GEOLOGY OF THE INTERMOUNTAIN WEST
an open-access journal of the Utah Geological Association
ISSN 2380-7601
Volume 5 **2018**

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Cover

Stacked microbial carbonate mounds in the lacustrine Uinta Formation just below the sequence boundary at the base of the Duchesne River Formation. (Location: MS24 Red Cap in the northern part of the Uinta Basin)

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Trace Fossils and Fluvial-Lacustrine Ichnofacies of the Eocene Uinta and Duchesne River Formations, Northern Uinta Basin, Utah

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ABSTRACT

Trace fossil assemblages in a fluvial-lacustrine sequence stratigraphic context hold significant potential for expanding our understanding of environmental controls and continental basin-fill history. The succession of the Eocene Uinta Formation and four members of the Duchesne River Formation is extremely well-exposed in the Uinta Basin of northeastern Utah, revealing a robust stratigraphic framework to document broad-scale fluvial-lacustrine facies architectures and associated trace fossil assemblages. Greenish- and gray-colored mudstone beds with interbedded tabular sandstone representing lacustrine environments contain the trace fossils *Arenicolites* and *Gordia* (= *Haplotichnus*). In contrast, red mudstone beds with interbedded channelized sandstone representing upstream fluvial and alluvial environments contain a variety of insect trace fossils, including *Scoyenia, Ancorichnus*, and nest structures. Transitional, interfingering lithologies of wetland or shallow, short-lived lacustrine environments on the alluvial plain contain the trace fossil *Steinichnus*. Although there are many small-scale (bed-scale) physical sedimentary structures and trace fossils from continental subenvironments, this study focuses on the large-scale (member-scale) change in trace fossil assemblages, with results indicating that the ichnofacies corroborate continental sequence stratigraphic interpretations in a fluvial-lacustrine setting.

INTRODUCTION

The concept of ichnofacies, which was originally proposed by Seilacher (1967), has been expanded by many subsequent workers (e.g., Frey and Pemberton, 1984; Bromley and Asgaard, 1993; Smith and others, 1993; Buatois and Mángano, 1995; Genise and others, 2000; Ekdale and others, 2007; Genise and others, 2010). Initially Seilacher (1967) proposed a single continental ichnofacies that now has been developed into six continental ichnofacies: *Scoyenia*, *Mermia*, *Corprinisphaera*, *Entradichnus, Termitichnus,* and *Celliforma* ichnofacies (Buatois and Mángano, 2011) (figure 1). Additionally, the mostly shallow marine *Skolithos* ichnofacies has been documented in coastal lacustrine environments (e.g., Buatois and Mángano, 1995, 2007). Marine ich-

Citation for this article.
Sato, T., Chan, M.A., and Ekdale, A.A., 2018, Trace fossils and fluvial-lacustrine ichnofacies of the Eocene Uinta and Duchesne River Formations, northern Uinta Basin, Utah: Geology of the Intermountain West, v. 5, p. 209–226.

nofacies models are used widely for deciphering and reconstructing paleoenvironments through integrating sedimentological and paleontological data. However, there are far fewer studies of continental ichnofacies integrated within a fluvial-lacustrine sedimentologic and sequence stratigraphic context (Buatois and Mángano, 2004, 2009). Additional works of Hasiotis (2002, 2003) contribute insights on paleoecologic interpretations for understanding continental communities.

This study documents the ichnology of a well-exposed fluvial-lacustrine depositional system of the uppermost Eocene Uinta and Duchesne River Formations of the northern Uinta Basin. Well-exposed trace fossils are: (1) identified to ichnogenus level, (2) placed in a sequence stratigraphic context, and (3) evaluated as trace fossil assemblages or ichnofacies in vertical stratigraphic successions.

GEOLOGICAL CONTEXT

Geologic Setting

The Uinta Basin is a prolific oil-producing basin in northeastern Utah. It is a part of a Laramide lake basin system, straddling the states of Wyoming, Colorado, and Utah (figure 2), which emerged during the latest Cretaceous to early Paleogene (Dickinson and others, 1988). The Uinta Basin is surrounded by several hinterlands, such as the Uinta Mountains to the north, Sevier

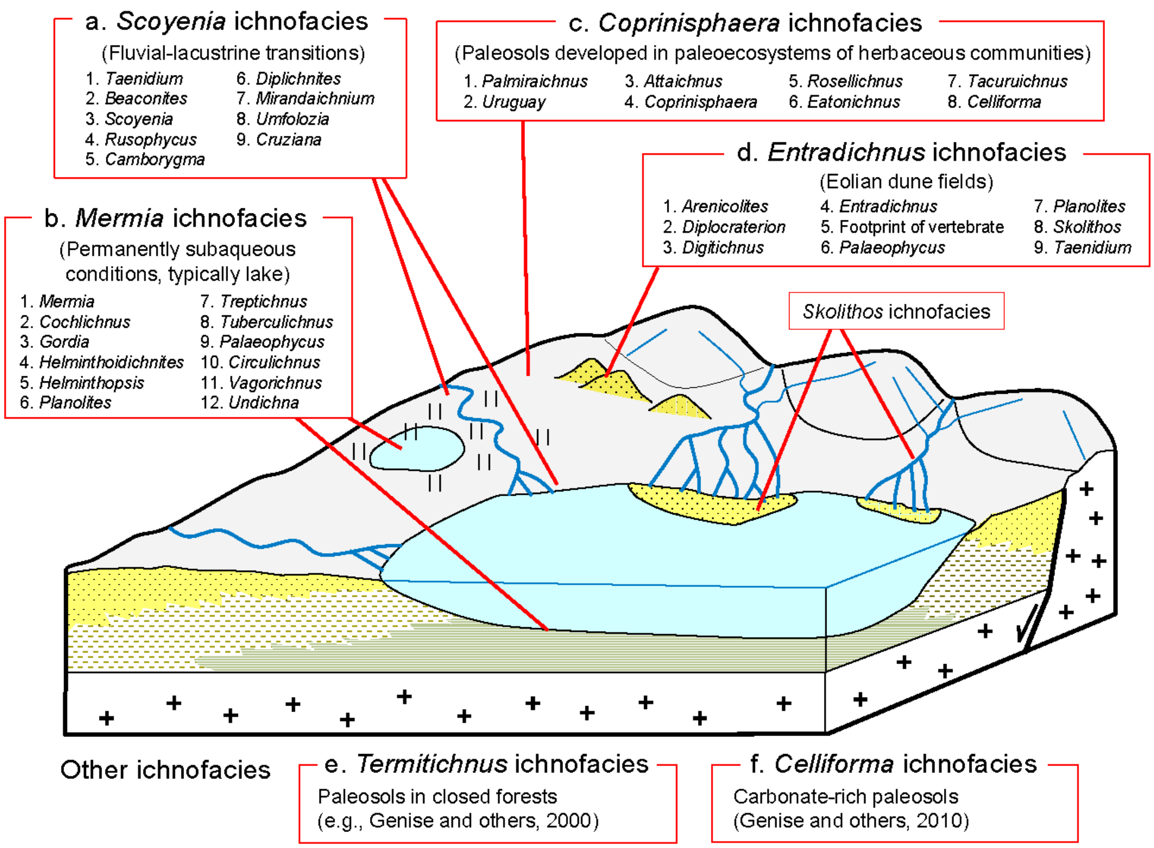

Figure 1. Six continental ichnofacies (a to f) and marginal lacustrine *Skolithos* ichnofacies in a non-marine depositional setting (modified from Buatois and Mángano, 2007). Trace fossil (ichnongenus) compositions of continental ichnofacies models: (a) *Scoyenia* ichnofacies, (b) *Mermia* ichnofacies, and (c) *Coprinisphaera* ichnofacies are from Buatois and Mángano (2007). The composition of (d) *Entradichnus* ichnofacies is from Ekdale and others (2007). (e) *Termitichnus* ichnofacies (e.g., Genise and others, 2000) and (f) *Celliforma* ichnofacies (Genise and others, 2010) are both paleosol-related ichnofacies, and have convoluted histories (see the detailed historical contexts in Buatois and Mángano, 2011).

fold-thrust belt (FTB) to the west, Douglas Creek arch to the east, and the Uncompahgre uplift and San Rafael Swell to the south. This asymmetric basin is bounded on the north by a high-angle reverse fault in the foothills of the Uinta Mountains (e.g., Fouch, 1975; Bruhn and others, 1983, 1986).

Paleocene-Eocene strata of the Uinta Basin consist of the Wasatch and related formations (fluvial), Green River (lacustrine), Uinta (fluvial-lacustrine transition), and Duchesne River (fluvial) Formations (figure 2). This study focuses on late-stage basin-fills of the uppermost Uinta and Duchesne River Formations, which generally comprise coarser-grained deposits than the underlying, renowned petroleum source rock of the Green River Formation. The Duchesne River Formation is subdivided into four lithologically distinct units: Brennan Basin (Db), Dry Gulch Creek (Dd), Lapoint (Dl), and Starr Flat (Ds) Members in ascending order (Andersen and

