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The theropod that wasn't: an ornithopod tracksite from the Helvetiafjellet Formation (Lower Cretaceous) of Boltodden, Svalbard

JØRN H. HURUM[1,2], PATRICK S. DRUCKENMILLER[3], ØYVIND HAMMER[1]*,
HANS A. NAKREM[1] & SNORRE OLAUSSEN[2]

[1]*Natural History Museum, University of Oslo, PO Box 1172, Blindern, 0318 Oslo, Norway*

[2]*The University Centre in Svalbard (UNIS), PO Box 156, 9171 Longyearbyen, Norway*

[3]*Department of Geosciences, University of Alaska Museum, University of Alaska Fairbanks,
907 Yukon Drive, Fairbanks, AK 99775, USA*

**Corresponding author (e-mail: ohammer@nhm.uio.no)*

Abstract: We re-examine a Lower Cretaceous dinosaur tracksite at Boltodden in the Kvalvågen area, on the east coast of Spitsbergen, Svalbard. The tracks are preserved in the Helvetiafjellet Formation (Barremian). A sedimentological characterization of the site indicates that the tracks formed on a beach/margin of a lake or interdistributary bay, and were preserved by flooding. In addition to the two imprints already known from the site, we describe at least 34 additional, previously unrecognized pes and manus prints, including one trackway. Two pes morphotypes and one manus morphotype are recognized. Given the range of morphological variation and the presence of manus tracks, we reinterpret all the prints as being from an ornithopod rather than a theropod, as previously described. We assign the smaller (morphotype A, pes; morphotype B, manus) to *Caririchnium billsarjeanti*. The larger (morphotype C, pes) track is assigned to *Caririchnium* sp., differing in size and interdigital angle from the two described ichnospecies *C. burreyi* and *C. billsarjeanti*. The occurrence of a quadrupedal, small to medium-sized ornithopod in Svalbard is puzzling, considering the current palaeogeographical reconstructions and that such dinosaur tracks have mainly been described from Europe but not North America.

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Globally, only a small number of sites preserve evidence of dinosaurs that lived at polar latitudes. In the Arctic, skeletal remains and footprints of Jurassic and Cretaceous dinosaurs are known from Alaska, Canada, Siberia and Svalbard (Gangloff 2012). The first indisputable evidence that dinosaurs inhabited the palaeo-Arctic was discovered in 1960 at Festningen, in western Spitsbergen, Svalbard. These discoveries consist of ornithopod dinosaur tracks in a Lower Cretaceous (Barremian–Aptian) sandstone unit of the Helvetiafjellet Formation (Lapparent 1960, 1962). New tracks were subsequently discovered when the same locality was revisited in the early 2000s (Hurum *et al.* 2006). Other Spitsbergen dinosaur tracks from the same formation were also reported at Hanaskogdalen and Ullaberget, in the doctoral work of Ivar Midtkandal (Midtkandal *et al.* 2007), and at Olsokneset, described in a popular paper by Smelror *et al.* (2006).

In 1976, two tracks were discovered in eastern Spitsbergen in the Helvetiafjellet Formation at Boltodden in the Kvalvågen area (Fig. 1), which were described as belonging to a medium-sized theropod by Edwards *et al.* (1978). In 2012 and 2014, we revisited the Boltodden site and, during the course of our field investigations, discovered numerous other individual footprints and at least one trackway. Based on pes morphology and the presence of several manus imprints, we interpret the new finds, as well as two previously described tracks, as being made by an ornithopod and not a theropod. Here, we describe the new tracks and also provide, for the first time, a detailed palaeoenvironmental context for the site.

Ornithopod ichnotaxonomy has been in a state of flux. Of large ornithopod ichnotaxa, eight Barremian and nine Aptian ichnogenera have been described worldwide (Díaz-Martínez *et al.* 2015). In their recent review of large ornithopod dinosaur tracks, Díaz-Martínez *et al.* (2015) only considered three genera valid. *Iguanodontipus* in the Berriasian–Valanginian, *Caririchnium* in the Berriasian–Albian and, finally, *Hadrosauropodus* in the

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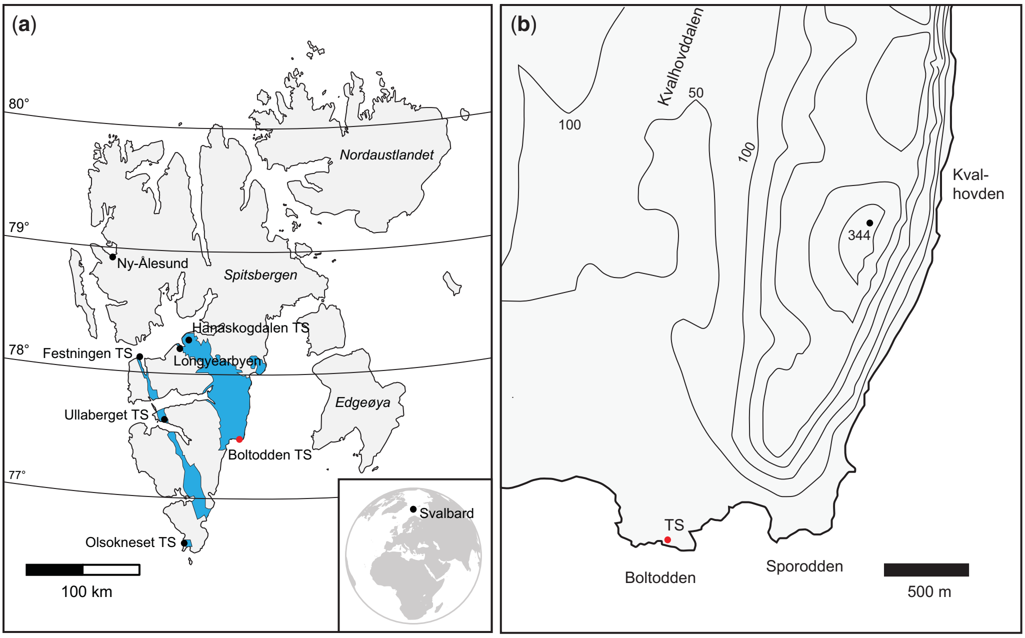

Fig. 1. (**a**) Map of Svalbard showing the study area at Boltodden in the Kvalvågen area and other tracksites (TS) described from Spitsbergen. Outcrops of the Adventdalen Group (Jurassic–Cretaceous) are shown in a darker shade (simplified: cf. Dallmann *et al.* 2002). (**b**) The Boltodden tracksite and the Kvalhovden stratigraphic reference site.

Aptian–Maastrichtian. From this review, it follows that all large ornithopod tracks from the Barremian are of the genus *Caririchnium*. Four ichnospecies of *Caririchnium* are known (Díaz-Martínez *et al.* 2015): *C. magnificum* is found in Berrasian–Albian-aged deposits of Brazil and Spain; *C. kortmeyeri* is only known from the Aptian–Albian of Canada; *C. billsarjeanti* is from the Aptian of Switzerland; and *C. lotus* is known from the Barremian–Albian of China and Spain (for a discussion, see Díaz-Martínez *et al.* 2015). In the Aptian, only one *Hadrosauropodus* species is known, *H. kyoungsookimi*, which is found in Korea.

