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GAS-ESCAPE STRUCTURES AND THEIR PALEOENVIRONMENTAL SIGNIFICANCE AT THE STEVEN C. MINKIN PALEOZOIC FOOTPRINT SITE (EARLY PENNSYLVANIAN, ALABAMA)

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ABSTRACT: Small circular structures are common in shale at the Steven C. Minkin Paleozoic Footprint Site (Union Chapel tracksite). Researchers originally identified them as rainprints (and therefore indicators of subaerial exposure), but closer examination shows them to be gas-escape structures (which do not require subaerial exposure). Considering the lack of mudcracks or other evidence of desiccation, it seems likely that the Union Chapel trackways were made on wet or submerged surfaces.

INTRODUCTION

During preliminary work on the Union Chapel tracksite, researchers were intrigued by numerous circular pits on track-bearing surfaces (Fig. 1). The pits are shallow and many have raised rims. Rainprints (or raindrop imprints) are commonly associated with trackways, and at first we uncritically identified them as rainprints and used them as evidence of subaerial exposure. In time, work by Pashin (2005) and others made it clear that the tracks were made on a freshwater intertidal flat, where raindrop imprints would not be surprising. However, other observations mounted against the interpretation of the circular pits as rainprints, and indeed against any subaerial drying of the beds. I now interpret the tracks to have been made either under water or on a very wet subaerial surface.

THE STEVEN C. MINKIN PALEOZOIC FOOTPRINT SITE

The Steven C. Minkin tracksite has yielded the largest number of well-preserved vertebrate trackways of any Carboniferous site in the world (Pyenson et al., 2001; Haubold et al., 2005). The site is an inactive part of the Union Chapel Mine of the New Acton Coal Mining Company, near the community of Union Chapel in Walker County, Alabama (USA). As described by Pashin (2005), the track-bearing strata lie within about 1 to 6 meters below the Newcastle coal seam (Mary Lee coal group) in the upper Pottsville Formation (Lower Pennsylvanian, Westphalian A = Langsettian). The site was discovered in late 1999 and has been extensively collected since then, mainly by members of the Alabama Paleontological Society.

Trace and body fossils were collected from mine spoil, the vertical highwall being too dangerous to approach for intensive study. Thus, the detailed stratigraphy of trace fossils and other sedimentary structures is unknown, though some relationships can be inferred from the association of structures on single slabs.

COMPARISON OF RAINPRINTS AND GAS-ESCAPE STRUCTURES

Researchers on both sides of the Atlantic realized from the first that vertebrate trackways are commonly associated with rainprints and mudcracks (Cunningham, 1839; Lyell, 1841, 1845, 1852; Buckland, 1842; Redfield, 1842; Vanuxem, 1842; Deane, 1844, 1845). Lyell (1845, v. 2, p. 167) wrote that William Buckland was the first to recognize rainprints as such during a lecture in 1838, creating a sensation in the “incredulous public.” However, many so-called rainprints have been interpreted by others as gas-escape structures (Desor, 1850; Twenhofel, 1921, 1932; Moussa, 1974). Superficially, rainprints and gas-escape structures may look much alike (Figs. 1, 2), despite different processes of formation. Rainprints occur on subaerial surfaces, whereas gas-escape structures are made within both subaerial and submerged substrates. Both may form circular pits on a sedimentary surface, and distinguishing them requires close observation, as was recognized very early.

William Buckland (1842, p. 57) cautioned in regard to the Permian-Triassic New Red Sandstone near Birmingham, England,

> The origin of these holes appeared to have been the rise of bubbles of air through the bottom of little partial shallow ponds of water on the mud, the general surface of which, from its convex form, had allowed no water to rest upon it ... a slab of new red sandstone ... from near Birmingham, containing a few impressions of vegetables, was covered with small tubercles in close contact with one another, and apparently caused by the deposition of sand in holes formed by the rise of bubbles of air from a subjacent bed of clay ... some of the cavities, and casts of cavities, ... which have been attributed to rain-drops, may have been due to the extrication of air-bubbles; care would therefore be necessary to distinguish between these two causes of phenomena, which have hitherto been exclusively attributed to rain.

