Did evaporite cements and infiltrated silts assist preservation of reptile tracks in Permian desert sediments?

Kirsten E. Flett a,b,⁎, Carol Hopkins c, Jessica H. Pugsley a, Alexander T. Brasier a

a School of Geosciences, University of Aberdeen, Scotland AB24 3UE, UK
b School of Earth Sciences, University of Bristol, Life Sciences Building, Tyndall Avenue, Bristol BS8 1TQ, UK
c PetroEDGE, Conwy, Wales, UK

A R T I C L E   I N F O

Article history:
Received 17 November 2023
Received in revised form 24 January 2024
Accepted 26 January 2024
Available online 2 February 2024

Editor: Dr. Catherine Chagas

Keywords:
Interdune
Halite
Vertebrate trace fossil
Silt infiltration
Hopeman Sandstone

A B S T R A C T

Many Permian desert tracks are found in formations dominated by rather homogeneous aeolian quartz arenites. This raises questions around how they got preserved. Here we test the hypothesis that strong palaeoenvironmental controls affect style and quality of footprint preservation in Permo-Triassic desert settings. To answer this, several examples of tracks and trackways from Moray, Scotland, are described in the context of their host sedimentary successions. We then discuss petrographic clues in the specific track-bearing layers with regard to taphonomy. Two key sections were logged and sampled at Hopeman Beach: (i) Hopeman Coastal Section A, being a site from which tracks have previously been recovered; and (ii) Hopeman Coastal Section B, a section still exhibiting several in-situ tracks. Tracks were also examined on the surfaces of metre-scale quarried blocks within Clashach Quarry. Logging was also undertaken at quarries in Quarrelwood near Elgin. Collected samples were examined optically and with a scanning electron microscope. Hopeman Coastal Section A exhibits convolute bedding best interpreted as dewatering structures; a putstular bed that could be linked to growth of evaporite crystals impinging on a sediment-binding microbial mat; adhesion ripples formed by dry, wind-blown sand sticking to a wet or damp surface; and laterally continuous pebble layers that are the result of ephemeral sheet floods. The oscillation-rippled layer from which NMS footprint specimen G.1997.60.1 was extracted exhibits a halite cement and petrographic evidence for re-worked halite, and these rippled sediments were most likely de-positioned in an interdunal lake. Hopeman Coastal Section B similarly exhibits metre-scale planar cross beds and occasional coarser-grained lag deposits that are consistent with aeolian dunes that were episodically inundated by sheet floods. Samples containing halite and lesser amounts of gypsum or anhydrite were collected from the same layer as the in-situ Hopeman Coastal Section B tracks. Metre-scale planar cross-bedded quartz arenites of Cutties Hilllock quarry were clearly deposited in an aeolian dune setting. Some sands in the Cutties Hilllock Sandstone with scoured bases were aeolian sediments that were reworked by fluvial processes. We conclude that this study demonstrates three different modes of track preservation in the Permian Moray area: (i) indentation of near-surface layers constituted by particles of fine silt that in many cases had infiltrated between sand grains of aeolian dunes; (ii) trackways in sediments deposited around the margins of lakes in the interdunes, with early cementation by evaporites, noting that in the studied cases the halite cement might have helped preservation of the tracks in the sense of long-term fossilisation, but probably not anatomical preservation (i.e. quality of fidelity); and (iii) indentation of clays that had been deposited in some interdunal lakes.

© 2024 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction — Permian reptile tracks

Tracks of desert-dwelling reptiles have been reported from across the Permo-Triassic sediments of Pangea (see Voigt and Lucas, 2018; Klein and Lucas, 2021), including for example from South Africa (Marchetti et al., 2019a); North America (Brickenden, 1852; Huxley, 1859; Murchison, 1859; Huxley, 1877; Watson and Hickling, 1914; Mckeever, 1991; Hopkins, 1999a); Europe (Haubold and Katzung, 1978; Gand and Durand, 2006; Voigt and Haubold, 2015). Some of the first studied localities were from Scotland, with good examples around Dumfries (Grierson, 1828; McKeever and Haubold, 1996; Marchetti et al., 2019c) as well as long-known but comparatively less well reported examples in Moray (Brickenden, 1852; Huxley, 1859; Murchison, 1859; Huxley, 1877; Watson and Hickling, 1914; Mckeever, 1991; Hopkins, 1999a). Indeed more than 400 trackways were discovered by quarrying in Moray between 1996 and 2004, 43 % of which exhibited tail drags, with...
individual tracks ranging from 10 mm to 260 mm wide (Hopkins, 2004). Most tracks are digitigrade or foreshortened so track length is not a reliable indicator of track size in these Moray localities. However unlike, for example, dinosaur tracks found in Triassic fluvial settings, where tracks are preserved and visible because of strongly contrasting grain size differences between clays and coarse sands (e.g. Szewczyk et al., 2020), many Permain desert tracks – including those of Moray – are found in formations apparently dominated by compositionally and texturally mature (thus rather homogenous) aeolian quartz arenites. This raises questions around how they got preserved in the rock record?

Previous studies have suggested that high fidelity footprints in Permain terrestrial strata of Dumfries are actually preserved in clay-enriched layers (McKeever, 1991, 1994) whereas those of the homogenous quartz arenites of the Hopeman Sandstone of Moray are supposedly of lower fidelity and less well preserved (McKeever, 1991). This difference could imply that palaeoenvironmental controls on both morphological quality and chances of preservation of tracks in ancient desert environments are to be expected. Yet a study of the similarly homogeneous Permain Coconino Sandstone of the USA suggested that underprints (impressions caused by deflection of laminae below the surface on which the animal walked) can preserve relatively well-formed tracks in unconsolidated, clay-poor quartz arenites (Brand and Kramer, 1996).

It is therefore interesting to more closely examine the hypothesis that strong palaeoenvironmental controls on style and quality of track preservation are found in Permian desert settings. Exploring this further now requires studies that place tracks in their palaeoenvironmental context. Several works have had a dominant focus on either the tracks or their likely makers (e.g. Hunt and Lucas, 2006; Clark and Corrance, 2009; Voigt and Lucas, 2018; Marchetti et al., 2019b); however most of the tracks described here are not of sufficient quality to be able to give an accurate systematic description that would support classification. Some works also focus on the ancient sedimentary environment (Williams, 1973; Clemmensen, 1987), but (with some exceptions, e.g. Szewczyk et al., 2020) relatively few have recently examined the context of how Permain tracks were ultimately preserved within their ancient sedimentary environments or have used petrographic techniques to help interpret causes of track preservation. Our focus here is therefore not on the ichnology or maker of the prints but on the modes of preservation of those prints through geological time.

Aiming to decipher the factors leading to favourable preservation of tracks in the Hopeman Sandstone, we here describe several examples of tracks and trackways and the sedimentology of their host sediment successions. We focus on some representative collected specimens, plus some tracks exposed on metre-scale blocks extracted through recent quarrying activity. We then discuss petrographic clues in the specific track-hosting layers that highlight how they were preserved, illuminating possible palaeoenvironmental factors favouring vertebrate track preservation in terrestrial Permain desert successions.

1.1. Geological background: the Hopeman and Cutties Hillock Sandstones

The Hopeman Sandstone Formation is dominated by metre-scale planar cross-bedded quartz arenites, exposed in coastal sections and quarries in the vicinity of Hopeman to the north of Elgin (Fig. 1). Palaeoenvironments were interpreted as aeolian star dunes with interdunal areas by Clemmensen (1987). True bedding is not easy to discern, but the dip is very gentle, such that the spatial dune morphologies are interpretable, but the coastal exposure is of relatively limited stratigraphic thickness. The Hopeman Sandstone Formation is dated as Upper Permian on the basis of a dicynodont skull found at Clashach Quarry (reported by Hopkins, 1999a, 1999b, and described by Clark, 1999).