Geological setting

The Barents Sea platform and its exposed part, Svalbard, are located on the NW corner of the Eurasian continental plate (Fig. 1). In the Early Cretaceous, Svalbard was situated at 63–66° N (Torsvik *et al.* 2012). The Mesozoic basin fill in the western margin of the Barents Platform was deposited within the Mesozoic Atlantic rift system (Faleide *et al.* 2008). In contrast, the Triassic–Lower Cretaceous basin fill in Svalbard and the western platform areas were deposited in a subsiding epicontinental sag basin (Steel & Worsley 1984; Faleide *et al.* 2008; Worsley 2008; Midtkandal & Nystuen 2009; Glørstad-Clark *et al.* 2010). Although these areas experienced no major extensional or compression tectonics, the deposition of the Mesozoic basin fill was controlled by faulting, halokenesis in some basins, volcanism, and the vertical movement and tilting of major structural elements (Steel & Worsley 1984; Grogan *et al.* 1999, 2000; Glørstad-Clark *et al.* 2010; Anell *et al.* 2014; Senger *et al.* 2014).

The nearly 2 km-thick Middle Jurassic–Early Cretaceous Adventdalen Group is dominated by mudstone and heterolithic fine-grained sandstone–mudstone (Steel & Worsley 1984; Mørk *et al.* 1999). The Adventdalen Group is subdivided into four formations (Mørk *et al.* 1999). The Bathonian–Valanginian Agardhfjellet Formation, like its offshore counterparts in the Barents Sea, the Fuglen and Hekkingen formations, was deposited under conditions with a low sediment supply and periodic high organic production in an inner- to outer-shelf environment (Dypvik *et al.* 1991). The overlying Valanginian–Hauterivian Rurikfjellet Formation consists of inner-shelf mudstone passing upwards into prodelta/lower shoreface/distal delta-front environments and defines a large-scale regressive unit (Gjelberg & Steel 1995). The overlying Helvetiafjellet Formation, in which the dinosaur tracks are found, is a sandstone-dominated Barremian–early Aptian unit, up to 155 m thick. It was deposited in fluvial, deltaic, tidal and paralic environments

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(Gjelberg & Steel 1995; Midtkandal & Nystuen 2009). Finally, the uppermost formation of the group is the Aptian–Albian Carolinefjellet Formation, which is more than 1200 m thick and consists of shallow shelf sandstones and offshore mudstones with scattered carbonate beds (Maher *et al.* 2004).

In the Early Cretaceous, the sediment source area in Svalbard and the western Barents Sea was towards the north or NW (Steel & Worsley 1984; Gjelberg & Steel 1995; Midtkandal & Nystuen 2009). This drainage pattern is linked to the opening of the Amerasian Basin (Lawver *et al.* 2002; Golonka *et al.* 2003; Dörr *et al.* 2012) and associated volcanism (Senger *et al.* 2014 and references therein). The sudden influx (i.e. forced regression: Gjelberg & Steel 1995) of the SE-directed fluvio-deltaic Helvetiafjellet Formation above the distal clastic deposits of the Rurikfjellet Formation is an obvious response to uplift in the north (Steel & Worsley 1984; Gjelberg & Steel 1995; Midtkandal & Nystuen 2009). The presence of bentonites, a change from mature quartz arenites to the sudden appearance of lithic or arkosic arenites, interbedded lava flows and emplacement of intrusive basalts (Edwards 1979; Maher *et al.* 2004; Corfu *et al.* 2013; Senger *et al.* 2014) reflect volcanism during deposition of the Helvetiafjellet Formation. Data from Svalbard and the northern Barents Sea, including Franz Josef Land, suggest short-lived volcanism around the Barremian–Aptian transition (Corfu *et al.* 2013). The erosive boundary at the base of the Helvetiafjellet Formation atop the underlying Rurikfjellet Formation is interpreted as a response to forced regression and incision (Gjelberg & Steel 1995; Midtkandal & Nystuen 2009). No Upper Cretaceous sediments have yet been recorded in Svalbard.

Correlation and age of the succession and dinosaur tracks

Until recently, the Barremian age of the Helvetiafjellet Formation was inferred from stratigraphic relationships and plant fossils (Grøsfjeld 1992; Mørk *et al.* 1999). Apart from plant fragments, macrofossils are scarce. A recent U–Pb zircon date from a bentonite in a core (well DH 3, Adventdalen) returned an age of 122.8 ± 0.4 Ma (Corfu *et al.* 2013), which indicates an earliest Aptian age. The bentonite occurs near the middle part of the Helvetiafjellet Formation. Alternatively, recent palynological studies suggest a Barremian age for the entire formation, and an early Aptian flooding surface (Fig. 2a) above the Helvetiafjellet Formation (Midtkandal pers. comm.). The basal part of the Helvetiafjellet Formation in central Spitsbergen is a subaerial unconformity surface: that is, a sequence boundary (Midtkandal & Nystuen 2009). The formation thickens towards the south and SE (Parker 1967), without any systematic change in the amount of marine facies associations (Gjelberg & Steel 1995). This suggests higher accommodation space to the south and SE. The formation was sourced from the NW and had the main drainage system orientated towards the SE (Gjelberg & Steel 1995; Midtkandal & Nystuen 2009). Although biostratigraphic resolution is poor, the interpreted incised valley fill and aggrading nature of the lower part of the formation (Nemec 1992; Gjelberg & Steel 1995; Midtkandal & Nystuen 2009) suggest near-chronostratigraphic correlation between eastern and western Spitsbergen.

The dinosaur tracks at Boltodden are situated in the lower part of the Helvetiafjellet Formation (Fig. 2) and therefore are likely to be Barremian in age or close to the Barremian–Aptian boundary, similar to most of the other reported dinosaur tracks from the formation (Heintz 1963; Hurum *et al.* 2006; Midtkandal *et al.* 2007).

Facies of the succession with the dinosaur tracks

The succession at Boltodden that includes the dinosaur tracks is subdivided here into lower and upper units, informally defined as Unit A and Unit B, respectively (Fig. 3). Based on correlations with nearby Kvalhovden, these units belong to the basal part of the Helvetiafjellet Formation. Units A and B can also be correlated with the subdivision given by Onderdonk & Midtkandal (2010), who subdivided the Helvetiafjellet Formation at Kvalhovden into seven numbered units and interpreted their facies associations. We also adopt these subdivisions and their general interpretations for the Boltodden locality. At Kvalhovden, Unit 1 and Unit 2 consist of displaced slide blocks with fluvial, braided stream-deposited sandstone overlain by coastal floodplain deposits, similar to the facies association that is normally seen at the base of the formation all over central Spitsbergen (Edwards 1979; Gjelberg & Steel 1995; Midtkandal & Nystuen 2009). Unit 3 is a mixture of collapse scar fill and delta-front facies associations. Unit 4, with its mouth bar progradation, can also be seen as small clinoforms (Fig. 2a). Overlying this, Unit 5 is a 16 m-thick sandstone-dominated section interbedded with thin mudstone and coal beds that is interpreted as being part of progradational delta plain. Unit 6 is 6 m thick and represents a renewed mouth bar progradation. The final unit, Unit 7, represents near-shore facies and is the transition to the overlying conformable open shelf mud deposits of the Carolinefjellet Formation. Nemec *et al.* (1988)

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Fig. 2. (**a**) Well-exposed outcrop of the Helvetiafjellet Formation along the sea cliff at Kvalhovden, facing east. The summit is 344 m above sea level. The subdivision of units is from Onderdonk & Midtkandal (2010). (**b**) Overview of Boltodden, looking towards the west. The helicopter has landed on the top surface of Unit B. (**c**) Medium- to

