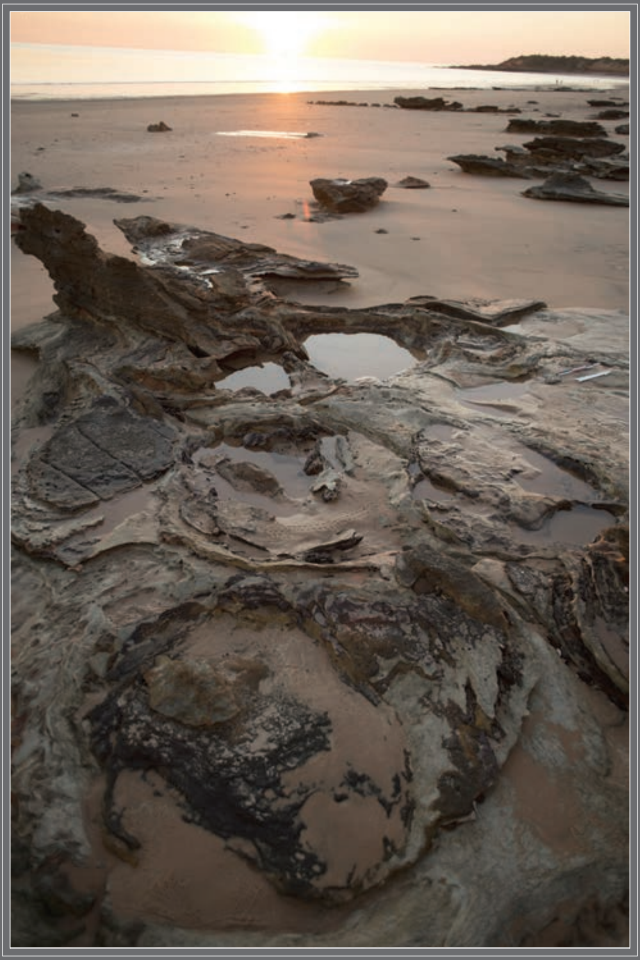
DINOSAURIAN TRACKS

AND RELATED GEOLOGICAL FEATURES

OF THE

REDDELL POINT–ENTRANCE POINT AREA, BROOME, WESTERN AUSTRALIA



PALAEONTOLOGICAL SURVEY

AS PART OF THE

2018 BROOME SAFE BOAT HARBOUR SITE ASSESSMENT PROCESS

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September 2018

Salisbury, S. W. and Romilio, A. 2018. *Dinosaurian tracks and related geological features of the Reddell Point—Entrance Point area, Broome, Western Australia; palaeontological survey as part of the 2018 Broome Safe Boat Harbour site assessment process*. viii + 42p.

On the front cover: A partial sauropod trackway in exposures of Broome Sandstone on Reddell Point Beach. © Steven Salisbury

On the back cover: A theropod dinosaur track (*Megalosauropus broomensis*)
© Damian Kelly

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ACKNOWLEDGEMENTS

The information presented in this report represents the culmination of many years of research and local engagement. Through it all we have benefited greatly from the generous support of Broome's enthusiastic community of avid 'dinosaur trackers'.

We are particularly grateful to members of the Dinosaur Coast Management Group, most notably Dianne Bennett and Michelle and Leon Teoh. Prior to their departure from Broome, Louise Middleton and Nigel Clark also spent considerable time with us both tracking and sharing their knowledge of dinosaurian tracks in the survey area, while Kevin Foulkes shared much of what he knew from his time tracking with his father, the late Paul Foulkes.

For insights into the cultural significance of dinosaurs tracks in the Broome Sandstone and their links to the Song Cycle along the Dampier Peninsula coastline, we thank Goolarabooloo, in particular Richard Hunter, Phillip Roe, Frans Hoogland and late Joseph Roe, members of the Yawuru Community, most notably Micklo Corpus and Stephen 'Bart' Pigram, and members of the Yawuru Cultural Advisory Group. For ethnographical insights into cultural links with dinosaurian tracks and orthography we thank Prof Stephen Muecke (University of Adelaide) and Kim Akerman.

For insights into the history of dinosaur tracking in the Broome area we thank Robyn Wells and Kylie Jennings (Broome Historical Society and Museum). Damian Kelly has also been extremely generous with his time helping to photograph both dinosaurian tracks and trackers, as well as Kevin Smith and Nadia Rebasti to whom we are grateful for sharing their photographic images.

For fieldwork in the survey area carried out between 2011 and 2017 and for discussions on many aspects of the area's dinosaurian track fauna and related geology, we thank members of the UQ Dino Lab (Linda Pollard, Jay Nair, Andreas Jannel, Dr Ryan Tucker, Dr Matt Herne, Sarah Gray, Pippa Slater (nee Chamberlain), and David Kennedy), Nathan and Rani Middleton, Prof Jorg Hacker and Shakti Chakraverty (Airborne Research Australia), Dr Robert Zlot and Dr George Poropat (formerly CSIRO), Dr Michael Bosse (ETH Zurich), Tim Flannery and Damian Hirsch. Dr Vic Semenuik is also thanked for invaluable discussions on the Quaternary deposits that occur within the survey area. For discussions on National Heritage listing we thank Carmen Lawrence, Kelly Mullen, Kathy Eyles, Sarah Titchen, Jeremy White and Toni Hart (Department of Environment and Energy).

Our July 2018 survey work was funded through Shire of Broome and the Western Australian Department of Transport. Research carried out prior to July 2018 that contributed to information presented herein was funded through the Australian Research Council (DP140101745) and The University of Queensland.

GLOSSARY

Ankylosaur: herbivorous dinosaur belonging to the group Ankylosauria ('*fused lizard*'). Ankylosaurs were heavily armoured herbivores that walked on all four legs. They typically have five to four fingers and/or toes, making their manual (hand) and pedal (foot) tracks hard to distinguish from each other (see thyreophoran).

Breakwater: an artificial offshore structure that protects a harbour, anchorage or marina from waves. Breakwaters intercept longshore currents and tend to prevent beach erosion within the area they enclose.

Cenozoic Era: interval of geological time from 66 million years ago to the present day, divided into the Palaeogene Period (66–23 Ma), the Neogene Period (23–2.6 Ma) and the Quaternary Period (2.6 to the present day).

Couplet: paired and sequential footfalls of a quadrupedal (four-legged) trackmaker that in combination representing one manual (hand) and one pedal (foot) track, both from the same body side.

Cretaceous Period: interval of geological time from 145–66 million years ago (see 'Mesozoic Era').

Digital: in the context of a living animal or track that it has made, relating to the digits of either the manus (hand) or pes (foot).

Footprint: a synonym for a single track (see 'track' and 'trackway'). In the context of the proposed Safe Boat Harbour, 'footprint' is also used to refer to the area (in m^2 or km^2) covered by the construction.

Hardstand: a paved area for parking heavy vehicles.

Holocene Epoch: interval of geological time that spans the last 11,700 years (see 'Quaternary').

Horizon: an interface indicative of a particular position in a stratigraphic sequence of sedimentary rocks (see 'stratum' and 'stratigraphy').

Ichnite: a trace fossil that can be a track/footprint, trackway, burrow, etc., made by a once living organism.

Ichnology: the study of tracks and traces left by both extinct and modern animals (see 'Track'; and 'Trace fossils').

Ichnofauna: a fauna based on ichnological evidence (e.g., tracks).

Ichnotaxonomy: a system of taxonomy (biological classification) that is based on tracks and other traces (see 'Trace fossils'). Fossilised tracks are classified separately to body fossils (e.g., fossilised bones), and the relationship between an ichnotaxon and body fossil taxon is not always clear. For example, *Megalosauropus broomensis* is the name given to a particular type of track, normally attributed to a theropod dinosaur. When we talk about *M. broomensis*, we are referring to a type of track, not a type of dinosaur (the trackmaker).

Lithology: the general physical characteristics of a rock or rocks.

Manual: in the context of a living animal or track that it has made, relating to the manus or hand.

Mesozoic Era: interval of geological time from 252–66 million years ago, divided into the Triassic Period (252–201 Ma), the Jurassic Period (201–145 Ma) and the Cretaceous Period (145–66 Ma). Also knows as the 'Age of Dinosaurs' or the 'Age of Reptiles'.

Neogene Period: interval of geological time from 23–2.6 million years ago (see 'Cenozoic Era').

Ornithischian: herbivorous dinosaur belonging to the group Ornithischia ('*bird-hipped*'). Ornithischian dinosaurs include heterodontosaurids, thyreophorans (armoured dinosaurs), ornithopods, marginocephalians (horned and domed dinosaurs) and related forms (see 'ornithopod' and 'thyreophoran').

Ornithopod: herbivorous dinosaur belonging to the group Ornithopoda ('*bird foot*'). The majority of ornithopods walked on two legs, but some were quadrupedal. The feet of ornithopods typically leave three-toed tracks that often lack any clear impressions of digital pads.

Palaeogene Period: interval of geological time from 66–23 million years ago (see 'Cenozoic Era').

Pedal: in the context of a living animal or track that it has made, relating to the pes or foot.

Pleistocene Epoch: interval of geological time from 2.6 million years ago to 11,700 years ago (see 'Quaternary').

Quaternary Period: interval of geological time from 2.6 million years ago to the present day, divided into the Pleistocene Epoch and the Holocene Epoch.

Saurischian: dinosaur belonging to the group Saurischia ('*lizard-hipped*'). Saurischian dinosaurs include the sauropods and theropods (including birds) (see 'Sauropod' and 'Theropod').

Sauropod: herbivorous dinosaur belonging to the group Sauropoda ('*reptile foot*'). Sauropods walked on four pillar-like legs and had long necks and tails. Their feet superficially resembled those of elephants, and had five toes, with the first toe usually being the largest; the hands usually retain a thumb but the other digits can be reduced or absent. Their pedal (foot) tracks are usually round to oval-shaped depressions, sometimes with digital impressions. The manual (hand) tracks are considerably smaller than the pedal tracks, and are usually round or kidney-shaped.

Sediment, sedimentary, sedimentology: sedimentary rocks are formed from pre-existing rocks (sediments) or pieces of once-living organisms. Sedimentology is the study of sedimentary rocks and the processes that form them

Stratum (plural = **strata**): layer of rock characterized by particular lithologic (physical) properties and attributes that distinguish it from adjacent layers.

Stegosaur: herbivorous dinosaur belonging to the group Stegosauria ('*roofed lizard*'). Stegosaurs had plates running down their neck, back and tail, which was spiked at the tip. Most stegosaurs walked on all fours, but trackway evidence shows that some were also capable of walking on their hind legs, similar to most ornithopods. Stegosaur feet typically have three toes, whereas the hands can have five or four fingers (see thyreophoran).

Stratigraphy: the discipline of geology concerned with the order and relative position of strata (layers of rock) and their relationship to the geological timescale.

Theropod: carnivorous dinosaur belonging to the group Theropoda ('*beast foot*'), which also includes birds. Theropods walked on their hind legs and had bird-like feet, leaving three-toed tracks that often show traces of claws and digital pads within each of the digital impressions.

Thyreophoran: herbivorous dinosaur belonging to the group Thyreophora ('*shield bearers*'); the armoured dinosaurs. There are two main groups of thyreophorans, the ankylosaurs and the stegosaurs (see 'ankylosaurs' and 'stegosaurs').

Trace fossil: a fossilised indication of behaviour or activity left behind by an animal. Although traces often are tracks, they also including burrows, eggs, nesting sites and feeding traces and scratches (either in the rock or on body fossils).

Track: synonymous with footprint, the mark left behind by the single foot or hand of a trackmaker.

Trackmaker: the animal responsible for making a track/footprint. Trackmakers are classified separately to tracks.

Tracksite: any area where there is a concentration of ichnites, typically tracks. Tracksites are delineated arbitrarily and can range from clearly defined, unbroken surfaces with multiple tracks, trackways or both, to isolated boulders with a single track.

Track horizon: the sedimentary horizon in which tracks and other fossil traces occur.

Track surface: the sedimentary surface on which a trackmaker walked.

Trackway: a series of two or more successive tracks made by single trackmaker.

Transmitted track: footprint impressions caused by the transmission of pressure to sedimentary layers directly beneath the track surface

True track: the impression made by a trackmaker on the track surface.

EXECUTIVE SUMMARY

In 2017/2018, funding through the Royalties for Regions scheme was allocated to the Western Australian Department of Transport (DoT) to undertake planning and investigations for a safe boat harbour (SBH) facility in Broome. The Broome Boat Harbour Advisory Group, chaired by the Shire of Broome (SoB), selected the coastline between Entrance Point and Reddell Point (= Reddell Point Beach) as the preferred site for this development.

As of July 2018, the preliminary concept for the proposed SBH facility for Reddell Point Beach includes protective breakwaters, a harbour that provides a turning circle for vessels, a boat ramp, a wharf and hardstand, and trailer parking. The proposed entrance to the harbour is from the south-eastern end of the facility. The main footprint of the proposed facility covers the middle one third of the beach, extending for approximately 500 m along the astronomical high tide mark and seaward for around the same distance to the edge of the outer reef. When the entrance channel and adjacent spending beach are taken into account the overall footprint extends close to the south-eastern end of the beach over a distance of 650 m. At this size, the overall footprint of the proposed facility covers approximately 1.9 km^2.

At the request of SoB and DoT, The University of Queensland was engaged to assess the potential impact of the proposed SBH facility concept at Reddell Point Beach on any National Heritage listed dinosaurian tracks in the Broome Sandstone of this area. An area encompassing approximately 3.5 km^2 of coastline, from the southern end of Reddell Beach to just north of Broome Jetty was surveyed from 15–18 July, corresponding with spring tides that extended to 0.86 m low tide mark. This stretch of coast includes the full extent of the proposed SBH facility on Reddell Point Beach, as well as adjacent areas of interest that either could potentially be impacted indirectly or could offer alternative sites. The results of earlier survey work, carried out during the course of earlier research between 2011 and 2017, some of which included spring tides that exceeded 0.3 m low tide mark, was also included. Data collected during surveys undertaken by members of the Dinosaur Coast Management Group between 2015 and 2018 was also included where it could be verified.

There are extensive exposures —approximately 1.2 km^2—of Broome Sandstone throughout the intertidal zone in the survey area. It forms a near continuous reef that runs parallel to the shore from the southern end of Reddell Beach around Entrance Point to Broome Jetty, over a distance of 3.8 km. The outer reef is 200–300 m wide for most of its length.

Dinosaurian tracks are a common feature of the Broome Sandstone within the survey area. The majority of track-bearing horizons seem to be concentrated in two main bands: the first starting close the astronomical high-tide mark and extending for 30–40 metres seawards; the second between the 2.5 and 1 m low tide mark, close to the seaward edge of main reef system. Additional concentrations of track-bearing horizons occur between the two main bands, particularly at Reddell Point, the south-eastern end of Reddell Point Beach and the south-western side of Entrance Point.

Over 140 National Heritage listed dinosaurian track-bearing surfaces in the Broome Sandstone were recorded in the survey area. Many of these surfaces preserve multiple tracks and trackways, so the total number of individual tracks is much higher. Some areas, such as Reddell Point are heavily trampled and probably include hundreds of individual tracks and trackways. We conservatively estimate that there are more than 500 individual tracks in the survey area, potentially spanning many tens, if not hundreds of thousands of years of dinosaurian activity between 140–127 million years ago.

