Dinosaur footprints associated with an ephemeral pool in the Middle Jurassic of Yorkshire, UK

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ABSTRACT - A thin mudstone intercalation within channel sandstones of the Saltwick Formation (Middle Jurassic) of the Cleveland area of Yorkshire shows a succession of invertebrate traces followed by dinosaur tracks and then shrinkage cracks. The tridactyl prints, all made by the same type of small bipedal dinosaur, show an interesting range of morphologies, including imprints of the metatarsal area, consistent with their having been made in soft cohesive mud of varying moisture content. Some of the tracks indicate that the foot was moved backwards during withdrawal. Such foot movement can also be observed in modern emu locomotion. The pattern of shrinkage cracks is partly controlled by the prints. This sequence is comparable to the sequence of traces and structures which have been observed in a recent ephemeral pool and is interpreted as having formed in a similar environment. Uniquely for the Yorkshire area, the prints and cracks are infilled by small, now sideritised, pellets possibly of invertebrate faecal origin.

Keywords: *dinosaur, footprints, preservation, Jurassic, England, emu, faecal pellets.*

INTRODUCTION

Tracks are the commonest type of dinosaur fossil and provide important evidence of the gait, speed, habit and facies preference of these animals; evidence which often cannot be obtained from other sources. However, because of the vagaries of preservation, the interpretation of tracks can sometimes be difficult and often depends on key examples - 'fossil Rosetta Stones' - to provide crucial evidence whose unambiguous interpretation can be used to shed light on other examples. Thus, for instance, the wider recognition of swimming tracks and swimming dinoturbation in the Middle Jurassic of Yorkshire (Romano & Whyte, 2003; Whyte et al., 2007) is underpinned by the relationships displayed by one particular ichnocoenosis (Whyte & Romano, 2002). The case study presented here, of a thin siltstone and its dinosaur tracks and trackways, provides another such instructive example and is of considerable importance not only for the interpretation of other Yorkshire tracks but also in a wider context.

GEOLOGICAL CONTEXT

The Cleveland area (fig. 1) is an inverted basin which, throughout the Jurassic and Cretaceous, accumulated a sequence of almost exclusively marine sediment (Hemingway, 1974; Rawson & Wright, 2000; Romano & Whyte, 2003). The only exception is the Aalenian to Bathonian – an interval of at most 11 Ma (Gradstein et al., 2004) (fig. 2) – when the area was uplifted and sediments were deposited in a fluvial to paralic environment. The uplift, linked to volcanic doming in the northern North Sea (Underhill & Partington, 1993), led to an erosional break between the Lower Jurassic (Whitby Mudstone Formation; Toarcian) and the basal Middle Jurassic (lower Aalenian) Dogger Formation, which is a thin, clastic marine unit (fig. 2). The overlying Ravenscar Group (Aalenian to Bathonian) is a predominantly non-marine sequence and is characterised by the abundance of dinosaur footprints (Romano & Whyte, 2003 and references therein; Whyte et al., 2007). The highest strata of the Ravenscar Group is disconformably overlain by the Cornbrash Formation (fig. 2), which is of basal Callovian age and marks the return to an exclusively marine sequence. Occasional marine units within the Ravenscar Group form the basis for its lithostratigraphic subdivision (fig. 2). In addition to the lower and upper disconformities, there are breaks in the succession at the base of, and within the basal part of, the Scalby Formation (Whyte et al., 2007) (fig. 2). There most probably are many other small breaks and time gaps within the Dogger Formation and Ravenscar Group succession. Indeed within the Ravenscar Group, each of the many surfaces with dinosaur prints, including that described herein, documents a break in deposition and at least a small time gap.

The chief characteristic feature of the Ravenscar Group, and particularly of its non-marine formations and members, is dinosaur tracks and trackways (Romano & Whyte, 2003; Whyte et al., 2007). The bulk of these prints are indeterminate, but it has been possible (Romano & Whyte, 2003; Whyte et al., 2006, 2007) to recognise and characterise amongst them 30 different morphotypes, including 19 morphotypes attributed to tridactyl bipeds. Though some of these tridactyl morphotypes can be assigned to described ichnospecies, it has been convenient (Romano & Whyte, 2003; Whyte et al., 2006, 2007) to retain the informal categorisa-

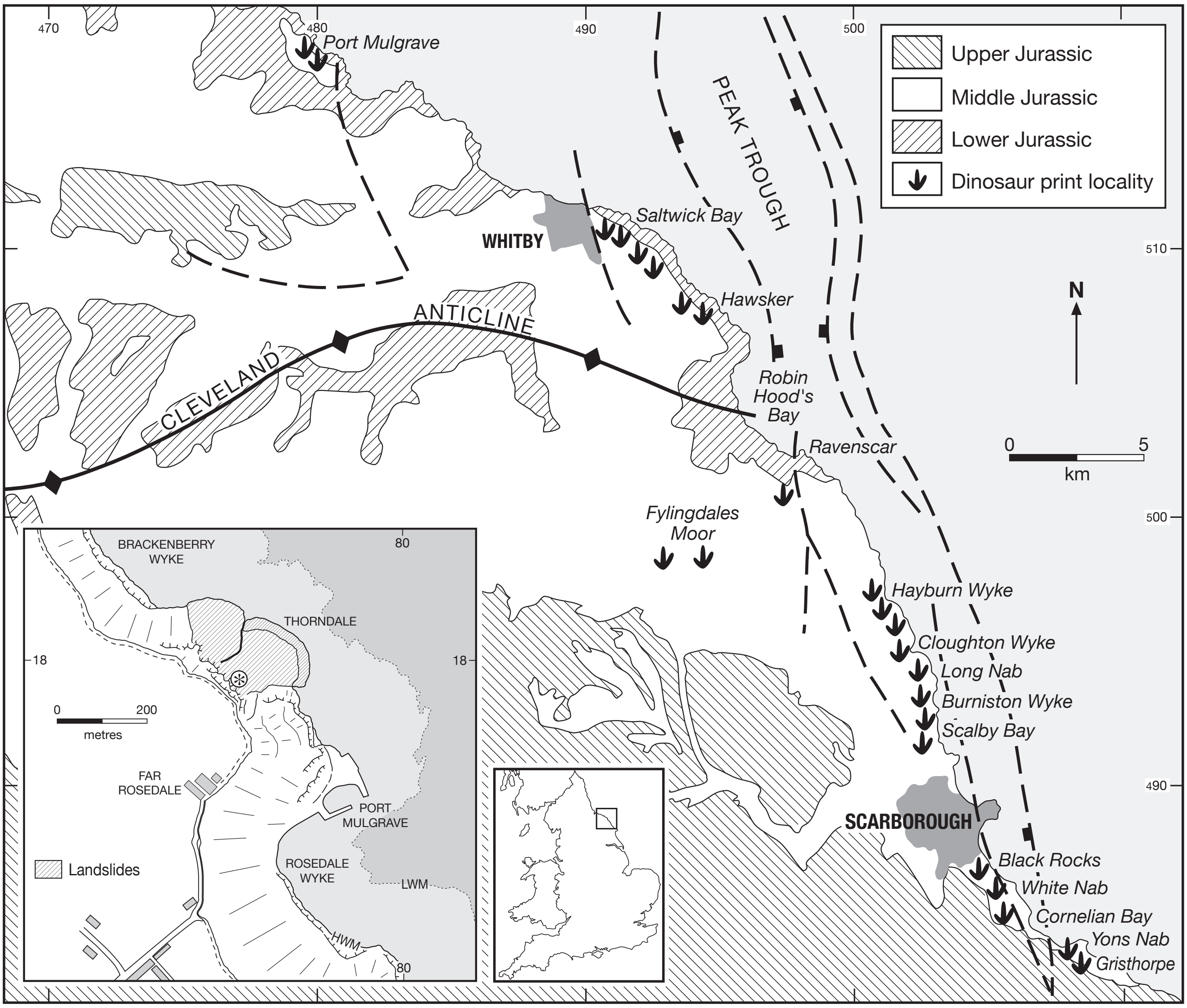


Figure 1 – Simplified geological map of eastern Yorkshire between Port Mulgrave and Gristhorpe, showing principal dinosaur print localities. Inset maps show position of the area within England and detail of the Port Mulgrave area. Asterix in latter map indicates the locality described in the text.

