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Ichnofacies of an Ancient Erg: A Climatically Influenced Trace Fossil Association in the Jurassic Navajo Sandstone, Southern Utah, USA

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SUMMARY: Arid eolian environments usually exhibit a paucity of organism traces, but some eolianite facies in the geologic record contain a great abundance of trace fossils, which characterize a distinctive ichnofacies, herein termed the *Entradichnus* Ichnofacies. This arid landscape ichnofacies is exemplified by a locally dense and diverse invertebrate trace fossil assemblage, which is preserved in the Navajo Sandstone, a Jurassic eolianite exposed in the Paria Canyons Primitive Area in southern Utah. The trace fossils (*Planolites*, *Palaeophycus*, *Skolithos*, *Arenicolites*, *Entradichnus*, *Taenidium* and *Digitichnus*) all appear to be the products of shallow burrowing by desert-dwelling arthropods, such as beetles and other insects, that kept pace with the dune migration. The paleoclimate was monsoonal, characterized by rainy summers and windy (but relatively dry) winters. The burrowed beds were produced during long-lived pluvial intervals that brought higher than usual amounts of moisture to the Navajo dune fields. Most of the sand in the Navajo at the study site was deposited as dry grain flows during the winter months, and the only possibility of rainfall or dew precipitation came during the summer months. Nevertheless, the burrowers apparently were active year-round and exploited resources within both dry and damp sand.

INTRODUCTION

It is widely understood that the most important practical applications of ichnology are in the area of paleoenvironmental interpretation. The analysis of trace fossils and trace fossil associations provides powerful tools for interpreting the bathymetry, salinity, oxygen concentration, hydrodynamic energy and substrate consistency in subaqueous settings (Seilacher, 1964, 1967a; Ekdale et al., 1984; Frey and Pemberton, 1984; Ekdale, 1988; Pemberton et al., 1992, 2001; Bromley, 1996; McIlroy, 2004) and for interpreting substrate character and soil formation in subaerial settings (Retallack, 1984, 2001; Donovan, 1994; Buatois et al., 1998; Genise et al., 2000).

Paleoclimatology is a major interest in historical geology, yet paleoclimatologic applications of ichnology have received only limited attention (Bown and Laza, 1990; Hasiotis and Dubiel, 1994; Genise, 1997; Genise et al., 2000; Retallack, 2001). The eolian realm, especially ancient erg settings (inland sand seas), offers significant promise for using trace fossils to assist in interpreting paleoclimatic conditions (Loope and Rowe, 2003).

Eolian facies in the geologic record typically are depauperate—and often entirely devoid—of trace fossils. Although a plethora of organism traces may

be observed quite commonly in modern sand dunes, only rarely are trace fossils seen in ancient eolianites. The reason for this apparent discrepancy may lie at least partly in the sedimentology of sand dunes. An eolian dune usually has a gently, sloping windward side (the stoss), which is erosional, and a more steeply dipping leeward side (the foreset or slip face), which is depositional. This dual character of a sand dune as both an erosional and depositional environment is what allows the dune to move forward in accordance with the predominant wind direction. However, the situation is different for echo dunes, which are built-up against a cliff, because deflation erosion is much reduced, and the preservation potential for trace fossils is correspondingly raised (Fornós et al., 2002).

The vast majority of organism traces observed in the loose sand of modern dunes are seen on the erosional stoss side of the dune, and thus they are rarely preserved in the ancient record. There often seems to be more animal life on the stoss side, apparently because of its lower dip angle, broader surface area and more abundant vegetation. As can be observed in modern dunes, traces also do occur on the depositional slip face of the dunes, where they may be deformed by caving and slumping of the loose sand on the more steeply dipping slope.

Many of the trace fossils recorded in ancient eolian systems occur in subaqueous (or at least moist) interdune facies rather than in the subaerial dunes themselves (Hanley and Steidtmann, 1973; Ahlbrandt et al., 1978; Gradzinski and Uchman, 1994; Buatois et al., 1998; Smith and Mason, 1998). Nevertheless, well-preserved trace fossils have been described in the foreset cross-strata of ancient dunes in a number of inland erg settings (McKee, 1944; Brady, 1947; Hanley et al., 1971; Walker and Harms, 1972; Picard, 1977; Ekdale and Picard, 1985; Sadler, 1993; Braddy, 1995; Loope and Rowe, 2003).
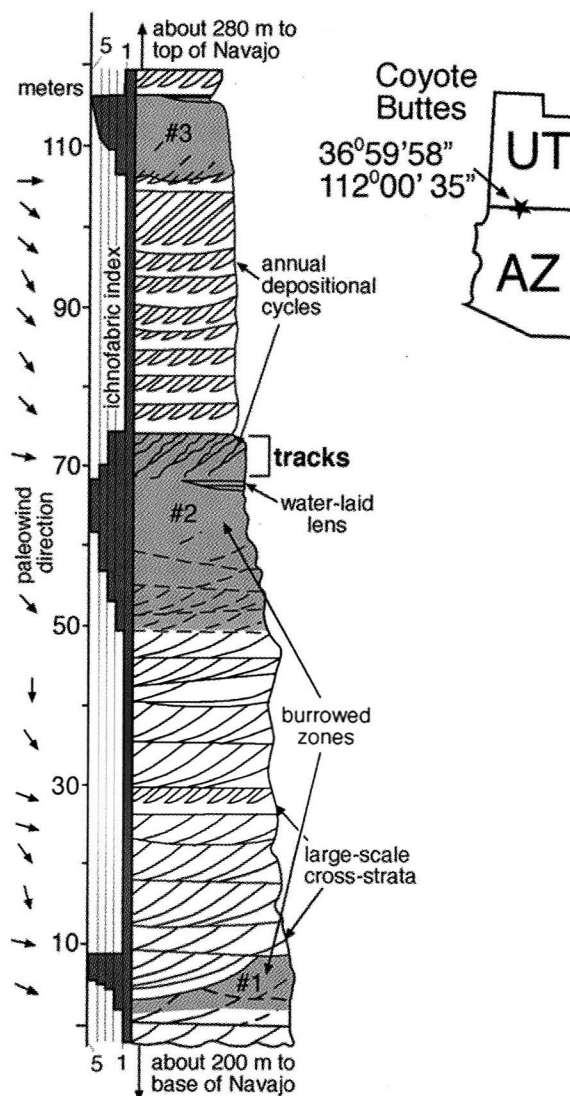

FIGURE 35.1 Idealized column of the studied portion of the eolian Navajo Sandstone (Lower Jurassic) and location map of the primary study area at Coyote Buttes, Kane County, southern Utah (modified from Loope, 2006, Fig. 1).

