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New Avian tracks from the lower to middle Eocene at Fossil Hill, King George Island, Antarctica

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Abstract: Trace fossils are long known to exist in the Fossil Hill Formation (lower to middle Eocene) at Fildes Peninsula, King George Island, Antarctica. During fieldwork in 2009, abundant new avian tracks were recovered, which are analysed here. Three avian ichnotaxa are distinguished. The most common impressions are tridactyls and tetradactyls with slender digit imprints II–IV and a posterior hallux. They are included in the ichnogenus *Gruipeda*. In addition tridactyl and tetradactyl footprints with short and thick digit impressions are conferred to *Uhangrichnus*. The third ichnotaxon is a tridactyl impression with broad and short digits assigned to *Avipeda.* The latter taxon is here documented for the first time from Antarctica. These avian tracks are preserved in volcaniclastic sediments consisting in reddish-brown layers of mudstone intercalated with coarse sandstone. The sequence represents lacustrine environments which seasonally dried and were episodically refilled.

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Key words: avian footprints, Cenozoic, Gondwana, ichnotaxonomy

Introduction

Invertebrate traces are widely known from Antarctica from Paleozoic (e.g. Gevers *et al*. 1971), Mesozoic (e.g. Scasso *et al*. 1991, Miller *et al*. 2001) and Cenozoic rocks (e.g. Covacevich & Lamperein 1972, Yang & Shen 1999, Fielding *et al*. 2000, Nelson *et al*. 2008, Miller *et al*. 2009). Vertebrate trace fossils, on the other hand, are extremely rare, and the record is presently restricted to dicynodont footprints described from the Early Triassic Fremouw Formation (MacDonald *et al*. 1991), and avian tracks from the Eocene Fossil Hill Formation, at its type locality, Fossil Hill on King George Island (Covacevich & Lamperein 1969, 1970, 1972, Covacevich & Rich 1982, Li & Zhen 1994). Here we present, describe, and analyse new avian tracks from the Fossil Hill locality, Antarctica, and integrate these data to the previous ichnological remains.

Location and geological setting

The Fossil Hill locality is at a small elevation above sea level, located on Fildes Peninsula of King George Island, South Shetland Islands, Antarctica (62°10'50"S–62°11'28"S, 58°55'27"W–58°56'38"W; Fig. 1). The ichnological site has been known since the end of the 1960s for its abundant and well preserved palaeobotanical and ichnofossil remains (e.g. Covacevich & Lamperein 1969, 1970, 1972, Covacevich & Rich 1982, Li & Zhen 1994, Yang & Shen 1999). As a result of the unusually rich fossil content, the area was declared an Antarctic Specially Protected Area (ASPA), No. 125 (ATCM 2009). All trace fossils reported to date were recovered from the Fossil Hill Formation (Smellie *et al.* 1984, Fontes & Dutra 2010), a sedimentary unit which belongs to the Fildes Peninsula Group (Hawkes 1961).

The trace fossil bearing section, located in the lower unit of the Fossil Hill Formation, was previously named Unit 1 by Covacevich & Lamperein (1972), and as Bed 2 by Xue *et al*. (1996). It consists of grey-yellow, coarse-grained tuffaceous sandstone interlayered with reddish brown mudstone forming units of up to 100 cm thickness (Fig. 2). The section is characterized by "window lattice-like" structures, which indicate tectonic stress after diagenesis (Xue *et al*. 1996). Supported by the sedimentological evidence and petrological analysis such as a low content of boron, Xue *et al*. (1996) dismissed a marine interpretation for theses sediments, but proposed deposition in an intermontane lake with intermittent and rapid deposition by volcanic and seasonal floods.