tion into morphotypes. This is because of problems in the ichnotaxonomy and out of a desire not to complicate these further pending fuller morphometric analysis.

The lowest non-marine unit within the Ravenscar Group is the Saltwick Formation (fig. 2), which is well displayed in the stratotype sections near Whitby [NZ 902 115 to NZ 913 112], though only the lowest parts can be easily accessed in the sheer sea cliffs (Romano & Whyte, 2003; Whyte et al., 2007). This section is dominated by floodplain and lacustrine mudrocks with thin sheet sandstones of crevasse splay origin and contains a diverse variety of track types (Romano & Whyte, 2003; Whyte et al., 2007). These include the ichnotypes of the quadrupedal *Deltapodus brodricki* Whyte & Romano, 1996 and the swimming *Characichnos tridactylus* Whyte & Romano 2002 (respectively morphotypes Av and Ci of Romano & Whyte, 2003). About 12 km further north (fig. 1) the lowest part of the Saltwick Formation is also seen in cliff sections near Port Mulgrave [NZ 797 179]. Here the section is at a higher present day altitude than at Whitby and is fronted by a complex of landslides of various ages (fig. 3) caused by failures within the underlying Whitby Mudstone Formation. Thick sandstones, representing a stacked and laterally linked channel deposit (up to 10 m thick), dominate the cliff sections (figs. 3, 4). The cross-bedding of these sandstones shows especially well on weathered faces (fig. 4c, d) and in addition ripple marks, erosion surfaces and lag deposits with rip-up clasts (fig. 4b) are present. These sandstones are separated from the underlying ferruginous sandstone (0.68 m) of the Dogger Formation (fig. 4a) by at least 1.10 m of carbonaceous

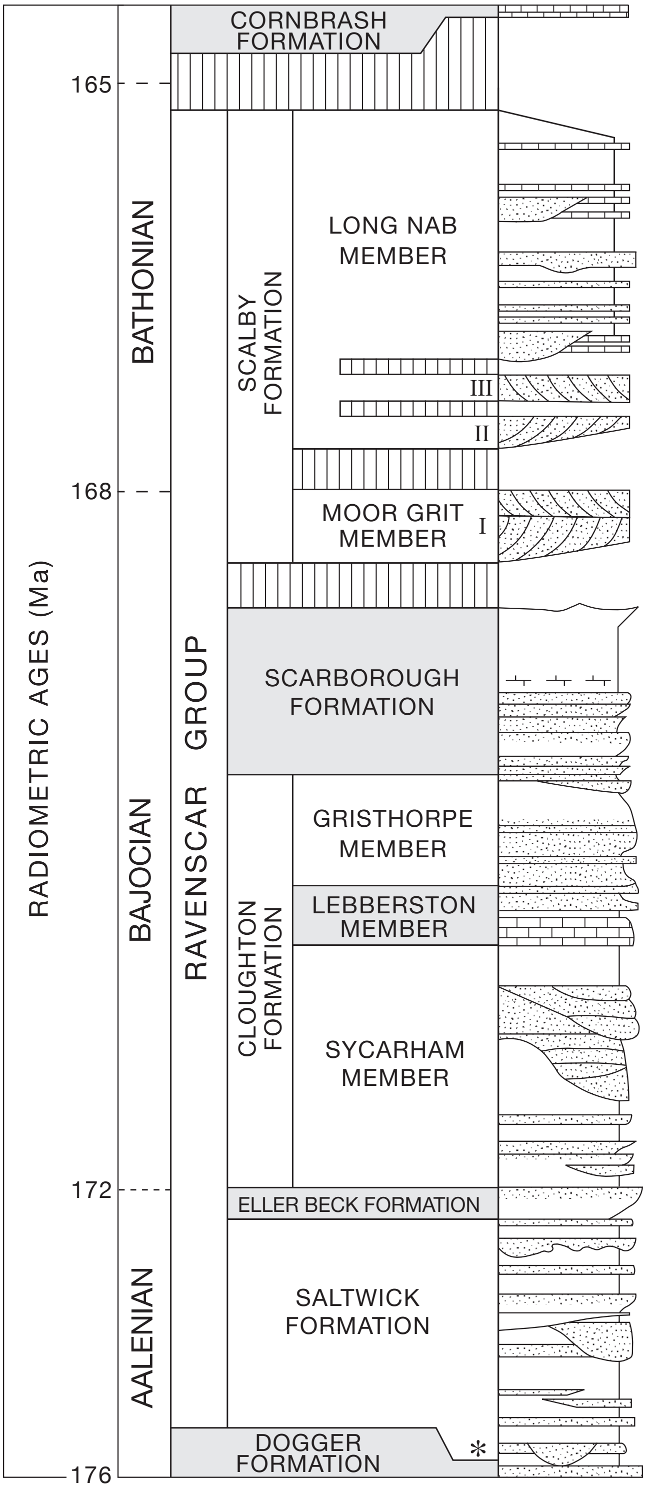


Figure 2 – Lithostratigraphy, chronostratigraphy and radiometric age estimates of the Middle Jurassic rocks of the Cleveland Basin (modified from Romano & Whyte, 2003: fig. 3). Marine units are stippled and asterix indicates approximate level of described horizon.

heterolithic mudrock with a coarser central portion. The channel sequence is overlain by mudrocks and thin (2 m) sheet sandstones (fig. 4a), containing stems of horsetails (*Equisetum columnare*) preserved in vertical growth position. Abundant blocks of the sandstones can be accessed and observed within the landslips and particularly in the most recent, and still active, slip, which developed in the mid 1990's (fig. 3) (Rawson & Wright, 2000). These slabs often display the sedimentary features of the channel deposits and also their vertebrate and invertebrate trace fossils. The vertebrate ichnofauna differs in composition from the coeval rocks at Whitby, particularly in the relative scarcity of sauropod and *Deltapodus* tracks (Romano & Whyte, 2003; Whyte et al., 2007). One unusual deposit from within the channel beds at Port Mulgrave is a thin track-bearing siltstone, which contains tridactyl morphotypes not found at Whitby.