Around 7 km inland, within Quarrelwood to the west of Elgin, is a further exposure of late Permain sediments (Fig. 1). Following Benton and Walker (1985), the Cutties Hillock Sandstone Formation is treated here as a potentially different unit from the Hopeman Sandstone Formation. It has an unconformable lower contact with the Rosebrae Beds of the Old Red Sandstone (Benton and Walker, 1985). It comprises pebbly beds at the base, interpreted by Benton and Walker (1985) as sheet flood deposits, overlain by cross-beded quartz arenites interpreted as barchan dune deposits (Benton and Walker, 1985). Reptile remains of Elginia, Gordania and Gelia were found in Cutties Hillock Quarry, although comparatively few tracks have been reported (Benton and Walker, 1985). Some tracks discovered “300 yards W.N.W. of ‘Elginia’ Quarry, Cutties Hillock” were illustrated by Watson and Hickling (1914), showing that examples are known from this area.

Trace fossils of the Hopeman Sandstone are reported to include the ichnogenera Chelichnus, Laoporus, Palmichnus and Herpetichnus (McKeever, 1991), although this Permian tetrapod ichnotaxonomy was revised by McKeever and Haubold (1996) who suggested these were all better referred to as species of Chelichnus. The validity of Chelichnus has recently been further challenged (Marchetti et al., 2019b, 2019c). Despite their importance and their discovery around 170 years ago (Brickenden, 1852), the Hopeman Sandstone Formation tracks and trackways have been somewhat overlooked in recent decades, and comparatively few photographs of them have been published in the scientific literature (e.g. Watson and Hickling, 1914; Sarjeant, 1974; Hopkins, 1999a, 2004; Ogilvie et al., 2000).

2. Materials and methods

2.1. Field sites

Fieldwork was conducted between January 2022 and January 2023 at Hopeman Beach; Clashach Quarry; and Quarrelwood in Moray, Northeast Scotland (Fig. 1). Two key sections were logged and sampled at Hopeman Beach: (i) 11 samples were taken from Hopeman Coastal Section A (Fig. 2), being a site from which a track was removed illegally and from which the remaining tracks were extracted by staff of the National Museum of Scotland for safe keeping (Fig. 3 and Appendices A and B); and (ii) 4 samples were taken from a section still exhibiting several in-situ tracks, hereafter referred to as Hopeman Coastal Section B (log shown in Appendix B, image A). Tracks were also examined on the surfaces of metre-scale quarried blocks within Clashach Quarry (Fig. 4), known for its metre scale planar cross bedded quartz arenites (Appendix C) commonly interpreted as aeolian dune deposits (Clemmensen, 1987). As the blocks have been extracted from the quarry face their full original context was challenging to decipher, but the lithology and sedimentology of the larger blocks could be examined, and two representative samples were taken for electron microscopy. Grain sizes were determined in the field using a grain size chart and later confirmed using electron microscopy on sub-samples. These sites are protected as they lie within the Covesea–Clashach Site of Special Scientific Interest. Careful sampling was undertaken with prior consent of NatureScot and the owners of the site.

Logging was also undertaken at quarries in Quarrelwood, with 7 samples taken with permission of the landowners and NatureScot. This included logging and analysis of a small unnamed section to the west of Cutties Hillock Quarry (Appendix B, image C).

2.2. Museum specimens

A number of ichnological samples in museum collections, some of which can be seen in Fig. 5, were examined for this study. In the majority of cases the original stratigraphic context of the specimens had been lost. In several cases only the name of the quarry of origin was known. An exception was specimen G.1997.60.1 of the National Museums of Scotland (Fig. 3; Appendix A), which is a rippled slab extracted in 1997 from the outcrop described here as Hopeman Coastal Section A. This specimen, described further below, was collected in the presence of one of the present authors (C. Hopkins).
2.3. Laboratory analysis

Broken chips of field samples, generally measuring 10 to 30 mm in diameter, were examined optically and with a scanning electron microscope. Some samples were cut with a rock saw, but following discovery of halite in some samples this was avoided wherever possible as fresh water is used to cool the blade. Some cut samples were also hand-polished with alumina prior to electron microscopy.

Optical microscopy included use of a Nikon SMZ25 Zoom Stereomicroscope equipped with a DS-Fi2 camera and Nikon Elements D software. Scanning electron microscopy (SEM) was conducted in the Aberdeen Centre for Electron Microscopy, Analysis and Characterisation (ACEMAC) facility at the University of Aberdeen using a Carl Zeiss Gemini SEM 300 VP Field Emission instrument equipped with a Deben Centaurus CL detector, an Oxford Instruments Nano Analysis Xmax80 Energy Dispersive Spectroscopy (EDS) detector, and an Aztec software suite. Prior to electron microscopy samples were coated with a thin coat of carbon under vacuum.

2.4. Modelling the footprints

An iPhone 14 Pro with an inbuilt LiDAR scanner was used to generate 3D models of the samples. The Scaniverse app was chosen to collect and process the data with a range of 0.5 m and manually rotated around the entire sample from 90° (map view) to c. 30° and c. 60° angles to allow for the best coverage and accuracy. The models were imported as mesh and photorealistic ‘true colour’ overlay to the LIME software application (Buckley et al., 2019) as .OBJ files. In LIME angle corrections of 90° pitch (required for all Scaniverse models), the angle of bedding and/or cut of samples were made to ensure that the models were level. The models were then ‘false coloured’ for elevation and dip angle, and contour lines were also applied at 1–0.5 mm intervals depending on the model. The model textures were projected to panels in LIME and exported at 0.5 mm resolution for figures generated following the Falkingham et al. (2018) standard protocol.

2.5. Clarifying terminology

Some vertebrate ichnologists whose primary aim is linking tracks with their makers have considered the term “preservation” as more or less synonymous with “morphological preservation” (Marchetti et al., 2019d), whereby a “poorly-preserved” track is one that lacks morphological features that can be related to the anatomy of the track-making organism, even if that track has not been significantly affected by diagenesis (for example Mancuso et al., 2016; Marchetti et al., 2019d). Others continue to use “preservation” in the broader, traditional sense of the word, such that a poorly registered track might be considered “well preserved” if it is not substantially altered through diagenesis, whether or not it lacks anatomical detail (e.g. Gatesy and Falkingham, 2017; Falkingham and Gatesy, 2020). Gatesy and Falkingham further define the extent to which a track reflects the trackmaker’s anatomy. Here we generally follow the latter approach in our use of the term “preservation” (as is common in sedimentological and palaeoenvironmental studies), but accept that good “morphological preservation” of anatomical details greatly assists that branch of vertebrate ichnologists focussed on attribution.
of a print to a maker (McKeever and Haubold, 1996; Hunt and Lucas, 2006; Voig and Lucas, 2018; Marchetti et al., 2019d). We follow recent authors in using the term “track” to mean a single footprint, and generally follow the definitions of Leonardi (1987), including taking “trackway” to mean a series of footprints, usually understood to consist of at least 3 sequential sets.
3. Results

3.1. Hopeman Coastal Section A — field sedimentology

Here we describe the field sedimentology of samples in a stratigraphic order from base to top of the section. A short sedimentary log for the track-bearing section of Hopeman Coastal Section A is shown in Appendix B, image A. The section starts with c. 10 cm of planar laminated, cm thick layers of medium grained sandstone that are interlaminated with 5 mm thick layers of coarse-grained sandstone. This is overlain by a 1 cm thick layer of poorly sorted, well rounded coarse quartz grain pebbles, the latter up to 8 mm in diameter. That layer is in turn overlain by a c. 15 cm thick medium grained quartz rich, light-coloured layer with convolute bedding exposed in cross-section (Fig. 2A). Lateral to this is an undulating, pustular surface, with coarse sand grains filling depressions in medium grained quartz arenite (Fig. 2B). Sample HA1 was taken from this pustular horizon. The layer from which HA1 was taken correlates laterally with a series of strongly asymmetrical ripples, steep on one side and shallow on the other, with coarser sand grains on the steeper side than the lee-ward side (Fig. 2C).

