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# Trace Fossils of the Eocene Green River Lake Basins, Wyoming, Utah, and Colorado

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## Abstract

Trace fossils produced by insects, annelids, molluscs, birds, mammals, reptiles, amphibians, and fish are diverse in the Green River and roughly correlative formations, and provide clues to interpret sedimentary environments, stratigraphy, and paleoecology of continental organisms during the Early to middle Eocene (~53–43 Ma). The Green River Formation represents an excellent case study to better understand the composition and distribution of trace fossil assemblages in continental lake basins with dynamic tectonic and climatic histories. Bioturbation representing the subaerial exposure and pedogenesis of lacustrine and lake-margin sediments is useful for the recognition of mappable stratigraphic surfaces. The traces are mainly produced by air-breathing organisms in lake-margin terrestrial environments. In shallow water deposits of the freshwater and saline Green River lakes, trace fossil assemblages include simple trails and burrows, and are generally low diversity and have high bioturbation intensities. In saline to hypersaline lakes, moderate to high diversity assemblages are concentrated in areas with freshwater input to lake-margin settings, such as the distal delta plain or shallow water areas lakeward of fluvial input. In hypersaline lake sediments deposited in shallow littoral areas and mudflats, trace fossils are typically associated with subaerial exposure, and include meniscate backfilled burrows that cross-cut sediments deposited in shallow water. Vertebrate trace fossils are most commonly preserved in mudflat environments of the saline lakes, and include footprints of birds, mammals, and reptiles.

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## 12.1 Introduction

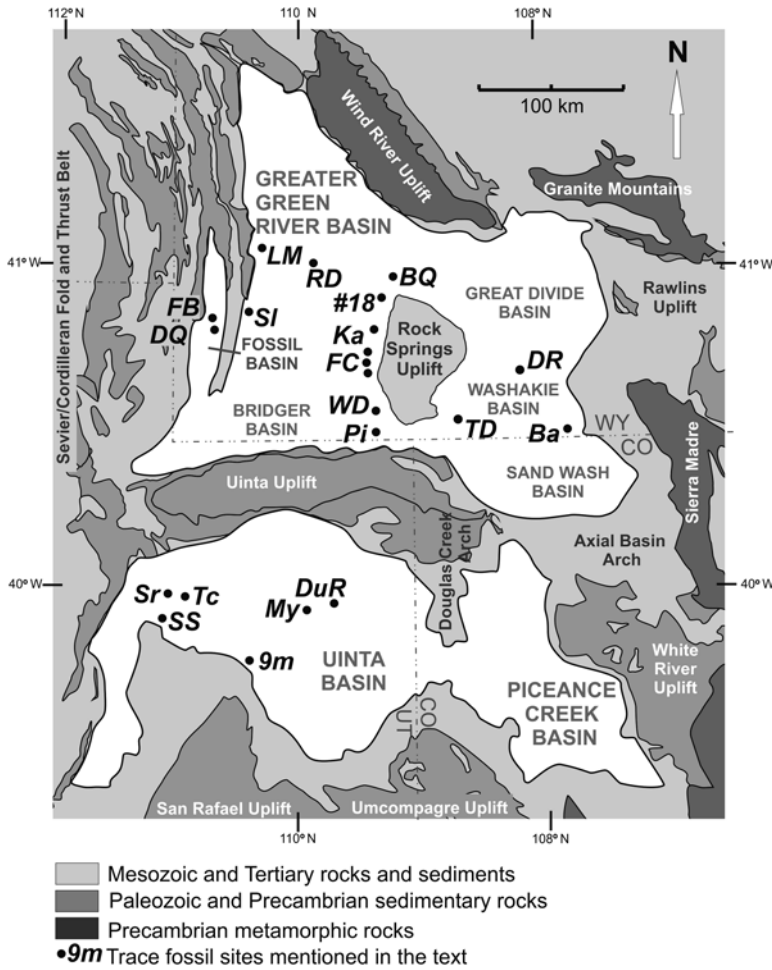
Animal and plant trace fossils in the Early to middle Eocene (~53–43 Ma) Green River and roughly correlative formations are abundant and diverse. They can be used as tools for the paleoenvironmental and stratigraphic interpretation of lacustrine to terrestrial settings in the Green River basins of Wyoming, Colorado, and Utah. This chapter provides a summary of the types of trace fossils present, their typical associations with depositional environments, and the types of environmental conditions they represent. The majority of the trace fossils were produced in shallow lacustrine and lake-margin environments, and many of the traces were produced by air-breathing organisms (e.g., insects, mammals, birds). The distributions of different trace fossil assemblages and their stratigraphic applications are considered in the context of the lake-type basin model (Bohacs et al. 2000, 2007; Scott et al. 2012a). Examples are presented from several localities in the Green River basins to summarize the known trace fossil assemblages, and to illustrate their utility for interpreting environmental conditions and environments (Fig. 12.1). The trace fossils can also be used for the more detailed sequence stratigraphic interpretation of lacustrine and lake-margin deposits, and are helpful for recognizing progradational cycles in successions that represent both lowstand and highstand lake levels (Scott 2010).

Sedimentation rate is the dominant control on the degree of overprinting and cross-cutting of trace fossils in both continental and marine settings, and is an important consideration for the stratigraphic application of trace fossils of the Green River and associated formations (Scott et al. 2012a). In continental basins, different trace fossil assemblages, or suites, can be closely associated because traces produced subaqueously in lacustrine or riverine areas are often cross-cut by traces produced by a different set of organisms after exposure of the substrate. In some examples, evidence of subaerial exposure is not recorded by the sediments themselves. Instead, the evidence is provided by trace fossil

assemblages that grade into the next as a substrate dries. The degree of overprinting by burrows increases with substrate stability through time, and can correspond to increases in water-table depths. Conceptually, this gradational association between trace fossil assemblages representing substrate moisture conditions (e.g., Hasiotis 2007) is similar to the lateral transitions between shallow marine ichnofacies. For example, the *Cruziana* and *Zoophycus* ichnofacies in the lower shoreface to offshore transition in marine basins are not discrete assemblages but instead grade into one another as environmental conditions change across sedimentary profiles (Pemberton et al. 2012).

Traces produced by terrestrial invertebrates in pedogenically modified sediments may also provide insights into the climatic conditions prevalent in basin margin areas during the Early to middle Eocene (Smith et al. 2008a; Golab 2010). Changes in climatic conditions during the Early to middle Eocene (e.g., Zachos et al. 2001, 2008; Smith et al. 2014) may also have indirectly influenced the composition of vertebrate footprint assemblages through time due to the probable relationship between climate and the rapid evolution of mammals and birds at this time (e.g., Woodburne et al. 2009a, b; Dutchak 2010). The distribution of vertebrate footprints may also be indirectly related to climate through the control of climate on sedimentary environments and the dominant conditions that contribute to the preservation of tracks, such as in arid lake-margin mudflats.

Numerous authors have documented and interpreted the significance of trace fossils in the Green River and correlative formations of Wyoming, Utah, and Colorado (Table 12.1; Fig. 12.2). Vertebrate trackways of mammals and birds and invertebrate trails in lake margin carbonates surrounding Lake Uinta have been studied by Curry (1957), Erickson (1967), Moussa (1968, 1970), D'Alessandro et al. (1987), Greben and Lockley (1992), Foster (2001), Yang et al. (1995), Hamblin et al. (1998, 1999), Lockley et al. (1999), Sarjeant et al. (2002), and Olson (2014). Trace fossils produced in terrestrial environments in the Green River and correlative formations in Wyoming and



**Fig. 12.1** Map showing the Green River lake basins in southwest Wyoming, northeast Utah, and northwest Colorado. Trace fossil sites mentioned in the text and Table 12.1 are figured. **Wyoming:** #18 White Mountain at #18 crossing, *Ba* Baggs area, *BQ* Bird Quarry in the Jack Morrow Hills, *DQ* Dayvault Quarry, *DR* Delaney Rim (near Wamsutter; includes North Barrel Springs), *FB* Fossil Butte National Monument, *FC* Firehole Canyon

area (includes Firehole Canyon, Middle Firehole Canyon, Sage Creek, and Chicken Springs Draw), *Ka* Kanda, on White Mountain, *LM* Little Mesa, near LaBarge, *Pi* Pipeline area, *RD* Reardon Draw, *SI* Slate Creek, *TD* Trail Dugway, *WD* Wildhorse Draw. **Utah:** *9 m* Nine Mile Canyon, *DuR* Duchesne River, *My* Myton area, *Sr* Strawberry Reservoir area, Strawberry Canyon, *SS* Soldier Summit, *Tc* Timber Creek

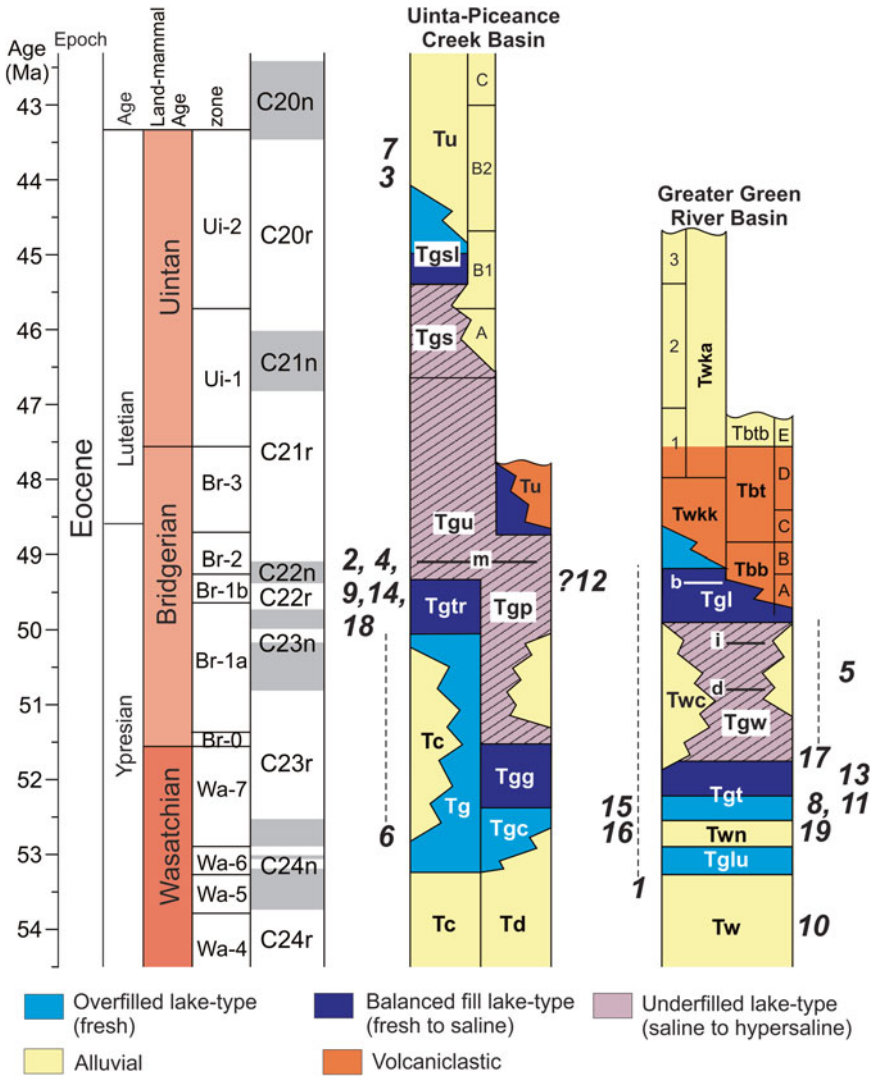
Utah have been studied by D’Alessandro et al. (1987), Hasiotis and Honey (2000), Zonneveld et al. (2006), and Golab (2010). Leggitt and Cushman (2001), Leggitt and Loewan (2002), and Leggitt et al. (2007) studied caddisfly larval cases associated with bioherms of the freshwater Tipton Member in Wyoming. Lamond and Tapanila (2003) reported “embedment cavities” of invertebrates in lacustrine stromatolites. Leggitt and

Cushman (2003) reported flamingo-like nest mounds from the Wasatch Formation in Wyoming. Roehler (1988) reported abundant burrows in deltaic deposits of the Cottonwood Creek Delta, Tipton Member in the Washakie subbasin, Wyoming. Deeper lacustrine trace fossils such as fish swimming traces have been studied by Martin et al. (2010) from Fossil Lake in Fossil Basin, Wyoming.

**Table 12.1** Trace fossils in the Green River and correlative formations of Wyoming, Utah, and Colorado. Numbering corresponds with stratigraphic position shown in Fig. 12.2

Reference	Age	Stratigraphy	Location	Traces (general)	Ichnotaxa
1. Bohacs et al. 2007	Early-middle Eocene	Green River Formation (Tipton, Wilkins Peak, Laney); Wasatch Formation (Lumen Tongue, Niland Tongue, Cathedral Bluffs)	Greater Green River basin	Bird, insect, mammal trackways; annelid, insect burrows, arthropod nests	<i>Steinichnus</i> , <i>Scoyenia</i> , <i>Planolites</i> , <i>Palaeophycus</i> , <i>Scolicia</i> , <i>Fuersichnus</i> , <i>Edaphichnium</i> , <i>Haplotoichnus</i> , <i>Eatonichnus</i> , AMB, insect and bird trackways, insect nests, spider traces
2. Curry 1957	Middle Eocene	Green River Formation (Parachute Creek Member)	Timber Creek, Uinta basin	Bird, insect/nematode, lizard, mammal	Shorebird tracks, cf. <i>Presbyorniformipes</i> , lizard tracks, cf. <i>Cochlichnus</i> , mammal tracks
3. D'Alessandro et al. 1987	Late Eocene	Duchesne River Formation	Duchesne River, near Vernal, Uinta basin	Insect burrows, annelid and other arthropod burrows	<i>Ancorichnus</i> , "Muensteria", <i>Palaeophycus</i> , <i>Scoyenia</i> , <i>Skolithos</i> , rhizoliths
4. Erickson 1967	Middle Eocene	Green River Formation	Tucker (Soldier Summit area), Uinta basin	Bird trackway and feeding traces	<i>Presbyornis</i> tracks and feeding traces, cf. <i>Presbyorniformipes</i>
5. Foster 2001	Middle Eocene	Cathedral Bluffs Member, Wasatch Formation	Jack Morrow Hills, "Bird Quarry", GGRB	Salamandar trackway	<i>Ambystomichnus</i>
6. Golab 2010	Early Eocene	Colton Formation and Green River Formation (Lower, Sunnyside Delta)	Nine Mile Canyon area, Uinta basin	Insect trails, burrows and nests; crayfish burrows, rhizoliths	<i>Celliforma</i> , <i>Camborygma</i> , <i>Cochlichnus</i> , <i>Ancorichnus</i> , rhizoliths, "AMB"; <i>Macanopsis</i> , <i>Scoyenia</i> , <i>Steinichnus</i> , <i>Haplotoichnus</i>
7. Hamblin et al. 1998, 1999	Middle-Late Eocene	Duchesne River Formation and Uinta Formation	Myton, Uinta basin	Mammal tracks	Perissodactyl tracks, uinathere tracks
8. Lamond and Tapanila 2003	Early-mid Eocene	Green River Formation (Tipton Member)	Delaney Rim, Washakie basin	"Embedment cavities"	Embedment cavities in stromatolites, produced by brine shrimp or insects
9. Moussa 1968, 1970	Middle Eocene	Green River Formation (Parachute Creek)	Soldier Summit, Uinta basin	Bird, insect/nematode	cf. <i>Cochlichnus</i> , bird tracks, mammal (perissodactyl) tracks
10. Hasiotis and Honey 2000	Early Eocene	Wasatch Formation (Main Body)	Washakie basin	Crayfish	<i>Camborygma</i>

<b>11.</b> Leggett and Cushman 2001; Leggett and Loewan 2002; Leggett et al. 2007	Early-middle Eocene	Green River Formation (Tipton Member)	Essex Mountain, Big Sandy, Little Mesa, GGRB	Caddisfly larval cases	n/a
<b>12.</b> Lockley et al. 1999	Eocene	Green River Formation	Strawberry Canyon, Uinta basin	Mammal trackways	Perissodactyl, bird, lizard, carnivore (creodont)
<b>13.</b> Martin et al. 2010	Early-middle Eocene	Green River Formation (Fossil Butte Member)	Dayvault Quarry, Fossil basin	Fish swimming and feeding traces	<i>Undichna</i>
<b>14.</b> Olson 2014	Middle Eocene	Green River Formation	Tucker (Soldier Summit area), Uinta basin	Bird (stilt-like) tracks	<i>Juncitarsus</i> trackway
<b>15.</b> Roehler 1988	Early-middle Eocene	Green River Formation (Cottonwood Creek Delta, Tipton Member)	Baggs, Washakie basin	“Worm burrows”	cf. <i>Planolites</i>
<b>16.</b> Sarjeant et al. 2002	Early Eocene	Wasatch Formation	Baggs, Sand Wash basin	Mammal tracks (carnivore)	creodont trackway
<b>17.</b> Scott 2010	Middle Eocene	Green River Formation (Wilkins Peak Member)	Bridger basin	Bird, mammal, and reptile tracks; insect trackways and burrows	<i>Taenidium</i> , <i>Ancorichnus</i> , <i>Skolithos</i> , <i>Scovenia</i> , <i>Helminthoidichnites</i> , <i>Macanopsis</i> , <i>Planolites</i> , <i>Palaeophycus</i> , <i>Steinichnus</i> , <i>Arenicolites</i> , <i>Lockeia</i> , perissodactyl, bird, carnivore tracks, rhizoliths
<b>18.</b> Yang et al. 1995	Middle Eocene	Green River Formation (Parachute Creek)	Timber Creek, Uinta basin	Bird trackway	<i>Presbyorniformipes</i>
<b>19.</b> Zonneveld et al. 2006	Early Eocene	Wasatch Formation (Main Body)	Fossil basin	Terrestrial burrows	<i>Lunulichnus</i>