THE SILTSTONE AND ITS DINOSAUR TRACKS

The distinctive, thin (2 cm), micaceous siltstone and its trackways have been observed within several slipped blocks of the channel sandstone. It is not possible to locate this siltstone in the exposed rock face above the loose blocks and it appears that the horizon was of limited extent. The brown-weathering, laminated siltstone is distinguished by the presence of dinosaur footprints and desiccation cracks (fig. 5a, b), both with a pelletal infill. The upper surface of the siltstone is marked in places by a complex network of invertebrate trails/burrows, which predate and are cut by both tracks and desiccation cracks (fig. 5b). The manner in which some of the desiccation cracks are controlled by and extend from the tips of the toes of tracks indicates that they are later than the prints.

The different prints within the siltstone can be assigned to morphotypes Bix, Bviii and Bxi of Romano & Whyte (2003) (fig. 6a-d, 7a, c). The tridactyl forms assigned to morphotype Bix resemble other prints of that type in size, relative proportions and divarication of the digits, but are unusual in showing well-preserved padding of the digits (fig. 7a). These prints also show tuberculate skin-like texture on the pads (fig. 7a) (but see below) and relatively stout claws or semi-claws on the digit tips. The digit tips are also distinguished by being dug into the siltstone so that they are the deepest part of the print and are overhung by the siltstone (fig. 7c).

The prints assigned to morphotypes Bviii and Bxi and illustrated in Romano & Whyte (2003: fig. 20) are distinguished from each other and from the other prints in the siltstone by differing degrees of rearward extension of the heel and metatarsal area of the footprint (fig. 6a-d). The trackway, including the figured example of morphotype Bviii (Romano & Whyte, 2003: fig. 20), was made by a small dinosaur which can be estimated to have been 0.46 m high at the hips and walking (relative stride length = 1.13) at a speed, estimated using Alexander's formula (Alexander, 1976), of 0.65 ms^{-1} (= 2.34 kph or 1.45 mph).

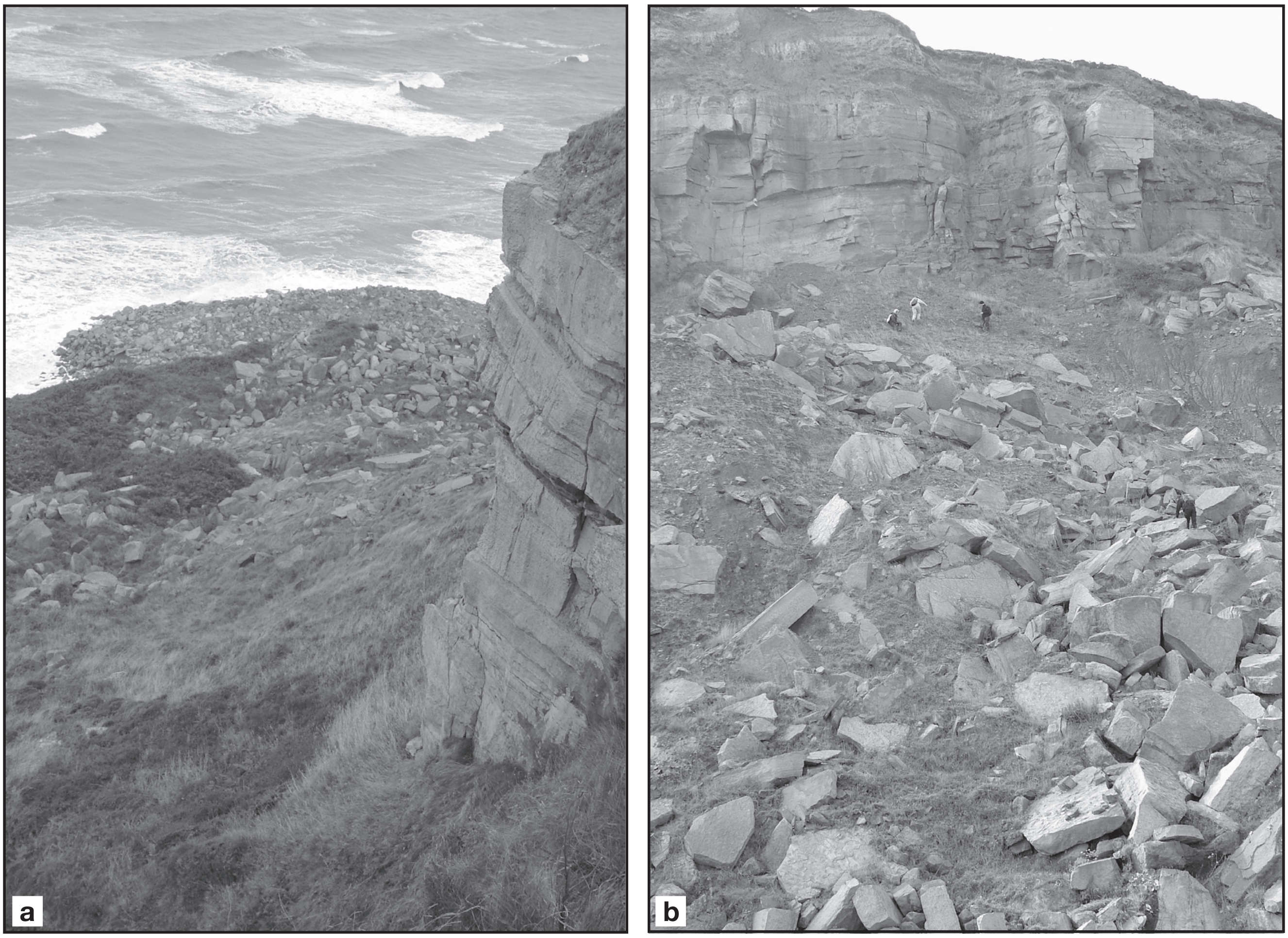


Figure 3 – Views of the Port Mulgrave landslips, showing thick sequence of amalgamated sandstones representing a channel fill in the back scar and the boulder fields of slipped rock from which the specimens were recovered. Note the figures below the rock face in b for scale.

The sequence of invertebrate and vertebrate traces followed by desiccation cracks suggests that the silt was deposited within an isolated pool which gradually dried out. It is not clear whether the sediment accumulated within a channel during a water low-stand or whether it formed in a chute pool or slack associated with a bar top environment, but the small scale cross-bedding of the overlying sandstone suggests the latter. The prints in the siltstone have formed in cohesive silt of various degrees of softness (see also below). Prints of morphotype Bxi, which show the greatest degree of metatarsal extension, were made by animals sinking deeper in the wettest silt while the other print types were made in progressively drier and firmer sediment. Despite the substrate-controlled posterior variations, all of the prints show similar digit patterns and could have been made by the same type of dinosaur, though more than one individual could have been involved.

The overhung and toe heavy nature of the prints is comparable to prints, which we have observed, made by modern emus (*Dromaius novaehollandiae*) (fig. 7b, d-f). Striae (sensu Romano and Whyte, 2003; = striations Milàn, 2006; = slide marks Currie et al., 2003) on the side of some emu prints (fig. 7e) show that the foot was initially moving forward as it was emplaced on and began to sink into the substrate but that thereafter a near-vertical sinking motion is dominant (cf. Milàn, 2006). During retraction the foot tips forward, so that some residual weight is placed on the tips of the digits, and the foot is then withdrawn backwards and upwards, so that the overhanging sediment at the front of digit imprints is preserved (fig. 7b, d-f).

