Dinosaur tracks from the lower Purbeck strata of Portland, Dorset, southern England

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Dinosaur tracks from strata below the Cherty Freshwater Member, Lulworth Formation, Purbeck Limestone Group, of Dorset had not been recorded formally until 2002 when Professor Michael House published a preliminary note, in the *Proceedings of the Dorset Natural History and Archaeological Society*. He flagged the 2001 discovery of a number of blocks of the 'Thick Slatt', Hard Cockle Member, with casts of dinosaur tracks preserved on their lower surfaces, in a quarry on the Isle of Portland. New light is shed on the source of the tracks, and the history of their discovery is documented. The methods employed to record them are described. The traces are placed in their stratigraphic and palaeoenvironmental settings.

In this paper, how the tracks were made is described, and most importantly it is concluded that they are preserved as transmitted casts. Three distinct types of tridactyl track attributable to bipedal dinosaurs are recognized, as well as isolated tracks which are interpreted as belonging to quadrupedal dinosaurs. Evidence is presented to support the interpretation that one of the tracks assigned to a quadrupedal dinosaur was produced by a sauropod. Despite their apparent differences, it is suggested that the majority of the tridactyl tracks were left by one species of dinosaur which was almost certainly herbivorous and lived in groups. One trackway may have been made by a carnivorous dinosaur.

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Introduction

Dinosaur tracks (individual footprint/print) and trackways (two or more consecutive footprints/prints) recorded from the late Jurassic - early Cretaceous Purbeck Limestone Group of Dorset, southern England, in both manuscript and published accounts were thoroughly checked and documented (Ensom, 1995a, 1995b). Amongst these were three early records of tracks allegedly from the Lower Purbeck Beds, Catalogue Numbers 51, 52 and 55 (Ensom, 1995a). No.51 later proved to be a trackway horizon (i.e. two or more consecutive tracks or prints) in the 'Middle Purbeck Beds' at Worbarrow Tout, No. 52 was preserved on a fallen block on the shore of Worbarrow Tout and as such could not be assigned a 'Lower Purbeck' source with certainty, and No. 55 was a specimen recorded in the 19th Century, which does not appear to have survived in any collection. Ensom (1995a) noted the discovery by Jane Francis of tracks in the Transition Bed at the top of the late Jurassic Portland Limestone Group and immediately below the Purbeck Limestone Group on the Isle of Portland (Francis personal communication, 1994). A short note confirming this discovery was later published (Francis, 1996).

The absence of any confirmed tracks from the 'Lower Purbeck Beds' encouraged a continuing search for tracks in these beds as opportunity presented itself. During the 1980s research on the Purbeck Limestone Group on Worbarrow Tout (NGR SY 869 796) by one of us (Ensom, 1985a) revealed curious irregular depressions on the surface of stromatolitic limestones just above the Portland Limestone Group. These aroused suspicions that there may have been dinosaur activity this low in the Purbeck sequence (Julian Andrews personal communication, 1985), but despite careful observation, no unequivocal tracks were recorded.

In 2001, a chance find of the casts of dinosaur tracks on the basal surfaces of overturned blocks of limestone in the Coombefield South quarry complex, by a dog-walker with connections to the Isle of Purbeck, where dinosaur tracks were well known, quickly led to the discovery of a large number of dissociated tracks. They had been excavated and tipped during earlier stripping of the Purbeck Limestone Group to permit extraction of the commercially important Portland limestones from a quarry nearby. Some initial mapping and photographic recording of the tracks, while still on the tips, was carried out by Justin Delair and Michael House. Detailed mapping of all traceable evidence of these tracks was completed by Delair in 2004, after the death of Professor House, and once the blocks had been lifted clear of the waste tips. Ian West and Ms Caroline Clasby, both of Southampton University, carried out stratigraphical and sedimentological investigations, the latter as part of an undergraduate project. A short report on the discovery was written by House (2002), and Ensom (2006a) provides a brief report on work undertaken in 2003-2004. West (http://www.soton.ac.uk/~imw/portdino) gives a comprehensive review of these, and related, discoveries in their stratigraphical and sedimentological context. In conclusion, a verbal report of 'fossil footprints' found on Portland during September 1961, was relayed that month to one of us (JBD) by the late Ernest Oppé of Worth Matravers. If genuine this is of historical value only, as the finds were never verified and recorded; the stratigraphic horizon and locality at which they had been found is unknown. The presence of footprints remained a well kept secret by those who knew!

In 2002, one of us (PCE), then employed by the Natural History Museum, London, was contracted by the Dorset County Council (DCC) to advise on a number of aspects of the discovery, including how many trackway horizons were represented by the recovered tracks, to correlate the track-bearing horizon with the local succession, to provide a detailed record of the tracks and other features preserved with them, to record them photographically, and finally to provide a priority list for recovery and protection. This work was carried out in 2003 and 2004 (Ensom, 2003, 2004). As noted above, one of us (JBD) had simultaneously continued the mapping of the tracks which had been started with Michael House. This paper brings together the results of these two studies. The acronym DORCM = Dorset County Museum, Dorchester, DT1 1XA and is used to indicate items deposited in their collections, either permanently or on long loan.

Methods used for recording the tracks

Over 23 blocks of stone, some weighing several tonnes, with tracks preserved as casts, were identified and lifted from the jumble of stones tipped alongside an access road within the quarry complex, and placed on a relatively level piece of ground where access to them could be gained with ease. The lift (Figure 1a) was financed by the then owners of the site, Hanson Bath and Portland Stone and was carried out by Portland Plant Hire, supervised by Andy Stone (Quarry Foreman for Hanson), and with guidance from Richard Edmonds and Chris Pamplin (Dorset County Council).

The blocks were numbered using paint spray used for block identification in the quarries. These numbers were later made more permanent when one of us (PCE) carved them into the sides of the blocks. A further two blocks were identified within the tips and numbered 24 and 25. This numbering scheme was then used throughout the recording process to insure that no ambiguity could arise. All the tracks and other associated features on the base of each block were recorded onto squared paper using a metre square recording grid divided by tensioned strings into 100 x 0.1 m^2 (Figure 1b). Each track was given a unique reference on the drawn plan, using the block number and a letter. Notes and measurements made in notebooks used this annotation.

Originally the plan had been to have photographs of all the lifted and numbered blocks made at night, using suitable lighting and a 'cherry-picker' to provide a view perpendicular to the surface. In the event, money was not forthcoming so photography was carried out when the sun was low in the sky, both early in the day and then later. In 2003 a Pentax SLR camera with macro lens with 35 mm colour transparency Fujifilm; in 2003, and in 2004 a Nikon Coolpix SQ digital camera were used. Mini blackboards measuring 4.5 x 9 cm carrying the unique reference for each print were placed adjacent to the tracks across each block. An oblique general view of the block, and then detailed shots of each track, were taken. A 10 cm scale bar was included in each shot (Figure 1h). This system was very suitable for recording many tracks quickly in the short window of opportunity as the sun, when present, was low in the sky and thus provided the raking light required to show up these features.

In addition to the scale drawings produced, a series of 1:1 polythene sheet plans were produced (Figure 1c). Thick gauge polythene sheet was cut to the size of each block and the edges of the block, and tracks along with other notable features recorded using black spirit-based felt-tip pens. Each sheet carries the block number. The aim of this exercise was to provide a back-up for the plans, and templates for any future display or storage developments. They have already proved their worth in considering the options for the reduction in block size. On the numbered blocks, a total of 78 tracks, i.e. individual prints, and 29 putative tracks were identified. From this total, 14 trackways were recognised, along with three possible trackways.

Location

The quarried blocks with the casts of tracks on their lower surfaces were discovered adjacent to an access road within the Coombefield South quarry complex at Southwell on the Isle of Portland (Figure 2a). House (2002) reported that they had come from Suckthumb Quarry. The quarry foreman, Andy Stone (personal communication, 2006) indicated that these blocks were all that remained of a more extensive area of limestone pavement which had been removed as overburden from north Goatsfield Quarry and possibly south Star Quarry (NGR 687 705), to the south of Suckthumb Quarry, all within the Coombefield South complex (Figure 2b); the quarrying took place around 1996. Stone recalls that these blocks were set aside by the contractors, who had undertaken the removal of overburden, to be split for walling stone; fortunately they escaped this fate!

Stratigraphy

The recently discovered trackway horizons occur towards the base of the Lulworth Formation of the Purbeck Limestone Group. House (2002) identified the bed as the Thick Slatt (House 1958, figure 8) a view which has been accepted by all those studying these tracks. West refers to the bed as the Hard Slatt (http://www.soton.ac.uk/~imw/portdino). The 'Shingle' of quarryman's parlance lies below the Hard Slatt. West equates these horizons with the 'Cypris' Freestone and Hard Cockle members respectively, and identifies the sediments immediately above the Thick Slatt as belonging to the Soft Cockle Member (Figure 2c). Rawson (2006) leans towards the view that the Jurassic – Cretaceous boundary is below the 'Cypris Freestones', placing the Thick Slatt (=Hard Cockle Member) very close to the base of the Cretaceous.

Sedimentology

In a section measured in the south west of Goatsfield Quarry (NGR SY 68774 70339) the Thick Slatt is 1.23 m thick, with a parting 0.68 m above the base. The bed lies 5.05 m above the base of the Soft Cap and approximately 7 - 8 m above the top of the Portland Limestone Formation; access constraints prevented a precise measurement being taken. The Thick Slatt rests on a 0.02 m thick marly-clay which in turn is underlain by thin, flaggy and ripple marked coarse-grained limestones (0.28 m thick). These are underlain by argillaceous limestones/calcareous clays.

Halite pseudomorphs are preserved at the base of the Thick Slatt. Just above the base of the bed is a thin parting of calcareous clay or argillaceous micrite which may equate with one horizon with dinosaur track casts. This suggestion is based on the presence of similar sediment surviving on, and associated with, some of the tracks and the surfaces on which they are preserved. If this is the case, the dinosaurs walked over a surface above that upon which the casts are preserved. Therefore some, if not all are transmitted casts (Ensom, 1982, 1983). This has significance for any interpretation of the tracks (Ensom, 1995a, 2002; Romano and Whyte, 2003; Manning, 2004).

The bottom of Block No. 22 revealed three horizons with halite pseudomorphs. The first coincides with the preserved base of the quarried block, the middle horizon with casts of tracks is 0.06 m above this. A further 0.02 m above this there is another horizon of halite pseudomorphs. The top of the block was 0.76 m above this. The presence of this flaggy base to the Thick Slatt may offer one explanation as to why the tracks were not immediately seen after the beds were excavated. Another is suggested by Andy Stone who points that the quarried blocks were likely to have been covered with clay and soil when first tipped.

