INTRODUCTION

Syndepositional sedimentary structures play a unique role in our ability to interpret the geological record. These features are preserved in situ and record features of an environment that co-occurred with sediment deposition. Interpretation of synsedimentary features, however, relies on adequate natural and experimental analogues to...

Experimental rain prints and gas escape structures as a framework for interpreting circular imprints in shales of the Pottsville Formation (Pennsylvanian, Alabama)

Julie K. Bartley1 | Patrick J. Gilliland2

1Geology Department, Gustavus Adolphus College, St. Peter, MN, USA
2Department of Geosciences, University of West Georgia, Carrollton, GA, USA

Correspondence
Julie K. Bartley, Geology Department, Gustavus Adolphus College, St. Peter, MN, USA.
Email: jbartley@gustavus.edu

Funding information
This research received no external funding and was supported by institutional resources at the University of West Georgia and Gustavus Adolphus College.

Abstract
Coal-bearing, fine-grained clastic rocks of the Pennsylvanian Pottsville Formation contain well-preserved vertebrate and invertebrate trace fossils and disarticulated plant fossils. These fossil-bearing rocks also contain small, circular imprints that resemble raindrop impressions but have also been interpreted as structures formed by gas bubble escape from wet sediment. Because rain prints are associated with arid, subaerially exposed depositional conditions and gas escape structures with water-saturated, organic rich sediments, the interpretation of the circular structures profoundly impacts the palaeoenvironmental reconstruction and interpretation of the life habits of the trace-makers. In this project, rain prints and gas escape structures were produced to compare these two hypotheses regarding mode of formation and to gain insight into interpretations of similar circular pits in the geological record. The results indicate that gas escape structures form most readily in fine-grained sediment under water-saturated conditions, in contrast to rain prints, which form most readily in unsaturated sand. A comparison with experimental structures suggests that the Pottsville shales preserve gas escape structures, not raindrop impressions, suggesting that the environment was rarely desiccated. Because rain prints and gas escape structures are superficially similar, genetic interpretations should not be based on these similarities, but rather on the differences observed between them. Reexamination of circular pits in the sedimentary rock record might require adjustment of environmental interpretations.

KEYWORDS
coal, estuary, experimental sedimentology, gas escape structures, Pottsville Formation, rain prints, tidal flat, vertebrate trackway, Warrior Basin

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2021 The Authors. The Depositional Record published by John Wiley & Sons Ltd on behalf of International Association of Sedimentologists
constrain interpretations of palaeoenvironments. Such actualistic studies, such as the now-classic flume experiments to produce bedforms (Costello & Southard, 1981) are invaluable in establishing specific criteria for recognising and interpreting sedimentary structures. In similar spirit, this study assesses formation of sedimentary structures from an actualistic perspective.

Small, circular pits occur on bedding surfaces in shales, siltstones and sandstones throughout the geological record and have been variously interpreted as rain prints or drip marks (Getty & Hagadorn, 2008; Lanier et al., 1993; Pandey et al., 2014; Woodworth, 1900) and gas escape structures (Rindsberg, 2005). Several previous workers have acknowledged that similarities in shape, scale and sedimentary rock association makes reliable identification difficult (Metz, 1981; Moussa, 1974). Because rain prints are typically associated with arid, subaerially exposed depositional conditions and gas escape structures with water-saturated, organic-rich sediments, the origin of the circular structures profoundly impacts the palaeoenvironmental reconstruction of sedimentary rocks containing these structures and hence interpretations of palaeoecology of associated fossils.

The Steven C. Minkin Palaeozoic Footprint Site of central Alabama contains both well-preserved amniote and invertebrate trace fossils and abundant synsedimentary circular impressions. The locality has been cited as a Konzentrat-Lagerstätte (Hunt et al., 2005) due to the presence of numerous ichnotaxa of vertebrate trackways (Cincosaurus, Nanopus, Attenosaurus) and invertebrate traces (Rindsberg & Kopaska-Merkel, 2005) on bed tops and bases in shales from the Mary Lee coal group. In addition, well-preserved, although disarticulated, diverse plant fossils occur in these beds, representing lycophytes, sphenophytes and pteridosperms (Dilcher et al., 2005). The abundance of fossils makes this locality an excellent window into animal behaviour and ecology on a Pennsylvanian tidal flat. The abundant circular pits occurring in the same beds as the fossils provide an ideal case study for investigating this category of sedimentary structure and an opportunity for actualistic sedimentology to provide insight into their mechanism of formation. Based on field evidence, Rindsberg (2005) concluded that the circular imprints at the site were produced by gas escape, although Buta and Kopaska-Merkel (2016) identified rare structures that are probably rain prints. In this study, both rain prints and gas escape structures were produced experimentally and used to refine criteria useful for distinguishing these two mechanisms that can produce circular pits on bedding planes in fine-grained sediment.