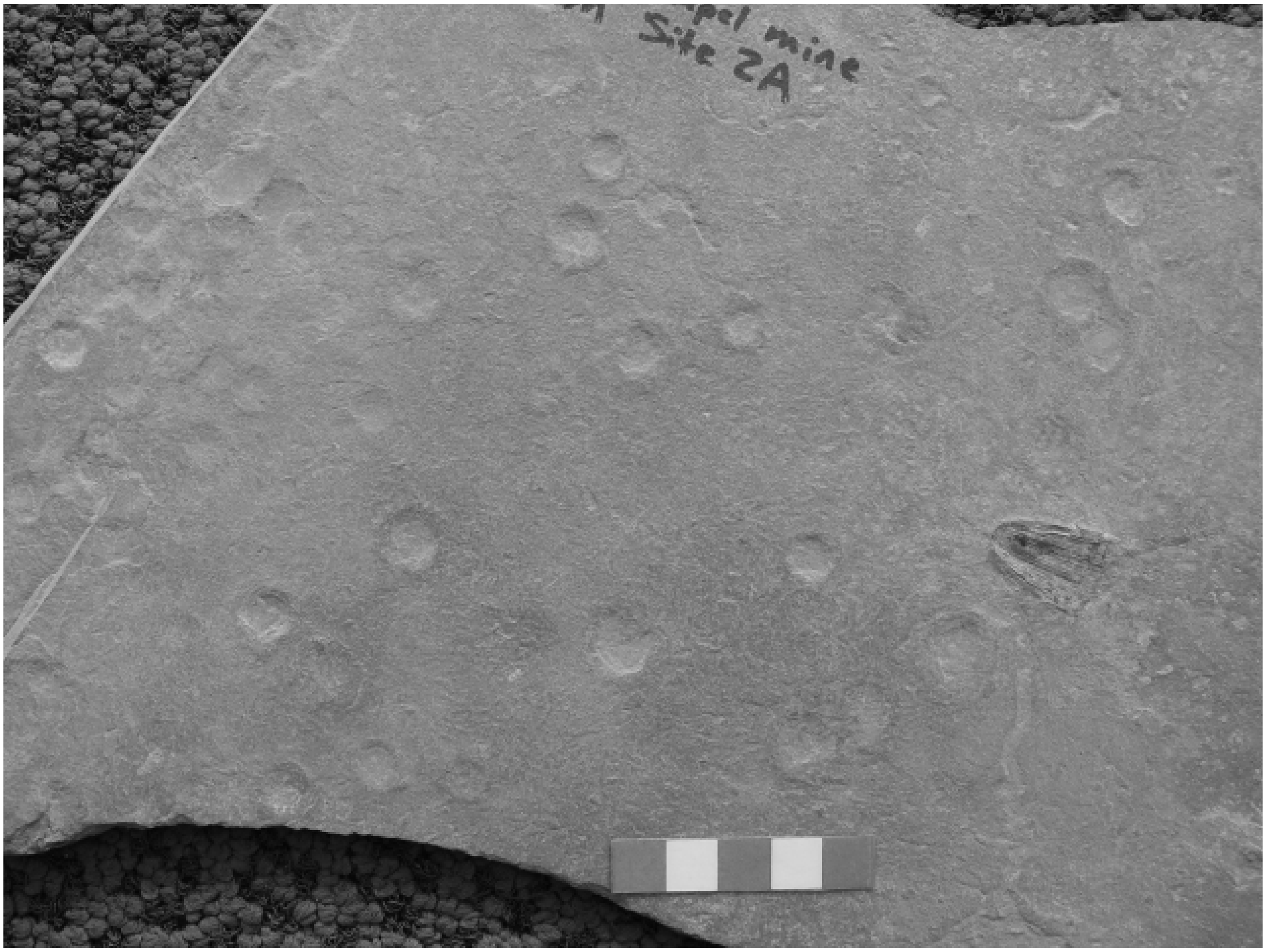

FIGURE 1. Gas-escape structures in shale from the Steven C. Minkin Footprint Site, Walker County, Alabama. UCM 2072, collected by David C. Kopaska-Merkel (Geological Survey of Alabama). The scale is in centimeters.

