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# TRANSGRESSIVE EROSION EXPRESSED AS A *GLOSSIFUNGITES*-BEARING WOODGROUND: AN EXAMPLE FROM THE BLACKHAWK FORMATION, UTAH

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ABSTRACT: Horizontal and inclined U-shaped trace fossils are commonly associated with the *Cruziana* and *Glossifungites* ichnofacies, but have rarely been described as a component of the *Teredolites* ichnofacies (xylic substrates). This study provides several examples of morphologies of *Glossifungites saxicava* from the Campanian Sunnyside Coal (Blackhawk Formation) that exhibit both xenoglyphs and bioglyphs. *Glossifungites* along this surface are locally present as compound ?*Thalassinoides suevicus-Glossifungites*, which may represent a combination of commensalism, an exploited structural weakness, refugium from predators, and/or a secondary behavior of the presumed crustacean tracemakers. The trace-fossil assemblage also contains *Teredolites clavatus* and *Teredolites longissimus* and *Radichnus* isp. locally. Stratigraphically, this trace assemblage is important because it marks a marine flooding surface/transgressive surface of erosion between the Sunnyside and Grassy members of the Blackhawk Formation.

## INTRODUCTION

Horizontally oriented U-shaped trace fossils (*Rhizocorallium* and *Glossifungites*) are frequently described in terms of ichnotaxonomy and relationship to the *Cruziana* and *Glossifungites* ichnofacies (see thorough summary in Knaust 2013). Where they occur in firmgrounds, these passively filled U- or tongue-shaped trace fossils generally have been classified as *Rhizocorallium jenense* (e.g., Knaust 2013), although Belaústegui et al. (2016), recognizing the absence of a true spreite, proposed reclassification as *Glossifungites saxicava*, a proposal endorsed herein.

Despite its distinct appearance and abundance in the geologic record, Glossifungites saxicava (i.e., Rhizocorallium jenense sensu Knaust 2013) is rarely described from xylic substrates. This is puzzling because bioeroded and bioturbated xylic substrates (Teredolites ichnofacies) and Glossifungites are both commonly associated with transgressive erosion and subsequent marine flooding (Pemberton and Frey 1985; MacEachern et al. 1992; Pemberton et al. 1992; Nouidar and Chellaï 2002; Rodríguez-Tovar et al. 2007; Savrda et al. 2016). Horizontal U-shaped burrows in a transgressed Miocene coal were described by Vitális (1961), and MacEachern et al. (2010) briefly mentioned similar structures in the Teredolites ichnofacies. The record of passively filled U- or tongue-shaped ichnotaxon in xylic substrates is otherwise sparse. Xylic firmground refers to the nature of the "woodground" (sensu Bromley et al. 1984) in that it represents firm substrates comprised of vegetable particulate. Such firmground substrates that include preserved activity of burrowers (e.g., Thalassinoides or Glossifungites) likely represent a softer end of the woodground spectrum than those dominated by boring activity (e.g., Teredolites).

Here we describe the morphology of *Glossifungites saxicava* from an area with well-established stratigraphy linking the depositional surface to drastic relative sea-level change. Additionally, we describe the xylic firmground trace assemblage, and examine the compound and complex

trace fossil associations between horizontal U-shaped trace fossils and other ichnofossils.

#### GEOLOGIC BACKGROUND

The trace fossils discussed herein are located in the Campanian Blackhawk Formation at the top of the Sunnyside Member, in the Sunnyside Coal (Fig. 1A). The Sunnyside Coal is the most laterally extensive coal in the Blackhawk Formation, marking the change from aggradational to progradational stacking patterns (Bohacs and Suter 1997). In the Beckwith Plateau area (above Sunnyside Parasequence 3), the Sunnyside Coal was initially formed as a large raised mire, but later peat formed on the uneroded remnants of incised valley interfluves as sea-level rose, before drowning and subsequent progradation of the Grassy Member (Grassy Parasequence 1; Davies et al. 2006). This upper portion of the Sunnyside Member contains both a sequence boundary and a transgressive surface (Fig. 1B). However, the sequence boundary is interpreted to occur within the coal, whereas the marine flooding surface and the transgressive surface of erosion is at the top of the coal (Davies et al. 2006) where the trace fossils reported in this study occur.

