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Dinosaur footprints from the Duntulm Formation (Bathonian, Jurassic) of the Isle of Skye

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Synopsis
The first *in situ* dinosaur tracks from Scotland were discovered at the top of the Duntulm Formation (Bathonian, Jurassic) near to Staffin in northeastern Skye. Fifteen individual tridactyl footprints were recorded of which two pairs appear to have been part of the same trackway. The footprints are preserved as natural moulds on a mud-cracked sandstone surface. The individual track sizes range from about 30 cm to over 50 cm in length with narrow to broad digits suggestive of having been made by a medium to large bipedal dinosaur.

Introduction

Dinosaur fossils of any kind are rare in Scotland. Apart from a dubious record of a single track of a small saurischian dinosaur from Caithness (Sarjeant 1974), only loose blocks on the foreshore around the coast of the Trotternish Peninsula, Isle of Skye, have produced tracks and trackways of dinosaurs. Since the discovery of the first dinosaur track in 1982 (Andrews & Hudson 1984) in the Lonfearn Member of the Lealt Shale Formation, Isle of Skye, another loose block with tracks and partial trackways has been found from the Valtos Sandstone Formation at Rubha nam Brathairean, Isle of Skye (Clark & Barco Rodriguez 1998; Clark 2001a). The single track of 1982 was found in close proximity to the trackways of the Valtos Sandstone Formation at Rubha nam Brathairean and is thought to be that of an ornithopod (Haubold 1971) due to the broad digits with rounded distal ends, although it was originally described as a theropod track (Andrews & Hudson 1984). The tracks from the Valtos Sandstone Formation form two partial trackways and a number of individual tracks of the ichnogenera *Grallator* and *Eubrontes* (Clark & Barco Rodriguez 1998; Clark 2001a). The latest tracks and partial trackways are the first *in situ* dinosaur tracks, as well as the youngest evidence for dinosaurs, in Scotland.

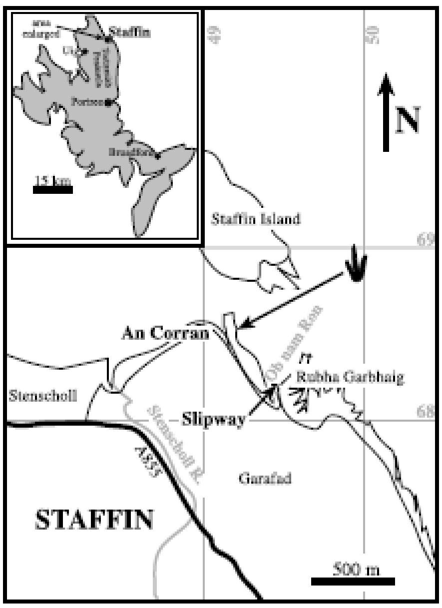

FIG. 1. Locality map for An Corran dinosaur tracks on the Isle of Skye.

After the discovery of the single dinosaur footprint in 1982, it was not until the early 1990s that further dinosaur discoveries were made in Scotland. A cetiosaur limb bone from the Valtos Sandstone Formation (Bathonian) (Clark *et al*. 1995) and a theropod tibia from the Broadford Beds Formation (Hettangian), also from the Isle of Skye (Benton *et al*. 1995), were the first dinosaur bones from Scotland. Since then, several more bones including a small coelophysid-like caudal vertebra, a large cetiosaur caudal vertebra and a rib, as well as several indeterminate dinosaur bones have been found from the Valtos Sandstone Formation (Clark & Barco Rodriguez 1998; Clark 2001a). The latest discovery of dinosaur bones on the Isle of Skye, made in 1997, was of a thyreophoran ulna and radius from the Bearreraig Sandstone Formation (Clark 2001b) and may be the earliest record of a europodan dinosaur. The discovery of dinosaur tracks from the Duntulm Formation extends the record of dinosaurs from the Isle of Skye higher in the Bathonian and suggests a medium to large bipedal theropod, for which no osteological remains have so far been found, existed on what is now the Trotternish Peninsula.

Stratigraphical and sedimentological setting

The tracks were found at the top of two bioturbated calcareous sandstones. The lower of the two sandstones contained paired vertical burrows (?*Arenicolites*), immediately below level A, and

Rhizocorallium on the top surface of a sandstone approximately 10 cm below level A (see Figs 2, 5), and the upper sandstone immediately below level B contained large numbers of simple vertical tubes (*Skolithos*). A similar bed of *Rhizocorallium* has been found underlying a track-bearing horizon in Upper Jurassic sediments in Portugal and Middle Jurassic sediments of the Red Gulch Dinosaur Tracksite in Wyoming, USA (Kvale *et al*. 2001), and are frequently found elsewhere associated with terrestrial vertebrate tracks (Lockley *et al*. 1994; Kvale *et al*. 2001).