Desor (1850) repeated the warning. Lyell (1851, p. 241-242), studying Carboniferous trackways at Joggins, Nova Scotia, noted that rainprints were also present there, and compared them to marks made by falling rain, dripping water, and gas bubbles in the nearby Bay of Fundy tidal flats. Lyell even performed an experiment to clarify their distinction.

> Being desirous of ascertaining whether air-bubbles, rising through mud and bursting as they reached the surface, could give rise to cavities similar to those caused by the fall of rain, I poured some pounded mud from Kentville on a small quantity of water, and shook the basin containing it, upon which numerous bubbles of entangled air rose through the mud, and, on bursting at the surface, left cavities resembling in size the ordinary rain-prints from Nova Scotia, but very different in character. Nearly all of them were perfectly circular, with a very sharp edge, and without any rim projecting above the general surface. In a few cases, however, there was a slight, narrow rim, sharper and more even than that of a rain-print. In no instance was this rim connected with a greater depression at one end of an oval concave depression. Most of the pits produced by these air-bubbles were different also from rain-prints, in being deeper than they were wide. Their sides were very steep, and often over-arching, the cavity below the surface being wider than the opening at the top. The axis of some few of these deeper cavities was oblique to the surface of the mud. Where two bubbles had touched, a vertical thin parting wall of mud was left between them.

Later observations would show that there is considerable variation in the form both of rainprints and of gas-escape structures (Twenhofel, 1921), and authors continued to caution investigators about their superficial resemblance (Twenhofel, 1921; Lahee, 1941; Shrock, 1948; Moussa, 1974; Potter et al., 1980). Twenhofel (1921) noted that pits can be caused by raindrops, hailstones, dripping water, spray and splash, stranded bubbles, drifting bubbles, bubbles forming at the surface of a submerged substrate, and bubbles forming within the substrate and rising upward through it. All have a convex-downward form that can be used as an indicator of the top and bottom sides of a loose slab or a layer in complexly folded rock (Shrock, 1948).

Rainprints are impact structures (Fig. 2). Like meteorite craters, rainprints are formed by the impact of a

