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Paleoenvironmental Controls on the Preservation of Tetrapod Swim Tracks From the Lower to Middle Triassic Moenkopi Formation, Utah

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Paleoenvironmental Controls on the Preservation of Tetrapod Swim Tracks From the Lower to Middle Triassic Moenkopi Formation, Utah

A Thesis submitted in partial satisfaction of the requirements for the degree of

Master of Science

in

Geological Sciences

by

Tracy Joseph Thomson

June 2014

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DEDICATION

Special thanks is given to my parents who supported and encouraged my scientific interests from young age right up to buying me field vehicles for my excursions into southern Utah. I’m grateful to Jim Madsen for advice and encouraging me in my youth to follow my dreams of becoming a paleontologist. I would like to recognize Paul Bybee who first showed me swim tracks from the Moenkopi Formation in Capitol Reef National Park on a field trip and piqued my interest in these remarkable traces. Also thanks to Tony Ekdale for providing me with an excellent foundation in ichnology and to Randy Irmis for putting my work on Early Triassic tracks in context with the body fossil record. Thanks to all my colleagues in Utah for information on fossil localities and encouragement throughout my project. I especially thank my advisor, Mary Droser, for her excellent direction throughout this study and her indulgence of my interest in vertebrate paleontology. Her expertise has taught me much and made my research approaches in this field stronger.

Lastly, I would like to thank my wife, Alicia, and my four-year-old son, James, for allowing the many boxes of rocks and fossils to occupy our apartments over the years and for supporting me in so many ways through the long years of school and work. I share this accomplishment with them.
ABSTRACT OF THE THESIS

Paleoenvironmental Controls on the Preservation of Tetrapod Swim Tracks From the Lower to Middle Triassic Moenkopi Formation, Utah

by

Tracy Joseph Thomson

Master of Science, Graduate Program in Geological Sciences
University of California, Riverside, June, 2014
Dr. Mary L. Droser, Chairperson

Tetrapod swim tracks attributed to reptiles occur abundantly throughout Lower to Middle Triassic deposits across the western United States. In central and southern Utah these swim track localities are stratigraphically restricted to the upper portion of the Torrey Member of the Moenkopi Formation. Here they show detailed features such as longitudinal striae and disc-shaped claw impressions that must have required specific substrate conditions in order to be produced and preserved. A suite of sedimentologic and ichnologic observations at several swim track localities demonstrates the widespread development and persistence of subaqueous firmground substrates buried by crevasse splay deposits in the interdistributary areas of a large lower delta plain. The heterolithic stratigraphy is typical of interdistributary bays and channels and generally consists of decimeter-scale fining-upward cycles of mud- and siltstone beds below the track-bearing
horizons and thicker, massive or cross-bedded sandstones above. Siltstone and sandstone beds show low angle accretion sets, vary laterally in thickness, and commonly pinch out so that they cannot be correlated regionally. Common sedimentary structures indicate predominately quiet subaqueous conditions with periodic higher energy events. These include trough cross stratification, climbing ripples, rip-up clasts, and soft sediment deformation. Track surfaces often exhibit localized dewatering structures and load casts in addition to flute casts and current crescents indicating unidirectional current flow. Mudcracks are rare. The low diversity invertebrate ichnoassemblage is comprised of locally high densities of relatively diminutive traces and reflects stressed brackish water faunas. These characteristics are almost certainly augmented by delayed biotic recovery following the end-Permian mass extinction and resulted in extremely low degrees of bioturbation. This lack of biogenic mixing promoted semi-consolidation of dewatered mud substrates resulting in the widespread production and persistence of firmgrounds capable of recording and maintaining detailed swim tracks. The subsequent burial of these firmground surfaces under coarser-grained crevasse splay deposits resulted in sharp heterolithic contacts further facilitating the preservation of detailed track features.
LIST OF FIGURES

Figure 1: Locality Map ........................................................................................................3

Figure 2: General stratigraphy and subdivisions of the Moenkopi Formation ..............5

Figure 3: Swim traceways and footmark morphotypes ................................................... 8-9

Figure 4: Key for the measured sections in Figures 5-9 ....................................................14

Figure 5: Measured sections from the San Rafael Swell region .................................... 15-16

Figure 6: Measured sections from the Teasdale Uplift region ..................................... 17-18

Figure 7: Measured sections from the Circle Cliffs Uplift region, part 1 .................... 19-20

Figure 8: Measured sections from the Circle Cliffs Uplift region, part 2 .................... 21-22

Figure 9: Measured sections from the Monument Upwarp region .............................. 23-24

Figure 10: Swim track locality outcrops ...................................................................... 27-28

Figure 11: Sedimentology .............................................................................................. 29

Figure 12: Ichnology ...................................................................................................... 36-37

Figure 13: Direct and indirect track features ............................................................... 40-41

Figure 14: Venn diagram .............................................................................................. 43
INTRODUCTION

Vertebrate tracks from Lower to Middle Triassic deposits worldwide have been useful in advancing paleoenvironmental and paleoecological interpretations not possible from observations of the body fossil record alone (e.g., Diedrich, 2011; Lovelace and Lovelace, 2012). The body fossil record of the Lower to Middle Triassic Moenkopi Formation is geographically restricted to deposits in Arizona and New Mexico and is dominated by temnospondyl amphibians. Skeletal material that can be attributed to reptiles is rare. The abundant, diverse, and geographically widespread occurrences of reptile tracks throughout the formation (e.g., Peabody, 1948; Klein and Lucas, 2010) suggests that reptiles were much more diverse both ecologically and taxonomically than what is currently represented by the body fossil record. However, a better understanding of the paleoenvironmental and taphonomic controls that affect various track occurrences is essential for correctly interpreting the diversity and paleoecology of Early to Middle Triassic reptiles in western North America.