**Fig. 12.2** Eocene stratigraphy of the Green River lake basins in southwest Wyoming, northeast Utah, and northwest Colorado. Geochronology of Smith et al. (2014). Stratigraphic units after Smith et al. (2008c): *Tg* Green River Formation, *Tgl* Lumen Tongue, *Tgt* Tipton Member, *Tgw* Wilkins Peak Member, *Tgl* Laney Member, (*Tgl*)*b* buff marker; *Tgc* Cow Ridge Member, *Tgg* Garden Gulch Member, *Tgtr* transitional interval; *Tgp* Parachute Creek, *Tgu* upper member, *Tgs* saline facies, *Tw* Wasatch Formation, *Twn* Niland Tongue, *Twc* Cathedral Bluffs Tongue, *Tb* Bridger Formation, *Tbb* Blacks Fork Member, *Tbt* Twin Buttes Member, *Tbtb* Turtle Bluff Member, *Twkk* Washakie Formation, Kinney Rim Member, *Twka* Washakie Formation, Adobe Town

Member, *Tc* Colton Formation, *Td* Debeque Formation, *m* Mahogany Zone, *Tu* Uinta Formation. Number scheme follows order of authors in Table 12.1, and illustrates general stratigraphic range of cited studies. 1 – Bohacs et al. 2007; 2 – Curry 1957; 3 – D’Alessandro et al. 1987; 4 – Erickson 1967; 5 – Foster 2001; 6 – Golab 2010; 7 – Hamblin et al. 1998, 1999; 8 – Lamond and Tapanila 2003; 9 – Moussa 1968, 1970; 10 – Hasiotis and Honey 2000; 11 – Leggitt and Cushman 2001; Leggitt and Loewan 2002; Leggitt et al. 2007; 12 – Lockley et al. 1999; 13 – Martin et al. 2010; 14 – Olson 2014; 15 – Roehler 1988; 16 – Sarjeant et al. 2002; 17 – Scott 2010; 18 – Yang et al. 1995; 19 – Zonneveld et al. 2006



Bohacs et al. (2007) were the first to consider the trace fossils of the Greater Green River basin in Wyoming as a tool for interpreting water tables and soil moisture content of lake-margin settings in the different lake-type basins. Scott (2010) used the evaporitic Wilkins Peak Member of the Green River Formation and correlative Cathedral Bluffs Member of the Wasatch Formation in Wyoming to develop a model for the distribution of vertebrate and invertebrate trace fossils in underfilled lake-type basins. Sato et al. (2014) focused on the use of terrestrial and lake-margin traces for the stratigraphy of the fluvio-lacustrine Duchesne River and Uinta formations in the Uinta basin, Utah. Each of the ichnological case studies presented by these authors contributes to a better understanding of the paleoecology of vertebrates and invertebrates known from the Green River basins. Each study can also be applied to understanding changes in environmental conditions, as they were related to changing climate, tectonics, and/or drainage patterns as recorded by the dynamic sedimentary fill of each of the Green River basins.

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## 12.2 Lake-Type Basins and Trace Fossils in the Green River Formation

The lake-type basin model (Carroll and Bohacs 1999; Bohacs et al. 2000) can be successfully integrated with the ichnofacies model for lake basins to help simplify interpretations of environmental conditions that influenced the preserved trace fossil assemblages in different localities (Buatois and Mángano 2004, 2009; Bohacs et al. 2007; Scott et al. 2012a). Factors controlling sedimentation (e.g., energy levels), hydrochemical conditions (e.g., salinity, oxygenation, mixing regime), and the behavior of trace-producing organisms, combine to determine the assemblage of trace fossils. The distribution and composition of lithofacies associations and their stratigraphic packaging reflects the lake-type basin, whether it was overfilled with respect to water and sediment input, in balance with the input, or underfilled with respect to the flux of water and sediment

(Carroll and Bohacs 1999; Bohacs et al. 2000). The types of sedimentary environments associated with these different lake-type basins, environmental conditions, and trace fossil assemblages are also dependant on the relationship between the accommodation in the basin and if the water can overspill the bounding sill(s) (Buatois and Mángano 2004, 2009; Bohacs et al. 2007).

Overfilled lake-type basins are characterized by lakes that are open, spill into an adjacent basin, and receive an abundant influx of water and sediment deposited in progradational fluvial to deltaic deposits (Bohacs et al. 2000). Water tables are expected to be shallow and sedimentary substrates soft, contributing to a trace-fossil association assemblage containing soft-ground burrows (e.g., *Planolites*) produced in subaqueous substrates (Buatois and Mángano 2004). Balanced fill and underfilled lake-type basins both are characterized by trace fossil assemblages produced in subaerial lake-margins containing burrows produced in soft (e.g., *Planolites*) and firm or cohesive substrates (e.g., *Taenidium*, *Steinichnus*). In underfilled lake-type basins, these assemblages (i.e. *Scoyenia* ichnofacies) can be found in the basin center and basin margin, but in balanced fill lake-type basins, these assemblages are found only at the basin margins (Scott et al. 2012a). Terrestrial trace types, or those formed in pedogenically modified sediments, are most abundant towards the basin margins where topographic gradients are relatively steep and water tables are relatively low.

Underfilled lake-type basins can contain sub-aerially exposed alluvial facies and terrestrial trace fossils near the basin center, such as in the Wilkins Peak Member in the central Bridger sub-basin (Scott 2010). The stratigraphic packaging of distinct lithofacies macroassociations can be sharply juxtaposed in underfilled lake-type basins, with very different sets of sedimentary and hydrochemical conditions represented by a sharp contrast between stacked lithofacies assemblages (Smith et al. 2014). Sharp contrasts in the vertical packaging of sediments and trace fossils assemblages are present in underfilled basins because the entire sediment and solute load in the

basin accumulates, and any changes in the amount of water input to the basin are reflected in the sedimentary record. Shorelines fluctuate at a variety of scales in underfilled basins, and their movement across the basin floor can be followed using by trace fossils (e.g., *Skolithos*, *Taenidium*).

In contrast, the shorelines of lakes in overfilled lake-type basins are relatively stable and lake-margin areas are typically wet and poorly drained (Bohacs et al. 2000). The lakes are fresh because water and solutes are able to spill over the lake-bounding sill. Sedimentation is dominated by siliciclastic deposition, and terrestrial, lake-margin, and lacustrine facies associations contain very little carbonate sediments (Bohacs et al. 2000). Trace fossil assemblages in these lake-type basins are thus dominated by burrows produced in sandy soft substrates by organisms that are most abundant in freshwater habitats, such as gastropods, bivalves, ostracodes, and oligochaetes (Buatois and Mángano 2004, 2009; Bohacs et al. 2007). The trace fossil assemblages are associated with freshwater shallow lacustrine and siliciclastic lake margin environments, such as those present in the Luman Tongue of the Wasatch Formation, Wyoming (Bohacs et al. 2007) and the lower portion of the Tipton Member in the Greater Green River basin (Fig. 12.3). Shorelines remain near the basin margins in overfilled lake-type basins, and terrestrial trace fossils are not present in basin center deposits.

The aerial extent of lakes in balanced-fill lake-type basins fluctuates between expanded water bodies that nearly fill the basin when lake waters are at the bounding sill, and restricted water bodies during times of decreased rates of water and sediment input or subsidence in the basin (Bohacs et al. 2000). These types of lakes preserve thick packages of lacustrine oil shales in basin margin and basin center areas, such as the Rife Bed of the Tipton Member and the LaClede Bed of the Laney Member of the Green River Formation in Wyoming. The balanced fill lakes were probably deeper than underfilled lakes, and were stratified, saline, and oxygen-poor. Trace fossils are not typically observed in oil shales, and during times of expanded balanced fill lake-types, trace fossil assemblages are thus limited to lake-margin

environments at the basin margins (Fig. 12.4). During times of restricted lakes, such as the evaporitic shallow lacustrine and lake-margin facies of the Buff Marker of the Laney Member in the Washakie subbasin, simple traces were produced in soft substrates (e.g., *Planolites*). Possible vertebrate footprints maybe preserved in very shallow water or emergent sediments. This trace fossil assemblage is similar to the evaporitic mudflats of the underfilled Wilkins Peak Member, but with substrates relatively soft and wet. Lake-margin deposits from the transition of balanced fill to underfilled lake-type in the Uinta basin, as in the Soldier Summit area (Fig. 12.5), contain trace fossils characteristic of emergent, but not hypersaline, settings.

Basin center areas in balanced fill lake-type basins typically remain filled with water until the basins are eventually filled with sediment from progradational deltaic sediments, such as the Sand Butte Bed of the Laney Member, Wyoming (Smith et al. 2008c; Chetel and Carroll 2010). Trace fossils may be lacking from entire sedimentary successions of basin center deposits in balanced fill lake-type basins if the lakes remained stratified and oxygen-poor, as seen in the majority of the LaClede Bed of the Laney Member. Fossil Lake in Fossil Basin, Wyoming, however, provides an example demonstrating that oxygenation events in balanced-fill lake-type basin can contribute to the formation and preservation of fish swimming and feeding traces on horizons that are interbedded with fish body fossils (Martin et al. 2010).

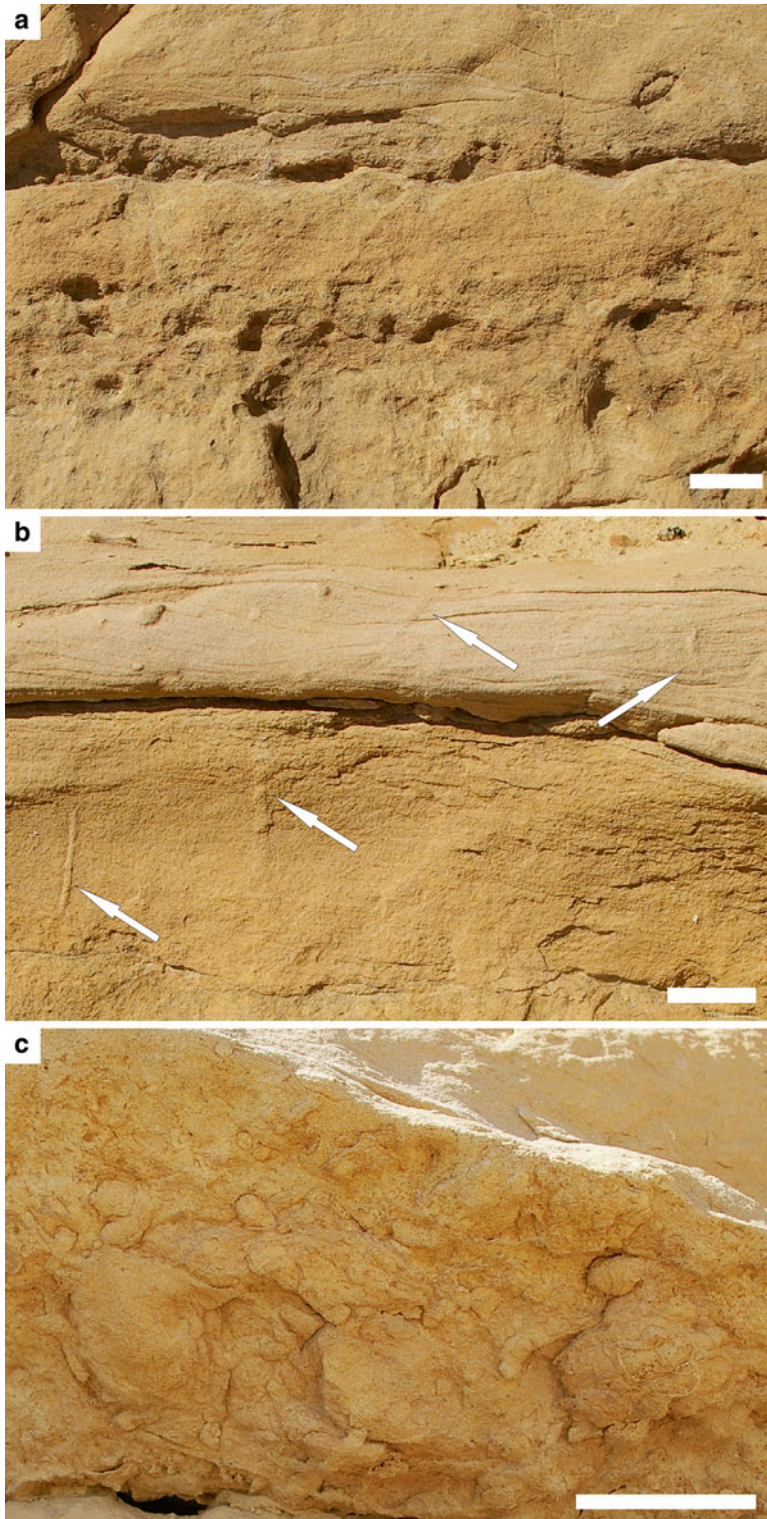
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## 12.3 Environmental Conditions Influencing Trace Fossils in the Green River Lake Basins

### 12.3.1 Subaerial Exposure

Some types of trace fossils are good indicators of very shallow water depths or the subaerial exposure of a substrate (e.g., vertebrate footprints, *Taenidium baretii*), but many of the trace types present in lake basins are simple in form and are

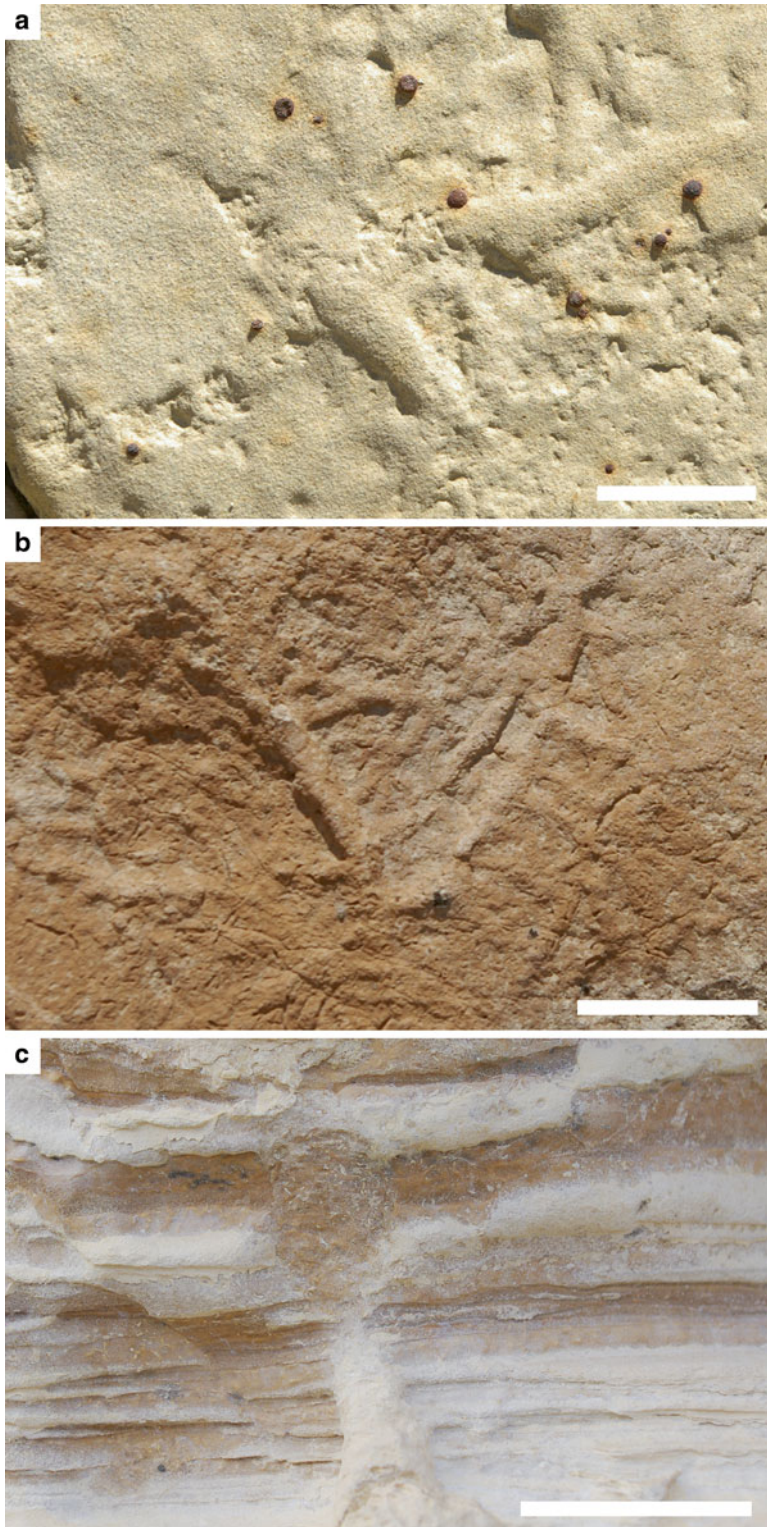




**Fig. 12.3** The overfilled Tipton Member in the southern Bridger subbasin (Pipeline east section). All scale bars 2 cm. (a) Heavily burrowed horizons with simple burrows in soft substrates (*Planolites* and *Palaeophycus*); note