Three different types of dinosaurian tracks occur within the survey area: sauropod tracks, theropod tracks and ornithopod tracks. The preservation of tracks ranges from 'true' tracks that preserve details of the hand and foot morphology of the trackmakers, through to partially eroded tracks, pedestals, and various forms of transmitted tracks. Some aspects of the sauropod tracks in the survey area point to the presence of a new track type that is distinct from the six other types of sauropod tracks already described from the Broome Sandstone. The high density of some of these sauropod tracks in some parts of the survey area might also provide evidence of sauropod herding behaviour. The high abundance of theropod tracks in the survey area and adjacent areas (such as Reddell Beach) relative to other parts of the Dampier Peninsula is also significant, and may point to possible habitat preferences for these trackmakers. Of cultural significance, theropod tracks in the survey area form part of the Northern Tradition of a Song Cycle that travels along the Dampier Peninsula coastline, and feature in Bugarrigarra (Dreamtime) stories about Marala, the Emu Man. Reddell Point Beach also preserves a track that is assignable to *Wintonopus middletona*. This is one of the first confirmed ornithopod tracks in the entire Broome area, and only the fourth track (in the world) that can be linked to this ichnotaxon.

The Reddell Point–Entrance Point area preserves the most southerly dinosaurian track-bearing surfaces in the Broome Sandstone within the West Kimberley. These tracksites may therefore sit within a unique part of the great delta system that formed the Broome Sandstone 140–127 million years ago. The dinosaurs that inhabited this area may have lived in the most coastal of all the palaeoenvironmental settings that formed part of the Broome Sandstone delta system, and could therefore represent a unique part of the palaeontological story that we are beginning to reconstruct for this area. In the context of this broader story, all the tracks in the survey area are important, and only in their entirety can they help us to reconstruct this prehistoric 'lost world' of the Kimberley.

Dinosaurian tracks in the Broome Sandstone form one of the key values associated with the West Kimberley National Heritage Area, and, as such, are afforded protection under the 1999 Environmental Protection and Biodiversity Conservation Act. In its current form, the construction and maintenance of the proposed SBH facility on Reddell Point Beach would have a significant impact on the National Heritage listed dinosaurian tracks in the Reddell Point–Entrance Point area. All the Broome Sandstone and its associated dinosaurian track-bearing surfaces within the greater footprint of the SBH would be either destroyed, permanently buried or subject to increased risk of erosion. As such, the National Heritage values associated with this area would be lost. In addition to probable changes in the movement and distribution of sand along Reddell Point Beach, it is also likely that the construction of the proposed SBH could affect the transport, erosion and deposition of sand on adjacent beaches and headlands. This could potentially include the permanent burial or increased rate of erosion of significant National Heritage listed dinosaurian track-bearing surfaces and associated geological and cultural features at the southern end of Bungurunan and the small south-east facing beach on Entrance Point.

We cannot see how the aforementioned impacts can be avoided or mitigated. Shifting the position of proposed SBH to either the northwest or the southeast of Reddell Point Beach would do little to avoid any significant impact on National Heritage values.

If the proposed location of the SBH facility is maintained, the only way any significant impacts on National Heritage values can be avoided is if the overall direct footprint of the facility is greatly reduced. This could be achieved either by making it much smaller and reducing the size of both the harbour and the breakwater, or by moving to a design that is farther offshore, such that the harbour area is not directly above the intertidal exposures of Broome Sandstone. Whether either of these options meets the requisite criteria for the SBH and/or is even feasible is not something we can comment on at this point. Any new design would need to be assessed on its own merits.

A more desirable alternative would be to shift the location of the SBH to an area where there are fewer or no National Heritage listed dinosaurian tracks, thereby avoiding any significant impacts on National Heritage values. The area starting immediately south of Broome Jetty and extending north to the Kimberley Port Authority's slipway appears to preserve little in the way of dinosaurian tracks. Moving the SBH facility to this location would undoubtedly have its own sets of location issues due to the close proximity of Broome Jetty and other KPA infrastructure, and potential indirect impacts on adjacent track-bearing surfaces from changes to sand transport, particularly those at the southern end of Entrance Point, would also need to carefully considered. But the overall impact on National Heritage values would likely be minimal. In terms of the impact on the natural aesthetics of the area, this part of Entrance Point is already partly developed, being situated close to the jetty and existing public boat launching facilities. The few sauropod tracks that do occur along the foreshore are on detached blocks and could be removed and placed on display in an interpretive centre or similar that could be located nearby. We therefore feel that this area is much better suited to a safe boat harbour facility than Reddell Point Beach.

There is enormous potential for dinosaur-themed tourism within the survey area. The high abundance of tracks, their quality, diversity, scientific significance, links to indigenous culture and ease of access make this particular area ideally suited to visitation. As public awareness of the scientific and cultural significance of National Heritage listed dinosaurian tracks in the Reddell Point–Entrance Point area increases, we expect more people will want to come and experience this unique part of Broome (and indeed Australia). In a few years' time, we would not be surprised if Reddell Point and Reddell Point Beach were more popular for 'dinosaur track spotting' than nearby Minyirr (Gantheaume Point). It is easy to forget that this is one of only a handful of picturesque beaches close to Broome where people can easily experience globally unique dinosaurian tracks. There is currently nowhere else in Australia other than the Dampier Peninsula where people can see sauropod tracks, and this is one of the best beaches to do it. It is an incredible natural asset that Broome needs to embrace. We look forward to working with Broome Shire, the WA Department of Transport, the Kimberley Port Authority, the Dinosaur Coast Management Group, Nyamba Buru Yawuru, Goolarabooloo and other indigenous groups, along with the greater Broome community to promote and manage this unique area.

Figure 1. Broome school girl Maddison Sprigg alongside one of Broome's theropod dinosaur tracks (*Megalosauropus broomensis*). © Damian Kelly.

1. INTRODUCTION

BACKGROUND

The Broome Sandstone on the Dampier Peninsula, Western Australia, preserves the most diverse dinosaurian track fauna in the world. Twenty one different types of tracks have been identified, preserved in over 70 tracksites scattered over approximately 80 km of coastline from Roebuck Bay north to Minarriny (Coloumb Point) (Glauert, 1952; Colbert and Merrilees, 1967; Long, 1990, 1992a, 1993; Thulborn et al., 1994; Long, 1998, 2002; Thulborn, 2002; Rich and Vickers-Rich, 2003a; Willis and Thomas, 2005; Thulborn, 2009, 2012; Commonwealth of Australia, 2011; Salisbury et al. 2017; Romilio et al., 2017). With the exception of a few fragments of bone from other fossil localities in Western Australia (Long, 1992b, 1995; Long and Cruickshank, 1996; Long and Molnar, 1998; Agnolín et al., 2010; Salisbury and Long, 2018), this ichnofauna constitutes the primary record of dinosaurs for the western half of Australia, with many of the tracks having no obvious counterpart among described body fossils from other parts of the continent.

The dinosaurian ichnofauna of the Broome Sandstone comprises five different types of tracks made by predatory theropod dinosaurs, at least six types of tracks assigned to long-necked herbivorous sauropods, four types of tracks assigned to two-legged herbivorous ornithopods, and six types of tracks assigned to armoured dinosaurs. Among the tracks is the only confirmed evidence for stegosaurs in Australia. There are also some of the largest dinosaurian tracks ever recorded, with some of the sauropod tracks being 1.7 m long.

In recognition of their outstanding heritage value, dinosaurian tracks in the Broome Sandstone were included in the West Kimberley National Heritage Area in 2011 (Place ID 106063; Commonwealth of Australia, 2011).

Cultural Significance

In addition to their scientific value, dinosaurian tracks in the Broome Sandstone also have a unique cultural significance. Three-toed tracks assigned to *Megalosauropus broomensis* form part of a Song Cycle that extends along the coast and then inland for 450 km, tracing the travels of a Bugarrigarra (Dreamtime) creator being called Marala, the Emu Man (Anonymous, 1999; Major and Sarjeant, 2001; Salisbury et al., 2017).

Marala's tracks at Minyirr (Gantheaume Point) and Reddell Beach are referred to in a number of Bugarrigarra stories that form part of the Northern Tradition of the Song Cycle. The most notable of the publicly known stories involves Marala and some female sea spirits. At Bungurunan, a small beach just to the north of Reddell Point, Marala encountered a group of Ngadjayi—spirit women from the sea who had come out of the water to harden their skin in the sun and delouse each other with jungkur (lice sticks). When Yinara, the most senior woman in the group, sensed that Marala was coming, she told the younger women to turn towards the land and to not look at him. Marala saw the women and walked over to them. Although Yinara positioned herself between Marala and the others, he was still able to get very close. Curious to see him, some of the women turned to watch Marala as he walked past. Yinara was able to drive Marala away, but was angry with the younger women and shamed them for disobeying her. The spirits of Yinara and the other Ngadjayi moved into the sky and can be seen today as the constellation known as Pleiades. Stone pillars representing the Ngadjayi still stand today at the top of the beach at Bungurunan, and the rock platforms nearby preserve three-toed tracks that show where Marala walked (Salisbury et al. 2017; **Fig. 2).**

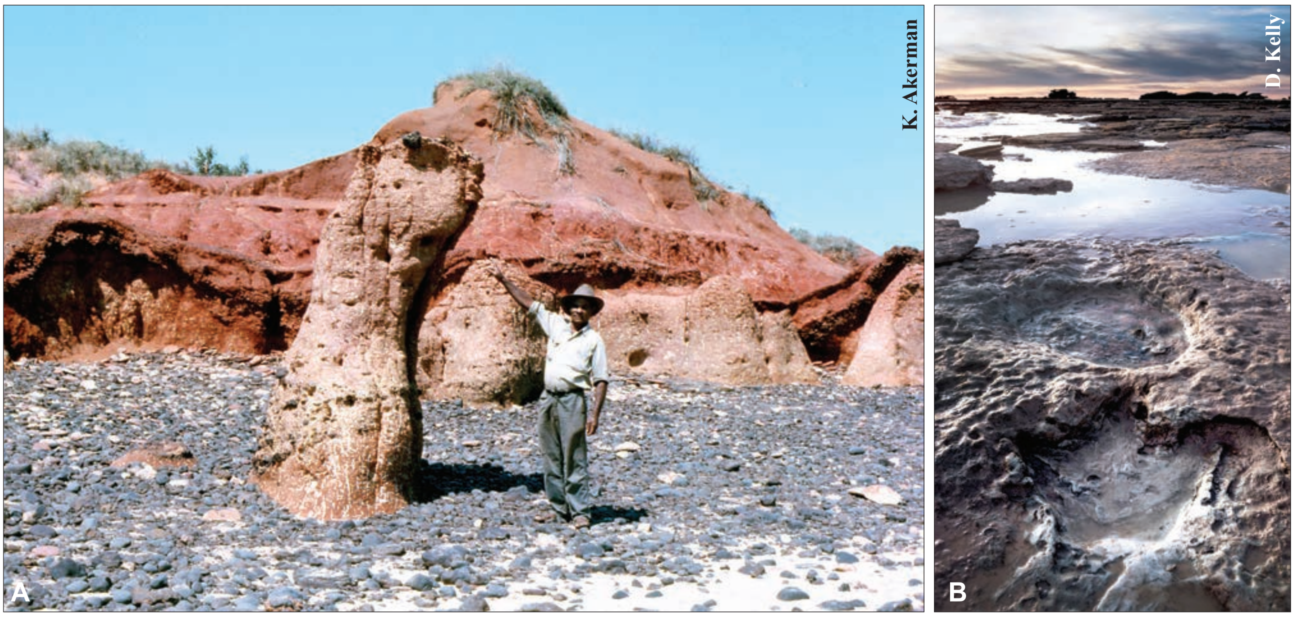

Figure 2. Cultural significance of geological structures at the southern end of Reddell Beach. **A**, stone pillars representing the Ngadjayi occur at Bungurunan, a small beach just north of Reddell Point. The late Paddy Roe points to Yinara, the tallest of the pillars (August 1976). **B**, three-toed theropod pedal impression near Bungurunan represent Marala's tracks. © Kim Akerman. © Damian Kelly.

PROPOSAL FOR A SAFE BOAT HARBOUR FACILITY ON REDDELL POINT BEACH

In 2017/2018, funding through the Royalties for Regions scheme was allocated to the Western Australian Department of Transport (DoT) to undertake planning and investigations for a safe boat harbour (SBH) facility in Broome.

To progress planning for the facility, DoT has been working with the Shire of Broome (SoB), which chairs the Broome Boat Harbour Advisory Group (BBHAG). The BBHAG includes members from DoT, Nyamba Buru Yawuru, the Kimberley Port Authority and community members representing a range of stakeholder groups. The coastline between Entrance Point and Reddell Point (hereafter referred to as Reddell Point Beach) has been selected by the BBHAG as the preferred site for a SBH (**Fig. 3**).

Figure 3. Aerial view of Reddell Point–Entrance Point overlaid with a schematic of the proposed Safe Boat Harbour (SBH). Image supplied by Broome Shire Council.

OBJECTIVES OF THE SURVEY

At the request of SoB and DoT, The University of Queensland was engaged to assess the potential impact of the proposed SBH at Reddell Point Beach on National Heritage listed dinosaurian tracks in the Broome Sandstone. Although our team has documented dinosaurian tracks in this area during the course of previous research between 2011 and 2017, the full extent of track-bearing surfaces along this stretch of coast and their broader significance was unclear. As such, additional palaeontological survey work in the area was deemed necessary.

The specific aims of the survey were as follows:

(i) *Determine the extent of National Heritage listed dinosaurian track-bearing surfaces and related geological features in the Broome Sandstone in the area around Entrance Point and Reddell Point, including the types of tracks preserved and their relative abundance, along with other data relevant to assessing their broader scientific context*;

(ii) *Provide advice and recommendations on potential management and mitigation measures (including possible offsets) that could be implemented during the planning, design and construction process of the proposed SBH at Reddell Point Beach.*

2. SURVEY METHODS

SURVEY AREA

The survey area encompassed approximately 3.5 km of coastline, from the southern end of Reddell Beach (Bungurunan) to just north of Broome Jetty (**Figs 4, 8**). This stretch of coast includes the full extent of the proposed SBH on Reddell Point Beach, as well as adjacent areas of interest that either could potentially be impacted indirectly or could offer alternative sites. The survey area was divided into seven distinct zones (A–G), assigned arbitrarily based on the most obvious geographic landmarks and/or areas of interest. Each zone was surveyed from the astronomical high tide mark down to approximately the 0.9 m low tide mark. As such, the entire survey area had a perimeter of approximately 8.3 km, and covered a total area of 1.5 km^2.

SURVEY DATES

The 2018 survey was carried out from 15–18 July, corresponding with spring tides that extended to 0.86 m. The results of earlier survey work, carried out during the course of earlier research between 2011 and 2017, some of which included spring tides that exceeded 0.3 m, was also included. Data collected during surveys undertaken by members of the Dinosaur Coast Management Group between 2015 and 2018 was also included where it could be verified.

