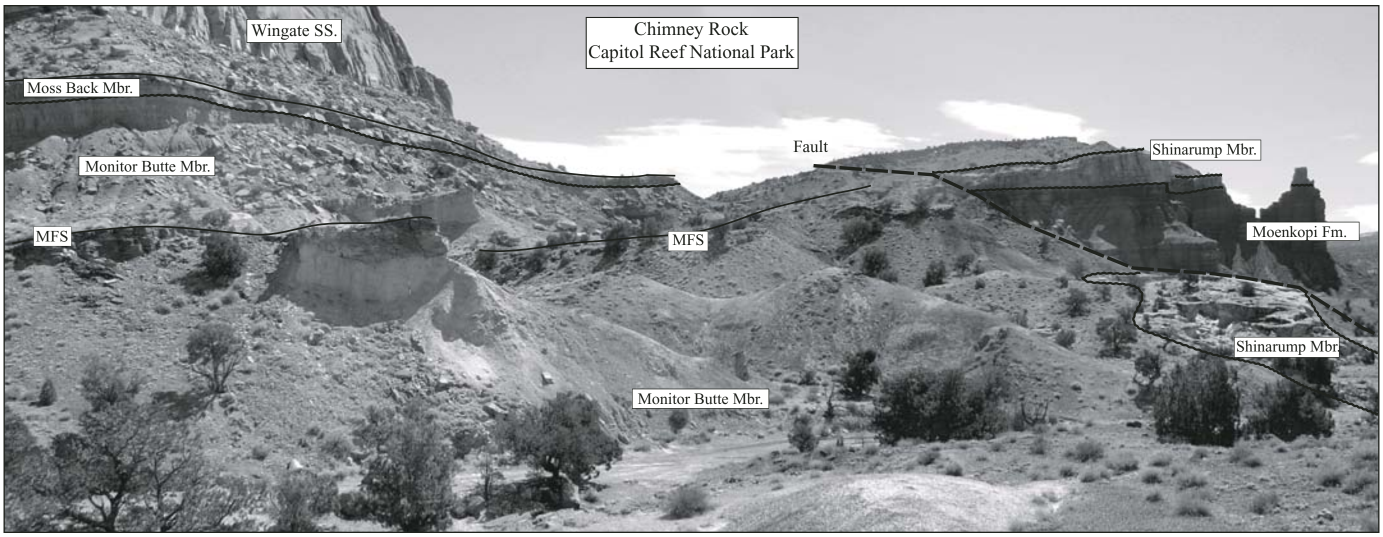

Figure 26. Interpreted photo panorama of the lower part of the Chinle Formation at Chimney Rock in Capitol Reef National Park (Stop 3.4b). MFS—maximum flood surface.

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