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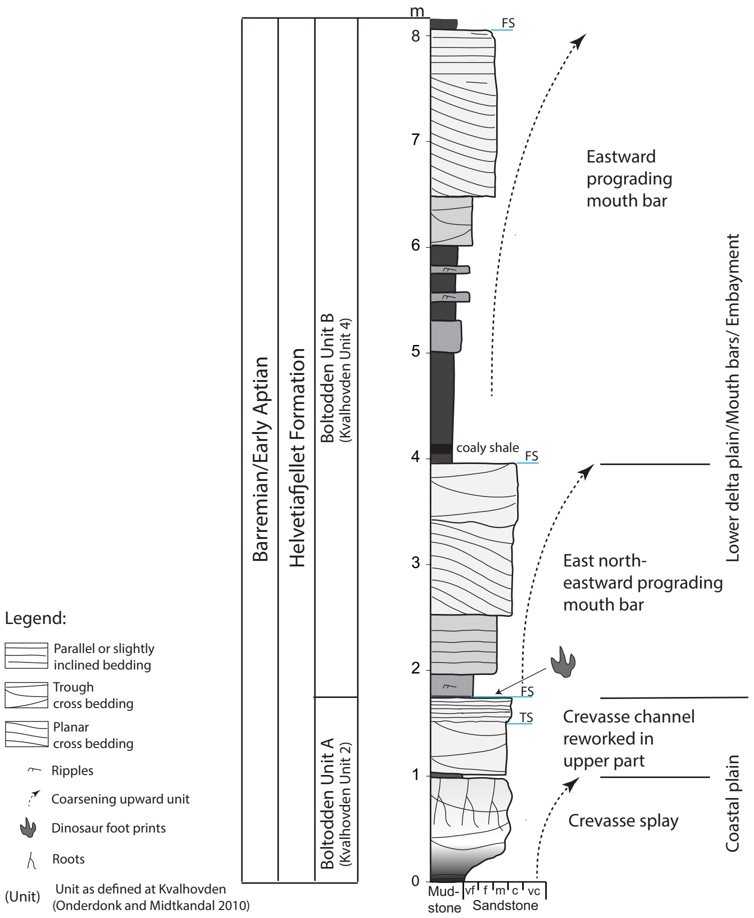

Fig. 3. Sedimentological log through the lower middle part of the Lower Cretaceous Helvetiafjellet Formation at the Boltodden tracksite (see Fig. 2a for the proposed stratigraphic position) showing lithologies, sedimentary and biogenic structures, and interpretations of depositional environments. TS, transgressive surface; FS, flooding surface.

interpreted the uppermost part of the formation as barrier bar deposits.

Unit A (probably Unit 2 at Kvalhovden) at Boltodden is 1.8 m thick and consists of two prominent sandstone beds. The lower sandstone bed (0–1 m in Fig. 3) consists of a coarsening-upwards succession from mudstone to trough cross-stratified medium- to coarse-grained sandstone with rootlets (Fig. 2e). The trough axis varies from 160–340° to 170–350°. Decimetre-scale slump scar and convolute bedding are observed laterally. A thin silt–mudstone bed caps this bed. A sharp basal boundary is seen in the overlying 70 cm-thick (1–1.8 m in Fig. 3), box-shaped trough cross-stratified medium-grained sandstone with an upper horizontal to slightly inclined laminated part with coarser-grained sandstone. The dinosaur footprints are seen on the surface of this bed (Figs 3 & 2d). Laterally,

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Fig. 2. (*Continued*) coarse-grained, poorly sorted sandstones with 2D dunes interpreted as an eastwards-prograding mouth bar. Upper part of the lower coarsening-upwards unit in Unit B (see Fig. 3). (**d**) Sandstone bed showing medium-grained cross-stratified sandstone in the lower part passing up into a horizontal laminated, medium- to coarse-grained upper part. The dinosaur tracks occur at the top surface of this bed. Upper crevasse splay in Unit A. The stick is 70 cm long. (**e**) A 1 m-thick coarsening-upwards unit from siltstone at the base to low-angle trough cross-stratified medium-grained sandstone above with rootlets (arrow), interpreted to be crevasse splay deposits. Lower crevasse splay in Unit A.

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the lower sandstone bed in Unit A is downfaulted with no striation or slickensides, suggesting a large-scale slump scar. This interpretation is consistent with Unit A being laterally equivalent to the slump blocks in Unit 1 or Unit 2 at Kvalhovden.

Unit A is interpreted as two stacked interdistributary bay deposits, as crevasse splays within a lower-delta or coastal-plain facies association. The lower sandstone bed with a defined coarsening-upwards trend and rootlets suggest a more distal crevasse splay, while the sharp-based upper 70 cm-thick sandstone bed might suggest a more proximal facies (i.e. crevasse channel: Elliott 1974). The horizontal to slightly laminated, somewhat coarser-grained sandstone in the upper part of the 70 cm-thick sandstone bed is here suggested to be reworked crevasse channel deposits, probably by sedimentation in the upper flow regime, most likely on a beach/margin of a lake or interdistributary bay. The 70 cm-thick sandstone bed is overlain by a mudstone lamina that defines the base of the first prograding mouth bar of Unit B (Fig. 2c). We therefore suggest that the dinosaurs were walking on a beach, probably within an interdistributary bay or lake, and the tracks were preserved by mud from a flooding event.

Unit B corresponds to units 3 and 4 at Kvalhovden, where Unit 3 consists of an approximately 10 m-thick mudstone unit followed by a 20 m-thick Unit 4, which has three defined coarsening-upwards (Cu) units. The thick mudstone Unit 3 at Kvalhovden is missing at Boltodden, and Unit B consists only of two well-defined Cu units. The lower Cu unit (1.7–3.9 m in Fig. 3) consists of mudstone laminae followed by ripple-laminated fine-grained sandstone at the base, then a horizontal bedded fine-grained sandstone that passes upwards into large-scale ENE-migrating high-angular planar cross-stratified medium- to coarse-grained sandstone, occasionally with tangential bottom sets. The top set has an erosive boundary to the high-angular planar sets and consists of a more low-angular cross-stratified sandstone with a similar grain size. The lower Cu unit is interpreted to represent mouth bar progradation. Upper low-angular cross-strata probably result from a shift in drainage: for example, as an avulsion of the distributary or crevasse channel.

The upper Cu unit (3.9–8.1 m in Fig. 3) has a nearly 2 m-thick mudstone in the lower part intersected by very-fine-grained ripple-laminated sandstone in the upper part. Coaly mudstone is seen near the base. The sandstone in the upper 2 m is fine to medium grained with a low-angular planar cross-stratification, and is much better sorted than the first Cu units at 1.7–3.9 m in Figure 3. This Cu unit is also interpreted as mouth-bar progradation, but thicker mudstone and finer grain size with better sorting suggest a more distal facies, probably developed into a deeper standing body of water. The uppermost 0.4 m of this Cu unit shows horizontal laminated well-sorted fine-grained sandstone, suggesting that the mouth bar was capped by a beach. This upper Cu unit is capped by shale representing a new flooding surface. Apart from the thick delta-front mudstone of Unit 3 in the profile, presented by Onderdonk & Midtkandal (2010), the Unit B section at Boltodden follows their interpretation of mouth-bar progradation. Unit 3 varies in thickness at Kvalhovden from missing to more than 50 m owing to the position of the underlying sliding blocks. Unit 3 is missing on the intact horst blocks.