Above this is a matrix-supported lag deposit which includes quartz pebbles measuring up to 2 cm in diameter (Fig. 2D). This layer can be traced laterally over an area of at least 5 m. A series of interbedded medium and coarse-grained sandstones, and a further prominent lag deposit, are found in the succeeding c.15 cm of the section.

Next is the rippled layer from which National Museums of Scotland specimen G.1997.60.1 was removed in 1997 (Fig. 3). The ripples are of low amplitude and fairly flat topped, measuring c. 4 cm crest to crest (Figs. 3, 2E). Samples HA2 and HA3 were collected from the western end of this layer, and HA4 and HA5 from the eastern end of the same layer (several metres away) which lacks prominent ripples (Fig. 2F).

The next c. 30 cm is notably finer grained, comprising interlaminated fine and medium grained quartz sandstone, capped by a coarse-grained pebble lag that exhibits quartz pebbles measuring 2 mm to 2 cm in diameter. The remainder of the logged section (Appendix B, image A) consists of metre-scale planar cross-bedded sandstones. These comprise of medium and coarse-grained quartz arenite layers with parallel laminae that can be traced continuously over several metres, and some pebble lags where cross-laminae are truncated. Samples HA9, HA10 and HA11 were taken in this planar laminated part of the section (Appendix B, image A).

Lateral to these planar cross-bedded sandstones and so not on the log shown in Appendix B, image A) is a metre-scale trough cross-bedded package. Where exposed, this trough cross-bedded package cuts down into the metre-scale planar cross-bedded sandstones and exhibits cm-scale rip-up clasts of mud within it (Fig. 6A, B).
Specimen G.1997.60.1 (Fig. 3; Appendix A) is in the collections of the National Museums of Scotland (Edinburgh). Depth maps (Fig. 3) show the displacement of sediment and sedimentological features well. The specimen comprises layers of medium to coarse grained quartz arenite, with some c. 5 mm thick laminae of very coarse grains. The top surface exhibits oscillation ripples (Fig. 3A).

3.2. Hopeman Coastal Section A — electron microscopy results

In the electron microscope sample HA1 was found to contain a pervasive cement of a mineral comprising sodium and chlorine (i.e. halite; Fig. 7A). In general, smooth-faced quartz crystals seem to exhibit much less halite coating than more rounded grains in this sample.

Electron microscopy and EDS analysis show that sample HA3, from immediately above HA2, being a quartz arenite with rounded, medium sand-sized grains, contains halite cement between the quartz grains (Appendix D, image A).

Sample HA4, which immediately underlies the same track-bearing layer, and was located close to HA5 (Fig. 2F), shows graded lamination. The largest grains are c. 400 μm in diameter, and finest grains are c. 100 μm in diameter (very fine sand to medium sand). This sample similarly contains patches of fluorite, as well as very minor baryte. Most interesting in HA4 is a single clast of feldspar, measuring c. 100 μm across its longest axis, which has a distinct but starkly isolated coating of halite (Fig. 7B). Extensive searching revealed very little other halite in this sample.

Sample HA5 comprises rounded grains of quartz with quartz overgrowth cements. Grains measure c. 200 to 400 μm in diameter (fine to medium sand). This sample was found to lack halite. However a cement composed of calcium and fluorine (i.e. fluorite) was found here in places (Fig. 7C).

Electron microscopy of HA6 reveals that rims of small amounts of halite surround some grains, and in places the halite seems to be found within a corroded silica cement (Appendix D, image B). A fluorite cement is also found in some layers of this sample (Appendix D, image C).

Much of the pore space between the quartz grains of HA7 is filled by halite cement (Appendix D, image D). Sample HA8 is similar and also shows halite filling pore spaces between well-rounded grains of quartz.

Fig. 4. Images of the surface of a quarried block in Clashach Quarry, exhibiting several tracks: A) an overview of the studied area of the block, with three of the described tracks arrowed. Black square highlights the print shown in image C. 15 cm ruler for scale; B) a close-up of some of the tracks, showing the distance between two tracks on the right side of the track (363 mm). The black colour is from manganese weathering. 15 cm ruler for scale; C) print highlighted in the square in A, showing three-digit impressions towards the front of the impression, clearly visible because of manganese weathering; D) a series of 3 parallel linear marks interpreted as claw marks.
Microscopy shows sample HA9 comprises medium sand-sized well-rounded quartz grains and exhibits some iron oxide patches which appear bright in backscatter images (Appendix D, image E). No halite was observed in the SEM. The same is true of sample HA10, although it contains some mm-sized grains. In contrast, some halite was found on a fractured quartz grain and on a quartz cement in sample HA11, which is dominated by medium sand-sized quartz grains and was from near the top of the logged section here. Interestingly there seems to be an association between an iron and sulphur containing mineral (pyrite) and halite, which surrounds it in places (see EDS data in Appendix E).
3.3. Hopeman Coastal Section A — track description

The track of specimen G.1997.60.1 (Fig. 3; Appendix A) is a patch of disturbed sediment measuring 200 mm across at its maximum extent, and 100 mm perpendicular to that, although the boundaries of this depression are diffused and hard to define (Fig. 3, Appendix A). A distinct rim of very coarse sand-sized grains stands proud of the surface on one side of the depression (Fig. 3). The depression is filled with very coarse sand grains that measure c. 1 mm across.

A second depression is a rather indistinct (and thus challenging to illustrate without photogrammetry) accentuation of ripple troughs that measures c. 100 mm in width and 60 mm in length. There is no raised rim of sediment associated with this mark.

In one corner of the slab is an area in which the ripple crest appears to have been down-pressed (Appendix A, images B and C). This depression measures c. 120 mm in length and 80 mm in width.

3.4. Hopeman Coastal Section B — field sedimentology

The sedimentary log for Hopeman Coastal Section B is included in Appendix B, image B. Here are a series of metre-scale planar cross-bedded fine to medium grained sandstones, with track-bearing laminae in the measured section dipping at 22° towards a dip direction bearing of 244°. The log (Appendix B, image B) was measured perpendicular to lamina dip, rather than perpendicular to true bedding which is hard to deduce.

The lowermost 40 cm of the logged section (Appendix B, image B) comprises orange-weathered fine to medium grained quartz arenite with a minor feldspar component. These sandstones are planar cross-bedded on a metre scale, with continuous laminae that can be traced laterally for several metres. Stratigraphically 20 cm higher (as measured perpendicular to lamina dip) is a surface exhibiting a series of around 17 in-situ tracks illustrated in Fig. 8 and Appendix F and described further below. Sample HB1 was taken from the top surface of this lamina, a few metres away from the tracks to avoid damaging them.

A c. 1 cm thick, orange-coloured ferruginous layer directly above the tracks has been recessively weathered and exhibits inverse grading (fine sand at the base of the layer and up to granule sized grains above). Sample HB2 was taken from this layer.

The next 14 cm is fine grained sandstone, also with orange-coloured weathering (Appendix B, image B). From 75 cm on the log upwards there are a series of cm-scale interlaminated fine and medium grained planar cross-bedded sands with ferruginous weathering. Sample HB3 is mostly grains of quartz with some feldspar.

Sample HB4 is of a similar quartz-dominated composition to sample HB3, and it has a similar range of grain sizes (fine to medium sand), with grains being rounded to well-rounded.

3.5. Hopeman Coastal Section B — electron microscopy results

Sample HB1 is a quartz arenite, dominantly composed of well-rounded quartz grains measuring c. 200 μm in diameter (fine sand). EDS element mapping reveals patches of sodium and chlorine (interpreted as halite), which coats quartz grains and cements, as well as coating potassium feldspar (Fig. 9A).