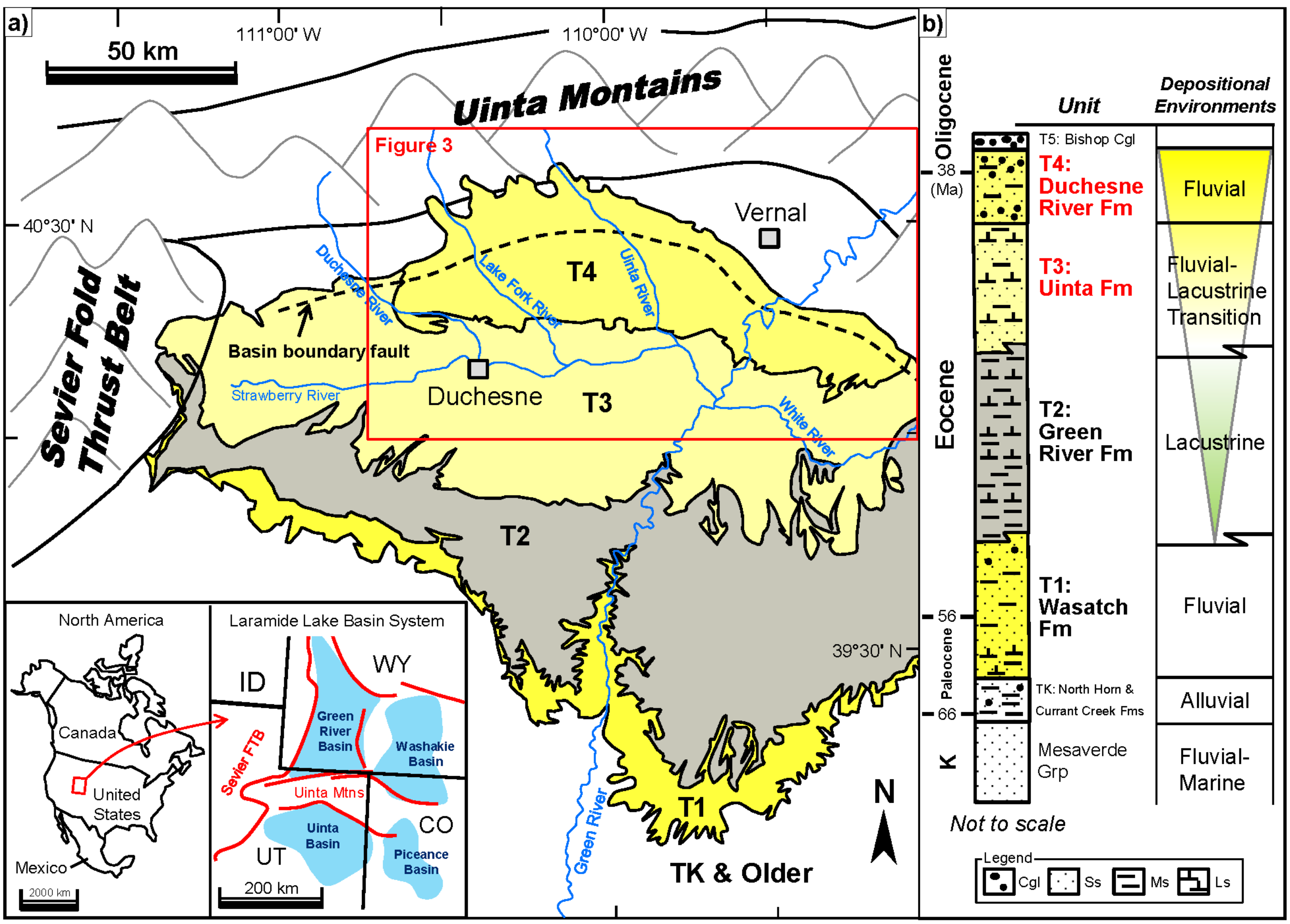

Figure 2. (a) Geological map of the Uinta Basin. Regional dip is to the north and formations get progressively younger toward the Uinta Mountains. The basin is surrounded by high mountain ranges of the Uinta Mountains and Sevier fold-thrust belt (FTB). The map of Laramide lake basin system is from Dickinson and others (1988). The geological map is modified from Andersen and Picard (1974), Bryant and others (1989), Bryant (1992), Hintze and others (2000), and Sprinkel (2006 and 2007). (b) Schematic geologic column showing the Paleogene sequence of the Uinta Basin (modified from Hintze and others, 2000). T2 to T4 exhibits a typical upward-coarsening/shallowing lacustrine basin-fill succession. Abbreviations: Cgl–conglomerate, Ss–sandstone, Ms–mudstone, Ls–limestone. Figure modified after Sato and Chan (2015).

Picard, 1972) (figure 3). A regional study detailed in Sato and Chan (2015) depicts the sequence stratigraphic framework and basin-scale facies architectures of the Duchesne River Formation (figures 3 and 4).

Previous Studies

A small number of sedimentological studies focus on the Uinta and Duchesne River Formations, despite their excellent exposures. In contrast, the Green River Formation including that in Wyoming has received much attention documenting sequence stratigraphy and ichnology (e.g., Bohacs and others, 2000; Keighley and others, 2003; Bohacs and others, 2007). Andersen and Picard (1972) presented a comprehensive regional stratigraphy and proposed the four member subdivisions of the Duchesne River Formation used here. D'Alessandro and others (1987) is so far the only published ichnological study of the Duchesne River Formation. It should be noted that the study area of D'Alessandro and others (1987) is situated in the western part of the Uinta Basin, where the "Undivided Duchesne River Formation" was proposed by Bryant and others (1989), and it includes proximal fluvial deposits time-equivalent to distal lacustrine deposits of the Uinta and Green River Formations. The formation studied by D'Alessandro and others (1987) is probably time-equivalent to the Uinta or Green River Formation, and thus is not covered by this study. There is no comprehensive ichnology study on the Uinta Formation, although some continental trace fossils from this formation were reported by Hasiotis (2002).

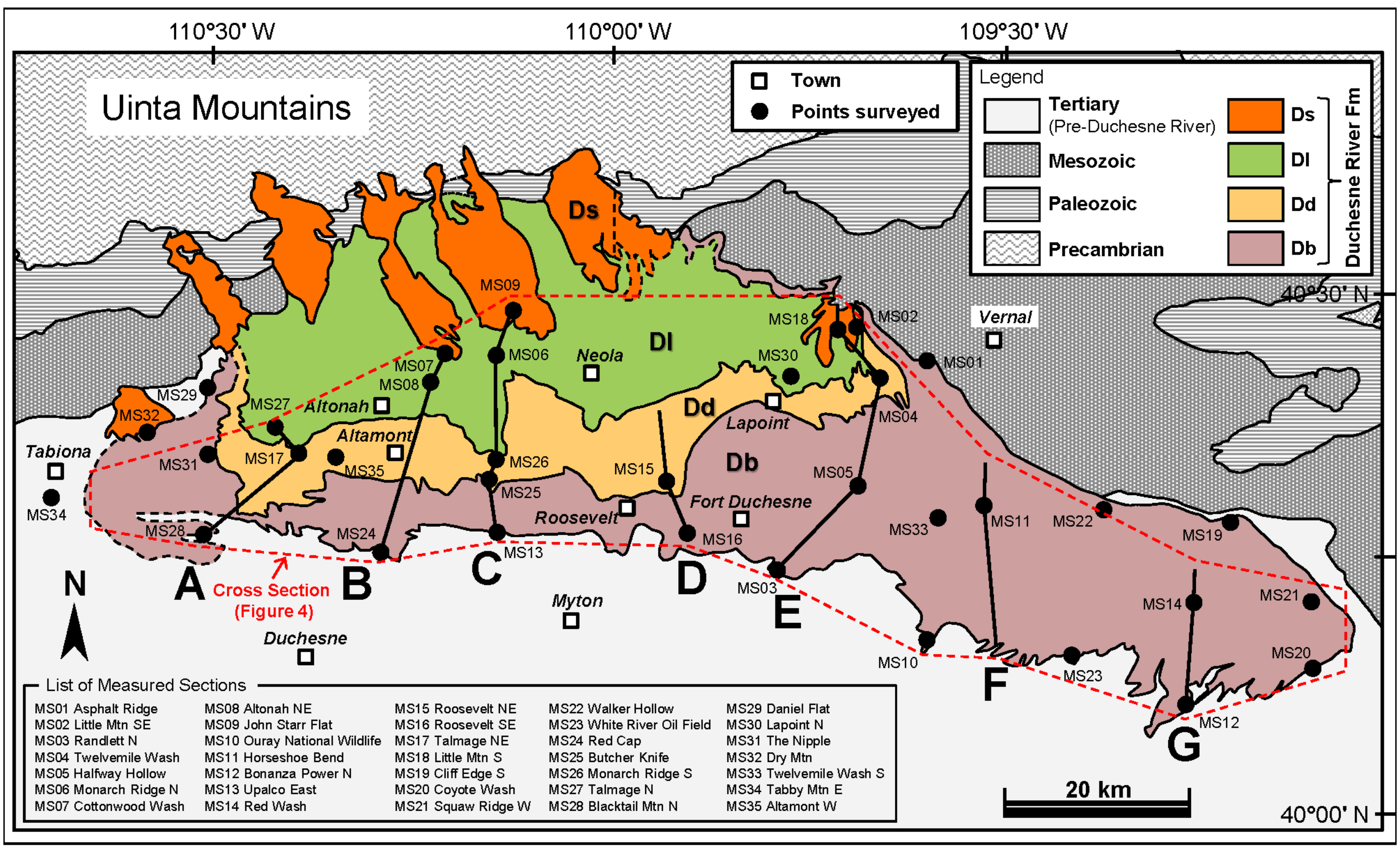

Figure 3. Geological map of the Duchesne River Formation in the Uinta Basin. Regional dip is to the north and the Duchesne River Members (Db: Brennan Basin, Dd: Dry Gulch Creek, Dl: Lapoint, and Ds: Starr Flat) get progressively younger toward the Uinta Mountains. The locations of 35 measured sections (MS), composite sections A to G (black lines), and the location of the cross section in figure 4 (dashed red polygon) are shown on the map. The map is modified after Andersen and Picard (1974), Rowley and others (1985), Bryant and others (1989), and Sprinkel (2006, 2007). Figure modified after Sato and Chan (2015).