Unit B, which here is interpreted as two prograding mouth bars, might also be interpreted as two parasequences (Van Wagoner *et al.* 1988).

Methods

The tracks were mapped using a combination of techniques. The coordinates of the tracks were recorded using a Leica total station (theodolite and laser range finder). Each track was photographed with a scale bar and magnetic compass, then outlined with chalk and photographed again. Using Adobe Illustrator, the photographs were scaled, rotated, translated and traced to produce the overview map (see later).

For photogrammetry, between 12 and 17 photographs were taken of each track from different positions in azimuth and altitude. The images were combined into a 3D model using the free photogrammetry software Autodesk 123D Catch, converted to a 3D ASCII point-cloud file in Meshlab, then imported into the free GIS software QGIS v. 2.4 (QGIS Development Team 2014). The point cloud was gridded (interpolated to a regular grid) to produce an elevation map, and contoured. Additional morphometrics were measured directly in the field. Past v. 3.02 (Hammer *et al.* 2001) was used for reduced major axis (RMA) regression, and for plotting and analysing compass directions. Use of size-class terminology follows Marty (2008) and Díaz-Martínez *et al.* (2015).

Description of the tracks

A total of 36 clearly defined footprints were documented at the Boltodden site, including two pes morphotypes, one manus morphotype, and one pes and manus trackway (Table 1). Medium-sized tridactyl pes prints with associated manus prints are the most common morphotype, and larger tridactyl tracks are less common. The prints are preserved as true tracks with varying degrees of erosion. Some of the tracks show partial collapse of sand into the print from along the sides, which influences

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Table 1. *Details of tracks shown in Figure 5*

Track number	Width (cm)	Length (cm)	Type	Comments	Morphotype
Area 1					
1	24	20	Pes	Three distinct claw impressions	A
2	25	20	Pes	Like track 1	A
3	36	33	Pes?	Questionable track, not included in the study	
4	?	20	Pes	Only two toes visible	A
5	19	22	Pes	Poorly preserved	A
6	?	28	Pes	Only two toes visible	A
7		20	Pes	Only two toes visible	A
Area 2					
8	35	41	Pes	Large ornithopod; clear print; part of ‘left’ toe covered	C
9	?	?	Pes?	Dimensions uncertain, simple oblong shape	C
Area 3					
10*	*c.* 30	*c.* 24	Pes	Dimensions uncertain; right foot	A
11*	33	30	Pes	Left foot	A
12*	31	26	Pes	Right foot	A
13	11	11	Manus		B
14*	13	12	Manus	Between prints 11 and 12	B
15	25	24	Pes	Approximate measure	A
16	?	?	Manus	Dimensions uncertain	B
17*	?	?	Manus	Dimensions uncertain; behind print 10	B
18	28	31	Pes		A
19	28	25	Pes	In line with print 18, next in sequence? missing ‘heel’	A
20	?	?	Manus	Split by crack	B
21*	9	11	Manus	Furthest back in trackway?	B
22	*c.* 36	*c.* 30	Pes?	Questionable track, not included in the study	
23	?	?	Pes?	Simple oblong shape	A
24	7	10	Manus	Roundish	B
25	7	11	Manus	Reniform	B
Area 4					
26	28	26	Pes	Missing ‘right’ toe	A
27	24	*c.* 22	Pes	Poorly defined	A
28	25	24	Pes	Hard to define toes	A
Area 5 – Edwards et al. (1978) tracks					
29	28	?	Pes		A
30	29	30	Pes	Good track with clear metatarsal pad	A
31	12	9	Manus	Associated with pes 29 and 32	B
32	28	26	Pes	Clear track	A
33	26	26	Pes	Deep; small but with good claw impressions; ‘heel’-sliding?	A
34	11	10	Manus	Not as well defined	B
35	12	9	Manus		B
36	?	?	Manus		B

*Part of the same trackway.

the overall morphology of the tracks, particularly the terminal digit shape. No skin impressions were noted. All of the tracks are preserved on the same horizon: however, the track-bearing surface is only partly eroded into view and the central area of the mapped site (Figs 4 & 5) remains covered by sandstone (Fig. 4). It is likely that many of the shallow rounded depressions found on the track horizon are also prints, but they lack clearly defined foot characteristics such as toes or a triangular shape. Some of these even show spacing and alignment expected with a trackway. Their preservation may

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Fig. 4. Aerial photograph of the tracksite at Boltodden, Kvalvågen. The main trampled areas (A1–A5: see the text) lie in the same stratigraphic horizon and are separated by an area of relatively smooth sandstone surface in the centre of the picture.

be a result of erosion or, alternatively, they may represent undertracks (for a discussion of the variation in ornithopod tracks, see Santos *et al.* 2012).

Clearly discernable individual prints (mapped in Fig. 5) occur in five areas: Area 1 lies in the SW and includes six relatively small pes imprints; Area 2 is a single large pes imprint along with one other large poorly defined print at the north end of the site; Area 3 is in the centre of the study site, and includes eight larger pes imprints, a number of relatively small circular manus imprints and a number of indistinct depressions; Area 4 has three pes imprints; and Area 5 is at the eastern end, and has four large pes and four manus imprints. The two previously described prints (Edwards *et al.* 1978) are represented here by tracks 30 and 32. Widths and lengths are plotted in Figure 6a. The rose plot of clearly orientatable tracks ($n = 15$) is shown in Figure 6b. The directions are not randomly distributed (Rao's test for uniform circular distribution, $U = 200$, $p = 0.002$) but bimodal, pointing either to the north or the south.

Morphotype A

We mapped 19 tridactyl pes tracks of this morphotype. All 19 prints are of similar size and are wider than long (mean width, 26.9 cm; mean length, 24.7 cm: see Table 1). The pes tracks in Area 1 are identical in morphology to those of areas 3–5. Digit III is consistently longer than digits II and IV. The individual digits are broadly triangular in outline and symmetrical in shape. The terminal digit morphology varies from U-shaped to V-shaped. Distinct claw impressions appear present in track 32, while a more blunt claw impression next to it in track 30 is more commonly seen (Figs 7 & 8). However, it is likely that soft-sediment deformation and erosion influenced the original shape. Phalangeal pads are weakly discernable on some prints. The interdigital angle varies from 32° to 40°, and total divarication ranges from 62° to 82°. The metatarsophalangeal pad impression is usually distinct, and is posteriorly rounded (Fig. 6, track 12) to straight (Fig. 6, track 1), or even weakly bilobed (Fig. 6, track 11).