When viewed in the electron microscope sample HB2 dominantly comprises well rounded grains of quartz, with grains measuring from 150 μm to 1 mm in diameter, although the significant majority of grains are less than 300 μm in diameter (fine to medium sand). Some grains have euhedral quartz overgrowths. Halite, plus some laths of a mineral comprised of calcium and sulphur (presumed to be gypsum), appears to have precipitated on grain surfaces and in places on this quartz cement (Fig. 9B). The halite is dominantly found cementing porosity in the slightly coarser laminae (Fig. 9C).

Grains in sample HB3 measure 200 μm to 300 μm in diameter (fine to medium sand). Halite coats the quartz and feldspar grains, with some small crystals of gypsum also found on feldspars (Fig. 9D). Halite seems less abundant on smoother quartz cement crystal surfaces than on the rougher grain surfaces.

There is an apparent association between halite and iron oxide in sample HB4 (see Appendix G) with some minor dendritic halite growth on quartz grains.

3.6. Hopeman Coastal Section B — track descriptions

At c. 65 cm on the log (Appendix B, image B) there is a trackway of 16, possibly 17 impressions (Fig. 8; Appendix F) (‘HB Trackway 1’). Tracks are quite evenly spaced, and if we are to assume that both manus and pes are represented here, then stride lengths range from c. 12 to 15 cm. Pace angulation is c. 60°, and rotation from the midline around 15°. Individual tracks range from 35 to 50 mm wide, with a trackway width of c. 150 mm. The tracks vary in shape, being circular, horseshoe-shaped, and semi-circular, some of which have vague digit-like impressions. The tracks are foreshorted or incomplete with...
impressions of c. 30 to 50 mm lengths (Fig. 8A, Appendix F). The up-dip margin of the impression is the deepest, and a mound of displaced sediment is found behind many of the tracks.

A further set of at least 7 sub-digitigrade prints on the same surface (‘HB Trackway 2’) exhibits tracks with digit impressions. The tracks are of similar size to those seen on Trackway 1. The digit impressions of the track highlighted by arrow 1 in Appendix F vary between 10 and 20 mm in length. The track shown by arrow 2 is presumed to be part of the same trackway but does not display the digits as clearly. This second track measures 80 mm in width. Identification of the manus and pes is difficult, so a clear trackway pattern cannot be determined. Therefore pace angulation and rotation from the midline could not be confidently measured on this trackway.

Around 10 m to the north (seawards) of the logged section (Appendix B, image B), and on a lamina of fine to medium sand that could be traced laterally to approximately 1.15 m stratigraphically above the first set of impressions (again measuring vertically perpendicular to lamination, rather than true bedding), is a third set of at least four other imprints (‘HB Trackway 3’). The impressions are 40 to 55 mm wide, with up to four digit-like protrusions clearly visible (Fig. 8B; Appendix F image B). Digits are clearly labelled I–IV on image B in Appendix F. Digit lengths were measured as I = 14 mm, II = 11.2 mm, III = 10.4 mm and IV = 10 mm. As there is insufficient evidence for a clear trackway pattern, trackway width, pace angulation and other parameters could not be determined.

3.7. Clashach Quarry — sedimentology description

Clashach Quarry measures c. 200 m across. The east side exposes rocks that are topographically and stratigraphically higher than those of the west side. In the east are thick beds each measuring metres to several metres in thickness of white quartz arenite with metre-scale planar cross-beds that dip at around 20° towards the south-west (Appendix C). Tracks are often associated with the white quartz arenites of the east.
Fig. 8. In situ tracks at Hopeman Coastal Section B: A) close-up of HB Trackway 1; B) the third set of tracks (HB Trackway 3), on a different surface c. 10 m to the north, with arrows pointing to the tracks. Note clear impressions of the digits.

Fig. 9. Electron microscopy of samples from Hopeman Coastal Section B: A) backscatter electron image of HB1 showing halite (light grey, arrowed) coating quartz grains (dark grey); B) EDS element map of HB2, showing halite (Na and Cl, blue), plus some laths of gypsum (Ca and S, red), which both appear to have precipitated on grain surfaces and in places on quartz cement; C) backscatter electron image of HB2, showing that the halite (light grey) is dominantly found cementing porosity in the slightly coarser grained laminae (grains are quartz, which appears dark grey); D) EDS element map of HB3, showing halite (Na and Cl, blue) that coats the quartz (Si, green), with some small crystals of gypsum (Ca and S) also present.
side, including on the surfaces of blocks that have a millimetre-thick coating of yellow-coloured siltly fine-grained material. Pebbles are notably absent from this section, with the coarsest observed grains being of well-rounded medium sand.

In the west are thinner beds with red discolouration. The latter beds lie close to the line of a fault that cuts through the quarry. A Dicynodont skull was found in a block reported to be from the top of the strata on the western side of the quarry, in a block of homogeneous sandstone (Clark, 1999; Hopkins, 1999a, 1999b; Cruickshank et al., 2005).

3.9. Brief lithological descriptions of track-bearing specimens from Clashach foreshore sections (Fig. 5).

Specimen ABDUG12471 was illustrated in Hopkins (1999a) (her Fig. 4), with a new photograph shown here in Fig. 5A and photogrammetry in Appendix H. This is a 155 cm long, 27.5 cm wide block of buff-coloured medium grained quartz arenite. Specimen ABDUG12328 is a c. 36 cm long, 10 cm wide and 1 cm thick specimen of friable, parallel-laminated fine to medium-grained quartz arenite with some iron oxide (Fig. 5B; Appendix I, image A). The track-preserving surface comprises silt-sized grains between particles of fine sand, immediately underlying laminae comprising coarser grains (fine to medium sand). Specimen CH-7 is a c. 20 cm long, 1 cm wide triangular-shaped specimen of yellow–orange-coloured parallel laminated quartz arenite exhibiting several footprints (Fig. 5C). In cross-section of the slab around four thin pale-coloured silt laminae are seen interlayered with c. 2 to 3 mm thick bands of fine to medium grained sand.

During field work in June 2022, two extracted blocks of parallel-laminated quartz arenite measuring 3 to 4 m across were examined. Samples of this track-bearing horizon were taken and labelled as KEF Clashach 1.

3.8. Electron microscopy of Clashach Quarry silt within quartz arenite

Electron microscopy of a sample that contains a yellow silt layer (similar to those which preserve tracks, see Section 3.9) shows it to be comprised of c. 50 μm to 200 μm diameter clastic grains (silt to fine sand), with larger (medium sand) grains either side of that layer, ranging up to 300 μm in diameter (Fig. 10A, B). The majority of the grains are well-rounded quartz, with a lesser component of feldspar. Quartz overgrowths are visible in CL. Many of the tracks found on these surfaces are smaller and more detailed than those described from the Hopeman foreshore sections (Fig. 5).

3.9. Brief lithological descriptions of track-bearing specimens from Clashach Quarry

Specimen ABDUG12471 is a c. 36 cm long, 10 cm wide and 1 cm thick specimen of friable, parallel-laminated fine to medium-grained quartz arenite with some iron oxide (Fig. 5B; Appendix I, image A). The track-preserving surface comprises silt-sized grains between particles of fine sand, immediately underlying laminae comprising coarser grains (fine to medium sand). Specimen CH-7 is a c. 20 cm long, 1 cm wide triangular-shaped specimen of yellow–orange-coloured parallel laminated quartz arenite exhibiting several footprints (Fig. 5C). In cross-section of the slab around four thin pale-coloured silt laminae are seen interlayered with c. 2 to 3 mm thick bands of fine to medium grained sand.

During field work in June 2022, two extracted blocks of parallel-laminated quartz arenite measuring 3 to 4 m across were examined. Samples of this track-bearing horizon were taken and labelled as KEF Clashach 1.