Palaeobotanical remains at Fossil Hill consist of abundant wood, leaf imprints and palynomorphs (e.g. Cao 1992, Poole *et al*. 2001, Li & Zhou 2007, Fontes & Dutra 2010). The analyses suggest that the area was covered by forests dominated by gymnosperms, with shadow-tolerant angiosperms growing in the understory, in environments of low disturbance (Poole *et al*. 2001). The vegetation suggests that the climate was wet, and warm to cool, similar

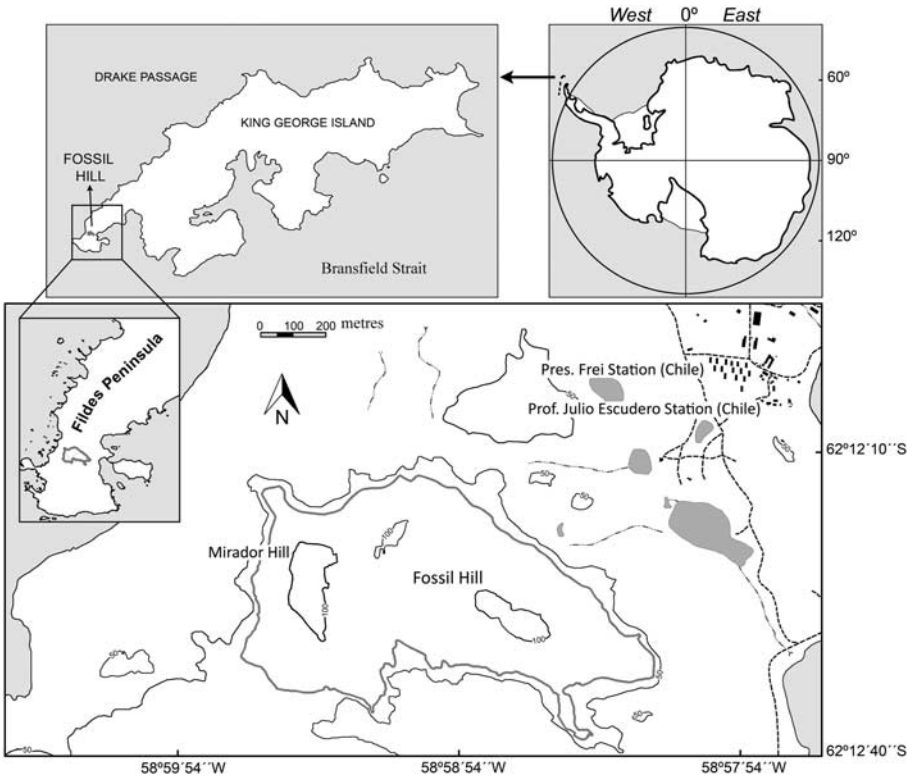

Fig. 1. Map of the Fildes Peninsula, King George Island, Antarctica, showing the location of the Fossil Hill site. The location of detailed study area is modified from ATCM (2009).

to other Eocene localities from Antarctica (Poole *et al*. 2001, and references cited therein).

Radiometric ages of the Fossil Hill Formation (e.g. Shen 1994) together with the palynological and floral records of the locality (Cao 1992, Li 1994), constrain the age of the unit to the lower to middle Eocene.

Material and methods

The material was discovered by two of the authors (HGM, MAL) during the 2009 Instituto Antártico Chileno (INACH) field campaign to King George Island. Vertebrate trace fossils described here are represented by moulds and casts.

Table I. Summary of measurements on the preserved footprints. Linear measurements are expressed in millimetres and angles in degrees.