A geographically widespread and abundantly occurring component of the vertebrate track assemblage from the Moenkopi Formation is comprised of swim tracks produced by buoyant or semi-buoyant reptiles that preserve exceptionally detailed features such as disc-shaped claw impressions and longitudinal striae (Thomson and Lovelace, 2014). These swim tracks are most abundant and best preserved in the upper portion of the Torrey Member in central to southern Utah. The paleoenvironmental conditions and substrate properties required for the detailed production and preservation of fossil tracks has been explored (e.g., Scrivner and Bottjer, 1986; Falkingham et al.,
2011) and localized occurrences of well-preserved tetrapod swim tracks are known (e.g., McCrea et al., 2004; Milner et al., 2006; Bennett et al., 2014). The widespread distribution of well-preserved swim tracks has thus far only been reported from Lower to Middle Triassic deposits of western North America (Thomson and Lovelace, 2014), suggesting the operation of regional paleoenvironmental controls on their production and preservation. The well exposed Moenkopi Formation provides an ideal natural laboratory for investigating these controls using the sedimentology and ichnology from several swim track localities.

For ease of discussion the terminology proposed by McAllister (1989) for subaqueous traces produced by buoyant tetrapods (footmark, footmarks, and traceway) is used to avoid confusion with those produced under fully terrestrial conditions in dry or moist substrates (track, tracks, and trackway).

GEOLOGICAL SETTING

The uplift of the Uncompahgre Highlands in western Colorado and the Mogollon Highlands in central Arizona during the Pennsylvanian formed a gently dipping northwestward slope. Sediments forming the Moenkopi Formation were deposited on a broad shelf between these eastern highlands and a miogeosyncline to the west during the Early-Middle Triassic (Blakey, 1974). Localized tectonic uplift in central and southern Utah beginning in the Late Cretaceous produced four main regions where the Moenkopi Formation is well-exposed. From north to south they are the San Rafael Swell, Teasdale Uplift, and Circle Cliffs Uplift, with the Monument Upwarp to the east (Blakey, 1974) (Fig. 1).
Figure 1: Locality map showing the four regions of Moenkopi Formation outcrop, swim track localities, and the region where Torrey Member outcrops are characterized by greater than 40 percent ledge forming sandstones (after Blakey, 1974). The four regions are A) San Rafael Swell, B) Teasdale Uplift, C) Circle Cliffs Uplift, and D) Monument Upwarp.
Stratigraphy and Paleoenvironments

The Moenkopi Formation is bounded above and below by the Tr-1 and Tr-3 regional unconformities (Pipiringos and O’Sullivan, 1978) and records both terrestrial and marine depositional environments on a passive margin (Stewart et al., 1972; Blakey, 1974). Terrestrial units are characterized by sequences of red beds and intertongue with marine units composed of buff or gray limestones that correlate with the thicker, basinal marine Thaynes Formation to the west. In central and southern Utah the formation is divided into five formal members (Fig. 2). In ascending order they are the Black Dragon, Sinbad, Torrey, and Moody Canyon (Blakey, 1974).

The *Meekoceras* ammonite assemblage from the Sinbad Member and the Timpoweap Member (southwestern Utah) shows that they represent chronologically equivalent tongues of the lower Thaynes Formation that were deposited during the early Olenekian (late Smithian) of the Early Triassic (Stewart et al., 1972; Lucas et al., 2007a, 2007b; Brayard et al., 2013). The overlying Torrey Member, which directly overlies and, in some places, intertongues with the Sinbad Member, is therefore at least partly Early Triassic in age and possibly earliest Middle Triassic at the youngest.

The Torrey Member thickens from less than 45 meters to the east to greater than 90 meters to the west. It is a complex unit with an east-west lateral progression of four distinct facies with each facies generally forming a bilobed geographic distribution pattern (Blakey, 1974). The overall shape of this pattern is recognized by a line demarcating where the percentage of ledge-forming sandstone making up the member drops rapidly below 40 percent to the northwest and remains
**Figure 2:** General stratigraphy and subdivisions of the Moenkopi Formation in south-central Utah with the approximate stratigraphic position of swim track sites indicated. Ages of individual members are approximate.
greater than 40 percent to the southeast (Fig. 1). This pattern in the geographic
distribution of higher volumes of sandstone were interpreted as representing periodic
impulses of sediment input within the lobes of a mature deltaic system (Blakey, 1974)
herein called the Torrey Delta.

Mickelson et al. (2006) presented three stratigraphic sections representing the
entire thickness of the Torrey Member from the San Rafael Swell, Capitol Reef National
Park (Teasdale Uplift), and Glen Canyon National Recreation Area (Monument Upwarp)
and adapted a lithofacies model for meandering river estuarine systems produced by
Smith (1987) in an attempt to describe the paleoenvironment. However, the sections lack
vertical scale and the Smith (1987) model is based on stratigraphic logs from modern
environments 5 to 10 meters thick, an order of magnitude less than the total thickness of
the Torrey Member. Additionally, certain characteristics of the Smith (1987) model (e.g.,
fining-upward sequence) do not fit the Torrey Member which exhibits an overall
coarsening-upward sequence with sandstone bed thicknesses increasing upsection.