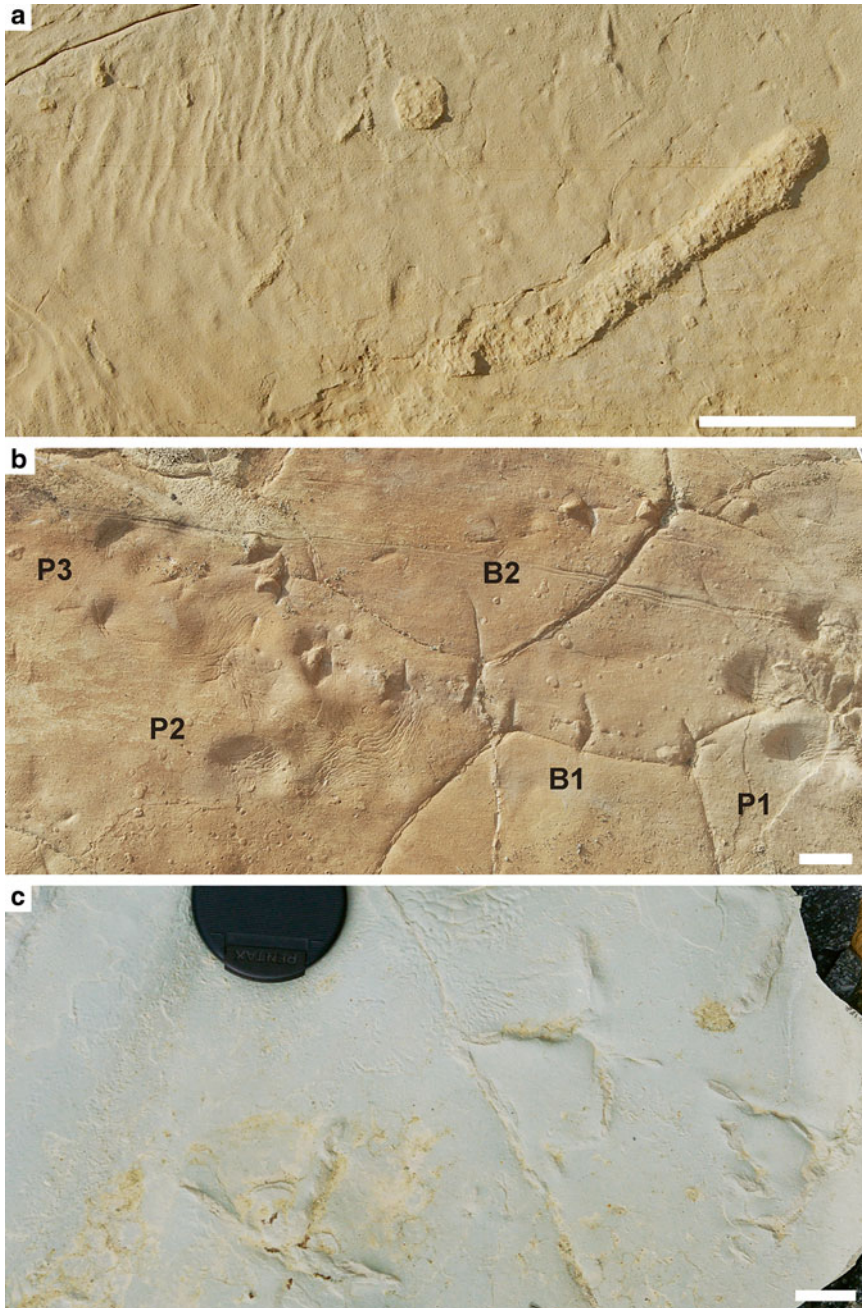
bivalve shell at top right. (b) Simple vertical to oblique burrows (*Skolithos*) in soft sandy substrate (arrows). (c) Bivalve resting traces (*Lockeia*) and simple burrows in soft substrate on the base of heavily bioturbated horizon





**Fig. 12.4** The balanced fill Laney Member in the Greater Green River Basin, Wyoming. All scale bars 2 cm. A-C, fluvio-lacustrine facies at North Barrel Springs on Delaney Rim, Washakie subbasin. D-E, Buff Marker at Trail Dugway on Kinney Rim, Washakie subbasin. F, Lower LaCledde Bed at Wildhorse Draw, southern Bridger subba-

sin. (a) Cross-cutting backfilled burrows in soft sand substrate, with poorly defined bioturbation. (b) High density cross-cutting simple horizontal burrows in soft substrate (*Planolites*). (c) Heterolithic organic-rich and organic-poor shallow lacustrine carbonates burrowed by vertically oriented meniscate backfilled burrow (*Taenidium*)



**Fig. 12.5** The balanced fill to underfilled basin transition in the Soldier Summit area, Utah. Scale bars all 2 cm. **(a)** Field photo of very thin carbonate mudstone bed with surface texture similar to “elephant skin”, showing cohesiveness of muddy substrate. Traces on surface include tiny invertebrate trails and backfilled burrows cross-cutting

surface. **(b)** Field photo of well preserved vertebrate footprints on desiccated mudstone bed, including two trackways of a plover-like bird (numbered B1 and B2), and one trackway of 3-toed perissodactyl (3 footprints on slab, numbered P1, P2, and P3). **(c)** Deeply impressed bird footprints in carbonate mudstone bed



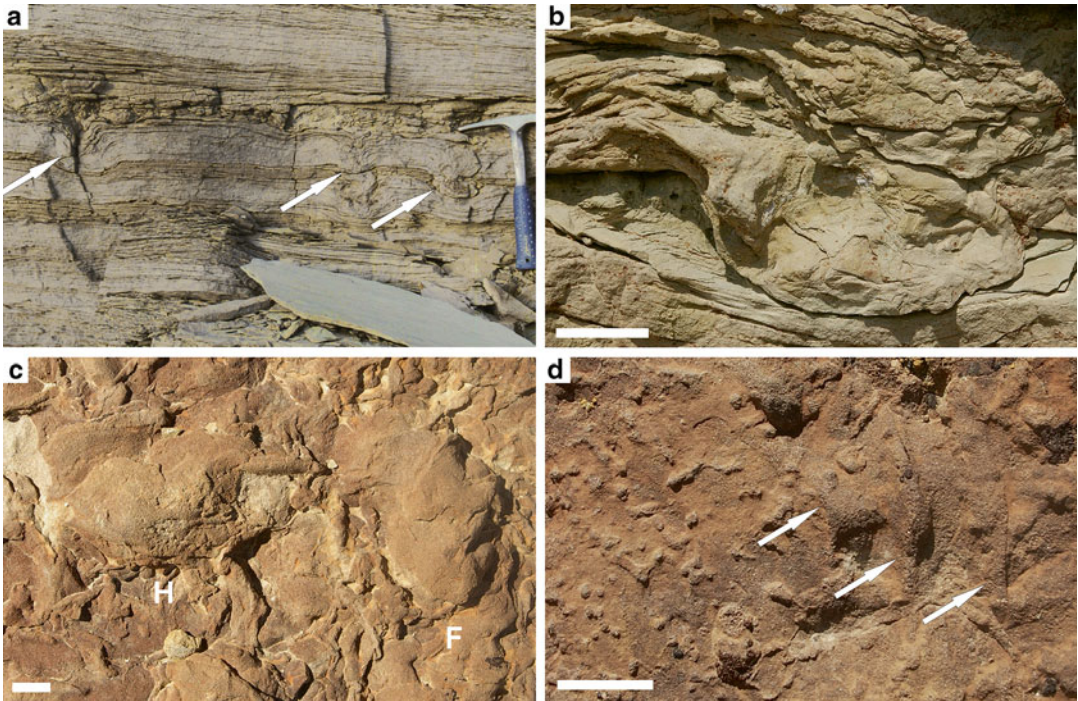
not diagnostic of either subaerial or subaqueous depositional environments (e.g., *Planolites*, *Skolithos*). It is important to consider the detailed morphology of the traces, such as the sharpness of the burrow margins (e.g., sharp or soft) and any preservation of ornamentation (e.g., scratch traces), the type of fill (e.g., aggregate backfilled), and cross-cutting relationships between traces and other sedimentary features (e.g., desiccation cracks). For example, *Skolithos* produced in soft-substrate sandstones of the Tipton Member of the southern Bridger subbasin are associated with high-intensity burrowed horizons with *Planolites* (Fig. 12.3). The traces originate from several horizons within a ~4 m thick sandstone package and are interpreted to have been produced in shallow lake waters and preserved in fluvio-deltaic deposits. In contrast, sharp-walled *Skolithos* burrows are present in thin bedsets of calciclastic sandstones (~1 m) interpreted as storm deposits of the Wilkins Peak Member in the southern Bridger subbasin (Scott et al. 2012a, fig 10b). The traces originate only from the uppermost horizon of the bedset, and extend downwards into a wave-ripple-laminated substrate. All evidence within this thin sedimentary package together shows that lake-levels dropped, and that the burrows were probably produced on the freshly subaerially exposed substrate, possibly by tiger beetle larvae.

### 12.3.2 Substrate Consistency

Details in the morphology of vertebrate footprints and invertebrate burrows, trails, and trackways provide clues to the degree of water saturation in substrates at the time of trace formation, and help to interpret the drainage of subaerially exposed substrates (e.g., Laporte and Behrensmeyer 1980; Davis et al. 2007). The trace morphology can indicate whether or not the traces were produced in saturated substrates of lacustrine environments, or in subaerially exposed, firm and moist substrates (e.g., Genise et al. 2009). Microbially bound or clay-rich substrates preserve a greater degree of morphological detail than substrates lacking some way of

stabilization before preservation (e.g., Marty et al. 2008; Scott et al. 2010; Carmona et al. 2012). Determining the substrate consistency at the time of trace formation can be useful for interpreting whether the traces were produced syn-depositionally or whether the traces were formed post-depositionally under different conditions than those affecting the deposition of the sediment. Recognizing this gap in time is especially important for using terrestrial trace fossils for stratigraphy.

Vertebrate footprints can be used to interpret substrate consistency (e.g., Scrivner and Bottjer 1986) using four main categories: (1) soft, soupy and fully saturated sandstones; (2) wet to saturated, partially stabilized sandstones; (3) wet to saturated, partially stabilized carbonate mudstones; and (4) firm, desiccating carbonate mudstones, siltstones, and sandstones. In the Wilkins Peak Member of Wyoming, deeply impressed and poorly formed mammal footprints preserved in cross-section (Category 1) in the basin-center arkosic sandstones of delta-plain environments show that the sands were saturated or were within very shallow water when the footprints were produced (Fig. 12.6a–b). Mammal and bird footprints and reptile swimming marks in similar environments retain some morphological features of the producers (Category 2) and show that the traces were produced in substrates that were stabilized in some way, either by slightly desiccated clays or by microbial mats (Fig. 12.6c–d and 12.7a–b). Examples of footprints in Category 2 are often associated with sedimentary features characteristic of very shallow standing water, such as low-amplitude symmetrical ripples. Deeply impressed bird footprints that preserve the original morphology of the impressions (Category 3) were observed near Soldier Summit, Utah, and are interpreted to have been produced in wet, soupy substrates of mudflats and muddy pools on lake margins (Fig. 12.5c). It appears that the carbonate mud was sufficiently cohesive to retain the original morphology of the tracks. Mammal and bird footprints that are shallowly impressed and retain some morphological detail of the original tracks (Category 4) were produced in firm and moist substrates, and/or were



**Fig. 12.6** Mammal footprints in saturated sandy substrates of the basin center clastic units of the Wilkins Peak Member in the Bridger subbasin. All scale bars 2 cm. (a) Multiple deeply impressed small mammal footprints (arrows) into rippled and thinly bedded arkosic sandstone unit “D” at Kanda, White Mountain. Hammer for scale. (b) Close-up longitudinal section of mammal

footprint in the lower part of the arkosic sandstone unit “D” at Firehole Canyon. (c) Reptile footprints in the arkosic sandstone “D” at Firehole Canyon. F – front, H – hind. (d) Reptile claw marks (arrows; swimming traces) with simple burrows (*Planolites*) in substrate possibly stabilized with clay and organic film, in “D” sandstone at Firehole Canyon

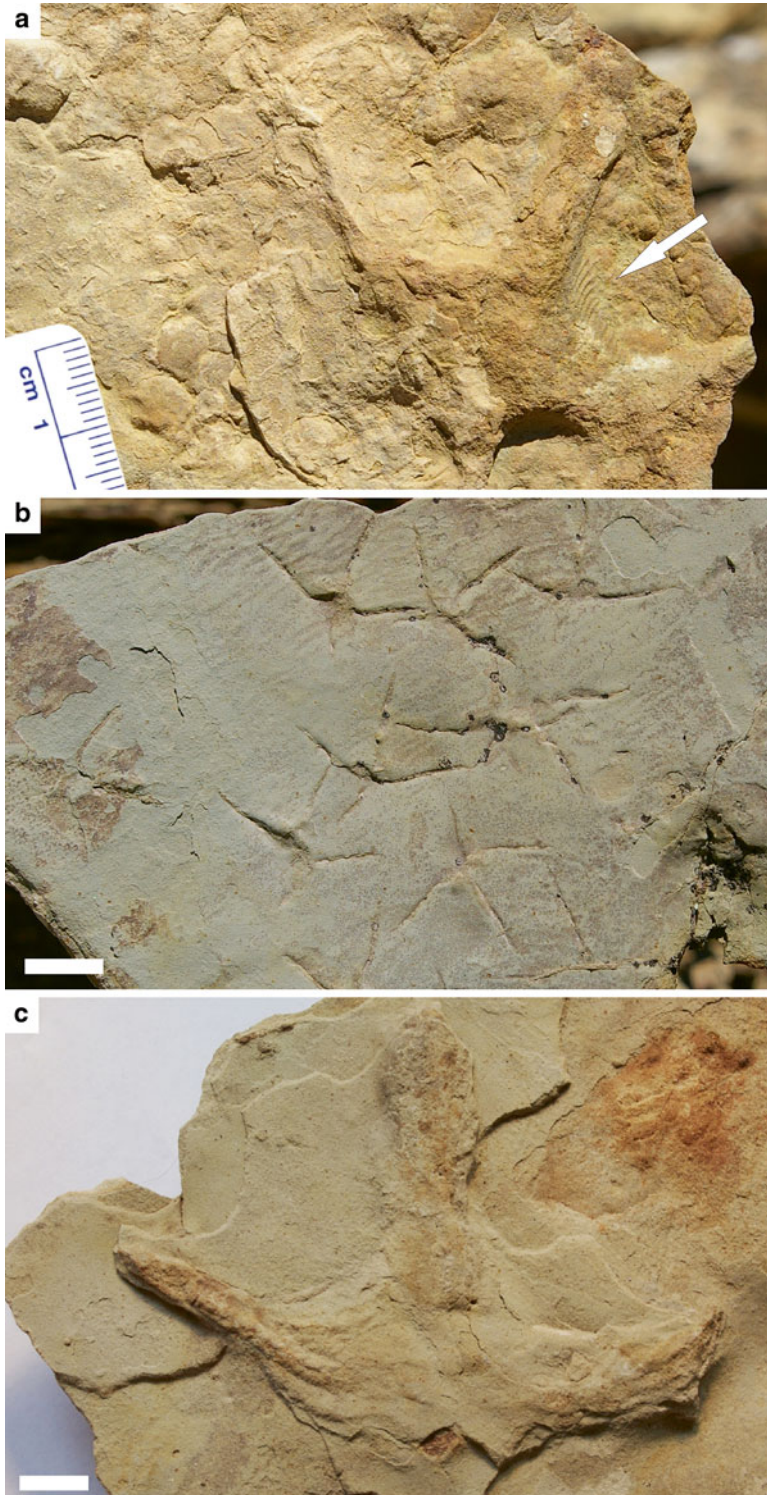
underlain by packed sediment (Fig. 12.5b and 12.8a–b), or in tuffs (e.g., the “Strawberry Slab”, Lockley et al. 1999). Environments of deposition associated with this morphological category include shoreline areas on low-gradient evaporitic mudflats or small, drying pools on lake-margin plains. Shallowly impressed mammal footprints that are associated with evaporite pseudomorphs are typically poorly preserved in substrates that may have been disrupted by salt efflorescence (Fig. 12.8; cf. Scott et al. 2010).