3.10. Electron microscopy of track-bearing specimens from Clashach Quarry

SEM imaging and EDS analysis of a piece of CH-7 shows grains to be dominantly rounded to well-rounded quartz, although some more angular grain faces are found. Laminae with grain sizes around 100 to 150 μm in diameter (very fine to fine sand) are seen interlayered with laminae where grain sizes are larger, around 200 to 250 μm in diameter (fine to medium sand). Some clay can be seen in pore spaces (Fig. 10D), but no evaporites are present. Iron oxides are visible in backscatter electron images, confirmed by EDS (see Appendix J).

Electron microscopy shows KEF Clashach 1 is a quartz arenite, with the largest quartz and feldspar grains being c. 250 μm in diameter (fine to medium sand), and a significant percentage being c. 200 μm in diameter (fine sand). Grains range from sub-angular to rounded, with most being sub-rounded. Finer silt grains fill much of the pore space between the larger sand-sized clasts (Appendix I, image B).

3.11. Clashach Quarry — track descriptions

Specimen ABDUG12471 exhibits a trackway comprising at least 38 impressions, each measuring 25 to 35 mm in length, preserved in positive hyporelief. Print widths on the left side of the trackway (as viewed in
of the foreshortened tracks (shown in Fig. 4B) arguably form a trackway pattern, with a consistent distance of separation of around 360 to 370 mm between successive tracks on each side of the trackway. These particular tracks are semi-circular to circular, with widths ranging from 9 mm to 120 mm. The imprints possess a mound of displaced sediment behind them, such that determination of the print margin is difficult so accurate measurement of foot length was not possible. Trackway width ranges from 300 to 350 mm. If they form a trackway then pace angulation can be tentatively measured at around 85°, with rotation from the midline at around 20°. Some other sets of 3 to 4 digit-like marks are elongate, each measuring from c. 35 to 60 mm in length and c. 5 mm in width, spaced c. 35 mm apart. These are interpreted further in Section 4.8.

3.12. Quarrelwood quarries — field descriptions

Quarrelwood near Elgin (Figs. 1 and 11) contains several small, abandoned quarries, one of the largest being Cutties Hillock. Here are metre-scale planar cross-beds in otherwise homogeneous-looking and uniformly fine-grained quartz arenites (Fig. 11A). Differences in grain sizes and compositions between laminae could not be discerned with a hand-lens at Cutties Hillock. A sample of the planar cross-bedded Cutties Hillock Sandstone was taken for electron microscopy (LSM 1).

Around 150 m west of Cutties Hillock quarry is a small un-named quarry (Fig. 11B). A log of this section is shown in Appendix B, image C. The basal 40 cm of the section here is a bed of fine-grained sand that has an undulating top surface (Fig. 11B and Appendix B, image C). Above this is a 5 cm thick recessively weathered red–brown clay layer from which a clay sample was collected.

Sample QW2 was collected from a 6 cm thick fine-grained sandstone bed directly above that clay, and this bed exhibits an undulating base (Fig. 11B and Appendix B, image C).

There is a further 1 cm thick clay layer 55 cm above the base of the section, which is in turn overlain by a 5 cm thick fine-grained sandstone (Fig. 11B and Appendix B, image C). 60 cm up from the base is a c. 15 cm thick, sharp based, fine grained sand unit. The remainder of the visible section comprises fine-grained sandstones that exhibit similarly sharp, scoured bases (Appendix B, image C). Samples of the sandstone were taken at c. 80 cm (named QW5); c. 135 cm (QW6); and c. 185 cm (QW7) above the base of the section for further petrographic analysis.

3.13. Electron microscopy of Quarrelwood specimens

Cutties Hillock Sandstone sample LSM-1 was revealed to contain well-rounded grains of quartz, measuring 150 μm to 250 μm in diameter.
Some of the quartz grains exhibit overgrowths of quartz cement, and coatings of iron oxide (Fig. 12A). Platy clay was observed between some grains.

The clay from the small un-named quarry (Fig. 11B) has a platy morphology (Fig. 12B), and EDS shows high concentrations of Si, Al, O, K and Mg, consistent with illite (Fig. 12C). Very small grains of feldspar and quartz can be seen mixed into the clay sample.

Viewed in the electron microscope, QW2 comprises sub-angular to rounded quartz and feldspar grains, ranging from c. 100 μm to 250 μm in diameter, with small amounts of platy clay (illite), plus iron oxide coatings on some grains (Fig. 12D). Small amounts of halite are spatially associated with the iron oxide (Fig. 12E). Cathodoluminescence shows a quartz cement binding the grains together (Fig. 12F).

The vast majority of grains in sample QW5 are quartz, with a minor component of feldspar, and some platy clay. A mixture of iron oxide and halite is found cementing some of the grains (Fig. 13A). Most grains are c. 150 μm in diameter, although some are up to 400 μm across. Cathodoluminescence shows the grains ranged from sub-angular to rounded in morphology prior to growth of quartz cements (Fig. 13B).

Sample QW6 is a quartz arenite (Fig. 13C). The CL image of Fig. 13D shows that the original subrounded grains of quartz exhibit little apparent quartz cement overgrowth. Pore spaces between these quartz grains were infilled by a mixture of halite and iron oxide (Fig. 13C, E, F). Small crystals of a mineral comprising calcium and sulphur (gypsum or anhydrite) are found at several grain boundaries and are interspersed with the pore-filling halite and iron oxide (Fig. 13E, F).
3.14. Quarrelwood tracks

Cutties Hillock Quarry is known for its vertebrate body fossils (Benton and Walker, 1985), but few tracks have been noted from the quarries in Quarrelwood except those of Watson and Hickling (1914). One red coloured block from the small quarry west of Cutties Hillock has irregular and indistinct cm-scale impressions preserved in positive hyporelie on one surface (Appendix K). Four tracks are discernible from this block that had evidently fallen from the sandstone bed immediately above the first clay horizon (Appendix B, image C).

4. Discussion

Before considering factors affecting track preservation, we must examine the palaeoenvironmental conditions under which the tracks were formed, and extract clues from the tracks themselves.

4.1. Palaeoenvironments of the Hopeman Sandstone Formation

Field and laboratory observations here allow refinement of the palaeoenvironmental setting in which the Hopeman Sandstone tracks were made, enabling informed discussion of possible palaeoenvironmental controls on track preservation in these sections.

4.2. Clashach Quarry: aeolian dune

Following Clemmensen (1987), some of the track-bearing beds in Clashach Quarry would have been the surfaces of star dunes at the time of deposition. The planar cross beds observed on the quarry walls are consistent with this interpretation of an aeolian dune setting (Appendix C) and unlike the Hopeman Coastal Sections do not contain features such as pebbles. The footprint-bearing blocks examined within the quarry are therefore best interpreted as having formed within aeolian dunes.
4.3. Hopeman Coastal Section A: interdune

The Hopeman coastal sections examined here were once part of an area of sand sheet, interdune or ephemeral fluvial deposits, lying between the star dunes (Clemmensen, 1987). According to Williams (1973), some of the Hopeman coastal section sediments could be interpreted as playa facies. At the base of Hopeman Coastal Section A are examples of convolute bedding that are best interpreted as dewatering structures (Fig. 2A). These are common in the Hopeman coastal section (Hurst and Glennie, 2008). The pustular bed shown in Fig. 2B is lateral to the convolute bedding shown in Fig. 2A so could also have been caused by the de-watering, perhaps when a coarser grained sediment was deposited in the troughs of ripples, pushing down on the troughs and forcing water upwards at the crests. Alternatively the origin of this texture could be linked to growth of evaporite crystals impinging on a sediment-binding microbial mat (c.f. Noffke et al., 2001), or perhaps sedimentation around evaporite-related adhesion structures and their partial collapse, as observed in modern sedimentary environments by Nagtegaal (1973) and Kocurek and Fielder (1982). In a study of modern environments Goodall et al. (2000) described similar-looking pustular or blister textures to growth of salt crusts. These possibilities fit with the presence of a pervasive halite cement in the layer (Fig. 7B), and the observation of strongly asymmetrical ripples at around the same stratigraphic level. These strongly asymmetrical ripples (Fig. 2C) are here interpreted as adhesion ripples like those described by Kocurek and Fielder (1982) from the Cambrian Galesville Sandstone of Wisconsin, USA. Adhesion ripples have previously been recorded from Permian sedimentary rocks of north-west Europe (Glennie, 1972; Nagtegaal, 1973; Glennie et al., 1978). These are formed by dry, wind-blown sand sticking to a wet or damp surface (Reineck, 1955; cited in Kocurek and Fielder, 1982). Adhesion ripples commonly migrate upwind, and may climb over each other (Hunter, 1969). Kocurek (1981) recorded adhesion ripples in modern interdune areas, consistent with the palaeoenvironmental interpretation presented here.