1.1 Geological Setting

During the Pennsylvanian Period, the Alleghanian and Ouachita orogenies occurred as Gondwana collided with Laurentia, closing the Rheic Ocean (Golonka et al., 1994). The rising Appalachian and Ouachita mountains shed debris westward and northward, respectively, into a vast deltaic complex that covered much of northern Alabama, northwestern Georgia, and Tennessee (Pashin, 2005). Thick successions of Pennsylvanian clastic material cap the Palaeozoic succession throughout the Cumberland Plateau and Valley and Ridge Province of the southern Appalachians and are the source of much of the region's coal today. In the Black Warrior Basin, the largely flat-lying coal-bearing strata of the Pottsville Formation (Early Pennsylvanian) contain most of the bituminous coal resources of Alabama (Pashin, 2005).

The Pottsville Formation is a thick (ca 3,000 m) succession of shale, sandstone and coal that thickens to the southwest (Horsey, 1981). The depositional setting of the lower Pottsville has been interpreted as prodelta to back-barrier, with significant marine influence (Horsey, 1981). Lower Pottsville sandstone is compositionally mature and contains some marine fossils; bedforms are consistent with barrier island and tidal channel deposits. Coal beds are thin in the lower Pottsville Formation, although they are locally economically important. In contrast, the upper Pottsville is best interpreted as a delta plain dominated by fluvial processes. Fine to very fine-grained sandstone and shale dominate the upper Pottsville, and sandstones are commonly micaceous, poorly sorted and organic rich. Coal units are thicker, laterally persistent and associated with dark grey, carbon-rich shales (Horsey, 1981).

Abundant, well-preserved vertebrate and invertebrate trace fossils are preserved on bedding planes of thinly bedded shales and siltstones at the Steven C. Minkin Palaeozoic Footprint Site, at the now inactive Union Chapel Mine in Walker County, Alabama. The ichnofossil assemblages have been the subject of intensive amateur and professional collecting efforts (Buta & Minkin, 2005) and several studies have documented the vertebrate trackways (Haubold et al., 2005; Martin & Pyenson, 2005), invertebrate traces and burrows (Lucas & Lerner, 2005; Rindsberg & Kopaska-Merkel, 2005), and flora (Dilcher et al., 2005). The fossil-bearing horizons, sometimes informally called the Cincosaurus beds, are located 1–6 m below the Newcastle coal seam of the Mary Lee coal group, within the upper Pottsville Formation. This part of the Pottsville comprises regionally recognisable depositional cycles that shallow upward from marine shale through shoreline to fluvial-deltaic sandstone to a fluvial-deltaic coal-bearing zone at the top (Pashin et al., 1991). The samples of interest derive from the upper, fluvial-deltaic portion of the sequence, although the precise stratigraphic position is unknown, as nearly all were collected from spoil piles, rather than from the hazardous highwall of the mine. The abundance of amniote trackways, insect trace and body fossils, and terrestrial coal-swamp plants in these beds suggests a freshwater to brackish setting (Kopaska-Merkel &
BARTLEY AND GILLILAND

Buta, 2012); the regular rhythmicity of fine laminae suggests tidal influence (Minkin, 2005). The trace-bearing beds of interest, then, were probably deposited very near base level in an estuarine tidal flat.

2 | MATERIALS AND METHODS

2.1 | Characterisation of shale

Shale samples containing circular impressions were collected from spoil piles containing the *Cincosaurus* beds at the Steven C. Minkin Palaeozoic Footprint Site. Shales were examined by hand lens and low-power microscope to characterise grains and sedimentary structures.

To characterise mineralogy, a subsample from a typical shale bearing circular imprints was taken and powdered with a ball mill. Powders were sprayed onto an amorphous glass fibre filter to obtain random grain orientation. X-ray diffraction patterns were obtained at the X-Ray Diffraction Facility at the University of West Georgia and processed by the Reference Intensity Ratio Method (Chung, 1975).