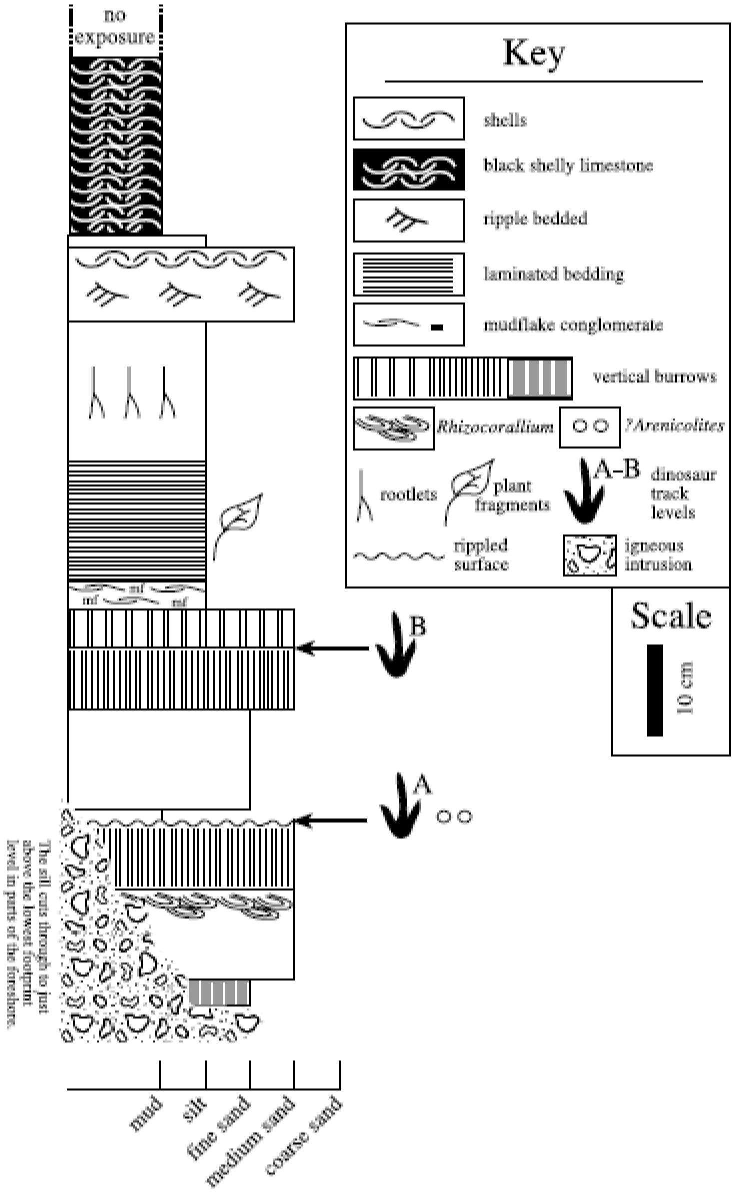

FIG. 2. Dinosaur track-bearing sedimentary section of the Duntulm Formation exposed at An Corran.

All the dinosaur tracks found in the Middle Jurassic sediments of North America are smaller, being anything from less than 5 cm to 20 cm (Lockley *et al*. 1998b). The only occurrence of similar sized dinosaur tracks come from the Entrada–Summerville successions of the Upper Jurassic of North America (Lockley *et al*. 1998a,b). Many of the Middle Jurassic dinosaur track sites in North America may be Upper Jurassic in age although those mentioned above are still considered to be from the Middle Jurassic (Lockley *et al*. 1996b).

Although Middle Jurassic tracks and trackways are rare, trackways of both sauropods and theropods have been recorded from Ardley Quarry in Oxfordshire, England (Day *et al*. 2002a,b, 2004) and the Cleveland Basin, Yorkshire (Romano & Whyte 1996, 2003; Whyte & Romano 2001a). The theropod tracks are larger than the An Corran tracks by between 10 and 20 cm and have a smaller pace angulation (about 117˚ for one trackway and 132˚ for another compared to the approximate 180˚ of at least one of the An Corran paired tracks (tracks 8, 9; see Table 2) and longer stride than those diagnostic of *Megalosauripus* (Haubold 1971) (about 300 cm compared to *c*. 200 cm for the An Corran tracks). The Ardley Quarry tracks were tentatively assigned to *Megalosaurus* and are comparable to *Megalosauripus lusitanicum* from the Upper Jurassic of Portugal (Lockley *et al*. 1998b; Day *et al*. 2004). The bedding plane at Ardley Quarry represents a carbonate mudflat that flanked a marine lagoon and contains abundant burrows (Day *et al*. 2004). This is similar to the An Corran environment, although there is less marine influence, if any, at the level A track horizon.

There are a variety of different track types recorded from the Middle Jurassic Cleveland Basin sequences of Yorkshire including probable stegosaurian tracks (Whyte & Romano 2001b), sauropod tracks and a number of different tridactyl tracks (Romano & Whyte 1996, 2003; Whyte & Romano

2001a). Romano & Whyte (2003) described 17 different tridactyl track morphotypes from the Middle Jurassic Ravenscar Group of the Cleveland Basin. They also suggested that it may be possible to assign the tridactyl tracks to either ornithopod of theropod morphotypes based on imprints with broad digits and a lack of claw impressions for the former and narrow digits with claws present for the latter.

