Memoirs of Museum Victoria 74: 63–71 (2016) Published 2016

ISSN 1447-2546 (Print) 1447-2554 (On-line)
http://museumvictoria.com.au/about/books-and-journals/journals/memoirs-of-museum-victoria/

A close look at Victoria's first known dinosaur tracks

Anthony J. Martin

Department of Environmental Sciences, Emory University, Atlanta, Georgia 30322 USA (geoam@emory.edu)

Abstract

Martin, A.J. 2016. A close look at Victoria's first known dinosaur tracks. *Memoirs of Museum Victoria* 74: 63–71.

Lower Cretaceous (Aptian-Albian) rocks of Victoria, Australia are well known for their dinosaur body fossils, but not so much for their trace fossils. For example, the first known dinosaur track from the Eumeralla Formation (Albian) of Knowledge Creek, Victoria, was not discovered until 1980. This specimen, along with two more Eumeralla tracks found at Skenes Creek in 1989, constituted all of the dinosaur tracks recognised in Lower Cretaceous strata of southern Australia until the late 2000s. Unfortunately, none of these first-known dinosaur tracks of Victoria were properly described and diagnosed. Hence, the main purpose of this study is to document these trace fossils more thoroughly. Remarkably, the Knowledge Creek and one of the Skenes Creek tracks are nearly identical in size and form; both tracks are attributed to small ornithopods. Although poorly expressed, the second probable track from Skenes Creek provides a search image for less obvious dinosaur tracks in Lower Cretaceous strata of Victoria. The Skenes Creek tracks were also likely from the same trackway, and thus may represent the first discovered dinosaur trackway from Victoria. These tracks are the first confirmed ornithopod tracks for Victoria, augmenting abundant body fossil evidence of small ornithopods ('hypsilophodontids') in formerly polar environments during the Early Cretaceous.

Keywords Cretaceous, dinosaur, footprint, ichnology, ornithopod, trace fossil, track.

Introduction

Victoria is world famous for its dinosaur body fossils, which reflect the best-documented polar-dinosaur assemblage in the Southern Hemisphere (Rich et al., 2002; Rich and Vickers-Rich, 2003; Kear and Bruce, 2011; Benson et al., 2012). The first known dinosaur body fossil in Victoria, a theropod ungual from the Wonthaggi Formation (Aptian) found by William Ferguson in 1903, was also the first Australian dinosaur fossil known to science (Rich and Vickers-Rich, 2000; Rich and Vickers-Rich, 2003). However, dinosaur trace fossils, such as tracks, nests, burrows, and other direct evidence of dinosaur behavior in the Cretaceous rocks of Victoria remained unnoticed by palaeontologists until 1980, 77 years after the first recognised body fossil. This ichnological drought ended when Thomas H. Rich and Patricia Vickers-Rich discovered and collected a dinosaur track from the Eumeralla Formation (Albian) at Knowledge Creek, Victoria (Rich and Vickers-Rich, 2000) (fig. 1).

Another eight years passed before two more dinosaur tracks were noticed in a Eumeralla Formation stratum at Skenes Creek in early 1989. In 2006, I recognized two large theropod tracks in the Wonthaggi Formation at the Flat Rocks ("Dinosaur Dreaming") dinosaur dig site, near Inverloch, Victoria; Tyler Lamb then found another at the same site in 2007 (Martin et al., 2007). Three years later, the largest assemblage of polar-dinosaur tracks in the Southern Hemisphere – made by small- to moderate-sized theropods – was discovered in the Eumeralla Formation at Milanesia Beach (Martin et al., 2012). Recently, closely associated tridactyl and tetradactyl tracks were described from Dinosaur Cove, and were interpreted as non-avian theropod and avian in origin, respectively (Martin et al., 2014). Otherwise, the only other trace fossils ascribed to non-avian dinosaurs in Lower Cretaceous strata of Victoria include possible burrows (Martin, 2009). Nests, toothmarks, gastroliths, coprolites and other such trace fossils apparently have not yet been discovered (Martin, 2014).

The Knowledge Creek track has been figured in numerous publications, and was much reproduced for educational purposes (Rich and Vickers-Rich, 2000, 2003). However, it and the Skenes Creek tracks have not been described nor interpreted in detail. Thus the main purposes of this study are to: (1) thoroughly document these tracks; (2) interpret their dinosaur makers and preservational modes; (3) assess the palaeontological importance of the tracks; and (4) suggest how this information might be used to prospect for more such tracks in Lower Cretaceous strata of Victoria.

Methods

The three specimens are in the Museum Victoria Palaeontology Collection (NMV P); thus they are available for further study by qualified researchers. I measured the tracks with Mitutoyo digital calipers, using minimum-outlines for track widths, lengths, and other parameters (fig. 2). Digit-impression lengths

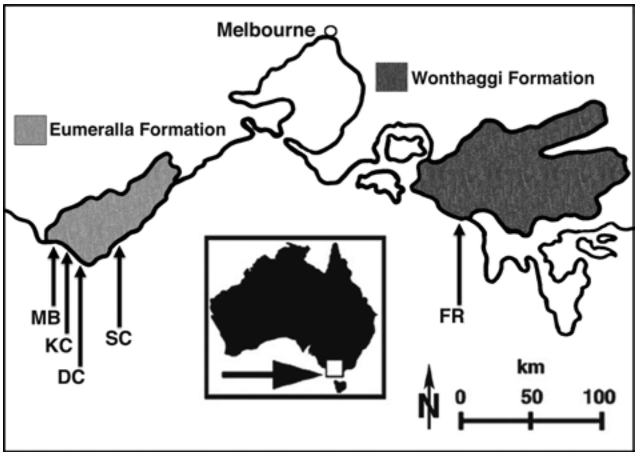

Figure 1. Locality and outcrop map for Early Cretaceous dinosaur tracks found thus far in Victoria, with the three tracks described in this study coming from Knowledge Creek and Skenes Creek. Key and latitude-longitude coordinates for each of the tracksites, from east to west: Flat Rocks (FR), S38° 45.3', E145° 40.9'; Skenes Creek (SC), S38° 42.9', E143° 44.4'; Dinosaur Cove (DC), S38° 46.9', E143° 24.3'; Knowledge Creek (KC), S38° 45.3', E143° 20.9'; Milanesia Beach (MB), S38° 45.3', E143° 19.3'.