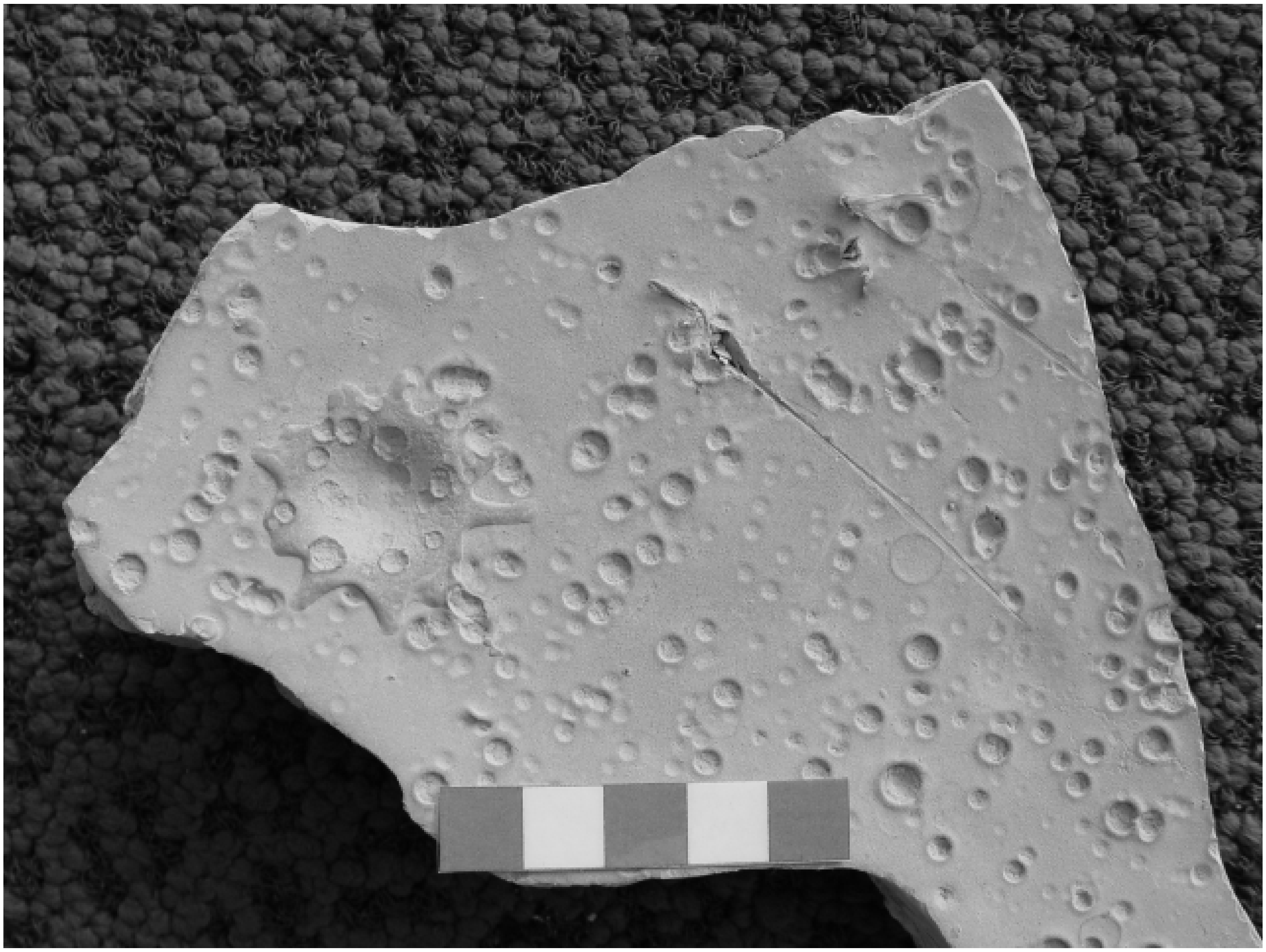

FIGURE 2. Modern rainprints in dried mud from Lehigh Portland Cement Quarry, Leeds, Alabama, collected by W. Edward Osborne (Geological Survey of Alabama). The scale is in centimeters. The largest print, showing a spattered rim, is too large to be the impression of a normal raindrop and may be the result of drip or hail. It is overlapped by the rainprints from subsequent raindrops. Some rainprints overlap one another as well.

falling body on the earth. The meteorite rapidly is converted to fluid, while the raindrop is already fluid; accordingly, each spreads outward in a roughly even manner, creating the familiar circular pit or crater with a raised rim. Unlike gas-escape structures, rainprints are limited in size and are generally 5 to 15 mm wide (Potter et al., 1980). Within a broad range, the angle of impact has little effect on the circularity of the pit, but wind-driven, obliquely falling raindrops may create elliptical imprints (Lahee, 1941, p. 54, fig. 30). The edges of the pit are raised and are commonly uneven due to spattering; in the case of water droplets, surface tension plays a role in shaping the impacting droplet, especially of larger droplets (Edgerton and Killian, 1939) (Fig. 2). Slurried or weakened sediment may fall back into the crater, shallowing it.