The sandstone of the Grassy Member directly overlies the coal in the study area (Fig. 2), and contains swaley and hummocky cross-stratification with *Ophiomorpha* isp. and *Thalassinoides* isp. (Fig. 3A) that grades upwards into low-angle bedding and trough cross-bedding. Hummocky and swaley cross-stratification are typical of modern open water conditions above storm wave base (Hunter and Clifton 1982; Dumas and Arnott 2006), as can be seen in the distal shoreface deposits of the Blackhawk (Kamola and Van Wagoner 1995). The base of the sandstone is similar to facies described from the Grassy Member as middle shoreface environments (O'Byrne and Flint 1995), whereas the top conforms to the sedimentological descriptions of upper shoreface/ barrier island.



FIG. 1.—Lithostratigraphy and sequence stratigraphy of the study area. **A**) Lithostratigraphy in the study area modified from the East of Woodside and Price River sections of Balsley (1982). Ages are taken from stratigraphic chart of Howell and Flint (2003). The star indicates the top of the Sunnyside Coal where the *Glossifungites* trace fossils are found. **B**) Parasequences and stratigraphic relationships in the Grassy and Sunnyside members (modified from Howell and Flint 2003). The Sunnyside Coal sits on top of the highest Sunnyside parasequence (S3), with the *Glossifungites* surface marking the transgressive surface of erosion over the Upper Sunnyside Sequence Boundary.

# TRACE-FOSSIL DESCRIPTIONS

# **Overview of Suite/Assemblage**

The basal surface of the sandstone contains abundant hyporeliefs that subtend into the coal (Fig. 3A–3D). Small (< 1 cm) *Teredolites clavatus* is the most abundant ichnofossil associated with this surface (Fig. 3C–3D). A moderate number of *Glossifungites saxicava* of various morphologies and sizes is also present (Fig. 3B–3D). *?Thalassinoides suevicus* (Fig. 3B–3D), *Radichnus* isp. (Fig. 3C), and *Teredolites longissimus* (Fig. 3B) comprise lesser components along this surface.

# Description of Glossifungites saxicava

The shape and size of *Glossifungites saxicava* along this surface are highly variable. Specimens may be short, having little development of the

"limbs" of the trace (Fig. 3B, 3C), or may have an elongate shape due to long limbs (Fig. 3C). The limbs vary between parallel to highly asymmetrical (quasi spiral-shaped) (Fig. 3C, 3D). Where originating from a *?Thalassinoides suevicus*, the *Glossifungites* limbs meet, creating a dominantly horizontal U-form. The diameters of the limbs of the specimens described here (e.g., North Carolina Museum of Natural History specimens: NCSM 11710-11711 and uncatalogued examples) range from 1.1–2.7 cm. However, they may narrow towards the aperture to 0.48 cm in extreme cases.

The fill is rather homogeneous. There are two types of external ornamentation noted on the *Glossifungites* specimens: linear features parallel to bedding (Fig. 3E) and cross-cutting linear features (Fig. 3F). *Glossifungites* is the only trace fossil that occurs with *?Thalassinoides suevicus* as a compound trace fossil along this surface.



FIG. 2.—Measured section for the study location in the northwestern portion of the Beckwith Plateau (star on map). Map modified from O'Byrne and Flint (1995). The traces lie along the contact of the Sunnyside Coal and the Grassy Member. The Grassy Member here is a sandstone containing swaley and hummocky cross-stratification with *Ophiomorpha* and *Thalassinoides* that transition upwards to low angle bedforms topped by trough cross-bedding.

The morphologies of *Glossifungites* in this study are consistent with the emended description of *Rhizocorallium jenense* by Knaust (2013). Although the overall planiform shape of the specimens in our study is often more like that of the auriform variety of *R. commune*, our *Glossifungites* specimens are similar to *R. jenense* (cf. Knaust 2013) in that the trace fossils are passively filled and locally display faint, closely spaced, net-like scratches. Recent ichnotaxonomic revision infers these passively filled, scratch marked trace fossils are more properly named *Glossifungites saxicava* (Belaústegui et al. 2016).

## Description of Radichnus isp.

*Radichnus* isp. in this study is represented by a series of horizontal indentations (positive hyporelief) on the base of the sandstone that are individually up to a few centimeters long, generally 2–3 mm wide, and taper toward both ends. Swaths of indentations can be up to  $8.5 \times 7.5$  cm in size, and may be larger and more persistent, yet are obscured by the cross-cutting of other trace fossils. These trace fossils are in-line with the basal surface of the sandstone and are less than a four millimeters deep.