2.2 | Experimental sedimentary structures

A series of experiments was conducted using different combinations of mud, silt and sand; these were done by students, both as part of an individual research project (Experiment 1, PJG) and as classroom experiments (Experiment 2, see Acknowledgments). Sediment was obtained from several sources and characterised for each experiment (see below).

Experiment 1 used three sources for sediment. Clay-rich mud, containing little silt (called ‘mud’ in these experiments), was obtained from the sediment settling tanks of the Carroll County Water Authority, where suspended sediment is gravity-separated from water of the Little Tallapoosa River as part of the drinking water treatment process. Sediment was treated with bleach to remove organic matter prior to use. A silty, fine-grained sand (called ‘silty sand’ for these experiments, to distinguish from clean sand) was obtained from backswamp areas of Buffalo Creek in Carroll County, Georgia. Well-rounded fine quartz, was used as the clean sand fraction. Combinations of these three sediment types were used in Experiment 1. Mud and silty sand were mixed to produce mud:silty sand ratios between 4:1 and 1:4. Mud and clean sand were mixed in a 1:1 ratio. Finally, clean sand and mud were used alone. For each experiment, sediment was placed in an aluminum baking dish to a depth of ca 3 cm. Three water levels were used, to simulate degrees of exposure: (a) unsaturated, subaerially exposed; (b) saturated, subaerially exposed; (c) saturated and shallowly (<0.5 cm) submerged.

Rain prints were produced in three ways: (a) exposing sediment to natural rainfall; (b) creating droplets with a garden hose and sprayer to create a shower of droplets; (c) using a large syringe filled with water to create one or a few droplets at a time.

Gas escape structures were produced by injecting a slurry containing water, sugar and dry yeast into the lower portion of a water-saturated sediment tray. Each yeast solution contained 100 ml of warm water, 30 g of sugar and 1 packet of dry yeast. The mixture provided moisture and nutrients to the yeast, stimulating production of carbon dioxide via fermentation and gas bubble production, thereby simulating natural release of gases by microbial communities below the sediment-water interface. Approximately 10 ml of solution was injected slowly, to avoid disrupting the sediment surface, at each of four to six locations in each pan. Pans were left undisturbed until bubbles formed, between 1 and 48 hr after injection, depending on sediment consistency, room temperature and yeast activity.

Experiment 2 was conducted by students in a geology course at Gustavus Adolphus College, in order to further explore experimental conditions that might produce gas escape structures. These students examined only gas escape structures, using a different set of sedimentary substrates. For Experiment 2, mud was obtained by sampling local glacial till, the main source of suspended load in local watersheds. This sediment contains more silt compared to the mud collected from the Little Tallapoosa River. Sand was removed from field-collected sediment by dry sediment through a 63 µm sieve. An unsieved fraction containing some fine sand was also used (called ‘till’ in this experiment). Commercially available play sand, composed of well-sorted, well-rounded fine quartz, was used as the clean sand fraction. In Experiment 2, gas escape structures were generated only in water-saturated exposed or shallowly submerged sediment.

3 | RESULTS

3.1 | Characterisation of Pottsville shale and circular pits

Shales bearing circular pits are medium grey in colour and occur as flaggy plates 1–3 cm thick in the spoil piles from which they were collected. Shales are moderately to well-laminated with laminae <1 to 3 mm thick. Grain sizes are dominantly clay, with subordinate silt. Bed tops are finer, with micaceous clay capping most lamina sets. X-ray diffraction results (Table 1) indicate a mixture of quartz, muscovite, feldspars and clay minerals, consistent with hand sample observations.

Circular pits are relatively common features in the shales of the footprint-bearing horizons. Imprints occur
most commonly as pits on upper bedding surfaces (concave epirelief), generally 2–12 mm in diameter, and 0.5–2 mm deep (Figure 1A,B). Pits are also observed in convex hyporelief, on the lower surfaces of beds (Figure 1C). Additionally, bed tops sometimes show circular structures in convex epirelief (Figure 1D). Concave pits on bed tops may be surrounded by a raised rim up to 1 mm in height (Figure 1B through G). Circular structures overlap one another occasionally and rarely show interference or cross-cutting relationships (Figure 1B,E). Pits can occur on the

| Mineral   | Weight % |
|-----------|----------|
| Quartz    | 39.4     |
| Andesine  | 25.5     |
| Orthoclase| 1.5      |
| Kaolinite | 17.2     |
| Muscovite | 16.2     |
| Vermiculite| 0.2    |