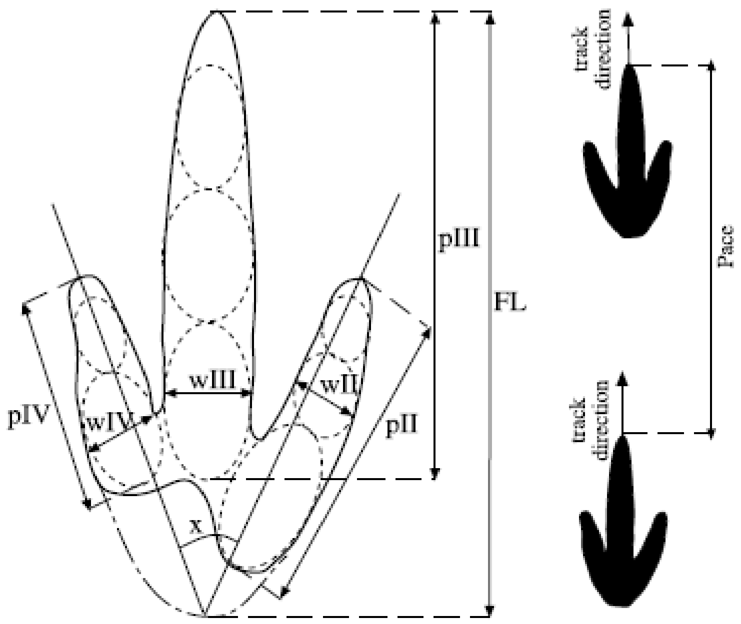

FIG. 3. Measurements taken of dinosaur tracks after Thulborn (1990).

The top of the exposed section is a dark coloured calcareous bioclastite containing large numbers of an oyster (probably *Praeexogyra hebridica*). The presence of the oyster bed, and a section of Kilmaluag Formation (formerly known as the Ostracod Limestones as defined by Anderson (1963) (Harris & Hudson 1980)) exposed in the overlying sill, suggests that the track-bearing sediments are from the upper part of the Duntulm Formation (formerly known as the Lower Ostrea Beds as defined by Anderson (1948)) (Hudson & Harris 1979; Bell & Harris 1986).

The Kilmaluag Formation is characterized by calcareous mudstones and marlstones that are frequently nodular. The base of the formation is defined by the loss of oyster biosparites of the underlying Duntulm Formation. In Trotternish, several thin sandstone units are found in the Kilmaluag Formation that are absent in the southern exposures of this formation (Harris & Hudson 1980). It is also from the Kilmaluag Formation that Waldman & Savage (1972) recorded the first Mesozoic mammal from Scotland as well as other terrestrial vertebrates (Waldman & Evans 1994).

In the Duntulm Formation there is evidence for low hinterland runoff and exposed hypersaline mudflats with the formation of stromatolitic algal limestones with gypsum pseudomorphs (Bradshaw *et al.* 1992). Some of these algal limestones are exposed about 100 m south of the track-bearing sandstones (Anderson 1948); although these were not observed during the course of this study. The sediments of the Duntulm Formation probably represent an alluvial mud-flat deposit with brackish ephemeral lagoonal sediments lacking the hypersalinity of the preceding Valtos Sandstone Formation (formerly known as the Concretionary Sandstone Series (Harris & Hudson 1980)) (Hudson 1983; Bell & Harris 1986; Morton & Hudson 1995). It appears that the trackbearing sediments were not exposed during the surveys conducted by Haldane in 1934 and Anderson in 1936 (six inch field map of Skye (7NE) and Anderson's field notes held in the British Geological Survey in Edinburgh – LSA 212). The track-bearing horizon has only recently become exposed in February 2002, as a result of the removal of some large boulders during the construction of the new Staffin slipway in May 2000, allowing changes in the distribution of drifting sand in Staffin Bay. The track-bearing horizon was only temporarily exposed and became engulfed in over 1 m thickness of drifting sand in July 2002.

Material and methods

All the tracks from the Duntulm Formation were found *in situ* at An Corran, Stenscholl, Staffin, Isle of Skye (Fig. 1 [NG491686]; Fig. 2, level A) except for one track that was found as a loose block on the beach at the same locality (track 16, private collection, Glenview Inn). The loose block comes from a horizon 18 cm above the main track horizon. No *in situ* tracks were found at this level (Fig. 2, level B). The tracks have recently become exposed as a result of erosive wave activity influenced by the recent development of the new Staffin slipway at Rubha Garbhaig 450 m SE of An Corran. It is not expected that the tracks will survive long, although further tracks may appear as the upper layers are removed. A silicone rubber mould has been made of tracks 6, 7, 8 and 9 (see Fig. 6c, d) (following the methods