A MODERN PARADIGM

A modern ephemeral pool (fig. 8a), which provided an instructive and comparable sequence to the Middle Jurassic example, has been observed by the authors in a working sandstone quarry near Huddersfield, West Yorkshire. Here, on one of the abandoned benches of the quarry, thinly laminated muds and silts had accumulated in a pool which, when visited, was in the process of drying out. While

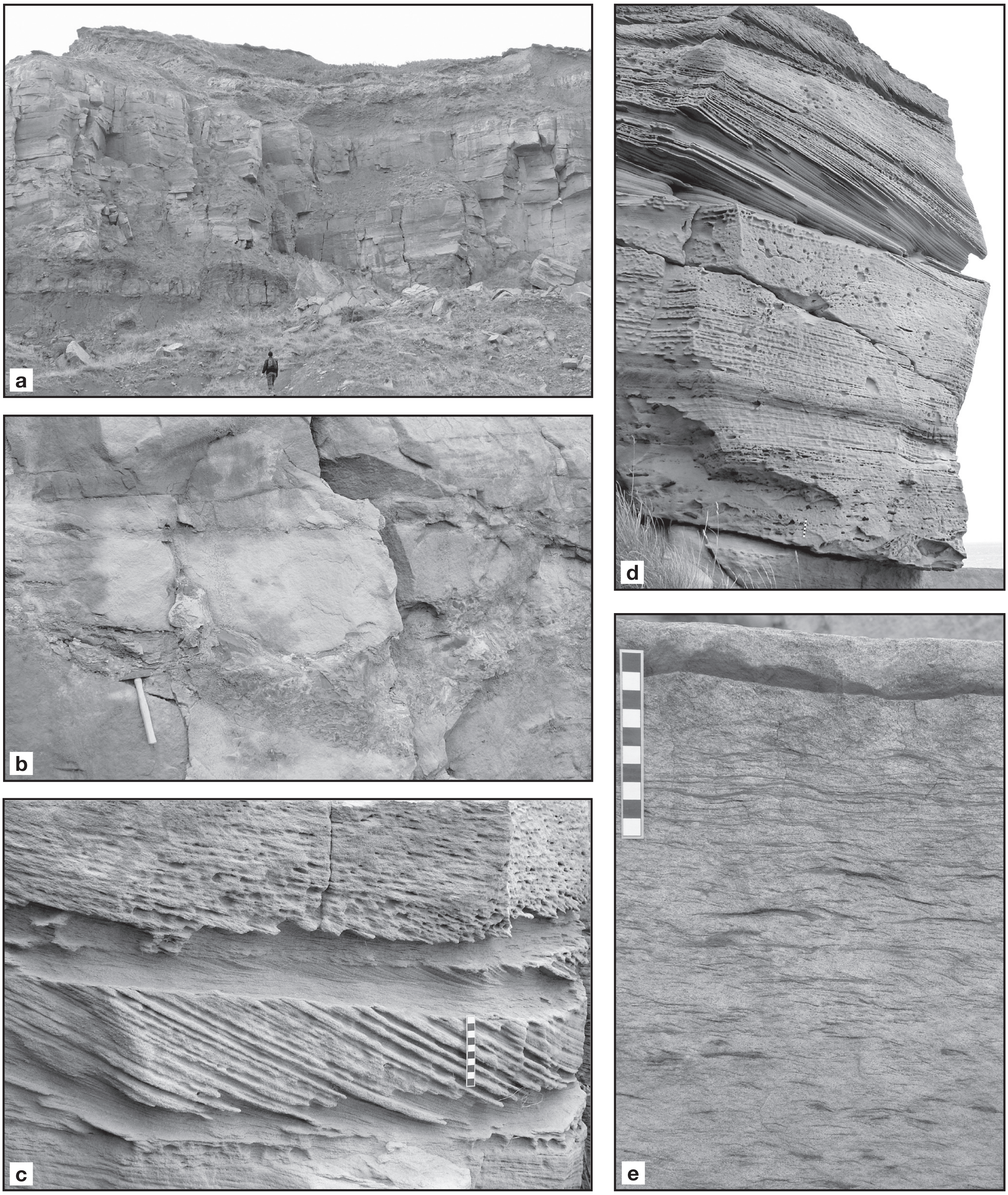


Figure 4 – Features of the channel sandstones in the back scar of the Port Mulgrave landslips. a) showing details of the stratigraphy of the channel sandstones. The Dogger Formation is the first prominent unit above the shales of the Whitby Formation at the base of the exposure. The bed with *Equisetum columnare* is the uppermost prominent unit in the scar face. Figure gives scale. b) erosional base and mud-flake conglomerate within the sandstone sequence near the base of the channel infill. Hammer (30 cm long) gives scale. c) and d) cross-bedded units in the channel sandstones showing differential weathering. Scale bar is 10 cm long. e) ripple cross-laminated sandstone with localised and sheet-like sideritisation (see text for details). Scale bar is 10 cm long.

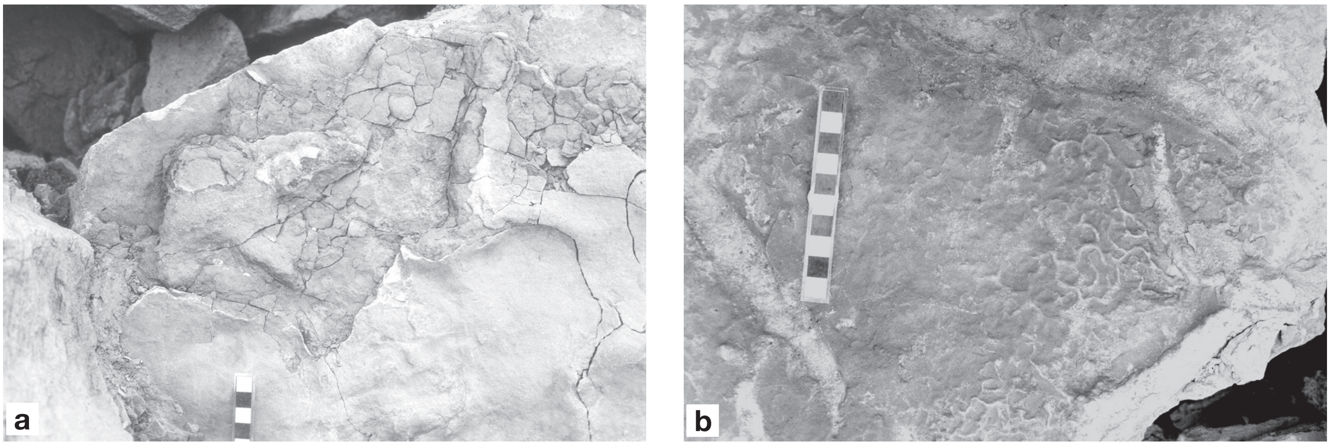


Figure 5 – Features of the siltstone sequence shown on loose blocks from Port Mulgrave. a) siltstone viewed from above showing underlying sandstone, dinosaur footprint, desiccation cracks and overlying sandstone. b) basal surface of overlying sandstone showing invertebrate trails and infill of desiccation cracks. Scale bar is 10 cm long.

some parts of the pool were still water covered, other peripheral regions showed transitions from saturated sediment through to hard, dry mud-cracked sediment (fig. 8a-fc). The sediment surface in the remaining water-covered areas of the pool was marked by the trails of an indeterminate invertebrate (possibly an annelid or nematode). In other parts, toad (fig. 8c) and bird trackways and particularly those of domestic dogs (fig. 8b, d-f) predominated.