GEOLOGIC SETTING

The Jurassic Navajo Sandstone was deposited as enormous eolian dunes (probably mainly transverse dunes) in an immense erg in the arid continental interior of the western United States (Kocurek and Dott, 1983; Blakey, 1994; Loope et al., 2004). With a stratigraphic thickness reaching 0.75 km and an areal extent of more than 0.33 million km², the Navajo Sandstone is one of the thickest and most extensive stratigraphic units in North America. Although clear-cut biostratigraphic indicators are few, the Navajo

Sandstone generally is regarded as Early Jurassic in age (Peterson and Pipiringos, 1979).

The massive Navajo Sandstone is a familiar sight to geologists and tourists alike, as it forms the spectacular 'White Cliffs' in some of America's most famous and scenic national park lands, including Zion, Capitol Reef, and Canyonlands National Parks, Dinosaur, Grand Staircase-Escalante and Rainbow Bridge National Monuments, Glen National Recreation Area and Paria Canyons Primitive Area. This study focuses on the North Coyote Buttes section of the Paria Canyons Primitive Area along the Utah–Arizona border in Kane County, Utah, where

the Navajo Sandstone is exceptionally well exposed (Fig. 35.1; see also Loope et al., 2001; Loope and Rowe, 2003).

ORGANISM TRACES IN DUNES

Despite the meager record of eolian trace fossils in general, it is clear that many organisms indeed live in dune fields. Even though standing water and vegetative cover may be sparse, a surprisingly large diversity of invertebrates and vertebrates is known to inhabit dune fields all over the world today (Cloudsley–Thompson and Chadwick, 1964; Crawford, 1981, 1986, 1991; Louw and Seely, 1982; Wallwork, 1982; Cloudsley-Thompson, 1991; Costa, 1995).

As mentioned earlier, it is mainly those traces on the depositional side of dunes that are preserved in the fossil record. The traces may be seen in the avalanching slip face as well as in the plinth at the base of the slip face, where wind ripple strata accumulate. Although the eolian trace fossil record is extremely sparse and highly localized, trace fossils in eolianites may be locally abundant and diverse (White and Curran, 1988; Curran and White, 1991, 2001; Curran, 1994; Phelps, 2002). Surface tracks and trails are rarely preserved, so eolian trace fossils are mainly shallow burrows of invertebrates and undertracks of vertebrates.

For effective preservation of traces, the dune sand needs to be slightly moist, i.e., neither totally dry nor totally saturated with water (McKee, 1947; Sadler, 1993; Fornós et al., 2002; Phelps, 2002). This obviously was the case for the Navajo Sandstone trace fossils described in this chapter. As observed in modern dunes, unlined traces that were created in loose, dry sand could not have persisted without collapsing and crumbling when succeeding sediment layers were deposited by the action of the desert winds. Most of the Navajo Sandstone trace fossils are sharply defined and show little evidence of caving-in under totally dry conditions or of slurrying in water-saturated conditions, and there is little evidence to suggest that the burrows remained open for some time. Thus, it appears that the sand was damp (but not soaked) when the burrows were created. Some of the burrows exhibit meniscate backfill that must have been produced as the animal moved through the sediment, and other burrows contain structureless fill that may have been passive.

TRACE FOSSILS

Locally abundant invertebrate trace fossils at Coyote Buttes were preserved in the eolian cross-strata of Navajo Sandstone. They include the following ichnotaxa (listed here in approximate order of abundance): *Planolites beverleyensis, Palaeophycus tubularis, Skolithos linearis, Arenicolites* (two ichnospecies), *Entradichnus meniscus, Taenidium serpentinum,* and *Digitichnus laminatus.*

Planolites beverleyensis—The most abundant burrows are simple, unlined, unbranched, non-meniscate, horizontal burrows that often occur in very dense patches with numerous cross-overs (Fig. 35.2). In most cases, there is no regular geometric pattern to the courses of the trails, which appear like random scribbles on the bedding plane (*sensu* Seilacher, 1967b). The burrow fill is similar to but slightly darker than the surrounding sediment. Dimensions: tunnel diameter is 5 mm.

Palaeophycus tubularis—Thinly walled burrows, oriented parallel to subparallel to the slipface, are evident at several sites, where the dark-colored linings render them quite visible (Fig. 35.3). The burrow fill is the same as the surrounding sediment. They exhibit approximately the same size range and geometric aspect of the associated *Planolites*, which are unwalled, so it is possible that the *Paleophycus* and *Planolites* were made by the same organisms behaving in different ways. However, the reason why the organism lined its burrow in one place and not in another is unclear. Dimensions: tunnel diameter is 5 mm.

Skolithos linearis—Short, unlined, vertical shafts are common at all sites. They are oriented more or less perpendicularly to the dipping foreset laminae, and thus they occur at an angle to the horizon. Because the burrow fill is the same as the surrounding sediment, and the burrow margins are somewhat indistinct, these shafts often are only faintly visible in vertical section. *Cylindricum*, an ichnogenus that is sometimes applied to short vertical burrows, is regarded here as a junior synonym of *Skolithos*. Dimensions: shaft diameter is variable and averages about 5 mm; shaft length is up to 3 cm.