The blocks of Thick Slatt at Coombefield are a hard pelletoid limestone, blue when fresh but weathering cream to pale brown. West has identified an oolitic component in the sediment (http://www.soton.ac.uk/~imw/portdino) which he

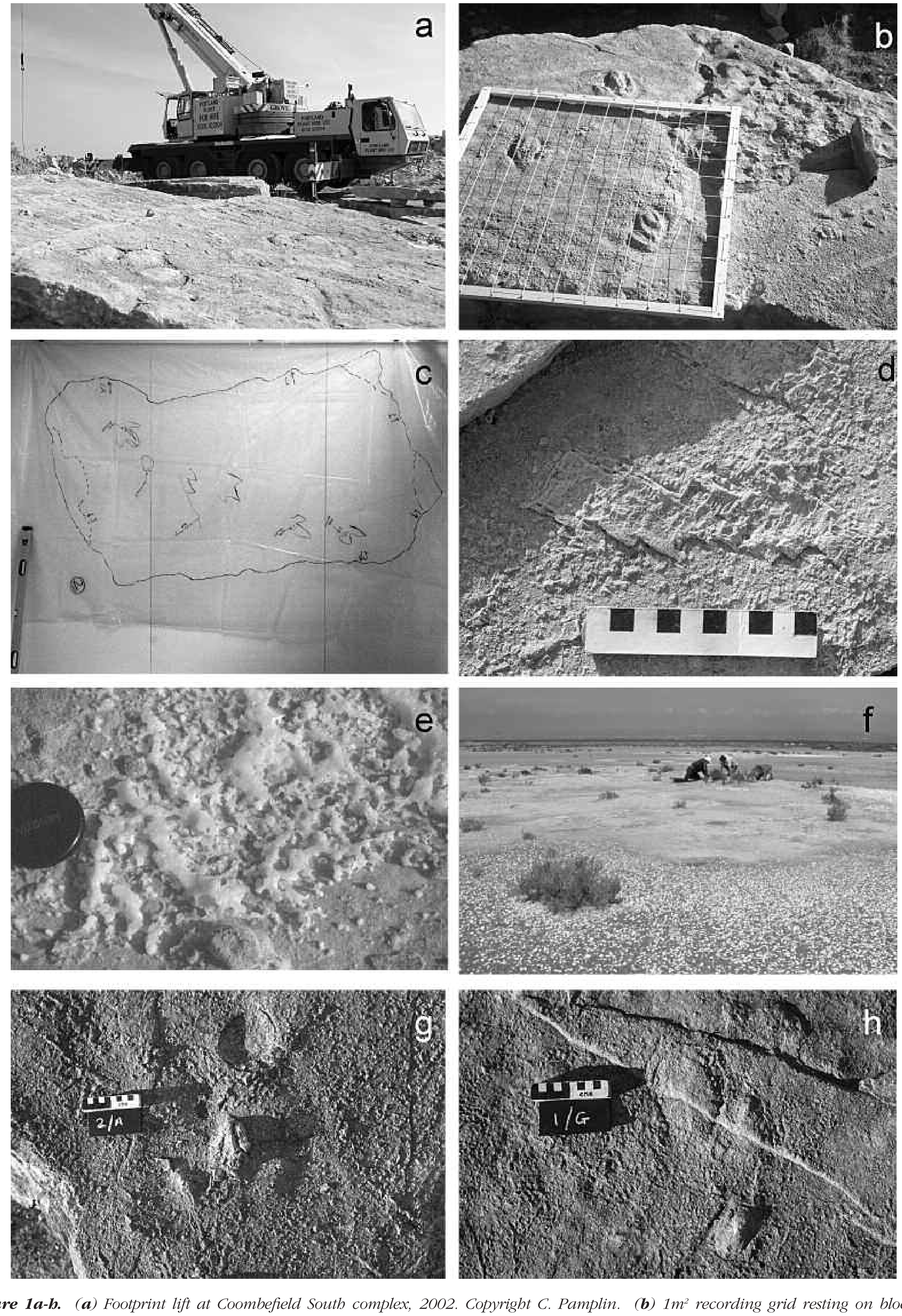


Figure 1a-h. *(**a**) Footprint lift at Coombefield South complex, 2002. Copyright C. Pamplin. (**b**) 1m² recording grid resting on block 7. (**c**) Polythene plan (1:1) of the surface of block 2. Image courtesy of R. Edmonds. (**d**) 'Strings' of pseudomorphs after halite, on the base of block 22. Scale bar 0.1 m. (**e**) Modern 'strings' of halite crystals on salt-flats, Limassol, Cyprus. Copyright J. Francis. Lens cap for scale. (**f**) Salt flats at Limassol, Cyprus. Copyright J. Francis. (**g**) 'Upbulge' structure associated with Track 2A. Scale bar 0.1 m. (**h**) Microfault cutting track, block 1. Scale bar 0.1 m.*

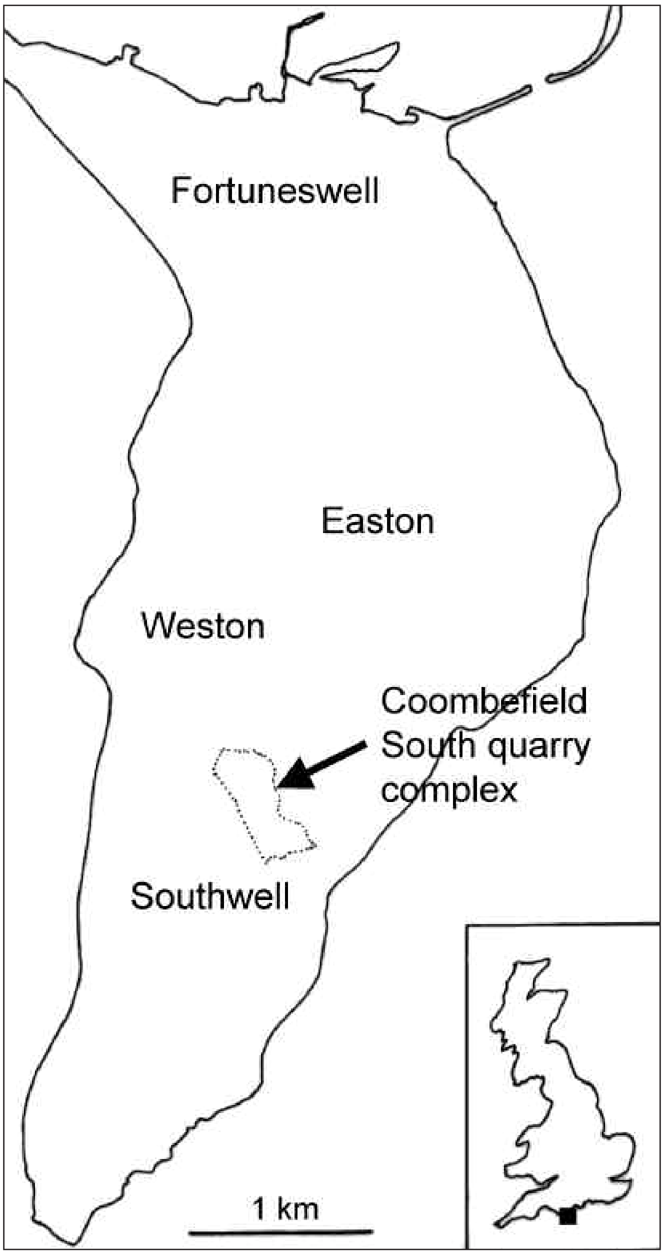


Figure 2a. *The Isle of Portland showing location of source quarry.*

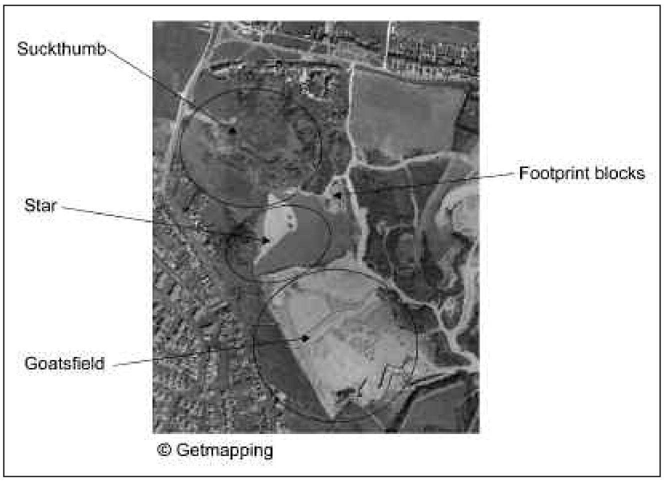


Figure 2b. *Aerial view of the Coombefield quarry complex, identifying sites mentioned in the text. Photograph copyright Getmapping.*

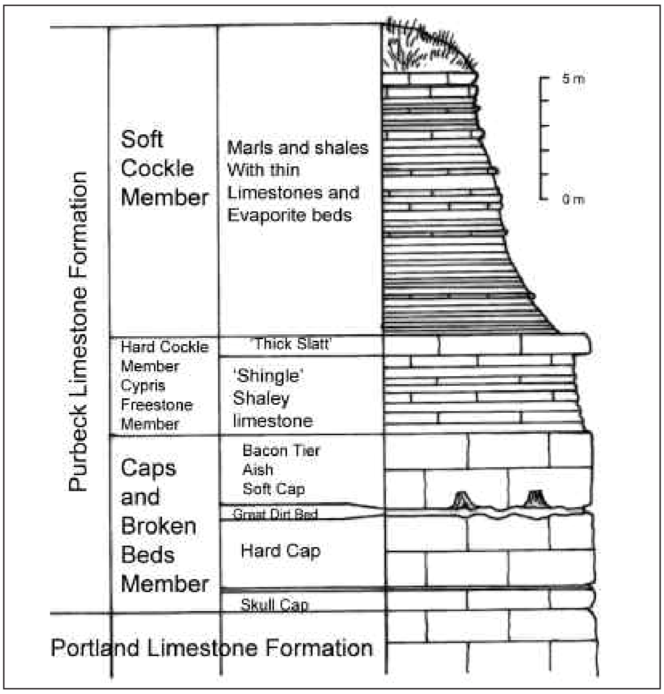


Figure 2c. *Idealised section through the Lulworth Formation, based on the cliffs on the west coast of the Isle of Portland. Redrawn from West http://www.soton.ac.uk/~imw/portdino.*

suggests originated as a transgressive carbonate sand sheet. The thickness of the track-bearing blocks varied from 0.42-0.86 m. This may represent the variability of this bed which according to Andy Stone, thinned and gradually disappeared across the area which was quarried. The flaggy nature of the sediments at the base of the bed with several halite pseudomorph horizons, as seen in Block No. 22, may indicate an initial influx of sediment, subsequent reworking and further salt flat development before the main transgressive event. Sometimes there is evidence that the halite crystals would clump together to form strings (Figure 1d), a feature documented by Jane Francis on modern salt flats at Limassol in Cyprus (Figure 1e). Ripple marks are also present (Figure 4e), along with a number of curious 'upbulges', which are briefly discussed by West (http://www.soton.ac.uk/~imw/portdino.htm#dinupbulge) who suggests that mud clasts may have been the cause of these very unusual structures. The 'upbulges' (Figure 1g) are sometimes, but not exclusively, associated with trackways. Ensom (2006b) has suggested that they may be produced by gas bubbles or small-scale mud diapirs. A single specimen has been accessioned into the collection of the Dorset County Museum, DORCM G 11679. The same note recorded impersistent small-scale faulting (Figures 1h and 5b), exhibiting throws of less than *c.*20 mm, which is well exhibited on the lower surface of some of the blocks. Similar faulting has been observed in stacked blocks of the Thick Slatt at Bowers Quarry, immediately north of Weston, Portland (NGR SY 683 718). Francis (personal communication, 2006) suggested that if gas was implicated in these structures, it could be methane escaping from rotting organic matter in the sediments underlying the Thick Slatt. Conceivably, dinosaurs walking on the carbonate sands just above the buried salt flat's surface could be invoked as the trigger for transient gas release, or alternatively the seismic shocks from movement on locally active faults as discussed below. While the former has a certain charm, the presence of tracks cut by micro-faults (Figure 1h) suggests an event post-dating the formation of these tracks. As all the blocks we have examined have been transported, we have been unable to determine any directional signatures from ripple marks or other structures.