Laterally continuous layers of larger grains including cm-sized quartz pebbles are the result of ephemeral sheet floods, recorded in the sedimentary record as deflation lags that remained after aeolian winnowing of the fines (Fig. 2D).

The layer from which NMS footprint specimen G.1997.60.1 was extracted itself exhibits oscillation ripples (Figs. 2E, 3), formed in a standing body of water, most likely here a lake. This surface was exposed to considerable abrasion from wave action, so the ripples may have been denuded over time, reducing their amplitude, and flattening the crest. The sedimentary versus diagenetic origins of halite around this layer (e.g. Fig. 7C) are considered further below.

Above this level the sediments are finer grained with metre-scale planar cross beds and occasional coarser-grained lag deposits (Appendix B, image A). These are best interpreted as aeolian dunes that were episodically inundated by sheet floods.

Lateral to the dunes at Hopeman Coastal Section A, the package of trough cross-beded sandstone with rip-up mud clasts (Fig. 6) is interpreted as an ephemeral fluvial channel deposit.

4.4. Hopeman Coastal Section B: interdune

The tracks of Hopeman Coastal Section B (Fig. 8) are found on planar cross-beds constructed of millet seed sand grains (Fig. 9), with occasional coarser-grained lags. Hopeman Coastal Section B is therefore also considered to result from aeolian dunes that were affected by episodic sheet floods. The potential primary vs secondary origins of the halite and calcium sulphate in this section are considered further below.

In summary, there is abundant evidence that the track-hosting sediments of Hopeman Coastal Section A were deposited in intermittently wet interdune environments, including drying lake beds that were fed by sheet floods and ephemeral fluvial channels, and we infer from petrography that evaporation of ponded waters resulted in sediment-cementing halite precipitation of rippled track-bearing layers. The tracks of Hopeman Coastal Section B are found preserved on the surfaces within dunes that were relatively low-lying and episodically flooded.

4.5. Palaeoenvironments of the Cutties Hillock Sandstone Formation

The large-scale planar cross-beded quartz arenites of Cutties Hilllock quarry, composed of fine sand-sized well-rounded grains (Figs. 11, 12 and Appendix B, image C), were clearly deposited in an aeolian dune setting. These are similar-looking dune deposits to those of Clashach Quarry (Appendix C), although the Cutties Hillock sandstones contain a little more clay.

The sediments of the small quarry to the west of Cutties Hilllock (Figs. 11, 12) were deposited in an environment in which layers of illite clay could accumulate, consistent with a standing body of water (Moraes and De Ros, 1990) that may have been ephemeral. The petrography of the sands with scoured bases (Figs. 11B, 12, 13) suggests they were aeolian sediments that were reworked by (ephemeral) fluvial processes, as found in other fluvial–aeolian successions in the Permian–Triassic salt basins of NW Europe (e.g. Mader, 1983; Meadows and Beach, 1993). The overall palaeoenvironment for the deposits of Quarrelwood was an aeolian dune system with ephemeral rivers and lakes, so not dissimilar to that of the Hopeman coastal sections.

4.6. Hopeman Coastal Section A — track interpretation

Hopeman Coastal Section A tracks can be seen in Fig. 3. There is a prominent ejection rim to the rear of the clearest track (Fig. 3), which is very consistent with a footprint origin, but there is otherwise little interpretable anatomical detail preserved. It is evident from the sedimentology that the trackmaker walked through an interdunal environment that was at least periodically wet.

4.7. Hopeman Coastal Section B — track interpretation

There are vague impressions of 3–4 toes on some of the tracks of HB trackway 2 (Fig. 8) giving an indication of the direction of travel to the present-day northeast (52° on beds now dipping to the southwest). That the up-dip margin of the impression is the deepest, and a displacement rim behind many of the tracks may also indicate the trackmaker was moving up-dip, digging its toes in to gain traction or purchase.

4.8. Clashach Quarry — track interpretations

Specimen ABDUG12471 digit impressions are vague (Fig. 5) but recognisable on several of the tracks, with their orientation suggesting slight lateral rotation of the foot. The sinuous ridge measuring c. 3 to 5 mm across and c. 3 mm in depth, that can be traced between the tracks along the length of the specimen, crossing through tracks along the right side of the trackway is presumed to be a tail drag impression of low sinuosity, preserved in positive hypo relief (Hopkins, 1999a). The position of the tail drag; width of tracks; and orientation of the right side tracks and their associated toe drags are all consistent with a scenario where the animal was walking along a sloped surface of unconsolidated sediment, i.e. a sand dune, slipping down the slope towards the right as it walked. The lateral rotation of the foot exhibited on the downslope side of the track could be attributed to slippage of the foot or a more propulsive kick-off stroke on that side, as the animal tried to maintain its course. This may also account for the deeper impressions on the right, or that more weight is borne on the downslope feet. The tracks on the presumed downslope side (right) show less overlap than those on the left, and two sets of toe impressions are evident in some tracks on the right, suggesting manus–pes pairs. This difference in print morphology may be a
result of different placement of the downslope feet during locomotion due to the extra effort required to maintain direction. There are also many indeterminate invertebrate traces on this surface, primarily vertical burrows, and other isolated vertebrate tracks, some displaying toe impressions, but no other discernible trackways. That the tracks and associated tail drag are present on two exposed surfaces (see Appendix H) confirms that at least those on the lower surface are transmitted underprints, and not surface tracks.

The two most prominent prints of ABDUG 12328 are of similar form and size and may form part of the same trackway, but that cannot be assumed in the absence of further tracks that would be needed to confirm a clear trackway pattern. Other smaller tracks on the same surface are oriented in different directions and are preserved only as toe or claw imprints, comprising up to four toe imprints. The incomplete nature of preservation of the rest of the foot, and the lack of displaced sediment behind the tracks, strongly suggests there are underprints. That little or no impression of the heel of the foot recorded is consistent with (but not proof of) the impressions being formed in a shallow subsurface silt layer, rather than being a surface impression. But if so, then noting that the tracks do not continue through the 1 cm thick specimen, it seems likely that the animal was walking on a sandy dune surface that was only a few millimetres above the silt layer, pushing its toes down into the silt lamina below.

Interpretation of CH7 tracks is like that of ABDUG12328, in that there are apparent claw marks from an animal pushing its toes into a sand dune, indenting a silt layer.

The tracks on the blocks in Clashach Quarry that were observed in June 2022, comprising elongated claw scrapes measuring 35 to 60 mm in length (Fig. 4) with occasional foreshortened tracks are best interpreted as impressions of the distal phalanges and claws that have scraped through sand dune sediment during locomotion, or as a result of the animal slipping backwards down a sloping surface. This is consistent with the sedimentological interpretation of an aeolian dune setting for these particular examples.