Conditions for producing and preserving rainprints are limited by the cohesiveness of the sedimentary surface upon which a raindrop falls (Blackwelder, 1941; McKee, 1945). If the sediment is too soft, then it will settle back into a flat surface after impact. If it is too hard, the impact will leave no imprint at all. The ideal surface is one that is plastic enough to be distorted by impact, but firm enough to retain its shape afterward. Moreover, only a light rain will do. Heavy rain will create so many overlapping rainprints that only the last few could be distinguished, and the soaked sediment is unlikely to remain firm enough to hold their forms. Finally, the surface must be buried before the rainprints are erased, and by sediment whose deposition does not itself erase the record, such as wind-driven sand. The presence of rainprints should not be considered as evidence of a humid climate, but rather is suggestive of aridity.

Thus, it should not be surprising that rainprints are uncommon in the overall geologic record. However, they do occur at many tracksites; the preservation of footprints requires similar sedimentary coherence, neither too soft nor too firm. Rainprints are common, for example, in the famous Triassic-Jurassic tracksites of the Connecticut Valley (Shrock, 1948). In each of these occurrences, rainprints typically occur on the same bedding planes as mudcracks — further evidence of desiccation.

Gas-escape structures are not as familiar as rainprints, though they are common in the geologic record, and even now many questions remain. Most of the more recent studies have focused on gas-escape structures in carbonate rather than clastic sediment, in connection with porosity and petroleum geology. In general, gas is either trapped in rapidly deposited sediment, or is generated there by microbial processes (Hammond, 1978; Reineck and Singh, 1980, p. 66-67, 249-250). The gas may consist of air, oxygen, carbon dioxide, methane, or other fermentative gases. In each case, buried gas is less dense than surrounding sediment, and therefore tends to rise through it. In relatively coarse, permeable sediment, gas generally seeps upward through pores between sand or pebbles without moving them; but in relatively fine, impermeable sediment such as clay and algally laminated carbonate, the gas may build up as bubbles that push aside sediment as they rise, forming a vertical shaft that may widen into a pit at the top. In fine-grained carbonate sediments, gas bubbles may be trapped beneath the surface long enough for the sediment to become cemented; afterward, the pores may be filled with calcite cement (*fenestrae* or *birdseyes*). These may be indistinguishable in hand specimen from horizontal burrows.

Where gas bubbles pierce the substrate vertically, the surrounding sediment either falls back into the shafts, if it is very soft, or else retains the form of the shafts, if it is relatively firm. The shafts may closely resemble the vertical burrow *Skolithos*, but without the lining characteristic of that trace fossil. Unlike burrows, which are sometimes branched, the shafts of gas-escape structures should be unbranched. In soft sediment, where material has fallen back into the shaft, the result may be a series of convex-downward laminae shaped like a stack of saucers or cups. Material carried upward by released gas may form a cratered mound at the surface (Shrock, 1948; Reineck and Singh, 1980, p. 57).

Gas-escape structures are common in rapidly deposited sediments having a high organic carbon content, such as microbially laminated, fine-grained carbonate rocks. Bubbles of methane and other gases can result from the decomposition of buried organic matter (Goemann, 1939; Häntzschel, 1941; Hammond, 1978).

Although the descriptions of rainprints and gas-escape structures seem very different here, at the surfaces of beds, the circular pits can look much alike, and can even be confused with vertical burrows (Clarke, 1923). Some vertical burrows can be recognized as such by the presence of linings, which are particularly necessary in incohesive substrates. However, escape structures made by animals may not always be distinguishable from gas-escape structures.

GAS-ESCAPE STRUCTURES AT UNION CHAPEL

Circular pits are very common on trace-fossil-bearing surfaces at the Steven C. Minkin Paleozoic Footprint Site. They are 4 to 11 mm wide and about 1 mm deep, and resemble rainprints, which are common at other tracksites. However, they are not rainprints, but gas-escape structures, as shown by the following observations.