The Thick Slatt is frequently exposed in quarries on Portland, but apart from an unexplained bulge on a loose block at Bowers Quarry, as yet, no convincing evidence has been found of tracks at this horizon from non-coastal locations. In July 2003, one of us (PCE) was shown casts of tridactyl tracks on the base of the upper leaf of a divided Thick Slatt on the coast at Black Nore above Mutton Cove (NGR SY 6799 7133). While tracks are present within the Thick Slatt at Black Nore, the Coombefield tracks are preserved towards the base of the Thick Slatt, though there is evidence for one or more additional trackway horizons within the Thick Slatt at this location. While West's interpretation of the deposit as a transgressive calcarenite sheet could explain the occurrence of not less than two track horizons within the bed, each being dependent on the relative timing of track making and the migration of the sand sheet, there is good evidence that dinosaurs moved across the same area at different times (see interpretation under Tridactyl tracks).

PALAEOGEOGRAPHY AND PALAEOENVIRONMENT

Allen (1998) summarises the palaeogeography of the region as follows: The area [south-west Britain and north-west Europe] featured part of a complex of small active massifs (expressed as peninsulas and archipelagos) in temporarily silting-up seaways. It was bordered on the west and southwest by narrow arms of the widening Protoatlantic, on the northeast by the Boreal Sea, and far to the south by the closing Tethys.

Within this broad framework, Portland lay at the western end of the Portland –Wight Basin, the northern margin of which was controlled by movement along both the Purbeck Fault to the east-north-east of Portland, the depocentre of which was just west of the Needles on the Isle of Wight, and the Abbotsbury - Ridgeway Fault to the north-west of Portland with its associated small depocentre in the Friar Waddon area (Underhill, 2002). Underhill (2002) suggests that the relay ramp formed by the offset between these two faults, which he demonstrates were active over an extended period – latterly during the deposition of late Jurassic and early Cretaceous sediments, had underlain the 'swell' postulated by Townson (1975) as the control on the deposition of the Portland Limestone Group on Portland. This same basin geometry continued to influence sedimentation and the sediments deposited during Purbeck times. The variation in sedimentation rate is well demonstrated by the relatively attenuated sequence, *c.*11.25 m (West http://www.soton.ac.uk/~imw/portdino), of Caps and Broken Beds Member and the 'Cypris' Freestone and Hard Cockle members preserved on Portland, compared to *c.*21.5 m at Worbarrow Tout (Ensom, 1985a), and 25.9 m at Durlston Bay (House, 1989).

While ammonites are at times abundant in the Portland Limestone Group, and are indicative of a normal marine environment, the bulk of the Purbeck sediments were deposited in a restricted marginal marine environment where swings from freshwater to more saline conditions were not uncommon. In the basal strata, West (1975) suggests that the sediments were deposited in conditions ranging from moderately hypersaline subtidal and intertidal to very hypersaline intertidal to supratidal. Within this restricted basin, tidal influence is likely to have been negligible with wind induced water movement playing an important role in sedimentary processes. This lack of a true tidal influence is supported by Radley (2002) who shows that the Lulworth Formation's molluscan faunas are either of low or high salinity type, with no evidence of incursions of normal marine taxa.

Previously we have referred to the salt flats at Limassol on Cyprus (Figure 1f), a blindingly bright and inhospitable environment (Jane Francis personal communication, 2005). In Limassol the mean daily temperatures range from 12.4°C in January to 27.1°C in August with a daytime maxima of 40° C which is similar to the mean annual range given by Allen (1998) of *c.* >15°C – 25°C. Based on her study of the Purbeck fossil forests, Francis (1983) was able to deduce a strongly seasonal climate with hot arid summers and wetter winters, a view endorsed by Allen (1998) who estimated annual rainfall of <500 mm.

From the above, we may piece together a picture of a landscape occasionally inhabited by dinosaurs whose tracks we are starting to find. To the north of faults running from the Isle of Wight, west through Ballard Down and so to Lulworth, and then from around Chaldon Down to Abbotsbury, existed a subdued landmass where there was no deposition and even erosion of earlier deposits. Small but frequent movements along these faults, saw the area to the south subsiding, most significantly in the area immediately west of the Isle of Wight. This isolated coastal plain saw evaporites forming during the hot and arid summers, and fresh to brackish water deposits produced during the wetter winters. Carbonaceous fragments are not uncommon on the base of the Thick Slatt. There seems every likelihood that conifer forests similar to those described by Francis (1983), which had covered this area earlier in the Purbeck sequence and which had been inundated by the hypersaline waters after movement along the bounding faults (Underhill, 2002), were still colonising ground above 'sea-level' when the Thick Slatt was deposited.

THE FORMATION OF THE TRACKS

When a terrestrial vertebrate walks over sediment, a number of parameters such as the thickness, type and plasticity of the sediments at and below the surface, and the weight of the animal, and how it is moving or standing, all influence the form of the trace left behind (Ensom, 1995a, 2002; Romano and Whyte, 2003; Manning, 2004). The mechanical and physical characteristics of a single sedimentary surface will change both laterally, and seasonally. Romano and Whyte (2003) provide a detailed discussion of the available descriptive terminologies used for dinosaur tracks, especially in the context of their work on a clastic sedimentary sequence in the Middle Jurassic of Yorkshire. They define four categories which provide a framework, albeit in their words - sometimes inadequate, for their descriptions. These are summarised as follows:

Surface print (track) – a mould on, and subsequent cast of the surface over which an animal walked.

Underprint (track) – formed where sediments split along a bedding plane through a mould and cast, so each of the resultant two, or more, elements have parts of both mould and cast preserved.

Transmitted print (track) – formed where layers of sediment below the sediment surface being walked on are also distorted and yields one or more 'moulds' and 'casts' each varying from the last with distance from the surface of origination.

Overprint (track) – where the fill of the surface print preserves features of the original track.

All the 'Coombefield' tracks are preserved as 'casts' on the base of, or within, the Thick Slatt. At first examination, the variety of track casts suggests the presence of several species of dinosaur. The majority of tracks were produced by dinosaurs with tridactyl feet walking bipedally. There appear to be three varieties, or morphs, of tridactyl tracks (Figure 3). One isolated, and two linked non-tridactyl tracks are ascribed to dinosaurs walking quadrupedally. Before discussing these tracks, there is a need to understand how many trackway horizons there are, and how the tracks are preserved.

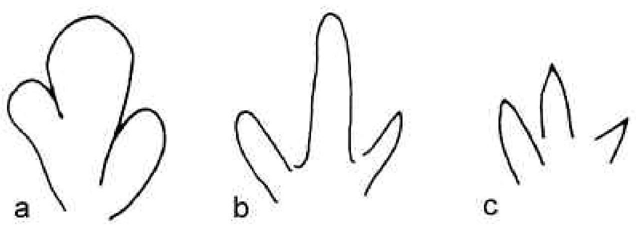


Figure 3. *Tridactyl print morphotypes. (**a**) spatulate, (**b**) elongate, (**c**) triangular.*

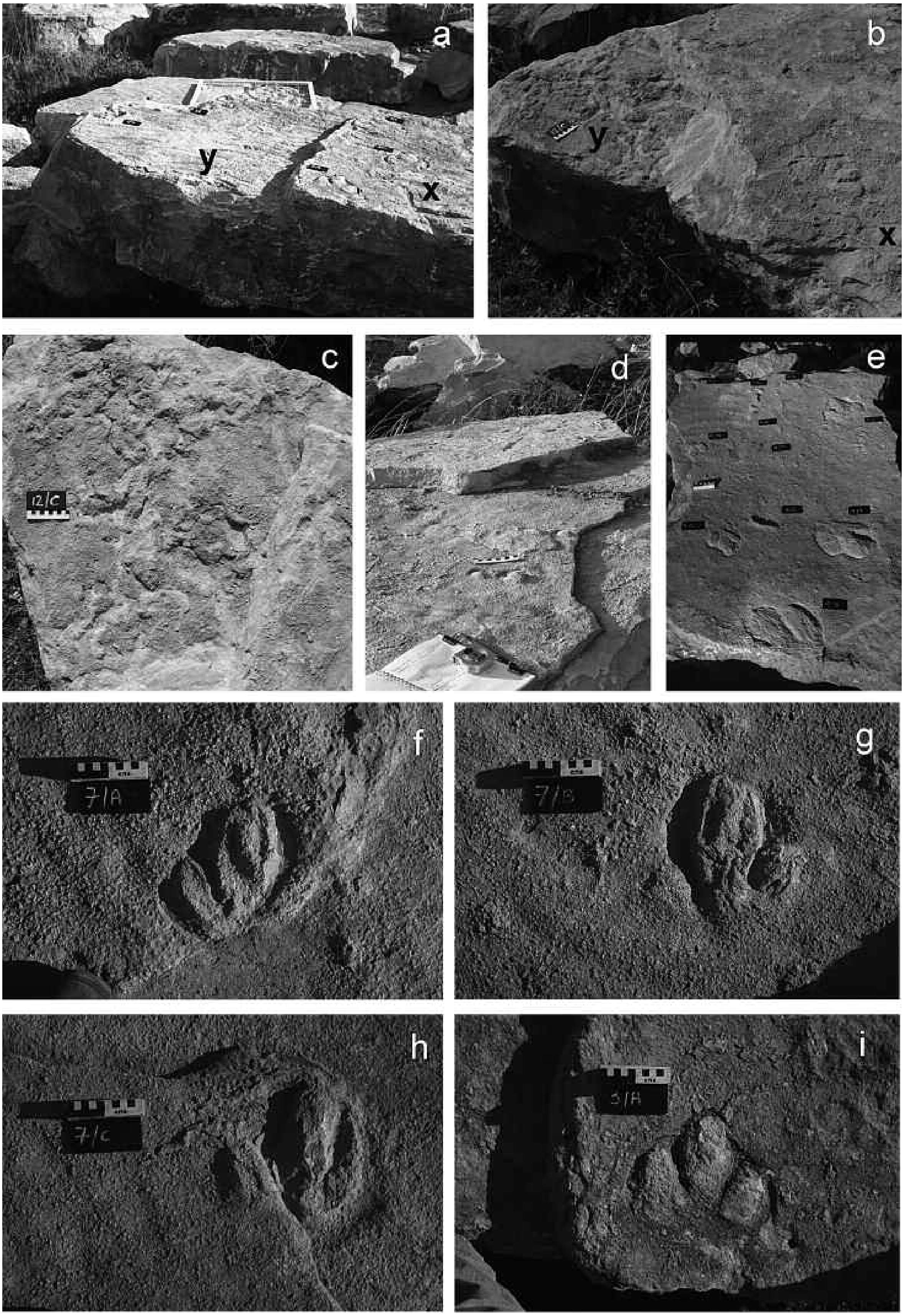


Figure 4a-i. *All scale bars 0.1 m unless otherwise stated.* ***(a)*** *Two track horizons exposed on block 3. x is the lower, and y the upper, surface. 1m² grid for scale.* ***(b)*** *Lower and upper track surfaces on block 12. x is the lower, and y the upper, surface.* ***(c)*** *Detail of block 12 showing higher trampled horizon with track. Pseudomorphs after halite are present on both surfaces.* ***(d)*** *An upper track horizon is seen in the foreground on block 22.* ***(e)*** *Transitory sedimentary structures: Symmetric ripple marks occur on part of the surface of block 4.* ***(f)*** *Track 7A on a ripple marked surface. Note the absence of the mud-rim around the distal end of the middle digit.* ***(g)*** *Track 7B on a ripple marked surface.* ***(h)*** *Track 7C is present on both the lower ripple marked surface, and a bedding plane above that, providing clear evidence of transmission. Note the lack of a mud-rim around the distal end of the middle digit.* ***(i)*** *Track 3a showing a well formed mud-rim laterally and distally. Pseudomorphs after halite are preserved on the displaced sediment within the mud-rim.*