### 12.3.3 Drainage

The depth and orientation of burrows produced by air-breathing invertebrates, whether they are horizontal, vertical, or three dimensional burrow

networks, can be used to interpret the position of the water table and the drainage of a substrate (e.g., Hasiotis 2007). In particular, meniscate backfilled burrows (e.g., *Taenidium barretti*, “adhesive meniscate burrows”; Smith et al. 2008b) appear to be the most useful indicator of drainage in the Green River and correlative formations. Small (~4 mm diameter) and medium-sized (~7 mm diameter) meniscate backfilled burrows with dominantly horizontal orientations are associated with sedimentary features that indicate a moist to wet substrate, typically interpreted as being near the lake shoreline (Fig. 12.9). In contrast, the larger meniscate backfilled forms (~2 cm diameter) may be present in horizontal orientations at shallow depths from the paleosurface from which the burrows originated, or they may be dominantly vertical up to ~1.5 m depth

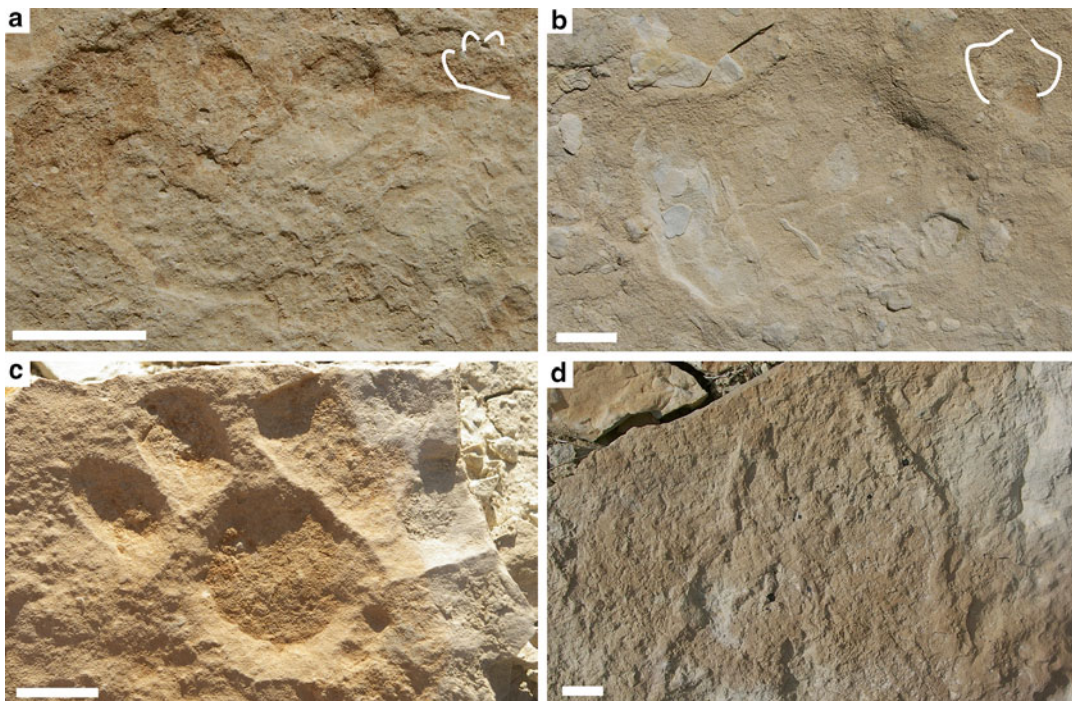




**Fig. 12.7** Bird footprints in the basin center clastic unit “A” of the Wilkins Peak Member in the Bridger subbasin at Firehole Canyon. All scale bars 1 cm. (a) Cast of bird footprint preserving skin impressions on footprint wall

(arrow). (b) Several plover-like bird footprints preserving micro-ripples or “elephant skin” texture showing clay stabilization of substrate. (c) Cast of large *Presbyornis*-like bird footprint





**Fig. 12.8** Trace fossils from the evaporative mudflat facies in the basin center Wilkins Peak Member, Bridger subbasin, Wyoming. All scale bars 2 cm. Line drawings showing interpretations of footprints. A-D – at Firehole Canyon above the “D” sandstone. (a) Plan view of 4-toed (probable perissodactyl) footprint into firm substrate with possible salt efflorescence. (b) Plan view of relatively well

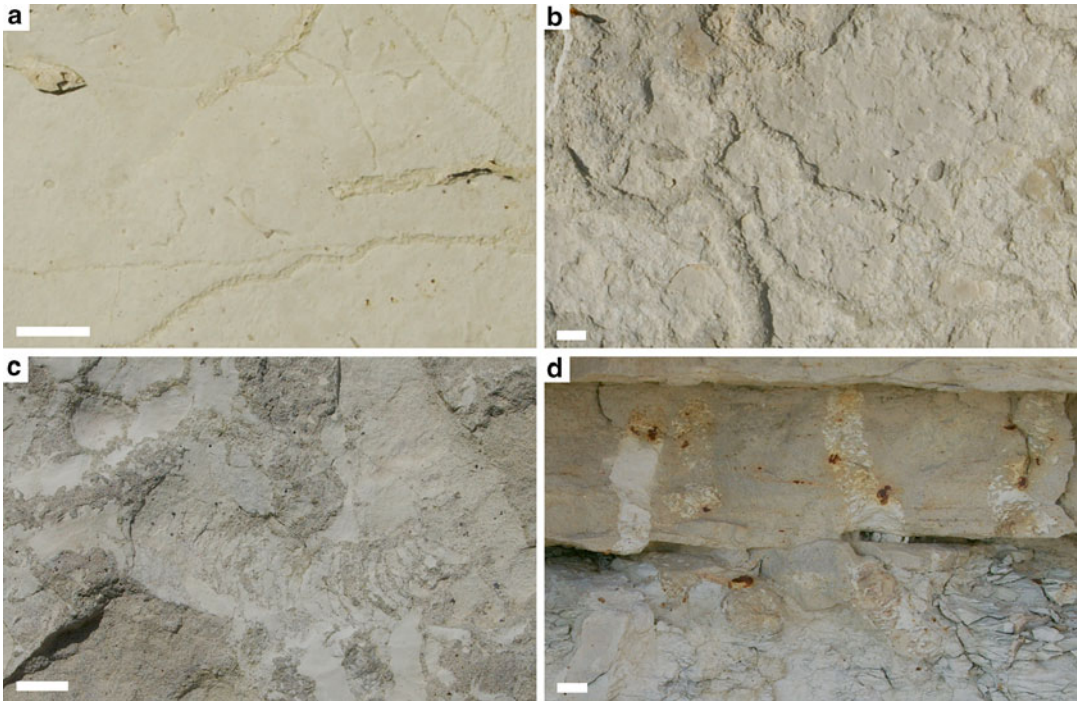
preserved 3-toed footprint (probable perissodactyl). Note broken mudchips on surface. (c) Plan view of carnivore footprint showing 4 digits and metatarsal pad. Note that margins of footprint are sharp but fine details are not preserved, possibly due to salt efflorescence. (d) Plan view of two large invertebrate tunnels on top surface of bed. Irregular morphology is attributed to salt efflorescence

(Fig. 12.9). Examples of these deeply penetrating burrows were observed in several places in fluvio-deltaic sandstone deposits with trough cross-stratification or climbing ripples (e.g., Slate Creek, western Bridger subbasin). Simple vertical burrows (*Skolithos*) are also sometimes more than half a meter in depth, such as in the rippled sandstones of splay-like fans near the shoreline in the underfilled basin center (Fig. 12.10a–d; e.g., Wilkins Peak Member, Bridger subbasin) or at the balanced fill basin margin (Fig. 12.10e; e.g., Tipton Member, southern Bridger subbasin). These large burrows were probably produced by tiger beetles or spiders once the substrate was exposed. Deep, vertically oriented examples of *Taenidium* and *Skolithos* are common in laminated and rippled sandstones beds more than ~50 cm thick, which are interpreted to be well

drained. In contrast, the smaller, horizontally oriented examples are preserved in siltstones and carbonates, and are interpreted to signify that the water table was relatively high when bioturbation took place and substrates were poorly drained.

### 12.3.4 Sedimentation Rate and Hiatuses

Burrow intensity and the vertical distribution of trace fossils from marine and lacustrine deposits can be used to interpret sedimentation rates, and they can also show whether or not deposition was episodic or continuous (Buatois and Mángano 2007; Gingras et al. 2011). In the arkosic sandstones of the basin center Wilkins Peak Member, Wyoming, for example, sedimentary structures



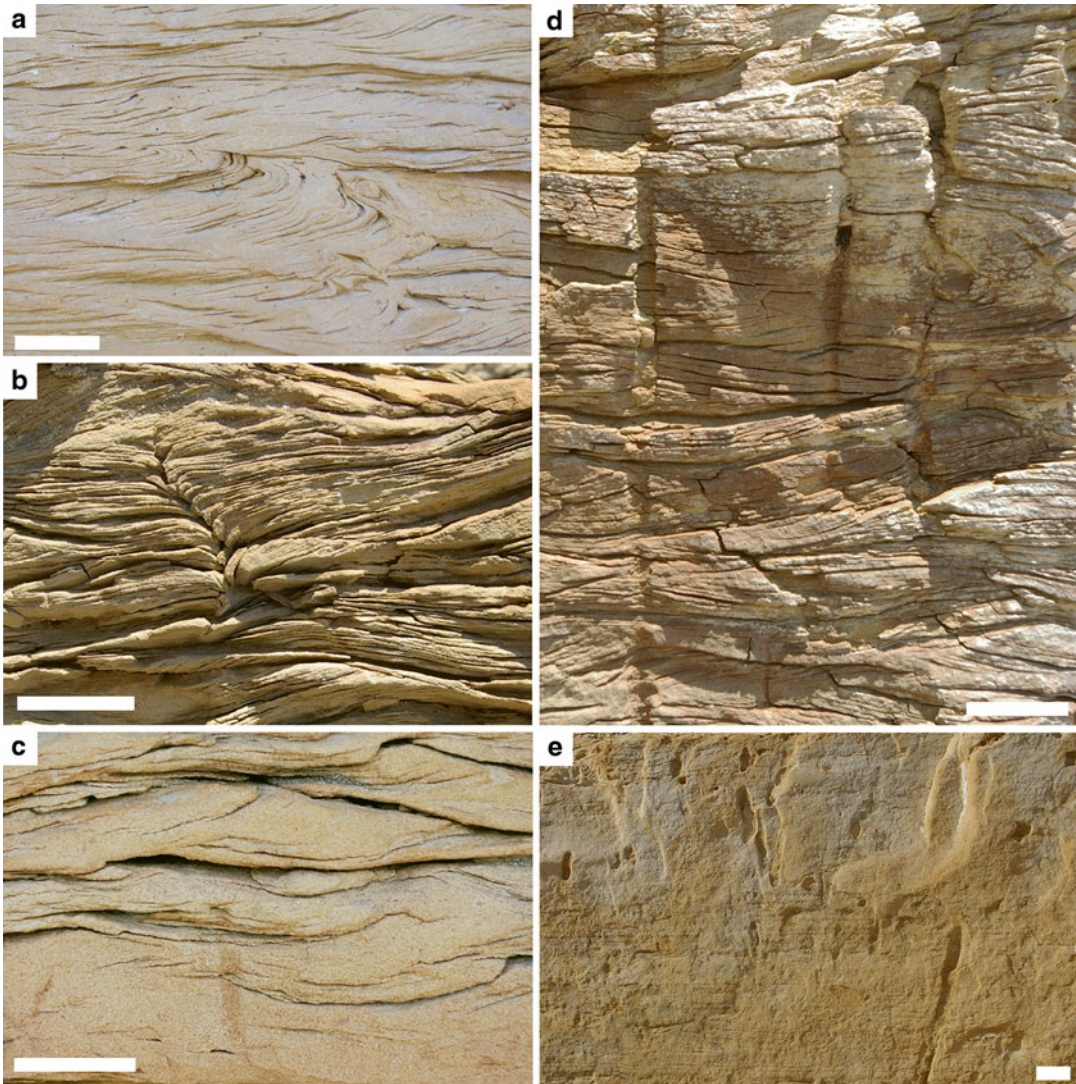
**Fig. 12.9** Backfilled burrows in lake-margin deposits at Slate Creek on the western margin of the Bridger sub-basin. All scale bars 1 cm. (a) Small-sized (~3–4 mm diameter) backfilled burrows and trails (~1–2 mm diameter) in laminated carbonate mudstone from emergent very shallow lacustrine sediments. (b) Dominantly horizontal medium-sized (~7–10 diameter) backfilled burrow networks in desiccating mudflat sediments.

(c) Horizontally oriented large-sized (~25 mm diameter) meniscate backfilled burrow cross-cutting carbonate mud drape deposited on mudflat/very shallow lake. (d) Vertically oriented large-sized (~18 mm diameter) meniscate backfilled burrows penetrating through fluvial sandstones into underlying mudstones. Note muddy fill of burrows. Burrows extend for another meter into substrate below

such as climbing ripples in very fine- to fine-grained sandstones, dune-scale cross bedding, and large-scale trough cross-stratification are associated with the progradation of clastics into the lake. The sedimentary structures alone are not diagnostic of continuous or episodic deposition or of any particular depositional environment. However, when ichnology is used in conjunction with sedimentology, sedimentation rates and episodic deposition is recognized and used to interpret the arkosic sandstone units as delta-front clinothems, sheet floods, or channel bars. Trace fossils such as *Skolithos*, *Helminthoidichnites*, *Taenidium barretti*, and *Planolites* mark horizons within the sandstone successions that represent standing water or waning flow during periods of slow deposition in channels on the delta plain.

In some thick packages (up to 5 m thick) of climbing rippled very fine- to fine-grained sandstones interpreted as mouth bars in the basin center arkosic sandstones, trace fossils are lacking, and the association with water escape structures and sheared rippled crests help to demonstrate that the deposition was continuous and within the lake (Fig. 12.10a). In contrast, some packages with climbing rippled fine-grained sandstones lack water escape structures and contain deep vertical burrows produced by terrestrial organisms (Fig. 12.10d). Although deposition was likely nearly continuous, there were periods of quiescence in these distal splays or sheet flood deposits onto the delta-plain (Fig. 12.10b–d). These examples illustrate the utility of invertebrate burrows to help recognize variable sedimentation





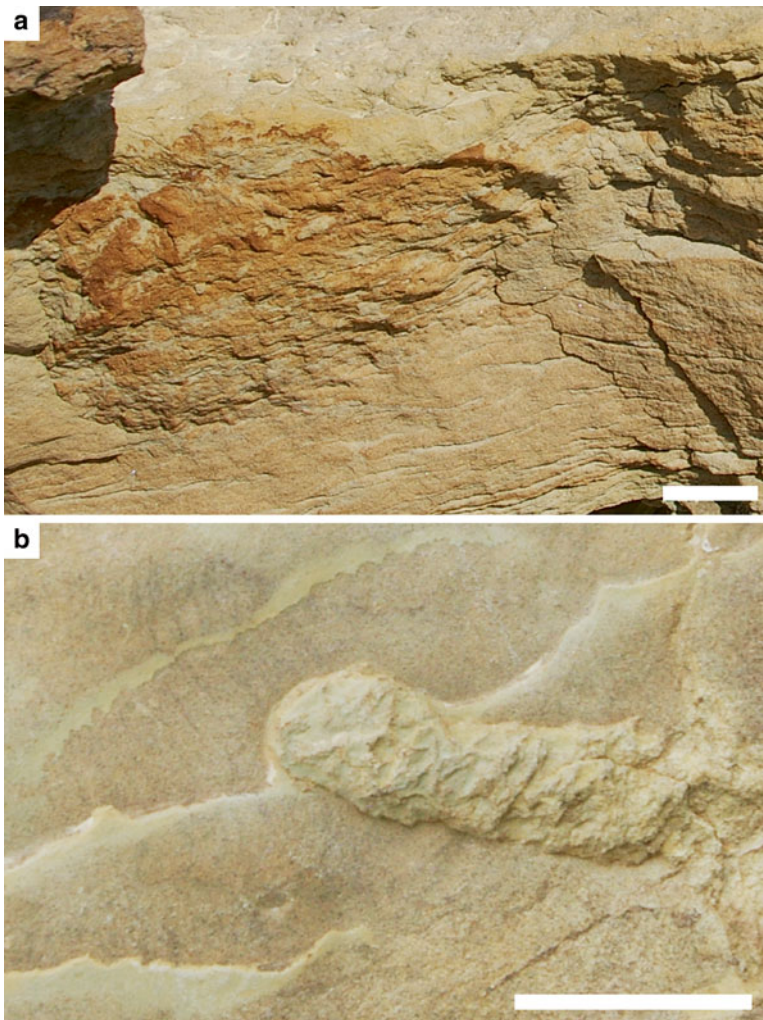
**Fig. 12.10** Vertical burrows as evidence of sedimentation rate and subaerial exposure in fluvio-lacustrine and deltaic sandstones of the basin center Wilkins Peak Member (A-D) and basin margin Tipton Member, Bridger subbasin (E). All scale bars 2 cm. (a) Sheared ripple crests in climbing rippled bedset of the deltaic sandstone “D” at Chicken Springs Draw in the Firehole Canyon area, basin center Wilkins Peak Member. Sedimentation rate high; no bioturbation. (b) Downward-deflected laminae of “escape trace” in rippled sandstones of the delta-plain sandstone “A” in

Middle Firehole Canyon. Sedimentation rate high but periodic. (c) Small-sized *Skolithos* burrow in rippled sandstone of fluvio-lacustrine facies at top of “A” sandstone in Middle Firehole Canyon. Sedimentation rate lower and periodic. (d) Medium-sized vertical burrows (*Skolithos*) through rippled sandstone on delta-plain of “A” sandstone at Middle Firehole Canyon. Subaerial exposure following deposition. (e) Vertical to oblique burrows (*Ptilonichnus*-like, *Skolithos*) in exposed foreshore sandstones of the basin margin Tipton Member in the Pipeline area

rates (e.g., escape traces), as well as to help determine if deposition occurred within Lake Gosiute or on the surrounding delta plain.