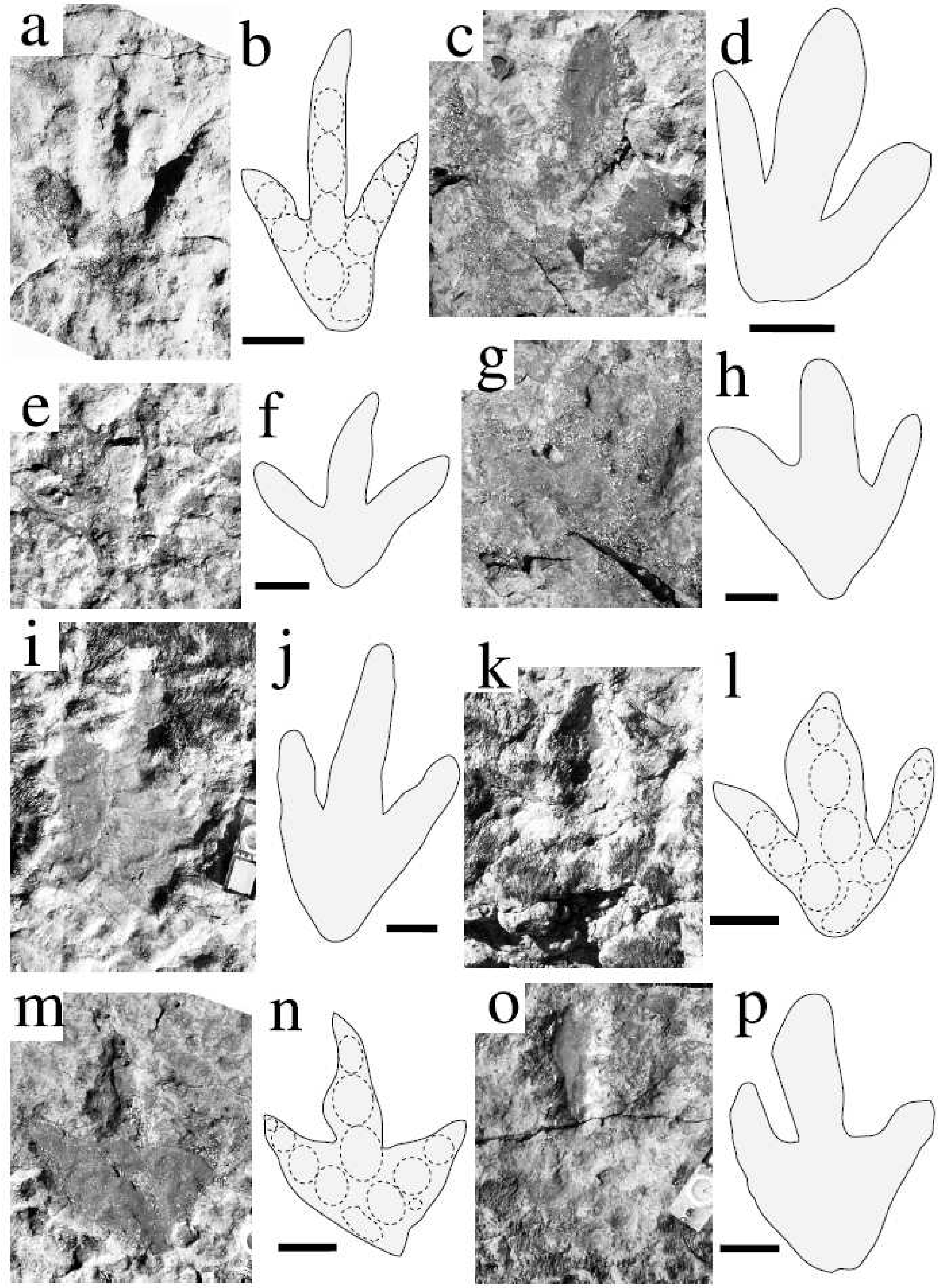

FIG. 4. Field photographs and corresponding outline drawings of the An Corran level A dinosaur tracks showing variation in shape and preservation: (**a b**) track 1(L); (**c**, **d**) track 4 (R); (**e**, **f**) track 5 (L); (**g**, **h**) track 6 (L); (**i**, **j**) track 7 (R); (**k**, **l**) track 8 (L); (**m**, **n**) track 9 (R); (**o**, **p**) track 10 (L). (L) = left pes; (R) = right pes; scale bar = 10 cm; approximate foot pad outlines added to some tracks.

described by Clark *et al*. 2002) and perhaps, in the future, one or two tracks will be removed as a permanent record. A fibreglass cast of these tracks has been made and deposited in the collections of the Hunterian Museum, Glasgow (GLAHM114806).

As the tracks can only be seen between high tides, all measurements and photographs were taken when tidal conditions allowed. The preservation of the tracks did not allow all tracks to have all standard measurements taken (tracks 2, 3, 14, 15 have only the basic measurements of track length (FL) and direction). The measurements of FL, digit length (pII–IV), digit width (wII–IV), pace and toe II–IV divarication angle were taken according to techniques described by Thulborn (1990, figs 4.5b, 4.8c, 4.9d, 4.10a) (Fig. 3). Other tracks found on Skye from the Lealt Shale Formation (GLAHM V1980) and the Valtos Sandstone Formation (GLAHM 101273) have been re-examined and measured using these techniques for comparison.