# **Description of ?**Thalassinoides suevicus

*?Thalassinoides suevicus* is present as dominantly horizontal, 1–2 cm wide, branching trace fossils with ovate cross-sections that can exceed 20 cm in length. Branching is dominantly Y-shaped, with a few T-shaped exceptions (Fig. 3A–3D). The trace fossil walls are unlined and weather relatively smoothly with the exception of some longitudinally directed linear ridges. Tunnels may terminate into a U-shaped *Glossifungites* structure. The authors chose to refer to these traces as the dominantly horizontally oriented *Thalassinoides suevicus* (e.g., Kamola 1984; Pemberton and Frey 1984; Myrow 1995), however, the assignment is in question, as discussed below, if the longitudinal-directed linear ridges are actually bioglyphs which would necessitate naming these traces *Spongeliomorpha* isp.

# Description of Teredolites clavatus and Teredolites logissiumus

*Teredolites* isp. occur as two forms along the surface: (1) as an abundant round-to-ovate plan-view 0.9-1.8 cm trace fossil less than 1 cm deep (Fig. 3C, 3D); and (2) as rare clusters of 0.5 cm wide, less than



FIG. 3.—*Glossifungites* burrows and associated traces. **A**) *Glossifungites* at the top of the Sunnyside Coal (blue arrow), overlain by swaley cross-stratified, *Ophiomorpha*bearing sandstone of the Grassy Member. **B**) *Glossifungites* as short limb toponomic expressions (Gs) and as a circular form (Gc) at the termination of a *?Thalassinoides suevicus* (Th), with *Teredolites longissimus* (Tl). **C**) Base of sandstone with *Radichnus* isp. (Rd) (purple arrows = scratches), *Teredolites clavatus* (Tc), *?Thalassinoides suevicus* (red arrows = linear features that are possibly xenoglyphs), and *Glossifungites* with various morphologies such as elongate symmetrical (Gh) and short limbs (Gs). **D**) Other examples of previously mentioned trace morphologies and auriform varieties of *Glossifungites* (Ga). **E**) *Glossifungites* with xenoglyphs (red arrows). **F**) Distal, medial portion of the base of the outer *Glossifungites* tube showing net-like scratches (green arrows). Solid colors in scale bars each represent one centimeter vertically.

4 cm long, slightly undulating horizontal structures (Fig. 3B). The round to ovate plan-view structures are referred to *Teredolites clavatus*, although the shallow nature of the trace fossils does not allow differentiation of the tapered club shape that is typically associated with *Teredolites* (e.g., Bromley et al. 1984). Some of the ovate

representations of *T. clavatus* may be shallowly emplaced distal portions of *Glossifungites/Diplocraterion* (Fig. 3D); however, the shallow preservation precludes potential identification of the diagnostic U-shape. The horizontal clusters are referable to *Teredolites longissimus* (e.g., Kelly and Bromley 1984).

#### DISCUSSION

# Substrate Influence on Burrow Toponomy

The xylic substrate imparts a different toponomy on Glossifungites due to a higher coal compaction ratio (e.g., Sheldon and Retallack 2001) than that of mudstone. More specifically, these trace fossils are more shallowly inclined, and possess a widened plan view compared to more familiar Rhizocorallium morphologies preserved in mudstone. Horizontal widening due to compaction has been noted by Crimes (1975) and is dependent on the substrate. Additionally, trace ornamentation in xylic substrates is different than in mud substrates due to grain size and shape differences. This substrate-dependent ornamentation of the trace fossils is present in the form of xenoglyphs (Bromley et al. 1984) and probably partly explains why bioglyphs are so faint or poorly preserved throughout: the xenoglyphs are pervasive and they make it much more difficult to observe the bioglyphs. Additionally this applies to the ?Thalassinoides suevicus in which the horizontal xenoglyphs make it difficult to recognize the requisite bioglyphs that definitively distinguish the ichnogenus Spongeliomorpha. In this instance, the xenoglyphs and bioglyphs share a similar orientation.

# Interrelationship between Thalassinoides and Rhizocorallium/ Glossifungites

Examples of both *Rhizocorallium* and *Thalassinoides* interconnected with disparate ichnotaxa have been documented in the rock record (e.g., *Thalassinoides-Phycodes*: Miller 2001; *Rhizocorallium-Ophiomorpha*: Seilacher 2007). Such interconnections are caused either by a single organism initiating different behaviors in the same burrow system (compound ichnofossil) or by later burrows adjoining pre-existing burrows (composite ichnofossil) (Pickerill 1994). Whereas some *Glossifungites* clearly cross-cut the *?Thalassinoides suevicus* in the study area (Fig. 3C, left of photo), other *Glossifungites* on this surface are round forms (Fig. 3B,3D) that appear to initiate at the termini of *?Thalassinoides suevicus*, and several are more ambiguous in nature.