4.9. Halite in the Hopeman and Cutties Hillock sandstones: a syn-sedimentary cement?

Evidence for halite cementing some of the track-exhibiting interdunal quartz arenites of the Hopeman Sandstone is seen in Figs. 7 and 9 and Appendix D. Samples containing halite and lesser amounts of gypsum or anhydrite were collected from the same layer as the in-situ Hopeman Coastal Section B tracks (Figs. 8 and 9), and from multiple layers above and below. As these samples were collected close to the sea it could have been presumed that the salts were simply derived from modern sea spray. There is certainly petrographic evidence that some of the halite precipitates post-date burial quartz cements (Fig. 9A and Appendix D), such that not all halite here can be syn-sedimentary and there must have been some local post-depositional mobilisation. Some such intra-formational dissolution and re-precipitation are surely to be expected, given the solubility of halite. Additionally a possible burial diagenetic origin for the halite could be considered, noting that fluorite cements that are similar to those seen in Fig. 7C and Appendix D image C have been interpreted by Williams (1973) and McKeever (1992) as formed during burial diagenesis. However multiple lines of evidence argue that – despite the probability that some of the halite was re-distributed during and following burial – there was also notable syn-sedimentary halite deposition here.

Relatively strong evidence for syn-sedimentary halite in the Hopeman coastal sections is found in sample HA4, shown by the SEM EDS element map of Fig. 7B. Petrography shows the halite isolated on a single feldspar clast within the rock, from immediately below the track-bearing layer of NMS specimen G.1997.60.1. According to the law of included fragments the inference must be that the halite-coated feldspar grain (Fig. 7B) was re-worked from a short distance (metres) away at the time the rippled layer was deposited. Extensive searching for pseudomorphs after syn-sedimentary halite during this study revealed only a few possible examples (Appendix L), though their presence was clearly noted by Williams (1973) in the approximate location of Hopeman Coastal Section A.

If the undulating, pustular bed surface lateral to the adhesion ripples in Hopeman Coastal Section A (Fig. 2B) was the result of evaporite growth (cf. Nagtegaal, 1973; Goodall et al., 2000; Noffke et al., 2001; Kocurek and Fielder, 1982) then this would also support the contention that at least some of the halite in that track-bearing interdunal section is of primary sedimentary origin.

Further, the halite is unlikely to be derived from modern seawater as it was not only found in proximity to the sea at the Hopeman coastal section. Halite (mixed with iron oxide that might have been desert varnish, and calcium sulphate) was found within samples collected in the un-named quarry to the west of Cutties Hillock in Quarrelwood, more than 5 miles away from the current coastline (Fig. 13). Cathodoluminescence images of sample QW6 allow for an interpretation that halite was early, as the halite, iron oxide and gypsum surround original grain shapes that seemingly lack quartz overgrowths (Fig. 13C to F). From this it can be inferred that the Quarrelwood halite was likely pre-burial in timing.

The palaeoenvironmental evidence in the Hopeman coastal sections and those of Quarrelwood is also consistent with episodically wet, evaporitic settings in which syn-sedimentary halite deposition would be anticipated. Syn-sedimentary cementing halite is also known from other regional Permo-Triassic sections including the Danish Bunter Sandstone Formation (Laier and Nielsen, 1989). Consequently we find that there is sufficiently robust evidence to infer that the animals that made the tracks at Hopeman Coastal Section A walked across a drying lake-bed.

4.10. Modes of footprint preservation

McKeever (1991) suggested that footprints of the Hopeman Sandstone Formation were preserved by casts of dry sand infilling moulds in wet sand. However the new evidence reported here suggests there were at least three other methods of track preservation in the Permian Moray area: (i) tracks in aeolian dunes preserved by grain-size differences, principally between indented layers of silt and infilling sand; (ii) tracks preserved in sediments deposited around the margins of ephemeral lakes in the interdunes, with early cementation by evaporites helping to bind the sediment; and (iii) clays were trapped in some ephemeral interdunal lakes, with some tracks likely formed when the lakes were drying out, with flood waters then filling the casts with sands.

4.10.1. Preservation of transmitted footprints by grain-size contrasts in laminated aeolian dune sediments

Petrographic evidence (Fig. 10A, B, observations of ABDUG12471) shows that in the dune facies, grain size differences between the indented substrate and infilling cast, rather than compositional differences between the substrate and cast, were responsible for track preservation. Several tracks of the eastern end of Clashach Quarry were preserved by impressions in millimetre-thick layers of silts to very fine sands that are infilled by relatively pure, fine to medium-grained quartz arenites (e.g. Fig. 5).

One possibility is that the layers of silts and very fine sands were trapped, deposited and impressionable when the surfaces of the aeolian dunes were damp from dew (Mckee, 1947; McKeever, 1991). In such a model these fine-grained silt layers on dune surfaces might later dry out and harden into a crust that could potentially escape being blown away by the ensuing winds, prior to being buried by sand. Tracks formed by animals walking directly on surface silt layers might be expected to exhibit cracking, similar to that seen around modern tracks on surfaces of coastal dunes of Aberdeenshire (Appendix M). In such cases, the trackmaking surface has some cohesion prior to the trackmaking event, and cracks form in the displaced sediment surface as the track is impressed.
There are alternative mechanisms for producing impressionable silt laminae in aeolian sediments. One is that the finest grained sediments may have been deposited in the trough of an advancing ripple (Fryberger and Schenk, 1988), such that the plane of the silt is a subsurface feature (‘pin stripe lamination’) and may not itself have been a former dune surface on which a trackmaker could have walked. In this scenario, an animal walking on a sandy surface above the ‘pinstripe’ silt would indent down into it, and the impression would be filled by the overlying sand. Preferential cementation of pin stripe laminae may occur during early diagenesis because these finer-grained layers are the last to retain evaporating fluids as the sediment dries (Fryberger and Schenk, 1988), helping to preserve both the silt lamina and the print.

A further possibility is that some silt grains may have infiltrated between the coarser grains and accumulated as subsurface layers where pore throats restricted their further downwards movement (Ahlbrandt and Fryberger, 1980; Pye, 1983), and cemented during early diagenesis. Petrographic evidence for this should be recorded, and an example could be seen here in Fig. 10A. These shallow subsurface infiltrated silts would also be impressionable.

The above mechanisms are all possible. It is likely that some of these silt layers were subsurface features, such that the tracks they preserve technically represent transmitted underprints and not true surface tracks, although the surface on which the animal walked may at times have been within a centimetre of the impressioned layer. Previously Brand and Kramer (1996) reported high fidelity underprints in the Permian Coconino Sandstone of Arizona, and we here suggest that indention of below surface but near-surface infiltrated silts accounts for development of some of the relatively clear tracks in the Permian Hopeman Sandstone (Fig. 5).

4.10.2. Halite-assisted preservation of tracks in salty interdune lake sediments

Evaporation of waters around the margins of interdunal lakes resulted in precipitation of halite. This early halite cement may have assisted track preservation in such interdunal settings as found at Hopeman Coastal Sections A and B. A study of modern vertebrate tracks around Lake Manyara in Tanzania found that salt crusts precluded registration of small tracks, and the large impressions that were made lacked morphological details (Cohen et al., 1991). Halite also adversely affected the morphology of tracks made in microbial mats of modern tidal flats of Tunisia and Egypt (Marty et al., 2009). From this, and the relatively low fidelity of many of the Hopeman coastal section tracks (e.g. Figs. 3 and 8), it seems the halite cement (and possible but unproven surficial crusts) in the Hopeman Sandstone Formation interdune sediments might have helped preservation of the tracks in the sense of long-term fossilisation, but probably not morphological preservation (i.e. quality of fidelity) in the sense of Marchetti et al. (2019d).