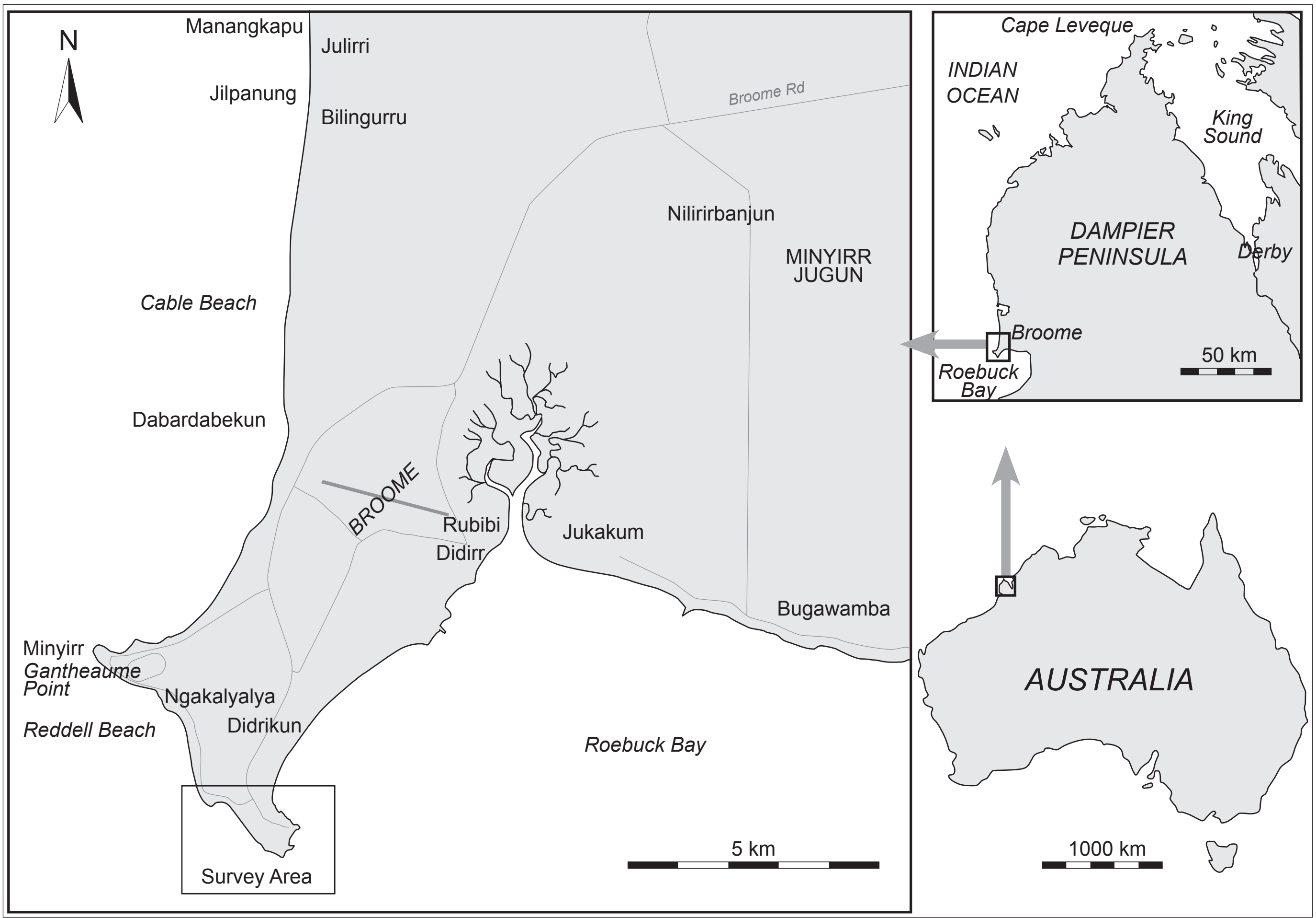

Figure 4. Schematic map of the Greater Broome Area showing the location of the survey area.

SITE ACCESS AND PERMITS

The survey area falls with the tenured land of the Kimberley Port Authority (Reserve 28650). Appropriate approvals from the Kimberley Port Authority and Shire of Broome to conduct the survey were obtained (KPA ref CRE70/148402).

INDIGENOUS PLACE NAMES

Place names used in this study (**Figs 4, 8**) follow those used in Salisbury et al. (2017) and Romilio et al. (2017) and correspond to ethnographic sites on the Lurujarri Heritage Trail, and include mythological and ceremonial places (law grounds) associated with the Northern Tradition of the Song Cycle, camping areas of historical significance, and burial sites (modified and updated from those listed in Worms, 1944; Akerman, 1975, 1981; Bradshaw and Fry, 1989). The orthography used in this report follows that recommended by McGregor (1988) and Stokes and McGregor (2003) for the Nyulnyulan languages, unless stated otherwise. The first time a place name is used the non-indigenous equivalent (if one exists) is given in parentheses.

SURVEY PERSONNEL

The 2018 survey was undertaken by Dr Steven W. Salisbury and Dr Anthony Romilio, both from the School of Biological Sciences, The University of Queensland, Brisbane 4072, Australia.

Additional survey work that was carried out during the course of earlier research between 2011 and 2017 was undertaken by Dr Steven W. Salisbury, Dr Anthony Romilio and other members of the UQ Dinosaur Lab (Linda Pollard, Jay Nair, Andreas Jannell, Ryan Tucker, Matt Herne, Sarah Gray, Pippa Slater (nee Chamberlain), and David Kennedy), Jorg Hacker and Shakti Chakraverty (Airborne Research Australia), Robert Zlot and George Poropat (formerly CSIRO), and Michael Bosse (ETH Zurich). Survey work undertaken by members of the Dinosaur Coast Management Group, in particular that of Dianne Bennett, between 2015 and 2018 was also included where it could be verified.

Figure 5. Fossil track preparation and measurements. **A**, an orntihopod track overlaid with ~0.4 m of sand is manually exposed and cleaned by Dr Anthony Romilio for photographic data collection (survey zone C). **B**, trackway parameters of a Broome sauropod trackway are measured by Linda Polland and Dr Anthony Romilio and recorded by Jay Nair (survey zone B). © Steven W. Salisbury.

DATA ACQUISITION

The bulk of our survey work was carried out on foot when tides permitted. In most instances, site access was possible for around 8 hours each day of the survey (6am–10am and 2pm–6pm), such that approximately 30 hours were spent on the beach and reefs. We further estimate an additional 100+ hours were spent assessing parts of the survey area between 2011 and 2017 by our research team (see 'Survey personnel').

The WGS84 coordinates and extent of track-bearing surfaces and other geological features were recorded using either a hand-held GPS (Garmin GPSMAP 64S, with high-sensitivity GPS and GLONASS receiver) or a Samsung Galaxy 7 with 'GPS Waypoints' (version 2.4-Blucover Technologies; info@bluecover.pt) using the built-in GPS receivers of the smart phone (accuracy ~1.5–4 m). Coordinates were time-stamped (to seconds) and tagged with track descriptors to correlate with time-stamped digital photographs.

Figure 6. Ground-based photographic data collection can be vary from holding cameras in ones hands to using extendable tripods where the camera shutter is remotely triggered. Steve Salisbury demonstrates the latter technique on a set of large sauropod tracks (survey zone C). © Anthony Romilio.

Surfaces of interest were cleaned by hand to remove debris prior to taking photographs (**Fig. 5A**). Photographs were taken using either a tripod-mounted digital camera (either a Nikon 10 megapixel D80 or 16.2 megapixel Nikon Df with a Nikkor AF 24mm f/2.8D autofocus lens, with exposure and shutter speed set manually, illuminated either by natural light or a remotely activated Nikon Speedlight SB-6000; **Fig. 6**), iphone 6+ (12 megapixel, F2.2 autofocus lens) or Samsung Galaxy 7 (12-megapixel F1.7 autofocus lens). Photos were normally taken with the lens positioned approximately 1.5 m above the track surface, using a remote shutter release to reduce camera shake. All surfaces were photographed with a scale bar and north arrow aligned to magnetic north using a Brunton Compass (throughout the survey area magnetic north is 2.3–2.5° east of true north).

Photographs that encompassed larger areas were taken using Unmanned Aerial Vehicles (UAVs); either a DJI T600 INSPIRE 1 with on-board 12.76 megapixel X3 gimbal-mounted digital camera (model FC350, which has a 20 mm [35 mm format equivalent] f/2.8 lens; used prior to September 2016) or DJI Mavic Pro with on-board 12.71 megapixel 3-axis gimbal-mounted 4K camera with a 26 mm [35 mm format equivalent] f/2.2 lens (**Fig. 7**). UAV photographs were taken under natural lighting conditions, using auto settings for ISO, shutter speed and aperture.

The majority of track and trackway parameters were measured in the field using a carpenter's power return tape measure and a 30 m open reel fibreglass tape measure (**Fig. 5B**). For tracks and trackway dimensions that could not be measured directly in the field, measurements were taken in silico using ImageJ (version 1.46) on single photographs, and using Agisoft Photoscan Pro (version 1.1.6 build 2028 [64 bit]) on DEMs, with distances scaled against scale bars or points in the image for which the distance was already know. Other measurements, including divarication angles, digit extension lengths, and pace angulation, were also determined in this manner.

DATA ANALYSIS

Methods employed in post-survey data analysis followed those outlined in Salisbury et al. (2017) and Romilio et al. (2017). The GPS metadata used during ground- and UAV aerial-based photograph acquisition was not sensitive enough to distinguish positions less than 4 m apart and was subsequently disabled on the respective devices. Time-stamped waypoints with location descriptors from GPS devises were exported as KML and KMZ files and viewed in Google Earth Pro (version 7.3.2.5491).

For comparisons with other tracks and existing data, 3D digital models of some surfaces were created using photogrammetry. RAW photographs were converted to JPEG using Adobe Photoshop CS6 (version 13.0 x64), or to PNG-24 file format when acquiring images from video. Converted images were then added to Agisoft PhotoScan Professional Edition (version 1.26 build 2038 64 bit) to generate digital surface models (.ply, .obj, and .laz files) and orthophotographic mosaics (.png) for comparison and analysis. Comparisons were made with other dinosaurian tracks from the Broome Sandstone as described in Salisbury et al. (2017), along with additional data for earlier surveys of greater Broome area carried out between 2011 and 2017. Where necessary, additional comparisons were made with tracks described in the literature.

Figure 7. Photography of large track surface areas is facilitated through the use of UAVs as demonstrated by Dr Anthony Romilio (survey zone A).
© Damian Kelly.

3. RESULTS

GEOLOGICAL SETTING

At least five stratigraphic units were identified in the survey area, ranging from unconsolidated sands through to sandstone bedrock. Above the astronomical high-tide mark, sand-dominated dunes form the main headland of Entrance Point and Reddell Point, with small patches of endangered monsoon vine thicket persisting in some of the swales away from development. The low cliffs and eroded pillars around Reddell Point are formed by a distinctive set of consolidated muds, sandy muds and ironstone breccias, whereas at Entrance Point the low rocky headland is formed by the upper-most parts of the Cretaceous Broome Sandstone, and around the two boat ramps, much younger consolidated beach sands. As the tide retreats it exposes extensive rock platforms and coral-encrusted reefs of Broome Sandstone, buried in parts by a shallow blanket of highly mobile beach sand. Each of these units is described below, from youngest to oldest.

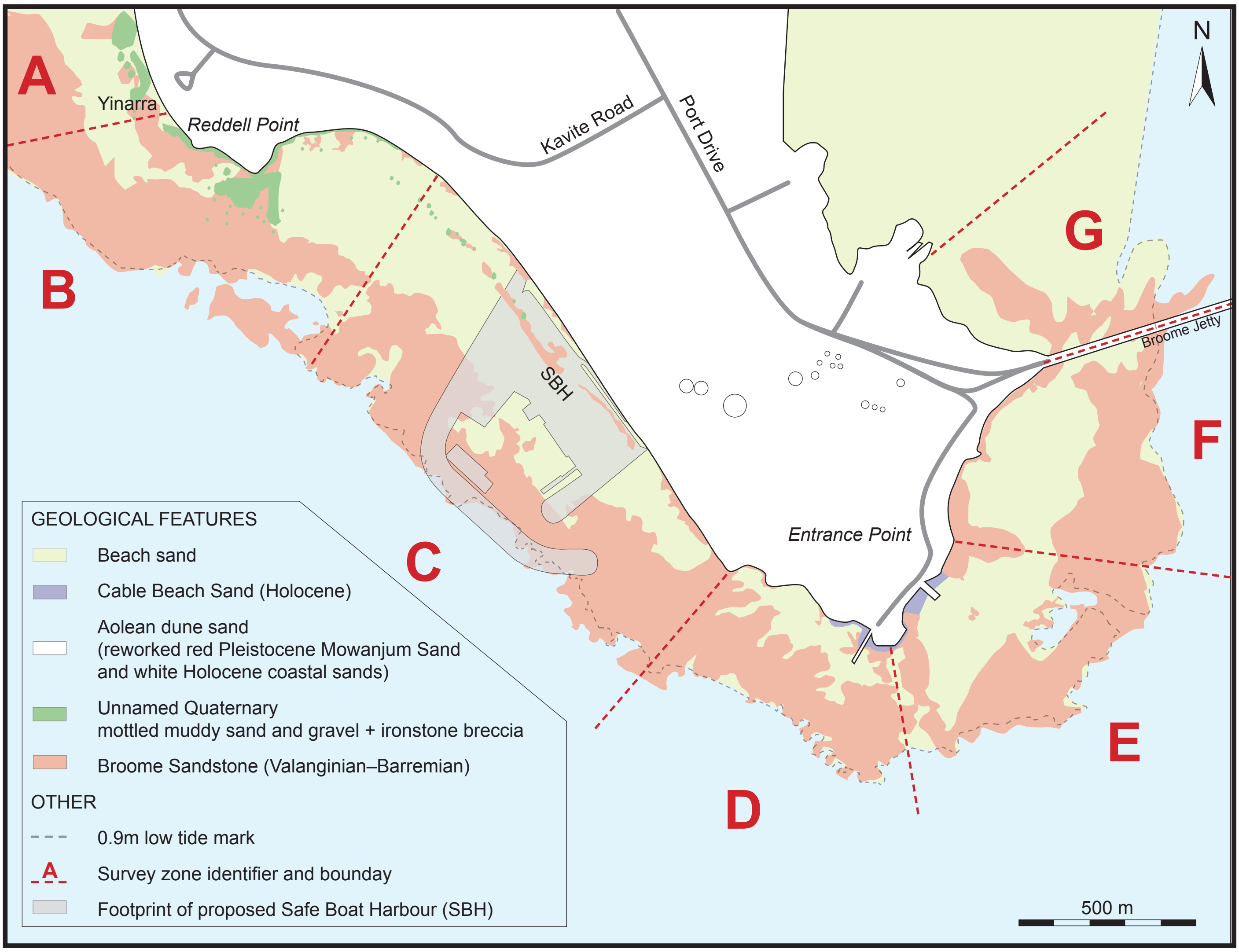

Figure 8. Schematic map of the survey area partitioned into zones A–G, with the proposed concept for the Safe Boat Harbour facility occurring in survey zone C. Geological features of the intertidal zone range from, but are not limited to, Early Cretaceous Broome Sandstone (Valanginian–Barremian) to modern beach sand.

Beach Sand (present day)

Unconsolidated, calcareous quartz beach sand extends through much of the upper 200 m of the intertidal zone within the survey area. Southeast of Reddell Point, in zone B, it dominates the first 230 m of beach from the astronomical high tide mark to approximately the 3 m low tide mark. Similarly, in the northwest two thirds of zone C, the first 180 m of beach, from 0 m to approximately the 5 m low tide mark is primarily blanketed in sand. In the southeast corner of zone C, the beach sand pinches out towards the high tide mark, and only forms a narrow, 60–80 m lens through the upper (0–100 m) of the intertidal zone. Around Entrance Point (zones E and F), the sand cover is restricted to the upper 200 m of the intertidal zone, bounded landward by a small outcrop of Cable Beach Sand either side of the main boat ramp (**Fig. 9A**), and to the south, northwest and seaward, by extensive exposures of Broome Sandstone (see below). In zone F, the beach sand dominates most of the upper half of the intertidal zone, from just below the astronomical high tide mark to a point around 270 m from the shore. Except for immediately around the jetty, and a 120 m wide reef of Broome Sandstone in the upper 170 m of the intertidal zone, zone G is also dominated by sand.