Ichnotaxa	*Gruipeda fuenzalidae*				*Avipeda isp.*		*cf. Uhangrichnus*	
Specimens	CPAP 16–35				CPAP 37–39		CPAP 40 & 41	
	mean	min	max	*n*	mean	*n*	mean	*n*
L	24.6	22.2	33.0	18	31.3	1	70.3	2
W	26.7	21.3	31.1	19	31.5	2	68.8	2
I	6.4	3.7	8.3	8	-		25.0	1
II	12.3	10.2	14.6	16	17.3	2	29.4	1
III	17.2	14.6	22.0	19	18.0	3	59.0	1
IV	13.5	11.4	16.2	13	17.6	2	33.8	1
II-III	51	35	65	16	34	1	53	1
III-IV	54	45	65	12	43	1	48	1
II-IV	103	90	117	17	72	2	100	1
I-III	151	130	162	8	96	1	-	
P	73.8	40.4	100.1	3	88.7	1	-	
SL	181.1	-	-	1	-		-	
PA	155	-	-	1	-		-	

L = footprint length, distance between the distal tips of digit III and the proximal boundary of the sole; W = footprint width, distance between the distal tip of digits II and IV measured perpendicular to the footprint axis; I, II, III, and IV = length of digit imprints I, II, III, and IV; II-III = angle formed by the axis of digits II and III; III-IV = angle formed by the axis of digits III and IV; II-IV = angle formed by the axis of digits II and IV; I-III = angle formed by the axis of digits I and III; PA = pace angulation, angle formed by the segments joining corresponding points of three consecutive tracks; P = pace, distance between the same point of two consecutive tracks of opposite side of the trackway; SL = stride length, distance between the same point of two consecutive tracks on the same side of the trackway.

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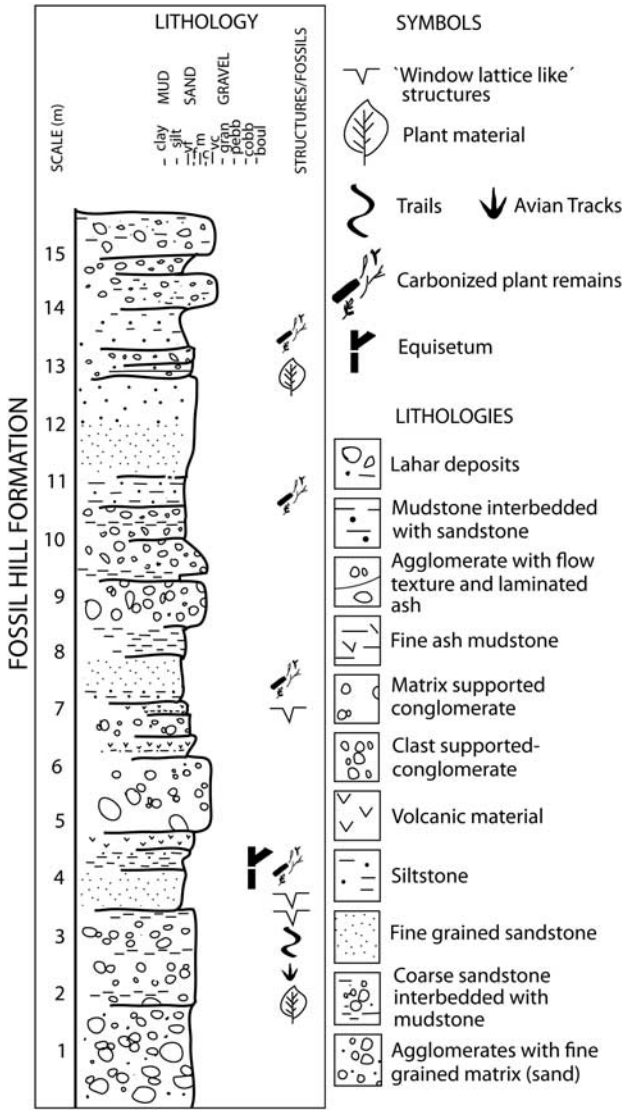

Fig. 2. Stratigraphic column of the Fossil Hill Formation, showing the avian footprints bearing section.

They are preserved in a reddish brown fine tuffaceous sandstone forming slabs of 10–20 cm thickness. They are housed in the Laboratorio de Palaeobiología of the INACH in Punta Arenas, as a part of the Colección Paleontológica de Cerro Fósil (CPCF). The data are summarized in Table I.