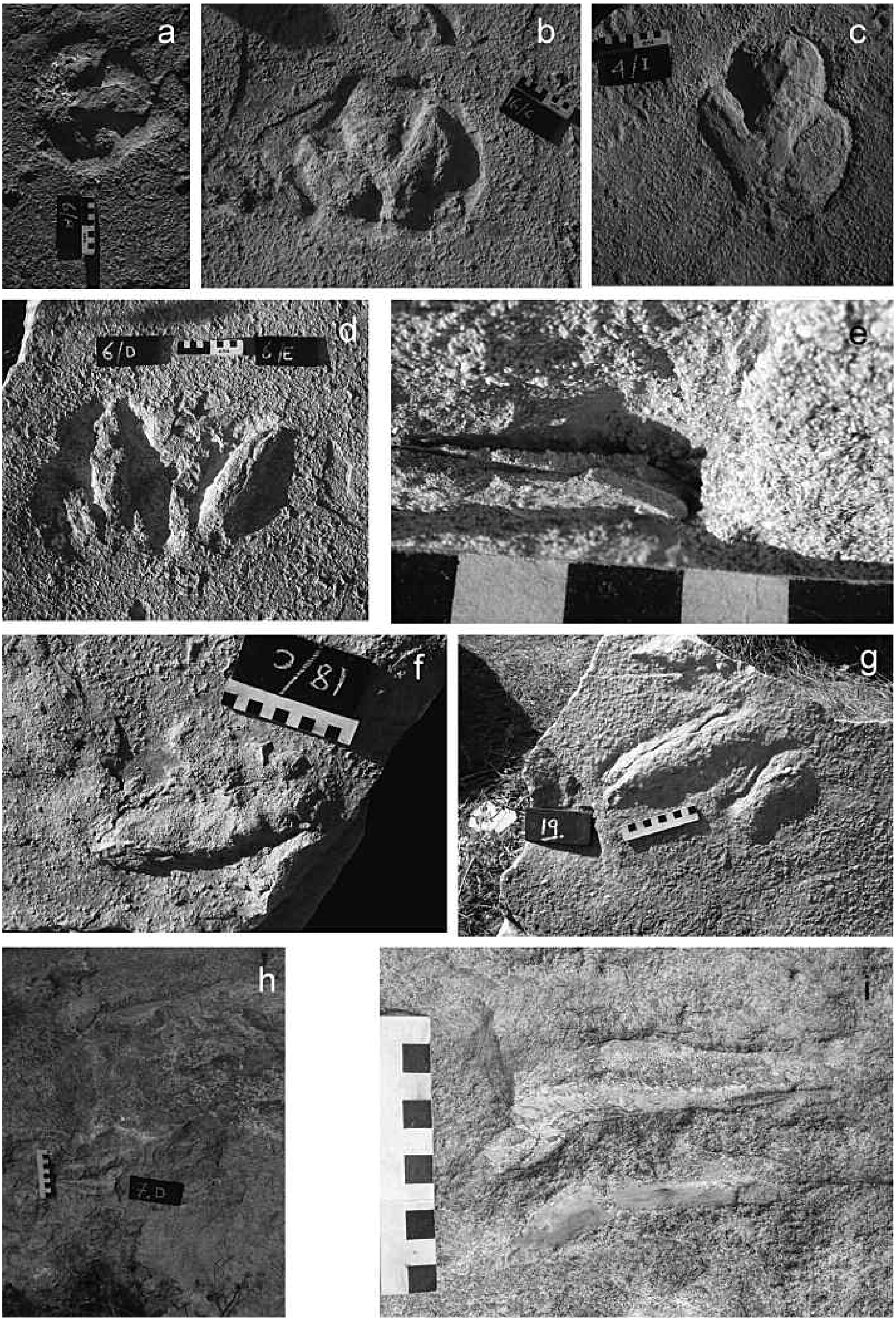


Figure 5a-i. *All scale bars 0.1 m. (**a**) Elongate digit type 6A, and (**b**) spatulate digit type 16C, both with wide mud-rims. (**c**) Track 4I with a narrow mud-rim. The displaced argillaceous sediment is preserved between the digits. The cast has flattened areas which indicates a non-compressive underlying sediment. (**d**) Tracks 6D and 6E are both of the elongate digit type. These adjacent tracks both exhibit a slight curve which suggests that there was an element of lateral, left to right, slip when they were formed. (**e**) Track 10I. Detail of disrupted bedding returned to correct way-up. Thin limestone laminae are turned down and truncated by the sediment plug of the left digit, forced down by the foot. Divisions on scale bar 1 cm. (**f**) Track 18C. Sediment appears to be rucked-up against the right side of the slightly curved middle digit, perhaps indicative of left to right slippage of the foot. (**g**) Track 19 4. Apparent replication of the middle digit cast is seen. This could be caused by shifting of the middle digit during formation, or be an artefact of transmission. (**h**) Block 7 showing relationship of distorted mud clasts to the putative sauropod track. (**i**) Detail showing distorted mud clasts, returned to their correct orientation, seen in section above 7D.*

How many trackway horizons does the Thick Slatt have?

Block No. 3 seems to show unequivocal evidence of two distinct trackway horizons (Figure 4a), one exhibiting ripple marks and the other not, though the presence of such a well defined structure thinning away from the camera serves as a salutary reminder of the vagaries of this bed! Block No.12 also shows evidence of two horizons (Figure 4b). The lower appears similar to other lower surfaces elsewhere on the site with two mud-rimmed tracks. An exposed bedding plane 0.05 – 0.06 m above this horizon has a rough, irregular appearance which may be due to sedimentary structures such as load casts, but which also has at least one track exposed (Figure 4c). This may represent localised dinosaur trampling. Block 22 has casts of tracks preserved on a bedding plane 0.06 m above the base of the block (Figure 4d); this could be a further example of a second trackway horizon, but may represent the main trackway horizon with the underlying strata attached.

The other blocks do not present us with this luxury, although sedimentary structures preserved on their undersides might provide a clue. Their often rapid lateral variation (Figure 4e) and the incomplete nature of the record of the quarried horizon, mean these features alone cannot be used as a satisfactory guide for distinguishing different horizons.

Description of the material

This paper has been written in the knowledge that the tracks recovered on blocks in *c*.1996 do not have an assured future. As part of the recording project, PCE was asked by Richard Edmonds to provide a priority list for recovery and long-term preservation in a museum or similar institution. The list was produced in 2004 and scrutinised by JBD. Irrespective of the specimens future, we believe that the material is of sufficient stratigraphic importance to receive a permanent literary record.

Formal ichnotaxonomic description of the specimens is not undertaken here because, as this paper demonstrates, there are real dangers in erecting ichnotaxa which attempt to describe the infinite shape variation so characteristic of this type of trace fossil, and especially so where the tracks are transmitted, i.e. they are not on the surface over which the animals moved (Ensom, 1995a, 2002; Manning, 2004). A set of data (plans, measurements, images and the reports) have been deposited in the Dorset County Museum and are accessioned DORCM NHMC LXXI.

Types of trackway

Placing the tracks in one of the four categories of Romano and Whyte (2003) as either surface prints, underprints, transmitted prints or overprints, has required careful study of the evidence. Preliminary examinations had pointed to the majority of tracks being either surface or transmitted prints.

The presence of transmitted prints on the lowest horizon is illustrated by Block No.7 which shows one trackway preserved on two levels. Tracks 7A (Figure 4f) and 7B (Figure 4g) are preserved on a ripple marked surface, while the next consecutive track, 7C (Figure 4h), is partially preserved on the ripple marked surface, but spalling of the thin limestone layer has revealed clear evidence of distortion to the sediment adjacent to, and overlying the cast.

Apart from this unequivocal evidence for transmission, we have observed a number of other features which point to the majority, probably all, of these tracks being examples of transmitted prints.

Fifty-four of the tridactyl prints have an actual or potential mould of a mud-rim preserved either laterally, to a lesser extent distally (Figures 4i and 5a), and occasionally proximally (Figure 4h). Plastic sediment was squeezed sideways under the weight of the foot. We suggest that wider (Figures 5a and 5b) or narrower (Figure 5c) rims were formed depending on the thickness of the plastic sediment. Tracks 6D and 7A (Figures 4f and 5d) are examples of the middle digit with no distal mud-rim. Figure 5e shows the disrupted bedding below the surface resulting from the displaced plastic layer. Track 18C (Figure 5f) shows sediment distorted laterally around the right side of the middle digit, and track 19 exhibits both distortion of sediment and an apparent replication of the cast alongside the left side of the middle and right digits (Figure 5g). Some of the rims have a sharply defined boundary, and what appears to be brittle fracture of the 'salt-flat' crust associated with the displacement of the mud. These sharply defined mud-rims have not been observed by us in other Purbeck tracks, though bulging of the sediment has, suggesting that these tracks represent an uncommon set of conditions.

We suggest that these rims formed when the foot pressed down on sediment previously cemented, perhaps still, by a salt crust and underlain by a thin and plastic, argillaceous sediment which in turn was underlain by a competent layer, or layers, of sediment (Figure 6). An extreme example of soft sediment displacement and distortion of the overlying sediment is seen in track 7D (Figure 10a) where a smooth sloping edge has been formed by sediment squeezed out from around the margins, especially proximal and lateral, of a very large track. Substantiating evidence for this distortion was revealed on the edge of the block where *c*.0.12 m above the cast surface, two bent mud clasts were preserved (Figure 5h-i). The clasts, each separated vertically by 0.025 m of limestone, have the same end distorted by *c*.0.02 m. The axis of this bend is in line with the margin of the track. These processes might be best described as intra-bed soft-sediment displacement.