The amount of beach sand in the survey area seems to be highly variable, and it is probably no less than a few meters thick at its deepest point. Between 2011 and 2018 we had seen that the sand cover in the survey area become mobilised during storm and surge events, stripped from the more exposed portions of beaches and redistributed either offshore or behind some of the more protected headlands. Large exposures of Broome Sandstone are periodically exposed as a result. The most recent example of this happened during January–February 2018, when approximately 1–1.5 m of sand was temporarily stripped from the south-eastern end of Reddell Point Beach (survey zone C) (**Fig. 22A**). During calmer weather, longshore drift appears to redistribute the sand more evenly along the beaches. The thickest sand cover seems to occur in the small embayment southeast of Reddell Point in the north-western corner of Reddell Point Beach (zone B). The presence of extensive amounts of coral along the margin of the reef that encircles the survey area suggests that the bulk of the sand movement occurs parallel to the beach rather than perpendicular to it.

The sand cover on Reddell Point Beach seems to be highly mobile, even during periods of stable weather. For instance, in the two-week period between 18 July and 5 August 2018, approximately 0.5 m of sand was stripped from the south-eastern corner of Reddell Point Beach (survey zone C). Photographs taken on 5 August 2018 by DCMG members show that large portions of track-bearing surfaces within the Broome Sandstone that were not visible during the survey period (15–18 July) were exposed (**Fig. 5A**). Other than the transition out of the spring tide that occurred after the survey period, no seasonably abnormal weather or surf conditions occurred during this time. Our records of track-bearing surfaces along this stretch of beach dating back to 2011 show a similar pattern, with many being buried as often as they are exposed. With this is mind, it is probably safe to assume that the sand cover throughout most of the upper intertidal zone (0–200 m) within the survey area, particularly within zones B and C, represents a thin (1–2 m thick) veneer over the underlying rocks of the Broome Sandstone.

Cable Beach Sand (Holocene)

The Cable Beach Sand consists of interlaminated coarse, medium and fine-grained calcarenite, with shell beds, and pebble beds, that likely represent part of the high intertidal zone during the end of mid-Holocene sea level high. Semeniuk (2008) determined the age of the Cable Beach Sand to be between 1090 ± 160 years BP and 2100 ± 180 years BP. Shallowly seaward dipping exposures of Cable Beach Sand unconformably overly the eroded upper parts of the Broome Sandstone in survey zones E and D, extending from just about the astronomical high tide mark to approximately 30 m offshore to the northeast and southeast of the east-facing jetty at Entrance Point, and for a similar extent to the east and west of the south-facing jetting (**Figs 8 and 9**).

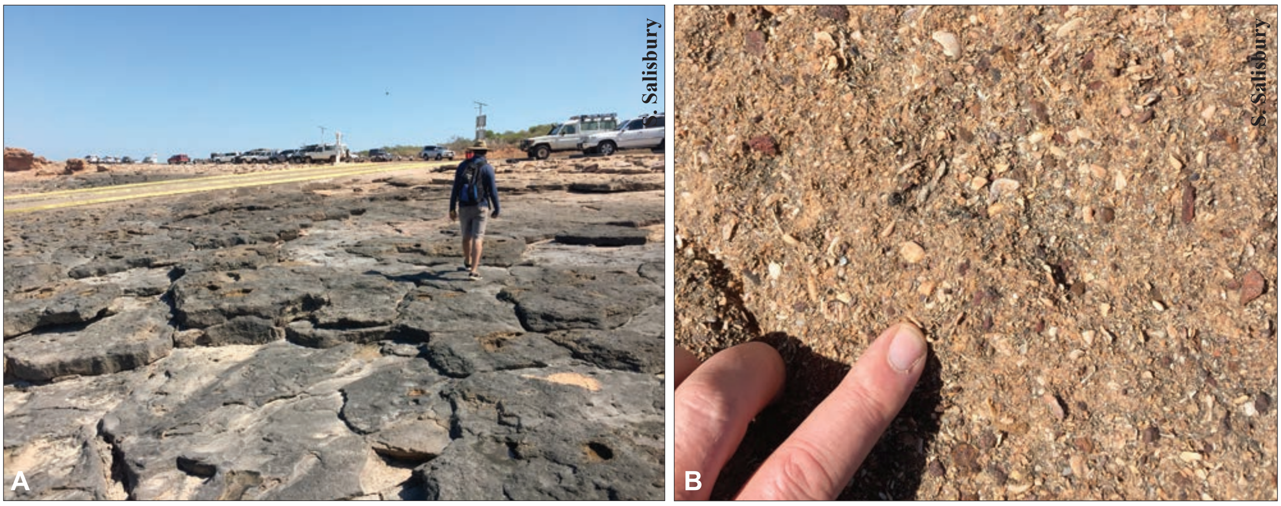

Figure 9. Cable Beach Sand. **A**, Dr Anthony Romilio walks upon the rocky exposures of Cable Beach Sand that borders the boat ramps at Entrance Point (survey zone E). **B**, close up of Cable Beach Sand, consisting of coarse, medium and fine-grained calcarenite, shells and pebbles. © Steven W. Salisbury.

Unnamed mottled muddy sand and gravel, and ironstone breccia (Quaternary?)

A distinctive sequence of yellow to brown/creamy coloured mottled muddy sands, muds and gravels, interbedded with breccias (boulder deposits) of dark grey to black ironstone clasts and ferruginised (iron-impregnated) sandstone form the low (6–8 m) cliffs and eroded pillars around Reddell Point in survey zones A and B (**Figs 8, 10**). Semeniuk (2008) briefly describes this unit in his account of the Holocene deposits of the Canning Coast, but refrains from naming it, presumably because of its assumed pre-Holocene age and complex origin. This unit sits atop eroded upper parts of the Broome Sandstone and also forms a zone between the red Pleistocene Mowanjum Sand (Pindan) and younger Holocene units (primarily the reworked Mowanjum Sand and white coastal dune sands; see below).

The clasts in the breccia are typically angular, and range in size from gravel (~2 mm) to large boulders up to 0.5 m in diameter. They consist of dark grey to black ironstone clasts and ferruginised (iron-impregnated) sandstone (**Fig. 10A–B)**. Some of the latter might represent the eroded remnants of the upper parts of the Broome Sandstone. Alternatively, as hinted at by Semeniuk (2008), they may have eroded from older ironstone duricrusts of the hinterland. Whatever their source, reworked red Mowanjum Sand appears to form the red matrix within the breccia, as well as finer layers where the clasts are restricted to yellow to brown/creamy coloured muddy sands and muds up to 10–15 cm in diameter, giving these horizons a distinctive mottled appearance. In the higher cliffs, the boundary between the finer mottled layers and breccias is sharp, with the breccia horizons finning upwards over one to two metres of stratigraphic thickness (**Fig. 10C**). Semeniuk (2008) considered these horizons to represent colluvial accumulations of sedimentary origin that formed at the landward interface of the intertidal zone.

Where the cliffs meet the beach, the sands within the breccias have eroded and the cliffs have collapsed, leaving boulders of resilient black ironstone and ferruginised sandstone clasts strewn over headland (**Fig. 10A**). A large finger of these eroded boulders extends seawards from Reddell Point over the Broome Sandstone, forming the northwestern boundary of Reddell Point Beach in survey zone B. A thin (2–5 m) strip of black ironstone boulders extends from this area for around 350–400 m, parallel to the beach and 80 m from the astronomical high tide mark (**Fig. 8**).

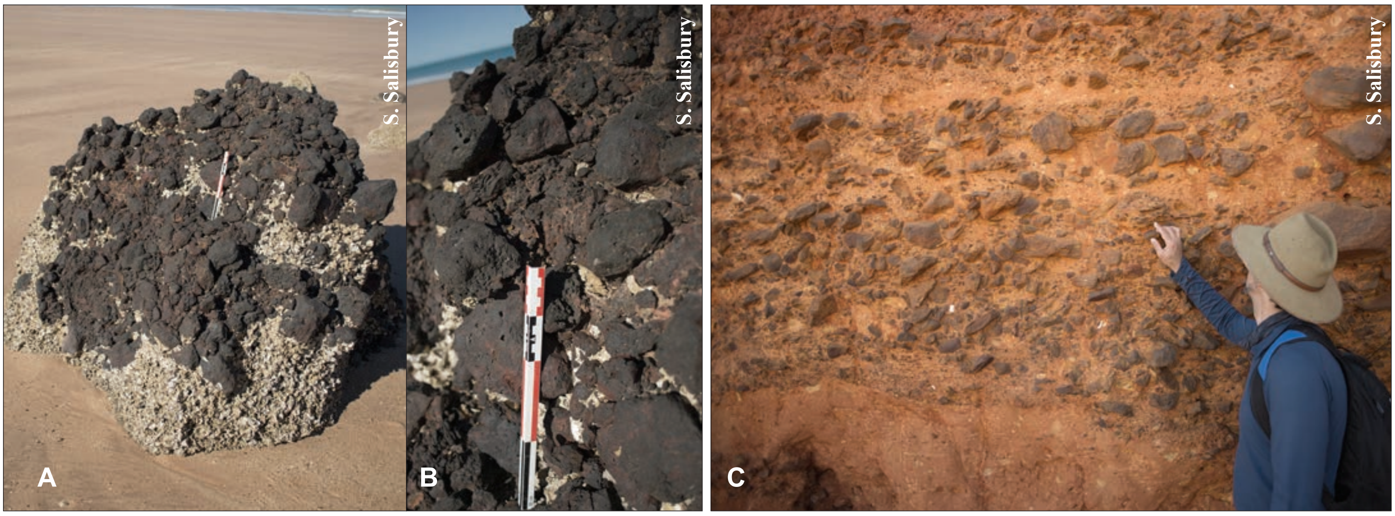

Figure 10. Unnamed mottled muddy sand and gravel, and ironstone breccia (Quaternary?). **A**, breccia of black ironstone clasts. **B**, close-up of clasts in A. **C**, Dr Anthony Romilio examines a sequence of breccias and sandy muds and gravels forming a low cliff at Reddell Point (survey zone B). © Steven W. Salisbury.

At Bungurunan, the small beach just to the north of Reddell Point in survey zone A, eroded pillars formed by the mottled muddy sand and gravel and ironstone breccias of this unnamed Quaternary(?) unit show where Yinara and the other Ngadjayi (female sea spirits) encountered Marala, the Emu Man, in one of the Bugarrigarra stories associated with the Song Cycle (**Figs 2, 11**). Yinara, the tallest of the pillars, stands proud of the sand, surrounded by the smaller pillars of the younger Ngadjayi. The rock platforms nearby preserve three-toed tracks that show where Marala walked (Salisbury et al. 2017; **see Fig. 1**). As such, this area is of high cultural significance, and provides the ideal starting point for people to learn about the rich cultural and scientific values associated National Heritage listed dinosaurian tracks on this part of the Dampier Peninsula coastline.

Figure 11. Prof. Carmen Lawrence, Patron of the Dinosaur Coast Management Group, alongside the Yinara pillar at Bungurunan (survey zone A). © Steven W. Salisbury.

Red sand dunes (Mowanjum Sand; Quaternary) and perched Holocene white coastal dune sands

Red desert sands of the Mowanjum Sand (known locally as 'Pindan') and white coastal dune sands that are perched upon then form the surface exposure over all of Entrance Point above the intertidal zone, overlying the older and much thicker Broome Sandstone (see below). The Mowanjum Sand is a structureless unit that consists mainly of red to orange quartz sand of aeolian (wind blow) origin derived in inland deserts, and is considered to be Pleistocene in age (between 10K and 2.6 million years old; Semeniuk 1984, 2008). Sheets and wedges of white sand, ferruginised sand and root-structured sand also occur within the main red sand (Semeniuk 2008), and can been seen in the dunes above Reddell Point Beach in survey zones B and C, and at Entrance Point adjacent to survey zone D. Younger dunes of Holocene age (<10K BP), consisting of reworked Mowanjum Sand form shore-parallel red dunes that are mixed or interfinger with perched Holocene coastal dunes derived from calcareous beach sands. Between the main foredune complex and Kavite Road and the industrial precinct in survey zones A–D, small patches of endangered monsoon vine thicket persist in the more protected swales formed by these Holocene dunes. In other parts of the Kimberley, similar patches of this unique dry rainforest are included in the West Kimberley Heritage Area because of the evolutionary refugial role they play in supporting high invertebrate richness and endemism.

Broome Sandstone (Valanginian–Barremian; 140–127 million years old)

General characteristics and age.

The Broome Sandstone is a terrestrially derived Mesozoic unit within the Canning Basin of north-western Western Australia that forms much of the underlying 'bedrock' of the Dampier Peninsula, including the survey area. It extends over approximately 200 km of the Dampier Peninsula coastline, offshore and south to Bidyadanga, and inland for approximately 100 km. Despite its immense extent, apart from a few hills, exposures of the Broome Sandstone are limited to the intertidal zone; inland, Palaeogene–Quaternary coastal deposits such as the Mowanjum Sand (see above) bury it upper surfaces. Boreholes across the different parts of the peninsula show that the preserved portion of the Broome Sandstone is at least 274 m thick (McWhae et al., 1956; Veevers and Wells, 1961; Playford et al., 1975; Gorter et al. 1979; Forman and Wales, 1981; Gibson, 1983; Yeates et al., 1984; Haines, 2011; Salisbury et al. 2017).

The type section of the Broome Sandstone occurs in the sea-cliffs at Minyirr. It is typically defined as alternating sequences of coarse-grained to fine micaceous sandstones, subordinate interbedded siltstones, conglomerates and poorly preserved soil horizons, deposited in marginal coastal plain settings, typified by a series of prograding deltas (McWhae et al., 1956; Brunnschweiler, 1957; Veevers and Wells, 1961; Playford et al., 1975; Forman and Wales, 1981; Salisbury et al. 2017). Exposures to the north of Broome around Walmadany (James Price Point) are typically more fluvial (riverine) in nature than those around Broome, which are thought to represent more coastal depositional settings.

The precise age of Broome Sandstone has been difficult to establish due to the absence of marine invertebrate fossils (which are important for global age correlations). The most precise age proposal is that Niccoll et al (2009), who used dinocysts and spore-pollen correlations to constrain the age to the middle-Valanginian to middle-Barremian age (140 to ~127 million years ago).

Exposures of Broome Sandstone in the survey area.

There are extensive exposures —approximately 1.2 km^2—of Broome Sandstone throughout the intertidal zone in the survey area. It forms a near continuous reef that runs parallel to the shore from the southern end of Reddell Beach (survey zone A) around Entrance Point to Broome Jetty (the boundary between survey zones F and G), over a distance of 3.8 km. The outer reef is 200–300 m wide for most of its length. The extent to which the outer reef system is exposed during large spring tides, when the low tide extends below 1 m, is considerably more extensive than that shown in the preliminary site proposal for the Safe Boat Harbour, which appears to be based on a satellite image that we estimate was taken with the ocean at around the 4–5 m low tide mark (**Fig. 3**). At 4–5 m, the entire outer reef system, which extends from approximately 200 to 500 m from the shore, is not apparent.