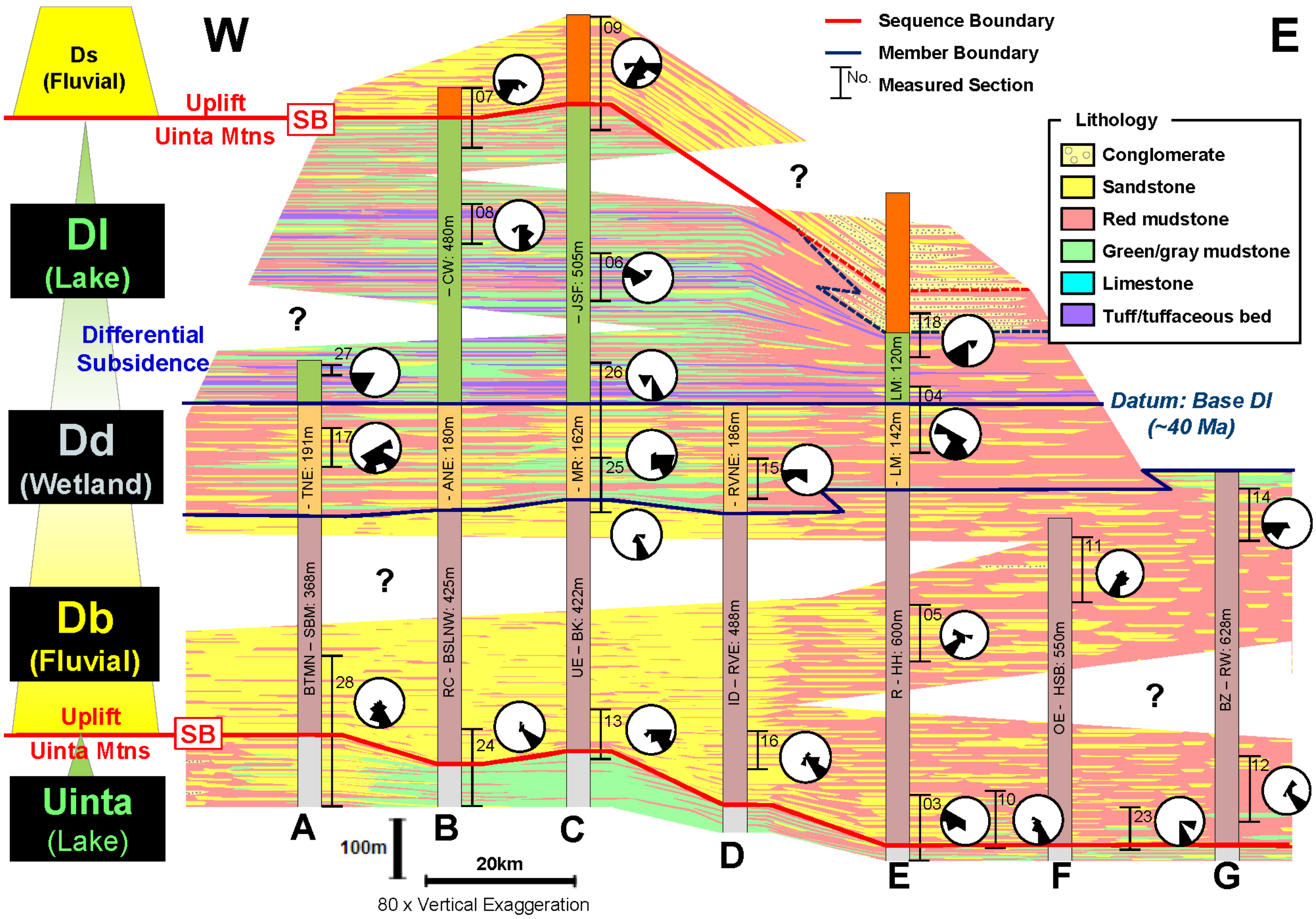

Figure 4. East-west regional correlations of composite sections A to G (see figure 3 for locations) showing the stratigraphic framework and detailed basin-scale facies architectures of the uppermost Uinta and Duchesne River Formations (modified from Sato and Chan, 2015). The stratigraphic datum is set at the base (basal tuffs) of Dl, which can be regarded as a nearly isochronous boundary (K-Ar ages of ~40 Ma reported by several researchers (McDowell and others, 1973; Andersen and Picard, 1974; Prothero and Swisher, 1992; Kelly and others, 2012). The succession of the uppermost Uinta and the Duchesne River Formations is characterized by upward-fining continental cycles.

METHODS

Basin-wide field work was conducted throughout the east-west and north-south exposure of the uppermost Uinta and Duchesne River Formations. The acquired measured geological sections at 35 locations (a total of 2970 m in length, described at resolution of 10 to 20 cm) were regionally correlated (figures 3 and 4). In this paper, trace fossils and their assemblages are described in relation to depositional environments on the basis of their presence or absence. Although trace fossils are abundant at some locations, identifications of ichnogenera are sometimes challenging due to poor preservation conditions, including modern weathering.

TRACE FOSSIL DESCRIPTIONS AND PALEOENVIRONMENTAL INTERPRETATIONS

The succession of the uppermost Uinta and Duchesne River Formations exhibits distinct fluvial-lacustrine facies changes in response to primarily tectonic uplift and subsidence of the Uinta Mountains and the adjacent basin (figure 4). Correspondingly, there are significant changes in observed trace fossils and their assemblages. In this section of the paper, lithofacies, biofacies (e.g., body fossil occurrence), and observed trace fossils of each unit are first described. Subsequently, depositional environments are interpreted in relation to the trace fossil assemblages, compared with continental ichnofacies models and their components. The Starr Flat Member (Ds), the uppermost unit of the Duchesne River Formation, is excluded from this ichnological study due to the insufficient amount of trace fossil data.

Uppermost Uinta Formation

Description

The lithofacies of the uppermost Uinta Formation is characterized by alternating beds of sandstone, mudstone, and limestone, typically comprised of upward-coarsening progradational parasequences. The formation is greenish- and gray-colored mudstone-dominated strata at the basin center (e.g., MS13, MS24) (figure 5), and gradually becomes sandy to the west (e.g., MS28) (figure 4). Between composite sections A and D, the formation occasionally contains conspicuous stromatolitic limestone mounds (figure 5) and thin-layered fossiliferous limestone containing garfish scales, gastropods, bivalves, and ostracods.

Trace fossils in the uppermost Uinta Formation are generally less abundant than in the overlying Brennan Basin Member (Db) of the Duchesne River Formation. Most of the traces are observed in epirelief on the top surfaces of tabular sandstones. They include *Arenicolites* isp. (U-shaped burrow with no wall), *Taenidium* isp. (horizontal burrow with meniscate backfill), and *Gordia* (= *Haplotichnus*) isp. (horizontal, small, simple trail with self-overcrossing), which are observed within the same sandstone bed with symmetrical wave ripples at MS24 (figures 6a and 6b). Buatois and others (1998) suggested that *Gordia* Emmons 1844 is synonymous with *Haplotichnus* Miller 1889, and we agree with that interpretation and therefore refer all such traces to *Gordia* in this paper. Additionally, *Planolites* isp. (horizontal, simple, straight to gently curved burrow), unidentified trace fossil A (horizontal to oblique, a series of ball-shaped burrows with distinct thick walls) (figure 6c), and unidentified B (slightly U-shaped, clustered, horizontal tubes) are preserved in this uppermost Uinta Formation unit.

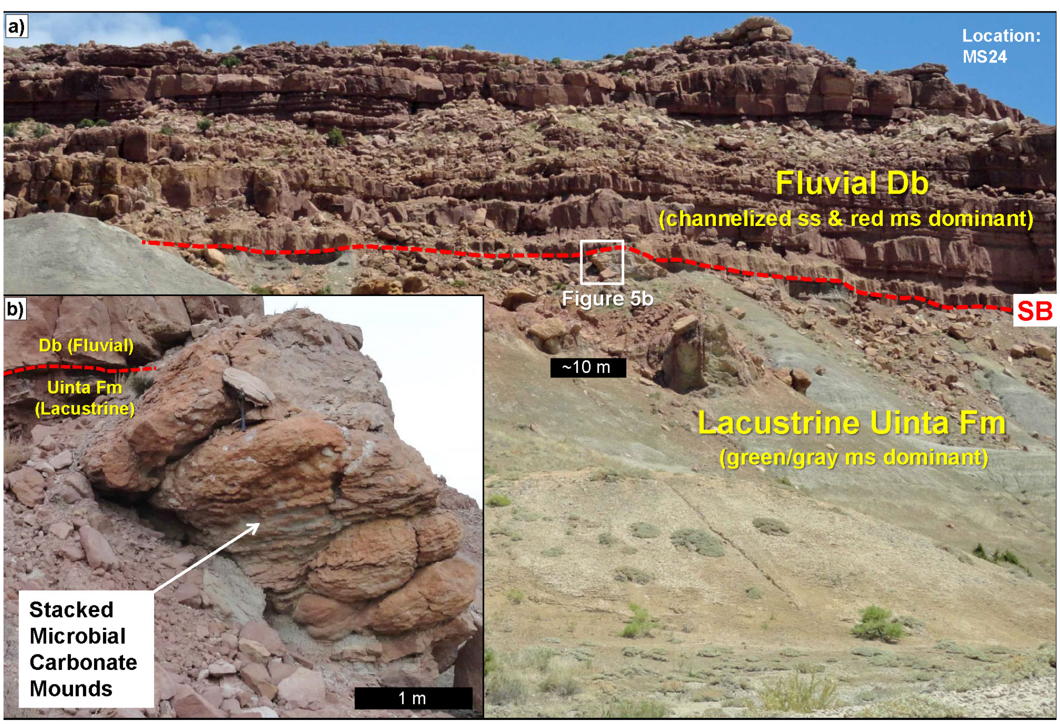

Figure 5. (a) Location MS24 (Red Cap) showing the distinct contact (i.e., sequence boundary [SB]) between the greenish- and gray-colored mudstone-dominated Uinta Formation (lacustrine) and overlying channelized sandstone-dominated Db (fluvial). (b) Close-up photo of stacked microbial carbonate mounds with stromatolitic structures in the uppermost Uinta Formation. Abbreviations: Ss–sandstone, Ms–mudstone.