More recent stratigraphic work in the Teasdale Uplift has supported the previous
conclusions of Blakey (1974) and suggested that the Torrey Member is actually a
stratigraphically complex unit consisting of multiple sequence boundaries with diverse
sedimentary facies including overbank/floodplain deposits, interdistributary bay fills,
crevasse splays, and tidal flats (Perkins and Kamola, 2004; Hall and Kamola, 2008).
Preliminary stratigraphy and sedimentology reported from track sites in Glen Canyon
National Recreation Area also indicate the presence of interdistributary bays and
channels in the upper Torrey Member in this region (Thomson, in press).
Paleontology

The body fossil record preserved in terrestrial units from the Moenkopi Formation is largely restricted to the Holbrook Member in Arizona and the Anton Chico Member in New Mexico and is dominated by abundant occurrences of temnospondyl amphibians (Morales, 1987; Boy et al., 2001; Lucas and Schoch, 2002; Nesbitt, 2005c). Reptile remains are rare, consisting of non-avemetatarsalian archosauromorphs and therapsid synapsids (Heckert et al., 2005; Nesbitt, 2005c; Schoch et al., 2010). Known reptiles from the Moenkopi Formation include the lepidosauromorph Anisodontosaurus greeri (Welles, 1947; Morales, 1987; Hunt et al., 1998), the poposauroid Arizonasaurus babbitti (Welles, 1947; Nesbitt, 2003; Nesbitt, 2005b, Schoch et al., 2010), and the rhynchosaur Ammorhynchus navajoi (Nesbitt and Whatley, 2004). No vertebrate body fossils have been reported from the coeval Red Peak Formation in Wyoming.

In contrast to the depauperate reptile body fossil record, an abundant medium to high diversity vertebrate trace fossil assemblage dominated by reptile tracks (e.g., Chirotherium, Rhynchosauroides, and Rotodactylus) is known from throughout the Moenkopi Formation (Peabody, 1948; Peabody, 1956; Klein and Lucas, 2010) and the Red Peak Formation (Lovelace and Lovelace, 2012). These tracks are so abundant that they were the first evidence of reptiles reported from Lower Triassic deposits of western North America (Longwell, 1928; Brady, 1935; Lull, 1942; Branson, 1947).

Elongate swipe marks (Fig. 3) have been reported from the Moenkopi Formation and interpreted as swim tracks for over 60 years. The first published references to swim tracks include track sites from Capitol Reef National Park that were considered among
the best examples of tracks of this type (Peabody, 1956). Swim tracks at several localities from Capitol Reef National Park were the focus of subsequent studies attempting to generally interpret the paleoenvironments under which they were produced (Lammers, 1964) and behaviors they recorded (McAllister and Kirby, 1998). The recognition of well-preserved tracks with systematic configurations on a track surface from Capitol Reef National Park resulted in the realization that similar marks from the coeval Red Peak Formation in Wyoming, originally interpreted as tool marks produced by bobbing driftwood (Boyd, 1975), were in fact tetrapod in origin (Boyd and Loope, 1984). Swim tracks have been reported from Glen Canyon National Recreation Area (Lockley and Hunt, 1995; Schultz et al., 1995; Lockley et al., 1998) and Grand Staircase-Escalante National Monument (Hamblin and Foster, 2000) but these reports did not attempt to place them in a detailed paleoenvironmental or behavioral context. Mickelson et al. (2006) mention swim tracks in their report on vertebrate and invertebrate trace fossils from the San Rafael Swell region, Capitol Reef National Park, and Glen Canyon National Recreation Area. The most recent studies of these swim tracks describe localities throughout western North America, identifies four distinct swim track morphotypes (Figs. 3C-F), and discusses behavioral interpretations, associated invertebrate trace fossils, and possible paleoenvironments (Thomson, 2011; Thomson and Lovelace, 2014; Thomson, in press).

Although invertebrate trace fossils have long been recognized from terrestrial deposits of the Moenkopi Formation in southern Utah (Gregory and Williams, 1947) and Arizona (Brady, 1935; McKee, 1954), they have only recently been described in detail.
Investigations of the Torrey Member in central and southern Utah resulted in the identification of a suite of invertebrate trace fossils consisting of *Fuersichnus*, *Palaeophycus*, and *Arenicolites* that was considered an example of the *Glossifungites* ichnofacies (Mickelson et al., 2006). However, these interpretations were challenged by Lerner et al., (2007) who compared them to an invertebrate ichnoassemblage at a single locality from the roughly coeval Ankareh Formation in north central Utah. The results of this comparison are dubious due to the strong possibility that these assemblages are sampling different paleoenvironments and/or are diachronous. Neither study is comprehensive enough for any broad-scale interpretations to be conclusive.