**FIGURE 1** Circular imprints from the Pottsville Formation, Steven C. Minkin Palaeozoic Footprint Site, Walker County, Alabama. Images were accessed from the Photographic Trackway Database (Buta & Crocker, 2005), and specimen numbers in the database are indicated: (A) Bedding plane top surface with typical circular imprints preserved in concave epirelief (UCM 1631); (B) Imprints with diameter >1 cm, with clear raised rims, evidence for interference (top centre of photograph), and exhumation of layers (UCM 1901); (C) Lower surface of a bedding plane showing imprints preserved in convex hyporelief (UCM 043); (D) Upper bed surface showing *Cincosaurus* trackway and imprints preserved in both concave epirelief (top arrow) and convex epirelief (bottom arrow). Trackway indicates facing direction for slab (UCM 037); (E) Upper bed surface with *Cincosaurus* trackway and a linear array of circular imprints. Arrow indicates interference between two structures (UCM 040); (F) Upper bed surface with linear array of circular imprints associated with a vertebrate trackway (UCM 010); (G) Rimmed imprints with both concave and convex relief, showing coarser material toward pit centres (UCM 1432). Scale bars are 1 cm.
same surfaces as vertebrate tracks and occasionally occur in linear arrays associated with trackways (Figure 1E,F; see also Rindsberg, 2005, Figure 3). Examination of circular pits in cross-section suggests lamina disruption several millimetres below the pit surface; in addition, craters commonly expose several stacked laminae (Figure 1B), and some pits show coarser material in their centres (Figure 1G).

### 3.2 Experimental sedimentary structures

Experimental rain prints produced by all three methods detailed above (natural rain, spray from a hose and drip from a syringe) produced similar structures. Grain size and water content of the substrate exerted primary controls on the formation of rain prints (Table 2). Rain prints formed most reliably in undersaturated, subaerially exposed substrates containing at least some silt or sand.

Experimentally produced rain prints range in size depending upon water droplet size and velocity. Fine spray produces smaller and shallower pits; large droplets produce larger, deeper pits. Natural rainfall and spray from a garden hose produce a range of pit sizes. Water dropped from a greater height (e.g. syringe held at different heights from the substrate) produces larger droplets. Overlap of pits is common, as is spatter, where smaller pits surround larger ones in an irregular pattern (Figure 2).

Experiments generating gas within sediment also produced an array of structures. Gas escape structures were produced only in water-saturated sediment that was either subaerially exposed or had a thin layer of standing water atop the sediment. Structures formed most reliably when a thin layer (1–2 mm) of standing water covered the sediment surface (SS conditions in Table 2). Undersaturated sediment did not produce gas escape structures regardless of grain size. Silt-poor mud and clean sand rarely preserved gas escape structures (Table 2), although Experiment 2 generated persistent structures in clean sand under conditions of subaerial exposure (Table 2).

Gas escape structures formed first as convex structures at the sediment top, which then collapsed to form concave pits (Figure 3). Disruption penetrated many layers and could occur within the sediment as well as at the sediment-water or sediment-air interface. Structures generally did not overlap, although a few instances of overlap did occur. Pits were typically between 2 and 10 mm in diameter, with larger structures forming when gas escaped from a particular point on the sediment surface continuously for several minutes. Rims were common but not ubiquitous features (Figure 3), and spatter was not observed. Collapse of pit edges was common, particularly when mud:silt ratios