In terrestrial deposits, trace fossils typically do not reflect the sedimentation rate of the substrate because they are produced during the pedogenic modification of the substrate after its deposition. However, terrestrial traces can be used together with other pedogenic features (e.g., degree of ped formation) to approximate the time represented by the paleosol, and to infer how

long the deposit was stable before deposition of overlying sediment (Genise 2004; Hasiotis 2007; Bedatou et al. 2009). Well developed social insect nests require extended periods of time to become established (e.g., Hasiotis 2007). In the uppermost beds of the progradational arkosic sandstones in the basin center Wilkins Peak Member for example, a small social insect nest, possibly produced by ants, demonstrates that the paleosurface was stable and exposed to the air for at least a year or two (Fig. 12.11a). Deeper, larger ant



**Fig. 12.11** Terrestrial trace fossils of the underfilled basin center in the sandstone unit “A” at Middle Firehole Canyon, Wilkins Peak Member, Bridger subbasin. All scale bars 2 cm. (a) Insect nest, possibly produced by ants, in rippled

fluvial sandstones at the top of the “A” sandstone. Note sharp margins of nest and high density simple burrows within nest area. (b) Well preserved backfilled burrow with scratch marks in clayey sand substrate (*Steinichnus*)



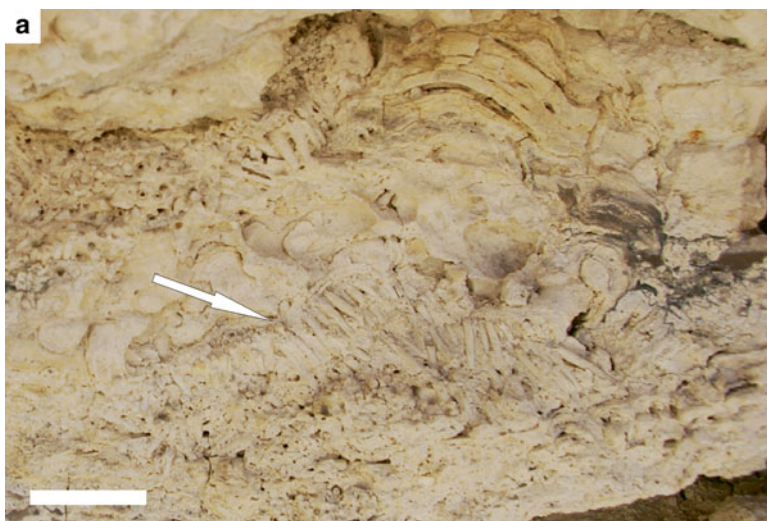
neests in the paleosols of the Colton Member of the Wasatch Formation in the Uinta basin show that the paleosols there were stable for an extended length of time (Golab 2010). Other examples of bee neests (e.g., *Celliforma*) and beetle brood cells (cf. *Coprinisphaera*) in weakly developed sandy paleosols in the Uinta basin (Golab 2010) and the southern Bridger subbasin help to demonstrate that those substrates were stable and exposed to the air for at least a year.

### 12.3.5 Salinity

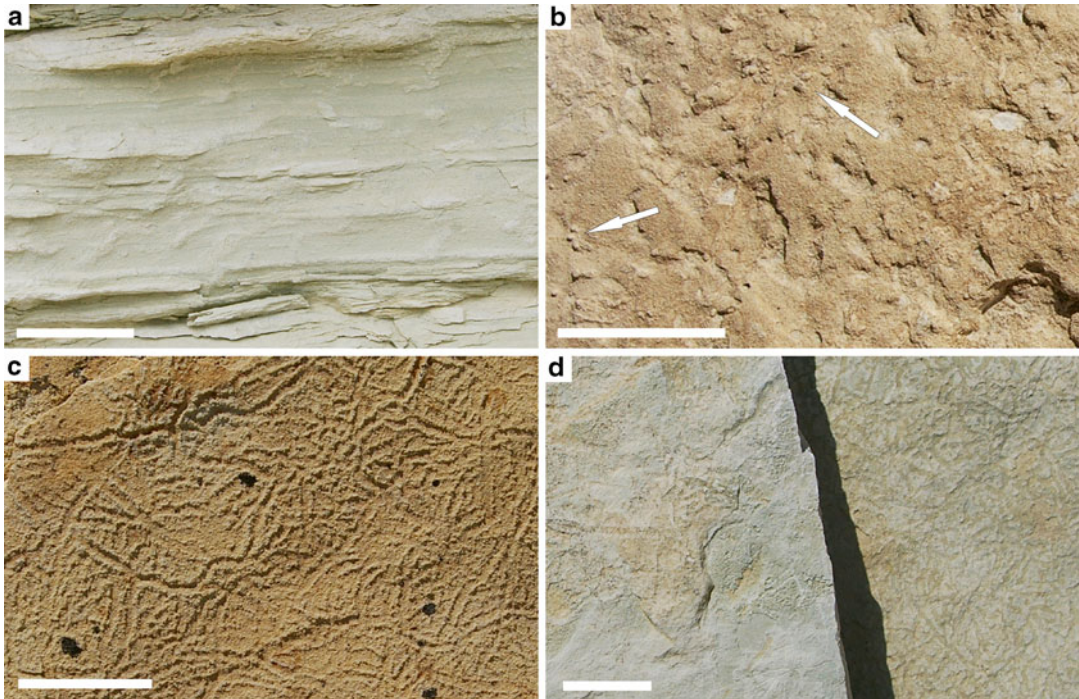
The Green River lakes varied in their salinity from freshwater to saline to hypersaline in different parts of the lake system at different times (e.g., Smith et al. 2008c). Evidence for paleosalinities includes evaporite minerals (e.g., Bradley and Eugster 1969; Deardorff and Mannion 1971) and stable isotopes (Doebbert et al. 2014). Gastropod and ostracode body fossils (e.g., Roehler 1988) and caddisfly larval cases (e.g., Leggitt et al. 2007) are present in the freshwater environments of the different lake-types (Fig. 12.12). In the saline to hypersaline lakes of underfilled basins however, body and trace fossils are rare except in isolated areas with localized freshwater input (Leggitt 2007;

Scott 2010). Trace fossils are commonly lacking in and around the saline and hypersaline lakes, probably due to hydrochemical stresses that preclude bioturbation or high interstitial salinities that lead to salt efflorescence and the poor preservation of burrows (cf. Scott et al. 2010).

The Wilkins Peak Member in the Bridger subbasin records fluctuating salinities in Lake Gosiute and climate-related periods of clastic and freshwater input (e.g., Smith et al. 2014). Trace fossils are preserved in saline to hypersaline lake-margin deposits (e.g., evaporitic mudflats) or in the areas where there was freshwater input into the lake (e.g., fluvio-deltaic areas and adjacent shallow lacustrine; Fig. 12.13a). The trace fossil assemblage typical of very shallow saline lacustrine environments is limited to simple forms of invertebrate traces present in high densities (e.g., cross-cutting *Helminthoidichnites*), and in some cases include diminutive vertical burrows (e.g., *Skolithos*, *Polykladichnus*) that were probably produced by insect larvae (Fig. 12.13b–c; Scott 2010). A moderately diverse assemblage of poorly preserved vertebrate footprints is also characteristic of these settings, including medium- to large-sized perissodactyls, as well as some medium to large-sized carnivores (Fig. 12.8). In deposits laterally or vertically adjacent to sites of freshwater input



**Fig. 12.12** Lacustrine caddisfly cases in freshwater shallow lacustrine facies at Reardon Draw in the Northern Bridger subbasin. Scale bar 2 cm. (a) Interbedded oriented caddisfly cases with laminar stromatolite



**Fig. 12.13** Shallow saline lacustrine trace fossils in the Wilkins Peak Member in the Bridger subbasin. All scale bars 2 cm. (a) Laminated organic-rich lacustrine marl within the “A” sandstone in Middle Firehole Canyon with vertical and oblique simple burrows (*Skolithos*, *Planolites*). (b) Plan view of very small vertical burrows (*Skolithos*, *Polykladichnus*) and horizontal burrows

(*Planolites*) in carbonate siltstone. (c) Bedding plane view of dense cross-cutting trails (*Helminthoidichnites*) in calcitic very shallow lacustrine unit above the “D” sandstone at #18 Crossing on White Mountain. (d) Densely cross-cutting simple trails (*Helminthoidichnites*) on bedding planes of dolomitic mudstone in sublittoral facies above the “E” sandstone at Firehole Canyon

(e.g., arkosic fluvio-deltaic sandstones), structure-less carbonate siltstones and mudstones deposited in lake marginal areas also preserve mm-scale iron-stained root marks and impressions of sedges or grass stems. These areas are interpreted as paludal marshes surrounding the lake. Deeper, sublittoral lacustrine deposits (e.g., kerogen-poor dolomitic mudstones) preserve rare and low-density simple trails (e.g., *Helminthoidichnites*) on bedding planes (Fig. 12.13d), but stagnant profundal environments that preserve oil shales do not contain trace fossils. These associations are typical of underfilled lake-types, which are well represented by the Wilkins Peak Member in Wyoming, and are also typical of some facies in of balanced fill lake-types, as represented by the Laney Member in Wyoming.

In contrast, freshwater lacustrine deposits represented by the overfilled Schegg’s Bed of the Tipton Member in the Greater Green River basin preserve an assemblage of burrows (e.g., *Planolites*, *Palaeophycus*, *Skolithos*, *Arenicolites*, *Lockeia*) in soft sandy substrates within the lake (Fig. 12.3). This relatively diverse trace fossil assemblage demonstrates that the lacustrine conditions were not stressful environments for the trace-producing organisms, which probably included oligochaetes, insects, and/or molluscs. In many cases, these burrows are associated with gastropod and bivalve shells, which further support this interpretation for the trace fossils. Vertebrate footprints have only rarely been found in lake margin areas associated with the freshwater Green River lakes.



### 12.3.6 Oxygenation

Kerogen-rich oil shales almost certainly represent lacustrine environments that lacked oxygen, and which were below the chemocline/thermocline. The preservation of the oil shales does not necessarily mean that the lakes were deep, but that they were stratified. Stratification of lakes occurs when the shallow waters are lower in density than the deeper waters, which can be due to higher salinities or lower temperatures in deeper waters (e.g., Cohen 2003). In modern tropical areas for example, air temperatures do not vary sufficiently between seasons to cause water bodies to overturn, and bottom waters become increasingly saline and oxygen-poor due to continued evaporation and lack of mixing with the atmosphere (e.g., Cohen 2003). Profundal facies associations are associated with these meromictic stratified lakes and also with high organic contents in lake sediments (e.g., Bohacs et al. 2000). With increasing salinity, water is capable of holding a decreasing amount of oxygen (Williams 1998). This association may have played a role in the preservation of widespread oil shale deposits, and also the lack of trace fossils in these facies.

Examples of trace fossils in sublittoral to profundal facies of the Green River Formation include fish swimming trails in lacustrine dolomitic shales of Fossil Lake, Wyoming (Loewen and de Gibert 1999; Martin et al. 2010), which demonstrate that oxygenation events affected the lake bottom waters. Fish body fossils are extremely abundant in the profundal lake deposits, which suggests that there were some freshwater areas in the lake, or that the epilimnion was fresh above the chemocline/thermocline. During mixing and oxygenation events, fish such as suckers (*Notogoneus*) swam to the lake floor to feed on detritus and possibly also on dead fish. The trace fossil evidence shows feeding marks of the suckers (Martin et al. 2010), and swimming marks circling in laminae just overlying fish body fossils (A. Aäse, pers. comm. 2013).

### 12.3.7 Taphonomic Processes

Environmental conditions that influence the taphonomy of trace fossils in the Green River basins are mainly related to: (1) high sedimentation rates and/or high flow velocity in fluvial channels; (2) the disruption of subaerially exposed substrates by salt efflorescence; (3) desiccation and repeated wetting and drying; and/or (4) the presence of roots. The effects of salt efflorescence are especially apparent on the poorly preserved mammal footprints of hypersaline lake margins in the Wilkins Peak Member in the central Bridger subbasin (Fig. 12.8). Evaporite (e.g., trona) pseudomorphs are also present. Rare examples of horizontally oriented insect burrow systems in these same deposits also show signs of disruption by efflorescence, which leads to the break-up of the burrow margins (Fig. 12.8d). A consideration of taphonomic processes is necessary before making inferences on the composition of the trace-producing community. For example, the trace fossil assemblage associated with evaporitic mudflats in the hypersaline Wilkins Peak Member does not contain bird footprints, but because of the poor preservation of the larger mammal tracks, it is possible that the lack of bird tracks may be due to destruction by taphonomic processes.

The original morphology of invertebrate and vertebrate trace fossils is partly controlled by the degree of substrate saturation with water, and whether or not the underlying sediments were soft or hard (Laporte and Behrensmeier 1980; Scrivner and Bottjer 1986; Scott et al. 2010). Carbonate- and clay-rich sediments may retain the original morphology of vertebrate footprints or burrows with sharper burrow margins than clean sandstones. Soupy carbonates, for example, preserve sharp margins of footprints not disrupted later by efflorescence or other processes that lead to the break-up of the most surficial sediments such as desiccation. In contrast, mammal footprints deeply impressed into soupy sandstones have soft, indistinct margins. Sandstones stabilized by clays and/or microbial mats apparently behave similarly to wet carbonate muds by retaining the original

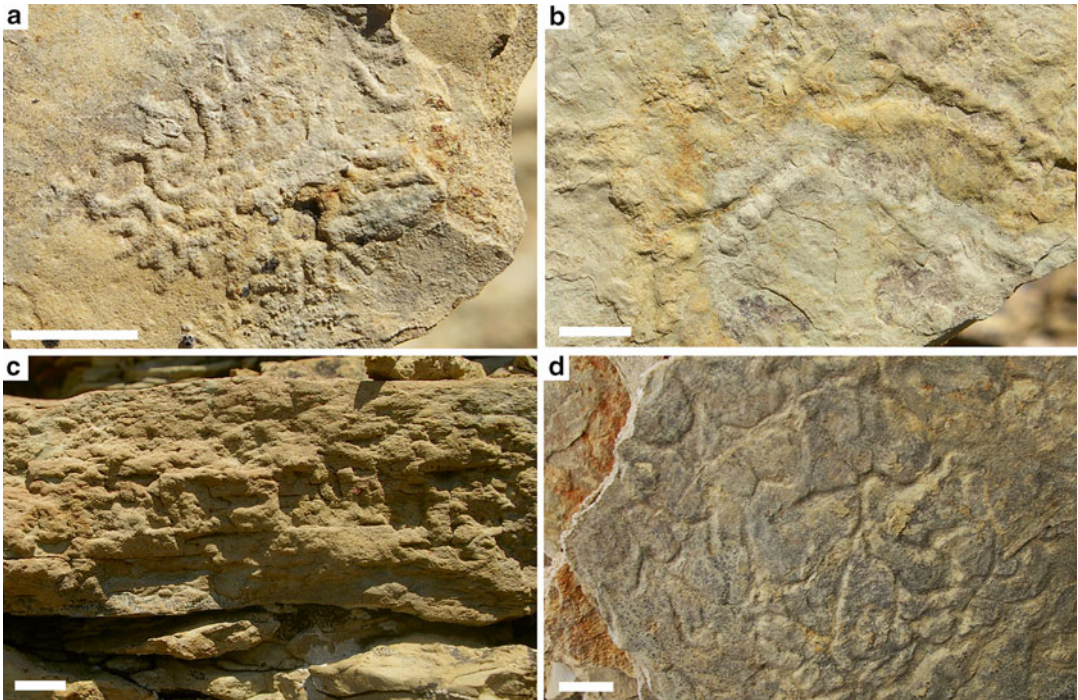
morphology of the traces with distinct boundaries and fine details, such as the tracksites in the Uinta basin (Fig. 12.5; cf. Marty et al. 2008).