**METHODS**

Detailed stratigraphic sections were measured at thirteen swim track localities from four regions (San Rafael Swell, Teasdale Uplift, Circle Cliffs Uplift, and Monument Upwarp) throughout central and southern Utah (Table 1; Figs. 4-9). Where possible the thickness between the main track horizon at each locality and the upper contact of the Torrey Member with the Moody Canyon Member was measured with a Jacob’s staff. This contact was used to demonstrate the stratigraphic position of each track horizon within the Torrey Member because it is often well-exposed and is a more accurate reference point than the upper contact of the Moenkopi Formation which is unconformable everywhere. The contact was identified as the lowermost buff to yellow siltstone bed, typically characterized by a rippled upper surface, occurring above the main track horizon at each locality.
Locality information for sites on land administered by the Bureau of Land Management are on file at the Utah Geological Survey (UGS). Trace fossil specimens from these sites were collected under permit number UT13-019S and are accessioned into the collections at the Natural History Museum of Utah (UMNH). Locality information for sites on land administered by the National Park Service are on file at the respective parks and specimens were collected from these sites under permit numbers CARE-2013-SCI-0014 and GLCA-2013-SCI-0008 and are accessioned into collections at Capitol Reef National Park (CARE) and Glen Canyon National Recreation Area (GLCA). Rock samples were collected and subsequently cut and polished in order to view details of their internal sedimentary structure.
<table>
<thead>
<tr>
<th>Region</th>
<th>Locality Number</th>
<th>Locality Name</th>
<th>Associated Ichnology</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Rafael Swell</td>
<td>Em0736</td>
<td>Banana Truck</td>
<td><em>Lockeia</em> small vertical traces</td>
</tr>
<tr>
<td></td>
<td>Em0737</td>
<td>North Butte</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Em0738</td>
<td>Washout</td>
<td><em>Lockeia</em> tetrapod scratch traces</td>
</tr>
<tr>
<td>Teasdale Uplift</td>
<td>TJT13-06</td>
<td>The Castle</td>
<td><em>Diplocraterion</em> <em>Lockeia</em> <em>Planolites</em> <em>Skolithos</em> small vertical traces</td>
</tr>
<tr>
<td></td>
<td>TJT13-07</td>
<td>Chimney Rock</td>
<td>small horizontal traces</td>
</tr>
<tr>
<td></td>
<td>TJT13-08</td>
<td>Cuts Canyon</td>
<td>tetrapod scratch traces</td>
</tr>
<tr>
<td>Circle Cliffs</td>
<td>Ga1350</td>
<td>Desert Flower</td>
<td><em>Planolites</em> <em>Skolithos</em> <em>Thalassinoides</em> small vertical traces small horizontal traces</td>
</tr>
<tr>
<td></td>
<td>Ga1351</td>
<td>Fiberglass Wash</td>
<td><em>Diplocraterion</em> <em>cf. Rusophycus</em></td>
</tr>
<tr>
<td></td>
<td>Ga1352</td>
<td>Little Dragon</td>
<td>None</td>
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<tr>
<td></td>
<td>Ga1406</td>
<td>Blue Bird Flats</td>
<td>tetrapod scratch traces small reptile tracks</td>
</tr>
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<td></td>
<td>GLCA 99</td>
<td>Horse Pasture Mesa</td>
<td><em>Diplocraterion</em> <em>Lockeia</em> <em>Planolites</em> <em>Skolithos</em> small vertical traces tetrapod scratch traces</td>
</tr>
<tr>
<td>Monument Upwarp</td>
<td>GLCA 317</td>
<td>Hite Overlook</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>GLCA 319</td>
<td>Farley Rhynch</td>
<td><em>Diplocraterion</em> <em>Skolithos</em> <em>Undichna</em> small reptile tracks tetrapod scratch traces</td>
</tr>
</tbody>
</table>

Table 1: Swim track localities and associated trace fossils
**Figure 4:** Key for the measured stratigraphic sections in Figures 5-9.
Figure 5: Measured stratigraphic sections from the San Rafael Swell region.
Figure 6: Measured stratigraphic sections from the Teasdale Uplift region.
Figure 7: Measured stratigraphic sections from the Circle Cliffs Uplift region, part 1.
Circle Cliffs Uplift 2
Figure 8: Measured stratigraphic sections from the Circle Cliffs Uplift region, part 2.
Figure 9: Measured stratigraphic sections from the Monument Upwarp region.
SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENTS

Sedimentology

All of the swim track localities with the exception of one (Ga1406) fall within the outcrops of the Torrey Member that are characterized by greater than 40 percent ledge forming sandstones and interpreted as demarcating the overall shape of the Torrey Delta lobes (Blakey, 1974) (Fig. 1). No tracksites preserving swim tracks have been found outside of this region despite prospecting efforts over the last three years. Swim track occurrences thus appear to be broadly correlated with the distribution delta sedimentary facies. The general sedimentary facies that characterizes swim track sites and much of the upper Torrey Member is comprised of heterolithic bedding with decimeter-scale, fining-upward cycles in overall coarsening-upward packages with sharp erosive contacts between most beds (Figs. 5-10).

Mudcracks and other desiccation structures such as bedded gypsum are rare. More common are examples of soft sediment deformation (Fig. 11D), fluid escape structures (Fig. 11E), and load casting. Swim tracks are preserved on the bases of coarser-grained siltstone and sandstone beds typically ranging in thickness from 5 to 20 centimeters (Figs. 10A-C) but sometimes as thicker than 2 meters (Fig. 10D). These beds generally increase in thickness upwards being separated by finer-grained mud and siltstones that decrease in thickness upwards. At many track localities a much thicker sandstone unit caps the outcrop that can be traced laterally much further than the thinner beds below it. At some localities very low angle accretion sets are visible within this unit (Figs. 10D-E) and is typically either massive or contains low-angle cross bedding (Fig. 11G).
Beds below the main track horizon commonly exhibit rhythmic interbedding of silt- and mudstone (Fig. 11E) or repeating decimeter scale, fining-upward sequences bounded by sharp bedding planes. Asymmetrical ripples are common on the tops of several silt- and sandstone beds that also show a small scale trough cross-bedded internal structure (Fig. 11A). In many instances sequential beds show alternating ripple and/or cross bedding orientations which correlate to the grain size of the bed. Examples of this occur in centimeters 0 to 20 of TJT13-06 (Fig. 6A), centimeters 100-125 of Ga1350F (Fig. 7A), and throughout the Ga1352 section (Fig. 8A). At a few localities ripple structures are preserved between stilt- and sandstone beds of similar grain size preserving ripple marks on both the upper and lower surfaces of these beds (Fig. 11B). Angular clay rip up clasts (Fig. 11C) are preserved at some sites such as at 93 centimeters in Ga1350F (Fig. 7A). Many of the track surfaces themselves have detailed sedimentary structures preserved on them including flute casts, flow lineations, current crescents (Fig. 11H), and gutter casts (Fig. 11I).
**Figure 10:** Swim track locality outcrops. White arrows denote swim track horizons and black arrows identify float blocks with swim tracks. Brackets indicate the sections measured at each site. **A)** GLCA 319. **B)** Ga1351. **C)** GLCA 317, section 1. **D)** TJT13-07 showing lateral accretion set. **E)** GLCA 319 showing lateral accretion set.
Figure 11: Sedimentary Structures. A) Trough cross-bedding from TJT13-06 at 42 cm, polished section. B) Ripple marks on the upper and lower surfaces of fine-grained sandstone beds from Ga1352 at 305 cm. C) Rip up clasts from Ga1350 at 93 cm. D) Flow rolls and soft sediment deformation from GLCA 317 section 1 at 60 cm. E) Fining upward cycle from Ga1351 at 15 cm. F) Fluid escape structure cast on the base of a sandstone bed from GLCA 319 at 80 cm. G) Low angle cross bedding from GLCA 319 at 140 cm. H) Current crescents on a track surface from TJT13-07 at 150 cm. I) Gutter cast on the base of a sandstone bed from GLCA 319 at 50 cm.
Interpretations