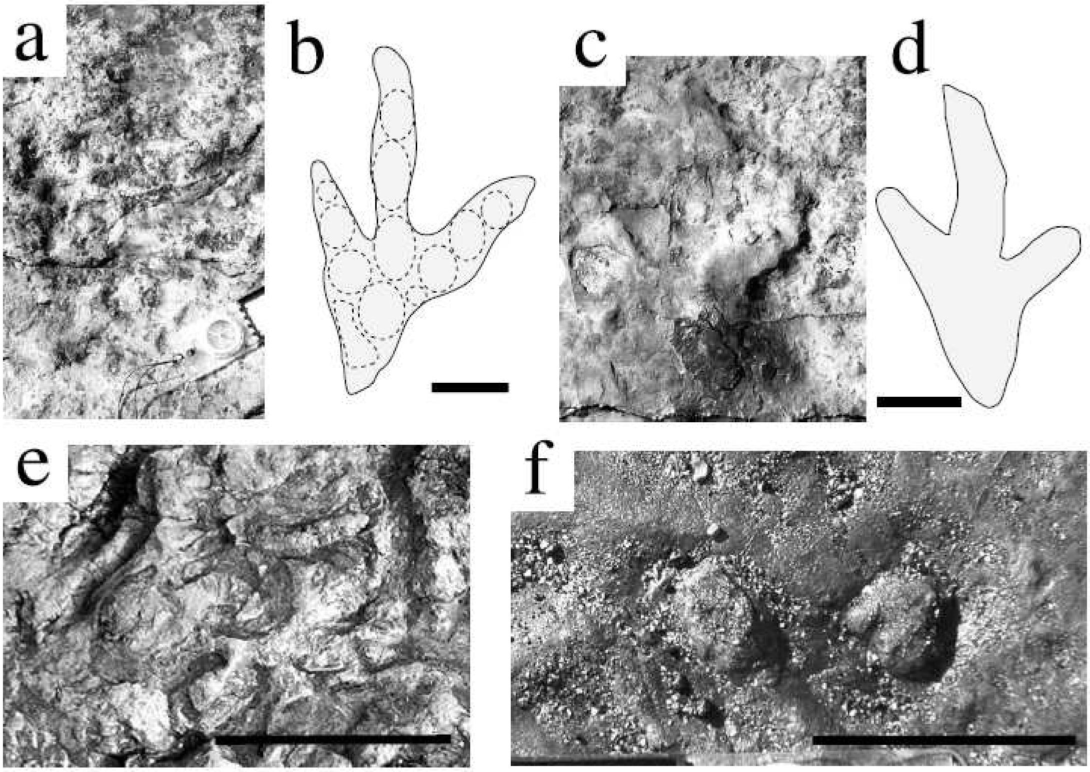

FIG. 5. Field photographs and corresponding outline drawings of the An Corran level A dinosaur tracks and burrows: (**a**, **b**) track 11(R) with approximate foot pad outlines; (**c**, **d**) track 12 (R); (**e**) *Rhizocorallium*; (**f**) top of paired burrow (?*Arenicolites*). (L) = left pes; (R) = right pes; scale bar = 10 cm.

Description

All the tracks (Figs 4a–p, 5a–d, 6a–b) are tridactyl pedes and are mostly in the size range 32–53 cm in length (FL). The only track that is shorter (track 16) came from level B and is 24 cm in length. The angle of divarication of the tracks averages about 52˚ whereas track 16 has an angle of 82˚. The ratios of pIII to wIII of all the level A tracks are not significantly different, although the pIII:wIII of the level B track is significantly lower. As the sediment is broadly similar at level A and level B (fine- to medium-grained sandstone with bioturbation) and the shapes of the tracks are different, it is likely that the tracks were made by two different species.

The Lealt Shale Formation track (GLAHM V1980) of Andrews & Hudson (1984) is comparable in footprint length (FL) to the An Corran level A tracks, with a smaller pIII:wIII ratio and greater divarication angle. The track from level B, however, is very similar to the Lealt Shale Formation specimen (GLAHM V1980) in both the pIII:wIII ratio and divarication angle, although it is substantially smaller (Table 1) suggesting that there is more than just a sediment consistency difference between the Lealt Shale Formation track and the An Corran level A tracks. This broad-toed Lealt Shale Formation track with a high divarication angle (GLAHM V1980) is now thought to have been made by an ornithopod dinosaur (Delair & Sarjeant 1985), and it is also likely that the An Corran level B track was similarly made by an ornithopod dinosaur.

The tracks from An Corran level A appear to be near-surface or surface prints where the distal ends of the digits are more deeply impressed than the proximal part of the imprint. There is a rim of sand around many of the less worn tracks, especially around the third digit (Fig. 4a, c and k show this structure best). The rim of sand is a useful feature in determining surface, or near-surface tracks (Romano &Whyte 2003). The tracks were preserved by being infilled with a grey silty mud.