4.10.3. Preservation of tracks in clay deposits

Presence of clay or mud is also known to enable track preservation (McKeever, 1991; Brand, 1996; Davis et al., 2007). It is notable that there is a greater abundance of clay in the Cutties Hillock Sandstone Formation (Figs. 12, 13) than in the Hopeman Sandstone Formation (Figs. 7, 9, 10). Despite this, the Hopeman Sandstone Formation has yielded far more tracks, and several with well-preserved anatomical detail (Fig. 5). That probably reflects differences in the amount of quarrying activity, and the smaller relative area of exposed bedding surfaces in Cutties Hillock Sandstone Formation quarries. From the latter we observed only some indistinct tracks preserved in quartz arenite (Appendix K) that were likely casts formed within the clay layers (Fig. 12). This is inconsistent with the suggestion of McKeever (1991) that higher preservation quality of Permian vertebrate tracks should be associated with sediments of higher clay content. Indeed, experimental work shows that fine sand can produce impressions of high morphological fidelity (McKee, 1947), and well-formed tracks are known from other Permian aeolian successions lacking in clay such as the Yacimiento Los Reyunos Formation of Argentina (Mancuso et al., 2016) and the Coconino Sandstone of Arizona, USA (Brand and Kramer, 1996).

4.11. Are these three styles of preservation found elsewhere?

Whether the factors affecting track preservation documented here are representative of styles of track preservation elsewhere requires consideration.

i) Grain-size contrasts in laminated aeolian dune sediments: Besides the Coconino Sandstone of Arizona (Brand and Kramer, 1996) and the Yacimiento Los Reyunos Formation of Argentina (Krapovickas et al., 2015; Mancuso et al., 2016), other Permian aeolian sediments where such a preservation mode may perhaps be found with further investigation might include the dune surfaces of the Piramboia Formation of Brazil (Francischi et al., 2018), and more locally the Corncockle Sandstone of Dumfries and Galloway (McKeever, 1991). The Jurassic aeolian Navajo Sandstone of Arizona and Utah was reported by Loope (2006) to exhibit tracks preserved by displacement of pin-striped laminae of fine-grained sand. Carbonate-rich Pleistocene aeolianites of South Africa are known to exhibit abundant vertebrate tracks (Helm et al., 2020, 2022), and in some cases anatomical detail was best seen in cases where a fine-grained sediment veneer was said to be present on the track surface. Grain size contrasts are evidently important for anatomical fidelity of fossil footprints in aeolianites, although whether infiltrated silts assist in the South African cases remains to be investigated.

ii) Evaporite-assisted preservation of tracks has not been commonly reported. Nevertheless the Triassic fluivo-lacustrine Auchenhew Beds of the Isle of Arran (UK) are known to exhibit both tracks and halite (Clark and Corrance, 2009), and similar applies to the Triassic Tarporley Siltstone of Shropshire (UK; King et al., 2005; McKie, 2017). Other Formations that have yielded both vertebrate tracks and evaporites include the Permian Aroyo de Alamillo Formation of New Mexico (USA), where gypsum is found in sandstones and siltstones, and halite in dolostone beds (Voigt and Lucas, 2017); the Permian Rio do Rasto Formation of Brazil, which includes evaporitic lenses (da Silva et al., 2012); and the Permian Carapacha Formation of Argentina, which includes some remobilised gypsum laminae although mud is evidently an important factor in preservation of some of the tracks in this fluvial lacustrine environment (Melchor and Swithin Sarjeant, 2004). This perhaps suggests that an association between evaporite growth and track preservation may be more globally widespread than just the cases reported from the Hopeman Sandstone here. Studies of South African Pleistocene aeolianites rich in shell fragment clasts indicate that early cementation, resulting from dissolution of the carbonate from clasts and its re-precipitation as intergranular cements, is a factor that assists footprint preservation (Roberts and Cole, 2003; Helm et al., 2020, 2022).

iii) Preservation of tracks in clays and muds is relatively common, with examples including the Teekloof and Balfour Formations of South Africa (MacRae, 1990; de Klerk, 2002). Mud-cracks were reported from both of those Permian fluvial floodplain cases, but no evaporites. Melchor and Swithin Sarjeant (2004) also reported that the preservation of the tracks they observed in the Carapacha Formation of Argentina was due to presence of muds and silts of playa lakes and mudflats. The Permian Tumlin Sandstone of the Bundsandstein of Poland exhibits tracks preserved as a result of intercalations of muds and sands in interdune deposits (Ptaszynski and Niedzwiedzki, 2004). Some tracks in the Hornburger Schichten and Tambacher Sandstein (Permian Rotliegend of Germany) are in clay and silt layers of playa lakes in an aeolian environment (Haubold and Katzung,
1978). Other examples where mud seems important for print preservation include some reported cases in the Triassic Fleming Fjord Formation lacustrine deposits of Greenland (Clemmensen et al., 2015; Lallensack et al., 2017).

Overall there is reason to believe that mud and clay are commonly important for track preservation, but that other factors such as cementation by evaporites may be more common than has been reported until now and so further works on this topic may prove insightful.

5. Conclusions

We conclude that there were at least three distinctive styles of track preservation in the Permian desert sediments of the Moray area, associated with particular facies:

1. Aeolian dune deposits with some of the best-preserved tracks in Moray are found at Clashach Quarry. The preservation of these tracks is a result of contrasts in grain size between silt laminae and infilling sands. Some of the silt layers may have been surface layers, impressioned when damp. Others are likely to have been near-surface silt layers formed by the infiltration of fine silt particles between coarser sand grains, with tracks transmitted down through sand from above. Contrasts in grain size between silt laminae and sand, and early diagenetic cementation of the silt, helped to preserve the tracks here.

2. Interdunal sediments are found at the Hopeman coastal section. Tracks were formed there in sediments deposited around the margins of ephemeral lakes, with early cementation of evaporites. It is possible that the halite cement helped in the preservation of the tracks in the sense of long-term fossilisation however the tracks are not of high fidelity.

3. At Quarrithewood there are both ephemeral fluvial sediments and aeolian dunes. It is possible that some tracks formed in the Cutties Hilllock Sandstone by indentation of intraformational clays, although further work is required to find clear examples of this.

As Permoo-Triassic desert sediments like those of the Hopeman and Cutties Hilllock sandstones were geographically widespread, we predict that similar palaeoenvironment-related styles of track preservation might be found in many other sites.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sedgeo.2020.106591.

Funding

Use of the ACEMAC Scanning Electron Microscope was facilitated by the School of Geosciences, University of Aberdeen. This research did not otherwise receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Kirsten E. Flett: Writing – review & editing, Writing – original draft. Methodology, Formal analysis, Data curation, Conceptualization. Carol Hopkins: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. Jessica H. Pugsley: Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Writing – review & editing. Alexander T. Brasier: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Data availability

Specimen G.1997.60.1 is in the collections of the National Museum of Scotland. Specimens CH7, ABDUG12471 and ABDUG12328 are in the museum collections of the University of Aberdeen. Other collected specimens are in the collections of the Department of Geology and Geophysics at the University of Aberdeen. Further specimens are in the collections of Elgin Museum.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

We thank the site owners, plus staff of NatureScot, Elgin Museum (Dave Longstaff, who showed KEF the field sites and loaned specimens, and Alison Wright) and the National Museums of Scotland (Stig Walsh and Nick Fraser) who assisted this study. Charlie Bristow (Birkbeck University) is thanked for engaging discussions on the outcrop at Hopeman. Electron microscopy was conducted in the Aberdeen Centre for Electron Microscopy, Analysis and Characterisation (ACEMAC) at the University of Aberdeen with the support of John Still. We would like to thank editor Catherine Chagué plus Ricardo Melchor and an anonymous journal reviewer for taking their time and effort into providing insightful comments and useful suggestions which have helped us to improve the quality of the manuscript.

References