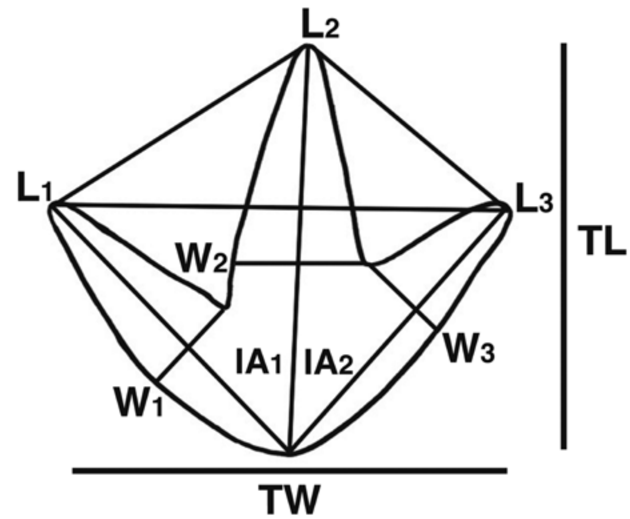

Figure 2. Track parameters measured in this study. Key: TW = total width; TL = total length; L1-L3 = digit lengths; W1-3 = digit widths; IA1-IA2 = interdigital angles. Anterior triangle defined by total track width (base of the triangle) and middle-digit length measured from that base.

were measured from the midline of each digit, and digit-impression widths were taken perpendicular to this midline and medially along the length of each impression. Interdigital angles were measured with a circular protractor, using a digit-impression axis radiating from a single point on the rear margin of the track, as depicted by Thulborn (1990, fig. 4.5). The anterior triangle length:width ratio (*sensu* fig. 2 in Lockley, 2009) was derived from measuring the base of a triangle, defined by the width between the lateral digit impressions and the length of the middle digit impression from that base. Semiquantitative and qualitative information, such as the host lithology and other descriptive traits of the tracks, were also noted. All data are provided here and summarized (table 1) so that future investigators may examine, test, or otherwise attempt to correct the results reported here.

Descriptions

Knowledge Creek Track. On December 18, 1980, Thomas Rich and Patricia Vickers-Rich discovered the Knowledge Creek track, cataloged as NMV P159790 (fig. 3, Appendix I). The track was located on a marine platform just above sea level and about 100 m east of Knowledge Creek. Rich and Vickers-Rich used hand chisels and rock hammers to extract and collect the track, which they brought to the museum.

The track is in a very fine-fine lithic arenite, although the track itself is filled with fine-coarse, moderately sorted quartz and lithic sand held together with hematitic cement. The bed is 36-47 mm thick and horizontally laminated in cross section, with no apparent disruptions of bedding by bioturbation. The area surrounding the track is flat, and lacks other physical or biogenic sedimentary structures on this surface. The track is preserved as a nearly flat but positive-relief (raised) epichnion, rather than a depression. It was weathered such that its form is expressed in nearly full relief.

The track is tridactyl and mesaxonic. It is almost equant in length and width: 106 mm long and 118 mm wide, with a length:width ratio of 0.90. The anterior triangle length:width ratio is 0.40, with a base (width) of the triangle of 118 mm and length from that base of 47 mm. Outermost digit impressions were 90 mm and 84 mm long (left and right, respectively), and the central impression is also the length of the track, 106 mm. Medial thicknesses of the three digit impressions, measured perpendicular to the long axis of each digit, are from left to right: 25 mm, 31 mm, and 30 mm. Using an average of 29 mm, digit-impression widths are about 27% of footprint length. Divarication between the outermost digit impressions is 85°, which combines an angle of 47° between the left and middle, and 38° between the right and middle. All three impressions are outlined completely. Digit impressions narrow distally, but are subrounded at their ends. The track bears three small, oval protuberances, two on the middle digit impression and one on the left. These structures on the middle impression are 4 x 8 mm wide (toward the distal end) and 4 x 5 mm wide (at the right intersection with the right impression), whereas the one on the left impression is 5 x 5 mm (outer edge). Each structure is labeled as "B" (for "burrow") on fig. 3b.

The sand fill varies from 4 mm thick at the posterior "heel" (proximal) end of the track to 8-10 mm thick at the anterior (distal) ends of each digit impression (fig.3c,d). Thus a longitudinal profile of the track would show a gradual thickening of the sand fill from posterior to anterior. A 1-mm thick, slightly curved thread-like structure, filled with the same reddish sand as the track, cross-cuts the grey lithic arenite below the right posterior portion of the track (fig. 3c).

Table 1. Measurements of dinosaur tracks from: Knowledge Creek (KC1), specimen P.159790; and Skenes Creek (SC1 and SC2), specimen P.208232. Key: L = length, W = width, L:W = length:width, IA1 = left-middle interdigital angle, IA2 = middle-right interdigital angle, D = divarication (interdigital angle between left and right), L1 = left digit length, L2 = middle digit length (same as track length), L3 = right digit length, W1 = left digit width, W2 = middle digit width, W3 = right digit width, at-L = anterior triangle length, at-W = anterior triangle width, at-L:W = anterior triangle length:width, n/a = not applicable. All measurements are in millimeters except for IA1, IA2, and D, which are in degrees.