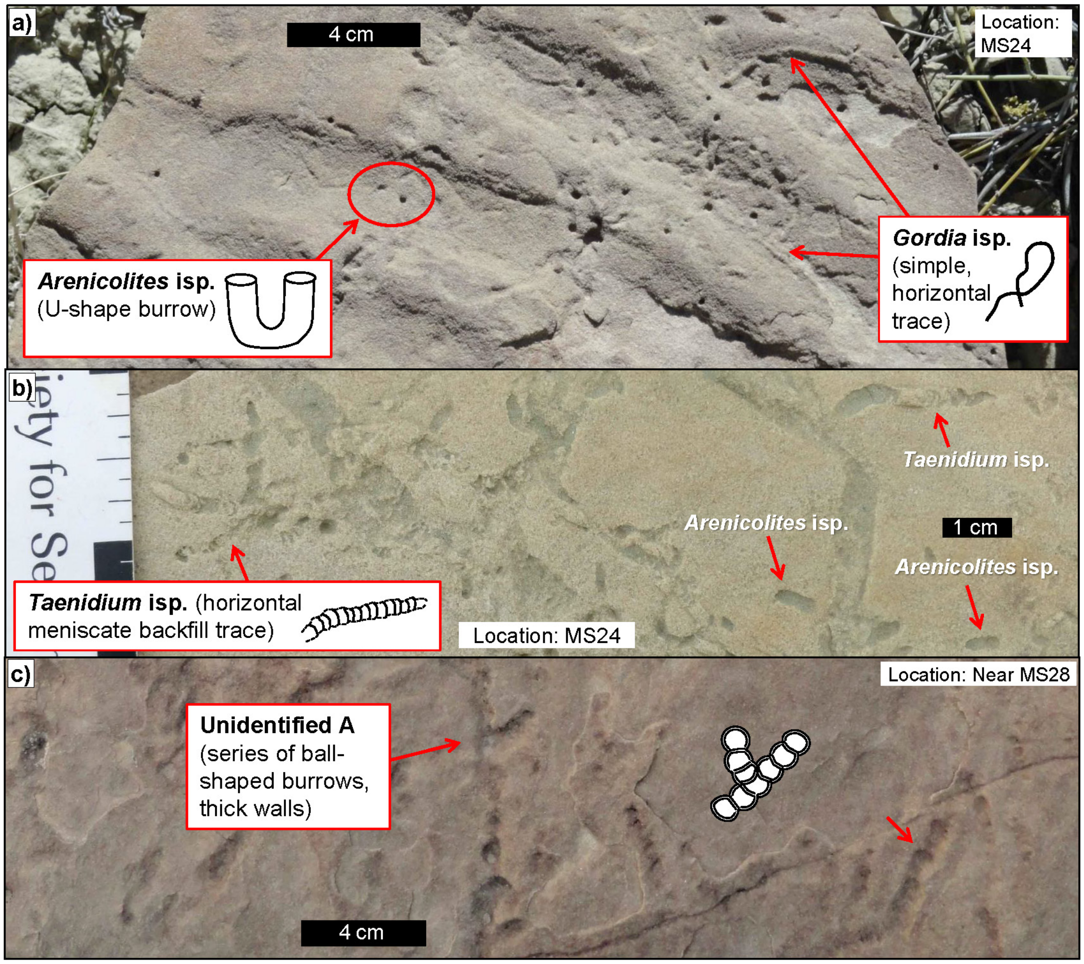

Figure 6. Trace fossils observed in the uppermost Uinta Formation. (a) *Arenicolites* isp. (U-shaped burrow with no wall) and *Gordia* isp. (horizontal, small, simple trail with self-overcrossing) appear on the top surface of asymmetric wave-rippled sandstone at MS24. (b) *Arenicolites* isp. and *Taenidium* isp. (horizontal burrow with meniscate backfill) on the bedding plane of tabular sandstone at MS24. (c) Unidentified trace fossil A (horizontal to oblique, a series of ball-shaped burrows with distinct thick walls) on the bedding plane of tabular sandstone near MS28.

Interpretation

The lithofacies of dominant greenish- and gray-colored mudstone with wave-rippled sandstone and conspicuous stromatolitic limestone mounds, clearly indicate an extensive lacustrine environment in the basin center. Gradual increase in sandstone to the western part of the basin indicates a transition into a marginal deltaic and fluvial system to the west. A lake environment of the Uinta Formation was also documented by several previous workers (Bruhn and others, 1986; Bryant and others, 1989; Davis and others, 2009).

The Uinta Formation trace fossil assemblage shows dominantly horizontal grazing traces. The trace fossil composition in this unit indicates a mixture of *Mermia* (e.g., *Gordia* isp.), *Scoyenia* (e.g., *Taenidium* isp.), and *Skolithos* (e.g., *Arenicolites* isp.) ichnofacies (figure 7). All these ichnofacies can occur in lake environments; *Mermia* ichnofacies represents low energy permanent subaqueous conditions, *Scoyenia* ichnofacies represents low to moderate energy fluvial-lacustrine transitions, and *Skolithos* ichnofacies represents moderate to high energy shoreline and delta environments (Buatois and Mángano, 2007). Occurrence of these ichnofacies is consistent with the stated lacustrine paleoenvironment interpretation based on lithofacies and biofacies.

Brennan Basin Member (Db)

Description

The lithofacies of the basal Brennan Basin Member (Db) of the Duchesne River Formation is dominated by trough cross-stratified, channelized sandstone, thin-layered sandstone and siltstone, and commonly mottled red mudstones, typically arranged in upward-fining parasequences (figure 8a). Db exhibits a significant contrast of lithofacies; a high net-sand-to-gross-thick-

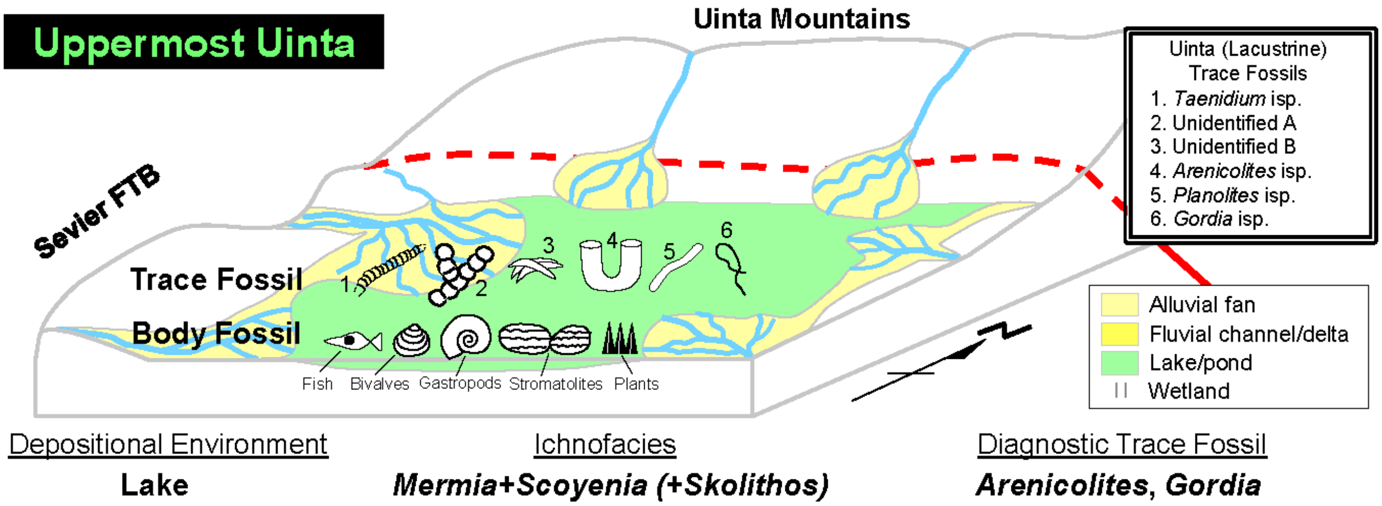

Figure 7. Paleoenvironmental reconstruction and trace fossil assemblage of the uppermost Uinta Formation. A lake environment developed during the deposition of the uppermost Uinta Formation. Trace fossil composition in this unit indicates a mixture of the *Mermia*, *Scoyenia,* and *Skolithos* ichnofacies. *Arenicolites* isp. and *Gordia* isp. are diagnostic trace fossils representing the uppermost Uinta environment.

ness ratio (NTG) facies in the western and a lower NTG facies in the eastern part of the basin (figure 4). Body fossils are scarce in this unit, although some mammal teeth (e.g., rodent) and bones (e.g., rhinocerotoid) were previously reported (e.g., Rasmussen and others, 1999; Kelly and others, 2012). A large but unidentified mammal bone was found in channelized sandstone at MS33 during the field work of this study (figure 3).

Trace fossils are very abundant, especially in the eastern part of the basin. Most of the traces are observed both in hyporelief and epirelief, and sometimes in full relief. Meniscate trace fossils, such as *Scoyenia* isp. (meniscate backfill with ornamented wall), *Ancorichnus* isp. (meniscate backfill with smoothly lined wall), *Beaconites* isp. (distinct, texturally heterogeneous meniscate backfill), and *Naktodemasis* isp. (thin and tightly spaced meniscate backfill) occur commonly and intensively in this unit (figures 8b to 8e). Also, *Celliforma* isp. (trunk burrow with oval-shaped chambers) (figure 9a), *Termitichnus* isp. (large trunk burrow with spherical-shaped holes) (figure 9b), and *Parawanichnus* isp. (large interconnected burrow system with galleries and chambers), which indicate social insect nest structures (e.g., Bown and others, 1997; Hasiotis, 2003), and unidentified ant nest or plant root structures (network or branching burrows with 2 to 3 mm diameters) are common in sandstone or siltstone beds. Additionally, *Skolithos* isp., *Planolites* isp., and *Palaeophycus* isp. are ubiquitous.

Interpretation

Lithofacies (channelized sandstone with red mudstone beds) and biofacies (mammal teeth and bones) indicate an extensive alluvial plain environment developed throughout the deposition of this unit. It indicates the progradation of the fluvial deposits of Db and the cessation of lake deposition of the Uinta Formation. Db exhibits a significant contrast of fluvial styles between the west (an amalgamated braided fluvial system with high NTG) and east (a relatively sinuous fluvial system with low NTG) (figure 4). This contrast is greatly influenced by the difference in climate and the number of source terrains (i.e., discharge control) (Sato and Chan, 2015).