The craters' rims show no sign of spattering. Uneven rims would be evidence for impact (compare Fig. 2); instead, the rims are raised in some cases, but are even (Fig. 1).

The circular pits occur on the same surfaces as undertracks (Fig. 3). Haubold et al. (2005) and Martin and Pyenson (2005) agree that nearly all the Union Chapel tracks are undertracks, that is, the part of a footprint that formed as a series of distorted laminae beneath the surface on which the animal walked. Thus, if they were rainprints, the circular pits cannot have been made during the same tidal cycle as the footprints on the same laminae, because the raindrops would have impacted a layer that was already buried when the animal walked there. However, if the pits are gas-escape structures, then they could have been formed at any time with respect to the undertracks.

In a few cases where vertical sections are available, *the pits can be observed to be only part of a larger vertical structure like a stack of saucers and may even penetrate through several laminae* (Fig. 4). Raindrop impact cannot penetrate deeply enough to produce a vertical stack of disturbed laminae; upward gas escape followed by settling sediment can.

The pits are not associated with mudcracks at Union Chapel. In most other tracksites that have rainprints, mudcracks are common. As shown above, preservation of rainprints requires rather special conditions that also favor the preservation of tracks and mudcracks.

Overlap of circular pits is unusual at Union Chapel (Fig. 5). Raindrops fall at random, so overlap of craters is expected even in a light rain, just as meteor craters overlap on the lunar surface. At Union Chapel, overlap is uncommon even on surfaces bearing many pits. This would be expected of gas-escape structures, where gas bubbles would be expected to follow a previously existing zone of weakness rather than punching through in a new place.

Some pits are associated with Undichna, *a swimming trace*. These bedding planes must have been covered by at least several centimeters of water at the time when the fish swam over it (Martin and Pyenson, 2005).

Circular pits commonly formed directly under tetrapod footprints. Unless a small raincloud follows a tetrapod like Al Capp's cartoon character Joe Btfsplk (Kitchen, 2004), it seems impossible for raindrops to follow a tetrapod's footsteps. However, it is easy for a person walking through a marsh (i.e., increasing the pressure in buried layers) to induce gas-escape structures nearby, sometimes several centimeters to the side (Martin and Rindsberg, 2004).

SIGNIFICANCE

The reinterpretation of "rainprints" as gas-escape structures makes sense in the Union Chapel context. The site was a freshwater intertidal flat within the delta of a large river, as shown by the presence of amphibian trackways, tidal lamination, and other clues (Pashin,