At Reddell Point (the north-western end of zone B), the south-eastern end of Reddell Point Beach (the south-eastern end of survey zone C) and the southern end of Entrance Point (zone D and the western side of zone E), the exposure of Broome Sandstone is almost unbroken from the astronomical high tide mark out to the 0.9 m low tide mark, extending over a distance of 300–350 m. Along Reddell Point Beach (the south-eastern half of survey zone B and all of survey zone C), the main exposure of Broome Sandstone starts around 190 m from the astronomical high tide mark at around the 2 m low tide mark, and from there extends out to point 420 m from the shore at the 0.9 m low tide mark. A second, narrower band of Broome Sandstone runs parallel to the shore, extending from the astronomical high tide mark out to approximately 7.5 m low tide mark, forming the upper 50 m of beach. Outcrops of Broome Sandstone in this area are partially buried by a thin (~1–2 m thick) veneer of beach sand. Some of the more prominent platforms are permanently exposed, but many of the others are buried as often as they are visible, indicating that the sand cover is not only relatively thin, but also very mobile (**Figs 5A, 9B**).

The small headlands at the southern end of Entrance Point (at the boundaries of survey zones D and E, and E and F) are each formed by Broome Sandstone. From the most southerly headland, similar to Reddell Point Beach, a thin (30–25 m) strip of Broome Sandstone connects the two headlands and hugs the coastline, extending northeast to Broome Jetty. A small exposure of Cable Beach Sand unconformably sits atop this band of Broome Sandstone either side of the south-east facing boat ramp. North of Broome Jetty, exposures of Broome Sandstone are limited to a narrow (100 m wide) continuation of the main reef system that runs parallel to the shore, ending just south of the Kimberley Port Authority slipway (**Fig. 7**). North of the slipway, at the southern end of Simpson's Beach, there appears to be minimal intertidal exposure of the Broome Sandstone.

Physical characteristics (lithology) of the Broome Sandstone in the survey area.

All the exposed strata of the Broome Sandstone in the survey area are essentially flat lying with no appreciable dip, as is the case in other parts of the Dampier Peninsula (e.g., Walmadany; Salisbury et al. 2017). As a consequence, the stratigraphically lowest (i.e., older) horizons are more seaward, while the higher (i.e., younger) ones are more landward. Although the outcrop is highly eroded by surf action, and the exposure is patchy, particularly where there is a lot of sand cover, based on the vertical extent of the intertidal exposures and sections exposed in the low cliffs, headlands and pillars throughout the survey area (**Fig. 12**), there is approximately 10–11 m of stratigraphy preserved. This thickness is consistent with adjacent beaches and the type area at Minyirr.

The outer-most exposures of Broome Sandstone are heavily encrusted in large corals and other marine invertebrates (**Fig. 13A**), making observations about their lithology difficult. From around the 1.5 m low tide mark, however, invertebrate encrustation is reduced, and for outcrops that are intermittently buried, surfaces are relatively clean.

Figure 12. Strata of the upper exposed section of Broome Sandstone. **A**, exposure at Entrance Point (survey zone E) with high-angle cross-bedding and channel structures. Nigel Clarke for scale. **B**, exposure at Reddell Point Beach (survey zone C). © Steven W. Salisbury.

Overall, the lithology and structure of the Broome Sandstone in the survey area is very similar to that described for the northern part of Reddell Beach by Gray (2015), and some of the horizons maybe be stratigraphically equivalent. The bulk of the section, particularly the lower eight metres, is dominated by a series of alternating, sub-centimetre thick sandstone and siltstone beds (**Fig. 13B**). The sandstone is a rusty red to orange in colour, while the siltstone is cream to white. Sedimentary structures within these laminated beds include symmetrical ripple marks, desiccation cracks, and rare invertebrate burrows (**Fig. 13B–C**) and dinosaurian track horizons (see below). Higher in the section, at approximately nine metres, cross-bedding (sets of inclined layers) and cross-cutting channel structures begin to appear. Some of these channels are over a metre in width, and they cut through the surrounding finer laminations and cross-bedding (**Fig. 12**). High angle cross-bedding on some eroded pillars in survey zone C on Reddell Point Beach exceeds 30–40º (**Fig. 13D**), as was observed by McCrea et al. (2012).

At Entrance Point, the upper 1–2 m of Broome Sandstone becomes more sand-dominated, and includes thin (10–30 cm) lenses that contain sub-angular rip-up clasts of what appear to be the paler coloured siltstone. Above these breccia layers, the laminated sandstone and siltstone with channels and cross-bedding returns. Rare fossilised impressions of plant—typically partial fronds of bennettitaleans, a cycad-like fern—occur in some of the upper-most parts of the section, usually within the siltstone laminations (**Fig. 13E**).

Figure 13. Exposures, sedimentary structures and fossil traces of the Broome Sandstone within the survey area. **A**, the stratigraphically lowest exposures are heavily encrusted with large coral colonies (survey zone C). **B**, fossil ripple marks (survey zone E). **C**, fossilised horizontal invertebrate burrows (survey zone C). **D**, high angle cross-bedding (survey zone C). **E**, fossilised impressions of bennettitalean frond fragments (survey zone C). © Steven W. Salisbury. © Anthony Romilio

Dinosaurian tracks are a common feature of the Broome Sandstone within the survey area, but are restricted to the lower 8–9 metres of the section within the finely laminated sandstone and siltstone, always below the start of the channels and cross-bedding. The majority of track-bearing horizons seem to be concentrated in two main bands: the first at approximately 7–9 metres (between the 9 and 7 m low tide mark), starting close the astronomical high-tide mark and extending for 30–40 metres seawards; the second at approximately 1–2.5 metres (between the 2.5 and 1 m low tide mark), close to the seaward edge of main reef system. Additional concentrations of track-bearing horizons occur between the two main bands, particularly at Reddell Point (survey zone B) and at the south-eastern end of Reddell Point Beach (survey zone C) and throughout survey zone D. The dinosaurian tracks are described in more detail in the following sections. Tracks that occur in the lower part of the section, in the main reef system, are typically encrusted with coral and other marine invertebrates. The track-bearing surfaces that are higher in the section and which are periodically buried in beach sand are typically much cleaner.

The lithologies and sedimentary structures observed in exposures of Broome Sandstone in the survey area point to a depositional setting that was most likely a low energy deltaic tidal flat, as has been proposed for the northern part of Reddell Beach by Gray (2015). The surface of the tidal flat was routinely traversed by dinosaurs, presumably moving along the coastline. With time, towards the top of the section as the delta system prograded (i.e., migrated seawards), parts of the tidal flat were cut by shallow drainage and/or river channels. It is possible that there was some degree of aeolian (wind-driven) deposition on parts of exposed sandbars, as has been suggested by McCrea (2012).

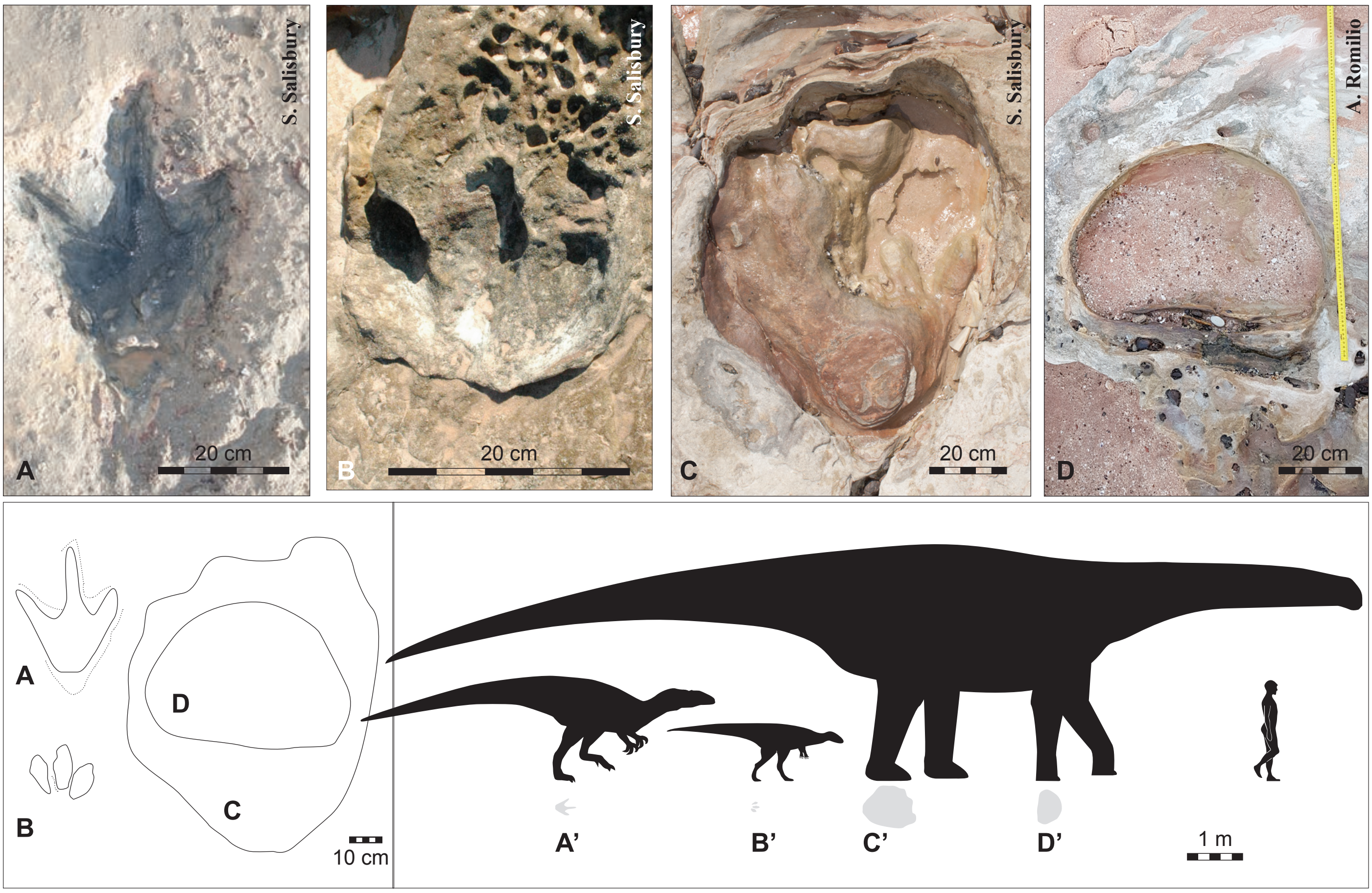

Figure 14. Dinosaurian track types within the survey area. **A**, theropod pedal impression (*Megalosauropus broomensis*; survey zone E). **B**, ornithopod pedal impression (*Wintonopus middletona*; survey zone C). **C**, sauropod pedal and (D) manual impressions (undescribed ichnotaxon; survey zone C). © Steven W. Salisbury. © Anthony Romilio

NATIONAL HERITAGE LISTED DINOSAURIAN TRACKS OF THE REDDELL POINT—ENTRANCE POINT AREA

We have recorded over 140 National Heritage listed dinosaurian track-bearing surfaces in the Broome Sandstone within the survey area. Many of these surfaces preserve multiple tracks and trackways, so the total number of individual tracks is much higher. Some areas, such as Reddell Point (survey zone B) are heavily trampled and probably include hundreds of individual tracks and trackways. We conservatively estimate that there are easily more than 500 individual tracks in this area, potentially spanning many tens, if not hundreds of thousands of years of dinosaurian activity 140–127 million years ago.

Main track types

Three different types of dinosaurian tracks occur within the survey area: sauropod tracks, theropod tracks and ornithopod tracks (**Fig. 14**). The preservation of tracks ranges from 'true' tracks that preserve details of the manual and pedal morphology of the trackmakers, tracks preserved as pedestals, through to partially eroded tracks, and various forms of transmitted tracks. Cross-sections through some tracks show the relationship between the true track (on the track surface traversed by the trackmaker) and the underlying transmitted tracks (the deformed layers directly beneath the true track), providing insights into the physical characteristics of both the trackmaker and track horizons (e.g., relative body mass, foot movement and sediment plasticity) (**Fig. 15A**).

The sauropod tracks are the most abundant track types and occur within zones A–F of the survey area and possibly in zone G. There are isolated pedal and manual tracks, coupled sets of manual and pedal tracks, and portions of trackways. Pedal tracks form large, pear-shaped depressions that are approximately 1.3 times as long as they are wide. The largest around 110–120 cm long, whereas the smallest are approximately 30 cm long, although most range in length from 60–70cm. The manual tracks are considerably smaller, forming shallow, kidney shaped depressions that are approximately 1.6 times longer than they are wide, but with the longest axis being perpendicular to that of the pedal tracks. Where the pedal and manual tracks occur in couplets or as part of a trackway, the pedal tracks are around four times the size of the manual tracks.

Figure 15. Dinosaurian tracks preservation. **A**, sauropod tracks preserved in cross-section (survey zone C). **B**, theropod and sauropod tracks preserved as true tracks (survey zone A). Note the tracks in B indicate coeval occurrence of theropod and sauropod trackmakers. © Steven W. Salisbury. © Damian Kelly

Some aspects of the morphology and trackway parameters of the sauropod tracks in the survey area point to the presence of a new track type that is distinct from the six other types of sauropod tracks already described from the Broome Sandstone by Salisbury et al. (2017). These tracks are characterised by long and broad impressions for the first three toes, and a gently tapered heel region (**Fig. 14C**), among other characteristics. Associated manual tracks are kidney-shaped and lack any indication of a pollex (thumb) impression (**Fig. 14D**). The morphological detail associated with some of these tracks, their occurrence in multiple trackways and the range of preservation styles that occur within the survey area is scientifically significant, and further research may lead to them forming the basis of a new sauropod ichnotaxon (track type). This sauropod ichnotaxon appears to be unique to the Broome Sandstone of the greater Broome area (i.e., Cable Beach–Minyirr–Reddell Beach–Entrance Point and Roebuck Bay), and does not occur in exposures farther north around Walmadany described by Salisbury et al. (2017). The high density of some of these sauropod tracks in some parts of the survey area (e.g., survey zone B and the southern end of survey zone C) might also provide evidence of sauropod herding behaviour.

Three-toed theropod tracks are the second most abundant track type in the area (**Fig. 14A**), and occur in surveys zone A, D and E. Most of these tracks appear to be assignable to *Megalosauropus broomensis*, the type tracks of which occur at Minyirr (Glauert, 1952; Colbert and Merrilees, 1967; Salisbury et al., 2017; Romilio et al., 2017). They range in size from around 25–55 cm in length, and occur as isolated tracks and trackways.

In survey zone A, at Bungurunan, there is a rare example of direct association between a theropod trackway and sauropod trackway (**Figs 15B, 17C**), in which one overprints the other. This is one of the few instances in the entire Broome Sandstone where we can infer a sequence of trackmaking events in the same track surface between two different types of trackmakers. Also of significance, in survey zone E there is a high concentration of theropod tracks assignable to *Megalosauropus broomensis*, seemingly made by multiple trackmakers, all on the same track surface (**Fig. 24A,B**). Such a concentration of tracks point to a possible aggregation of trackmakers, which, in the case of theropods, might point to behavioural interactions. This is also extremely rare in the Broome Sandstone and warrants further detailed research. Overall, the high abundance of theropod tracks in the survey area and adjacent areas such as Reddell Beach relative to other parts of the Dampier Peninsula is significant, and may point to possible habitat preferences for these trackmakers. Of cultural significance, theropod tracks in the survey area form part of the Northern Tradition of the Song Cycle, and feature in Bugarrigarra stories about Marala, the Emu Man (see 'Cultural significance').