Track	L	W	L:W	IA1	IA2	D	L1	L2	L3	W1	W2	W2	at-L	at-W	at-L:W
KC1	106	118	0.90	47°	38°	85°	90	106	84	25	31	30	47	118	0.40
SC1	106	115	0.92	37°	46°	83°	91	106	87	n/a	34	36	43	115	0.37
SC2	127	138	0.92	44°	27°	71°	102	127	103	n/a	n/a	n/a	43	138	0.31

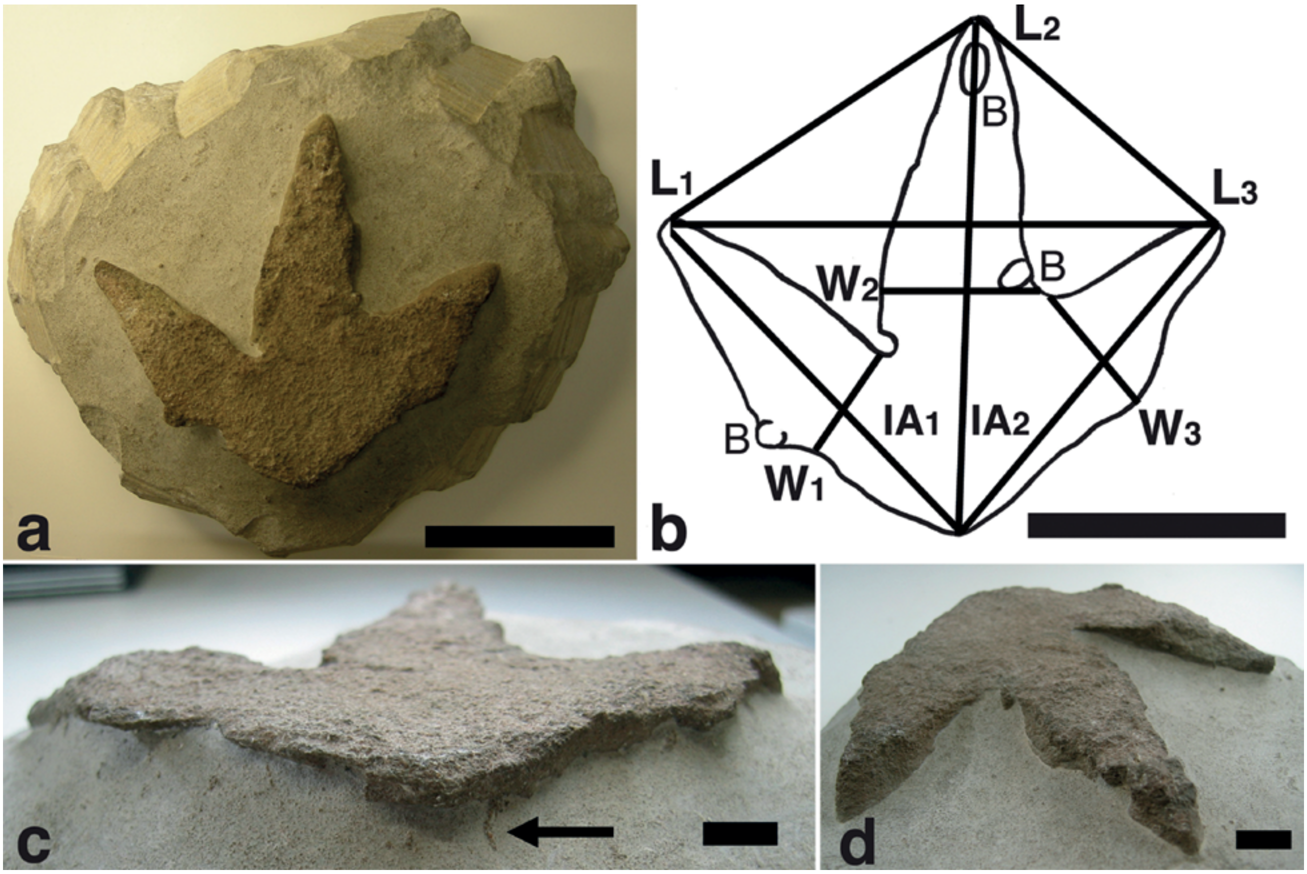

Figure 3. Knowledge Creek track, NMV P159790. a. Overall top view of track in collected slab, with bedding and chisel marks evident along edge; scale = 5 cm. b. Outline of track and parameters measured, with anterior triangle indicated (see Figure 2 for key), B = invertebrate burrows; scale = 5 cm. c. Posterior-edge view of track, showing full relief of track, thin fill of coarse sand, and possible small burrow below (arrow); scale = 1 cm. D. Anterior-oblique view of track, showing gradually thicker sand fill toward distal ends of digits; scale = 1 cm.

Skenes Creek Track 1. Helmut Tracksdorf, a local citizen and geologist from the Skenes Creek area, discovered two dinosaur footprints there in January 1989, with both cataloged as NMV P208232 (figs. 4-5, Appendix I). Tracksdorf alerted Museum Victoria about them, and personnel from the Museum collected the tracks on March 18, 1989. Although no additional information is available about who collected or cataloged these tracks, the exact field location of the tracks was just recently verified, having come from the supratidal marine platform of rock exposed between Skenes Creek and Browns Creek (Appendix II).

The most clearly defined of the two tracks (herein designated Skenes Creek Track 1) is in a 16 x 20 cm cut slab of very fine-fine, well-sorted lithic arenite. The bed is 25-41 mm thick, with seven parallel and symmetrical ripples sharing the top surface with the track. Assuming an arbitrary “north”

Figure 4. Skenes Creek Track 1, NMV P208232. a. Overall top view of track in collected slab, with rock saw cuts evident on three sides, as well as symmetrical and parallel ripple marks below track; scale = 5 cm. b. Close-up of track, showing raised relief and thin, laminated "platform" above ripple marks; scale = 5 cm. c. Outline of track and parameters measured, with anterior triangle indicated (see Figure 2 for key); scale = 5 cm.