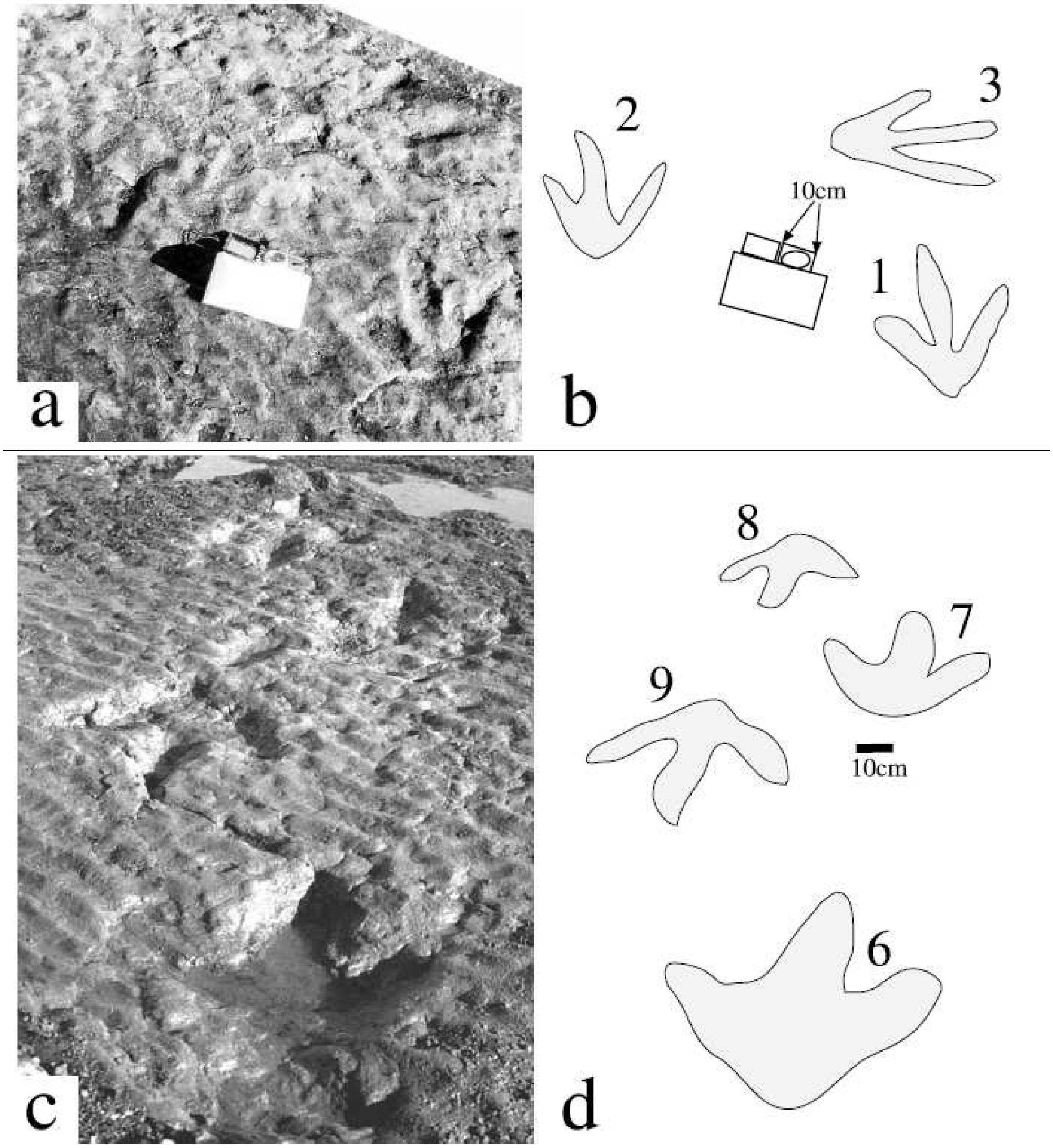

FIG. 6. Field photographs and corresponding outline drawings of the An Corran level A groups of dinosaur tracks and partial trackways. The photograph was taken at a shallow oblique angle (approximately 35˚). Track numbers correspond with Table 2.

It is difficult to be confident of the position of foot pads in any of the tracks, although an attempt has been made to infer their position in some tracks (Fig. 4b, l, n; Fig. 5b).

TABLE 1 Mean values for tracks at An Corran compared to values taken for tracks elsewhere on Skye (the specimens from Rubha nam Brathairean – Valtos Sandstone Fm = GLAHM 101273; Lealt Shale Fm=GLAHM V1980)

Track locality (formation)	Number of tracks (N)	FL (cm)	pIII:wIII	Divarication (degrees)	pace:FL
An Corran (Duntulm Fm) level A	11	44.2	3.4	52	2.0 (N = 2)
An Corran (Duntulm Fm) level B	1	24.0	2.0	82	–
Rubha nam Brathairean (Valtos Sandstone Fm)	7	23.5	4.2	56	4.1 (N = 2)
Rubha nam Brathairean (Lealt Shale Fm)	1	49.0	1.8	76	–

Results

Much of the data for the tracks from An Corran are similar even though there seems to be quite a range in FL from 37 cm to 53 cm. Track 16 is from level B is quite different as discussed above. Despite the differences in the sizes of the tracks from the various localities and formations, the ratio of the length of the digit III to the track lengths (pIII:FL) is similar.

The An Corran level A tracks fall between the Valtos Sandstone Formation small and large tracks based on their divarication angles. The pIII:wIII ratios are higher than that for the Lealt Shale Formation track (V1980), but little different from the An Corran level B track. The main differences lie in the higher divarication angle and the lower FL:wIII ratio which is lower in the An Corran level B track (Figs 7, 8).

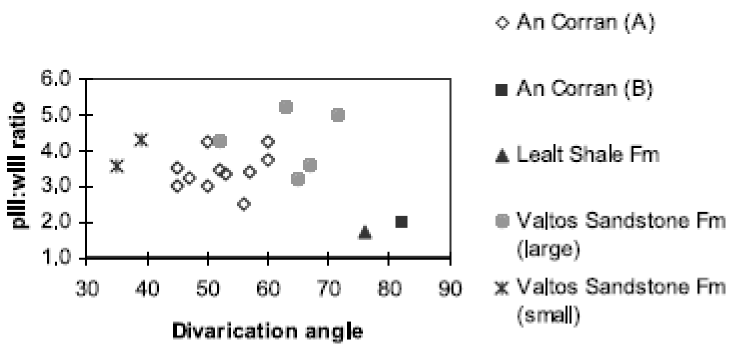

FIG. 7. Graph showing the relationship between the divarication angle and the length to width ratio of the third digit (pIII:wIII) of the dinosaur tracks from the Valtos Sandstone Formation, the Duntulm Formation and the Lealt Shale Formation. The Valtos Sandstone Formation is split into those tracks that were identified as *Grallator* (small) and those identified as *Eubrontes* (large). Track 16 from level B at An Corran is shown separately from the tracks of level A. The width of the third digit was measured as the maximum width within the proximal two-thirds of the length of the digit as the digit pads were not clear.

The pace angulation for the tracks where there are two tracks in alignment appear to approach 180˚ as the track directions and the pace direction almost coincide (Fig. 6c; Table 2). This means that the stride is almost double the pace length (Table 2).