Ichnotaxonomic assignment of the material follows Bertling *et al*. (2006), de Valais & Melchor (2008), and Lockley & Harris (2010), among other references. Some morphological types are left in open nomenclature, as a result of insufficient preservation or indistinctive morphological features.

Systematic ichnology

Avipeda Vialov, 1965

Type ichnospecies. *Avipeda phoenix* Vialov, 1965, p. 112, pls 13–14.

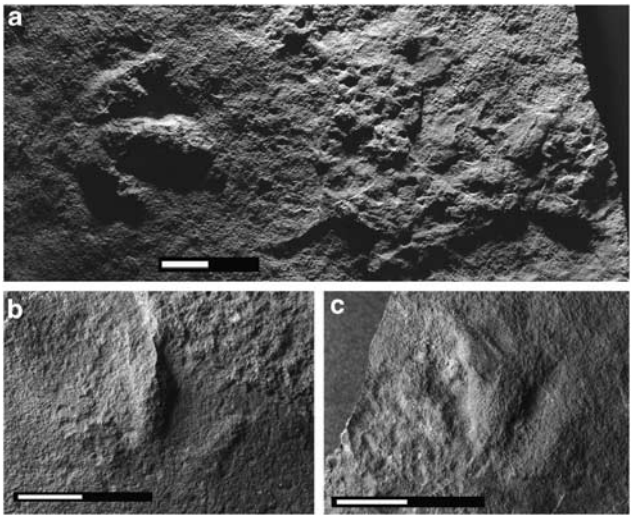

Fig. 3. Photographs of specimens of *Avipeda* isp. **a.** CPAP 39, **b.** CPAP 37, and **c.** CPAP 38. Scale bar: 2 cm.

Diagnosis. Avian footprints of small to large size, showing three short, thick digits, with distinct claws. Length of central digit (III) < 25% greater than that of the lateral digits. Total interdigital span 95° or less. Digits closely

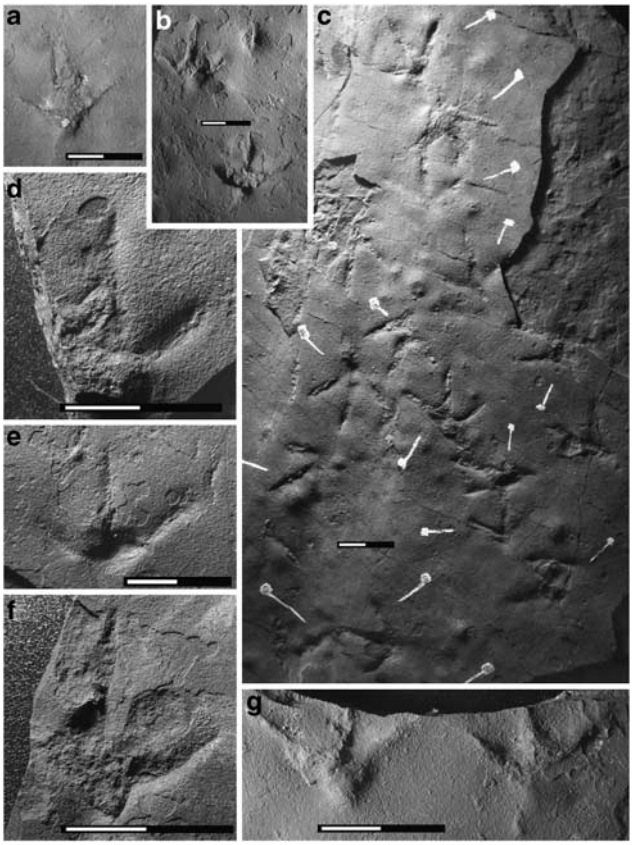

Fig. 4. Photographs of specimens of *Gruipeda fuenzalidae*. **a.** CPAP 20, **b.** CPAP 25, **c.** CPAP 36, **d.** CPAP 22, **e.** CPAP 29, **f.** CPAP 17, and **g.** CPAP 21. Scale bar: 2 cm.