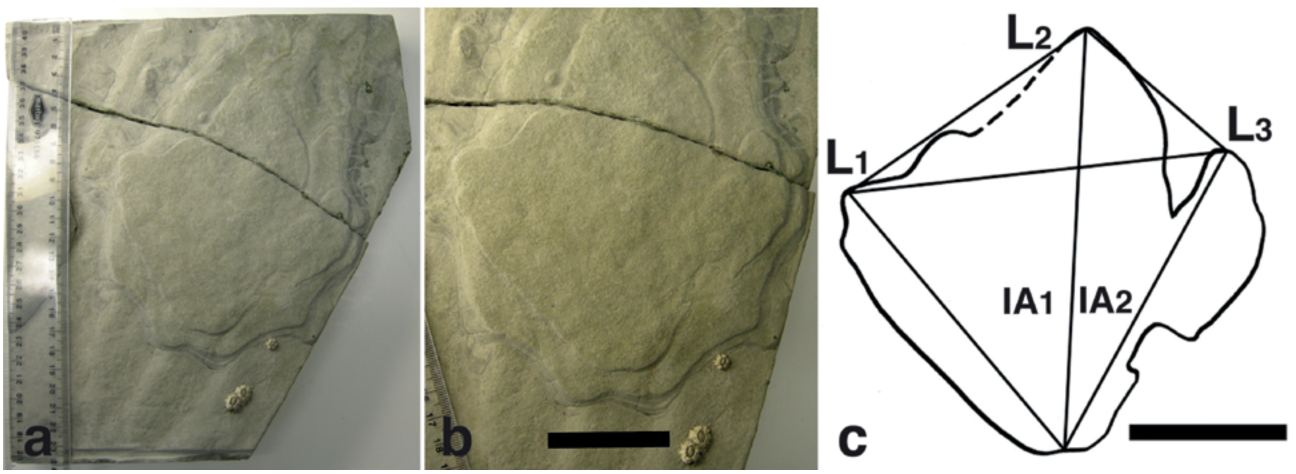

Figure 5. Skenes Creek Track 2, NMV P208232 (shared with Track 1). a. Overall top view of track in collected slab, with rock saw cuts evident on five sides and fracture cutting across anterior part of track; scale (left) in centimetres and millimetres. b. Close-up of track, showing raised relief and thin, laminated "platform" above ripple marks; scale = 5 cm. c. Outline of track and parameters measured, with anterior triangle indicated (see Figure 2 for key); scale = 5 cm.

defined by the axis of the middle digit impression, ripple-crests trend "northeast-southwest." Ripples have amplitudes of 4-7 mm and wavelengths of 30-40 mm; ripple bedding was also evident in cross-section. The track is preserved as a nearly flat, 1-2 mm thick positive-relief (raised) epichnion, but is filled with sand texturally and compositionally identical to the main host lithology. It is circumscribed and somewhat mimicked in outline by a 4-8 mm thick quadrilateral platform between it and the rippled surface. Bedding in the track and its platform is mostly planar and laminated, although slight variations in surface topography synch with underlying ripples.

The track is tridactyl, mesaxonic, and nearly equant in length and width, at 106 mm long and 115 mm wide; this results in a length:width ratio of 0.92. Outermost digit impressions were 91 mm and 87 mm long (left and right, respectively), and the central impression is the length of the track, 106 mm. The right impression has a seemingly complete outline, whereas the left is apparently expressed partially. The anterior triangle length:width ratio is 0.37, with a base (width) at 115 mm and length measured from that base of 43 mm. Medial thicknesses of the two complete digit impressions are, from middle to right, 34 and 36 mm. With an average of 35 mm, digit-impression widths are about 33% of footprint length. Divarication between the outermost impressions is 83°, which combines an angle of 37° between the left and middle, and 46° between the right and middle. Both the middle and right digit impressions narrow distally, but are subrounded at their ends. An unidentified modern barnacle is attached to the lower right-side edge of the track.

Skenes Creek Track 2. This probable dinosaur track (herein called Skenes Creek Track 2) was also cataloged as part of NMV P208232 (fig. 5, Appendix I). Based on its same specimen number and having many identical sedimentary traits as the Skenes Creek Track 1, I conclude that it was also discovered by Helmut Tracksdorf in 1989, then later collected from the same marine-platform bedding plane by Museum of Victoria personnel at the same time as Skenes Creek Track 1. This supposition is supported by two adjacent rock-saw cuts at the probable discovery site, which were relocated by Helmut Tracksdorf in 2013 and Mike Cleeland in 2014 (Appendix II).

The track is in a pentagonal slab (cut by a rock saw) with long dimensions of 24 x 21 cm; a fracture runs transversely across the track (fig. 5a). The lithology is identical to that hosting the Skenes Creek Track 1, consisting of a very fine-fine, well-sorted lithic arenite, with a bed thickness of 30-40 mm. The top surface of the bed has six parallel, symmetrical, and low-amplitude ripples underneath the track. Using an arbitrary "north-south" defined by the medial axis of the track, ripple-crests trend "northeast-southwest." Ripples have amplitudes of 5-7 mm and wavelengths of 25-40 mm; ripple bedding was visible in cross-section. Also like Skenes Creek Track 1, it is preserved as an almost-flat, positive-relief epichnion, filled with sand texturally and compositionally identical to that of its host rock. The track is circumscribed by two levels, one about 5 mm above the rippled surface and another inner and topmost level that is about 2 mm thick. Again, like Skenes Creek Track 1, bedding in both upper levels is mostly planar and laminated, with variations in surface topography corresponding with underlying ripples.

Skenes Creek Track 2 is apparently tridactyl, with three rounded points opposite another rounded end, which are assumed as the anterior and posterior parts of the track, respectively. Using this configuration, track length was 127 mm, whereas the width was 138 mm, resulting in a length:width ratio of 0.92. Owing to vague outlines of presumed digit impressions, width measurements were not attempted, but lengths could be measured, yielding 102 mm for the left digit impression and 103 mm for the right. Assuming this configuration, the interdigital angles were 44° (left-middle) and 27° (middle-right), for a divarication of 71°. The anterior triangle length:width ratio was also calculable, yielding a value of 0.31, with the base (width) the same as track width (138 mm) and length measured from that base of 43 mm. The posterior part of the track is slightly indented along its margin, and the lower-level outline just below the measured part of the track is bilobed. Three unidentified modern barnacles are attached on the lowermost bedding surface, all to the lower right of the track, but with one proximal and two more distal.