In survey zone C, at the southern end of Reddell Point Beach, there is a rare example of an ornithopod track (**Figs 5A, 14B**). This track is small, around 30 cm across by 20 cm in length, with three short, broad toe impressions and no indication of a heel. This particular track seems to be assignable to *Wintonopus middletona*, a type of ornithopod track unique to the Broome Sandstone recently described by Salisbury et al. (2017). *Wintonopus middletona* is extremely rare, known only from three other tracks, all of which occur in the Walmadany area. Hence, the track from Reddell Point Beach is the first confirmed case of *W. middletona* and one of the few ornithopod tracks in the entire Broome area. The presence of this particular track at Reddell Point Beach is scientifically significant in that it adds to our knowledge of this poorly known track type, and extends both its geographic and its stratigraphic range. Moreover, it alters our understanding of the inferred makeup of the dinosaurian trackmakers in the local area.

Additional comments on each of the survey zones (A–G; Fig. 8)

Zone A

Zone A includes part of a small beach known as Bungurunan. It occurs at the southern end of Reddell Beach, which preserves an extremely high abundance of National Heritage listed dinosaurian track-bearing surfaces (**Figs 16 and 17**). These are found within at least three distinct track-bearing horizons, the first between the 9 and 7 m low tide mark, starting close the astronomical high-tide mark and extending for 30–40 metres seawards (**Fig 16A**); the second between the 5 and 3 m low tide mark, 150–230 m from the astronomical high-tide mark (**Fig 16B–E**); and the third between the 2.5 and 1 m low tide mark, close to the seaward edge of main reef system (**Fig 17**). Other track-bearing horizons also occur scattered between these main zones.

The tracks of this zone are exclusively saurischian in origin, being made by sauropods and theropods. Sauropod tracks dominate, but there are high numbers of theropod tracks and trackways, pointing to the contemporaneous occurrence of two different types of dinosaurs. Some of the *Megalosauropus broomensis* trackways are the best examples in the Broome Sandstone, and are currently being researched as part of study focused on this particular track type.

Bungurunan is of high cultural significance, preserving eroded stone pillars that show where Yinara and the other Ngadjayi (female sea spirits) encountered Marala, the Emu Man, in one of the Bugarrigarra stories associated with the Northern Tradition of the Song Cycle (**Figs 2, 11**). Yinara, the tallest of the pillars, stands proud of the sand, surrounded by the smaller pillars of the younger Ngadjayi. The rock platforms nearby preserve three-toed tracks that show where Marala walked (Salisbury et al. 2017; **see Figs 15B, 16E, 17C**).

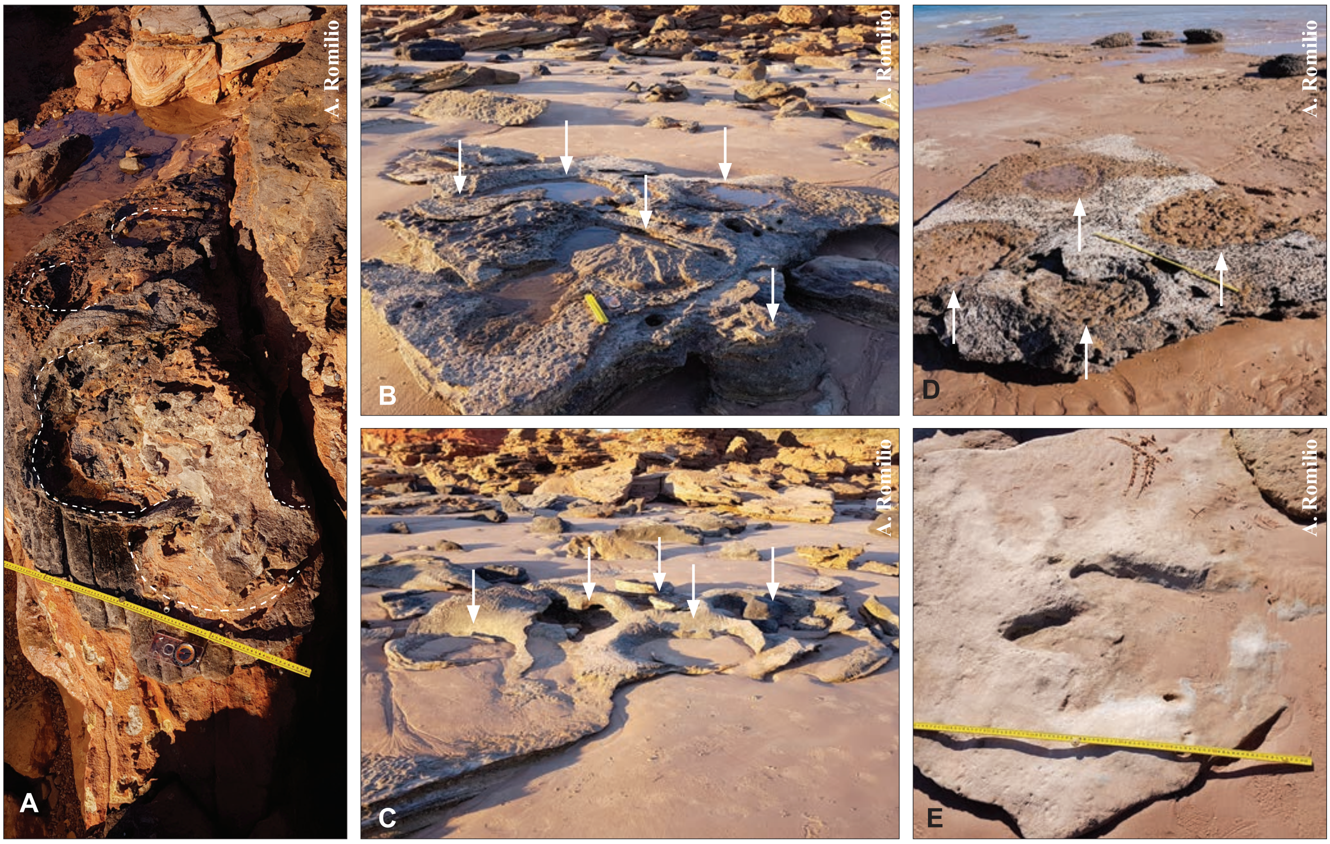

Figure 16. Survey zone A, National Heritage listed dinosaurian track-bearing surfaces. **A**, sauropod trackway located between the 7–9 m low tide mark. **B–D**, sauropod trackways located between the 3–5 m low tide mark. **E**, theropod track located near the 3–5 m low tide mark © Anthony Romilio

Figure 17. Survey zone A National Heritage listed dinosaurian track-bearing surfaces located between the 1–2.5 m low tide mark. **A**, sauropod trackway. **B**, sauropod trackway. **C**, sauropod trackway associated with at least one theropod trackway.

Zone B

Zone B encompasses Reddell Point and the north-western part of Reddell Point Beach. Similar to the southern end of Reddell Point, it is characterised by high abundance of dinosaurian tracks, and many of the track-bearing surfaces are likely continuous between the two areas (**Fig. 18**). Track-bearing surfaces occur right through the intertidal zone, but are more concentrated close the astronomical high-tide mark between the 9 and 7 m low tide mark (**Fig. 18D**), between the 5 and 3 m low tide mark (70–130 m from the astronomical high-tide mark; **Fig. 18D**) and between the 2.5 and 1 m low tide mark, 190–300 m from the shore and close to the seaward edge of main reef system (**Fig. 18A–C**).

The tracks of this zone are exclusively those of sauropods. Some of the track-bearing surfaces are heavily 'trampled' over a large area (200–300 m^2), and the concentration of tracks is so high that individual trackways are often difficult to discern (**Fig. 18A, D**). Significantly, these trample zones and adjacent track-bearing surfaces in survey zone B preserves a number of well-preserved manual tracks, which, being shallower than pedal tracks are often easily eroded. Additionally, tracks occur across a spectrum of erosional states, providing an important reference in enabling footprint identification.

Of historical significance, this area includes the first sauropod tracks discovered in Australia, made by the late Paul Foulkes back in the late 1980s. (**Figs 5B, 19**).

PREVIOUS PAGE
Figure 18. Survey zone B National Heritage listed dinosaurian track-bearing surfaces. **A**, Dr Anthony Romilio points to sauropod tracks. **B**, Dr Steven Salisbury records the GPS of part of a track-bearing surface that includes the coupled manual and pedal tracks of a sauropod. **C**, Dr Anthony Romilio shows a discernible sauropod trackway within the trample zone. **D**, sauropod tracks. **E**, sauropod tracks that possibly includes several coupled manual and pedal tracks. E, indistinct sauropod true tracks within trampled area. © Steven W. Salisbury. © Anthony Romilio

Figure 19. Survey zone B contains the first sauropod tracks identified in Australia. **A**, large sauropod tracks discovered during the late 1980s by the late Paul Foulkes. **B**, Billy Foulkes stands at the dinosaur tracksite his grandfather discovered (April 2014). © Steven W. Salisbury.

Zone C

Zone C covers the south-eastern two-thirds of Reddell Point Beach, spanning a distance of around 1 km. It contains a moderate abundance of dinosaurian tracks. Where the Broome Sandstone is exposed, track-bearing surfaces occur in two main zones that run parallel to the beach. The first, which contains a higher number of tracks, occurs close the astronomical high-tide mark between the 9 and 7 m low tide mark, forming the upper 50–70 m of the intertidal zone (**Fig. 21**). The second, which contains multiple trackways but fewer tracks overall, is between the 2.5 and 1 m low tide mark, 180–280 m from the shore (**Fig. 20**). Some tracks also occur between these two zones, particularly towards the south-eastern end of the beach (**Fig. 22**). Overall this end of the beach has the greatest concentration of tracks in zone C, most likely because it has less sand cover than the north-western end of the beach.

Sauropod tracks dominate survey zone C, many over a metre in length, and a number of these occur in trackways and show morphological details suggestive of a new track type that is yet to be described or named (**Fig. 22C–D**; see previous section on sauropod tracks). Significantly, zone C preserves the fourth known occurrence (in the world) of the ornithopod track *Wintonopus middletona* (**Fig. 21A,B**), and the only one south of the Walmadany area (see Salisbury et al. 2017). This newly discovered track preserves morphological details not seen in the previously described tracks, providing new insights into the pedal anatomy and movements of its trackmaker.

Figure 20. Survey zone C National Heritage listed dinosaurian track-bearing surfaces located between the 1–2.5 m low tide mark. **A**, Dr Steven Salisbury points to sauropod trackway. **B**, Dr Steven Salisbury points to large sauropod tracks. **C**, sauropod dinosaur coupled manual and pedal tracks preserved as true tracks. **D**, sauropod trackway preserved as pedestals with Dr Anthony Romilio and Dianne Bennett (DCMG). © Steven W. Salisbury. © Anthony Romilio.

Figure 21. Survey zone C National Heritage listed dinosaurian track-bearing surfaces located between the 7–9 m low tide mark. **A**, Louise Middleton shows Dr Bob Brown the ornithopod track that bears her name–*Wintonopus middletona*. **B**, close-up of *Wintonopus middletona*. **C**, aerial view of several trackways formed by large-bodied sauropods. **D**, water retained within a possible sauropod undertrack cools 'Missy the dinosaur-tracking dog'. **E**, coupled manual and pedal sauropod tracks. **F**, sauropod trackway. **G**, sauropod trackway with Dr Steven Salisbury and Leon Teoh (DCMG). **H**, sauropod tracks preserved with infill and in cross section. © Damian Kelly. © Steven W. Salisbury. © Anthony Romilio.

Figure 22: Survey zone C National Heritage listed dinosaurian track-bearing surfaces, between the 2.5–7 m low tide mark. **A**, Dianne Bennett (DCMG) with Steve Backshall (Deadly 60) after storm activity stripped vast amounts of sand from the south-eastern end of the beach, exposed the underlying Broome Sandstone. **B**, Jeremy MacMath (SoB) at the site of a currently unnamed, and likely new sauropod track type. **C**, close-up of the pedal impression of the unnamed sauropod track type. **D**, close-up of the manual impression of the unnamed sauropod track type. **E**, exposure with sauropod tracks.
© Kevin Smith. © Steven W. Salisbury. © Anthony Romilio.

Zone D

Zone D forms the southern headland and rocky foreshore of Entrance Point. It contains a moderate abundance of dinosaurian tracks (**Fig. 23**). They occur within three main track-bearing horizons. The first is only 10 m from the astronomical high tide mark towards the top of the beach, between the 9 and 8 m low tide mark. The second is between the 5 and 3 m low tide mark, 100–140 m from the astronomical high-tide mark (**Fig. 23A–B**), while the third between the 2.5 and 1 m low tide mark, close to the seaward edge of main reef system, starting at around 230 m from the upper limit of the beach (**Fig. 23C**). The shorter distance from shore of these track-bearing surfaces relative to those in adjacent survey zones seems to relate to the overall slightly steeper angle of the reef system compared with other parts of the survey area.

The majority of dinosaurian tracks in zone D pertain to sauropods, but there is at least one theropod track assignable to *Megalosauropus broomensis*. An ornithopod track has been recorded in this area by Dianne Bennett (Dinosaur Coast Management Group). Unfortunately, at the time of our 2018 survey, the surface that this track occurs in was buried by sand. Some of the sauropod tracks in zone D are noteworthy for the morphological detail that is apparent in some of the manual tracks. A partial trackway close to the edge of the rocky headland forms a popular location for weddings, with couples often standing in one of the tracks as they take their marriage vows.

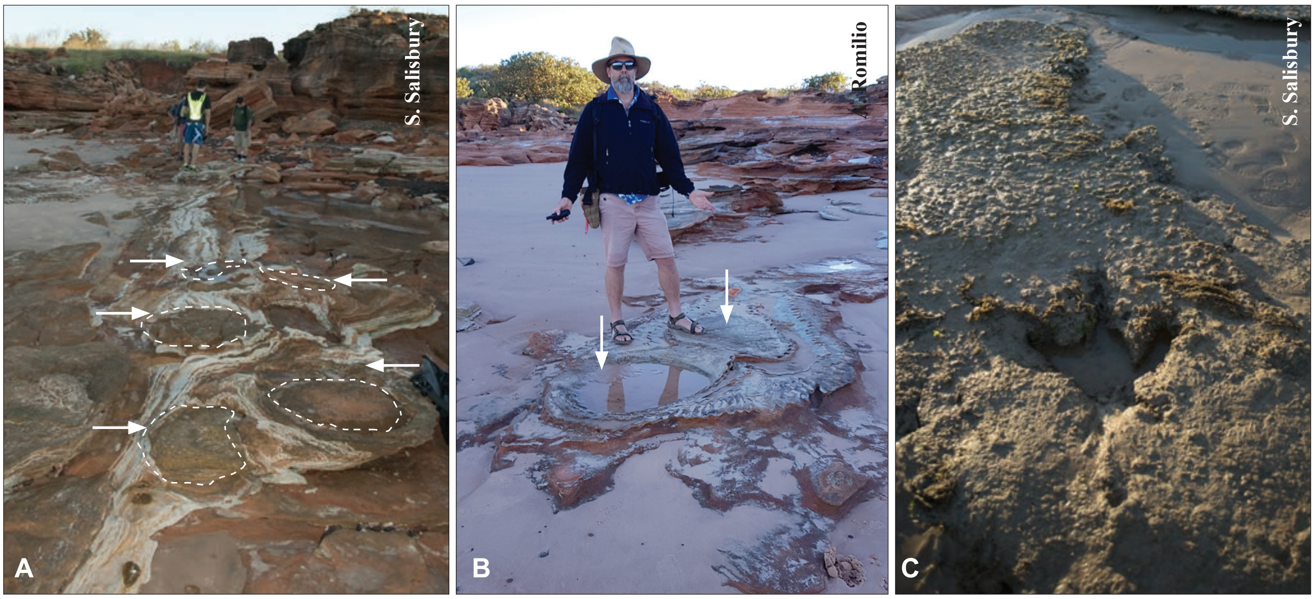

Figure 23. Survey zone D National Heritage listed dinosaurian track-bearing surfaces. **A**, sauropod trackway located between the 3–5 m low tide mark, with Kevin and Bill Foulkes, Jay Nair, and Damian Kelly. **B**, coupled manual and pedal sauropod tracks located between the 1–2.5 m low tide mark, as shown by Dr Steven Salisbury. **C**, theropod track located between the 1–2.5 m low tide mark. © Steven W. Salisbury. © Anthony Romilio.