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convergent or united proximally; webbing lacking or limited to the most proximal part of the interdigital angles (Sarjeant & Langston 1994, p. 12).

Remarks. Vialov (1965) named the ichnotaxon *Avipeda* as a term for all fossil bird tracks. Subsequently, however, Sarjeant & Langston (1994) amended and redefined the ichnogenus to embrace tridactyl tracks with thick digit impressions and without webbing marks. Their suggestion is followed here.

Avipeda isp.
Fig. 3

Material. CPAP 37, 38, and 39. The specimens are represented by two isolated tridactyl footprints (Fig. 3b & c) and two probably associated imprints, forming a partial trackway (Fig. 3a).

Description. The footprints are subequal in length and width (average length and width of 31.3 mm and 31.5 mm respectively). No sole mark is preserved and the proximal ends of the impression of the digits are not in contact. The impressions of the digits are thick, with a maximum width of 8 mm. They are straight and directed laterally. They lack distinguishable claw and digital pad marks. The imprints of the digits III, IV and II are subequal in length, in decreasing order, 18.0 mm, 17.6 mm, and 17.3 mm. The angles formed by the digit imprints are, on average, *c.* 34° between II and III, and 43° between III and IV. The average of the total divarication angle is 72°. The only measurable trackway parameter is the length of the pace of the partial trackway, which is *c.* 88.7 mm.

Remarks. The characteristics generally resemble the *Avipeda* ichnogenus, although the absence of certain specific features, such as the claw marks, is probably due to a preservational bias. Based on the general morphology, the Fossil Hill specimens resemble *Avipeda aduncа* Sarjeant & Langston, 1994, but the scarce available material precludes an ichnospecific assignment.

Gruipeda Panin & Avram, 1962

Type ichnospecies. *Gruipeda maxima* Panin & Avram, 1962, p. 465, pl. 7, fig. 25.

Diagnosis. Footprints showing four digits, three of which (II–IV) are directed forward and one of which (the larger, fourth (I)), is directed backward, spur-like and short. The interdigital angles between digits II and III and between digits III and IV are commonly less than 70°. The axis of digit I does not correspond with that of digit III, the interdigital angle between digits I and II is smaller than that between digits I and IV. When present, phalangeal pad marks displaying the relation I: 2, II: 2, III: 3, IV: 4. Webbing absent (de Valais & Melchor 2008, p. 152).

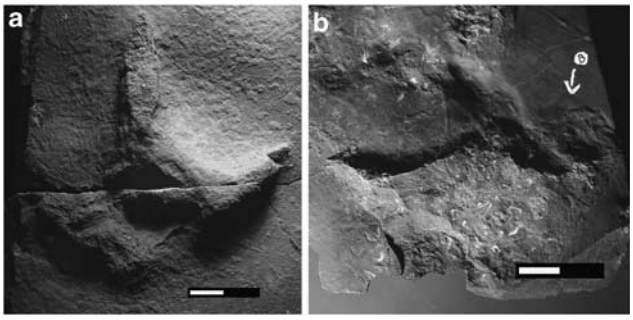

Fig. 5. Photographs of specimens of cf. *Uhangrichnus*. **a.** CPAP 40, and **b.** CPAP 41. Scale bar: 2 cm.

Remarks. The ichnogenus *Gruipeda* Panin & Avram, 1962, was erected mainly on the basis of the purported trackmaker. Sarjeant & Langston (1994) revised and emended the original diagnosis to embrace tridactyl or tetradactyl tracks, with slender and spread digit impressions and without webbing marks. This suggestion is followed here.