Interpretations and Discussion

The two most completely preserved tracks from Knowledge Creek and Skenes Creek (Track 1) were very likely pes impressions made by small 'hypsilophodontid' ornithopods akin to *Atlascopcosaurus*, *Fulgurotherium*, or *Leaellynasaura*, all of which are in the Eumeralla Formation (Rich and Vickers-Rich, 1999; Rich et al., 2010). These trace fossils thus constitute the first ornithopod footprints discovered in Lower Cretaceous rocks of Victoria; all others found since the 1980s have been attributed to theropods (Martin et al., 2007, 2012, 2014). The interpretation of tracks as ornithopod tracks is based on track forms, sizes, and their preservation in strata chronologically close to those containing the skeletal remains of these ornithopods in the Eumeralla Formation (Rich and Vickers-Rich, 2003; Kear and Bruce-Hamilton, 2011). The second probable dinosaur track from Skenes Creek (Track 2), although less definite in outline, is also likely from a small ornithopod and comes from the same bed as the other track. Furthermore, it may have been part of the same trackway as the more completely defined track.

The two comparable tracks from Knowledge Creek and Skenes Creek Track 1 are remarkably similar in size and form (Figure 6). Both tracks are tridactyl, presumably reflecting digits II-IV, with digit II-IV divarications of 85° (Knowledge Creek) and 83° (Skenes Creek Track 1). Their lengths and widths are nearly identical, their digit-impression widths vary by only a few millimeters, and middle digit-impression widths (digit III) are 27% and 33% of footprint length (Knowledge Creek and Skenes Creek Track 1, respectively). Moreover, their anterior triangle length:width ratios are nearly convergent, at 0.40 for the Knowledge Creek track and 0.37 for Skenes Creek Track 1. Their expression as positive-relief epichnia, along with the other less completely preserved Skenes Creek ichnite, is also noteworthy, implying their preservational conditions may have been similar as well. However, because the tracks are nearly symmetrical and do not show any pressure-release structures related to movement (*sensu* Martin et al., 2012), I cannot identify digit impressions II or IV in either tracks, nor state with certainty whether either represents a right or left footprint.

Both quantitative and qualitative traits indicate the Knowledge Creek and Skenes Creek Track 1 trace fossils are ornithopod tracks. Length:width ratios of about 0.9, digit II-IV divarications of 83-85°, anterior-triangle length-width ratios of about 0.4, relatively thick digits, and rounded (blunt) ends on digit impressions are all consistent with ornithopod tracks (Moratallo et al., 1988; Lockley, 2009; Mateus and Milàn, 2010; Martin et al., 2012; Farlow et al., 2012). Relatively small sizes of the tracks also agree with assessments of Eumeralla Formation dinosaur assemblages, which are dominated by small 'hysilophodontids' (Rich and Vickers-Rich, 1999; Rich et al., 2002). A possibly comparable ichnogenus in size and form to these tracks is *Dinehichnus* isp. (*sensu* Gierliński et al, 2009, fig. 7), reported from the Late Jurassic of Poland and North America, and interpreted as that of a small ornithopod (Lockley and Foster, 2006; Foster, 2007; Gierliński et al., 2009; Lockley et al., 2009). Furthermore, the Victoria tracks resemble *Iguanodontipus*, which has been attributed to Early Cretaceous iguanodontids (Sarjeant et al., 1998; Cobos and Gascó, 2012), although these are often much larger (Castanera et al., 2013). In Australia, *Wintonopus* of the Lower Cretaceous Winton Formation (Queensland) is another small ornithopod track comparable to the Victoria specimens (Thulborn and Wade, 1984; Romilio et al., 2013). In short, similarities between the Victoria tracks and these ichnogenera affirm that their likely tracemakers were small ornithopods. The tracks can be further used to estimate tracemaker size via a footprint formula of 4.0 x footprint length = hip height (Alexander, 1976; Henderson,

Figure 6. Skenes Creek Track 1 (left) and Knowledge Creek track (right) together, allowing for a side-by-side comparison. The slab holding the Knowledge Creek track is slightly thicker (~10 mm) than the Skenes Creek slab, hence they are not being viewed on exactly the same horizon; scale = 10 cm.

2003). Using this formula, the Knowledge Creek and Skenes Creek (Track 1) ornithopod tracemakers had hip heights of about 42 cm (based on 10.6 x 4.0 = 42.4 cm). Owing to its poor definition, the hip height of the trackmaker for Skenes Creek Track 2 was not calculated, but if it does indeed belong to the same trackway, it can be assumed as similar to that of Track 1.

Other dinosaur tracemakers that could have made tridactyl tracks include small theropods, such as those interpreted from the Eumeralla Formation dinosaur tracksite at Milanesia Beach (Martin et al., 2012) or a single non-avian theropod track from Dinosaur Cove (Martin et al., 2014). However, the Milanesia and Dinosaur Cove theropod tracks were "thin-toed," with middle digit widths of only 5-16% of footprint lengths. In contrast, digits of the Knowledge Creek and Skenes Creek tracks were more than twice as thick, at 27 and 33% of footprint lengths (respectively). Furthermore, most of the Milanesia Beach tracks had thin (sharp) clawmarks, which are also characteristic of theropods (Martin *et al*., 2012, and references therein). Avian theropods (birds) were also discounted as possible tracemakers for the Knowledge Creek and Skenes Creek tracks for the same reasons, as well as for having digital divarications of 83-85°; bird tracks more typically have divarications of 95-120° (Lockley et al., 1992; Falk et al., 2011; Martin et al., 2014). Both tracks also lack evidence of a digit I impression, a trait noted in two similarly sized avian tracks from the Eumeralla Formation at Dinosaur Cove (Martin et al., 2014).

The positive-relief (raised) expression of all three tracks, yet on bed tops as epichnia, is unusual for most fossil tracks. Fossil tracks are normally preserved either as depressions (negative-relief epichnia) or as natural casts on bed bottoms (positive-relief hypichnia) (Lockley, 1991; Farlow et al., 2012). Because all three specimens were recovered from marine platforms eroded by tides and waves, their positive-relief preservation implies that sediment filling the tracks was better cemented – and hence more resistant to weathering – than their host rocks. This differential cementation and weathering that resulted in convex dinosaur tracks on bed tops was also noted for large theropod tracks in the Wonthaggi Formation (Aptian) at the Flat Rocks ("Dinosaur Dreaming") dig site (Martin et al., 2007). An uneven fill and cementation probably contributed to the vague definition of Skenes Creek Track 2, in which the "true track" is buried below the outwardly expressed positive epichnion.