Zone E

Zone E straddles the area between the two public boat ramps at Entrance Point, and is bounded at its north-eastern end by a low cliff of Broome Sandstone that includes well preserved ripple marks, cross-bedding and channel structures (**Figs 12A, 13B**).

Dinosaurian tracks in this zone occur within two track-bearing horizons (**Fig. 24**). One horizon, only visible at the lowest tide mark (1.2–0.3 m), preserves one of the highest single concentrations of theropod tracks currently known within the entire Broome Sandstone (**Fig. 24A–B**). Preliminary research of this tracksite indicates evidence of gregarious behaviour among the theropod trackmakers. Isolated sauropod tracks and partial trackways occur in what appears to be the same horizon along the northern boundary of this survey zone, around 200 m from the astronomical high tide mark and west from the low cliffs north of the south east-facing boat ramp. The second track-bearing horizon occurs close to the astronomical high tide mark, and includes a sauropod trackway that can be seen from the edge of the Entrance Point carpark (**Fig. 24C**).

Figure 24. Survey zone E National Heritage listed dinosaurian track-bearing surfaces. **A**, Prof. Tim Flannery alongside multiple theropod trackways (indicated by arrows). **B**, additional theropod trackways located between the 0.3–1.2 m low tide mark. **C**, sauropod trackway located between 8–9 m tide mark, close to the Entrance Point carpark. © Steven W. Salisbury.

Zone F

Zone F encompasses the south-east facing beach and inlet to the south of Broome Jetty. Only a few dinosaurian tracks occur in this area. Some isolated sauropod tracks and partial trackways on detached rock platforms occur just below the astronomical high tide mark along the upper shoreline (**Fig. 25A–D**), while others occur in a much lower horizon near the edge of the outer reef, and these are largely restricted to the southern half of this survey zone (**Fig. 25E**). We were only able to locate one track in the northern half of this area.

Dinosaurian tracks in this area are exclusively attributed to sauropods. Other fossils include fossilised invertebrate burrows. Some are preserved in situ in exposures of Broome Sandstone close to shore and under the jetty, while many occur as in loose slabs. Some of these tubes and burrows can be attributed *Domichnia* ('dwelling' traces) or *Fodinchia*, ('feeding' traces) which has been recorded in Broome Sandstone in the Walmadany area (Salisbury et al., 2017:Fig. 17A, B), but these are much larger and may pertain to the ichnogenus *Thalassinoides* (**Fig. 25F**). Some of the other invertebrate traces might be assignable to *Palaeophycus*, which, to our knowledge, has not been reported from the Broome Sandstone (**Fig. 25G**).

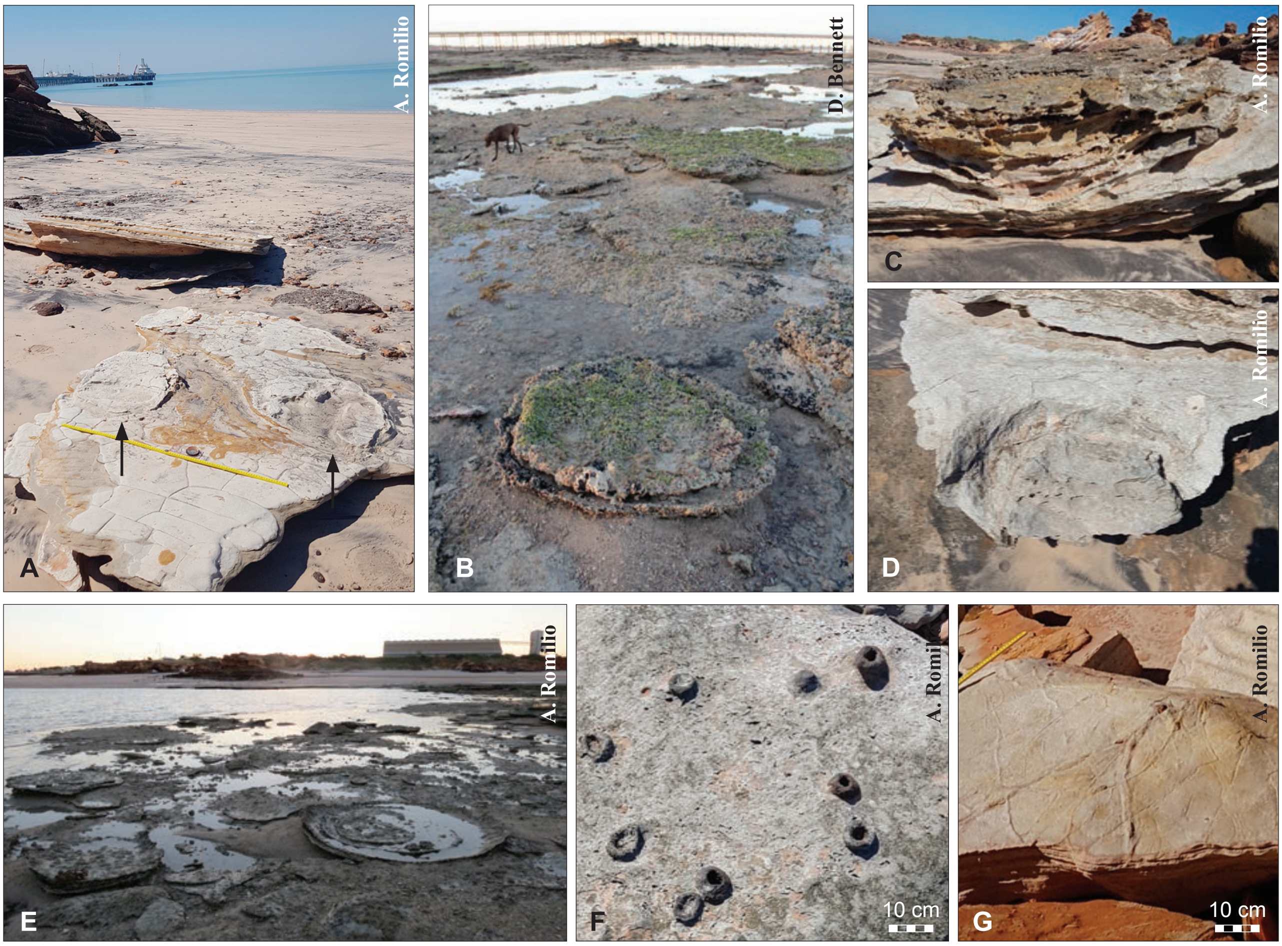

Figure 25. Survey zone F National Heritage listed dinosaurian track-bearing surfaces and related trace fossils. **A**, detached platform with a partial sauropod trackway. **B**, in situ circular structures that may represent sauropod tracks; **C**, isolated partial sauropod track in cross section. **D**, isolated partial sauropod true track. **E**, in situ circular structures that likely represent transmitted sauropod tracks. **F**, large invertebrate burrows assignable to *Thalassinoides*. **G**, horizontal invertebrate burrows assignable to *Palaeophycus*.

Zone G

Zone G, between Broome Jetty and the KPA slipway, does not appear to preserve any dinosaurian tracks in the exposed sections of Broome Sandstone. Some circular structures close to the shore have the appearance of sauropod tracks, although they could equally be erosional features (**Fig. 26A–B**). North of the slipway, in the inlet below the Broome Hovercraft hanger, we found no evidence of dinosaurian tracks in the intertidal zone.

Figure 26. Survey zone G with in situ circular structures. **A**, structure may represent a transmitted sauropod track. **B**, possible sauropod trackway. © Anthony Romilio.

4. DISCUSSION

OVERVIEW AND SIGNIFICANCE

Scientific significance of dinosaurian tracks and related geological structures

The Broome Sandstone is globally unique because of the high abundance of dinosaurian tracks it preserves, the geographical extent of the tracksites, and, most significantly, the unparalleled diversity of tracks that are represented (Salisbury et al. 2017). Nowhere else in the world has as many different type of dinosaurian tracks as the Dampier Peninsula. The Broome Sandstone also provides our only detailed look at Australia's dinosaurian fauna during the first half of the Cretaceous Period, between 127 and 140 million years ago; we have no other dinosaurian sites of this age in Australia. The tracks form the primary record of dinosaurs for the western half of Australia, and many of them have no obvious counterpart among described body fossils from other parts of the continent. For these reasons, dinosaurian tracks in the Broome Sandstone form one of the key values associated with the West Kimberley National Heritage Area, and, as such, are afforded protection under the 1999 Environmental Protection and Biodiversity Conservation Act.

Given the dynamic nature of the Dampier Peninsula coastline and the ephemeral exposure of the Broome Sandstone along its sandy beaches, we can never be completely sure that all the dinosaurian tracks and track-bearing surfaces within the survey area were observed. It is very likely that many more tracks than the ones we have reported on herein lie just beneath the sand on some of the beaches we walked over. Nevertheless, combined with our earlier research work in the area between 2011 and 2017, our 2018 survey gave us a much better understanding of the extent of dinosaurian tracks in this area, and we feel we have enough information to comment on their scientific significance.

The large geographic extent and varying stratigraphic position of dinosaurian tracksites in the Broome Sandstone means that it may be possible to determine the distribution and abundance of different types of dinosaurs in a range of habitats through time—something that is rarely possible with body fossils. Detailed digital mapping and stratigraphic work that we have carried out since 2011 is allowing us to reconstruct large parts of the Dampier Peninsula coastline, and determine the extent to which different tracksites and track-bearing surfaces relate to each other stratigraphically within the exposed sections of Broome Sandstone (see Romilio et al., 2017). This work will provide an unprecedented insight into the palaeoecology of Australian dinosaurs. The results will also provide an exciting platform from which to design management strategies for the dinosaurian tracksites of the West Kimberley National Heritage Area, which occur in a unique coastal setting on publicly accessible beaches.

As far as we know, the Reddell Point–Entrance Point area preserves the most southerly dinosaurian track-bearing surfaces in the Broome Sandstone within the West Kimberley. The tracksites are well south of those that occur further to the east on the northern shores of Roebuck Bay, and south of those on Reddell Beach, Minyirr and Cable Beach (Maralgun). From what we currently know of the geology and stratigraphy of the Broome Sandstone, these tracksites may therefore sit within a unique part of the great delta system that formed the Broome Sandstone 140–127 million years ago. The dinosaurs that inhabited this area may have lived in the most coastal of all the palaeoenvironmental settings that formed part of the Broome Sandstone delta system, and represent a unique part of the palaeontological story that we are beginning to reconstruct for this area.

In the context of this broader story, all the tracks in the survey area are important, and only in their entirety can they help us to reconstruct this prehistoric 'lost world' of the Kimberley. We can use the data collected during the course of this study to begin to assess the relative abundance of each of the main track types (sauropod, theropod and ornithopod) within the geological time represented in by the 10–11 section of Broome Sandstone that occurs in the survey area. Assuming the preserved section of Broome Sandstone represents many tens, if not hundreds of thousands of years of deposition, we can now start to map where individual track-bearing surfaces occur relative to each other, as well as other adjacent beaches such as Reddell Beach where we have similar data. Further work on the depositional environment associated with the sediments in which the tracks occur, and comparing these data through the section, will allow us to see how the dinosaurs were using the different habitats. To be able to even attempt to do something like this highlights just how significant and unique the Broome Sandstone is.

Some of the tracks and trackways that occur in the survey area are scientifically significant in their own right. Some of the sauropod tracks in this area provide important evidence for the recognition of a new type of track that is not seen anywhere else in the world. This is particularly true for tracks that occur at Reddell Point (survey zone B) and along parts of Reddell Point Beach (survey zone C). Reddell Point also preserves evidence of the passage of many sauropod trackmakers, seemingly all on the same track surface, and therefore presumably around the same time. Although we may never be sure, such evidence is very suggestive of these gigantic dinosaurs having traversed this part of the tidal flat in lumbering herd. Where they were going and exactly what these dinosaurs looked like is unclear, but trying to re-imagine this scene casts this small rocky headland in entirely new light. The Dampier Peninsula is the only place in Australia where evidence of this type of behaviour among sauropod dinosaurs can be seen. Of particular significance are 'sauropod thoroughfares', some of the best examples that are close to Broome.

The large number of theropod tracks in a single track horizon at Entrance Point in Survey zone E is also highly significant in its own right. This is one of the highest single concentrations of *Megalosauropus broomensis* that we are aware of in the Broome Sandstone, and may point to gregarious behaviour among the theropod trackmakers. At Bungurunan in survey zone C, there is also evidence for potential interaction between sauropod and theropod trackmakers. Significantly, these tracks include the smallest sauropod footprints currently known for the Broome Sandstone, and their association with comparatively large theropod tracks is reminiscent of one of the world's most famous 'dinosaur chase scenes', preserved in fossilised tracks in the Lower Cretaceous rocks of the Glen Rose Formation, Texas, where a theropod was apparently following a sauropod (Bird, 1944; Farlow et al., 2012; Thomas and Farlow, 1997; Falkingham et al., 2014).

The discovery on Reddell Point Beach (survey zone C) of the fourth known occurrence (in the world) of an ornithopod track that is assignable to *Wintonopus middletona* is also significant (**Figs 5A, 14B, 21 A,B**). This is the only confirmed example of an ornithopod track in the greater Broome area. Importantly, it hints at its trackmaker being a rare dinosaur in the Broome area (albeit for the palaeoenvironments that are preserved in zone C), and expands their geographic and stratigraphic range.

To conclude, the Reddell Point–Entrance Point area adds to the overall scientific significance of the Broome Sandstone, and preserves some unique aspects of its National Heritage listed dinosaurian ichnofauna.

Cultural significance

The theropod tracks preserved in the rocks at Bungurunan, the small beach at the northern end of Reddell Point (in zone A), form an important part of the cultural heritage of the Broome area and greater West Kimberley. They mark the place where the creation being Marala, the Emu Man, first encountered the Ngadjayi (female sea spirits), in a publicly known Bugarrigarra story linked to the Northern Tradition of the Song Cycle of the Dampier Peninsula coastline. The Dampier Peninsula is one of the few areas in the world where dinosaurian tracks are clearly integrated into indigenous creation stories (Major and Sargeant 2001; Salisbury et al. 2017). Bungurunan is an area where people can see and learn about this remarkable aspect of the dinosaurian tracks of the Broome Sandstone first-hand, where science and traditional culture come together in a truly unique way. The cultural dimension associated with the dinosaurian tracks in this area adds an additional layer of significance to their National Heritage value.