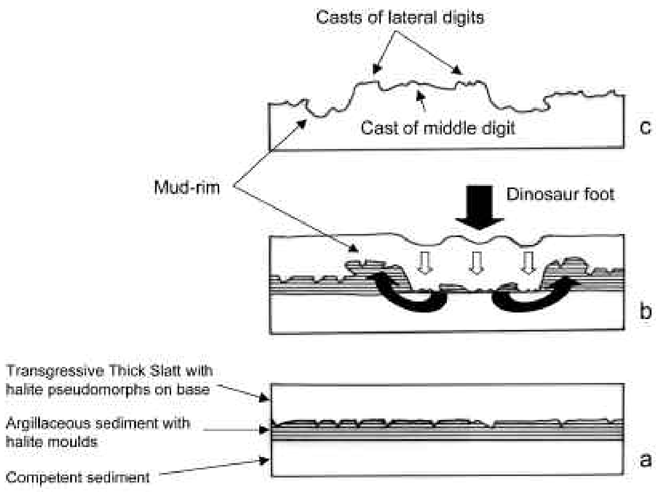


Figure 6. *Schematic diagram of mud-rim formation.* ***(a)*** *Sediment before impact of foot.* ***(b)*** *Sediment displaced by foot impact.* ***(c)*** *Eroded underside of block with track cast as discovered.*

The deformed calcareous clay or argillaceous micrite is sometimes preserved both in the rim around the track's cast, and even between the casts of the digits (Figure 5c). Where the calcareous clay has been eroded to expose the surfaces of these peripheral grooves, they appear to be contiguous proximally with the surrounding sediment, with sedimentary structures such as halite pseudomorphs preserved (Figure 4i). Halite pseudomorphs are often preserved on the less well defined heel casts, but generally absent from the most depressed surfaces of the digits. Evidence associated with Track No.16C (Figures 5b, 7a-d) provides an alternative view of cast formation. The sediment at the distal end of the middle digit of this print has spalled away, providing an opportunity to examine the relationship of the different 'micro-beds' to the cast of the print. Here the distal mud-rim's surface is composed of higher layers of sediment which are seen to be bent down by the middle digit. The same print also sheds light on the formation of these casts. The displaced mud has been forced under the distal edges of the lateral digit's casts. The proximal

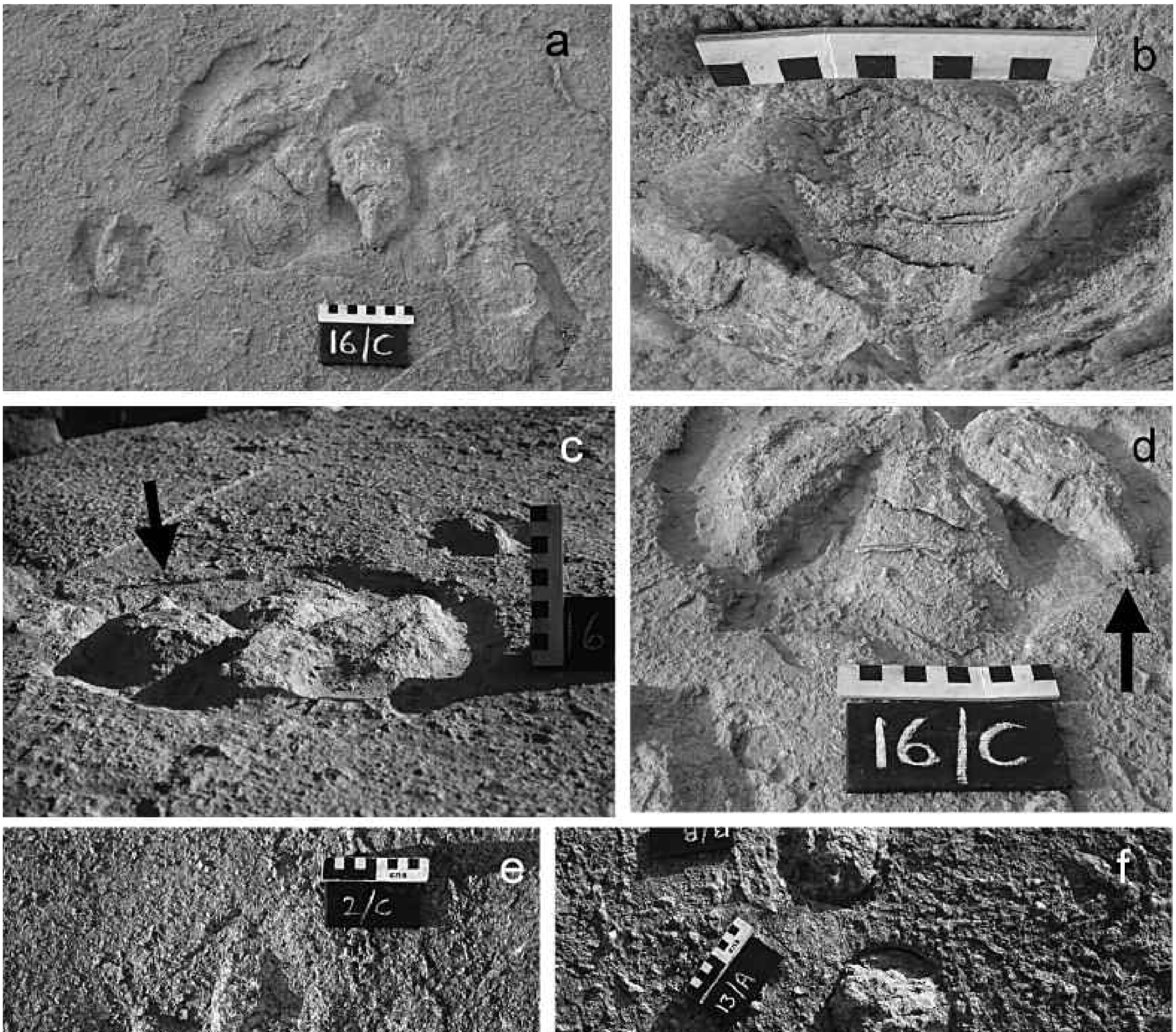


Figure 7a-h. *All scale bars 0.1 m. 7a-d. Track 16C. (**a**) Vertical view. The small feature at 8 o'clock is probably the distal tip of one digit probably transmitted from a higher level. (**b**) Distal view returned to correct orientation. Shows mud displacement beneath lateral digits. (**c**) Proximal oblique view. This shows the small claw cast (arrowed), a puncture failure feature. (**d**) Distal oblique view of claw cast (arrowed). (**e**) Track 2C. Fracture of overlying sediment between middle and right digits. (**f**) 13A Spatulate sub-type with joined elements. (**g**) 25B Spatulate sub-type with one element. (**h**) Track 9A.*

end of the middle digit of this print appears to lie over, and is not disrupted by the proximal ends of the lateral digits. This points to the formation of the casts of the lateral digits before that of the middle digit, if only by a fraction of a second (Figure 7b).

Track 2C (Figure 7e) not only shows this deformation, but also an irregular fracture, between the apices of the middle and right digits, in the sediment which overlies the cast. This shows that the sediment was sufficiently brittle to break under the strain of the displaced argillaceous sediment, supporting the transmission hypothesis.

The tracks made at slightly higher horizons on blocks 3 and 12 are difficult to interpret and we are not sure what category of print they belong to. Those on block 22 are more akin to the mud-rimmed prints and are interpreted as transmitted prints.

Manning (2004) in the conclusions to his paper states that 'The use of dinosaur tracks in comparative multivariate studies should be restricted to surface track features, for comparison with other surface track features. The inclusion of transmitted tracks in such studies invalidates any inferred taxonomic or osteological relationships, owing to the disparity between surface and subsurface track morphology and size'. The measurements, descriptions and our interpretations which follow should be viewed with this firmly in mind. Unsurprisingly, Manning (2004) also states that transmitted prints should not be used to calculate the hip heights of the originators of tracks.

Tridactyl tracks

The tridactyl tracks can be divided on a visual assessment into three types or morphs: spatulate, triangular and elongate (Figure 3).

Spatulate digits: Figures 4e-h, 5b-c, 7a-d, 9f. There are 42 tracks with one or more spatulate digits. These tracks invariably have mud-rims. The middle digits range in size from 9 – 22 cm long with the maximum width of the digit in the range 5 – 12 cm. The distance between the distal ends of the lateral digits ranges from 13 – 22 cm.

There are 12 sets of 2 or more consecutive prints preserved. Ten of these have provided an opportunity to measure pace (the distance between the same point on consecutive prints) and stride (the distance between the same point on the same foot in two consecutive prints). Wherever possible these measurements have been taken at the distal end of the middle digit:

Pace (18 measurements) ranged from 37.5 – 85 cm
Stride (7 measurements) ranged from 88 – 129 cm

The digits of these tracks sometimes exhibit a flattened lower surface (Figure 5c) on which the texture of the sediment, though not dissimilar to that surrounding the track, as previously noted, lacks halite pseudomorphs. The latter are often present on the less depressed proximal ('heel') surfaces. Track 13A (Figure 7f) seems to show evidence of disruption to the foot morphology, with an area of overlying sediment actually intruding between the middle and a lateral digit. This plug is truncated by the mud-rim at the proximal margin. A feature such as this may provide an insight into the structure and flexibility of the heel and digital pads – bearing in mind that they were not in direct contact with the sediment surface below these casts. Foot morphology may also be playing a role in tracks which preserve a series of grooves and ridges along the axis of the middle and lateral digits of some tracks (Figures 4f-g). These may result from the sediment between the foot and the underlying competent stratum being buckled along the axes of the digits. Sometimes the deformed calcareous clay is present in the grooves. The right digit of the spatulate print 16C shows a feature which is interpreted as the cast of a terminal phalange or claw (Figures 7c-d). This may appear to contradict our claim that the tracks are transmitted but does not. This feature can be described as 'a puncture failure feature at toe-off phase of the step cycle' (Manning personal communication, 2006). This simply means that as the foot left the ground, the claw penetrated down to the horizon of the transmitted cast and modified the existing cast's shape. This claw cast is short, relatively broad, and does not appear to be sharp.

Within this group, we include several tracks which exhibit between one and three more or less circular bulges which may be linked (Figure 7f), presumably as a tridactyl print cast, or discrete (Figure 7g). These are regarded as spatulate tracks that because of sediment thickness, and or physical properties, have not developed the true spatulate form.

Elongate digits: Figures 5a, 5d, 7h, 8a-d. There are 15 tracks which can be best described as having elongated digits, though some are sometimes an artefact of damage, as discussed above, and are actually spatulate prints (Figure 7h). Unsurprisingly they are present on blocks where spatulate prints are preserved, but only once are they associated with triangular digits described next. The lengths of the middle digits range from 12 – 25 cm with their maximum widths in the range 6 – 7.5 cm. The distance between the distal ends of the lateral digits ranges from 15 – 27 cm. Apart from 9A (Figure 7h), which is the first of a set of three consecutive spatulate prints (9A-B-C), none of the elongate prints form part of a trackway.

There are 13 tracks which despite having a broad mud-rim have more or less elongate digits and appear to be very different to the spatulate forms normally associated with mud-rims. Some of these casts have lost their lower surfaces. There is evidence that some tracks may have been partially 'welded' to the underlying sediment and consequently exhibit damaged digits (Figures 5a, 7h, 8a-c). The flattened casts previously mentioned are evidence of this squeezing together of sediment layers. The damage could have been sustained during quarrying, or alternatively the digit cast broke away with the underlying competent bed to which it had become attached. There seems a strong probability that we are seeing an artefact rather than a distinct track-type, and tracks 17A, 17B (Figures 8b-c) which outwardly appear to be more theropod than ornithopod, when examined in detail, blend features of both the spatulate and elongate morphs, lending support to this theory.

Amongst the elongated tracks, a number exhibit strongly curved digits (Figures 5d and 8d). These we interpret as transmitted casts of feet which have slipped sideways on the clay/argillaceous micrite layer. The middle digit in a slipped print will be close to the lateral digit in the direction of slip, and conversely, there is likely to be a greater distance between the other lateral digit and the middle digit. Mud-rims are more pronounced down slip. Replication of the middle digit may occur. Despite these comments, the possibility that these tracks belong to a species of tetrapod with naturally curved digits cannot be ruled out.

Triangular digits: Figures 1g, 7e, 8e-h, 9a-e. There are 19 tracks where the digits can be characterised as triangular in appearance. These tracks with 'triangular digits' are mostly less well defined than the tracks with spatulate and elongated digits. Casts of digits are sometimes absent and in some cases only an incomplete cast of one or more digits may be preserved (Figure 9e). They are absent on blocks where spatulate prints are preserved. Where measurements have been possible, the middle digits range in size from 9 – 13 cm long with a maximum width in the range 3 - 8 cm. The distance between the distal ends of the lateral digits ranges from 12.5 – 23.5 cm.