Track surfaces are mainly uniform, but the Knowledge Creek track contained three oval-outlined protuberances, which I interpret as cross-sections of invertebrate burrows (figs. 3a,b). The burrows would have been made in an originally thicker bed composed of the same medium-coarse sand that filled the track. A thin vertical structure with the same sand fill underneath and toward the rear of the track is also likely a burrow, but one in the underlying host lithology and passively filled by sand from above. Owing to insufficient details, ichnotaxa were not assigned to these burrows.

Skenes Creek Track 2, despite its larger dimensions and less definite outline, is similar enough to its companion track from the same site that it is also interpreted as a dinosaur track, and probably that of a small ornithopod. This supposition is based on its tridactyl form, rounded ends to the probable digit impressions, a length:width ratio of 0.92, and an anterior-triangle length:width ratio of 0.31, which again are consistent with ornithopod tracemakers (Lockley, 2009). One of the "interdigital" angles on Skenes Creek Track 2 roughly corresponded with that of Track 1 (44° versus 46°, respectively); however, divarication was notably different (71° versus 83°, respectively). As mentioned before, the original depressions ("true track") for both Tracks 1 and 2 are likely underneath the currently expressed positive-relief outline, filled with sand that later cemented differently from the surrounding substrate. These depressions may even cut across the ripples underneath the track or deformed surrounding sediments so that the subsequent fill and cementation of that fill affected the outward appearance and weathering of the tracks on the same marine platform.

Although no information was recorded about the spatial relationship of the Skenes Creek tracks on the marine platform when and where they were recovered in 1989, the rock-saw cuts corresponding to their locations were found by Helmut Tracksdorf in June 2014, which was confirmed by Michael Cleeland in February 2015 (Appendix II). Interestingly, the rectangular outlines of the rock-saw cuts are directly aligned and in a sandstone bed with low-amplitude ripples, with ripple crests oriented obliquely relative to the outlines. Furthermore, both tracks have similar forms and are atop ripples oriented the same with respect to footprint directions, i.e., "northeast-southwest" with tracks pointing toward an arbitrary "north." Consequently, these tracks likely belong to the same trackway and were made by the same individual ornithopod. If so, these would constitute the first discovered dinosaur trackway in Victoria, usurping a small-theropod trackway discovered at Milanesia Beach in 2010 (Martin et al., 2012). To test this preliminary interpretation, the exact distance between incisions will need to be measured, and rock-saw outlines should be compared to the shapes and orientations of the two recovered slabs. Conversely, if the tracks are not aligned (e.g., point in opposite directions) and the collected slabs do not correspond to the outlines, they can be reasonably attributed to separate trackways made by similar tracemakers.

Unfortunately, all three tracks are isolated specimens taken out of context from their original field exposures in 1980 (Knowledge Creek) and 1989 (Skenes Creek). Thus very little additional information can be said about the palaeoenvironments trodden by their ornithopod tracemakers. The Eumeralla Formation is interpreted as a series of fluvial channel-fill, overbank, and floodplain facies deposited in circumpolar rift valleys, with less common alluvial or lacustrine facies (Bryan et al., 1997; Tosolini et al., 1999; Vickers-Rich et al., 1999). Given this broad framework, the most probable palaeoenvironments for dinosaurs making preservable tracks would have been point bars or floodplains, which are common sites for dinosaur track preservation (Martin, 2014). If the Skenes Creek trackmaker was walking on a floodplain, ripples underneath these tracks might have been current ripples, exposed after water flowed over that surface. Similar modern occurrences of current ripples later cross-cut by vertebrate tracks, providing a possible analogue for the Skenes Creek tracks, were described from a Arctic point bar in Alaska (Martin, 2009b). The largest assemblage of dinosaur tracks from the Eumeralla Formation – found at Milanesia Beach and described from two separate slabs of the same sandstone bed – was also in what were likely floodplain sandstones (Martin et al., 2012). Indeed, the circumpolar setting of these river valleys during the Early Cretaceous meant that dinosaur tracks might have been made and preserved only seasonally, from spring through fall (Martin et al., 2012). If so, this limiting factor may account for the relative rarity of dinosaur tracks and other trace fossils in Lower Cretaceous strata of Victoria (Martin et al., 2012).

Conclusions

The first known dinosaur tracks from Victoria may be small and few, but nonetheless carry useful information about Early Cretaceous dinosaurs in Victoria. For one, the Knowledge Creek and Skenes Creek tracks are from localities where no dinosaur bones are yet known, therefore confirming a dinosaurian presence at each of these places. Secondly, the tracks demonstrate that dinosaurs – specifically small ornithopods – actually lived in the palaeoenvironments of these places. In contrast, most dinosaur body fossils in Victoria, such as those from the Flat Rocks ("Dinosaur Dreaming") site at Inverloch and Dinosaur Cove, were likely transported and deposited in fluvial channels (Rich and Vickers-Rich, 2000; Rich et al., 2003). Lastly, these tracks are the first discovered Early Cretaceous ornithopod tracks from Victoria, and the Skenes Creek tracks may represent the first discovered dinosaur trackway in Victoria. These finds thus supplement comparatively abundant body fossils of 'hypsilophodontids' in the Wonthaggi and Eumeralla Formations.

The preservation of these small ornithopod tracks as positive-relief epichnia, as well as those of large theropod tracks in the Wonthaggi Formation (Martin et al., 2007), also may be typical modes of preservation for dinosaur tracks in Lower Cretaceous strata of Victoria. Hence future researchers scanning bedding planes of the Wonthaggi and Eumeralla Formations might adjust their search images for raised tracks on bed tops, rather than just depressions. Furthermore, less definite forms of dinosaur, such as that of Skenes Creek Track 2, should not be so easily ignored or dismissed once found. Given all of these insights, I have every confidence that more dinosaur tracks will be discovered, whether from ornithopods, theropods, or other tetrapod taxa whose trace fossil records are not yet known from this otherwise palaeontologically well-studied area of Australia.