Arenicolites ispp.—Paired burrow openings commonly were observed in plan view, and 'U' burrows with two shafts were observed in vertical section in a few instances. A faint protrusive spreiten structure was observed in some specimens in the field, but a clear spreite could not be documented with certainty, so these 'U' burrows are assigned provisionally to *Arenicolites*. Two ichnospecies may be differentiated
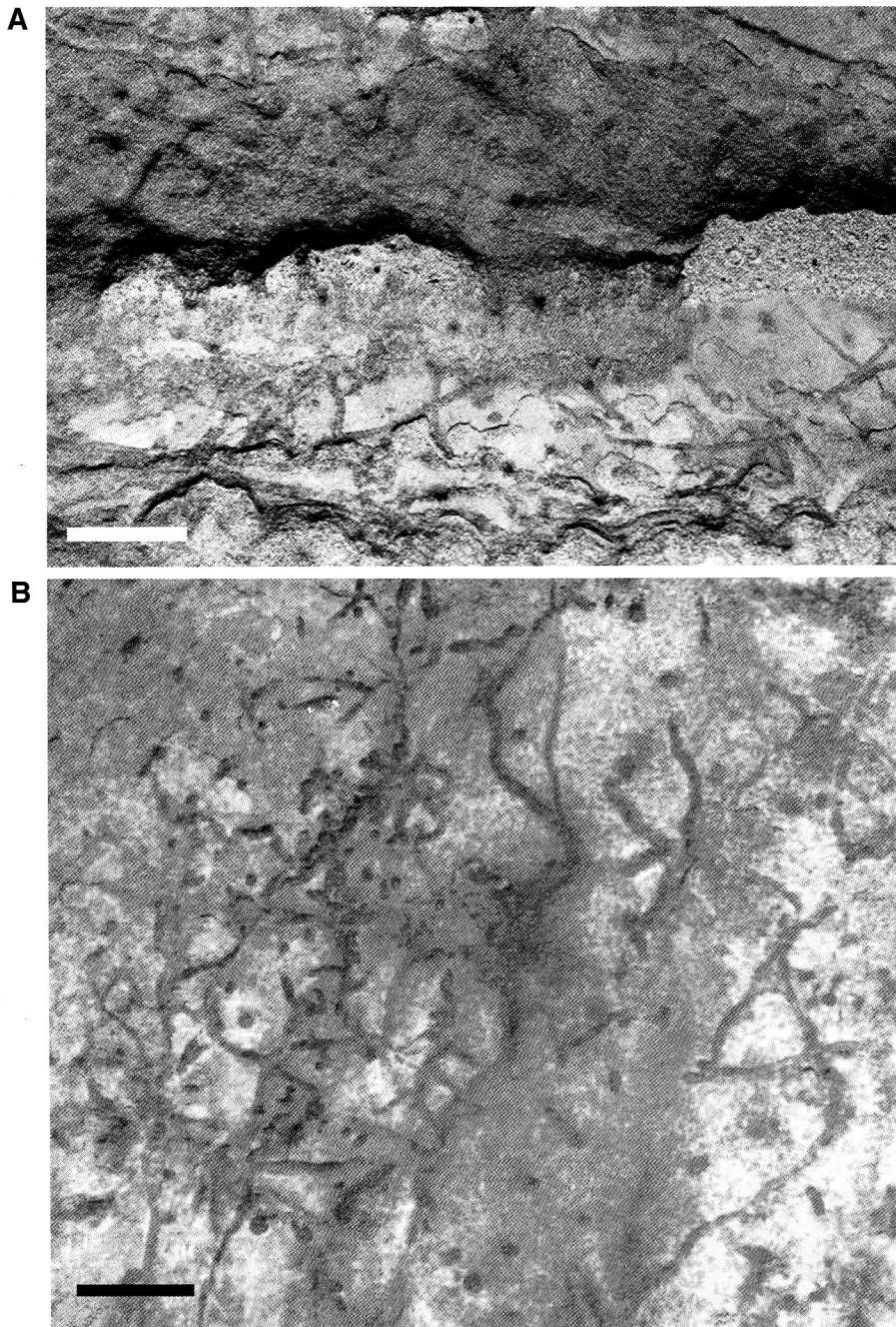
FIGURE 35.2 (A,B) *Planolites beverleyensis* (plan view) in Navajo Sandstone at Coyote Buttes, southern Utah. Scale bar equals 8 cm.

on the basis of size and shape. *A.* isp. 1 is the smaller form. On a number of bed surfaces one can observe a paired arrangement of shaft openings (Fig. 35.4), which suggests 'U' burrows, but a subsurface connection of two shafts to form a 'U' could not be demonstrated with certainty in most cases. The shafts appear to be unlined. Dimensions (*A.* isp. 1): shaft diameter is about 2 mm; space between paired shaft openings is about 2 mm. *A.* isp. 2 is the larger

form. The 'U' is broadly bow-shaped and shallow in depth in the sediment, and it is oriented perpendicularly to the slipface. The burrows are unlined. Dimensions (*A.* isp. 2): shaft diameter is 5 mm; span of the bow-shaped 'U' is about 5 cm wide and 2 cm deep.