The trace fossil composition in this unit indicates a mixture of *Scoyenia* (e.g., several types of meniscate backfill traces) and *Coprinisphaera* (e.g., insect nesting structures) ichnofacies (figure 10). Most of the intensively burrowed structures occur in contact with red mudstone beds indicating well-drained paleosols (e.g.,

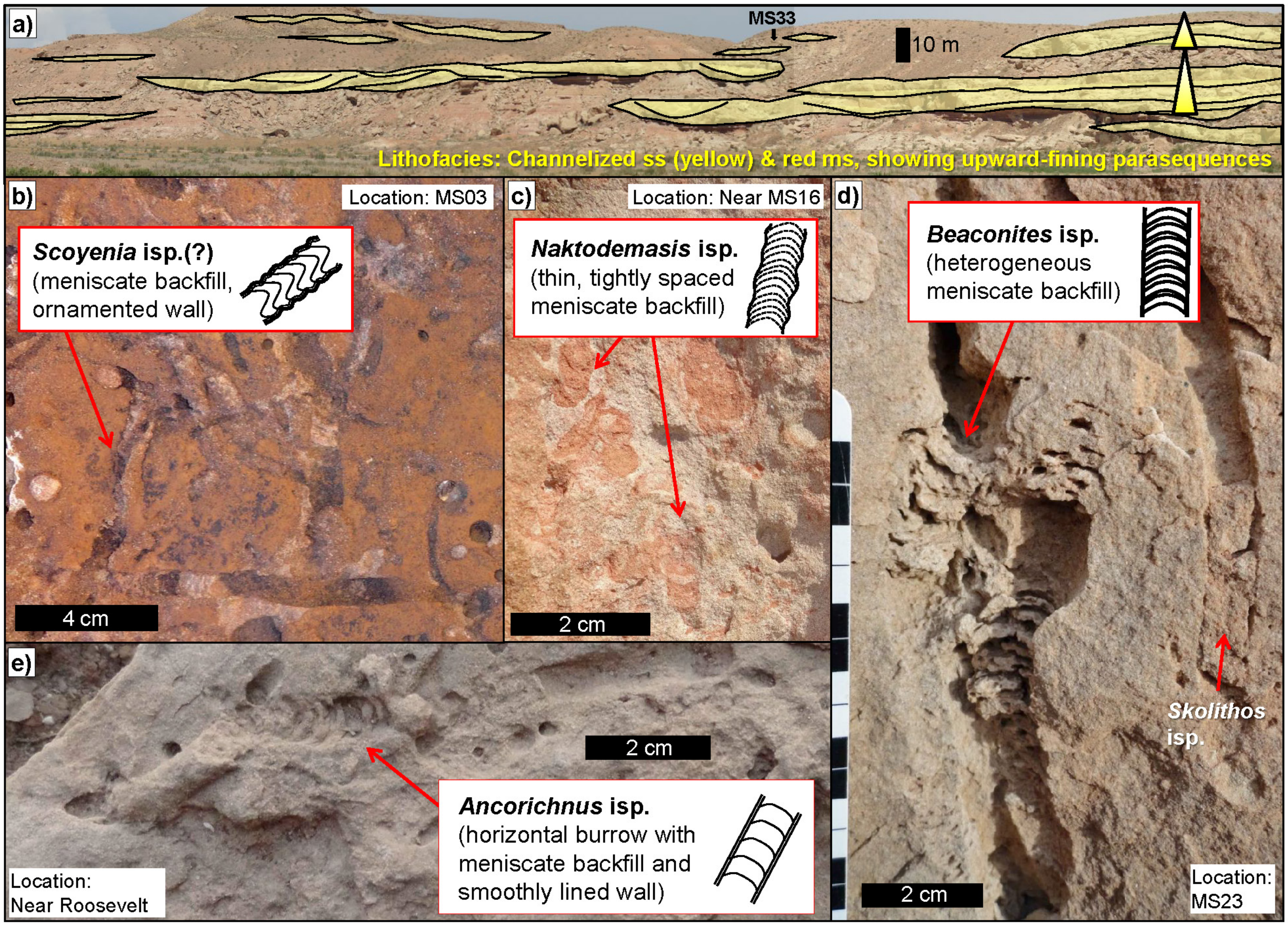

Figure 8. Lithofacies and meniscate trace fossils in the basal Brennan Basin Member (Db) of the Duchesne River Formation. (a) Typical lithofacies of Db at MS33 showing upward-fining parasequences of basal channelized sandstones (highlighted by yellow) and capped red mudstone beds. (b) *Scoyenia* isp. (meniscate backfill with ornamented wall) at the base of sandstone (hyporelief). (c) *Naktodemasis* isp. (thin, tightly spaced meniscate backfill with no wall) in a sectional view of sandstone (within *Termitichnus* isp.). (d) *Beaconites* isp. (distinct, texturally heterogenus meniscate backfill) and *Skolithos* isp. (simple, vertical cylindrical burrow) in a sectional view of sandstone. (e) *Ancorichnus* isp. (meniscate backfill with smoothly lined wall) at the base of sandstone. Abbreviations: Ss–sandstone, Ms–mudstone.

Kraus, 2002; Atchley and others, 2004; Kraus and Hasiotis, 2006) or within silty sandstone beds indicating pedogenically altered overbank deposits. Therefore, we interpret this assemblage as *Coprinisphaera* ichnofacies (i.e., paleosol trace fossil suites), because meniscate burrows can also be a part of this ichnofacies (e.g., Buatois and Mangano, 2007). The Db trace fossil assemblage shows a distinct difference from the underlying Uinta Formation (lake) assemblage.

Dry Gulch Creek Member (Dd)

Description

The Dry Gulch Creek Member (Dd) of the Duchesne River Formation is a transitional lithofacies between the underlying sandstone-dominated Db and overlying mudstone-dominated Lapoint Member (Dl). Dd typically shows alternating beds of channelized and tabular sandstone and greenish- and reddish-colored mudstone beds (commonly mottled) including intensive gypsum

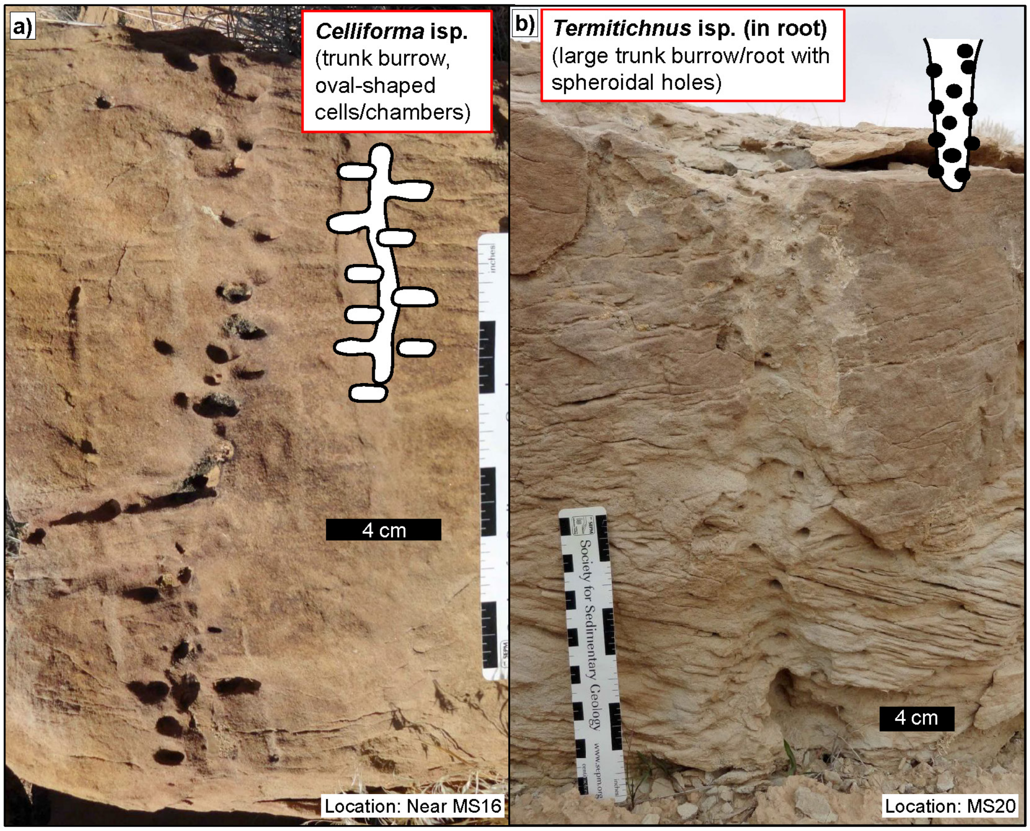

Figure 9. Insect nest traces in Db. (a) *Celliforma* isp. (trunk burrow with oval-shaped cells or chambers) in a sectional view of trough cross-stratified sandstone. (b) *Termitichnus* isp. in root (large trunk burrow with spherical holes) in a sectional view of trough cross-stratified sandstone.