Morphotype B

We documented 12 manus tracks that are associated with the pes tracks of morphotype A (e.g. Fig. 6, track 30 & Fig. 9). (Additional manus prints were also observed in Area 1 but were not measured or mapped owing to an incoming tide during the field

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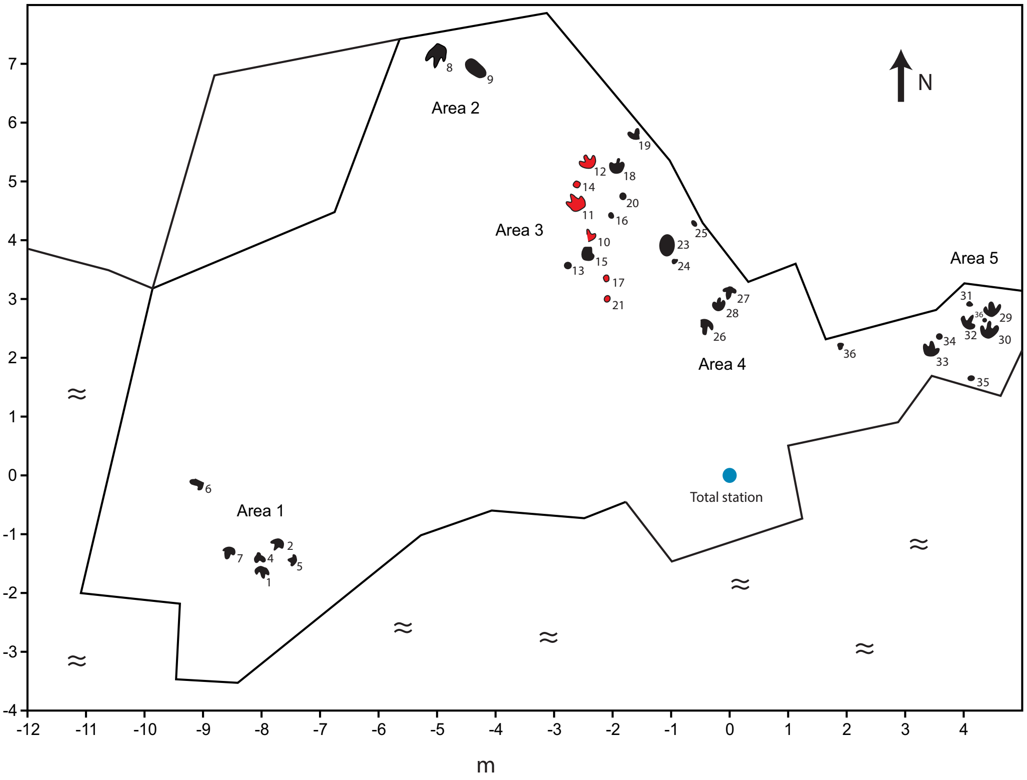

Fig. 5. Detailed map of clearly defined footprints at the Boltodden site, with the sea to the south and SW. A probable trackway is marked in red/grey. Tracks 3 and 22 were excluded from the study (see Table 1).

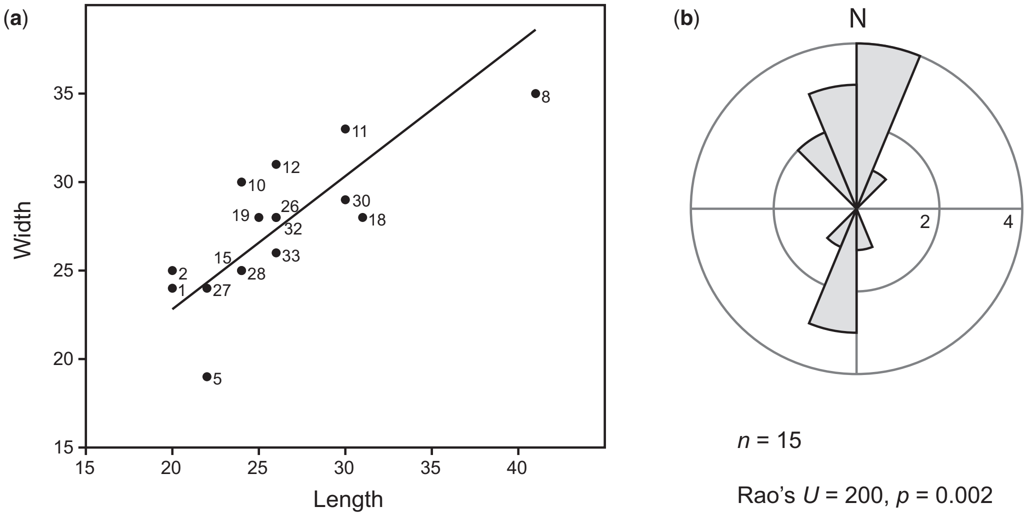

Fig. 6. (**a**) RMA regression of length (L) v. width (W) of pes tracks. $W = 0.75L + 7.8$; $R^2 = 0.60$; $p = 0.0005$, $n = 16$. (**b**) Rose plot of the directions of orientatable tracks.

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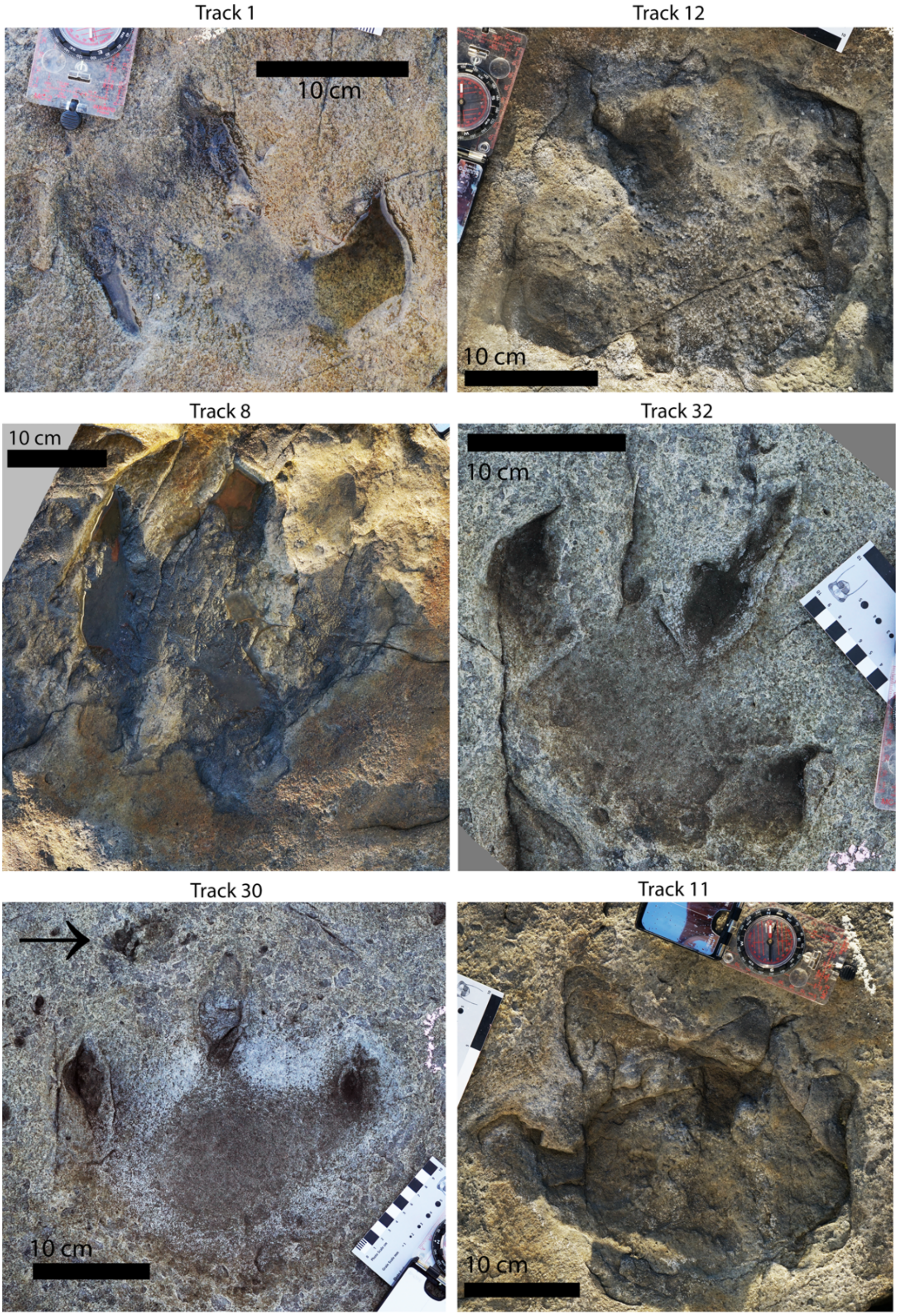