Entradichnus meniscus—As described by Ekdale and Picard (1985) in the slightly younger Entrada Sandstone to the northeast of Coyote Buttes (Fig. 35.5),

FIGURE 35.3 *Paleophycus tubularis* (plan view) in Navajo Sandstone at Coyote Buttes, southern Utah. Scale bar equals 3 cm.
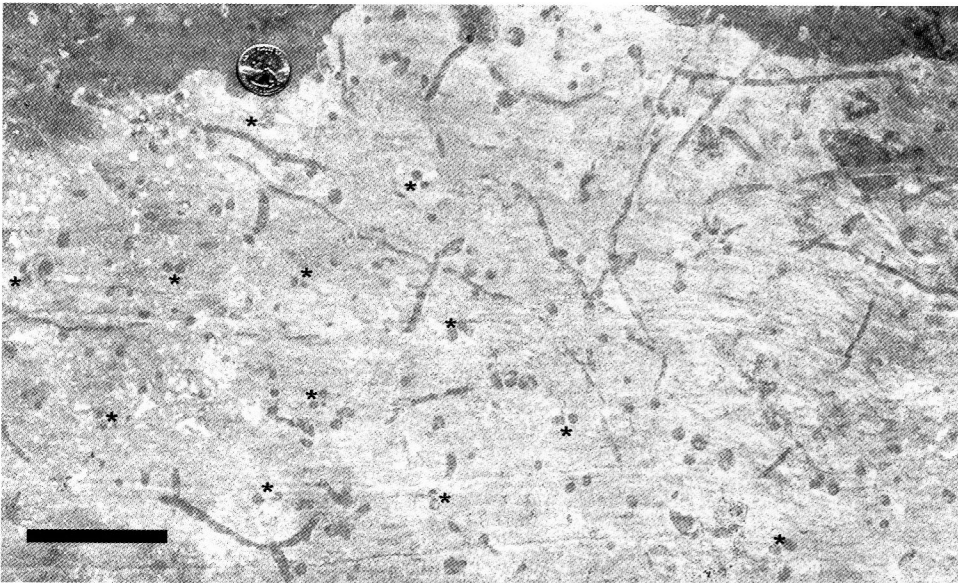

FIGURE 35.4 *Arenicolites* isp. 1 (plan view) in Navajo Sandstone at Coyote Buttes, southern Utah. Tiny black stars indicate paired openings to the U-shaped burrows. Scale bar equals 6 cm.

Entradichnus meniscus consists of a long, horizontal, unwalled, meniscate trail that was created as a shallow burrower moved-up the slip face of a dune in a fairly straight or gently curved line. The animal pushed small packets of sand behind itself as it moved through the sediment across the slip face, creating a string of slightly flattened menisci. Some minor surface collapse also occurred as the animal moved forward, which contributed to the crescentic aspect of the trail's internal structure. The menisci of *Entradichnus meniscus* differ from those of *Beaconites barreti* in lacking evidence of fecal material. The trails usually are gently curved, and they are preserved in epirelief. In some cases, clusters of *Entradichnus* radiate irregularly from a central mass of burrows, suggesting a hatching and subsequent dispersal of burrowers (Fig. 35.6). Dimensions: trail is 5–7 mm wide and up to 15 cm long.

FIGURE 35.5 *Entradichnus meniscus* (plan view) preserved in convex epirelief in the eolian Entrada Sandstone (Middle Jurassic) from the type locality south of Moab, Grand County, Utah (see also Ekdale and Picard, 1985). Scale bar equals 3 cm.
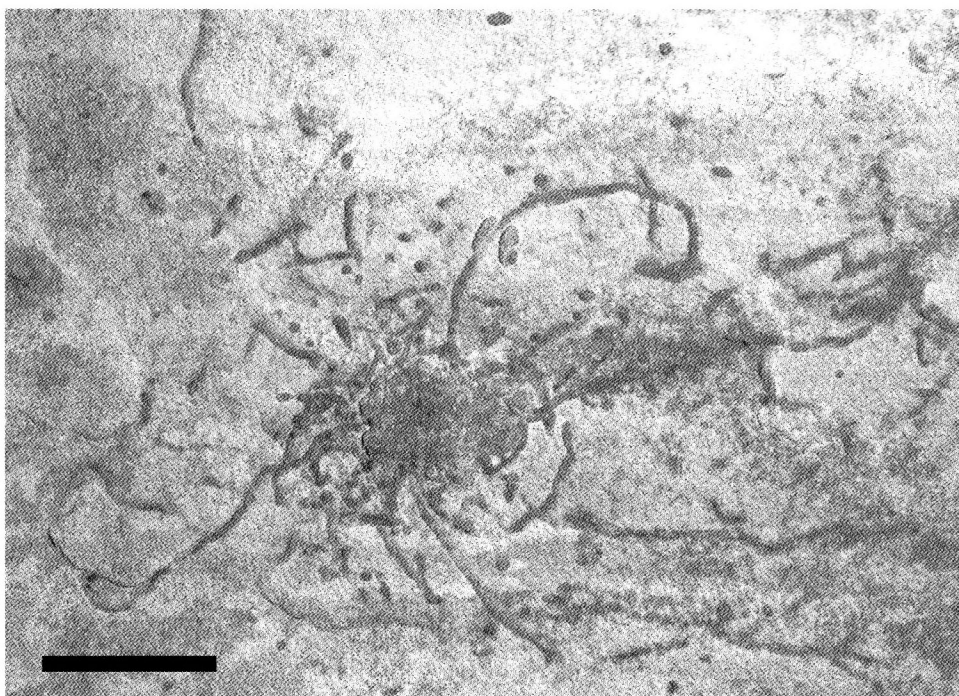

FIGURE 35.6 Clusters of radiating *Entradichnus meniscus* (plan view) in Navajo Sandstone at Coyote Buttes, southern Utah. Scale bar equals 10 cm.

Taenidium serpentinum—Thinly lined, meniscate burrows occur sparsely at all sites, typically in full relief within sand beds. They are mostly subparallel to the slipface, and they curve slightly upwards and downwards as well as sideways in the sediment. In contrast to *Entradichnus meniscus*, the menisci in *Taenidium serpentinum* are less regular in shape and spacing, and there is no evidence of roof collapse in the burrow. Dimensions: tunnel diameter is 5 mm.

Digitichnus laminatus—Short, stout, finger-shaped burrows are sparsely present at one site. They are oriented vertically with respect to the horizon in the dipping foreset laminae, and thus they occur at an angle to the bedding plane. The burrow shafts are

unlined, and the burrow fill is either structureless or horizontally laminated. Dimensions: shaft diameter is about 1 cm, and shaft length is about 3 cm.