Gruipeda fuenzalidae (Covacevich & Lamperein, 1970) nov. comb.
Fig. 4

Material. CPAP 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, and 35. The specimens are represented by several isolated footprints, two probably associated imprints in a partial trackway, and a trackway accounting for three tracks.

Description. The footprints are tridactyl or tetradactyl when the hallux (digit I) imprint is present. In that case, the arrangement is anisodactyl, with the impression of the hallux directed posteriorly and not aligned with the impression of the digit III. The footprints are between 22.2 mm and 33.0 mm long, with an average length of 24.6 mm. Their width ranges between 21.3 mm and 31.1 mm, with an average width of 26.7 mm. The average length of the impression of the digits III, IV, II, and I are, in decreasing order, 17.2 mm, 13.5 mm, 12.3 mm, and 6.4 mm. All digit imprints are united proximally. The digit impressions display acuminate distal tips, although no clear claw marks are preserved. Digital pad impressions and webbing marks are absent.

The average angle of divarication between the impressions of the digits II and III and of the digits III and IV are 51° and 54°, respectively. The angle formed by the hallux and the digit III imprint is *c.* 151°.

Only one trackway with three tracks and a partial trackway are preserved. The pace angulations is 155°, the stride length is 181.1 mm, while the average pace length is 73.8.

Remarks. Antartichnus fuenzalidae was created by Covacevich & Lamperien (1970) to include tridactyl or tetradactyl avian footprints, with the impression of digits II,

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III and IV of subequal shape and size but with a short impression of digit I, and the axis of digit I directed posteriorly. Subsequent studies carried out by de Valais & Melchor (2008) caused them to consider the ichnogenus as a junior synonym of *Gruipeda.*

Fildesichnus sheni Li & Zhen, 1994, from the Fossil Hill Formation, was named based on a single tridactyl slender-toed avian-like footprint. It is indistinguishable from the rest of the specimens and is here considered to be a junior synonym of *Gruipeda fuenzalidae*.

Uhangrichnus Yang *et al*., 1995
emend. Mansilla *et al*., nov.

Type ichnospecies. *Uhangrichnus chuni* Yang *et al*., 1995, p. 22, figs 3–5.

Emended diagnosis. Tridactyl tracks showing clear evidence of webbing between digits II–IV. Hallux impressions absent. The tracks are wider than long. The divarication angles between digits II–IV are commonly *c.* 100°. Digits II and IV are slightly curved inward rather than straight. The anterior margin of both web impressions between digits II and III, and III and IV is slightly concave anteriorly rather than straight or only slightly concave (modified from Yang *et al*. 1995, p. 22).

cf. *Uhangrichnus* Yang *et al*., 1995
Fig. 5

Material. CPAP 40 and 41.

Description. CPAP 40 is a tetradactyl preserved as natural cast (Fig. 5a), while CPAP 41 is a poorly preserved tridactyl track preserved as a natural mould in negative epichnia (Fig. 5b), both with short and thick digit impressions.

CPAP 40 is a footprint of 7 mm depth; both surfaces of the slab display some parts of the track. On the upper surface of the slab, most of the distal section of the digit imprint I is preserved as negative epichnia, indicating that the producer digit I is located above of the rest of the digits. The lower surface (Fig. 5a) presents the rest of the track as positive hypichnia, i.e. the impressions of digits II, III, IV and the sole mark. The length of the impressions of digits III, IV and II are, in decreasing order, 59.0 mm, 33.8 mm (incompletely preserved), and 29.4 mm; the length of the digit impression I is estimated at 25.0 mm. The angle between the impressions of the digits II and III is 53°, and between digits III and IV 48°, while the total angle divarication is 100°. The hallux impression is posteromedially directed, even though the angle formed with the digit imprint III is not known with precision.

The footprints have an average length of 70.3 mm and width of 68.8 mm. The impressions of the digits II–IV are united proximally; most of the width corresponds to claw imprints. Digit imprints II and IV are slightly curved inward. The webbing impression is limited to the base of digits, and the sole mark displays a rhomboid outline.