Three possible scenarios dominate the origin of these *Glossifungites*: (1) the biogenic sedimentary structures were produced in response to a change in behavior of the same organisms (presumably crustaceans); (2) they record contemporaneous behaviors of two different organisms (commensalism); or (3) previously formed *?Thalassinoides suevicus* provided a nucleus for burrow initiation by the *Glossifungites* tracemaker (substrate exploitation or protected refuge).

**Crustaceans Behaviors.**—*Thalassinoides, Spongeliomorpha*, and *Rhizocorallium/Glossifungites* all have been linked to crustacean tracemakers (Fürsich 1973). The similarities in burrow and outer tube size between the *?Thalassinoides suevicus* and *Glossifungites* may suggest the same large tracemaker. Moreover, Knaust (2013) suggested that *Radichnus*-like traces may represent a different behavior exhibited by the same tracemaker of *Rhizocorallium (Glossifungites sensu* Belaústegui et al. 2016), or shallow preservation of *Rhizocorallium (ibid)*, which could be an alternative interpretation for trace fossil presented herein. Allington-Jones et al. (2010) inferred that *Radichnus* isp. is a shallow scratch-mark pattern produced by crustaceans (e.g., crabs; Frey et al. 1984) when deposit feeding using their cheliped (e.g., Miller 1961).

**Commensalism.**—Commensalism or macrosymbiosis has been identified by Nara et al. (2008) in Pleistocene *Cryptomya*-lined (bivalve) crustacean burrows (*Psilonichnus*) by comparison to the use by modern *Cryptomya* of thalassinid shrimp burrows. The authors noted that modern *Cryptomya* burrow into the subsurface walls of the shrimp burrows for a protected (from environmental stresses and predation) sediment-water interface for waste expulsion and food/oxygen intake. This allows the *Cryptomya* to benefit from the resource influx provided by the crustacean's work to pass nutrient rich water through the burrow and waste out of it. Nara et al. (2008) suggested that this relationship might be a form of mild parasitism (not bodily) because it appears that the *Cryptomya* greatly decrease the amount of suspended particles (food resources) passed into the burrow. Therefore, such relationships might not truly be commensalism or macrosymbiotic since only one organism is benefiting from the relationship. Regardless of whether it is commensal or parasitic, the combination of burrows still represents an organismal association mediated by a favorable interaction.

Many modern organisms have shown such behaviors: *Montacuta elevata* on *Clymenella torquata* burrows (Gage 1968), *Scalibregma inflatum* or *Notomastus latericeus* on *Echiurus echiurus* burrows (Reineck et al. 1967), *Maera loveni* on *Nephrops norvegicus* burrows (Atkinson et al. 1982). Bromley (1996) provides an extensive list of symbiotic examples (burrow inhabiting and burrow compositing), many of which involve crustacean burrows. Gingras et al. (2002) also illustrated modern examples of nucleation of burrows by other organisms (*Nereis, Heteromastus*, and *Mya arenaria*) off of crustacean (crab) burrows.

**Burrow Initiation Nucleus.**—Preexisting ?*Thalassinoides suevicus* may have provided an easier access point to the sediment, or provided refuge from predators for the *Glossifungites*-producing organism. *Glossifungites/Rhizocorallium*-like morphologies have been noted in both modern and ancient traces with their aperture positioned at structurally weak sedimentological contacts (Triassic desiccation cracks: Knaust 2013; reusing *Rhizocorallium* tubes for burrow entrance: Seilacher 2007; horizontal fracture planes in modern peaty-clay firmground: Hodgson et al. 2015). Alternatively, burrows can provide a refuge from shallow infaunal and epifaunal predators as reported by de Gilbert et al. (2006) who observed (Pleistocene) vermiform trace fossils (*Cylindrichnus helix*) attached to crustacean trace fossils (*Ophiomorpha nodosa*).

#### **Depositional Environment**

The occurrence of *Thalassinoides*, *Teredolites*, and *Glossifungites* together in the xylic substrate of the study area is consistent with shallow water to littoral nearly fully marine conditions in the depositional environment (MacEachern et al. 2010). *Radichnus* isp. is associated with shallow or oft emergent marine conditions (e.g., back barrier; Allington-Jones et al. 2010). However, in this case, it more likely reflects the presence of a firm substrate in a marine setting due to erosion.

*Thalassinoides suevicus* has been described, in high abundance, at the top of coals along erosional boundaries with channels and potentially upper shoreface deposits in the Blackhawk Formation (Spring Canyon Member; Kamola 1984). These tidally influenced channels are likely marine influenced within the penetrative range of the salt wedge (Kamola and Van Wagoner 1995). Similarly, high abundances of *Teredolites clavatus* have been noted in the top of coal lying beneath the erosional contacts of Upper Cretaceous tidal channels or tidal inlets (Bromley et al. 1984). *Teredolites and Thalassinoides* in the current study site occur only in low-moderate abundances.