Swim tracks throughout the upper Torrey Member are found in a single sedimentary facies which is characterized by fining upward cycles of heterolithic bedding in overall coarsening upward packages. This bedding architecture is consistent with previous interpretations of a tidally-influenced deltaic deposition environment (Blakey, 1974; Perkins and Kamola, 2004; Hall and Kamola, 2008). The bedding sequences at swim track localities compare well to models of crevasse splay sequence types in interdistributary bay facies (Elliot, 1974) and to examples of interdistributary bay fills and channels from the Cretaceous Dunvegan Formation (Bhattacharya and Walker, 1991). These sequences also strongly resemble inclined heterolithic stratification sets from the Lower Devonian Wood Bay Formation figured by Thomas et al. (1987, fig. 4) and this stratification type has been proposed as one of the more important diagnostic features of tidally influenced point and channel bars (Thomas et al., 1987; Johnson and Dashtgard, 2014). The rhythmic interbedding of silt- and mudstones is typical of tidally influenced deposits within tidal-fluvial environments (e.g., Dalrymple and Choi, 2007).

The preservation of ripple marks on lower surfaces of coarser-grained beds indicates that the underlying substrate must have been somewhat cohesive and resistant to erosion during the transportation and deposition of the overlying sediment. This may have been facilitated either by microbial mat binding in calm shallow water, or by partial drying of the surface due to subaerial exposure possibly during low tides. However, the paucity of mudcracks indicates that prolonged subaerial exposure of the substrate was a rare occurrence and that deposition took place under predominantly subaqueous
conditions. This is further evidenced by the presence of soft sediment deformation, fluid escape structures, and load casting, showing that the prevalence of water saturated substrates was the norm.

Occurrences of asymmetrical ripple marks and trough cross bedding are the results of deposition under unidirectional current flows and the alternating orientations of these structures indicates that the sediments making up these beds were transported in from different directions. The finer-grained beds were laid down under low energy tidal or calm water conditions within abandoned channels and bays and the coarser-grained beds were deposited by periodic crevasse splaying which filled in the bays and channels bringing in sediment from a different direction. The very low angle accretion sets within the thick sandstone units capping most swim track localities reflect the migration of large channels across an originally low relief terrain.

Clay rip up clasts were most likely incorporated into overlying silt- and sandstone beds during flooding events and demonstrate the cohesive nature of the underlying mudstone beds from which they were derived. Current crescents like those described here were first recognized and described from the Moenkopi Formation in Arizona, and represent shallow water flowing around stranded objects such as bits of wood or clay pebbles, during the waning stages of current flow (Peabody, 1947). Gutter casts may represent drainage runnels cut into point bars as they were exposed during low tide or periods of low volume flow in the channels.

The sedimentology at these swim track sites shows evidence for the development, subaqueous exposure, and subsequent burial of cohesive, firmground substrates.
Altogether the sedimentary facies and its individual sedimentary features demonstrate that the swim tracks were produced in firmground substrates at the bottom of the interdistributary bays or abandoned channels and subsequently preserved as natural casts during periodic crevasse splay events.

**ICHNOLOGY**

Trace fossils record the behavioral interactions of ancient organisms with their environment. In deposits where body fossils are rare or non-existent, trace fossils may be the only evidence of life and thus reveal a “hidden” biodiversity (Hasiotis, 2007). Morphological and distributional patterns of trace fossil assemblages are useful for determining physicochemical stresses on the infauna (e.g., Pemberton and Wightman, 1992; Buatois et al., 1998; MacEachern et al., 2005). Additionally, suites of recurring invertebrate trace fossil associations (ichnofacies) are useful indicators of ancient depositional environments and substrate conditions (Seilacher, 1964, 1967; Frey and Seilacher, 1980; Pemberton et al., 1992), especially when considered in conjunction with associated sedimentary structures.

**Invertebrate Ichnology**

Trace fossils can be dense but an overwhelming majority of the beds at swim track sites completely lack bioturbation. Delicate vertical and horizontal burrows are sometimes visible in outcrop running through thinly bedded mudstones and can be easily seen in polished sections (Fig. 12A). Vertical burrows rarely overlap and do not completely disrupt bedding planes. This degree of bioturbation can be assigned an
ichnofabric index of 3 (Droser and Bottjer, 1986) and is a rare occurrence at swim track sites.

Several characteristics of the invertebrate trace fossils from these localities reflect the activity of opportunistic organisms under brackish conditions. Modern brackish water environments are typically characterized by an impoverished suite of marine benthic organisms, a distinct size reduction in some organisms, and locally high individual densities (Cognetti & Maltagliati, 2000). Decreasing burrow size attributed to a decrease in both organism size and diversity as a function of decreasing salinity has been reported from modern fluvial-tidal environments (Gingras et al., 1999; Hauck et al., 2009; Johnson and Dashtgard, 2014). These attributes of brackish water benthic fauna result in low diversity ichnoassemblages composed of typically diminutive marine forms occurring in localized high densities (Pemberton and Wightman, 1992).