Vertebrate tracks—Vertebrate tracks also are preserved in the eolian foreset beds of Navajo Sandstone at Coyote Buttes. They include *Grallator* (presumably made by theropod dinosaurs) and *Brasilichnium* (presumably made by therapsids). These are tetrapod trackways, which were described briefly by Loope and Rowe (2003), and which are examined more thoroughly in their sedimentologic context by Loope (2006). Thus, discussion of the vertebrate tracks in the Navajo Sandstone is not included in this paper.

TRACE MAKERS

Even though the diversity of invertebrate ichnotaxa in the Navajo Sandstone at Coyote Buttes is fairly high (seven ichnospecies), it is possible that the traces were made by a very small diversity of biotaxa. In fact, because five of the seven ichnotaxa (i.e., *Arenicolites*, *Palaeophycus*, *Planolites*, *Skolithos*, and *Taenidium*) exhibit nearly the same size range and preservational mode, they may very well have been produced by the same species of burrowing organism, the differences in trace fossil morphology resulting from differences in organism behavior and/or substrate character.

All the burrowers clearly were invertebrate animals, as the small size and characteristic morphologies of the burrows are inconsistent with any known vertebrate taxa inhabiting the Early Jurassic landscape, and the preservation mode and typical geometries of the burrows are inconsistent with any known vascular plant taxa occurring in western North America at this time.

It is most likely that the burrowers were arthropods (i.e., insects, arachnids and/or myriapods), as many types of modern arthropods are known to produce distinctive burrows in modern dunes (Ahlbrandt et al., 1978; Phelps, 2002), and also because trace fossils of burrowing arthropods have been reported in other Mesozoic occurrences in the region (Hasiotis and Dubiel, 1994; Hasiotis, 2003). The body fossil record of terrestrial arthropods in the Jurassic is very poor, and the body fossil record of arthropods in eolianites of any age is exceedingly sparse. Thus, we may only conjecture regarding the taxonomic affinities of the trace makers in the Navajo Sandstone.

Based on trace fossil size and morphology, reasonable candidates for the producers of the Jurassic *Arenicolites*, *Palaeophycus*, *Planolites*, *Skolithos*, and

Taenidium in the Navajo Sandstone would be insects. Similar burrows are produced in modern eolian dunes by various kinds of beetles (Order Coleoptera), including especially darklings (tenebrionids), histers (histerids) and scarabs (scarabaeids), which are very common and widespread inhabitants of desert ecosystems all over the world today (Cloudsley-Thompson and Chadwick, 1964; Crawford, 1981; Wallwork, 1982; Phelps, 2002). Desert sand roaches (Order Dictyoptera) create meniscate backfilled burrows resembling *Taenidium* in many deserts today (Crawford, 1981; Wallwork, 1982; Phelps, 2002). *Entradichnus* was interpreted by Ekdale and Picard (1985) to represent the plowing trails of larvae of crane flies (tipulids, Order Diptera), based on their similarity to trails made by crane fly larvae in modern desert dunes (Ahlbrandt et al., 1978). The plug-shaped *Digitichnus* shafts could be made by a variety of infaunal arthropods, possibly including scarab beetles and certain spiders that are known to dig shallow pits that resemble *Digitichnus* (Phelps, 2002).

Arachnids, such as scorpions and spiders, are also known as producers of distinctive burrows in eolian dunes today (Curran, 1994; Phelps, 2002), although the body fossil and trace fossil records of Early Jurassic arachnids are exceedingly sparse, and none of the burrows observed in this study in the Navajo Sandstone exhibit any definitive characteristics to suggest arachnid producers. Nevertheless, because diverse arachnids are common components of modern dune ecosystems (Crawford, 1981; Wallwork, 1982; Costa, 1995), as well as Cenozoic continental facies (Codington, 1992; Phelps, 2002), the possibility that arachnids burrowed in the Navajo Sandstone dunes cannot be ruled out.

There is no evidence in the trace fossil assemblage at Coyote Buttes of complexly branched and/or chambered burrow systems that could be interpreted as multi-celled domiciles or brooding structures of semi-permanent populations of social insects, such as ants, bees, wasps or termites.

PALEOECOLOGIC INTERPRETATIONS

This trace fossil assemblage in the Navajo Sandstone appears to be an ichnosuite of trace fossils representing a single ichnoguild of very shallow-tier, mostly horizontal burrows. Terrestrial arthropod taxa exhibit a wide range of feeding habits. While there is no direct or circumstantial evidence from the Navajo Sandstone burrows that the trace makers were sediment-ingesting deposit feeders, similarly there

is no direct evidence that they were grazing herbivores or predatory carnivores either.

Most of the Navajo Sandstone trace fossils were simple dwelling and/or unorganized grazing traces. It is possible, although not entirely certain, that the most abundant trace fossils were produced during very short intervals of time (i.e., in a matter of weeks) when an opportunistic explosion of many insects appeared on the scene to consume new plant material and organic detritus (including insect carcasses) that were accumulating as a result of short-lived wet conditions. This interpretation is suggested by observations of a common clustering pattern of burrows in some beds (Fig. 35.6; see also Loope and Rowe, 2003, Fig. 3b), possibly indicating a periodic hatching and dispersal of a new cohort of larval insects.

The trace fossil association reflects a single ichnoclade of burrowers (*sensu* Ekdale and Lamond, 2003) that dug open, unbranched tunnels and shafts in the sand, which were filled either actively or passively with the surrounding host sediment. With only a few exceptions (*Palaeophycus* and *Taenidium*), the Navajo Sandstone burrows are unlined, and none appear to contain fecal material. Adult insects today generally do not ingest sediment as food, as for example earthworms do (Ratcliffe and Fagerstrom, 1980), and in subaerial settings adult insects typically do not line their burrows with mucus or agglutinated sediment. However, it has been reported that some insect larvae produce organic secretions that have a potential of stabilizing burrow walls with a thin lining (Ratcliffe and Fagerstrom, 1980), although such a wall lining has not been reported in larval insect burrows in modern eolian dunes.