There are 6 sets of 2 or more consecutive prints preserved. Five of these have provided an opportunity to measure pace and stride. Wherever possible these measurements have been taken at the distal end of the middle digit:

Pace (8 measurements) ranged from 55 – 105 cm
Stride (3 measurements) ranged from 135 – 203 cm

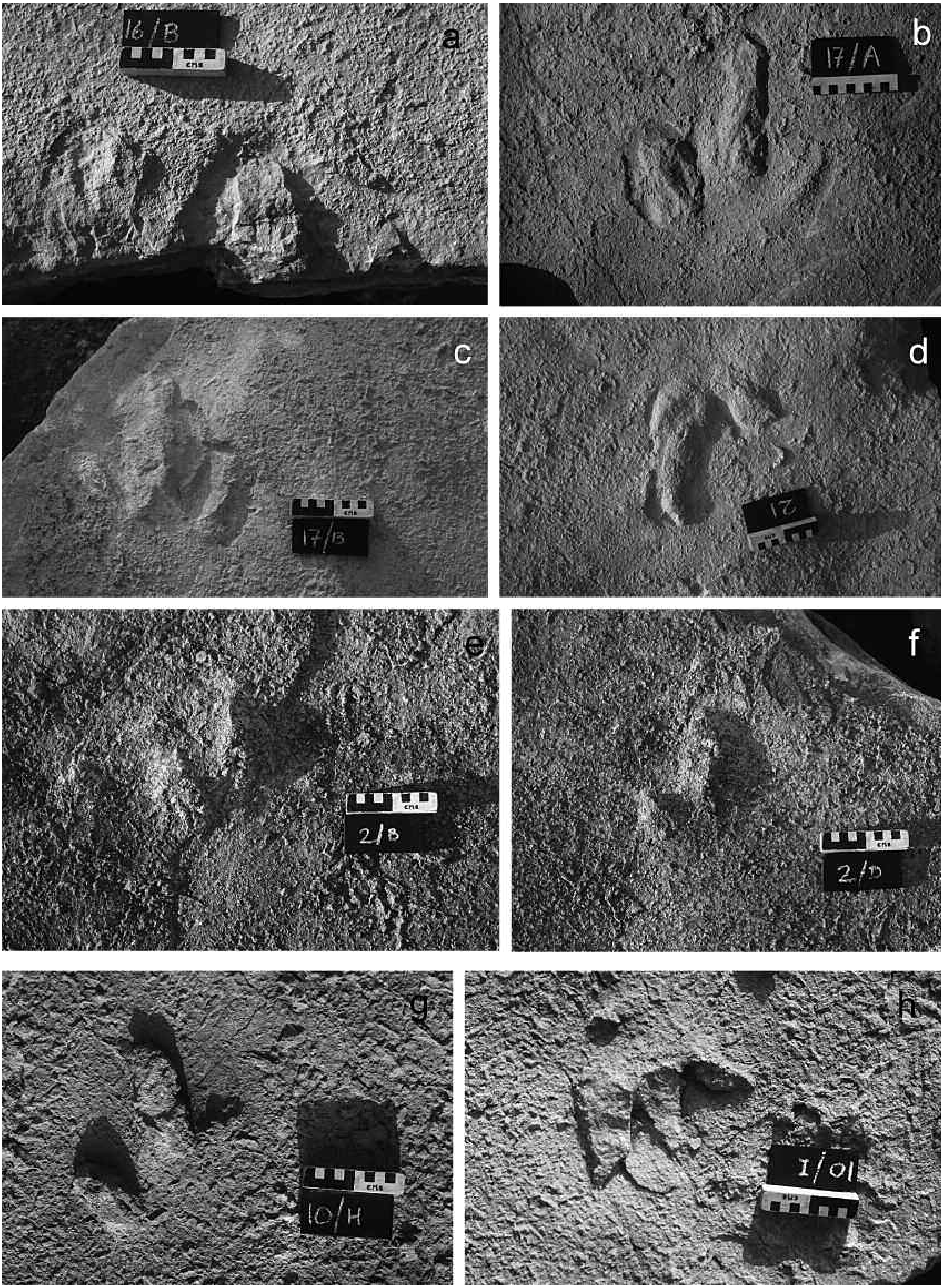


Figure 8a-h. *8a-c. Tracks with elongate digits where damage has been sustained to the cast with loss of some or a large part of it.* ***(a)*** *16B.* ***(b)*** *17A.* ***(c)*** *17B.* ***(d)*** *Track 21. A print with good evidence of lateral motion to the foot producing the curved shape and tightly spaced digits. 8e-h Tracks with triangular digits.* ***(e)*** *Track 2B.* ***(f)*** *Track 2D.* ***(g)*** *Track 10H.* ***(h)*** *Track 10I. All scale bars 0.1m.*

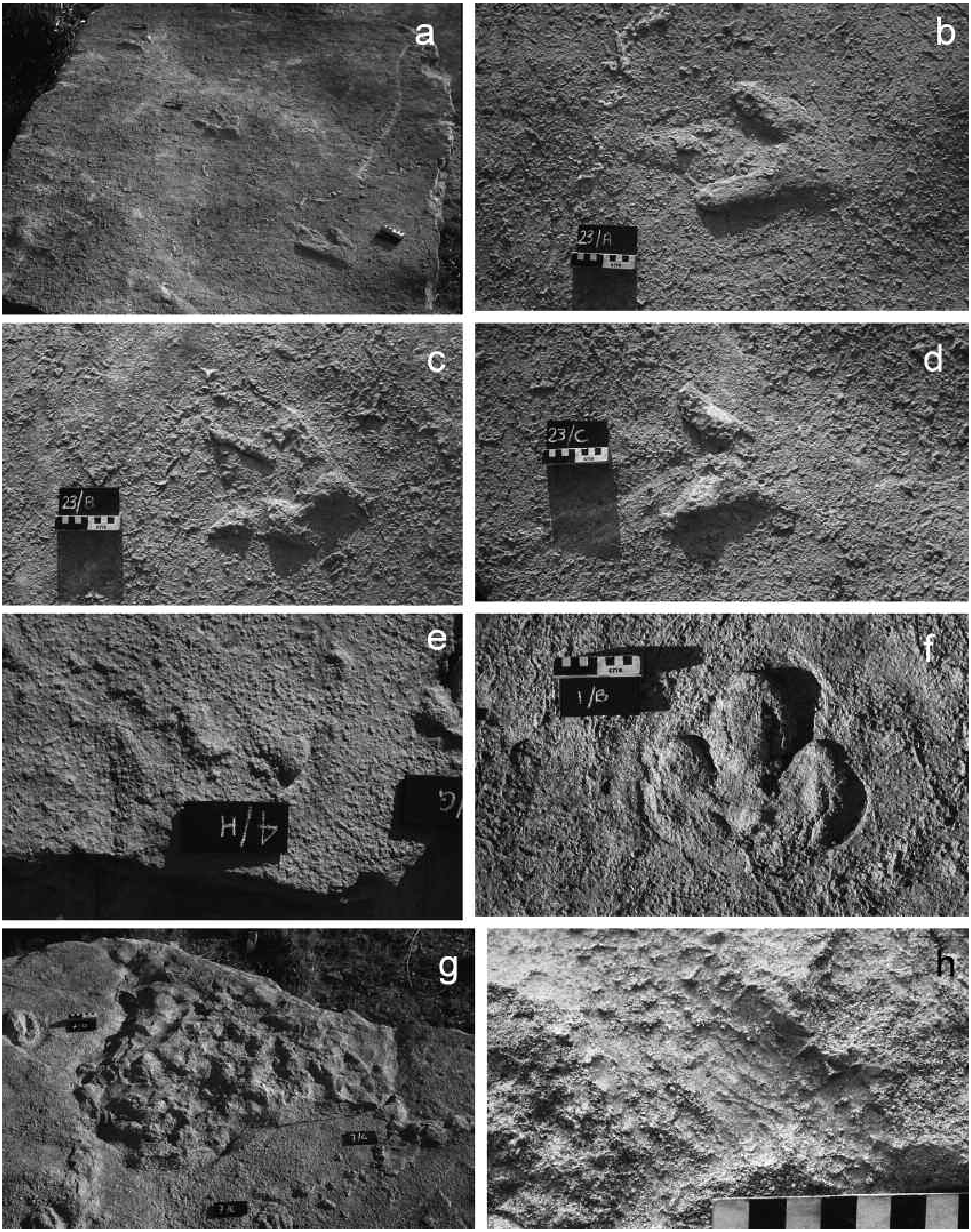


Figure 9a-h. *All scale bars 0.1 m.* ***(a)*** *Block 23.* ***(b)*** *Track 23A.* ***(c)*** *Track 23C.* ***(e)*** *04H. Track with only the tips of the digits preserved. Blackboard c. 0.09 m.* ***(f)*** *1B A cast of a spatulate print with the 'ghost' of a triangular digit preserved. 9g-h. Track 7D.* ***(g)*** *Oblique lateral view.* ***(h)*** *Detail of the disrupted surface.*

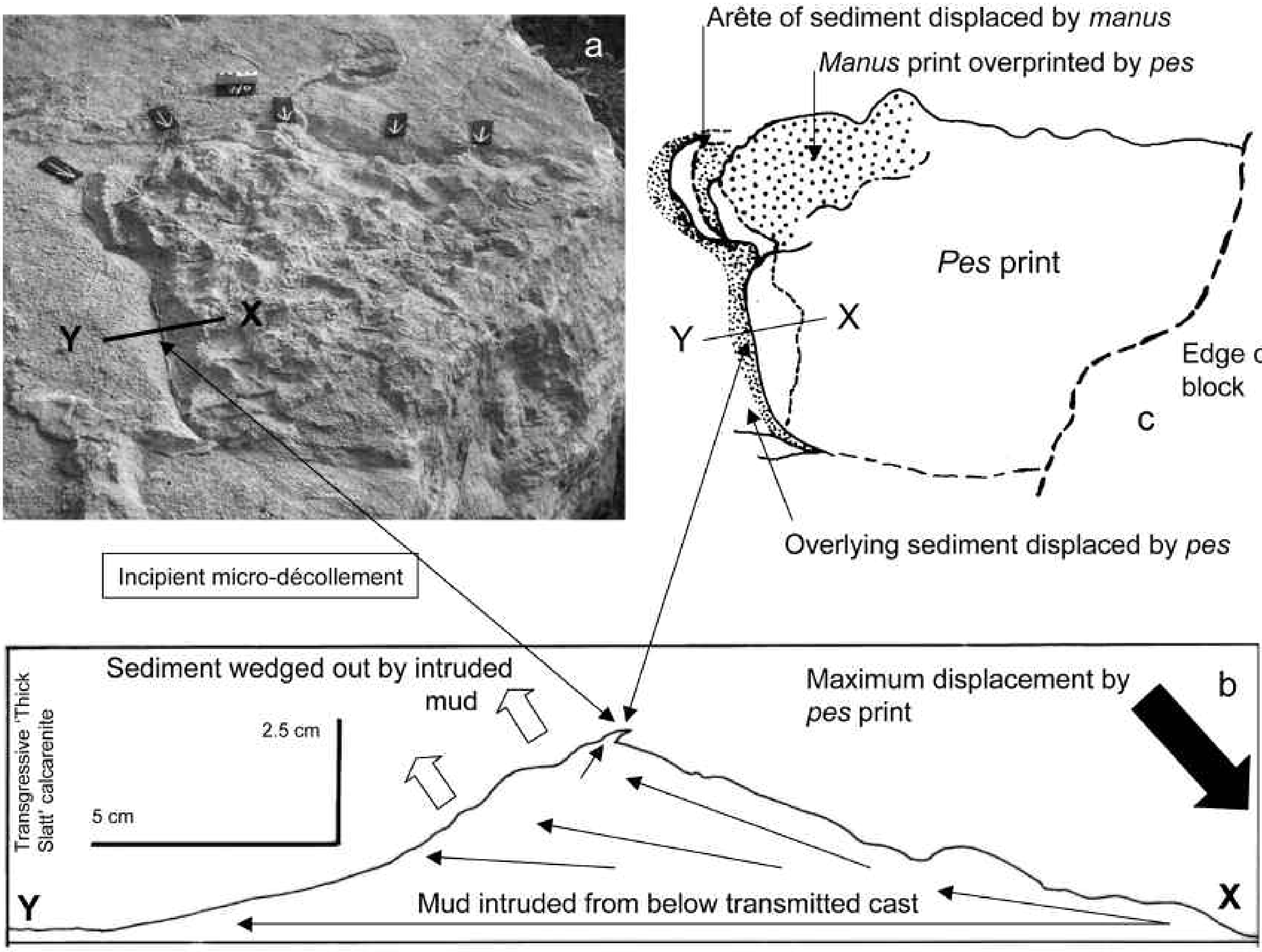


Figure 10a-c. *Track 7D. (**a**) The putative sauropod track showing smooth sided rim and disrupted bedding. Blackboards point to possible casts of the digits. Scale bar 0.1 m. (**b**) Mud displacement associated with 7D. (**c**) Diagram of putative manus - pes link.*