| Sediment type       | Exp. | Water | Rain prints       | Gas escape       |
|---------------------|------|-------|-------------------|------------------|
| Mud (silt-poor)     | 1    | U     | Do not form       | Do not form      |
| Mud (silt-poor)     | 1    | SE    | Form but collapse | Form but collapse|
| Mud (silt-poor)     | 1    | SS    | Do not form       | Form but collapse|
| Mud (silt-rich)     | 2    | SE    | Form but collapse | Form             |
| Mud (silt-rich)     | 2    | SS    | Form but collapse | Form             |
| Mud:silty sand > 2:1| 1    | U     | Form              | Do not form      |
| Mud:silty sand > 2:1| 1    | SE    | Form rarely       | Form but collapse|
| Mud:silty sand > 2:1| 1    | SS    | Do not form       | Form but collapse|
| Mud:silty sand ≤2:1 and >1:2| 1 | U | Form              | Do not form      |
| Mud:silty sand ≤2:1 and >1:2| 1 | SE | Form rarely       | Form             |
| Mud:silty sand ≤2:1 and >1:2| 1 | SS | Do not form       | Form             |
| Mud:silty sand ≤1:2 | 1    | U     | Form              | Do not form      |
| Mud:silty sand ≤1:2 | 1    | SE    | Form rarely       | Do not form      |
| Mud:silty sand ≤1:2 | 1    | SS    | Do not form       | Do not form      |
| Till (mud-silt-sand)| 2    | SE    | Do not form       | Form             |
| Till (mud-silt-sand)| 2    | SS    | Do not form       | Form             |
| Clean sand          | 1    | U     | Form              | Do not form      |
| Clean sand          | 1    | SE    | Do not form       | Do not form      |
| Clean sand          | 1    | SS    | Do not form       | Do not form      |
| Clean sand          | 2    | SE    | Do not form       | Form             |
| Clean sand          | 2    | SS    | Do not form       | Do not form      |
approached 2:1. Pits occasionally formed curvilinear arrays, but unpredictable arrangements of structures was much more common.

4 | DISCUSSION

Experimentally produced gas escape structures differ from experimentally produced rain prints. These distinctions form a set of characters that can be used to interpret circular imprints in sedimentary rocks and suggest that the circular imprints in the Pottsville Formation are gas escape structures.

4.1 | Recognising rain prints

Rain prints under experimental conditions form most reliably when sediment is undersaturated and contain at least some silt or sand. Rain prints do not form under subaqueous conditions, because the impact of the falling water droplet is absorbed by water, rather than by sediment. In addition, water-saturated sediment produces and preserves rain prints only occasionally (Table 2). These experimental conditions are aligned well with previous observations of rain prints (Klein, 1963; Metz, 1981) in which rain prints are associated with evidence for subaerial exposure in sedimentary rocks containing sand. The results of these experiments suggest that rain prints would be rare in saturated sediment and absent in subaqueous conditions and might be less common in muddy sediment. However, rain prints with other key features, such as spatter, have been observed to form in mud (Remin et al., 2014); rain prints also occur, albeit rarely, in Pottsville shales (cf. Buta & Crocker, 2005; Buta & Kopaska-Merkel, 2016), suggesting that these experiments did not capture the full range of natural conditions.

The resultant prints have a set of features beyond circularity that can assist in recognition. First, because they are impact structures, they always form as pits on bed tops; thus, on bed tops, they are preserved in concave epirelief. Where pits are filled by sediment from the overlying bed, they are
preserved in convex hyporelief. Rims are common, as is spatter (Figure 2). Larger rain prints, which are produced by larger droplets, are deeper than smaller rain prints.

### 4.2 Recognising gas escape structures

Gas escape structures are somewhat challenging to produce experimentally, but also appear to form and persist in a relatively limited set of conditions, which are largely distinct from the set of conditions in which rain prints typically form. Gas escape structures fail to form in sediment with a clay:silt ratio greater than 2:1 and are difficult to form in sand. Thus, formation of gas escape structures appears to require a substrate with moderate cohesion and relatively low permeability, probably because the sediment must be impermeable enough for gas to build up in the subsurface and produce a bubble while being cohesive enough to preserve a structure once it forms. Against this backdrop, the preservation of gas escape structures in clean sand (Table 2, Experiment 2) stands out as an interesting exception. The commercial play sand obtained in Experiment 2 was a different brand than that obtained in Experiment 1, and the sand was locally sourced from the Cambrian Jordan Sandstone. This sand is finer grained than many play sands and may have had a lower permeability than the play sand obtained for Experiment 1. Thus, the production of gas escape structures in only one clean sand trial probably indicates that gas escape structures can form in sand but are predicted to be somewhat rarer than in sediment with lower permeability. Substrates with higher permeability typically permit the escape of gases without pressure build-up. In addition, a substrate that is water-unsaturated permits dispersion of gas into air-filled pores, without the development of bubbles. Conversely, when clay:silt ratios are higher than about 2:1, bubbles form and escape but are not preserved, as the substrate collapses. No gas bubbles or escape structures were generated in unsaturated silt-poor mud.