The feeding habits of most desert arthropods today are poorly known, apart from the anecdotal observations of some of the most common taxa (Cloudsley-Thompson and Chadwick, 1964; Cloudsley-Thompson, 1991; Costa, 1995). The arachnids are carnivores, whereas the insects include a broad spectrum of carnivores, herbivores, detritivores (including coprophages) and omnivores. There is no obvious aspect of the horizontal burrows (e.g., *Planolites* and *Palaeophycus*) in the Navajo Sandstone to suggest that they were produced for purposes of predation, although some of the vertical burrows (e.g., *Skolithos* and *Digitichnus*) may have been domichnia of stationary predators.

There is no direct evidence of vascular plants, such as macroscopic plant fossils or root structures, in the Navajo Sandstone beds that contain the burrows described here. Therefore, a year-round source of lush plant growth to serve as food for herbivorous insects seems unlikely. However, a wide variety of blue-green algae (cyanobacteria), green algae and fungi are known to grow on and in modern desert soils, including eolian sand (Friedmann and Galun, 1974), and such microbial growth may serve as an important food source for small invertebrates (Costa, 1995). Thus, it is possible that the Jurassic burrowers in the Navajo dunes may have survived by feeding upon algal films or fungi that grew on sand grains during damp times. However, if there were abundant vascular plants inhabiting other parts of this inland erg environment, such as wetter interdune areas, plant detritus may have blown into the relatively dry dunes and provided a food source for the foraging insects there. In the unvegetated dune fields of the modern Namib Desert, Seely (1978) documented abundant populations of darkling (tenebrionid) beetles that apparently feed upon plant detritus that periodically blows in from adjacent areas.

PALEOCLIMATIC IMPLICATIONS

The paleoclimatic implications of cyclical bed forms and primary sedimentary structures in the Navajo Sandstone in southern Utah have been related to monsoonal conditions, in which dry and wet seasons alternated annually with different prevailing wind directions and average wind velocities (Chandler et al., 1992; Chan and Archer, 1999, 2000; Loope et al., 2001; Loope and Rowe, 2003; Loope et al., 2004). The two components of the annual monsoonal cycle in the Navajo Sandstone are (a) bundles of 20–50 individual grainflow layers representing the southeastward migration of dunes under the influence of prevailing northwesterly winds during the winter dry season, and (b) thin wedge-shaped layers of wind-rippled sand that were pushed up against the slip face during the rest of the year by northeasterly winds moving obliquely up the dune slope. In this low-latitude setting in the Northern Hemisphere, rain was most likely during the summer months (Loope et al., 2001; Loope and Rowe, 2003).

The trace fossil assemblage at Coyote Buttes is consistent with a monsoonal climatic setting. The invertebrate trace fossils described here occur most profusely in the grain flow layers on the dune slip faces. The trace fossils may have been produced—or at least preferentially preserved—in damp sand in the foresets of large dunes, possibly during rainy seasons, when the cyclical influx of moisture into the Navajo desert permitted insects to take advantage of the algal growth in the sand.

This trace fossil assemblage appears to reflect the periodic activity of insects, possibly r-selected opportunists, which took rapid advantage of rainy intervals in a monsoonal climate to feed and flourish. However, the sedimentologic context of the trace fossil occurrences suggests that the burrowing events were not simply related to annual cycles of wet and dry seasons. Instead, the burrowed beds appear to coincide with long-lived pluvial episodes that may have lasted for thousands of years during the history of the Navajo erg (Loope and Rowe, 2003). This scenario would explain why the burrows are very profuse in grainflow layers in certain parts of the Navajo Sandstone and absent from most of the rest of the formation. The insect fauna flourished only during these more hospitable pluvial intervals, and their traces therefore reflected the variable paleoclimatic conditions that affected this ancient erg environment.

The types of vegetation available to the hungry Jurassic insects is not known, as there are no macroscopic plant fossils or rhizoliths preserved in these sandstone beds, and no palynomorph studies have been attempted. Because there were no grasses or any other angiosperms existing on Earth at this time, and because arid conditions are not very conducive to gymnosperm growth, the dune flora may have consisted mainly of microscopic algae that periodically came to life and spread rapidly in the wet sand (Friedmann and Galun, 1974). The trace-making organisms apparently were surface or near-surface dwellers that fed at least partly upon the algal coatings of sand grains.

Many desert insects today exhibit seasonal activity cycles (Wallwork, 1982; Cloudsley-Thompson, 1991; Heatwole, 1996), including several groups of burrowing beetles, such as those that may have been responsible for producing the Navajo Sandstone burrows. The fluctuating monsoonal conditions in the Jurassic Navajo erg facilitated the cyclical activity of the resident insect fauna.

ENTRADICHNUS ICHNOFACIES

The three most widely accepted ichnofacies in continental settings are (a) the *Coprinisphaera* Ichnofacies, representing moist, herbaceous paleosols (Genise et al., 2000), (b) the *Scoyenia* Ichnofacies, representing floodplains and ephemeral streams (Seilacher, 1964; Buatois et al., 1998), and (c) the *Mermia* Ichnofacies, representing shallow and deep lakes (Buatois and Mangano, 1995; Buatois et al., 1998). The Navajo Sandstone trace fossil assemblage reported here clearly does not fit within any of these three well-documented non-marine ichnofacies.