These tracks have no mud-rims, but sometimes show slight lifting of the sediment around part or all the cast. Perhaps significantly, 1B (Figure 9f) and to a lesser extent the following tracks 1C and 1D, are spatulate but exhibit 'ghosts' of triangular casts preserved on their digits. Conversely the middle digit of 2A (Figure 1g) is slightly inflated while exhibiting a strongly triangular shape.

The trackway on Block 23 presents a mixture of poorly preserved tracks with 'triangular digits', but which show a mixture of features, one having a very feint long middle digit. There is a possibility that this is another example of preservational artefacts; these tracks probably owe their form to the state of the sediment over which the animals moved. It is speculated that the plastic clay may have been thicker and/or less plastic, or the overlying sediment thicker, than that which was distorted by the 'spatulate track' maker. Print 23A (Figure 9b) has the proximal/heel area showing sedimentary structures and surface detail which appears contiguous with the surrounding sediment. The long middle digit shows similar surface features, but only appears to be faintly impressed compared to the lateral digits. If this interpretation of the evidence is correct, the lateral digits and more distal part of the heel have been more effective at producing a cast than the middle digit. The middle digit of 23A closely resembles an experimental print generated in saturated sand (Romano and Whyte, 2003, Figure 8B). Print 23B (Figure 9c) is less well formed or preserved and appears much more angular/triangular. Print 23C (Figure 9d) is only partially preserved and is similar to prints such as 2A-E (Figures 1g, 7e, 8e-f).

Interpretation: As previously noted, transmission of prints adds a complicating dimension to the interpretation of animal tracks, filtering certain details, emphasising or distorting others. Despite these issues, our observations of the tridactyl transmitted tracks lead us to suggest that the majority originated from one species of dinosaur. This conclusion is based on: (1) Mud-rimmed casts when well preserved are spatulate in shape. (2) Non-spatulate digits with mud-rims are missing the lower part of the cast which transforms the digit from spatulate to elongate and relatively thin. (3) Mud-rimmed spatulate casts do not occur on the same surfaces as 'triangular' casts without mud-rims. (4) Spatulate casts sometimes have 'ghosts' of triangular casts preserved in them. (5) Triangular casts occasionally appear slightly spatulate.

Previously authors have tended to regard tracks with spatulate digits as belonging to herbivorous dinosaurs. Conversely prints with thin digits and claws have been ascribed to theropods. We have no unequivocal evidence of narrow claws (Romano and Whyte, 2003, figure 12) in the casts we have studied, though their absence may be because they are transmitted. We suggest that the spatulate form of the preserved digit casts is an artefact of sediment type and configuration. We also suggest that the various tridactyl track morphs are probably tracks of the same species of dinosaur.

If our interpretation is correct and the casts on the base of the bed are all morphs of the same foot-form which resulted from variation in substrates, the following scenarios might be envisaged:

1. Rapid sedimentation as the calcarenite sand sheet migrates. One dinosaur track formation event in the sediment above the lowest transmitted cast horizon with either: variable configuration of substrate, but uniform thickness of sediment between it and the track origination surface or, uniform substrate with variable thickness of sediment between it and the track origination surface, or, variable configuration of substrate with variable thickness of sediment between it and the track origination surface.

2. Slow migration of the calcarenite sand sheet. One, two, or more dinosaur track formation events probably occurring at the same horizon with: variable configuration of the substrate both at any one time, and through time, the latter almost certainly influenced by seasonal variation. As sedimentation proceeded, other track formation events produce trackway horizons higher in this bed.

If the tracks all originated in one event as in our first scenario, a group of the same species of dinosaur composed of different aged individuals present could be invoked based on track sizes and resultant variation in pace and stride for the majority of the preserved tracks. This occurrence would be more likely in herbivores where there is evidence for 'herds' (Thulborn, 1990), though Lockley (1991) does suggest carnivores also moved around in groups. With the exception of the short and blunt claw of track 16C, noted in our description of spatulate digits, the apparent absence of sharp claws, possibly a function of transmission, reinforces our present view that the dinosaurs responsible for the majority of the tridactyl tracks at the base of the Thick Slatt were almost certainly herbivores.

One trackway (23A-E, Figures 9a-d) exhibits characteristics which are unusual. The stride and pace is substantially greater than any other trackway on the site. The presence of heel and digit impressions does not support the case for a running dinosaur where the distal ends of the digits would be expected to leave impressions (Thulborn, 1990). We speculate that despite the absence of a distinct claw, this may be an example of a track made by a theropod.

Non-tridactyl tracks

Blocks 7 and 9 both carry features which cannot be linked to bipedal tridactyl dinosaurs. Initially 7D (Figure 9g) had been viewed by one of us (PCE) as an expanse of disturbed sediment, one side of which is unfortunately terminated by the edge of the block, with an area of *c.* 0.75 m^2. An origin as a trampled area produced by bipedal dinosaurs was considered a possibility. Trampled horizons such as this are known, such as one recorded in the Intermarine Member of the Dorset Purbeck succession at Worbarrow Tout (Ensom, 1985b). While drawing the plan of 7D the significance of the 'smooth' delineating and almost undisrupted rim became clear. This was evidence for significant sediment displacement, creating a marginal wedge of plastic argillite which abutted the core of disturbed sediment, and lifted the peripheral sediment surface (Figures 10a-b). The proximal end of the right rim has a depth of 0.04 m. The displaced mud appears to have intruded the displaced crust back over the disturbed sediment at the apex of the wedge, forming an incipient micro-décollement (Figures 10a-b). The nature of the preserved marginal rim indicates that this represents possibly two events, as described below.

As this originated in deposits laid down over a salt flat where we know dinosaurs were present, it is difficult to envisage what else could have been responsible apart from a dinosaur. If a dinosaur was responsible, there are two possible explanations. Either this is a resting trace, or a very large track. The shape of the disturbed area does not appear to bear any relationship to a dinosaur's body plan and there is no evidence for an associated pattern of tracks which might have resulted from it getting down and up again! A track is the stronger likelihood, and if genuine the very large size would offer an explanation of why no other related print is visible on this surface. The absence of any comparable tracks is unfortunate but unsurprising bearing in mind the tiny volume of preserved trackway blocks. If our interpretation of the previously noted bent mud clasts is correct, then the track origination surface is not less than *c.*0.35 m above this transmitted cast.

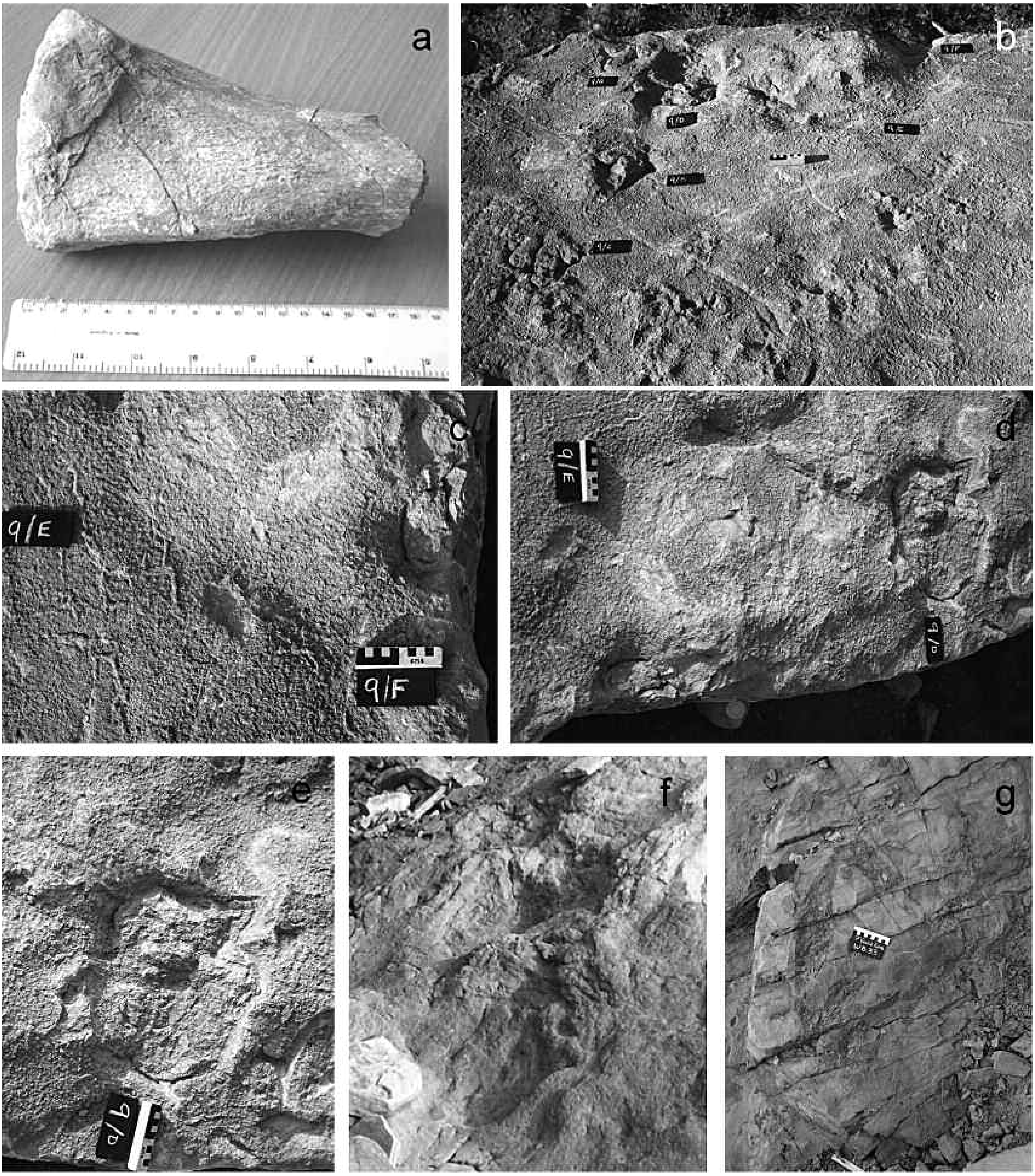
If the track scenario is correct, the maximum length of the track is 1.05 m. with a preserved width of 1.1 m. The contrast between the surface of the putative track cast and the surrounding sediment is startling. The former is highly disrupted, with only rare evidence distally of any preferred orientation. Parts of the surface are often recognizable as the undisrupted surface lying alongside; halite pseudomorphs are present on both (Figure 9h) and there is evidence of a tridactyl print caught up in this chaotic development.