Fig. 7. Photographs of selected tracks, orientated with magnetic north towards the top, except for tracks 1 and 8, which have north towards the bottom. The arrow for track 30 points to a manus imprint (track 36). Track numbers are as in Figure 5 and Table 1.

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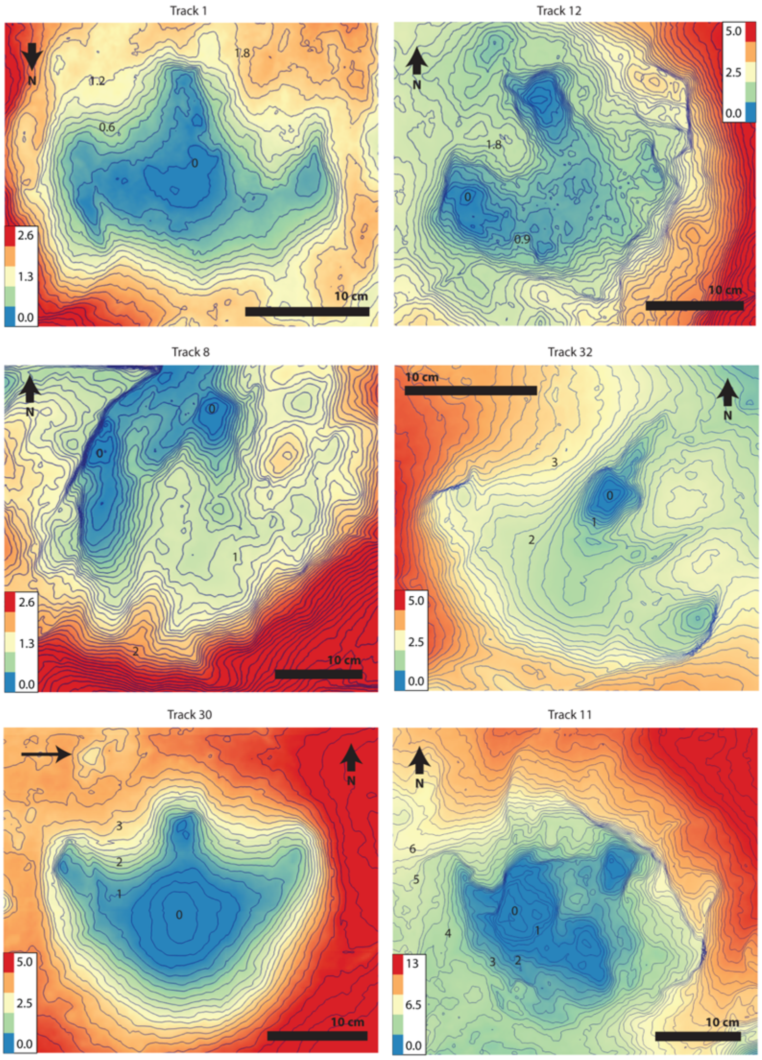

Fig. 8. Photogrammetric elevation maps of the tracks shown in Figure 7. Elevations in cm above the lowermost point are shown on selected contours. Note the reversal of north for track 1. Track numbers are as in Figure 5 and Table 1.

visit.) They are round to oval in shape, consistent in size and are slightly wider than long (mean width, 10.4 cm; mean length, 10.2 cm: see Table 1). Digit impressions were not observed. The manus tracks are placed in front of the pes morphotype A tracks, best seen in tracks 11 + 14 (Figs 5 & 9b), 30 + 36 (Figs 5, 7, 8 & 9a) and 33 + 34 (Fig. 5).

Track morphotype C

We recognize a second pes morphotype based on track number 8 (Figs 5 & 7), and a similar sized, but poorly preserved track number 9. Track 8 is considerably larger, about 25% longer than the rest of the morphotype A pes imprints at Boltodden, and is also longer than wide (width, 35 cm; length, 41 cm). Although track 8 appears to have a smaller total divarication angle than morphotype A, this is in part due to part of the imprint of ‘left’ toe being covered by sediment, making it appear more narrow than it really is (Table 1). Morphotype C is similar in shape to the tracks described from the Festningen locality by Lapparent (1960, 1962) and Hurum *et al.* (2006): however, it is smaller in overall size (the Festningen tracks average (width × length) 62 × 63 cm, this single track being (width × length)

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Fig. 9. (**a**) Some tracks in Area 5, with track numbers as in Figure 5 and Table 1. Tracks 36 and 31 are interpreted as manus imprints. The ruler is 63 cm long. (**b**) A pes (track 11) and manus (track 14) pair in Area 3. (**c**) Interpreted manus imprint in Area 3 (track 14). Magnetic north is towards the top. (**d**) Elevation map of track 14.

35 × 40 cm). The posterior margin of the distal metatarsal impression is nearly straight as in the Festningen tracks, referred to as a ‘quadrangular heel pad’ in Castanera *et al.* (2013*a*). The angles between the toes are about 30°, about 5° less than in the Festningen tracks (Hurum *et al.* 2006).

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Probable trackway

Pes tracks 10, 11 and 12 (morphotype A) are of similar size, are orientated in the same direction, and are spaced in a manner consistent with them being part of a trackway. In addition, manus track 14 is found in the expected position relative to track 11. Tracks 17 and 21 (manus) may also be part of this trackway. The distance from track 10 (right pes) to track 12 (right pes) gives a stride length (SL) of 125 cm. The pace length (PL) is then $SL/2 = 62.5$ cm. The mean foot length (FL) of tracks 11 and 12 is 28 cm, giving a PL/FL ratio of 2.3.

Discussion

Barremian climate of Svalbard

The succession with the dinosaur tracks is part of the Helvetiafjellet Formation in central Spitsbergen, interpreted as an overall paralic deposit (Midtkandal & Nystuen 2009). Identified facies associations include braided stream, distributary channels, interdistributary bay, delta/coastal plain with coal beds, mouth bar, barrier bar, tidal estuary, lagoon and transgressive shoreline (Steel & Worsley 1984; Nemec *et al.* 1988; Gjelberg & Steel 1995; Midtkandal & Nystuen 2009).