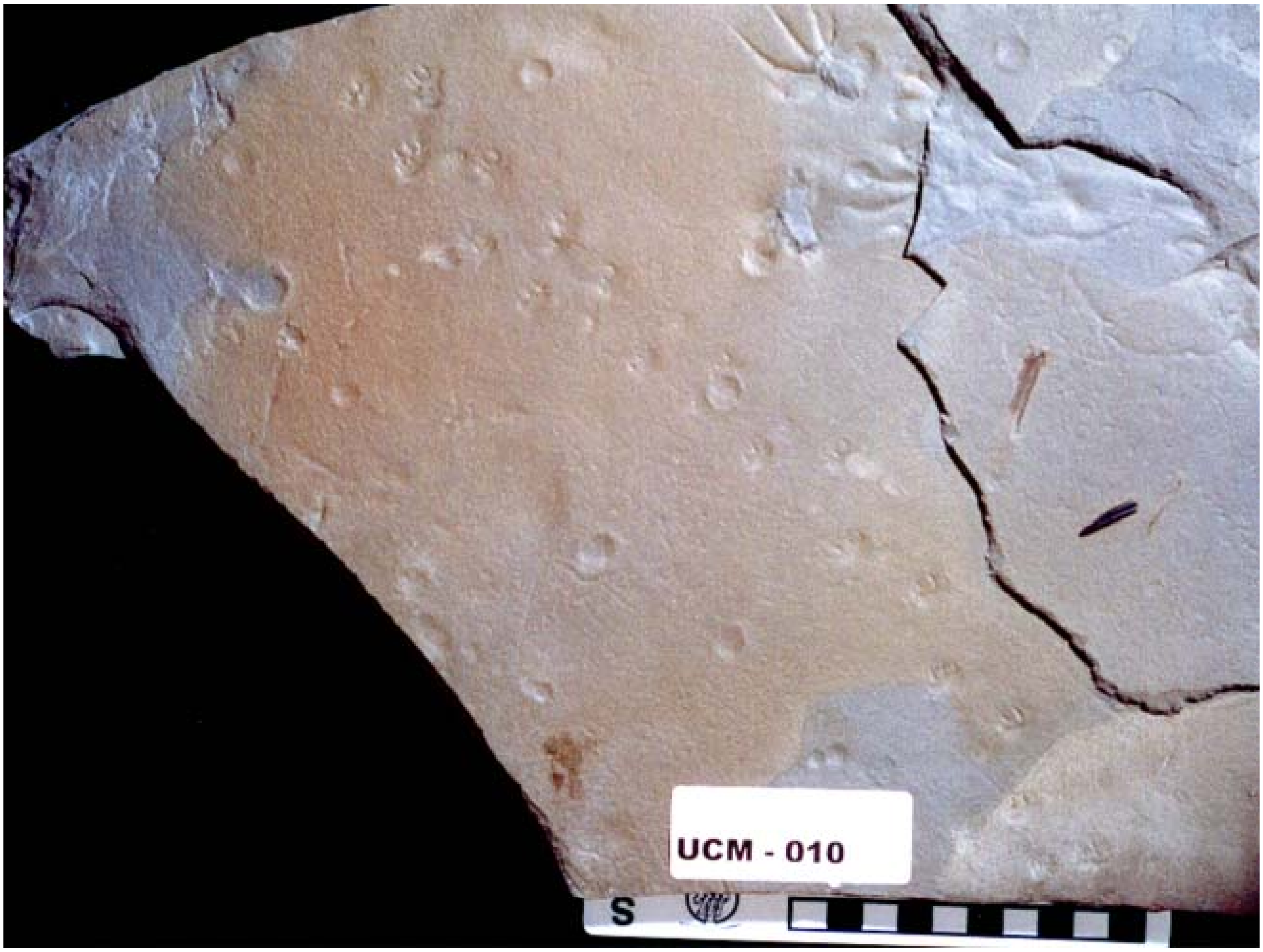

FIGURE 3. Gas-escape structures associated with vertebrate undertracks. UCM 10, collected by Steven C. Minkin.

2005). This is compatible with very rapid deposition in a humid climate. Plant debris is common and the shale is dark, probably due to high carbon content; the shale overlies a coal bed. There would have been ample nutrients to form gases of decomposition in muds that are known from their track taphonomy to have been soft, yet firm enough to hold a foot imprint (Martin and Pyenson, 2005).

Once the mind is cleared of illusory "rainprints," a truer model of the Union Chapel paleoenvironment can be constructed. Without rainprints, there is no evidence of dry substrates in the track-bearing beds. Indeed, Haubold et al. (2005) have shown that tracks made at the substrate surface are so indistinct that the uppermost sediment must have been very soft; only the undertracks show sharp details. This is in keeping with the preference of modern amphibians for moist environments.

As "rainprints," the circular pits were interesting but there was little reason to study them in detail with regard to trackways. As gas-escape structures, the pits are additional clues to sediment coherence, microbial activity, and maturation. Rainprints fall randomly, but gas-escape structures are intimately connected with tetrapod locomotion, and can even be considered as part of their walking traces (Martin and Pyenson, 2005).