Most of the dinosaur tracks suggest the animals were walking towards the NE and SW with the majority walking towards the NE (Fig. 9) which is nearly perpendicular to the wave ripple crest strikes
(299–119 to 340–160). This indicates that the animals were either walking towards the Minch Basin in the NE, or away from the Hebrides Basin in the south (Hudson 1964; Bradshaw *et al*. 1992). Very few of the tracks are of animals walking parallel to the ripple crests.

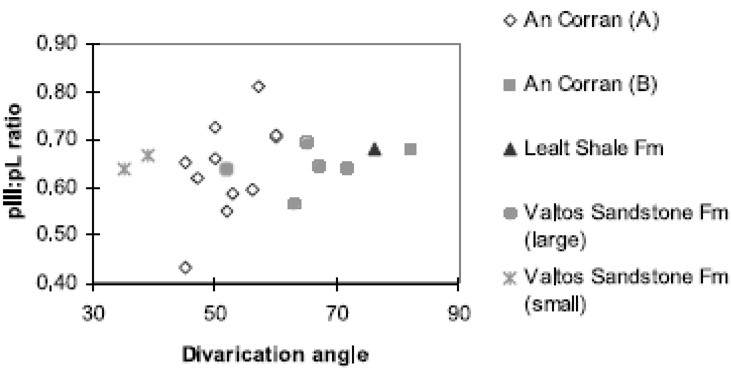

FIG. 8. Graph showing the relationship between the divarication angle and the ratio between the length of digit III and the length of the track (pIII:FL) of the tracks from the Duntulm Formation, the Valtos Sandstone Formation (see Fig. 7) and the Lealt Shale Formation.

Discussion

The relatively poor preservation of the An Corran dinosaur footprints makes it difficult to assign them to any particular ichnospecies. Although the amount of variation within this small set of tracks is quite high, it is possible to see some similarity between the larger Valtos Sandstone Formation tracks and the An Corran level A tracks (see Figs 4, 5, 6, 7 and Table 2). The main difference between these sets is the track length (FL) although the divarication angle is also slightly higher in the Valtos Sandstone Formation tracks.
Identifying a track-maker is very difficult as there are large tridactyl bipedal saurischian and ornithischian dinosaurs in the Middle Jurassic. The first dinosaur track found in Scotland has been placed both with the saurischians (Andrews & Hudson 1984) and the ornithischians (Delair & Sarjeant 1985). Despite the difficulty in assigning the An Corran tracks to an ichnospecies, there are a few taxa with which they can be compared.

The tracks from the Valtos Sandstone Formation, previously identified as *Eubrontes* sp. (Clark & Barco Rodriguez 1998), are similar to but substantially smaller than the An Corran level A tracks. The larger forms of *Eubrontes*, such as *E. giganteus*, compare well with the An Corran level A tracks. The divarication angle and pace angulation are all similar, but the smallest An Corran level A tracks are about the same size as the largest *E. giganteus* tracks, the pace is slightly shorter and the pace angulation appears to be higher at close to 180˚ (about 160˚ in *E. giganteus* (Upper Triassic–Lower Jurassic, North America) (Haubold 1971).

In *Megalosauripus* (Upper Jurassic and Cretaceous of North America, Asia and Europe) (Lockley *et al*. 1996a, 1998a) the tracks have a similar divarication angle, but are slightly shorter (*c*. 35 cm) (Haubold 1971) although those from Oxfordshire are substantially larger, between 60 and 70 cm long (Day *et al*. 2002a, 2004). *Megalosauripus* tends to have a smaller pace angulation (110˚ for Late Jurassic *Megalosauripus* from Turkmenistan (Lockley *et al*. 1996a) and 117˚ and 132˚ for the possible examples from the Middle Jurassic of Oxfordshire (Day *et al*. 2002a, 2004)), although the pace is about the same length. The diagnosis offered by Haubold (1971) suggests that the pace angulation can be as much as 140–160˚ in *Megalosauripus*.

Irenesauripus (Cretaceous, North America) has a very similar divarication angle (55–75˚), but a slightly larger track length (50–80 cm) and pace (*c*. 100 cm) (Haubold 1971). Another saurischian type track that can be compared to the An Corran tracks is *Gigandipus caudatus* (Upper Triassic, North America; Bock 1952) which has similar divarication angle (*c*. 45˚), track length (*c*. 50 cm), pace (100 cm), and pace angulation (180˚), but has a first digit impression at an angle of 90˚ to digit II (Haubold 1971). Although digit I has not been observed in any of the An Corran tracks, it is possible that this is related to the poor preservation and shallow impression of most of the tracks.

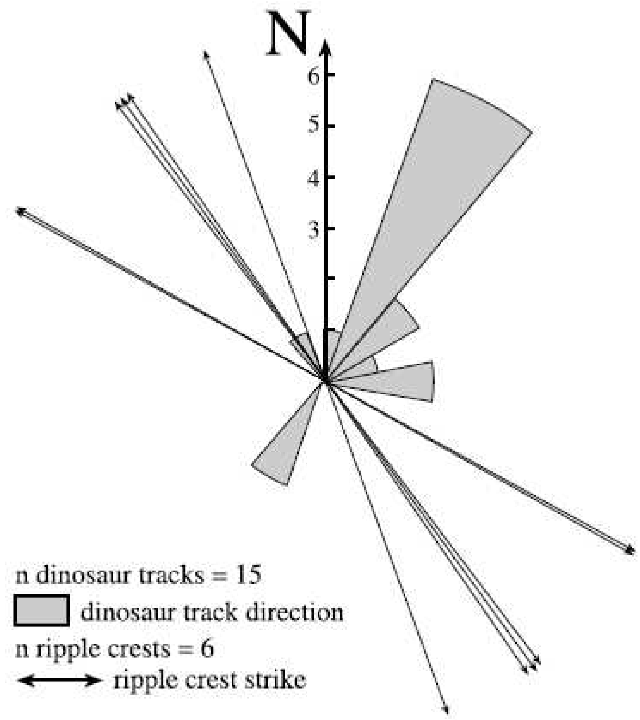

FIG. 9. Rose diagram of dinosaur track directions with ripple crest data superimposed from the Duntulm Formation, An Corran level A.