In the driest parts of the deposit, where shrinkage cracks were best developed and there had been curling of the upper layers within the sediment polygons, good examples of shallow surface prints of dogs and their transmitted print counterparts could be examined (fig. 8e,f). The prints had clearly been made while the sediment was still moist. Elsewhere dog trackways could be seen to traverse areas which were even wetter and in these instances the prints were deeper and showed extended metatarsal regions (fig. 8b) comparable to the posteriorly extended dinosaur prints (fig. 6a-d).

One feature of the modern paradigm, which has no counterpart in the Port Mulgrave siltstone, is the presence of rain-pits. This is probably more informative about the contemporary climate of Yorkshire than about the palaeoclimate of the Middle Jurassic, but might indicate a more distinctly arid season in the latter.

INFILL OF TRACKS AND CRACKS

The modern analogue does not extend to the infilling of the footprints and desiccation cracks. In contrast, the infill of both the dinosaur tracks and the shrinkage cracks within the siltstone is not only present but is of critical importance both for their preservation and interpretation. Uniquely for the Yorkshire Basin, the initial infill consists of siltstone pellets (figs. 6, 9) which have been completely sideritised. The pellets are rounded, sub-spherical to sub-elliptical or elongate in shape, and vary from 0.5 mm to 2.0 mm in size (fig. 9a, b). Pellets have also been observed lying in some of the invertebrate trails. The pellets are overlain by sandstone, which infills the upper part of some desiccation cracks and completely covers the siltstone surface, infilling invertebrate trails or in places resting on a slightly erosive contact.

The relationships suggest that, during or shortly after re-flooding of the pool, the pellets were washed into the traces and cracks by currents and that other sediment was either lacking or by-passing the area. The tuberculate texture on the pads of some tracks (fig. 7a) is most probably due to the presence of the pellets rather than a primary skin feature, especially as a similar texture can be seen on the sides of the infill of some desiccation cracks.

The origin of the pellets is however problematic. They are too large and well-differentiated to be floccules (Pryor & Van Wie, 1971). The presence of shrinkage cracks and local erosion of the siltstone surface might suggest that the pellets are rip-up clasts. However, their shape and rounded character do not resemble mud flakes. The lack of any internal sedimentary laminations also militates against their interpretation as intraclasts derived from the silt. The rounded shape and an internal structure, which is either random or weakly concentric (fig. 9b), is perhaps most consistent with a faecal origin (Pryor, 1975; O'Brien & Slatt, 1990). The variation in size and shape of the pellets would imply derivation from populations of a range of size and even from different types of organisms.

SIDERITISATION

The sideritisation of the pelletal infill appears to have occurred relatively soon after deposition and before significant compaction of the siltstone. Some pre-sideritisation deformation of the pellets can be seen (fig. 9a), but the sideritised prints and desiccation cracks have resisted compaction and, as a result, prints and cracks have locally distorted both overlying (fig. 5a) and underlying (fig. 6a-d) sandstones.

In addition to the pelletal infill, siderite is found in

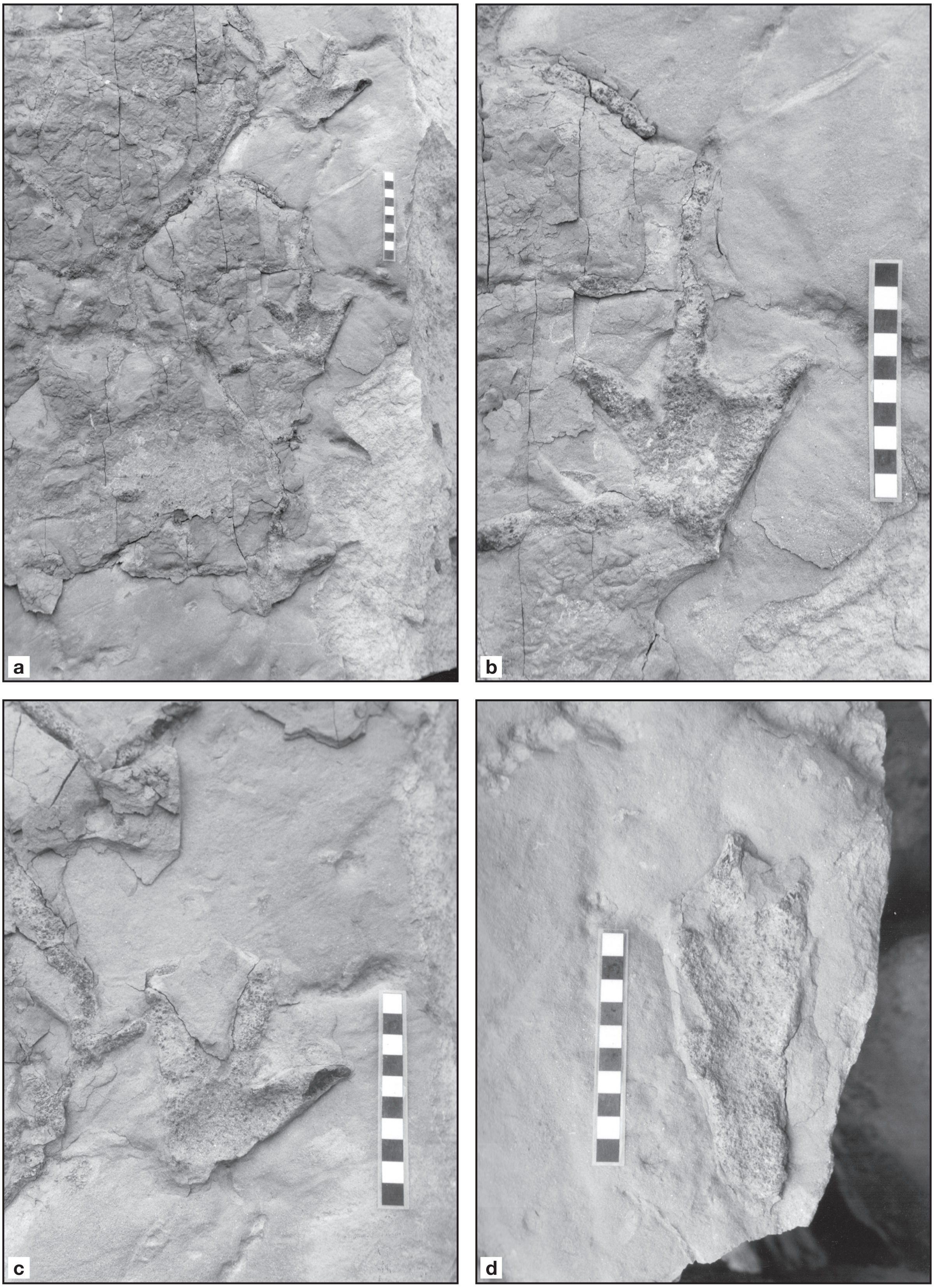


Figure 6 – Dinosaur footprints from the siltstone. a) trackway of three consecutive prints and associated desiccation cracks viewed from above. b-c) details of the second and third prints (morphotype Bxi) respectively of the trackway shown in a. d) print showing pronounced metatarsal extension (morphotype Bvii). This print was subsequently collected by and is in the collection of Mr B. Sharples of Haxby, Yorkshire Note the pelletal infills. Scale bar is 10 cm long