The water-saturated conditions required to form gas escape structures stand in contrast to the unsaturated conditions ideal for rain print formation. It is worth noting that rain prints can form in saturated, subaerially exposed muddy silts and sands. Such prints were observed in only one experimental trial and it is possible that this substrate was actually undersaturated at the time of print formation. Similarly, circular prints in a silt or sand-dominated sedimentary rock would probably have formed by rain, rather than by gas escape.

Like rain prints, gas escape structures have a set of features beyond circularity that can aid recognition in sedimentary rocks. First, because the force to generate the sedimentary structure comes from below, a gas escape structure can leave a record that crosses several horizons below the sediment-water interface. This structure may be convex upward in the subsurface, and only become concave upward when the gas bubble reaches the sediment-water interface and produces a collapse feature—a sinkhole in miniature. Because these features are not generated at the sediment surface, a bedding plane in a rock sample might intersect a gas escape structure at some point other than its ultimate termination at the ancient sediment surface. Hence, gas escape structures observed in a sedimentary rock can be expressed in convex hyporelief, concave hyporelief, concave epirelief or convex epirelief. Adjacent structures on a bedding plane could be produced at different times, producing a mixture of forms on a single surface. Some experimentally produced gas escape structures were rimmed, and rims often collapsed. Thus, gas escape would be expected to produce a mixture of rimmed and unrimmed structures throughout a bed (Figure 1B).

Additionally, upward movement of gas can entrain sediment, bringing material from the bottom of a lamina set toward the top. In graded laminae, this process will move coarser material into a finer layer. While graded laminae were not examined experimentally, upward movement of material toward the sediment-water interface was observed. This process might produce a circular pit with coarser material toward the interior of the pit (Figure 1G).

### 4.3 Interpreting circular imprints

Because rain prints and gas escape structures are superficially similar, genetic interpretations should not be based on these similarities, but rather on the differences observed between these structures. Both rain prints and gas escape structures should, in general, be circular in outline, although rain may form elliptical prints under windy conditions. In addition, the presence of rims is not diagnostic, as both rain impact and gas escape can produce rimmed pits.

Based on this study, it is argued that circular imprints occurring in arenites would be best interpreted as rain prints and that the presence of these structures suggest subaerial exposure and undersaturated sediment conditions at the time the prints were formed. It is worth noting that other impact structures may be included in this category, including drip marks and hail prints, as the mechanism of formation is similar. In addition, an interpretation of rain prints should include additional evidence from the sedimentary rock, beyond the presence of hemispherical concave impressions on bed tops. These features, many of which were noted previously (Rindsberg, 2005), are supported as diagnostic features by this work:

- Variable pit size across a surface, generally between 5 and 20 mm, although hail prints have the potential to produce a larger range of sizes (Remin et al., 2014).
- Correlation between pit diameter and depth, as larger features represent impact of larger droplets.
• Prints occur only in concave epirelief and convex hyporelief.
• Structures commonly overlap.
• Spatter is common (Remin et al., 2014), although it need not occur on every impact mark.
• Surfaces with rain prints may contain other subaerial exposure features.

In contrast, a presumptive diagnosis of gas escape is preferred for muddy rocks containing circular imprints. Although these experiments suggest that it is possible for rain prints to be preserved in such a rock, it is difficult to form them; therefore, additional evidence must be brought to bear before diagnosing circular imprints in mudstone as rain prints. Furthermore, these results suggest additional features to aid in the diagnosis of gas escape structures:

• Imprint diameter is variable, with little correlation between pit diameter and depth.
• Structures may crosscut another or show evidence of interference.
• Structures may penetrate several layers of sediment.
• Structures may have coarse grains in the centre, formed when coarser material is entrained by upward movement of gas.
• Structures may occur as convex or concave structures on bed tops or bed bases.
• Imprints may form clusters or linear arrays; for example, linear arrays may form because of bubble escape associated with animals walking on the sediment surface.

5 CONCLUSIONS

The experiments described here support the interpretation of Rindsberg (2005), that nearly all the circular imprints from the Pottsville Formation are gas escape structures, rather than rain prints. The host rock, a silty mudstone with muddy laminated tops, is unfavourable for the formation and preservation of rain prints, but would be expected to reliably preserve gas escape structures based on results of these experiments. In addition, several details of these circular imprints are consistent with gas escape or inconsistent with an interpretation of rain impact.

• Spatter is not observed.
• Linear arrays and clusters of imprints are common (Rindsberg, 2005) (Figure 1E,F).
• Structures penetrate several layers of sediment and imprints frequently have coarser material at their centres (Figure 1G).
• Structures are observed in convex hyporelief, concave epirelief and convex epirelief (Figure 1B,C,G).