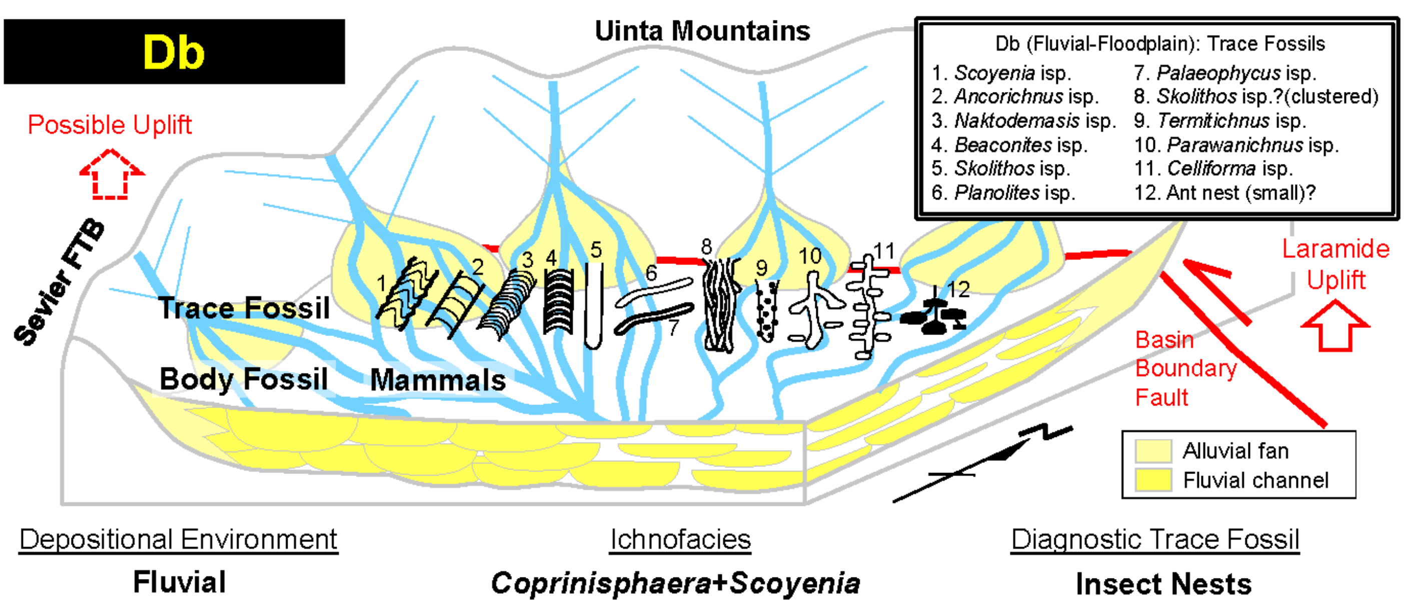

Figure 10. Paleoenvironmental reconstruction and trace fossil assemblage of Db. Lake Uinta has disappeared and fluvial systems developed on a widespread alluvial plain during the deposition of Db. Trace fossil composition in this unit indicates a mixture of *Coprinisphaera* and *Scoyenia* ichnofacies. Insect nests (e.g., *Celliforma* isp., *Termitichnus* isp., *Parawanichnus* isp.) are diagnostic trace fossils representing the Db environment.

veins and fragmented fossil plant/coaly layers (figure 11a). Dd exhibits contrasting mudstone colors across the basin; mixed greenish- and reddish-colored mudstone beds in the west and dominant reddish-colored mudstone beds in the eastern part of the basin (figure 4). Body fossils are scarce except for fossil plants found in the western part of this unit.

Trace fossils (in the western part of the basin) are abundant and recognized both in hyporelief and epirelief, and even in full relief. Meniscate trace fossils, such as *Scoyenia* isp., *Ancorichnus* isp., *Beaconites* isp., and *Naktodemasis* isp. commonly occur in this unit. *Steinichnus* isp. (large-diameter horizontal burrows with crossing scratch patterns) was observed at the base

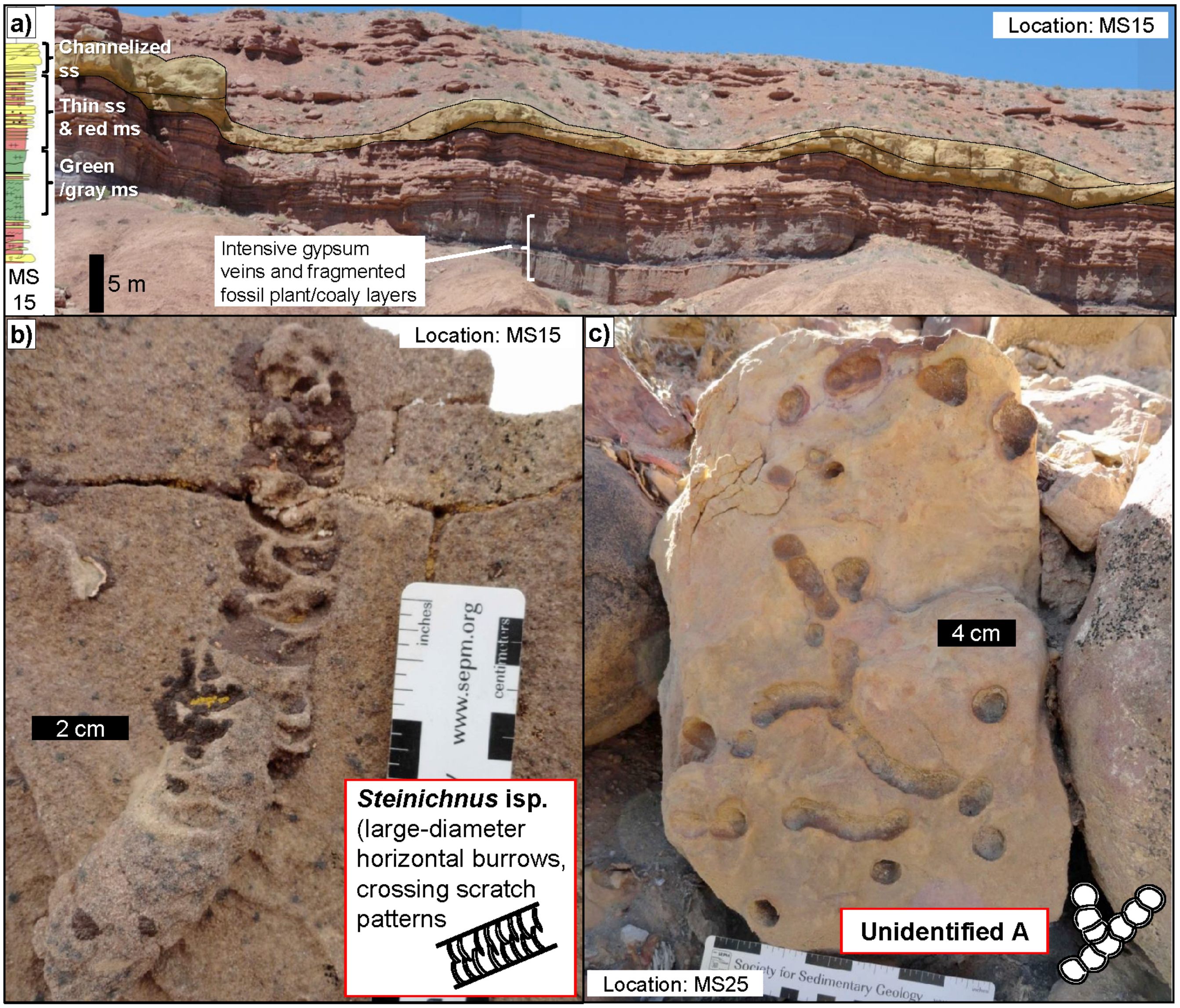

Figure 11. Lithofacies and trace fossils in the Dry Gulch Creek Member (Dd) of the Duchesne River Formation. (a) Upward-coarsening succession of basal greenish- and gray-colored mudstone beds with intensive gypsum veins and fragmented fossil plant/coaly layers, alternating beds of thin-layered sandstone and reddish-colored mudstone beds, and a capping channelized sandstone bed at MS15 (wetland to shallow lacustrine fill succession). (b) *Steinichnus* isp. (large-diameter horizontal burrows with crossing scratch patterns) observed at the base of cross-stratified sandstone at MS15. (c) Unidentified trace fossil A (horizontal to oblique, a series of ball-shaped burrow with distinct thick wall). Abbreviations: Ss–sandstone, Ms–mudstone.

of a cross-stratified sandstone at MS15 (figure 11b). Additionally, *Skolithos* isp., *Planolites* isp., *Palaeophycus* isp., unidentified trace fossil A (figure 11c) (see the description in the section of the uppermost Uinta Formation), unidentified trace fossil C (vertical and horizontal branching network burrow with no wall), and unidentified nest or root structures (network/branching burrows with 2 to 3 mm diameters, small ant nest?) are recognized in the western part of this unit.

Interpretation

Lithofacies (mixed greenish- and reddish-colored mudstone with interbedded channelized and tabular sandstone beds) and biofacies (layered fossil plants/woods) indicate frequent incursions of shallow and short-lived lacustrine or wetland environments on an extensive alluvial plain in the western part of the basin (i.e., to the west of MS15 NE Roosevelt). Trace fossil composition in this unit indicates a transitional ichnofacies (i.e., a mixture of *Scoyenia*, *Coprinisphaera,* and *Skolithos* ichnofacies) between those in the underlying Db and overlying Dl (figure 12). Although most of the ichnogenera in this unit are also recognized in Db, occurrences of unidentified trace fossil A (observed in the lacustrine Uinta Formation as described above) and *Steinichnus* isp. indicate some interventions of short-lived lake or wetland environments in Dd. *Steinichnus* possibly was made by insects, such as beetles or mole crickets (Bromley and Asgaard, 1979; Bohacs and others, 2007), and it is reported to be distributed in a higher water table environment (Bohacs and others, 2007).