The Early Cretaceous has been regarded as one of the warmest periods in the Phanerozoic. However, being situated at 63–66° N latitude (Torsvik *et al.* 2012), the Early Cretaceous climate of Svalbard is suggested to be seasonally variable. Based on studies from the Lower Cretaceous in the Sverdrup Basin, which was then situated further north of Svalbard (i.e. *c.* 75° N: Wynne *et al.* 1988; Torsvik *et al.* 2012), the climate changed from semi-arid and seasonal in the Late Jurassic and Valanginian to humid and cool in the Late Valanginian (Galloway *et al.* 2013). The common occurrence of glendolites (calcite pseudomorphs of ikaite, a hydrated calcium carbonate phase associated with near-freezing water temperatures: Selleck *et al.* 2007) in some of the units in the Rurikfjellet and Carolinefjellet formations (Mørk *et al.* 1999; Price & Nunn 2010; Dypvik & Zakharov 2012) also suggests a relatively cool climate in the Early Cretaceous of Svalbard.

However, there is also evidence for a warm climatic regime during deposition of the Helvetiafjellet Formation. The flora known for the formation includes gingkos and conifers (Heintz 1963; Harland & Kelly 1997), and occasionally thick bituminous coal seams with underlying seatearth (fireclay) with rootlets also occur in the Helvetiafjellet Formation (Nemec 1992). Together with abundant fossilized tree trunks and dinosaurs (ornithopod tracks) in Svalbard (Hurum *et al.* 2006), this suggest a well-vegetated and humid environment. In addition, the common occurrence of kaolinite as both a pore-filling mineral and in kaolinite beds may point to a warm or, at least, seasonally warm climate. The lower part of the Helvetiafjellet Formation sandstone consists of white kaolinitic quartz arenites, shifting to grey to greenish lithic arenites in the upper part. This shift in composition is related to the influx of volcanic fragments (Edwards 1979). On Kong Karls Land, the sandstones of the Helvetiafjellet Formation are unconsolidated and have probably never exceeded a burial temperature of 60–70°C (Larssen *et al.* 1993). Here, a claystone bed within arkosic arenite is dominated by kaolinite, suggesting soil profile processes that have leached unstable minerals. Although kaolinite soil profiles are often associated with warm climates, recent work has shown that kaolinite soil profiles probably also form in cooler temperate climates with seasonal growth during warm months (Sheldon & Tabor 2009). Although the kaolinite bed in Kong Karls Land does not represent a complete preserved kaolinitic soil profile typically associated with a tropical climate, it might suggest at least a seasonally warm climate during deposition of the Helvetiafjellet Formation in Svalbard. Finally, we have plotted occurrences of Cretaceous coal directly from the database of Boucot *et al.* 2013 (Fig. 10) that indicate a particularly high latitude for the Cretaceous northern wet belt coal, stretching to 77–78° N instead of the more typical 60° N.

The tracks

Edwards *et al.* (1978, pp. 940–941) described two of the tracks at the locality (tracks 30 and 32 in this paper) as ‘apparently made by a large carnosaurian dinosaur’ and attributed them to the Middle Jurassic theropod *Megalosaurus* due to the presence of sharp claw impressions. Thulborn (1990, pl. 10) refigured one track (our track number 32) and described it as:

> A theropod footprint attributed to *Megalosaurus*, in the Lower Cretaceous of Kvalvågen, Spitsbergen; about 23 cm wide. This is an unusually broad and short print, but has unmistakable indications of the claws.

Thulborn (1990) further suggested a list of possible characters discerning ornithopod and theropod tracks, noting that theropod footprints tend to be longer than wide, have V-shaped tapering digits, possess narrow toe and claw prints, less widely divergent digits than typical ornithopods, and a V-shaped rear half of the footprint.

In considering the Boltodden tracks, most characteristics of the pes indicate that they are, in fact, made by an ornithopod. In particular, the tracks are consistently wider than long, and the digit impressions are relatively broad and short when compared

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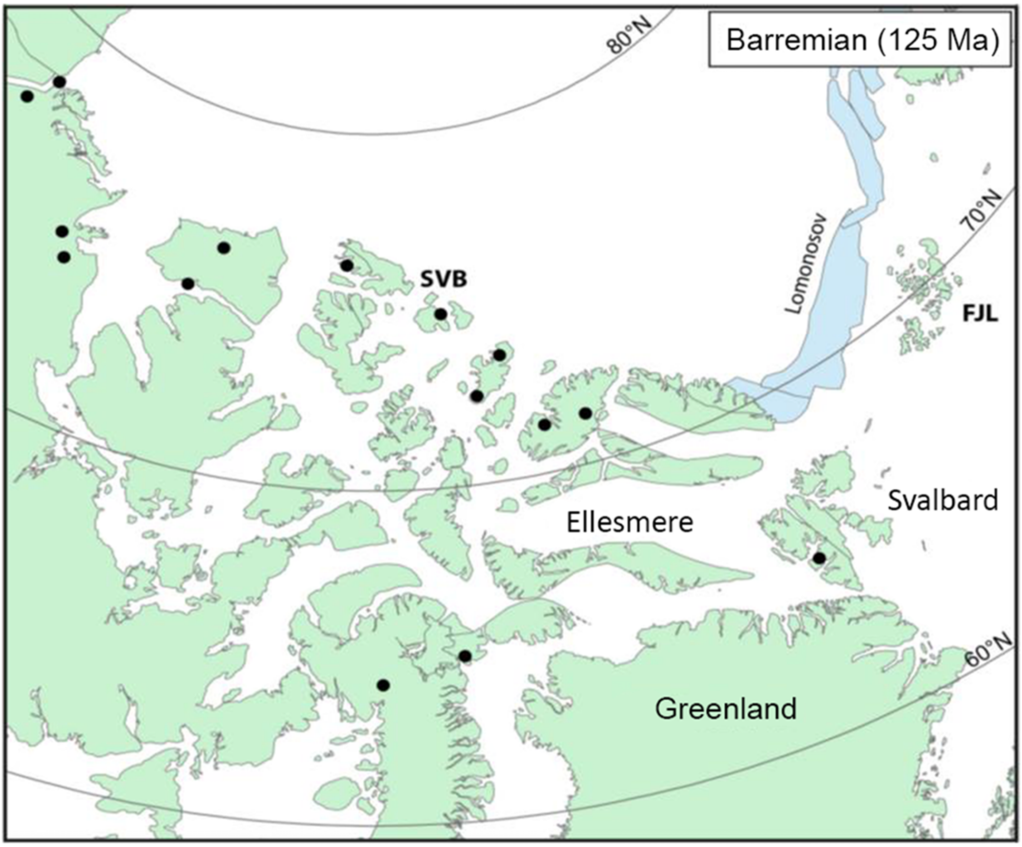

Fig. 10. Occurrences of coal in the Early Cretaceous, based on Boucot *et al.* (2013). FJL, Franz Josef Land; SVB, Sverdrup Basin.

to most unequivocal theropod tracks. Also, where preserved, the metatarsophalangeal joint impressions are broadly rounded and not narrowly V-shaped, as noted by Thulborn (1990). The primary reason that the Boltodden prints had been attributed to a theropod rest solely on the presence of sharp claw impressions (Edwards *et al.* 1978). We interpret this morphology to be a taphonomic artefact of soft-sediment deformation, whereby water-saturated sand partially collapsed at the tracking surface, resulting in distortion at the distal end of the digits and producing an artificially narrow toe outline, including a sharp claw-like morphology. The high moisture content of the sediment is inferred from the depositional setting, which was probably a beach (see earlier). As noted elsewhere (Milan & Bromley 2006; Jackson *et al.* 2009; Razzolini *et al.* 2014), collapse and flow of sediment with a high moisture content can significantly alter track morphology, resulting in erroneous conclusions regarding the trackmaker and other interpretations based on morphology.