Tracks identified as having been made by ornithopod dinosaurs that are of comparable size to the An Corran level A tracks include those thought to have been produced by *Iguanodon* (*Ornithoidichnites*, *Struthopus*, *Struthiopus* and *Wealdenichnites*) (Upper Jurassic– Lower Cretaceous; see Haubold 1971). The track length tends to be slightly longer (68 cm) and the pace shorter (<100 cm), but the divarication angle is of the same order (60˚). The only other comparable ornithopod track is that of *Amblydactylus* (Cretaceous, N. America) which also has a similar divarication angle, but longer track (64 cm) (Haubold 1971).

The width of the digits, however, suggests a bipedal theropod rather than an ornithopod as they are relatively narrow when compared to other tracks such as the Lealt Shale and An Corran level B tracks (Table 1, Fig. 7). Although the An Corran footprints are of Middle Jurassic age, it is more likely that they represent a form of *Gigandipus* based on the comparative measurements included above, despite the lack of a digit I impression.

Romano & Whyte (2003) devised a scheme for comparing ichnotaxa from the Middle Jurassic of the Cleveland Basin. The type **Bii** track is similar to the An Corran level A tracks, but it has a much larger divarication angle (about 80˚) and is nearly 20 cm shorter. The **Bi** tracks is of the correct length, with a quite close angle of divarication (*c*. 60˚), however the shape of the impression is quite different (perhaps reflecting a difference in sediment type or proximity to track surface).

As for the An Corran track from level B, it appears to be an ornithopod type track. *Gypsichnites pacensis* (Lower Cretaceous, Canada) has a very similar track length (29 cm) as well as divarication angle (*c*. 80–90˚). This track is closer to **Bii** (up to 35 cm) and **Biii** (up to 25 cm) type tracks of Romano & Whyte (2003) in terms of its size and angle of divarication between digits II and IV, although the digits do not taper and display an even rounding of the distal ends. As only one track is known from level B, it is not felt that a definite identification can be made.

TABLE 2 Measurements taken of tracks from Skye: 1–15, from An Corran level A; 16, from An Corran level B; GLAHM V1980, from the Lealt Shale Formation, Rubha nam Brathairean; GLAHM 101273/1–7, from the Valtos Sandstone Formation, Rubha nam Brathairean. Numbering of tracks as in Clark & Barco Rodriguez (1998); Clark (2001) (all length measurements in cm)

Track number	Divarication (degrees)	FL	pII	pIII	pIV	wII	wIII	wIV	Track direction (degrees)	Pace
1	57	41.0	22.2	33.2	19.4	9.7	9.7	6.9	033	–
2	–	32.0	–	–	–	–	–	–	022	–
3	–	49.0	–	–	–	–	–	–	110	–
4	50	37.0	15.5	24.4	15.5	6.7	8.0	5.8	022	–
5	60	49.0	19.5	34.5	19.5	6.0	8.1	6.0	009	–
6	50	53.0	28.0	38.5	25.5	7.4	9.1	9.4	040	110
7	45	52.0	23.8	33.9	23.2	8.9	9.6	8.1	026	–
8	56	42.0	15.0	25.0	25.0	8.0	10.0	7.0	214	103
9	53	42.0	20.8	24.7	20.3	8.8	7.3	8.8	212	–
10	47	48.0	21.8	29.7	20.8	7.9	9.2	7.6	053	–
11	52	41.0	17.5	22.5	20.5	5.2	6.5	5.0	086	–
12	45	47.0	14.6	20.25	13.5	406	6.7	3.8	031	–
13	60	42.0	25.6	29.8	23.0	8.0	8.0	6.4	060	–
14	–	44.0	–	–	–	–	–	–	066	–
15	–	40.0	–	–	–	–	–	–	324	–
16	82	24.0	11.0	16.3	10.5	4.6	8.3	4.9	–	–
GLAHM V1980	76	49.0	28.6	33.3	21.4	14.3	19.0	11.9	–	–
GLAHM 101273/1	35	19.5	7.5	12.5	7.5	1.5	3.5	1.5	–	77.5
GLAHM 101273/2	39	19.5	7.5	13.0	7.5	2.0	3.0	1.5	–	–
GLAHM 101273/3	65	27.5	13.5	19.0	9.5	3.0	6.0	4.0	–	99.5
GLAHM 101273/4	72	23.5	9.0	15.0	8.0	3.5	3.0	2.0	–	–
GLAHM 101273/5	67	28.0	13.5	18.0	9.5	3.0	5.0	4.5	–	–
GLAHM 101273/6	63	23.0	8.5	13.0	7.5	2.0	2.5	1.5	–	–
GLAHM 101273/7	52	23.5	8.0	15.0	8.0	3.0	3.5	2.5	–	–

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