The Pottsville shales show no independent evidence for subaerial exposure, but do show independent evidence for water saturation, in the form of undertracks and collapsed edges of footprints (Haubold et al., 2005; Rindsberg, 2005). Indeed, circular pits are often associated with tracks (see images in Buta & Crocker, 2005); these experiments support the notion that pressure exerted by walking tetrapods may have stimulated gas escape near the trackways.

Although the difference in inferred water depth between a rain printed surface (exposed and undersaturated) and a surface containing gas escape structures (saturated and exposed to shallowly submerged) is minimal, the environmental implications are substantial. The estuary or tidal flat suggested by the presence of gas escape structures would be submerged daily, while a subaerially exposed, rain printed surface might only receive intermittent water saturation, spending most time undersaturated. A firm interpretation of gas escape as the mechanism for generating the circular imprints, as suggested by Rindsberg (2005) and supported by experiments in this study, requires us to view the environment as one that was probably submerged at least daily, and was watersaturated most of the time. Thus, the Pottsville trace makers, both invertebrate and vertebrate, were traversing a wet, tidally influenced shoreline, rather than an intermittently desiccated surface. Other Pennsylvanian trackway sites have been interpreted as subaerially exposed, and the presence of rain prints has been used as a primary line of evidence supporting subaerial exposure (Lanier et al., 1993). Considering these experiments and the interpretation of the Pottsville structures, a reexamination of circular prints in fine-grained, laminated strata at other localities might yield useful information about the depositional environment.

Finally, these experiments lay out a set of criteria that permit future workers to better identify the probable origins of circular pits in sedimentary strata. The water-saturated conditions required to form gas escape structures stand in contrast to the unsaturated conditions ideal for rain print formation, suggesting that co-occurrence of these structures is rare. In addition, because rain prints and gas escape structures are superficially similar, genetic interpretations should not be based on these similarities, but rather on the differences observed between these structures.

ACKNOWLEDGEMENTS

We are grateful to the members of the Alabama Paleontological Society who helped us locate examples of circular imprints, and especially A.K. Rindsberg and A.J. Martin who stimulated this project with their questions and observations on the outcrop. The manuscript was greatly improved by the contributions of two anonymous reviewers. J.K.B. acknowledges the efforts of the students in her 2011 Evolution of the Earth course, who conducted Experiment 2
as a class project and demonstrated that this experiment could be replicated. L. Reiners and T. Eischen assisted in producing additional structures for analysis and photography. The Carroll County Water authority provided fine-grained sediment for Experiment 1.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Conceptualisation and investigation, P.J.G. and J.K.B.; writing, supervision, and project administration, J.K.B. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID
Julie K. Bartley https://orcid.org/0000-0001-8686-0906