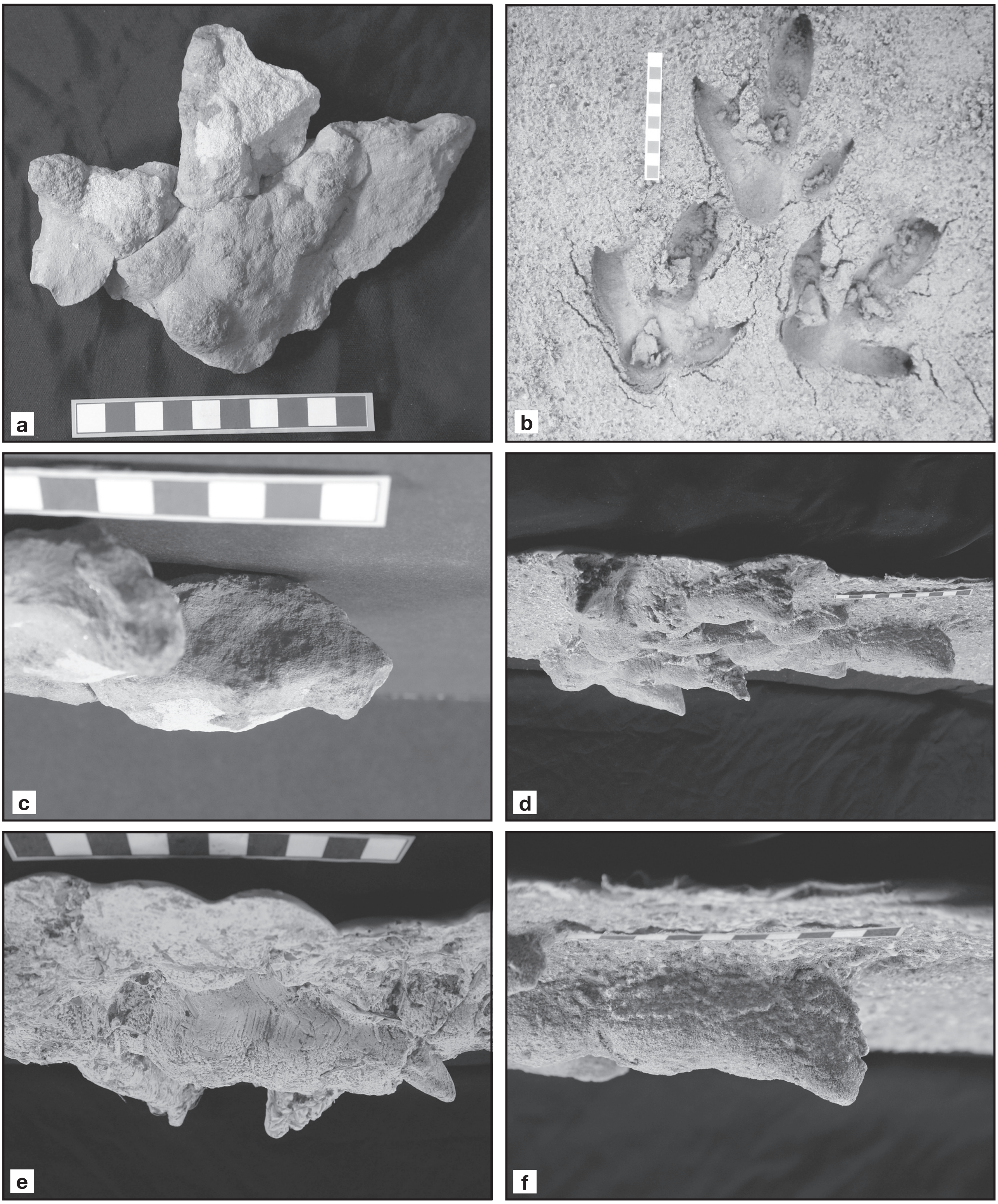


Figure 7 – Dinosaur footprint from Port Mulgrave and comparative modern emu prints. a) tridactyl dinosaur footprint viewed from below showing digital nodes with tuberculate skin-like texture. This print, which is also illustrated in fig. 5 a, is specimen number F00943 in the University of Sheffield collections. b) modern emu prints in sand viewed from above and showing toe heavy and overhung digit imprint terminations. c) side view of central digit (III) infill of print shown in a, exhibiting deeper and overhung digit termination. d) oblique lateral view of plaster cast of emu prints shown in b (University of Sheffield collections F00946). e) lateral view of plaster cast of a modern emu print showing striae on side of digit III and overhung termination (University of Sheffield collections F00855). f) detail of print shown in fig. b with overhung termination. Scale bar is 10 cm long.