The invertebrate ichnoassemblage at swim track sites is comprised of typically marine ichnogenera (e.g., *Diplocraterion*, *Thalassinoides*, and *Rhizocorallium*) with burrow diameters consistently less than 5 millimeters. The bivalve resting traces (*Lockea*) at these sites are also diminutive with overall lengths no more than 5 millimeters (Fig. 12B). The vertical traces *Skolithos* have very small tubes no more than 2 millimeters in diameter. At many localities the ichnogenera *Diplocraterion* and *Rhizocorallium* form beds of locally high individual densities (Fig. 12C) with an ichnofabric index of 2 and a bedding-plane bioturbation index of 2 (Miller and Smail, 1997).
The locally dense u-shaped dwelling traces (*Diplocraterion* and *Rhizocorallium*) at several swim track localities display areas of disturbed sediment called spreite between the paired tubes (Figs. 12D-E). Dwelling traces of this type typically have funnel-shaped openings. Spreite is a product of the organism’s response to either sedimentation (retrusive spreite) or erosion (protrusive spreite) as it migrates upward or downward in an effort to maintain a constant depth below the sediment/water interface (Goldring, 1962). The *Diplocraterion* and *Rhizocorallium* at swim track localities display only protrusive spreite and lack funnel-shaped openings (Figs. 12D-E) indicating predominantly erosive conditions during burrow occupation, abandonment of the burrow resulting in erosion of the openings, and finally burial and preservation. Small vertical burrows at some localities also show eroded tops and passive infilling by the overlying sediment (Fig. 12F).

The ichnogenera comprising the invertebrate trace fossil assemblage observed at these localities is characteristic of the *Glossifungites* ichnofacies, a substrate controlled ichnofacies restricted to firm but unlithified marine surfaces (Frey and Seilacher, 1980). In modern environments most of the organisms that exploit firmground substrates are suspension feeders that construct permanent dwelling structures with simple architecture (e.g., Pemberton and Frey, 1985; Gingras et al., 2001). These include the u-shaped burrows *Arenicolites*, *Diplocraterion*, and *Rhizocorallium*, the branching burrow system *Thalassinoides*, the non-branching burrow *Planolites*, and the vertical dwelling structure *Skolithos*, all of which are present at these swim track sites.
At locality Ga1351 traces assigned here to cf. *Rusophycus* are preserved as casts on the base of a swim track surface (Fig. 12G). These are bilobed traces with small striae running parallel to the median furrow. These striae can be considered bioglyphs because they are scratch marks engraved on the walls of the trace by the organism (Ekdale and de Gibert, 2010). The production and maintenance of bioglyphs requires fine-grained, firm, cohesive substrates with high shear strengths, factors which also favor their protection and preservation as currents bring in the coarser sand which subsequently casts the trace fossil (Crimes, 1975). Surfaces preserving swim tracks at several localities also show tiny scratch marks on the surface 1 to 2 millimeters in width and ranging from 1 to 3 centimeters in length. These traces probably either represent the random scratchings of bottom-walking arthropods or claw marks produced by small tetrapods swimming near the bottom.
Figure 12: Ichnology. A) Polished section showing delicate vertical burrows (white arrows) from TJT13-06 at 138 cm. B) Small *Lockeia* from GLCA 99 at 85 cm. C) Bedding plane with relatively high density assemblage of *Diplocraterion* from TJT13-06 at 115 cm. D) Side view of *Diplocraterion* showing protrusive spreite (white arrows) and lacking funnel shaped openings from GLCA 319 at 90 cm. E) *Rhizocorallium* showing protrusive spreite (white arrow) from Ga1351 at 130 cm. F) Polished section showing truncated burrows (black arrows) at an erosion surface (white arrow) and passive infilling by the overlying sediment from Ga1350 FS at 73 cm. G) *Rusophycus* with preserved bioglyphs from Ga1351 at 130 cm. H) *Undichna* from GLCA 319 at 98 cm. I) Small reptile tracks with triangular shaped digits (white arrows) from Ga1406 at 120 cm.
Vertebrate Ichnology

Various traces described as “enigmatic sinuous markings” and illustrated by Lockley et al. (1998, fig. 5) are present at the Farley Canyon locality (Fig. 12H) and are here interpreted as *Undichna* (fish swim traces). The amplitude and wavelength of these traces compare well with examples of *Undichna unisulca* described from the Lower Triassic Jialingjiang Formation of China (Lu et al., 2012). Examples of *Undichna* are known from other swim track sites throughout the Moenkopi Formation (Thomson and Lovelace, 2014).

At a few localities small reptile tracks and scratch traces either co-occur with larger swim tracks on the same surface or are preserved at different horizons within the section. Individual tracks are composed of four, equally-sized, triangular-shaped digits arranged in a hemi-circular pattern (Fig. 12I). Track surfaces often preserve both distinct footprints and elongated footmarks with size dimensions consistent with being produced by the same trackmaker.

Larger swim tracks at these localities exhibit both direct and indirect track features. Direct track features are only produced where the foot is in direct contact with the substrate (skin/sediment interface) whereas indirect track features are deformations due to the transmission of forces through the substrate during track production (Gatesy, 2003). Direct features include fine details such as phalangeal pads, striae, and scale patterns that cannot be recorded on undertracks which are indirect track features.

Direct features can be produced on “undertrack” dig traces like those described by Seilacher (2007) where the foot may punch through the overlying sediment and interact
directly with the potential track recording substrate below. However, the extremely elongate morphology of individual footmarks from the Moenkopi Formation as well as the offset nature of some traceways is evidence that the producer of these traces must have been a buoyant, swimming tetrapod with systematic limb stroke kinematics (McAllister, 1989; McAllister and Kirby, 1998; Thomson, 2011; Thomson and Lovelace, 2014).