Lapoint Member (Dl)

Description

The Lapoint Member (Dl) of the Duchesne River Formation is characterized by fine-grained deposits (i.e., mudstone and tuffaceous fine-grained rocks). It exhibits dominant greenish- and gray-colored mudstone interbedded with tabular sandstone beds (occasionally

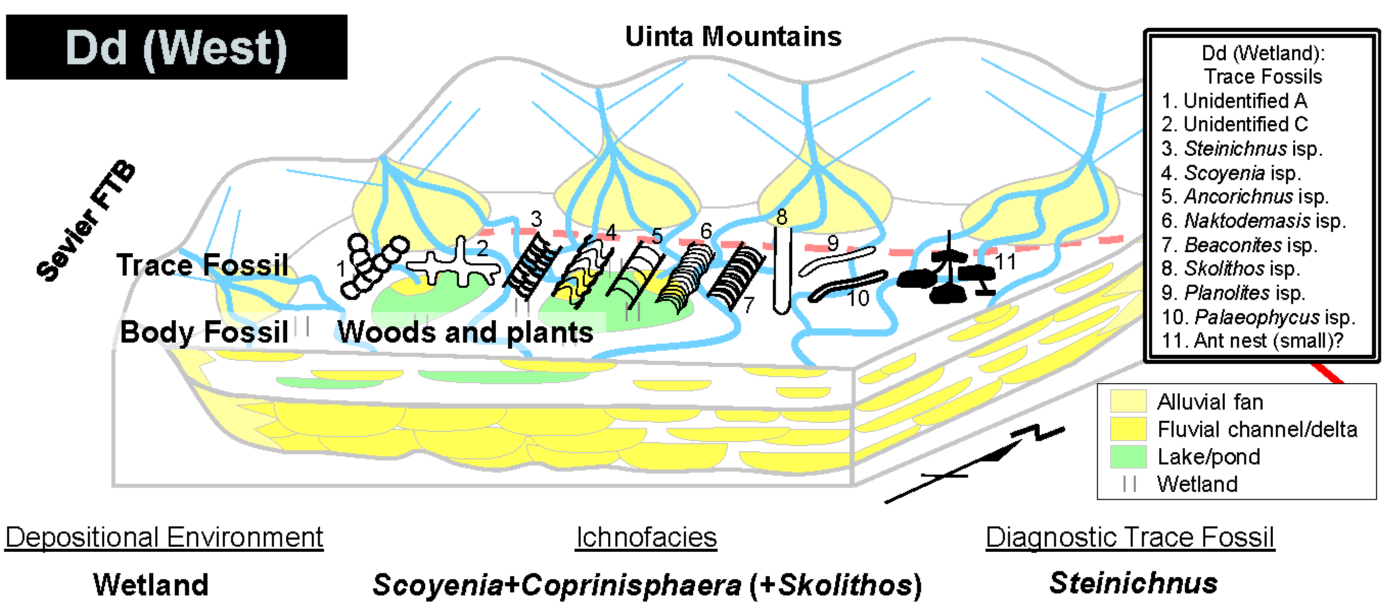

Figure 12. Paleoenvironmental reconstruction and trace fossil assemblage of Dd. Short-lived lake or wetland environments developed in the western part of the basin during the deposition of Dd. Trace fossil composition in this unit indicates a transitional ichnofacies (i.e., a mixture of *Scoyenia*, *Coprinisphaera*, and *Skolithos* ichnofacies) between those in Db and Dl. *Steinichnus* isp. appears to be a diagnostic trace fossil for this unit as it is reported to be distributed in a higher water table environment than the insect nesting traces (Bohacs and others, 2007).

wave-rippled), tuff, and limestone beds in the western part of the basin (figure 13a), and dominant reddish-colored mudstone beds in the eastern part of the basin (figure 4). Body fossils are generally scarce, although shell-rich (gastropods and bivalves) limestones and coaly, carbonaceous mudstone layers are observed in some locations (e.g., MS06) in the western part of the basin.

Trace fossils in the western part of this unit are sparse and tend to occur in epirelief on the top surface of tabular sandstones. Trace fossils observed in this unit are *Arenicolites* isp., *Gordia* isp., *Taenidium* isp., and *Planolites* isp. (figure 13), which is an assemblage similar to that of the uppermost Uinta Formation.

Interpretation

Lithofacies (dominant greenish- and gray-colored mudstone beds with wave-rippled tabular sandstone beds) and biofacies (gastropods and bivalves in fossiliferous limestones) indicate a widespread lacustrine environment in the western half of the basin. This extensive lake environment developed due to differential subsidence of the basin (Sato and Chan, 2015). The trace fossil assemblage

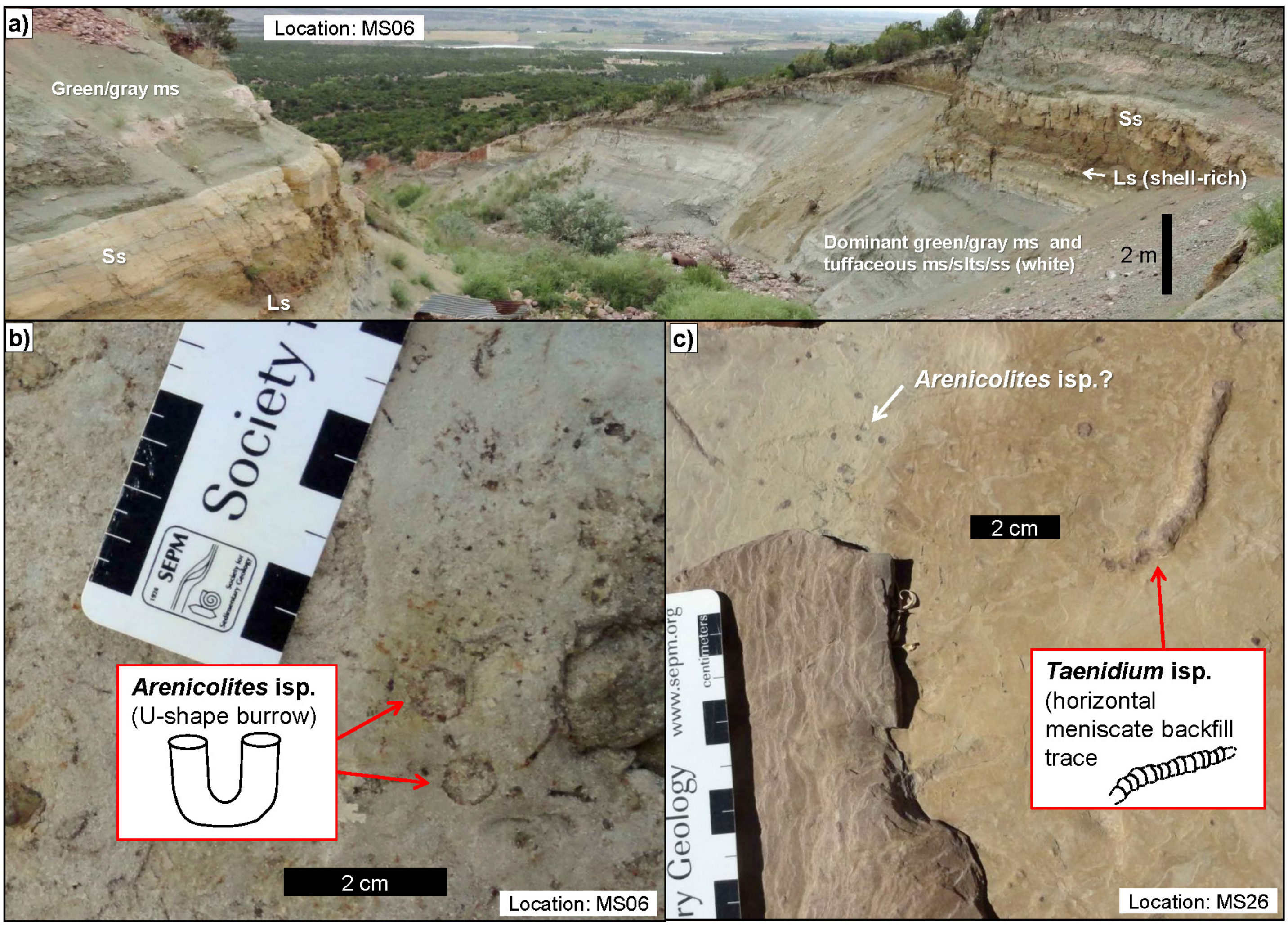

Figure 13. Lithofacies and trace fossils in the Lapoint Member (Dl) of the Duchesne River Formation. (a) Overlook of greenish- and gray-colored mudstone-dominated Dl (white tuffaceous and fine-grained rocks are also abundant) at MS06. Lithofacies (dominant greenish- and gray-colored mudstone beds and minor occurrences of wave-rippled tabular sandstone and thin fossiliferous limestone) indicates a widespread lacustrine environment. (b) *Arenicolites* isp. (U-shape burrow) on the top surface of tuffaceous silty sandstone. (c) *Taenidium* isp. (horizontal burrow with meniscate backfill) on the top surface of rippled silty sandstone. Abbreviations: Ss–sandstone, Slts–siltstone, Ms–mudstone, Ls–limestone.

in this unit indicates a mixture of the *Mermia*, *Scoyenia*, and *Skolithos* ichnofacies (figure 14), which is very similar to ichnofacies of the uppermost Uinta Formation. This evidence demonstrates the recurrence of lacustrine communities and a distinct difference from the fluvial-floodplain trace fossil assemblage observed in the underlying Db.