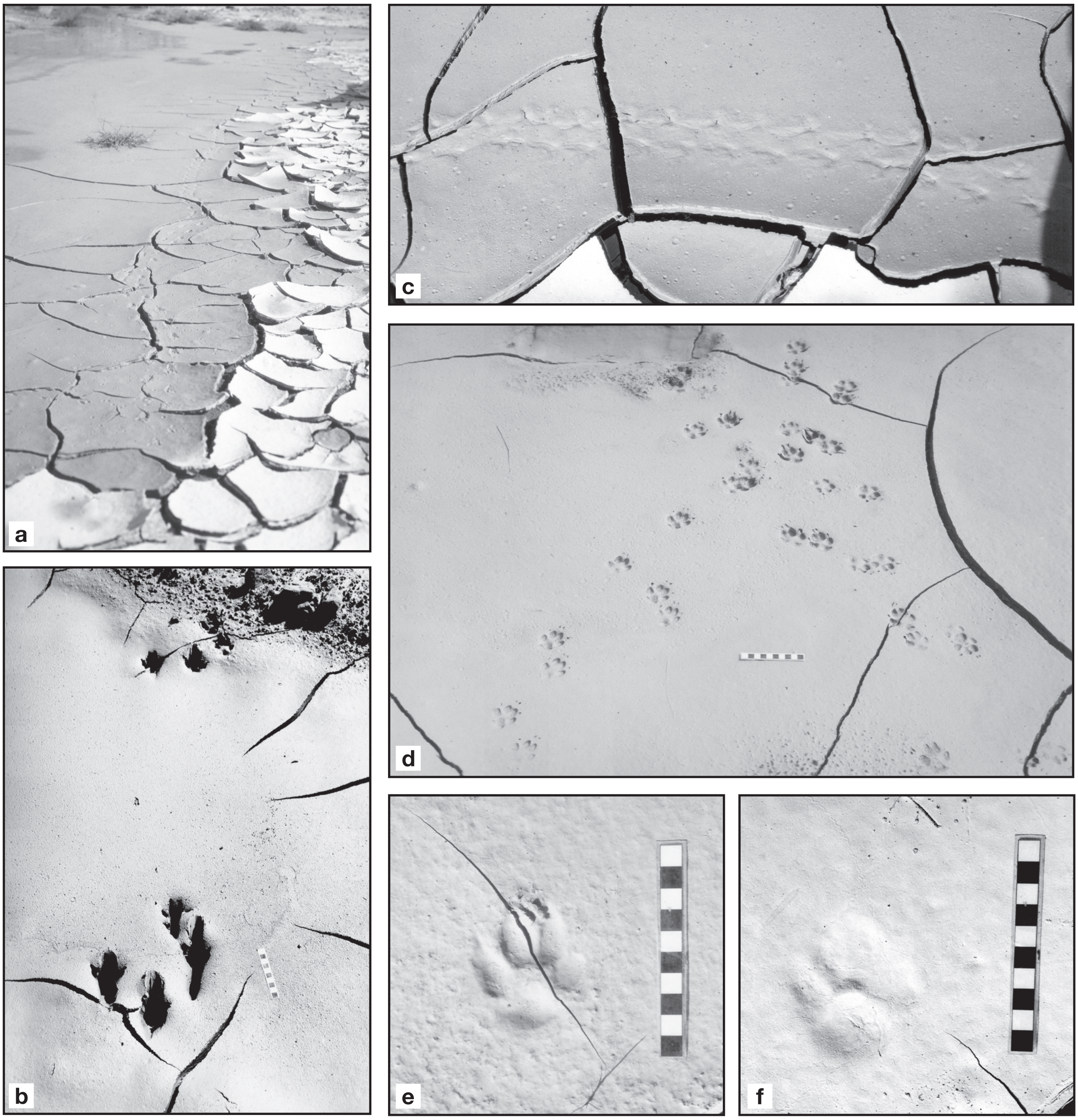


Figure 8 – Modern ephemeral pool, in Gilsons Quarry, Huddersfield, Yorkshire [SE 054 383], showing examples of sedimentary and biogenic structures. a) general view showing transition from wet area to marginal area with polygonal shrinkage cracks. b) detail of dog trackway showing deep prints with extended metatarsal regions. c) part of a toad trackway. d) dog trackways with shallow prints made in moist sediment. e) shallow surface dog print and f) its transmitted counterpart 10 mm below surface. Note the prints are all made prior to drying of sediment and development of shrinkage cracks. Scale bar is 10 cm long.

the channel sandstones, as diffuse localised cement patches and replacements within other vertebrate tracks, and also associated with finer-grained, ripple laminated beds (fig. 4e). In such places the development of siderite may be influenced by local porosity and eH/pH considerations (Curtis & Spears, 1968). Reduction of carbon associated with the faecal pellets may have helped to promote their sideritisation. Siderite is however also found as more massive developments as lenticular or tabular bodies (fig. 4e), which may cut across primary structures. Some of the sheets show a sharp border on one side and a gradational border on the other (fig. 4e).

Siderite cements are a common feature of Ravenscar

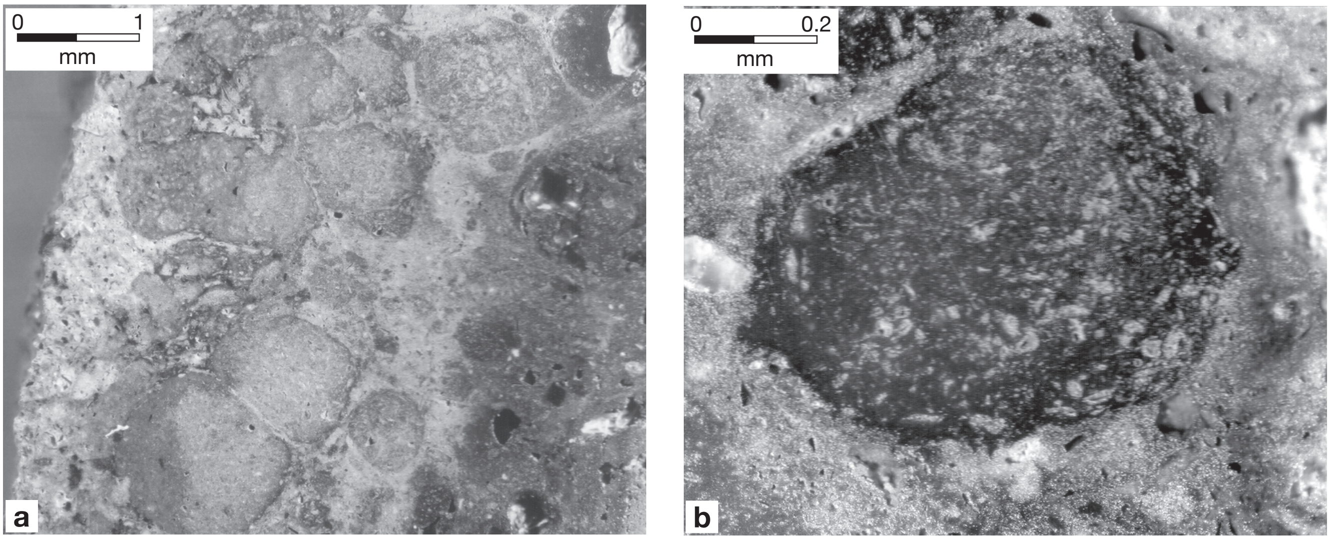


Figure 9 – Pelletal infill. a) general view of margin of a shrinkage crack showing pellets exhibiting minor compaction features. b) detail of a pellet from a shrinkage crack showing weakly concentric structure. Specimen F00944 in the University of Sheffield Collections.

Figure 10 (opposite) – Dinosaur prints and trackways from the Cleveland Basin and north Spain a) large tridactyl print viewed from below, Burniston Wyke. Specimen found by Peter Robinson and now in the collections of the Rotunda Museum, Scarborough (SCARB:2005.960). b) detail of specimen in fig. a, showing vertical striae on the side of the right digit imprint and overhung termination. c) dinosaur trackway showing prints with deepened digit tips, Barranco de la Canal (La Rioja) tracksite. d) detail of tridactyl print in foreground of fig. c. e) tridactyl print viewed from below, showing underprinted digit terminations, Hayburn Wyke (digital image kindly supplied by Ben Wedgwood). f) single underprinted digit imprint (right of centre), associated with curved invertebrate burrow traces, Burniston Footprint Bed, Burniston Wyke. Scale bar is 10 cm and lens cap is 5.8 cm.