We hereby name a fourth terrestrial ichnofacies, the *Entradichnus* Ichnofacies, for the recurrent trace fossil assemblage that typifies sparsely vegetated and unvegetated eolian dune fields in arid climatic settings (Fig. 35.7; Table 35.1). We offer the Navajo
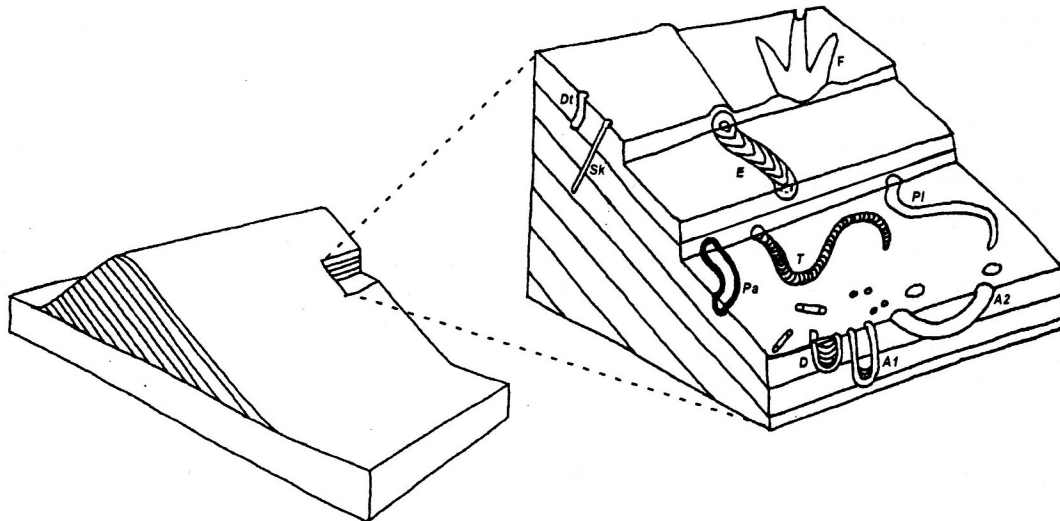

FIGURE 35.7 Idealized sketch of the typical ichnotaxa in the *Entradichnus* Ichnofacies. A1, *Arenicolites* isp. 1; A2, *Arenicolites* isp. 2; D, *Diplocraterion parallelum*; Dt, *Digitichnus laminatus*; E, *Entradichnus meniscus*; F, footprint of vertebrate; Pa, *Palaeophycus tubularis*; Pl, *Planolites beverleyensis*; Sk, *Skolithos linearis*; T, *Taenidium serpentinum*. (Note: *Diplocraterion parallelum* was not documented with certainty in the Navajo Sandstone at the Coyote Buttes study site.)

TABLE 35.1 Ichnotaxa that Typify the *Entradichnus* Ichnofacies in Eolianites

Ichnogenus	Formation (Reference)	Locality	Age
Arenicolites	Navajo (8)	Utah, USA	Jurassic, Early
	Tumlin(?)(5)	Poland	Triassic, Early
Digitichnus	Sossus (6)	Namibia	Pliocene–Holocene
	Entrada (4)	Utah, USA	Jurassic, Middle
	Navajo (8)	Utah, USA	Jurassic, Early
Diplocraterion	Navajo (?) (8)	Utah, USA	Jurassic, Early
	Tumlin (5)	Poland	Triassic, Early
Entradichnus	Entrada (4)	Utah, USA	Jurassic, Middle
	Navajo (8)	Utah, USA	Jurassic, Early
	Coconino(*) (1)	Arizona, USA	Permian, Early
Palaeophycus	Navajo (8)	Utah, USA	Jurassic, Early
	Tumlin (5)	Poland	Triassic, Early
	Casper(*) (2)	Wyoming, U.S.A	Permian, Early
Planolites	un-named eolianite (7)	Mexico	Pleistocene–Holocene
	Tsondab (6)	Namibia	Eocene–Miocene
	Navajo (8)	Utah, USA	Jurassic, Early
	Tumlin (5)	Poland	Triassic, Early
	Casper(*) (2)	Wyoming, USA	Permian, Early
	Cedar Mesa(*) (3)	Utah, USA	Permian, Early
Skolithos	un-named eolianite (7)	Mexico	Pleistocene–Holocene
	Navajo(8)	Utah, USA	Jurassic, Early
Taenidium	un-named eolianite (7)	Mexico	Pleistocene–Holocene
	Sossus (6)	Namibia	Pliocene–Holocene
	Tsondab (6)	Namibia	Eocene–Miocene
	Navajo (8)	Utah, USA	Jurassic, Early
	Coconino(*) (1)	Arizona, USA	Permian, Early
	Casper(*) (2)	Wyoming, USA	Permian, Early

References: 1. Brady, 1947; 2. Hanley et al., 1971; 3. Loope, 1984; 4. Ekdale and Picard, 1985; 5. Gradzinski and Uchman, 1994; 6. Smith and Mason, 1998; 7. Phelps, 2002; 8. this chapter. Question mark after formation name indicates uncertain ichnogeneric identification in the field. Asterisk after formation name indicates current ichnogeneric assignment of a previously un-named or differently named trace fossil based on the ichnotaxonomic scheme employed in this chapter.

Sandstone trace fossil association described herein as a typical example of this new ichnofacies.

Buatois et al. (1998, Fig. 5) reported a typical trace fossil association in Mesozoic dune and interdune facies that includes twelve ichnogenera, six of which occur in the Navajo Sandstone in the outcrops at Coyote Buttes. Descriptions of similar trace fossil associations have been reported in eolian sequences of other ages at other localities, including the Permian Coconino Sandstone in northern Arizona (Brady, 1947), Permian Cedar Mesa Sandstone in southern Utah (Loope, 1984, 1985), Permian Casper Sandstone in southern Wyoming (Hanley et al., 1971), Jurassic Entrada Sandstone in eastern Utah (Ekdale and Picard, 1985), Tertiary Tsondab Sandstone in Namibia (Smith and Mason, 1998), and Quaternary eolianite beds in Sonora, Mexico (Phelps, 2002).

Thus, this is a very widespread, recurrent trace fossil association that typifies arid eolian paleoenvironments.