We hinted above that the rim might not be entirely uninterrupted. The distal part of the right lateral margin and right distal margin of the cast exhibit some changes which might be related to a previously formed manus print being overstepped by the pes print (Figures 10a and 10c). This hypothesis is given further credence by the distinct parting seen across the disrupted sediment, and which passes distally over the area which could be attributed to the manus print (Figure 10a). This would be in keeping with the manus print having been made first, and then overstepped by the pes, incorporating the thin argillaceous parting. Further, this notion might also explain the two smooth rims with dividing arête seen on the lateral margin adjacent to this feature (Figure 10a). Proximally there is a smooth outline for a heel, though the deformed argillaceous sediment surrounding the track has been removed. Distally this track shows features similar to those seen in some spatulate prints where there may be little or no displaced sediment, and contact with the surrounding sediment, as seen here. Distally there are a series of irregularities which could be interpreted as casts of digits (Figure 10a). The appearance and size of this track is in keeping with the characteristics of tracks from elsewhere which have been attributed to large sauropod dinosaurs (Thulborn, 1990).

While the hypothesis that 7D represents a sauropod track (Ensom, 2003) may appear contentious, the serendipitous discovery by Dale Brocklehurst in Bowers Quarry of a large bone, which had fallen from the quarry face, was to prove to be of considerable interest. The bone's significance was recognised by Mark Godden, the Mine and Quarry Manager of Albion Stone, who arranged for it to be examined by experts, via Richard Edmonds. The specimen turned out to be a sauropod metatarsal (Figure 11a). Matrix adhering to the specimen pointed to a source in the Lulworth Formation at the level of the Thick Slatt.

Block 9 has two casts of tracks, 9D and 9F, and a curious bulge, 9E (Figure 11b) all in close proximity to each other. The surface of 9D is recessed, having lost the lower part of the cast, surrounded by relatively smooth sides and rounded rim which equate to the mud-rim walls previously described. Interestingly, the adjacent cast of a tridactyl print, 9A, has similarly lost its digits. The proximal edge closest to 9E forms a more or less well defined arc, though a sediment bridge is present for over 0.11 m, perhaps indicative of the sediment welding which may have led to the loss of the cast. The distal edge has two well developed digit-like plications which though coming very close to the surrounding sediment, remain discrete features. The track is *c.* 0.28 m long and 0.3 m wide. The form of this track is reminiscent of the pods of limestone which are represented by some of the manus prints of either sauropod or ankylosaur dinosaurs (Ensom, 1987, figure 2) found in the Cherty Freshwater Member at Sunnydown Farm in 1986.

Close by, and on the edge of the block, is track 9F (Figure 11c). Though only a small part is preserved, the track is clearly different to the tridactyl prints preserved on this block and elsewhere while closely resembling the preservation of 9D. It is suggested that the two are related. What is left of the cast is incomplete, and may have been attached to the bed below. The preserved margin is steep and relatively deep compared to the mud-rimmed casts. No other tracks of this type are preserved on this or other blocks.



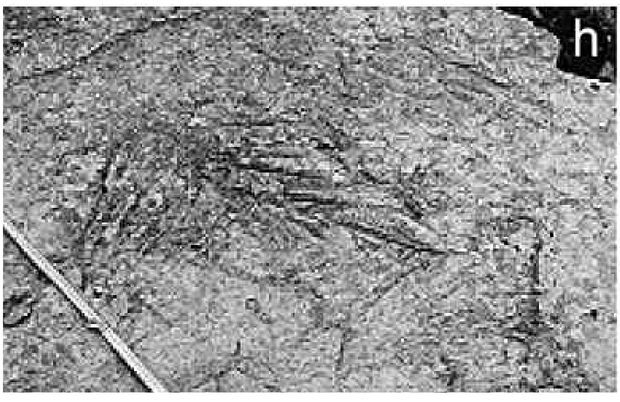


Figure 11a-h. *Scale bar 0.1 m unless stated otherwise. (**a**) Sauropod metatarsal (DORCM E 5405) from the Lulworth Formation, ?Hard Cockle Member, Bowers Quarry, Portland. Copyright the Dorset Natural History and Archaeological Society. Ruler with cm and inch gradations. (**b**) Block 9. General view showing relationship of putative quadrupedal dinosaur tracks, 9D-F. (**c**) Track 9F. (**d**) Track 9E. (**e**) Track 9D. (**f**) The disrupted surface of WB 29 (Ensom, 1985), Hard Cockle Member, Worbarrow Tout, Dorset. West suggests this hummocky surface could be caused by either the diagenesis of evaporates, or dinosaurs. Copyright I. West. (**g**) Intraclast-filled ?track cast in the equivalent of WB 33 (Ensom, 1985), Hard Cockle Member, Pondfield Cove, Dorset. (**h**) West's 'unidentified vee-shaped structure'. Fallen block of Thick Slatt near Mutton Cove, Isle of Portland, Dorset. Copyright I. West.*

Both tracks 9D and 9F appear to cut the margins of 9E, a low relief bulge which slopes more gently towards 9D and which lies between them. With no well defined margins, maximum and minimum dimensions of approximately 0.6 m and 0.5 m respectively, and a surface which is in no way comparable to the surface of track 7D, whether this is related to 9D or 9F, or is even a track at all, is unclear. The close proximity of 9E to 9D may not be a coincidence, with the latter the pes print coupled with the manus print partially preserved as 9D. However, the apparent cutting of 9E by 9D would not support this premise, though as a transmitted feature this may be misleading.

Frustratingly, no further tracks which could be linked to tracks 9D and 9F were found. Interpretation is difficult, but we believe that they provide tangible evidence of another quadupedal dinosaur on the site.

Other traces

Apart from these tracks, there are a number of other features across the site which are not easily categorised. They may be the result of invertebrate activity, partial penetration of the sediment by digits, or of the thickness of sediment between the surface of origination and the interface at which the trace fossil was formed.

Implications of the Portland tracks in a Purbeck context

Ensom (1995a) discussed aspects of the distribution of dinosaur tracks in the Purbeck Limestone Group. Amongst a number of observations, he commented that the stratigraphic distribution of tracks could be climate-related. The discovery of these tracks has provided those studying these strata with a much-needed spur to re-examine these lower beds in the light of these recent discoveries. Importantly we have been alerted to the presence of dinosaurs in environments thought to have been less hospitable than those higher in the sequence. We believe it is appropriate to draw attention to a number of observations made in recent years which may be pertinent to this search.

The basal Purbeck strata are well known for their complex evaporitic histories. A well known result of diagenetic alteration of evaporites is volumetric change with the potential for consequent distortion and disruption to bedding (West, 1964, 1965 and 1975). In 2003 West recorded (http://www.soton.ac.uk/~imw/portdino) the spectacularly disturbed surface (Figure 11f) of WB 29 (Ensom, 1985a) at Worbarrow Tout (NGR SY 869 796), which he suggests would correlate with the Thick Slatt trackway horizon. He speculates that the disruptions to this bed could be the result of either dinosaurs or evaporites. Based on the appearance of these disturbances, the former suggestion is very convincing. Alexander (1987) hints at the importance of animal activity as a trigger for synsedimentary deformation within the Middle Jurassic Ravenscar Group of the Yorkshire Basin, though never elaborates on this. Romano and Whyte (2003) are more forthcoming, and illustrate the significance of dinoturbation within these strata.

Approximately 2.75 m above this horizon in the adjacent Pondfield Cove are a group of intraclast filled depressions (Figure 11g), on the surface of the equivalent of Bed WB 33 (Ensom, 1985a), spotted by Alan Driscole, a member of a Geologists' Association field trip led by PCE in September 2004. This bed lies within strata belonging to the 'Cypris' Freestones and Hard Cockle members. These features are certainly candidates to be tracks, and bear a passing resemblance to the 'unidentified vee-shaped structure' from the stratigraphically similar Thick Slatt at Mutton Cove, reported and figured by West (http://www.soton.ac.uk/~imw/portdino) (Figure 11h). In our opening remarks we referred to the irregular depressions in the Caps at Worbarrow Tout, and on the basis of what we now know, these should be reassessed.

On a more general note, we may presume that the abundance of trackway horizons in any part of the Purbeck sequence will be the product of the subsidence rate of the Purbeck – Wight Basin, with consequent increase or decrease in the rate of sediment accumulation. A greater rate of subsidence with reduced sedimentation, or a flood produced by a storm surge, might lead to conditions where dinosaurs could be forced to swim (Whyte and Romano, 2001). A dinosaur will not leave tracks if water depths are too great. We do not know if water depths ever increased to such an extent during deposition of these strata; no swimming tracks have been recognised (Ensom, 1995a). On the basis of the evidence noted above, we believe that Worbarrow Tout provided 'terra firma' for the Purbeck dinosaur population for some of that time, but on the basis of the present study and the work of West (1975) and Underhill's interpretation (2002), the conditions in which swimming traces are more likely to be found in these basal strata could exist in the more easterly outcrops, from Worbarrow Tout towards Durlston Bay.

The future of the tracks

Discussions are taking place between the owners and other interested parties to see if at least the blocks highlighted by Ensom (2004) can be preserved. There is a possibility that key specimens may be deposited in a local museum, and other specimens may form part of a 'dinosaur henge monument' which would provide information for visitors summarising the significance of the specimens. Richard Edmonds is playing a lead role in these endeavours.

Conclusions

The specimens provide evidence of dinosaurs active in what has been perceived as a decidedly inhospitable environment, perhaps inhabiting emergent areas adjacent to the 'coastal' lagoons and salt flats which lay at the western end of the Portland – Wight Basin. South Dorset 145 Ma, lay in a climatic zone which saw strong seasonality, providing both winter rains and arid summers with high temperatures during which extensive salt flats developed. The timing of the track formation in relation to this annual cycle is unknown, though we deduce that the tracks were formed during the transgressive event which led to the deposition of the calcarenite which forms the Thick Slatt, Hard Cockle Member, Lulworth Formation of the Purbeck Limestone Group.

The distribution of tracks at this horizon on the Isle of Portland suggests that these dinosaurs faced limitations on where they could go. No evidence of swimming traces have been found, though we accept that the tracks preserved may have been made with very shallow water covering the prograding sand shoal which formed the Thick Slatt.

Available data suggest that there are at least two track bearing horizons within the Thick Slatt, and the most prolific of these is the lower surface of the preserved blocks. These prints are transmitted and are predominantly the product of bipedal tridactyl dinosaurs. While there are several different track morphs present, and despite the problems of working with transmitted tracks, we conclude that they are almost certainly the product of one species of dinosaur, the morphs being the result of the variable nature of the substrates over which the dinosaurs moved. One transmitted print of a substantial quadrupedal sauropod dinosaur has been identified. This determination received further credence by the discovery of a metatarsal of an indeterminate sauropod, apparently from the same stratigraphic level, in a nearby quarry. The tracks and the bone provide vivid evidence of life and death amongst the ruling reptiles in this less than hospitable, early Cretaceous, environment.

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