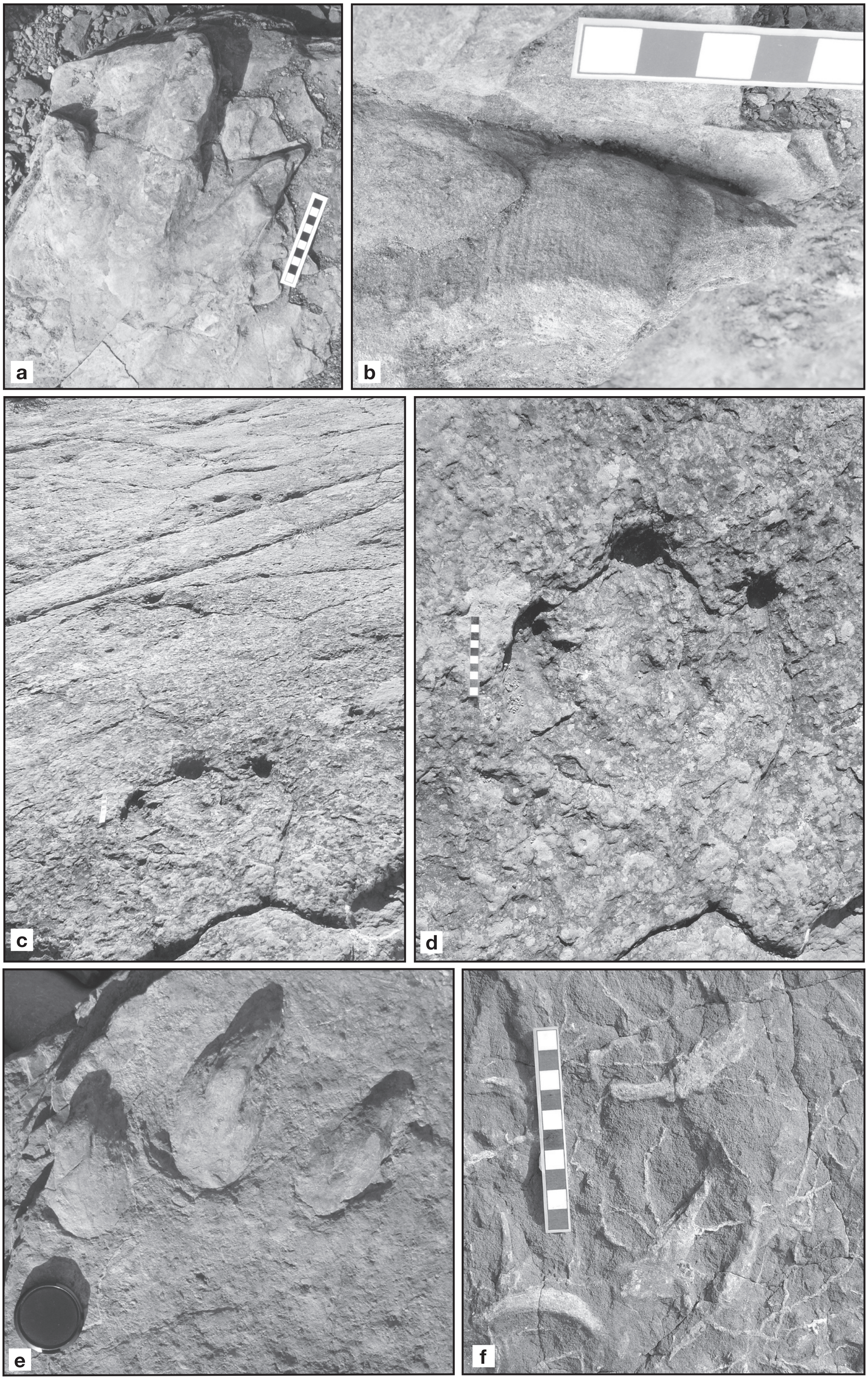
Group channel sandstones (Kantorowicz, 1985, 1986) but the sideritisation associated with the Port Mulgrave channel is unusually extensive. The sheet-like siderite developments suggest that the channel deposit has been an important aquifer and occupied by complex water bodies which interacted aggressively at their contacts. Volume of water movement may also have been important and the position of the channel towards the northern margin of the basin may have made it an important conduit for ground water flow from the centre of the basin. Because of the high carbon content of the source formations, this water would also have been reduced or anoxic to various degrees, favouring the precipitation of siderite.

DISCUSSION

Significantly, the pelletal infill shows that the dinosaur prints in the siltstone were left as open structures in soft but cohesive silt. In this they contrast with many other Yorkshire prints whose preservation suggests a squelch-like form in which infill began, or in which the print sides closed or contorted, as soon as the foot moved on (Whyte & Romano, 1981; Romano & Whyte, 2003).

The print morphologies exhibiting metatarsal extension, and especially morphotype Bviii (fig. 6d) are very similar to prints illustrated by Pérez-Lorente (2003: fig. 30) from the Cretaceous of Spain. They are also comparable to ichnospecies such as *Anomoepus* or *Moyenisauropus* (Ellenberger et al., 1970; Avanzini et al., 2001; Lockley et al., 2003; Romero Molina et al., 2003) but are locomotary rather than squatting prints. Similarly the prints of morphotype Bxi (fig. 6a-c) resemble *Dinosauropodes* in their backward extension (Romero Molina et al., 2003). The link between the form of prints, belonging to both morphotype Bxi and morphotype Bviii, and sediment consistency can be used to interpret occurrences of these morphotypes elsewhere within the Ravenscar Group. However, while they may be associated with, and variants of, morphotype Bix in the Port Mulgrave channel sandstone, this should not be assumed to be the case at other horizons.

The rearward retraction of the foot, deduced for the maker of the morphotype Bix prints at Port Mulgrave, is particularly significant and can be detected in other Yorkshire prints including a large specimen (35 cm long) from Burniston Wyke (fig. 1), which exhibits both overhung claws and groove marks on the digit imprints (fig. 10a, b). Underprinted tips of digit imprints may also represent manifestations of this emu-like motion of the foot (fig. 10e, f) (cf. Thulborn, 1990: p.129, fig. 5.12). In some cases underprinted tips of digits superficially resemble the bivalve resting trace, *Lockeia* (fig. 10e). During the course of the Fumanya Symposium, toe-heavy prints were seen at the Barranco de la Canal (La Rioja) tracksite (fig. 10c, d). Over hung toes can be seen in prints of the Yacimiento de Tenedas de Costalomo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tracksite (Fundación Dinosaurios, 2006) and retrograde foot retraction is implicit in their elegant reinterpretation by Torcida Fernández et al. (2005). An initial backward movement of the foot is also implicit in reconstructions of deep tracks from the Late Triassic of Greenland, before a final forward withdrawal of the foot through the sediment (Gatesy, 2003: fig.2C).

Other Yorkshire prints show an apparently different gait with no obvious backward movement of the foot. Thus, for instance, the original figured example of morphotype Bix exhibits a distinct but closed claw drag mark (Whyte & Romano, 1981; Romano & Whyte, 2003), indicative of forward movement of the foot during retraction. The apparently longer digit III imprint of prints belonging to morphotype Bvii (Romano & Whyte 2003: fig. 20) may also result from forward withdrawal of digits through the sediment. This suggests that the limbs of bipedal dinosaurs may have operated in different ways in different situations. Though the print makers at Port Mulgrave were smaller than modern adult emus, size was probably not a factor, as some prints of dinosaurs, which were considerably larger than emus, also show backward retraction (fig. 10a, b). The differences in limb movement most probably reflect differences in speed and depth of penetration of the foot into the substrate.

CONCLUSIONS

The Port Mulgrave siltstone opens a small but significant window in time allowing us, through its combination of organic and inorganic features, to see the history of the deposit and its changing environment. A drying pool, inhabited by invertebrates, was skirted by dinosaurs and, as desiccation progressed, its silts were riven by shrinkage cracks. The shrinkage cracks and dinosaur prints were then infilled by mud pellets of probable faecal origin and subsequently covered by sand.

The dinosaur prints, left as the silt dried out, show a morphological range reflecting varying degrees of substrate consistency with greater degrees of metatarsal extension in softer sediment. More importantly the preservation of some prints with deeper toe terminations, which are overhung by sediment, shows a rearward retraction of the feet similar to that which can be observed in some modern emu prints. Such movement has not previously been explicitly recognised in dinosaurs but can also be recognised in other occurrences both in Yorkshire and elsewhere. It contrasts with the forward toe drag reconstructed from some other footprints and indicates that bipedal dinosaurs had more than one pattern of foot movement.

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