Castanera *et al.* (2013*b*) recently discussed the problems of discerning ornithopod and theropod tracks, noting that the association of pes prints with manus prints (which are easily overlooked) can also provide important evidence in support of an ornithopod trackmaker. Our field investigations indicate that many of the morphotype A tracks, including those described in Edwards *et al.* (1978), are also associated with small, round to oval prints that we interpret as manus tracks. Collectively, overall print morphology and the presence of manus prints provide unequivocal evidence that the main Boltodden trackmaker was a medium-sized ornithopod. Finally, we do not believe that a subset of prints could be from a theropod given that all morphotype A prints are morphologically consistent and lack any indication of a posteriomedially orientated hallux. The Boltodden site provides yet another example of mistaken identity, where ornithopod tracks had previously been misinterpreted as having been made by theropods (Romilio & Salisbury 2011; Castanera *et al.* 2013*b*).

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The Boltodden tracks of morphotype A are all made by a small to medium-sized ornithopod that was at least facultatively quadrupedal. A number of different ornithopod ichnotaxa are known from the Cretaceous (Lockley *et al.* 2014; but see Díaz-Martínez *et al.* 2015). The Boltodden tracks are similar to those attributed to *Caririchnium* Leonardi, 1984, a quadrupedal trackway of comparable size known from numerous sites globally, including the Lower Cretaceous of Brazil, Colorado, the USA (Thulborn 1990, fig 6.32d) and several localities in Europe (Castanera *et al.* 2013*a*, *b*; García-Ortiz & Pérez-Lorente 2014 and references therein). The Boltodden tracks are most similar to *Iguanodontipus* Sarjeant *et al.*, 1998, and particularly *I. billsarjeanti* Meyer & Thuring, 2003 from the Aptian of Switzerland, now referred to *Caririchnium billsarjeanti* (Díaz-Martínez *et al.* 2015). The ichnospecies *C. billsarjeanti* has a tridactyl pes wider than long, with a length of 28–35 cm, and an interdigital angle of 30–35°, very similar to the Boltodden prints. The pace length of 62.5 cm is also consistent with *C. billsarjeanti* (62–72 cm: Meyer & Thuring 2003), partly strengthening the interpretation of tracks 10–12 as a trackway. In addition, the manus prints associated with *C. billsarjeanti* are similar in size, morphology and placement, being located anterior to the apices between digits III and IV (Meyer & Thuring 2003). Lockley & Wright (2001) discussed the position of the manus relative to the pes in quadrupedal ornithopod tracks and concluded that this varies even within trackways. This is also true for the Boltodden tracks. We therefore refrain from categorizing left and right tracks in our material. The main difference noted between *C. billsarjeanti* and the Boltodden prints is seen in the more pronounced claw impressions of some of the latter: however, this is interpreted as a taphonomic artefact, as discussed above. *Caririchnium kortmeyeri* (*Amblydactylus kortmeyeri* Currie & Sarjeant, 1979) have pointed digits that may be interpreted as claw impressions, but no associated manus tracks.

Castanera *et al.* (2013*b*, p. 11) recently noted that ‘quadrupedality inferred from trackways is scarcely documented for medium-sized ornithopods in the Late Jurassic–Early Cretaceous worldwide, except in Europe’. This makes the Boltodden tracks very interesting from both a locomotory and palaeobiogeographical perspective. First, the tracks establish that facultative quadrupedality was present in these small to medium-sized ornithopods, which have an estimated hip height of approximately 1 m (morphotype A), following Alexander (1976). Secondly, the tracksites were located at between 63° and 66° N in the Barremian when Svalbard was most probably isolated from mainland Europe and possibly Greenland/North America (Hurum *et al.* 2006; Torsvik *et al.* 2012). The presence of dinosaurs in Svalbard at this time suggests at least intermittent terrestrial connectivity between Svalbard and a larger landmass to the west (Greenland/North America). That the tracks are clearly from a quadrupedal ornithopod, and thus more like European forms, is puzzling. One possibility is that quadrupedal ornithopods were more widespread across Greenland/North America at this time than recognized but poorly represented by body or trace fossils, which seems likely to be at least partly true. Alternatively, a potential route of terrestrial connectivity that is not currently recognized by tectonic and palaeogeographical reconstructions permitted dispersal between Svalbard and Europe. Either way, the presence of dinosaur footprints in Svalbard indicates that they become widely distributed at high palaeolatitudes during the Cretaceous.

The large pes track of morphotype C (number 8 on Figs 5 & 7) is smaller than the tracks from the same horizon on the Festningen locality on the western side of Svalbard, but considerably larger than the other tracks at the Boltodden locality. In a review of iguanodontid tracks, Sarjeant *et al.* (1998, p. 200) stated that the ornithopod tracks from Festningen are morphologically distinct from other iguanodontid tracks but were made by a similar, albeit different, trackmaker. They diagnosed *Iguanodontipus* as:

> Tridactyl pedal imprints of a dinosaur, semidigitigrade, all three digits being of similar length. Central digit (III) directed forward and approximating to an equilateral triangle in shape. Digits II and IV directed almost laterally; they are somewhat less broad and have the form of isosceles triangles with rounded to sub-acute distal ends. Posterior of sole smoothly curved or very slightly flattened. Claws not defined. Trackway narrow: stride long.

Díaz-Martínez *et al.* (2015, p. 23) left only the species *Iguanodontipus burreyi* in the genus and emended the diagnosis to:

> Tracks belonging to Iguanodontipodidae with a small heel impression that is rounded, centered and narrow (as wide as the width of the proximal part of the digit III impression); long, narrow digit impressions with sharp distal ends.

This fits well with the morphology of the morphotype C track, but measurements of *Iguanodontipus burreyi* indicate that the length and width of the tracks varies from 23 to 30 cm and the interdigital angles from 35° to 50° (Sarjeant *et al.* 1998).

The Boltodden track morphotype C is larger than this (35 × 41 cm), and has a narrower interdigital divarication (30°). This suggests two alternatives. It may represent a juvenile individual of the ichnotaxon described from Festningen (Hurum *et al.* 2006) or indicate the presence of a new ornithopod

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taxon in the Barremian of Svalbard. Given that we currently have only a single well-preserved track and that it seems unlikely to have multiple co-existing species of medium-sized ornithopods in the Barremian of Svalbard, we refrain from naming a new taxon and, instead, refer this to *Caririchnium* sp., which is currently the only valid ornithopod ichnogenus recognized during this interval (Díaz-Martínez *et al.* 2015).

Conclusion

The Barremian tracksite at Boltodden, Svalbard presents an important high-latitude dinosaur tracksite, which we reinterpret as made by ornithopods rather than a theropod, as previously described. The ornithopod prints were formed while the animals walked along a lake margin or on a beach within an interdistributary bay. Mud deposited from river flooding or raised water/sea level preserved the tracks. We assign the tracks of the smaller (A, B) morphotype to to *Caririchnium billsarjeanti* and refer the larger morphotype (C) to *Caririchnium* sp.

Both morphotypes appear to be morphologically distinct from the tracks at Festningen, in western Spitsbergen. The occurrence of a quadrupedal, small to medium-sized ornithopod in Svalbard is puzzling, considering the palaeogeography and that such dinosaur tracks have mainly been described from Europe, but not from North America.

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