Acknowledgements

I am extremely grateful to Thomas (Tom) Rich and Patricia (Pat) Vickers-Rich for their guidance, mentorship, and friendship over the years, starting with a sabbatical I enjoyed at Monash University in 2006 and visits to Australia since then. I thank Erich Fitzgerald (Museum Victoria) for asking me to write this manuscript, as well as Lisa Buckley and Anthony Romilio for their insightful and helpful reviews. Appreciation is extended to David Pickering, Lesley and Gerry Kool, Michael and Naomi Hall, and Michael Cleeland for their time in the field with me, as well as educating this inexperienced Yank whenever he dropped in for a too-brief glance at their lovely Lower Cretaceous rocks. Helmut Tracksdorf and Michael Cleeland also were invaluable in helping to document the original discovery site of the Skenes Creek tracks. The Emory University Faculty Travel Fund and the Center for International Programs Abroad assisted with some of my travel expenses during various visits. Last but not least, I am indebted to my wife, Ruth, nicknamed "Lefty" by her fellow southpaw Tom, for her sinistral support during much of the research.

References

Alexander, R.M. 1976 Estimates of speeds of dinosaurs. *Nature* 262: 129-130.

Benson, R.B., Rich, T.H., Vickers-Rich, P. and Hall, M. 2012. Theropod fauna from Southern Australia indicates high polar diversity and climate-driven dinosaur provinciality. *PLoS ONE* 7(5): e37122.

Bryan, S.E., Constantine, A.E., Stephens, C.J., Ewart, A., Schön, R.W., and Parianos, J. 1997. Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin: implications for the break-up of eastern Gondwana. *Earth and Planetary Science Letters* 153: 85–102.

Castanera, D., Pascual, C., Razzolini, N.L., Vila, B., Barco, J.L., and Canudo, J.I. 2013. Discriminating between medium-sized tridactyl trackmakers: Tracking ornithopod tracks in the base of the Cretaceous (Berriasian, Spain). PLoS ONE 8(11): e81830.

Cobos, A. and Gascó, F. 2012 Presencia del icnogénero *Iguanodontipus* en el Cretácico Inferior de la provincia de Teruel (España). *Geogaceta* 52: 185-188.

Farlow, J.O., Chapman, R.E., Breithaupt, B., and Matthews, N. 2012. The scientific study of dinosaur footprints. Pp. 713–759 in: Brett-Surman, M.K., Holtz, T.R., Jr., and Farlow, J.O. (eds), *The Complete Dinosaur* (2nd Edition). Indiana
University Press: Bloomington, Indiana. 1112 pp.

Foster, J.R. 2007. *Jurassic West: The Dinosaurs of the Morrison Formation and Their World*. Indiana University Press. Bloomington, Indiana. 389 pp.

Gierliński, G.D., Niedźwiedzki, G. and Nowacki, P. 2009. Small theropod and ornithopod tracks in the Jurassic of Poland. *Acta Geologica Polonica* 59: 221-234.

Henderson, D.M. 2003. Footprints, trackways, and hip heights of bipedal dinosaurs: testing hip height predictions with computer models. *Ichnos* 10: 99–114.

Kear, B.P., and Hamilton-Bruce, R.J. 2011. *Dinosaurs in Australia: Mesozoic Life from the Southern Continent*. CSIRO Publishing: Collingwood, Victoria. 190 pp.

Lockley, M.G. 1991. *Tracking Dinosaurs: A New Look at an Ancient World*. Cambridge University Press: Cambridge, U.K. 264 pp.

Lockley, M.G., and Foster, J.R. 2006. Dinosaur and turtle tracks from the Morrison Formation (Upper Jurassic) of Colorado National Monument, with observations on the taxonomy of vertebrate swim tracks. Pp. 193-198 in: Foster, J.R., and Lucas, S.G. (eds), Paleontology and Geology of the Upper Jurassic Morrison Formation, *New Mexico Museum of Natural History and Science Bulletin*, 36: 249 pp.

Lockley, M.G., Yang, S.Y., Matsukawa, M., Fleming, F. and Lim, S K. 1992. The track record of Mesozoic birds: evidence and implications. *Philosophical Transactions of the Royal Society of London* 336: 113–134.

Lockley, M.G. 2009. New perspectives on morphological variation in tridactyl footprints: clues to widespread convergence in developmental dynamics. *Geological Quarterly* 53: 415–432.

Martin, A.J., 2009a. Dinosaur burrows in the Otway Group (Albian) of Victoria, Australia, and their relation to Cretaceous polar environments. *Cretaceous Research* 30: 1223–1237.

Martin, A.J., 2009b. Neoichnology of an Arctic fluvial point bar, North Slope, Alaska. *Geological Quarterly* 53: 383–396.

Martin, A.J. 2014. *Dinosaurs Without Bones: Dinosaur Lives Revealed by Their Trace Fossils*. Pegasus Press: New York. 460 pp.

Martin, A.J., Vickers-Rich, P., Rich, T.H. and Kool, L. 2007. Polar dinosaur tracks in the Cretaceous of Australia: though many were cold, few were frozen. *Journal of Vertebrate Paleontology* 27 (Supplement 3): 112A.

Martin, A.J., Rich, T.H., Hall, M., Vickers-Rich, P. and Vazquez-Prokopec, G. 2012. A polar dinosaur-track assemblage from the Eumeralla Formation (Albian), Victoria, Australia. *Alcheringa* 36: 171–188.

Martin, A.J., Vickers-Rich, P., Rich, T.H., and Hall, M. 2014. Oldest known avian footprints from Australia: Eumeralla Formation (Albian), Dinosaur Cove, Victoria. *Palaeontology* 57: 7–19.

Mateus, O., and Milán, J. 2010. A diverse Upper Jurassic dinosaur ichnofauna from central-west Portugal. *Lethaia* 43: 245–257.

Moratalla, J.J., Sanz, S.L., and Jiminez, S., 1988. Multivariate analysis on Lower Cretaceous dinosaur footprints: discrimination between ornithopods and theropods. *Geobios* 21: 395–408.