## 12.4 Sedimentary Environments and Trace Fossils in the Green River Basins

### 12.4.1 Lake Margins to Terrestrial Environments

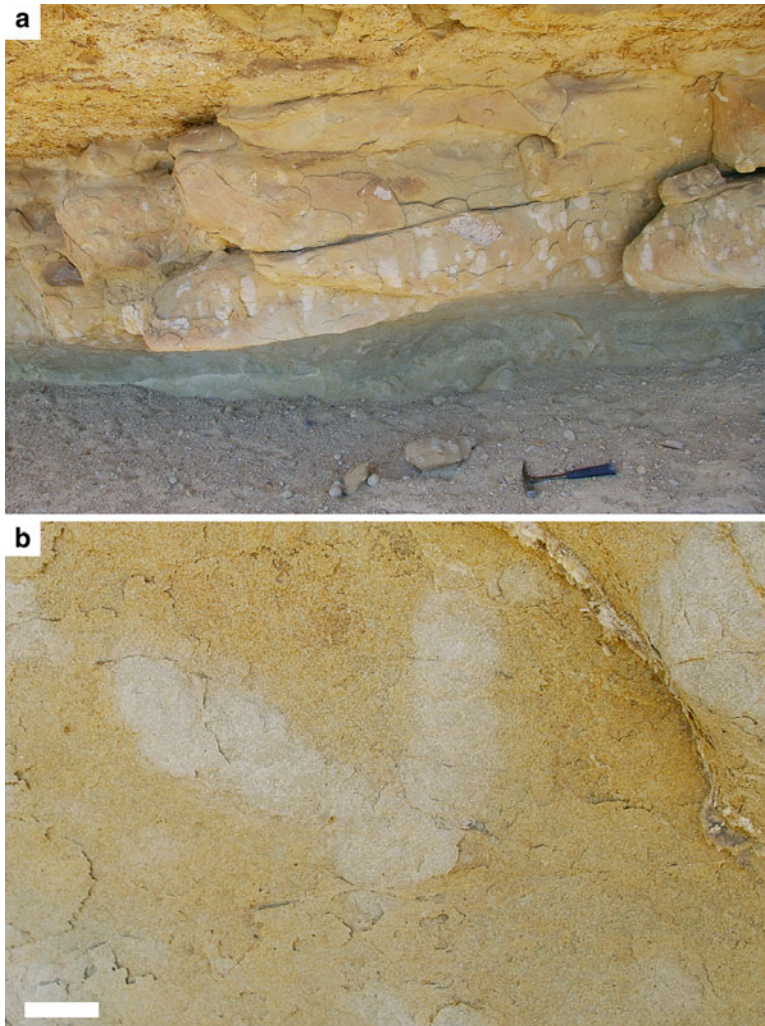
Most of the trace fossils described from the Green River and correlative formations were produced by air-breathing organisms, such as insects (e.g., D'Alessandro et al. 1987; Bohacs et al. 2007; Scott 2010; Golab 2010) and mammals and birds (e.g., Curry 1957; Moussa 1968, 1970), and possibly gastropods. Trace fossils produced in very

shallow water at the lake margins, subaerially exposed mudflats, and other marginal settings such as delta-plains and pools adjacent to the lake typically have moderate to high diversity, although the assemblages show pronounced heterogeneity. They contain vertebrate footprints (e.g., Foster 2001) and several types of burrows, including network-like burrow systems and terrestrial insect nests (Figs. 12.7, 12.11, 12.14; Scott 2010). Terrestrial deposits, outside of the typical range of lake-level rise-and-fall, preserve trace fossils produced in fluvial channels and overbank paleosols in the Wasatch (e.g., Zonneveld et al. 2006; Bohacs et al. 2007) Duchesne River (D'Alessandro et al. 1987), and Colton formations (Golab 2010). Some examples include: (1) large burrows probably produced by crayfish (e.g., *Camborygma*, *Lunulichnus*) in pedogenically modified mudstones that underlie



**Fig. 12.14** Invertebrate trace fossils in the basin center clastic unit “A” of the Wilkins Peak Member in the Bridger subbasin at Firehole Canyon. All scale bars 1 cm. (a) Branching and cross-cutting invertebrate tunnels on top of bed. (b) Arthropod trackway in soupy mud showing

displaced sediment on top of bed and median furrow. (c) High density bioturbation with simple soft-ground burrows (*Planolites* ichnofabric). (d) Branching tunnel network (cf. *Vagorichnus*) on base of bed



**Fig. 12.15** Terrestrial trace fossils in paleosols and alluvial fan deposits at the southern margin of the Bridger subbasin. **(a)** View of trace fossils probably produced by crayfish (*Camborygma*) at the base of the sandstone

shown in (a). **(b)** Close-up of branching burrow in sandstone shown in (b). Scale bar is 2 cm

channel deposits (Hasiotis and Honey 2000; Zonneveld et al. 2006) and alluvial fans (Fig. 12.15); (2) large carbonate-filled rhizoliths; and (3) insect brood cells and pupation chambers (e.g., *Celliforma*) (Golab 2010). Large (~2 cm diameter) meniscate backfilled burrows (e.g., *Taenidium baretti*) are common in fluvial and crevasse splay sandstones that are intercalated with paleosol mudstones. Some examples show that

these burrows originate from paleosurfaces ~1–2 m above the bioturbated horizons, such as in the Cathedral Bluffs Member on the western margin of the Bridger subbasin at Slate Creek (Fig. 12.9d). The vertical orientation and great depth of the burrows, produced by air-breathing organisms, demonstrate that the water tables were at or below these levels at the time, and that the substrates were probably well drained.



### 12.4.2 Deltas

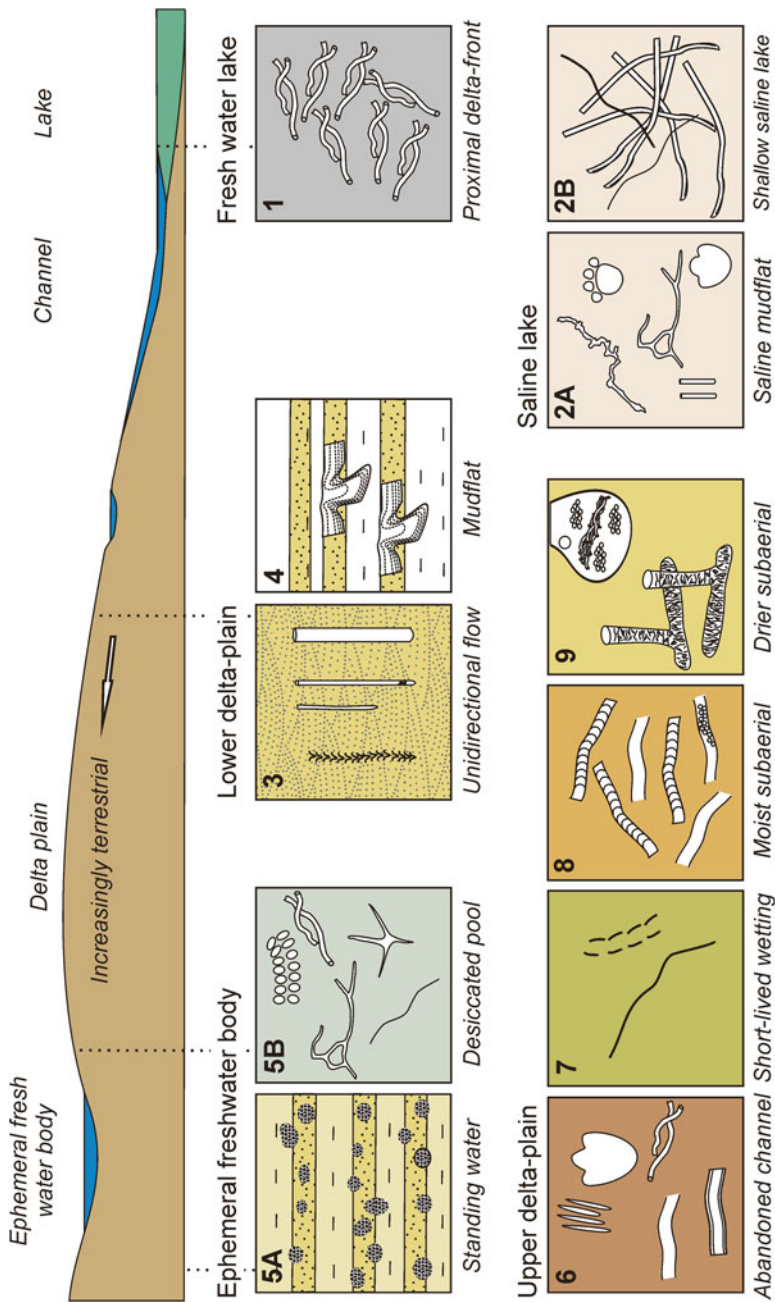
Deltas and delta plains in the Green River Formation are characterized by: (1) siliciclastic sediments containing evidence of trunk channels; (2) crevasse splays and sheet flood deposits; (3) weakly developed paleosols on overbank areas of the proximal to distal delta plain; and (4) mouth bars and bays in the proximal delta front (Culbertson 1961; Bohacs et al. 2007; Schomacker et al. 2010; Scott 2010; Smith et al. 2014). Deltas of overfilled lake-types (e.g., Farson Delta and other Schegg's Bed equivalents, Tipton Member), balanced fill lake-types (e.g., Bitter Creek Delta, Laney Member), and underfilled lake-types (e.g., arkosic sandstones, Wilkins Peak Member) represent Gilbert deltas and shallow water deltas. The facies associations in the different types of deltas are determined by the shoreline stability and depth of lake waters, as well as the amount of sediment input and rate of subsidence. Like the sedimentary facies, the trace fossil assemblages of deltas and delta plains also represent factors such as sediment input and sedimentation rates, stability of shorelines, and the inferred salinity of the lake waters.

Trace fossils are represented by a high diversity of types on delta plains, including: vertebrate footprints (e.g., bird, mammal) and swimming traces (e.g., crocodile, turtle); invertebrate traces produced in well drained subaerial areas (e.g., insect burrows and nests); and invertebrate traces produced in saturated substrates or in areas with thin films of standing water (e.g., insect trails and burrows, oligochaete burrows). Due to the variety of depositional environments in both subaerial and subaqueous settings of deltas, together with freshwater input into saline or hypersaline lacustrine areas, deltas are the most bioturbated setting of the Green River lake system, in overfilled, balanced fill, and underfilled lake-type basins (Fig. 12.16; Scott 2010).

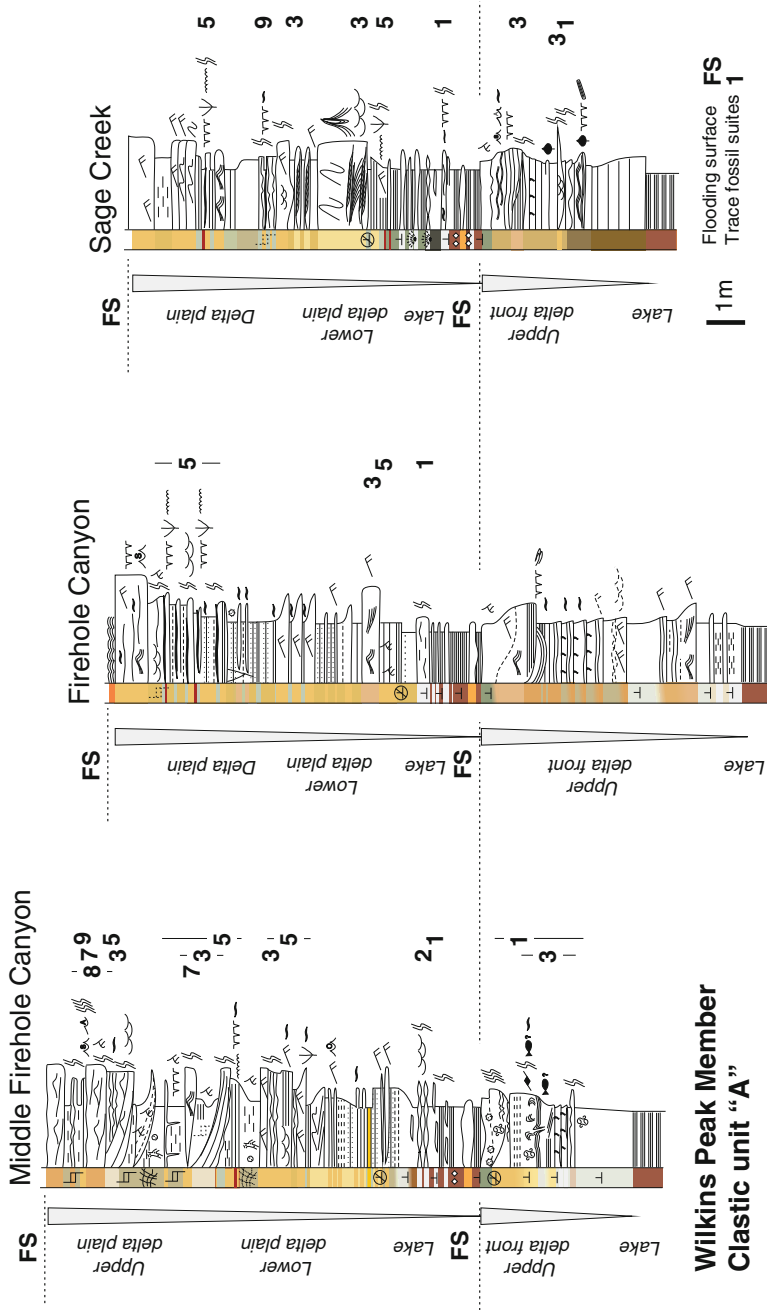
Progradational packages (~5–25 m thick) of arkosic sandstones in Wilkins Peak Member in the central Bridger subbasin provide an example of how trace fossils can reflect an increasing degree of subaerial exposure of the sediments upwards within stacked shallowing upwards

successions (Scott 2010). The clastic wedges prograded into the basin center during times of increased sediment input and relatively low lake levels, at times apparently controlled by changing precipitation to evaporation ratios and seasonality as related to eccentricity cycles (Smith et al. 2014). Each of the arkosic sandstone wedges contains two or more shallowing upwards successions separated by lacustrine flooding surfaces (Fig. 12.17). These packages are essentially parasequences, which represent the progradational stacking of clastic wedges deposited in the basin center during lowstands of Lake Gosiute. The units are overlain by lacustrine carbonates that have either sharp contacts with overbank deposits, or gradational contacts with fining upwards beds of siliciclastics deposited in flooded channels during lacustrine transgressions. The trace fossils are helpful for recognizing substrate conditions, for approximating the salinity of lake waters, and they are helpful for recognizing short-term and longer-term subaerial exposure.

Simple lacustrine trace fossils (e.g., *Planolites*, *Helminthoidichnites*) are more common in sublittoral and littoral facies associated with the arkosic sandstones of the Wilkins Peak Member than with lacustrine facies of the saline to hypersaline lake not influenced by freshwater input (Fig. 12.13a). Less extreme conditions would have characterized the areas of freshwater input into Lake Gosiute. Typically, the trace fossil diversity within lacustrine deposits of the saline to hypersaline Lake Gosiute is very low, and traces are simple in morphology (e.g., *Helminthoidichnites*), typically with high density (Fig. 12.13). Tunnel networks (e.g., *Vagorichnus*) and microbial mat textures were observed at the base of some coarsening-upwards sandstones (Fig. 12.14d). Mammal footprints produced in soupy, saturated substrates are often present within rippled very fine-grained sandstones of the subaerially exposed portions of the successions (Fig. 12.6). This facies also preserves very small (~1 mm) iron-stained root marks, and is interpreted to represent the marshy paludal zone where siliciclastics initially built out into the lake or into areas on the surrounding plain with



**Fig. 12.16** Schematic representation of trace fossil suites in lacustrine and deltaic facies of the underfilled Wilkins Peak Member in the Bridger subbasin. Trace suite numbers correspond to those represented in the stratigraphic sections in Fig. 12.16 and Fig. 12.19. See (Scott 2010) for full description of the trace types



**Fig. 12.17** Measured stratigraphic sections of the deltaic "A" sandstone unit in the basin center Wilkins Peak Member in the Bridger subbasin. Trace suite numbers

correspond to those shown in Fig. 12.15. See Scott (2010) for a full description of the trace types and lithofacies. Colors shown represent actual color



standing water, distal to the trunk channels that supplied the arkosic sediment.

The uppermost parasequences in the arkosic sandstones preserve terrestrial trace fossils near the lake center in the Bridger subbasin, and provide evidence of well drained substrates possibly related to high topographical gradients in the uppermost portions of fans (Fig. 12.11). Meniscate backfilled burrows in three size modes (e.g., ~4, ~7, and ~15–25 mm diameter) were probably produced by insects (cf. Counts and Hasiotis 2009), and are the most common traces in these settings. Other traces, also likely produced by insects, include *Ancorichnus*, *Steinichnus* (Fig. 12.11b), and *Planolites*. In rare examples, social insect nests, probably produced by ants, are preserved in the uppermost portions of the clastic wedges (Fig. 12.11a). Some facies interpreted to represent small pools of standing water on the delta plain preserve a trace fossil assemblage typically composed of bird footprints, simple burrows produced in soft substrates (e.g., *Planolites*; Fig. 12.14c), insect trackways in soupy substrates (Fig. 12.14b), and high-density tunnel networks, probably produced by insect larvae (Fig. 12.14a; Scott 2010).