The ichnotaxonomic status of the eponymous ichnotaxon of the *Entradichnus* Ichnofacies is worth noting briefly here, although a thorough ichnotaxonomic treatment is beyond the scope of this present chapter. Ekdale and Picard (1985, p. 8) stated that *Entradichnus* differs from *Taenidium* in being unlined, unbranched and always oriented along a single bedding plane (Fig. 35.5). *Entradichnus meniscus* typically is long and straight to gently sinuous with a uniform width of approximately 5 mm throughout the entire length of the tunnel. The menisci are composed of the same sediment as the host sediment, and there is no evidence of fecal matter in the menisci, as sometimes occurs in *Taenidium*.

D'Alessandro and Bromley (1987) regarded *Entradichnus* as a junior synonym of *Taenidium* at the ichnogeneric level, based on the mensicate internal structure in the tunnel. They equivocated slightly, however, and remarked that '*Entradichnus meniscus* may belong here [in *Taenidium serpentinum*], although the menisci appear to be closely spaced and rather flat' (D'Alessandro and Bromley, 1987, p. 754).

In the example from the Navajo Sandstone reported here, as well as in the Entrada Sandstone where it was first described, *Entradichnus* is straight or gently curving with very regular crescentic menisci and without a wall lining, and its course follows a single plane, exposing the trail in positive and/or negative semirelief on tops of beds. *Taenidium*, in contrast, is more sinuous with a thin but distinctly dark-stained lining and with irregularly shaped menisci, and in the Navajo Sandstone it usually occurs in full relief within a sand lamina.

Brady (1947) erected the new ichnogenus *Scolecocoprus* and two new ichnospecies, *S. cameronensis* and *S. arizonensis*, for mensicate trace fossils in the eolian Coconino Sandstone in northwestern Arizona. He inappropriately listed *Scolecocoprus* as a new genus of oligochaete annelid, and he mistakenly interpreted it as a worm burrow filled with fecal pellets. D'Alessandro and Bromley (1987) emended the diagnosis of *S. cameronensis* and reassigned it to the ichnogenus *Taenidium*, as *T. cameronensis*. However, they did not consider the other ichnospecies, *S. arizonensis*, which appears in the original published photograph (Brady, 1947, pl. 69, Fig. 2) to be very similar to the type specimens of *Entradichnus meniscus* (Fig. 35.8; see also Ekdale and Picard, 1985, pl. 2,

Fig. A,B). However, Brady's (1947) description of *S. arizonensis* was too vague to assert that it is identical to *E. meniscus*. Therefore, in consideration of the present ambiguity regarding the ichnotaxonomic status of *E. meniscus*, we provisionally retain it as a valid ichnogenus and ichnospecies.

The most distinctive hallmark of the *Entradichnus* Ichnofacies is *Entradichnus* itself, since most of the other ichnotaxa in this association (e.g., *Arenicolites*, *Palaeophycus*, *Planolites*, *Skolithos* and *Taenidium*) are facies-breaking traces that may be found in other non-marine and marine ichnofacies as well. *Entradichnus* is common in many eolianites from at least the Permian to the present and is unknown in non-eolian settings. Thus, despite the ichnotaxonomic questions regarding *Entradichnus*, it is the most apt name for this eolian ichnofacies.

CONCLUSIONS

The invertebrate trace fossil assemblage in the Navajo Sandstone at Coyote Buttes consists of *Planolites*, *Palaeophycus*, *Skolithos*, *Arenicolites* (two ichnospecies), *Entradichnus*, *Taenidium*, and *Digitichnus*. This diverse association of ichnotaxa represents essentially a monotypic ichnoguild of shallow-tier burrows characterizing an arid eolian habitat that apparently was devoid of macroscopic vegetation. By comparison with modern trace-making dune dwellers, it can be reasonably inferred that the Jurassic trace-making organisms were insects, including especially beetles, and perhaps also arachnids.
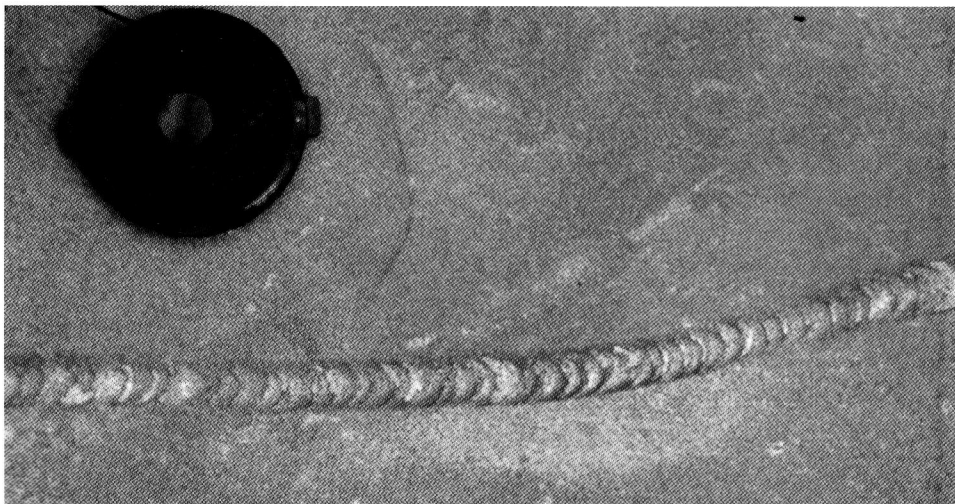

FIGURE 35.8 *Entradichnus meniscus* (plan view) in the eolian Coconino Sandstone (Permian) along the Colorado River in the Grand Canyon, Coconino County, Arizona (see also Brady, 1947). Lens cap is 5 cm in diameter.

The trace fossils occur mostly in the sand layers that accumulated as grain flows on the dune slip faces during long-lasting pluvial intervals when insects flourished and exploited the periodic algal growth in the sand and/or in-blown organic detritus for food. Thus, the trace fossil record supports the interpretation of a monsoonal climatic regime for the Jurassic Navajo erg.

This assemblage of trace fossils in the Navajo Sandstone exemplifies the *Entradichnus* Ichnofacies, which represents arid eolian paleoenvironments in the geologic record, extending from at least the Late Paleozoic to the present.

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