Rich, T.H., and Rich, P.V. 1989. Polar dinosaurs and biotas of the Early Cretaceous of southeastern Australia. *National Geographic Research* 5: 15–53.

Rich, T.H., and Vickers-Rich, P. 1999. The Hypsilophodontidae from southeastern Australia. Pp. 167–180 in: Tomada, Y., Rich, T.H., and Vickers-Rich (eds.), Proceedings of the Second Gondwana Dinosaur Symposium. *National Science Museum Monographs* 15. 296 pp.

Rich, T.H., and Vickers-Rich, P. 2000. *Dinosaurs of Darkness*. Indiana University Press: Bloomington, Indiana. 222 pp.

Rich, T.H., and Vickers-Rich, P. 2003. *A Century of Australian Dinosaurs*. Queen Victoria Museum and Art Gallery: Launceston, Tasmania. 124 pp.

Rich, T.H., Vickers-Rich, P., and Gangloff, R.A. 2002. Polar dinosaurs. *Science* 295: 979–980.

Rich, T.H., Galton, P.M., and Vickers-Rich, P. 2010. The holotype individual of the ornithopod dinosaur *Leaellynasaura amicagraphica* Rich & Rich, 1989 (late Early Cretaceous, Victoria, Australia). *Alcheringa* 34: 385–396.

Rich, P.V., Rich, T.H., Wagstaff, B.E., McEwen-Mason, J., Douthitt, C.B., Gregory, R.T., and Felton, E.A. 1988. Evidence for low temperatures and biologic diversity in Cretaceous high latitudes of Australia. *Science* 242: 1403–1406.

Romilio, A., Tucker, R.T., and Salisbury, S.W. 2013. Reevaluation of the Lark Quarry dinosaur Tracksite (late Albian–Cenomanian Winton Formation, central-western Queensland, Australia): no longer a stampede? Journal of Vertebrate Paleontology 33: 102-120.

Sarjeant, W.A.S., Delair, J.B., and Lockley, M.G. 1998. The footprints of *Iguanodon*: A history and taxonomic study. *Ichnos* 6: 183-202.

Thulborn, R.A. 1990. *Dinosaur Tracks*. Chapman & Hall: London. 410 pp.

Thulborn, R.A., and Wade. M. 1984. Dinosaur trackways in the Winton Formation (Mid-Cretaceous) of Queensland. *Memoirs of the Queensland Museum* 21: 413-517.

Tosolini, A.-M.P., McLoughlin, A., and Drinnan, A.N. 1999. Stratigraphy and fluvial sedimentary facies of the Neocomian lower Strzelecki Group, Gippsland Basin, Victoria. *Australian Journal of Earth Sciences* 46: 951-970.

Vickers-Rich, P., Rich, T.H., and Constantine, A. 1999. Environmental setting of the polar faunas of southeastern Australia and adaptive strategies of the dinosaurs. Pp. 181–195 in: Tomada, Y., Rich, T.H., and Vickers-Rich (eds), Proceedings of the Second Gondwana Dinosaur Symposium, *National Science Museum Monographs* 15. 296 pp.

Appendices

Appendix I. Specimen Label Information

Specimen label information for Knowledge Creek track: P.159790; Dinosaur track, Otway Group, Knowledge Creek, Victoria on wave platform about 100 m east of mouth of

Knowledge Creek. T. Rich Exp., 18-12-1980 [December 18, 1980]

Specimen Label Information for Skenes Creek tracks: P.208232; T.H. Rich Exp., 18-3-1989 [March 18, 1989] Skenes Creek (Catalog 149). Locality: Shore platform, Skenes Creek.

Appendix II. Discovery of the Skenes Creek Tracks

The specimen label for the two Skenes Creek tracks does not credit their original discoverer, and repeated inquiries posed to personnel at Museum Victoria and long-time volunteers did not result in anyone taking credit for finding them. So I was gratified to learn in 2013 that credit for their discovery should go to Helmut Tracksdorf, a geologist who lived in Victoria near Skenes Creek at the time of their discovery.

In October 2013, Mr. Tracksdorf read a blog post written by me referring to the track. Mr. Tracksdorf sent me an e-mail message, received on October 20, 2013, revealing that he was the person who found the tracks. According to his message, he then reported these tracks and their location to Museum Victoria personnel. Several months after reporting them, he did not receive a confirmation from Museum Victoria on whether or not the tracks were recovered. However, he later visited the site and saw where they had been cut out of the marine platform. The e-mail message was sent by Helmut Tracksdorf and received by me (Anthony J. Martin) at 5:43 p.m. on October 20, 2013. The full, verbatim text of the e-mail is available for reading with permission of both Mr. Tracksdorf and myself.

Later, on July 9, 2014, Trackdorf contacted me again via e-mail with more information about the probable original location of the tracks; he copied Thomas Rich, David Pickering, Lesley Kool, and Michael Cleeland onto this message. In this message, he described the rock-saw cuts on the marine platform as 50-100 m west of Browns Creek (east of both Skenes Creek and Petticoat Creek) and about 50 m south of the Great Ocean Road. Along with this description, Tracksdorf provided a Google Earth image of the locality, as well as photographs of the site and rock-saw cuts in the marine platform, with the photos taken in June, 2014 by Trackdorf's brother (name not given). These descriptions aided me in figuring the approximate latitude-longitude coordinates of the tracks. On February 17, 2015, Cleeland and his wife (Pip) stopped by the location to look for the rock-saw cuts on the marine platform, relocated them, and photographed the rock-saw cuts; these were aligned with one another and in a rippled sandstone very similar to those of the Skenes Creek tracks (NMV P208232). On March 2, 2015, he sent these photographs to Rich, Pickering, Kool, Trackdorf, and me. Given this confirmation, we were satisfied that this is indeed the discovery site of the tracks.

In deference to their long-established nickname as the "Skenes Creek tracks," I recommend retaining this location designation, rather than adopting the more geographically appropriate "Browns Creek tracks." I also suggest that future researchers searching for more such dinosaur tracks in this area might concentrate their efforts on rippled sandstones in the marine platform between Petticoat Creek and Browns Creek.