The relationships between trackways and gas-escape structures have never been studied in detail at any ancient or modern site. What are the relationships between animal weight and the size and distribution of gas-escape structures? Does it matter whether an animal is walking or running, and whether an animal treads softly or heavily? Can gas-escape structures be reactivated days later in natural environments, as seems likely? What determines the width of the pits? Some of these questions can be answered with Union Chapel material; others can be studied in modern terrestrial environments.

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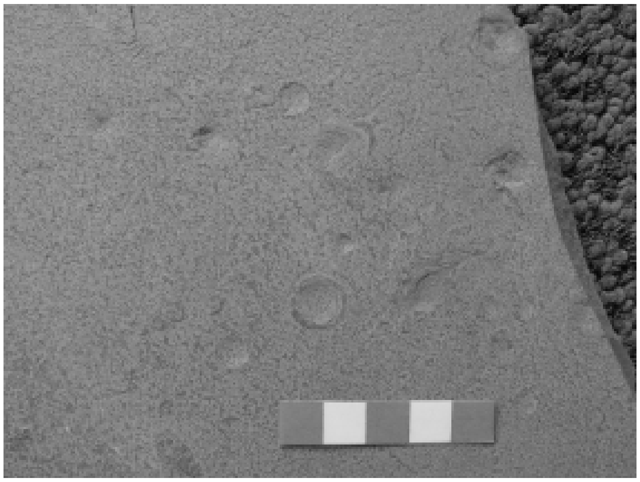

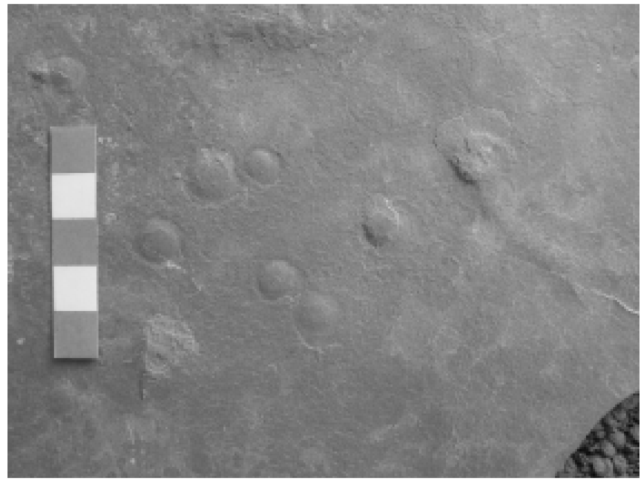

FIGURE 4. Gas-escape structures some of which penetrate several laminae of shale. UCM 1168, collected by David C. Kopaska-Merkel. A (left): Upper surface. B (right): Lower surface.

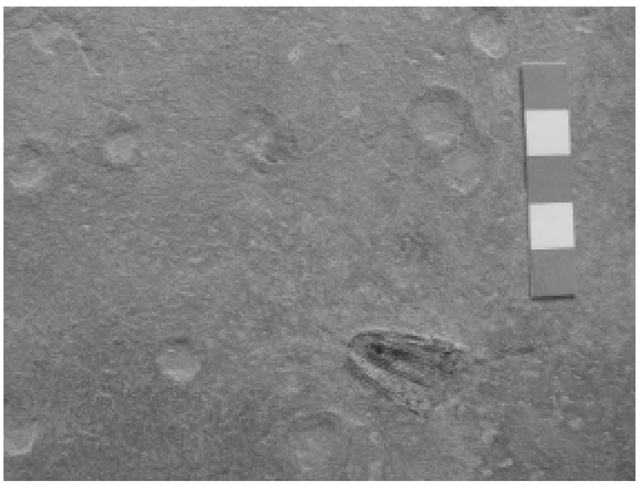

FIGURE 5. Partial overlap of gas-escape structures. Compare Lyell's comments quoted in the text. UCM 2072, upper surface; collected by David C. Kopaska-Merkel.

available. David C. Kopaska-Merkel and W. Edward Osborne reviewed the manuscript.

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