### 12.4.3 Evaporitic Lake Margins and Mudflats

At the Soldier Summit area of southwestern Lake Uinta in Utah, mudflat facies composed of thinly wavy bedded carbonate mudstones with some desiccation cracks preserve beautiful examples of bird (probably produced by *Presbyornis* or *Juncitarsus*) and mammal footprints (produced by perissodactyls), along with insect trails (e.g., *Cochlichnus*) (Fig. 12.5; Curry 1957; Erickson 1967; Moussa 1968, 1970; Olson 2014). Greben and Lockley (1992) found four main types of bird tracks in this area. Vertebrate tracks are common in the Uinta basin, and in general they are much better preserved than those from similar environments in the Greater Green River basin, where evaporate pseudomorphs are present and demonstrate that the mudflats there may have been covered in salt crusts.

Mudflats and paludal marsh areas that surrounded the central parts of saline to hypersaline Lake Gosiute of Wyoming when lake levels were low are composed of calcitic sandstones and siltstones, and dolomitic siltstones and mudstones of the Wilkins Peak Member. Evidence of desiccation, reed impressions, and mm-scale iron-stained root marks accompany a low-diversity trace fossil assemblage dominated by poorly preserved vertebrate footprints (Fig. 12.8; e.g., mammal) and simple, high density trails probably produced by insect larvae (e.g., *Helminthoidichnites*; Fig. 12.13c–d). Other traces sometimes present include high density diminutive (1–2 mm diameter) vertical burrows (e.g., *Skolithos*, *Polykladichnus*; Fig. 12.13b) and large (10 mm diameter), poorly preserved horizontal, branching tunnel systems (Fig. 12.8d). Sedimentary structures provide evidence of shallow flooding of mudflats and subsequent desiccation, including wavy bedding with calcite sands and dolomitic mudstone drapes, lenticular bedding, intraclast mudchip conglomerates, and desiccation crack polygons with mudchips preserved on bedding planes.

At several localities in Wyoming, particularly in the upper Wilkins Peak Member in basin margin areas of the Bridger subbasin, lacustrine and lake-margin mudstones and siltstones preserve a low diversity, high density trace fossil assemblage dominated by horizontal meniscate backfilled burrows (e.g., *Taenidium*; Fig. 12.9a–c). In most examples, the smaller-sized (~4 mm, ~7 mm) meniscate backfilled burrows have a horizontal orientation, and are found in sediments that are very closely associated with shallow lacustrine sedimentary structures (e.g., wavy bedding). In contrast, the larger forms (~15–25 mm) typically have a vertical component and show that the substrates had been drained to approximately 0.5–1 m depths. It is these larger forms that overprint lacustrine sediments, including oil shales and organic-poor mudstones that contain no other trace fossils. In cases where only the terrestrial traces are preserved in lacustrine sediments, the lacustrine environments are interpreted to have not been suitable for burrowing organisms due to environmental stresses such as

low oxygen levels, hypersalinity, or high turbidity. Examples of this association also include the Lower LaCledde Member in the southern Bridger subbasin (Fig. 12.4c), and in Lake Uinta from Colorado (cf. Tānasvuu-Milkeviciene and Sarg 2015, *this volume*).

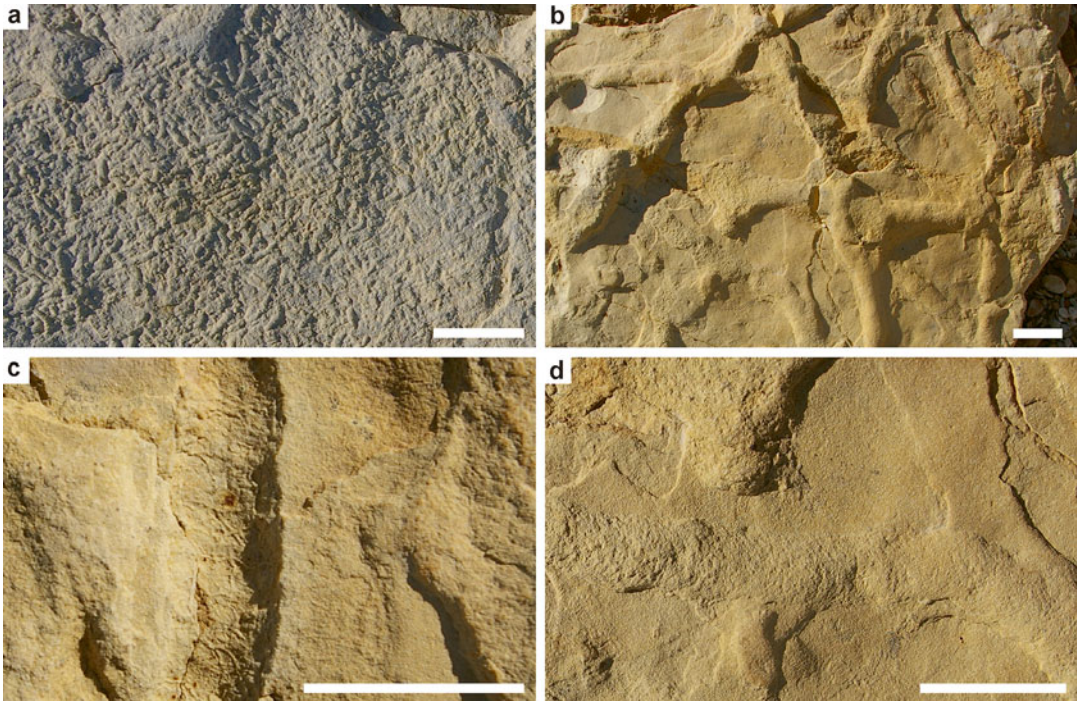
In subaerially exposed sand flat deposits of the Buff Marker, Lower LaCledde Bed, Laney Member, Washakie subbasin, Wyoming, a low-diversity, low-density trace fossil assemblage is preserved, together with reverse-graded sandstones, wavy bedded and desiccation-cracked sandstones, evaporitic horizons, synaeresis cracks, low-amplitude symmetrical ripples, and microbial-mat surface textures (e.g., gas escape structures, wrinkle marks). The traces were produced in saturated and probably microbially bound substrates adjacent to the lake, and include *Planolites*, *Helminthoidichnites*, and *Cochlichnus* (~4 mm diameter).

#### 12.4.4 Shallow Evaporitic Lacustrine

A low diversity assemblage of trace fossils characterizes shallow lacustrine areas in the evaporitic carbonate and dolomite lakes. In basin center areas of underfilled basins, high density simple trails are typically associated with wavy bedded siltstones and mudstones of the low-gradient littoral zone, and form an assemblage very similar to the subaerially exposed mudflats to which they are adjacent (Fig. 12.13c–d). In these settings, dolomitic mudstones may also contain a variety of different “shrinkage” or synaeresis cracks. Although these cracks appear similar to trace fossils, their origin is uncertain and they are likely best attributed to the shrinkage of the dolomitic muds or clays in saline waters, or to the shrinkage of microbial mats, or, in many cases, may be ascribed to evaporate pseudomorphs of bladed evaporates such as trona. These enigmatic structures are also present throughout these facies in the Green River basins (B. Töro, personal communication 2013).

The southern margin of the Bridger subbasin contains quartzose sandstones sourced from the Uinta Uplift, which were deposited in marginal lacustrine, shallow lacustrine, and fluvio-deltaic environments in Tipton and Wilkins Peak members. Shorelines of the expanded Lake Gosiute during Wilkins Peak time reached the southern margin of the underfilled lake-type, but were nevertheless saline to hypersaline except in areas where fluvial systems fed the lake. In shoreline areas with small channels at the southern basin margin, the trace fossil assemblage is relatively diverse for underfilled basins (Figs. 12.18, 12.19), and includes: (1) high density *Planolites* (~3 mm diameter) associated with microbial mat textures (wrinkle marks); (2) large branching burrows with burrow wall ornamentation (similar to *Scoyenia*); (3) vertical burrows up to 10 mm in diameter, soft walled burrow networks (cf. *Thalassinoides*); (4) vertebrate footprints produced in soft substrates (probably by rhinos or small uinatheres); and (5) medium-sized (~7–10 mm diameter) meniscate backfilled burrows that overprint the assemblage following lake-level drop. The sedimentary evidence, such as high amplitude symmetrical ripples also suggest that the depositional gradient may have been relatively high, allowing for increased fetch (Fig. 12.19d).

Trace fossils help to demonstrate the different salinities of the lake at different times and in laterally heterogeneous lake-margins. Higher in the section at the southern Bridger subbasin, shallow lacustrine deposits in the Wilkins Peak Member show evidence of sheet flooding from low-gradient areas into the lake (Smoot 1983). The trace fossil assemblage is low diversity, and is represented by large vertically oriented meniscate backfilled burrows (*Taenidium baretti*) that penetrate lacustrine sediments from subaerially exposed lake margin areas following lake level drop. In this example, no soft-substrate traces produced contemporaneously with initial deposition were observed, and the assemblage may signify that the lake waters were relatively saline (Fig. 12.20).



**Fig. 12.18** Expanded lake facies and trace fossils at the southern basin margin in the underfilled Wilkins Peak Member of the Bridger subbasin (Pipeline area). All scale bars 2 cm. (a) High density cross-cutting simple horizontal traces (*Planolites*) on rippled bedding plane. Traces associated with microbial mat textures. (b) Branching

horizontal burrow systems (cf. *Thalassinoides*) produced in soft substrates. (c) Linear features preserved on burrow wall with relatively sharp margins produced in soft substrate (cf. *Scoyenia*; compare with D’Alessandro et al. 1987). (d) Meniscate backfilled burrow (*Taenidium*) cross-cutting burrow network in (C)

#### 12.4.5 Shallow Freshwater Lacustrine

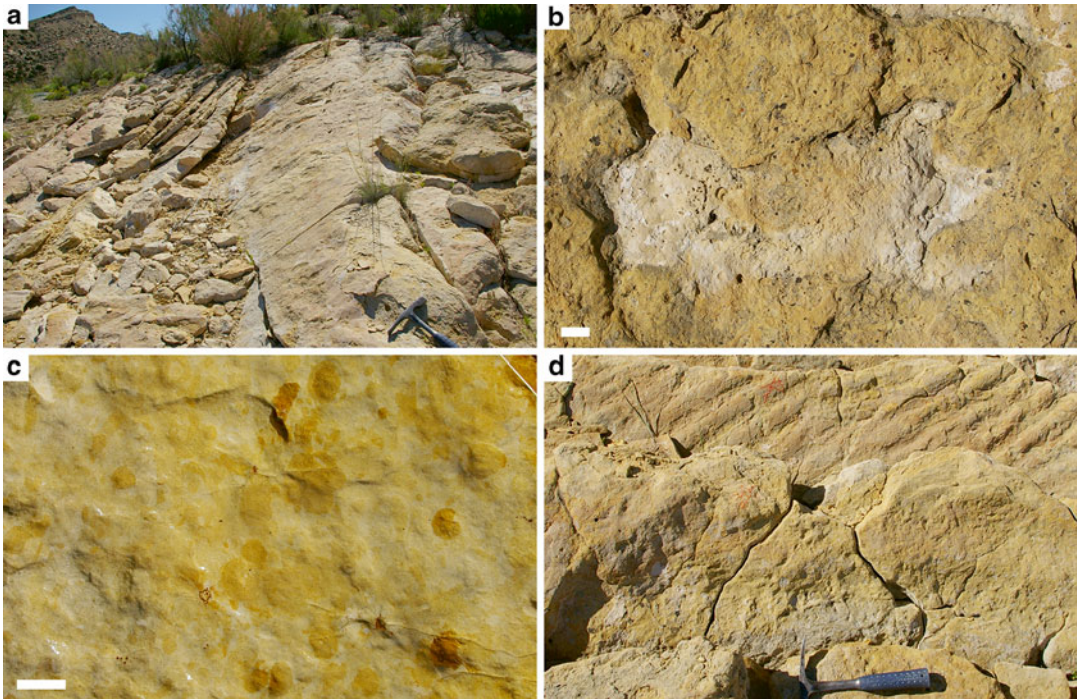
Shallow freshwater lacustrine deposits, characterizing the overfilled lake-type and expanded lakes of balanced fill basins, have been investigated for trace fossils in a small number of localities (e.g., Bohacs et al. 2007). Examples show the preservation of *Planolites* and *Palaeophycus*, vertical burrows (*Skolithos*), escape traces, U-shaped burrows (*Arenicolites*), and resting or locomotion traces of bivalves (e.g., *Lockeia*), all produced in soft substrates. The producers likely include insects (e.g., mayfly larvae), oligochaetes, gastropods, and/or bivalves. Quartzose sandstones forming fluvio-lacustrine deposits of the Tipton Member in the southern Bridger

subbasin contain abundant plant material along horizons that are entirely bioturbated with *Planolites* and *Palaeophycus* (Fig. 12.3). The Cottonwood Creek Delta of the Tipton Member in the Washakie subbasin also preserves soft-substrate burrows that were interpreted to have been produced by crustaceans and worms by Roehler (1988).

#### 12.4.6 Sublittoral to Profundal Lacustrine

Sublittoral to profundal lacustrine trace fossils are uncommon, although fish swimming trails (e.g., *Undichna*), branching tunnel networks (e.g., *Vagorichnus*-like), and tiny sinuous trails





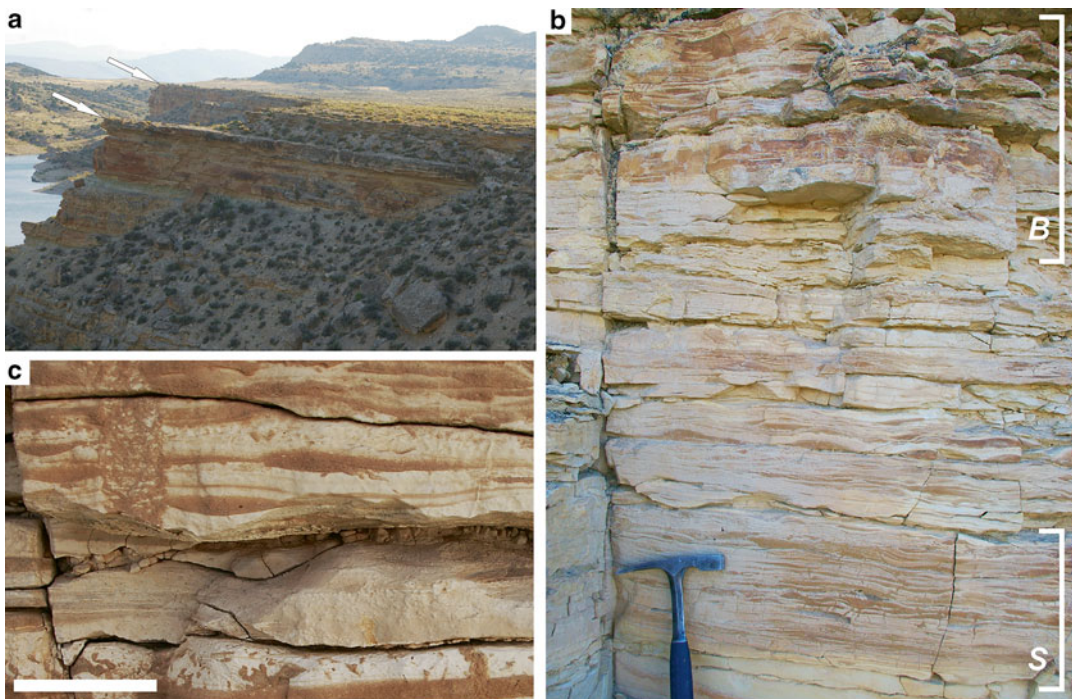
**Fig. 12.19** Expanded lake facies and trace fossils at the southern basin margin in the underfilled Wilkins Peak Member of the Bridger subbasin (Pipeline area). All scale bars 2 cm. (a) Structureless, bioturbated quartzose sandstone unit overlain by wave-rippled beds. Hammer for scale. (b) Mammal footprints (perissodactyl) in soft sandy substrate. Note 3-toed footprint towards right and 3-toed

footprint at left. (c) Entirely bioturbated sandstone shown in (F). Most burrows have structureless fill; some have meniscate fill. (d) View of symmetrical ripples in sandstones shown in (F). Hammer for scale. Note burrow networks, including meniscate backfilled burrows, in wave-rippled sandstones shown in foreground

(*Cochlichmus*) likely produced by insects and/or nematodes are found in the fish-fossil beds of Fossil Lake, Fossil Basin, Wyoming (e.g., Loewen and de Gibert 1999; Martin et al. 2010; A. Åase, personal communication 2013). Some of the fish swimming marks show feeding impressions on the sediment surface, and were produced by the sucker-like *Notogoneus* (Martin et al. 2010). Thin sandstone beds intercalated with oil shales below the Mahogany Zone in the Soldier Summit area of the Uinta basin contain large branching networks on the base of several beds, which are similar to *Thalassinoides* and may have been produced by crustaceans. Small bilobed trails (~5 mm diameter), possibly produced by aquatic insects, are associated with the larger networks (A. Martin, pers. comm. 2007). Very small (~2 mm diameter)

simple trails (e.g., *Helminthoidichnites*) are preserved in sublittoral deposits of laminated organic-rich wavy-bedded dolomitic siltstones overlain by deltaic siliciclastics in the Wilkins Peak Member of the Bridger subbasin (Fig. 12.13d).