REFERENCES
Buta, R.J. & Crocker, D.A. (2005) Trace fossils of the Steven C. Minkin Paleozoic Footprint Site, Walker County, Alabama: Interactive and interpretive website [online]. http://kudzu.astr.ua.edu/scm/
Buta, R.J. & Kopaska-Merkel, D.C. (2016) Footprints in stone: Fossil traces of coal-age tetrapods, Tuscaloosa, AL: University of Alabama Press.
Buta, R.J. & Minkin, S.C. (2005) The salvaging and documentation of trace fossils from the Union Chapel Mine. In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 19–27.
Chung, F.H. (1975) Quantitative interpretation of X-ray diffraction patterns of mixtures. III. Simultaneous determination of a set of reference intensities. Journal of Applied Crystallography, 8, 17–19.
Costello, W.R. & Southard, J.B. (1981) Flume experiments on lower-flow-regime bed forms in coarse sand. Journal of Sedimentary Research, 51, 849–864.
Dilcher, D.L., Lott, T.A. & Axsmith, B.J. (2005) Fossil plants from the Union Chapel mine, Alabama. In: Buta, R.J., Rindsberg, A.K., and Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 153–168.
Getty, P.R. & Hagadorn, J.W. (2008) Reinterpretation of Climacichnites Logan 1860 to include subsurface burrows, and erection of Musculopodus for resting traces of the trailmaker. Journal of Paleontology, 82, 1161–1172.
Golonka, J.R., Ross, M.I. & Scotese, C.R. (1994) Phanerozoic paleoecologic and paleoclimatic modeling maps. In: Embry, A., Beaumont, W. & Glass, D. (Eds.) Pangea, global environments and resources. Canadian Society of Petroleum Geologists Memoir, 17, 1–47.
Haubold, H., Allen, A., Atkinson, T.P., Buta, R.J., Lacefield, J.A., Minkin, S.C. et al. (2005) Interpretation of the tetrapod footprints from the Early Pennsylvanian of Alabama. In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 75–111.
Horsey, C.A. (1981) Depositional environments of the Pennsylvanian Pottsville Formation in the Black Warrior Basin of Alabama. Journal of Sedimentary Petrology, 51, 799–806.
Hunt, A.P., Lucas, S.G. & Pyenson, N.D. (2005) The significance of the Union Chapel Mine Site: A lower Pennsylvanian (Westphalian A) ichnological konzentratlagerstätte, Alabama, USA. In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 3–14.
Klein, G.D. (1963) Bay of FUNDY intertidal zone sediments. Journal of Sedimentary Research, 33, 844–854.
Kopaska-Merkel, D. & Buta, R. (2012) Field-trip guidebook to the Steven C. Minkin Paleozoic footprint site, Walker County, Alabama, Birmingham, Alabama Paleontological Society.
Lanier, W.P., Feldman, H.R. & Archer, A.W. (1993) Tidal sedimentation from a fluvial to estuarine transition, Douglas Group, Missourian-Virgilian, Kansas. Journal of Sedimentary Research, 63, 860–873.
Lucas, S.G. & Lerner, A.J. (2005) Lower Pennsylvanian invertebrate ichnofossils from the Union Chapel mine, Alabama: A preliminary assessment. In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 147–152.
Martin, A.J. & Pyenson, N.D. (2005) Behavioral significance of vertebrate trace fossils from the Union Chapel site. In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, 59–73.
Metz, R. (1981) Why not raindrop impressions? Journal of Sedimentary Research, 51, 265–268.
Minkin, S.C. (2005) Paleoenvironment of the Cincosaurus beds, Walker County, Alabama. In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 31–38.
Moussa, M.T. (1974) Raindrop impressions? Journal of Sedimentary Research, 44, 1118–1121.
Pandey, D.K., Uchman, A., Kumar, V. & Shekhawat, R.S. (2014) Cambrian trace fossils of the Cruziana ichnofacies from the Bikaner-Nagaur Basin, north western Indian Craton. Journal of Asian Earth Sciences, 81, 129–141.
Pashin, J.C. (2005) Pottsville stratigraphy and the Union Chapel limestone member, Black Warrior Basin, Alabama. In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 39–58.
Pashin, J.C., Ward, W.E.I., Winston, R.B., Chandler, R.V., Bolin, D.E., Richter, K.E. et al. (1991) Regional analysis of the Black Creek-Cobb coalbed-methane target interval, Black Warrior Basin, Alabama. Alabama Geological Survey Bulletin, 145, 1–147.
Remin, Z., Krogulec, T., Drela, T. & Surowski, M. (2014) The recognition of hailstone impressions in clay-rich sediment: Experimental results and relation to the Neoproterozoic case. Journal of Sedimentary Research, 84, 543–551.

Rindsberg, A.K. (2005) Gas-escape structures and their paleoenvironmental significance at the Steven C. Minkin Paleozoic Footprint Site (Early Pennsylvanian, Alabama). In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 177–183.

Rindsberg, A.K. & Kopaska-Merkel, D.C. (2005) Treptichnus and Arenicolites from the Steven C. Minkin Paleozoic footprint site (Langsettian, Alabama, USA). In: Buta, R.J., Rindsberg, A.K. & Kopaska-Merkel, D.C. (Eds.) Pennsylvania footprints in the black warrior Basin of Alabama. Birmingham: Alabama Paleontological Society, Alabama Paleontological Society Monograph, 1, pp. 121–141.

Woodworth, J. (1900) Vertebrate footprints on Carboniferous shales of Plainville, Massachusetts. Bulletin of the Geological Society of America, 11, 449–454.

How to cite this article: Bartley JK, Gilliland PJ. Experimental rain prints and gas escape structures as a framework for interpreting circular imprints in shales of the Pottsville Formation (Pennsylvanian, Alabama). Depositional Rec. 2021;00:1–10. https://doi.org/10.1002/dep2.142