Remarks. Covacevich & Rich (1982) reported two trackways accounting for eight footprints described as "Morphotype II", with the same general morphological characteristics as those of our material. We suggest they belong to the same ichnotaxon. We provisionally refer all the specimens mentioned herein to *Uhangrichnus* Yang *et al*., 1995. Specimens known to belong to *Uhangrichnus* do not display a hallux imprint. The hallux impression observed in the Fossil Hill material was detected in a sediment level slightly overlying the other digits, suggesting that hallux marks may not have been recognized previously due to preservational bias.

Discussions and conclusions

The ichnological assemblage discovered so far at Fossil Hill locality is composed of simple invertebrate traces (i.e. *Skolithos*, *Helmintoidichnites*, *Gracilichnus*; Yang & Shen 1999), arthropod traces (Covacevich & Lamperein 1972), and avian footprints assigned to three different ichnotaxa, *Gruipeda fuenzalidae*, *Avipeda* isp., and cf. *Uhangrichnus,* in addition to two groups of bird tracks described informally as "Morphotype I" and "Morphotype III" (Covacevich & Lamperein 1969, 1970,1972, Covacevich & Rich 1982, Li & Zhen 1994). Two badly preserved tracks referred to "Morphotype I" are large tridactyls, and have been assigned to ratites or phororhacoids (Covacevich & Rich 1982). "Morphotype III" is more abundant (nine tracks) and resembles the ichnogenus *Alaripeda* Sarjeant & Reynolds, 2001, based on criteria established by de Valais & Melchor (2008). It is important to note that all avian tracks were discovered in a single layer of 150 cm thickness, which suggests that at least five different kinds of birds gathered in this place.

Antarctica has yielded abundant avian fossil bones, but these are restricted to James Ross Island (e.g. Chavez 2007, Tambussi & Acosta Hospitaleche 2007, and references therein) and Isla Marambio (Seymour Island) (Acosta Hospitaleche & Di Carlo 2010, Hospitaleche & Reguero 2010). They were discovered in the Maastrichtian López de Bertodano Formation, the late Paleocene Cross Valley Formation, and in the late Eocene La Meseta Formation.

Avian tracks from the Fossil Hill Formation extend the avian record some 200 km to the north and fill the stratigraphical gap between lower to middle Eocene. In some cases, a relationship can be established between the record of fossil bones and tracks of Antarctic birds. For instance, "Morphotype I" tracks have been identified as Ratites or Phorusrhacidae indet. Bones of these group birds were discovered in the La Meseta Formation (late Eocene) of Isla Marambio (Van Tuinen *et al*. 1998) and in the López de Bertodano Formation (Late Cretaceous) of Vega

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Island (Case *et al*. 2006). Tracks described here as cf. *Uhangrichnus* ("Morphotype II") appear to be related to Anseriformes. Fossil remains of these water birds are known from the Maastrichtian López de Bertodano Formation (Clarke *et al*. 2005). Producers of tracks assigned to *Gruipeda*, *Avipeda* and cf. *Alaripeda* ("Morphotype III"), on the other hand, have not been identified to date.

During the early Paleogene, Antarctica was still united with other Gondwana continental blocks. Ratite birds or Phorusrhacidae must have used Antarctica as routes of dispersion. The ichnological evidence of big cursorial birds in the Paleogene of Antarctica agrees with the fragmentary fossil records of Ralliformes and Ratites on that continent (Chavez 2007, Tambussi & Acosta Hospitaleche 2007).

At Fossil Hill, the combination of invertebrate trace fossils, ripple marks, palaeobotanical remains, and avian footprints, indicates deposition on the banks of a shallow lake. This interpretation is not contradicted by the avian track record. An interpretation of the assemblage as shorebird ichnofacies (Lockley *et al*. 1994), on the other hand, is premature and only supported by the positive identification of Anseriformes.

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