Very thinly laminated oil shales, such as in the Rife Bed of the Tipton Member and the lower LaClede Bed of the Laney Member in the Greater Green River basin, have not revealed trace fossils preserved in these profundal facies. If trace fossils are preserved in sublittoral facies (e.g., thin wavy bedded and laminated siltstones and organic-rich mudstones), they signify that the bottom waters of the lakes were not anoxic, although they may have been oxygen-poor. Most of the trace fossils found in these facies are small (less than 5 mm diameter), are present on bed-



**Fig. 12.20** Stratigraphic surface with trace fossils at the southern margin of the Bridger subbasin, Pipeline area. (a) Two shallowing upwards units (*arrows*) bioturbated by meniscate backfilled burrows from upper surfaces. (b) Close-up of vertically oriented burrow (*Taenidium barretti*) with angular aggregate fill. Shrinkage cracks in white carbonate bed below. (c) Upper part of top unit, showing laminated carbonate

mudstones at base, wavy bedded carbonates and clastics, and bioturbated uppermost beds. Hammer for scale. (c) Close-up of vertically oriented burrow (*Taenidium barretti*) with angular aggregate fill. Shrinkage cracks in white carbonate bed below

ding planes, and are not easily observed in vertical sections or core. In some cases, larger (up to 2 cm diameter), meniscate backfilled burrows (e.g., *Taenidium*) are preserved within lacustrine oil shales (e.g., [Tänasvuu-Milkeviciene](#) and [Sarg this volume](#)), but they probably represent the subaerial exposure of the shales or overlying beds.

## 12.5 Utility of Trace Fossils for Stratigraphy and the Reconstruction of Environments

Trace fossil assemblages can be applied to the interpretation of environmental conditions prevalent in sedimentary paleoenvironments because animals and plants respond to these conditions

(e.g., salinity, water saturation, substrate drainage). The composition of the assemblages tends to be recurrent in different environments, where animal and plant communities repeatedly co-occur. The distribution of different trace fossil assemblages, whether heterogeneous or relatively homogeneous along a lake margin for example, is a useful consideration for the interpretation of lateral changes in environmental conditions. Heterogeneity is typically more pronounced in more extreme settings (e.g., [Scott et al. 2009](#)), such as those around saline to hypersaline Lake Gosiute during the deposition of the Wilkins Peak Member ([Scott 2010](#)). Morphological features of individual traces, such as those that provide clues to substrate conditions (e.g., degree of water saturation), are also tools that can be used together with sedimentology to interpret environmental conditions (e.g., substrate

drainage). The bioturbation intensity and depth of burrowing from a horizon are also important for interpreting sedimentation rate, depth of the water table, and hiatuses in sedimentation. The examples in the Green River and correlative formations given in this chapter illustrate the utility of trace fossils for recognizing these parameters and using them for environmental interpretations.

In settings with limited accommodation, the overprinting of more than one trace fossil assemblage on a single horizon represents a discontinuity surface useful for correlation and the sequence stratigraphic interpretation of the basin fill. Two examples of contrasting vertical packaging of sedimentary facies and trace fossil assemblages from the basin margin and basin center areas during deposition of the Wilkins Peak Member illustrate contrasting scenarios for the application of trace fossils to basin analysis and interpretation of subsidence rates in underfilled lake-type basins.

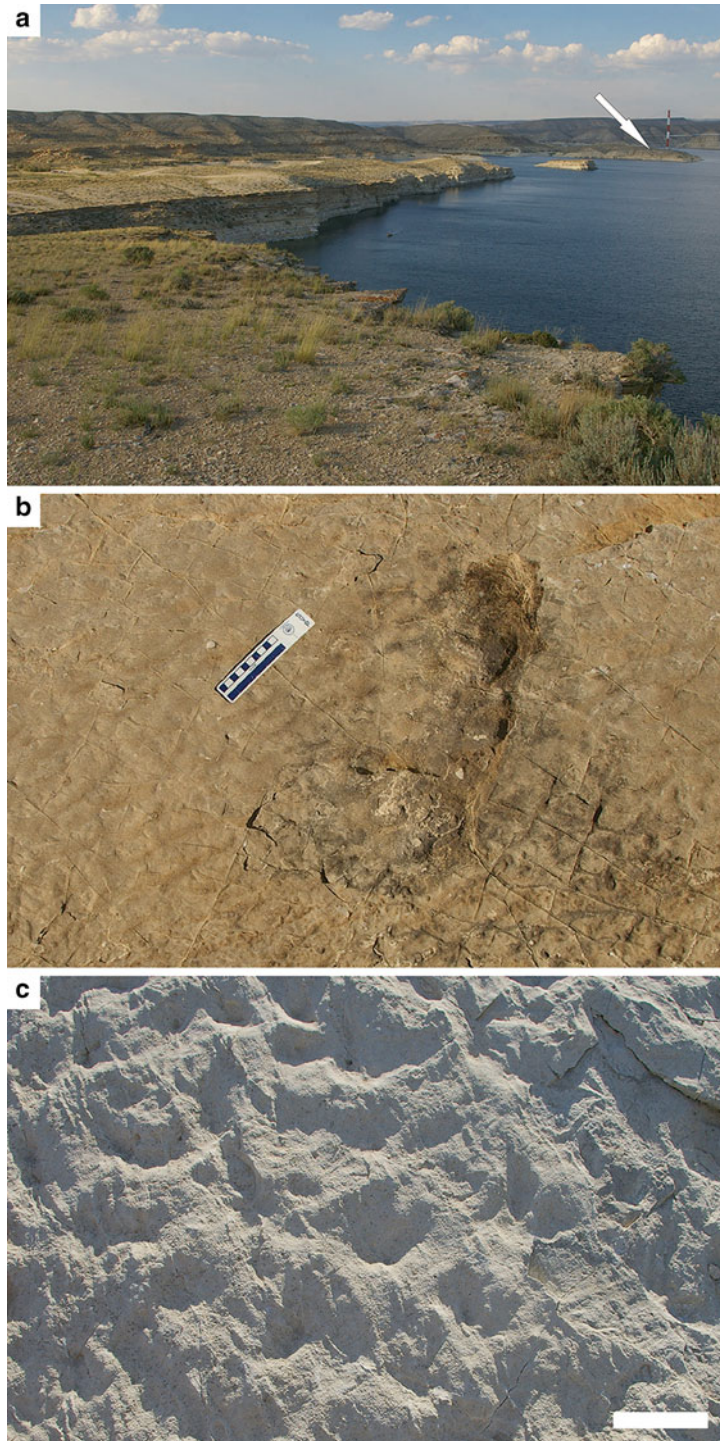
First, resistant and laterally extensive surfaces that are bioturbated by meniscate backfilled burrows illustrate this application to the stratigraphy of the Green River Formation, including a ~2.5 m-thick coarsening upwards succession of the Wilkins Peak Member in the southern Bridger subbasin (Fig. 12.20). The succession shallows upwards from laminated lake-beds, to rippled sandstones interpreted as underflows, to wavy bedded shallow water deposits, to desiccation cracked interbedded mudstones and sandstones interpreted as the eulittoral zone. The uppermost horizon is the colonization surface for the burrowers producing the meniscate backfilled burrows (*Taenidium baretii*). The monospecific trace fossil assemblage in this example shows that the conditions within the lake were not suitable for burrowers, but that upon subaerial exposure of the lacustrine sediments and water table drop, air-breathing organisms could colonize the substrate. Bioturbation intensity is highest (BI=3–5) at the uppermost horizon and burrows are oriented both horizontally and vertically to depths of up to ~1.5 m. The horizon is relatively indurated and resistant to erosion, and forms a surface that can be traced towards the lake center for almost 2 km

in outcrop. The lakeward extension of this surface preserves an unusual texture interpreted as being produced by the trampling of birds, possibly the flamingo-like *Juncitarsus* or *Presbyornis* (cf. Scott et al. 2012b) and large mammal footprints with symmetrical ripples (Fig. 12.21).

Second, progradational stacking patterns of shallow evaporitic lacustrine to delta plain environments of the basin center are recognized by their closely associated lithofacies and trace fossil assemblages (Scott 2010; see “Deltas” section above). The building out of the clastic units onto exposed evaporitic mudflats shows that siliciclastic deposition into the carbonate lake may be related to an increase in precipitation, which contributed to the transport of clastics into an otherwise solute-dominated lake basin (Smith et al. 2014). Each progradational succession comprises two or more shallowing upwards cycles (parasequences) representing progradation during lacustrine lowstands (Figs. 12.17, 12.22). These stacked successions are overlain by sharp flooding surfaces to kerogen-rich oil shales in topographically higher areas, or they are gradationally overlain by rippled lacustrine deposits in flooded channels (Fig. 12.22). Towards the tops of each of the progradational cycles, an abundance of terrestrial burrow types help to show increasing water table depths and terrestrialization of the deposits below the next carbonate lake flooding surface.

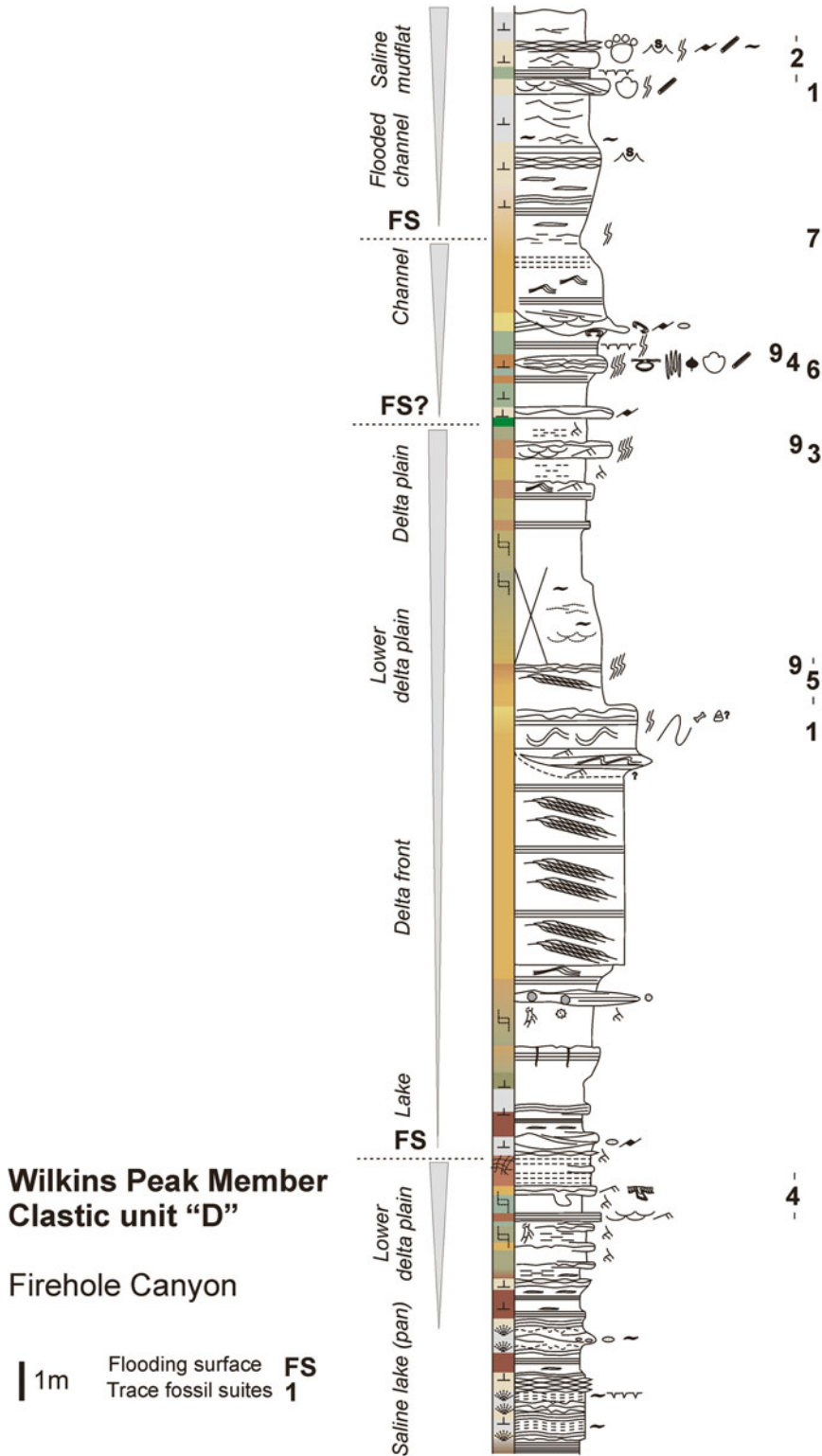
In the basin center, gradual facies changes from lacustrine to terrestrial environments in these siliciclastic packages up to 25 m in thickness represent the net accumulation of sediments and the vertical stacking of gradually changing trace fossil assemblages (Scott 2010). Rare overprinting of trace fossils produced in different sedimentary environments is observed in these basin-center deposits, which suggests that it was a high accommodation potential setting with abundant sediment supply during lacustrine lowstands. The uppermost subaerial facies of these clastic units could thus be considered as maximum regressive surfaces, marking the changes from lowstands to expanded lakes. In the basin margin examples in contrast, burrows produced by air-breathing terrestrial organisms overprinted





**Fig. 12.21** Stratigraphic surface with trace fossils at the southern margin of the Bridger subbasin, Pipeline area. (a) The surface shown in Fig. 12.20a can be traced in outcrop for almost 2 km (arrow) towards basin center. (b) Large mammal footprints (produced by *Uintatherium*) in rippled substrate at basinward locality (arrow in e). Scale is in cm. (c) Surface texture at basinward

locality (arrow in e) interpreted as soupy lacustrine muds trampled by gregarious birds such as *Presbyornis* or *Juncitarsus*. Compare with modern flamingo-trampled surface at Lake Bogoria (Scott et al. 2012b). Note moon-shaped morphology of posterior part of tracks showing movement of birds in one direction, and linear oriented “splash marks”. Scale bar is 5 cm



**Fig. 12.22** Measured stratigraphic section of the deltaic "D" sandstone unit in the basin center Wilkins Peak Member in the Bridger subbasin. Trace fossil suite numbers correspond to those shown in Fig. 12.15. See Scott (2010) for a full description of the trace types and lithofacies. Colors shown represent actual color

lacustrine deposits when lake-level dropped, but were not accompanied by an influx of sediment. This may signify a decrease in precipitation leading to lake-level drop at the transition from lacustrine highstand to lowstand, and the basin margin bioturbated surface could thus be considered a sequence boundary.

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## 12.6 Conclusions

Trace fossil assemblages in the Green River and correlative formations, like marine and other continental assemblages, represent the response of organisms to the environmental conditions prevalent in different depositional settings. Lacustrine sediments also provide evidence of environmental conditions such as hydrochemistry (e.g., evaporite deposits). Depositional environments such as fluvial channels and deltaic areas, bringing freshwater to otherwise saline lake margins, for example, are typically associated with trace fossil assemblages that are distinct from adjacent evaporitic areas, as described here for deltaic and evaporitic lake margin environments. In the Green River and correlative formations, there is a close relationship between the processes affecting deposition and the processes affecting the trace fossil assemblage in lacustrine and lake-margin settings. With pedogenically modified terrestrial deposits, however, the trace fossil assemblages are more closely related to the pedogenic conditions than to the original environment of deposition.

Terrestrial and lacustrine trace fossils have great potential as tools for paleoenvironmental interpretations of sedimentary deposits, and as important markers of stratigraphically useful horizons. Most ichnological research that focuses on the basin-scale distribution of trace fossil assemblages and integration with the lake-type model has been conducted in the Greater Green River basin of Wyoming and Colorado (e.g., Hasiotis and Honey 2000; Bohacs et al. 2007; Scott 2010). Most of the work done in the Lake Uinta basins has focused on vertebrate footprints (e.g., Curry 1957; Erickson 1967; Moussa 1968; Olson 2014), although some research has incor-

porated invertebrate trace fossils and facies analyses (D'Alessandro et al. 1987; Golab 2010; Sato et al. 2014). The stratigraphic application of the trace fossils in the Green River and correlative formations has been investigated by some authors (Bohacs et al. 2007; Scott 2010). Much work remains, however, to continue to describe case studies and develop models that improve the methodology and application of trace fossils to understanding the Green River lakes systems, as well as paleoecology in these basins during the Early to middle Eocene.

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