Direct track features characteristic of Moenkopi swim tracks include disc-shaped claw marks (Figs. 13A, F) and millimeter-scale striae running parallel to the longitudinal axis of individual footmarks (Figs. 13B, C, E, G). Disc-shaped claw marks are typically preserved on the posterior margins of individual footmarks and are produced as the digits are thrust posteriorly into the substrate during a swim stroke and then removed anteriorly as the animal continues swimming/drifting forward. Striae are interpreted as the result of scaly integument sliding through the substrate and are useful in determining foot motion during track production (*sensu* Gatesy, 2001). Also preserved on swim track surfaces are detailed indirect track features like marginal ridges or sediment displacement rims surrounding individual footmarks (Figs. 13A, B, D, F).
**Figure 13:** Direct and indirect track features. Direct features include disc-shaped claw marks (white arrows) and longitudinal striations. Indirect features included sediment displacement rims (black arrows). A) Ga1350 at 40 cm. B) Em0737 at 200 cm. C) Ga1352 at 70 cm. D) GLCA 319 at 80 cm. E) Ga1406 at 130 cm. F) TJT13-07 at 150 cm. G) Em0737 at 200 cm.
DISCUSSION

Tracks record useful information regarding the type of animal, the way it moves, and the environment it moves through (Baird, 1957; Baird, 1980; Padian and Olsen, 1984; Falkingham, 2014). Falkingham et al. (2011) proposed a ‘Goldilocks’ effect for plastic substrates in which only a narrow range of loads could produce tracks thus imposing a bias on the preserved track record that controlled by the weight of the potential track producing organism. However, this specific type of bias does not apply to swim tracks because the weight of the producer is supported by the water as evidenced by the fact that both large and small organisms were able to produce detailed tracks and traces on the same surface at many localities. But there did exist a number of contributing factors unique to the Early Triassic, similar to the concept of a ‘Goldilocks’ effect, that resulted in the widespread production and well-preserved nature of swim tracks. These factors were 1) delayed ecologic recovery resulting in the lack of well-mixed layers, 2) depositional environments that promoted the production of firmground substrates, and 3) the swimming or bottom walking behavior of reptilian tetrapods (Fig. 14).

The nearly complete lack of bioturbation at swim track sites in the Moenkopi Formation is typical of post-extinction deposits following the end-Permian mass extinction event and contrasts with pre-extinction deposits which contain a much wider diversity of ichnotaxa (Twitchett and Barras, 2004). It has been proposed that during the early Cambrian low levels of bioturbation resulted in the absence of an extensive mixed layer, thereby allowing fine-grained, low water content, firmground substrates to develop
Figure 14: Venn diagram showing the unique combination of factors (ecology, environment, and behavior) in Early Triassic delta systems that resulted in the widespread production and preservation of swim tracks. A) Production and preservation of potential track surfaces but no swim tracks are produced because there are no tetrapod trackmakers capable of aquatic locomotion present. B) Production and preservation of potential track surfaces but no swim tracks are produced because the water may be too deep or the habitat is otherwise unfavorable for the trackmaker. C) Production of swim tracks but they do not preserve details or may not be preserved at all due to biogenic mixing of the substrate. D) Production and preservation of detailed swim tracks and track surfaces when all the right factors are combined.
near the sediment-water interface (Droser et al., 2002; Droser et al., 2004; Jensen et al., 2005). These firmgrounds help to explain the well-preserved and detailed quality of trace fossils during this time (e.g., Droser et al., 2002). Similarly low levels of bioturbation in the Torrey Member must have had a similar effect on promoting the development and maintenance of firmground substrates.

The proliferation of wrinkle structures representing microbial mats on marine flooding surfaces in the Lower Triassic Virgin Member of the Moenkopi Formation indicates that in at least certain marine environments infaunal activity remained low (Pruss et al., 2004; Mata and Bottjer, 2011). Paleoecological studies of benthic marine communities from the Lower Triassic Thaynes Formation and marine units of the Moenkopi Formation (Sinbad and Virgin members) suggest a prolonged recovery period during the Early Triassic following the end-Permian mass extinction event. Both within habitat diversity and between habitat diversity remained low until the late Early Triassic when within habitat diversity began to recover (Hofmann et al., 2013; Hofmann et al., 2014). During the Early Triassic it would be expected that brackish water environments, such as the Torrey Delta, would have been even more depauperate than the still recovering marine benthos. The already low benthic faunal diversity that usually exists under “normal” brackish conditions would have been even further reduced and the resulting extremely low bioturbation levels would have promoted the extensive development and maintenance of firmgrounds in these environments.

Moenkopi swim tracks also provide insight into the substrate mechanics at the time they were produced and the conditions necessary for their preservation. Although
detailed structures on the swim tracks are not considered bioglyphs according to the
definition proposed by Ekdale and de Gibert (2010), they still would have required the
same substrate properties (fine-grained, firm, cohesive) in order to be produced and
maintained through burial.

The study of an exceptionally well-preserved assemblage of vertebrate tracks
from the Upper Miocene Copper Canyon Formation (Scrivner and Bottjer, 1986) showed
that the best impressions were formed in moist, fine-grained sediments. The range in
track morphologies from this formation are suggestive of sediments with varying water
content. Water-saturated sediments, either subaqueous or subaerial, resulted in track
morphologies with well-developed rims but lacking internal detail. Swim tracks from the
Moenkopi Formation, however, do show well-preserved detail. Partial drying of the
sediment was suggested as a method for increasing its cohesiveness and rapid burial as a
method for preservation (Scrivner and Bottjer, 1986). Because the swim tracks from the
Moenkopi Formation were formed under subaqueous conditions the recording substrate
was most likely water-saturated. The absence of mudcracks and the fluvial-deltaic
paleoenvironmental conditions suggest that partial drying of the sediments was probably
uncommon and not a factor in increasing substrate integrity. This means that these
substrates, being subaqueous and saturated, must have been semi-consolidated
firmgrounds with low water content in order to maintain integrity and preserve the
detailed structures and footmark shape (sensu Crimes, 1975).