# Comparison to Glossifungites Ichnofacies Occurrences

Pemberton et al. (1992) described a similar assemblage of trace fossils (*Thalassinoides* and *Rhizocorallium*) from a *Glossifungites* ichnofacies observed in the Blackhawk Formation; *Thalassinoides* was the dominant trace fossil in their study. The *Thalassinoides* of Pemberton et al. (1992) are more similar to the vertical *T. paradoxicus*, whereas the burrows in the current study are dominantly horizontal constituents like those of *T. suevicus*. It is likely that *Thalassinoides paradoxicus* was generally formed in firm substrates to prevent burrow collapse of the vertical shafts, whereas the creation of *T. suevicus* may not need such substrate requirements

(Myrow 1995). *Thalassinoides suevicus* is observed in coals of the Blackhawk (Kamola 1984) and the difference may reflect differences in excavation or circulation related to a xylic versus fine cohesive substrate. Notably, both the *Glossifungites* surface from Pemberton et al. (1992) in the Blackhawk and the *Teredolites* surface in this study mark parasequence set boundaries.

Short, oblique Rhizocorallium commonly mark omission surfaces with traces linked to other scavengers or suspension feeders such as Thalassinoides and Diplocraterion (Fürsich 1974). Belaústegui et al. (2016) documented a Glossifungites ichnofacies omission surface in marl with a similar trace fossil assemblage (Glossifungites saxicava, Spongeliomorpha iberica, and Gastrochaenolites ornatus) to the surface described herein. Fan-shaped Rhizocorallium was described associated with wave and tidal erosion surfaces in modern expressions of the Glossifungites ichnofacies by Pemberton and Frey (1985). The modern expression of Rhizocorallium in firmground assemblages, however, appears to be produced by smaller tracemakers (spionid polychaetes; Hodgson et al. 2015) compared to those responsible for the Glossifungites/Rhizocorallium in the Blackhawk Formation. The assemblage in this study is a Teredolites ichnofacies owing to the xylic substrate, but shares a similar low diversity, high abundance ichnofauna typically associated with the Glossifungites ichnofacies of Frey and Pemberton (1984) and Gingras et al. (2001). Additionally, in agreement with the Teredolites ichnofacies, is the preponderance of suspension feeders and crustaceans leaving their burrows to feed (indicated by Radichnus isp. in our study).

As currently defined, the *Teredolites* ichnofacies encompasses all woody substrates. However, it should be noted that there are likely differences between softer xylic firmground substrates with burrowers (e.g., reflected by *Thalassinoides, Glossifungites*) and substrates dominated by borers (e.g., reflected by *Teredolites*). Future researchers should focus on whether the firmness of xylic substrate is a function of shallow burial compaction, state of wood decomposition, or the nature of the plant composition in the substrate.

In the woodground described herein, there is a mixture of *Teredolites* borings and *Glossifungites/Thalassinoides* burrows suggesting a significant contribution by small woody particles to allow burrow excavation, with a mixture of larger wood clasts for boring as indicated by *T. longissimus*. While *T. clavatus* is present along this surface, these trace fossils are much reduced in depth in comparison to the monospecific assemblages as seen in Bromley et al. (1984), which may also be relevant to the condition of the substrate. The ichnological expression of a woodground is dictated by the spatial distribution of wood particulate and wood clast size, and may represent distributional variations as observed in modern substrates (e.g., Gingras et al. 2004) rather than the time averaging of evolving xylic substrate conditions.

#### CONCLUSIONS

This study describes the rarely reported styles of burrowing in xylic substrates reflected by the trace fossil morphologies of *Glossifungites* and *Radichnus* isp. The *Glossifungites* in this study area are occasionally part of a novel compound ?*Thalassinoides suevicus -Glossifungites* system that may represent commensalism, burrow excavation tactics, refugium necessities, or varying behavior of crustaceans. This *Teredolites* ichnofacies surface is similar to surfaces characterized by the *Glossifungites* ichnofacies in that it represents a firm substrate produced by transgressive erosion and subsequent flooded by marine conditions. In the Blackhawk Formation, both of these ichnofacies may contain *Glossifungites* and *Thalassinoides*. The *Glossifungites* ichnofacies, however, is expressed by a higher abundance of *Thalassinoides* with a larger percentage of vertical components (i.e., *T. paradoxicus*).

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