DISCUSSION

The stratigraphic sequence of the Duchesne River Formation was primarily controlled by tectonics (Sato and Chan, 2015). The uplift(s) in the Uinta Mountains and possibly the Sevier FTB created distinct sequence boundaries at the base of Db and Ds, and led to the development of an upward-fining fluvial sequence from Db (LST: lowstand systems tract) to Dd and Dl (TST/HST: transgressive/highstand systems tract) (figure 15). The trace fossil assemblages examined in this paper show distinct changes according to these systems tracts, corresponding to water-table-level changes (figure 15). *Mermia*, *Scoyenia*, and *Skolithos* ichnofacies of the uppermost Uinta Formation indicate relative high water-table conditions consistent with the TST/HST of the lacustrine environment, where the trace fossil assemblage typically represents subaqueous tracemaker communities. The dominant *Coprinisphaera* ichnofacies of Db suggests a change to lower water-table and pedogenic conditions typical of a LST. The lacustrine environment of the Uinta Formation was completely replaced with a relatively dry alluvial plain environment of Db over the basin, where the trace fossil assemblage typically represents terrestrial tracemaker communities such as insects. *Scoyenia*, *Coprinisphaera*, and *Skolithos* ichnofacies of Dd (TST/HST) indicate a transition into relative high water-table conditions, with the gradual incursion of wetland or subaqueous tracemaker communities. *Mermia*, *Scoyenia*, and *Skolithos* ichnofacies of Dl (TST/HST) indicate the recurrence of relative high water-table conditions with subaqueous tracemaker communities. These changes correspond to the large-scale (i.e., member-scale) changes in depositional environment. Thus this study cannot offer rigorous bed-by-bed analyses or interpretations on specific small-scale continental environments, such as channel, bar, and levee. In future studies, such detailed bed-scale analysis may lead to decoding a high resolution sequence and to the extraction of more specific trace fossil assemblages (ichnofacies). An ichnofabric approach might be useful for

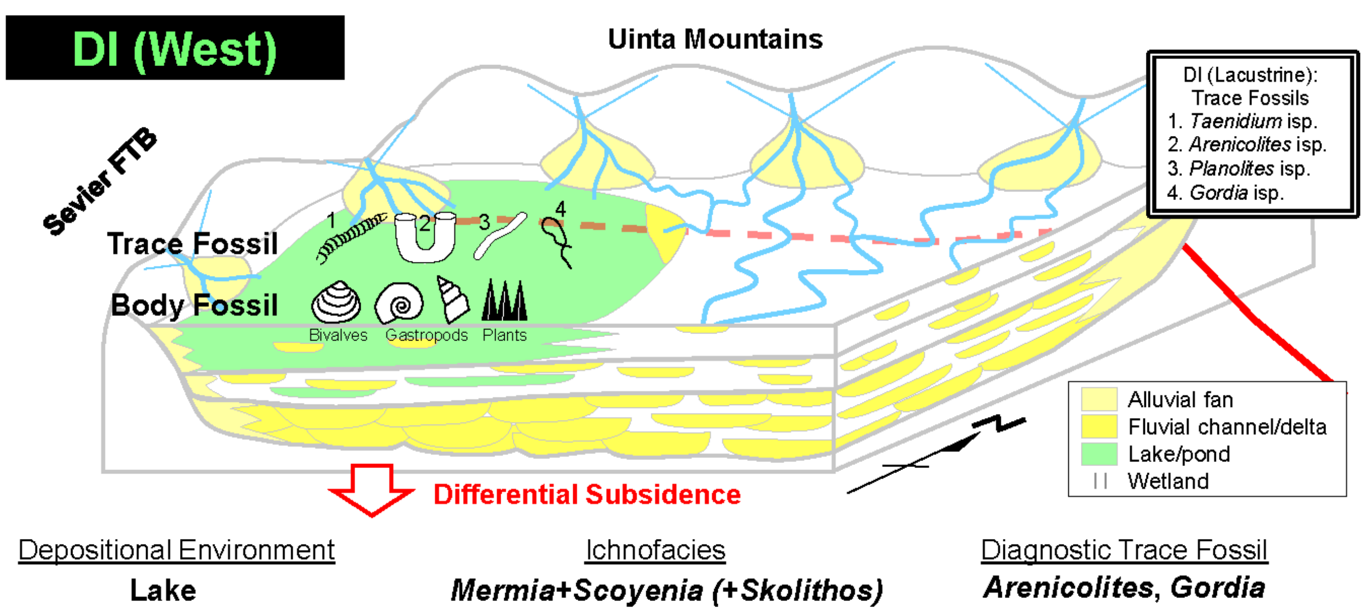

Figure 14. Paleoenvironmental reconstruction and trace fossil assemblage of Dl. An extensive lake environment developed during the deposition of Dl. The trace fossil association in this unit indicates a mixture of the *Mermia*, *Scoyenia*, and *Skolithos* ichnofacies, demonstrating the recurrence of lacustrine communities.

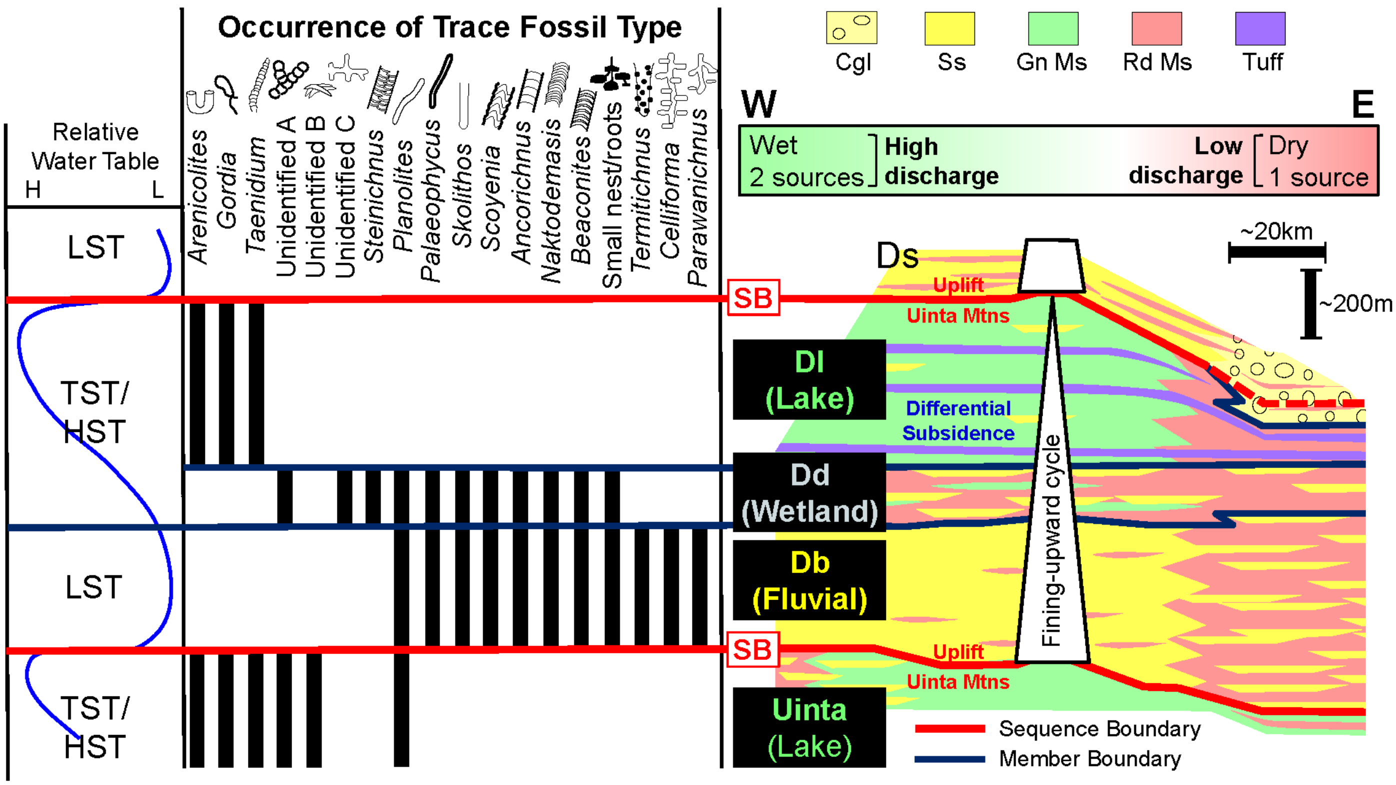

Figure 15. Synthesis of sequence stratigraphic framework and trace fossil occurrences of the uppermost Uinta and Duchesne River Formations. The uplift(s) in the Uinta Mountains and possibly in the Sevier FTB caused distinct sequence boundaries at the base of Db and Ds, and led to the development of an upward-fining sequence from Db (LST) to Dl (TST/HST). The internal basin-scale facies changes reflect laterally variable allogenic controls of discharge (high in the west and low in the east) and tectonic subsidence (higher subsidence rate in the west during the Dl deposition) (Sato and Chan, 2015). Trace fossil assemblages show distinct changes according to the water-table level. Abbreviations: Cgl–conglomerate, Ss–sandstone, Gn M–green mudstone, Rd Ms–red mudstone, Ls–limestone. Figure modified after Sato and Chan (2015).

this high-resolution analysis, because there are possibly multiple communities recorded within a sandstone bed. For example, traces in fluvial channels could be overwritten by the later paleosol communities after these channels are abandoned.

CONCLUSION

A regional outcrop-based study reveals the sequence stratigraphic framework and detailed basin-scale facies architectures of the uppermost Uinta and Duchesne River Formations. This paper documents remarkable changes in continental trace fossil assemblages according to fluctuations in the relative water-table level (i.e., member-scale sedimentary facies changes). Specifically, the uppermost Uinta Formation and Lapoint Member (Dl) of the Duchesne River Formation indicate extensive lacustrine environments and the corresponding trace fossil assemblage including *Arenicolites* and *Gordia*. By contrast, the basal Brennan Basin Member (Db) of the Duchesne River Formation exhibits a widespread fluvial environment and the corresponding trace fossil assemblage is characterized by a variety of insect trace fossils (e.g., *Scoyenia*, *Ancorichnus*, nest structures). The Dry Gulch Creek Member (Dd) of the Duchesne River Formation shows a transitional (i.e., wetland) environment where the intermediate trace fossil assemblages including *Steinichnus* are present. The large-scale (member-scale) change in trace fossil assemblages shows that the ichnofacies corroborate continental sequence stratigraphic interpretations and serve as a valuable indicator of paleoenvironmental change in a fluvial-lacustrine setting. The uppermost Uinta and Duchesne River Formations offer a valuable example of dramatic changes in communities of trace-making organisms in response to the tectonic control of the dynamic intermontane basin.

ACKNOWLEDGEMENTS

We thank Cari Johnson, Lisa Stright, and Lauren Birgenheier at the University of Utah for their useful comments on this project. Douglas Sprinkel at the Utah Geological Survey was a great supporter and provided valuable insight on the Uinta Basin geology. Stephen Hasiotis, University of Kansas, and Luis Buatois, University of Saskatchewan, provided helpful input on the identification of continental trace fossils. We acknowledge the Ute Indian Tribe and the Bureau of Land Management in Vernal and Ouray National Wildlife Refuge who generously provided essential permissions for the field work.

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