In addition to describing the contributions of sediment grain size and water
content to potential track production, Laporte and Behrensmeyer (1980) also emphasized
the importance of taphonomy on the preservation potential of Quaternary vertebrate tracks in Kenya. Specifically, they show that increased trampling (bioturbation) by other vertebrates combined with a low burial rate results in completely reworked sediments that obliterate identifiable tracks. Conversely, high burial rates and low degrees of vertebrate bioturbation promote well preserved isolated tracks. Very few track surfaces in the Moenkopi Formation show a high density of swim tracks. Hence, vertebrate bioturbation was low enough for individual footmarks to remain clear and the relatively frequent burial of these surfaces by crevasse splaying events also aided in their ultimate preservation.

Wherever swim tracks and current crescents are preserved together on the same surface their orientations are nearly always subparallel and opposite each other. This suggests that swim tracks were produced when the animal was swimming in an upstream direction (Thomson and Lovelace, 2014), most likely in interdistributary channels. The offset traceways at TJT13-07 (Fig. 3A) and TJT13-08 (Fig. 3B) show footmarks oriented opposite current flow with the traceways following a line about 40 degrees clockwise from the footmark directions. These traceways may be recording the animals’ attempt to cross channels by a “ferrying” method with their bodies angled into the current.

Track localities where no current or flow markers are preserved on the track surface probably represent interdistributary bays. Throughout the Torrey Member are outcrops with sharp contacts between bedding planes that should preserve swim tracks but none were found. Either the surface was not exposed long enough to allow track production or they may represent bay areas too deep for the swimming reptiles to reach.
the bottom and produce footmarks. Most modern interdistributary bays are shallow-water bodies which average 4 meters in depth (Coleman and Prior, 1982). Swim tracks preserved in bay deposits suggest a shallower water depth of about 1 to 2 meters.

Random footmarks that do not form recognizable traceways most likely represent bottom-walking behaviors similar to those observed in modern hippopotami where the body weight is supported by water permitting a range of locomotive styles (Coughlin and Fish, 2009). The preservation of subaqueous traceways and footmarks in the fossil record exhibiting these behaviors has recently been recognized in an assemblage of hippopotamus footmarks from Africa (Bennett et al., 2014).

The Torrey Delta and its associated paleoenvironments were favorable habitats for reptiles capable of functional aquatic locomotion with the firmgrounds providing the ideal medium for their swim tracks. These firmgrounds were widely developed and maintained due to the lack of bioturbation in brackish water environments exacerbated by delayed biotic recovery following the end-Permian mass extinction. Periodic flooding of the delta supplied coarser-grained material in the form of channel fills and crevasse splays thereby casting the swim tracks at sharp, heterolithic boundaries and enhancing their preservation.

Thus a unique combination of factors in Early Triassic delta systems (delayed ecologic recovery, depositional environments, and tetrapod swimming behavior) resulted in the production and preservation of swim tracks (Fig. 14). Although swim tracks are not uncommon throughout the rest of the Mesozoic (e.g., McAllister, 1989; Milner et al., 2006; Xing et al., 2013) and Cenozoic (e.g., McCrea et al., 2004; Bennett et al., 2014)
these occurrences are still localized in contrast to widespread and abundant like swim
tracks in the Moenkopi Formation. This suggests that it is not the swimming behavior
itself but the prevalence of unbioturbated substrates resulting from the unique
combination of ecological and environmental conditions during the Early Triassic that led
to the production and preservation of swim tracks in the Moenkopi Formation.

CONCLUSIONS

The presence of reptilian tetrapods capable of functional aquatic locomotion in
western North America during the Early/Middle Triassic is demonstrated by the
widespread occurrences of footmarks displaying diagnostic characteristics of production
under subaqueous conditions (Thomson and Lovelace, 2014). The exceptional detail of
sedimentary structures and footmarks preserved on swim track surfaces at these localities
are evidence of a very cohesive yet still impressionable substrate at the time of track
production. Analysis of the stratigraphy, sedimentology, and ichnology of swim track
localities supports previous interpretations that the Torrey Member of the Moenkopi
Formation was deposited as a large delta complex (Torrey Delta) with swim tracks being
produced in interdistributary channels and bays.

The stratigraphy at swim track localities is characterized by overall coarsening-
upward, heterolithic bedding with sharp bedding contacts. Rhythmic cycles of
interbedded and rippled silt- and mudstone below the track horizons is indicative of tidal-
fluvial environments and the coarser-grained, massive or cross-bedded sandstones
represent crevasse splays and channel fills. The low diversity, relatively diminutive size,
and locally abundant nature of the trace fossils at many localities reflect typical biotic
activity under brackish water conditions. This depauperate environment was exacerbated by delayed biotic recovery following the end-Permian extinction. This resulted in trivial levels of bioturbation in the Torrey Delta and the widespread development of unmixed, firmgrounds at or near the sediment/water interface. Firmgrounds provided the substrate conditions necessary for the production and exceptionally detailed preservation of tetrapod swim tracks.

Early to Middle Triassic reptiles either preferred or frequently traveled through Torrey Delta habitats, swimming across bays and channels and producing swim tracks. Periodic flooding of the delta transported coarser material and resulted in crevasse splaying can channel fills casting the swim tracks on heterolithic bedding planes. The frequently occurring intersection of specific behavioral, environmental, and taphonomic factors in the Torrey Delta resulted in the abundant and widespread preservation of well-preserved swim tracks throughout central and southern Utah.
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