Tourism potential

There is enormous potential for dinosaur-themed tourism within the survey area. The high abundance of tracks, their quality, diversity, scientific significance, links to indigenous culture and ease of access make this particular area ideally suited to visitation. People can easily access dinosaurian tracks from two public car parks, one at Reddell Point and the other at Entrance Point Boat ramp. Unlike nearby Minyirr (Gantheaume Point) where people have traditionally tried to see dinosaurian tracks, access at Reddell Point and particularly Entrance Point, is very safe—there is no need to climb over hazardous slippery rocks—and it is no surprise that these picturesque beaches are popular walking spots for many Broome locals. In addition, because of the unusual distribution of track-bearing surfaces, tracks can be seen on any tide (high or low).

Nadia Rebasti

Figure 27. Dinosaur educational tour conducted by Dianne Bennett of the Dinosaur Coast Management Group (DCMG). Dianne is instructing teachers and students from Broome North Primary School about the area's dinosaurian track fauna. Sauropod tracksite in survey zone E. © Nadia Rebasti.

The Dinosaur Coast Management Group has already started taking school groups to Entrance Point–Reddell Point Beach (**Figs 27, 28**). From the south-west facing boat ramp at Entrance Point they are able to get permission for a vehicle to go onto the beach, where they can drive around to the south-eastern end of Reddell Point Beach. From there it is a short walk to the spectacular sauropod tracks in that area. In addition to Gurbinwila (near the Broome Bird Observatory, which is not as popular given the time it takes to drive from town), this is one of the few places where a group can easily get close to tracks with a vehicle. At the time of writing this report, the DCMG were taking a group of 43 students from Broome North Primary School to Reddell Point Beach to see its dinosaurian tracks (**Figs 27, 28**).

Because of its cultural significance and links to places and stories in the Song Cycle, The Lurujarri Heritage Trail, which traces part of the Song Cycle, also often starts at Bungurunan (Reddell Point). Narlijia Cultural Tours, run by Bart Pigram, now takes people to Reddell Point to experience its dinosaurian tracks and learn about their links to Bugarrigarra stories. We very much expect other commercial tour groups to start incorporating this area into their itineraries in the near future.

As public awareness of the scientific and cultural significance of National Heritage Listed dinosaurian tracks in the Reddell Point–Entrance Point area increases, we expect more people will want to come and experience this unique part of Broome (and indeed Australia). In a few years time, we would not be surprised if Reddell Point and Reddell Point Beach were more popular for 'dinosaur spotting' than nearby Minyirr. The tracks are easier to find, and the area offers a more diverse suite of dinosaurian track types and rocks, and there are clear links to indigenous culture. It is easy to forget that this is one of only a handful of picturesque beaches close to Broome where people can easily experience globally unique dinosaurian tracks. There is nowhere else in Australia other than the Dampier Peninsula where people can see sauropod tracks, and this is one of the best beaches to do it.
It is an incredible natural asset that Broome needs to embrace.

Figure 28. Dinosaur educational tour conducted by members of the Dinosaur Coast Management Group (DCMG). **A**, Michelle Teoh conveys the dinosaurian track fauna diversity to students of the Broome North Primary School. **B**, students using creative methods to measure track parameters. Sauropod tracks include those in survey zones C–E. © Nadia Rebasti.

POTENTIAL IMPACTS ON NATIONAL HERITAGE LISTED DINOSAURIAN TRACKS ASSOCIATED WITH A PROPOSED SAFE BOAT HARBOUR ON REDDELL POINT BEACH

The Safe Boat Harbour facility that has been proposed for Reddell Point Beach is still in its concept phase. As such, details of the design and proposed construction process remain uncertain. Notwithstanding, the preliminary facility concept that we have been asked to comment on in this report has a direct footprint that covers approximately 1.73 km^2 of Reddell Point Beach, extending for approximately 500 m along the astronomical high tide mark and seaward for around the same distance to the edge of the outer reef. The proposed design includes protective breakwaters, a harbour that provides a turning circle for vessels, a boat ramp, a wharf and hardstand, and trailer parking (**Fig. 3**). The proposed entrance to the harbour is from the south-eastern end of the facility. One of the proposed requirement of the facility is that it allows safe boat launching on any tide.

Although the main footprint of the proposed facility covers the middle one third of the beach (or north-western half of survey zone C), when the proposed entrance channel and adjacent spending beach are taken into account the overall footprint extends close to the south-eastern end of the beach over a distance of approximately 650 m, and essentially encompasses the south-eastern two thirds of survey zone C. At this size, the overall footprint of the proposed SBH facility covers approximately 1.9 km^2.

In the following section, we outline what we regard to be the likely impacts the proposed SBH facility concept on National Heritage Listed dinosaurian track-bearing surfaces and related geological features in the survey area Although hypothetical, these impacts necessarily relate to the basic construction and maintenance options of the proposed design for the facility as outlined above (see Fig. 1).

Direct impacts

(i) Creation of the proposed harbour, boat ramp, wharf, hardstand, trailer parking area, and protective breakwaters. All National Heritage Listed dinosaurian tracks within the proposed footprint of the SBH facility would be directly and adversely impacted upon by its construction. The creation of the proposed harbour, the boat ramp, wharf, hardstand, trailer parking area and entrance channel would all require either the removal and/or the burial of any Broome Sandstone in the main footprint area. All the National Heritage listed dinosaurian tracks, track-bearing surfaces and their associated geological context would be lost. This would include numerous sauropod tracks and a number of partial trackways, all of which provide information on the temporal and spatial distribution of dinosaurian tracks in the region. **We regard this as a significant impact on the National Heritage values of this area.**

The tidal range along Reddell Point Beach is up to 10 vertical metres. With this in mind, a significant amount of beach sand and Broome Sandstone would therefore need to be removed in order to create a harbour that is deep enough to keep boats afloat, and/or to allow safe boat launching on any tide; one of the requirements of the SBH proposal. The results of our survey show that the bulk of the footprint of the proposed harbour area sits directly on a 200–300 m wide section of Broome Sandstone reef (**Fig. 8**). Any sand cover in the landward part of this area is probably minimal (< ~1–2 m). A significant amount of Broome Sandstone would need to be removed to create the proposed harbour area, particularly if it is meant to be deep enough to facilitate boat-launching on any tide. A similar amount of Broome Sandstone would also likely need to be removed in order to create the proposed entrance channel if the harbour is to be accessible on any tide. Contrary to the preliminary concept proposal for the SBH (**Fig. 3**), there is no natural channel through this area).

It seems unlikely to us that much, if any of the Broome Sandstone that would need to be removed to create the proposed harbour could be used as armourstone for the construction of the proposed breakwater. Being a sedimentary rock that easily erodes, Broome Sandstone does have the Australian Standard (AS 2758.6-2008) engineering attributes suitable for use as armourstone in the proposed breakwater. Another type of rock (e.g., either a granite or a high-grade metamorphic rock) or concrete 'armourstone' aggregate would need to be sourced and brought to the site to create the breakwater. Insofar as we understand the proposed SBH concept, its proposed requirements and our own understanding of oceanic conditions along this stretch of coastline, the proposed breakwater would need to be built-up to a minimum height that is well above the surface of the existing outer reef surface in order to provide sufficient protection on any tide for the harbour it is meant to safely enclose. Given the tidal range on this beach and the position of the harbour and launching facilities, the minimum height of the seaward wall of the breakwater would need to be around 10 m in order to safely protect the harbour during maximum astronomical high tides. The size of the breakwater may need to be even higher if cyclonic swells are taken into account.

(ii) Sand movement. The effect of the creation of the proposed SBH facility on the transport, erosion and deposition of sand within the survey area is difficult to comment on with too much certainty in the absence of detailed coastal modelling. However, in light of our own observations over seven years of research in the area that point to the dynamic nature of the sand cover in this area (**Fig. 22A**), we consider it is hard to envisage how sand movement would not alter as a result of the construction of the proposed SBH. We are of the opinion that the proposed breakwater that encircles the SBH would very likely inhibit longshore littoral transport of sand between Reddell Point and Entrance Point. There is then an increased risk that sand would likely accumulate, perhaps permanently, in one or both areas, as well as along the north-western side of the breakwater and possibly within the proposed entrance channel or along the south-eastern end of Reddell Point Beach (south-eastern end of survey zone C). There is then an increased risk that to the north-west of the SBH, this could result in the permanent burial of the extensive National Heritage listed dinosaurian track-bearing surfaces at Reddell Point (survey zone B; **Fig. 18**), and to the south-west, a number of important sauropod tracks and trackways that show morphological details suggestive of a new track type that is yet to be described or named (**Fig. 22B,C**) along with the only example in this area of *Wintonopus middletona*. Independent of the effect on dinosaurian tracks, the potential accumulation of sand within the entrance channel to the SBH would likely require regular dredging to keep it clear in order to facilitate 'all-tide' boat launching.

While we acknowledge that irregular storms and cyclonic events also have the potential to cause natural, large scale changes in sand cover during any given year (as was apparent for Reddell Point Beach during the early part of 2018; **Fig. 22A**), ambient conditions quickly return the sand to its normal distribution along the beach (**Fig. 5A**). There is an increased risk that this return to normal sand cover would not occur if the proposed breakwater and SBH were in place.

In addition to changes in the movement and distribution of sand along Reddell Point Beach (survey zones C and the south-eastern half of survey zone B), it is also possible that the construction of the proposed SBH could affect the transport, erosion and deposition of sand on adjacent beaches and headlands. This could potentially include the permanent burial or increased rate of erosion of significant National Heritage listed dinosaurian track-bearing surfaces and associated geological and cultural features at Bungurunan (survey zone A; **Figs 2, 7, 11, 15B, etc.**) and the small south-east facing beach on Entrance Point (survey zone D; **Fig 23**). Both of these areas also provide important access points for visitation (**Fig. 28**).

It is hoped that further studies of coastal processes and the changes which may result from the proposed SBH will be carried out in order to more definitively assess anticipated impacts on dinosaurian tracks in areas adjacent to the proposed SBH.

(iii) Increased rates of erosion due to boat traffic. Boat traffic in and out of the proposed SBH facility through the proposed south-eastern entrance channel would additionally result in increased wave spending along south-eastern corner of Reddell Point Beach (survey zone C). The effect of this could likely be increased erosion of any exposed National Heritage listed dinosaurian track-bearing surfaces in this area, which includes some of the survey area's most important tracks (**Figs 21 and 22B,C**). Alternatively, the creation of an artificial spending beach (to help dissipate this wave action) would necessitate these track-bearing surfaces needing to be removed or being permanently buried.

Erosion from wave activity in the intertidal zone is the main mechanism through which dinosaurian tracks in the Broome Sandstone become exposed. Although it follows that increased wave activity will result in further erosion and potentially expose new track-bearing surfaces, this process also necessitates the loss of existing track-bearing surfaces. Because it is the latter and not the former upon which the existing National Heritage status of this stretch of coastline was established, and it is on those track-bearing surfaces that can be recorded now that we have focussed on for this report, we regard increased erosion of existing track-bearing surfaces as an impact to the National Heritage values of this area.

(iv) Removal of track-bearing surfaces during the construction of the proposed SBH facility on Reddell Point Beach. Dinosaurian tracks can be photographed, digitally reconstructed in 3D, cast with silicon or latex and then artificially replicated (see Salisbury et al., 2017; Romilio et al., 2017), but once the in situ tracks are physically destroyed they are lost forever. During the construction of the proposed SBH facility on Reddell Point Beach, it might be possible to remove some tracks or parts of track-bearing surfaces rather than simply destroy or bury them. That said, the process of track removal is physically very difficult and not without consequence (Farlow et al, 2012; Faulkingham et al., 2014). Many of the exposed surfaces within the survey area are spatially extensive (see **Figs 20–22**) and attempting to remove them may result in their breakage. Even if they could be successfully extracted, once removed from the surrounding rock, tracks and other parts of track-bearing surfaces no longer have stratigraphic context, which is often central to interpreting their broader significance (e.g., via the environment in which they were formed, and their spatiotemporal and spatial relationship to other tracks in the region).

Removal of tracks also takes them out of the unique natural setting in which they occur. Their cultural value is also lost if they are removed from Country. Thus, even if a track is saved from destruction or loss, the overall heritage value is greatly diminished if it is taken out its natural context.

To conclude, the reasonably conceivable direct impact of the proposed SBH facility on National Heritage listed dinosaurian tracks and track-bearing surfaces on Reddell Point Beach is adverse. All the Broome Sandstone within the greater footprint of the SBH would be either destroyed, permanently buried or subject to increased erosion. As such, the National Heritage values associated with this area would be lost.

Advocating for the removal of tracks or successfully demonstrating that it can be done would set a dangerous precedent for the ongoing management of other tracksites on the Dampier Peninsula. In the 1990s, the temporary removal of a small section of track-bearing surface from the Walmadany area by the Western Australian Museum greatly strained relations between palaeontologists and the area's Traditional Custodians. While the tracks in question were later returned and placed back in Country, not long after other tracks were stolen from the same area and others in different parts of the Dampier Peninsula. The perpetrators were eventually caught, charged and jailed, and some of the damaged tracks recovered, but these events cast a dark shadow over the Dampier Peninsula's dinosaurian tracks and Australian palaeoentology that has taken decades to lift (see Salisbury et al. 2017, Appendix II). In light of these events and the hard lessons that have been learnt as a result, we a reluctant to advocate for the removal of tracks or track-bearing surfaces as a preferred management option.

Other impacts

One of the unique aspects of the National Heritage listed dinosaurian tracks and associated geological features of the Broome Sandstone is the spectacular coastal setting in which they occur. Bounded by the rusty red Mowanjum Sand ('pindan') on one side and the azure blue of the Indian Ocean on the other, it is hard to deny their aesthetic appeal. There is nowhere else in the world where dinosaurian tracks occur in such an inimitable setting.

As awareness of the dinosaurian tracks of the Dampier Peninsula grows, greater numbers of people will want to see and experience them. As discussed previously (see 'Tourism potential'), the Reddell Point–Entrance Point area has a number of key attributes (ease of access, diversity of tracks, links to indigenous culture) that will place it front and centre of this increase in local, national and international attention and visitation. Anticipating the increased interest in the National Heritage values associated with this area, the effect of the construction of the proposed SBH (through the direct impacts discussed above), and the permanent change it will have on the natural aesthetics of the surrounding area, need to be carefully considered. At the moment, with the exception of the odd glimpse of parts of the industrial precinct along Port Drive, Reddell Point, Reddell Point Beach and the south-eastern side of Entrance Point (survey zones A–D) offer near-unspoilt vistas of the Kimberley coast, complete with National Heritage listed dinosaurian tracks (e.g., see cover page).
The construction of the proposed SBH on Reddell Point Beach will irreversibly impact on the natural aesthetic value of the landscape associated with dinosaurian tracks in this area, arguably diminishing their heritage value. There is no escaping the fact that the juxtaposition of the proposed SBH and the (remaining) internationally significant National Heritage listed dinosaurian tracksites in this area will be a drastic departure from the current, virtually unspoilt setting.

RECOMMENDATIONS

In its current proposed form (**Fig. 3**), we are of the opinion that the construction and maintenance of the proposed SBH facility on Reddell Point Beach would have a significant impact on the National Heritage listed dinosaurian tracks in the Reddell Point–Entrance Point area. All the Broome Sandstone and its associated dinosaurian track-bearing surfaces within the greater footprint of the SBH would be either destroyed, permanently buried or subject to a greater risk of an increased rate erosion. As such, the National Heritage values associated with this area would be lost. In addition to changes in the movement and distribution of sand along Reddell Point Beach, we are also of the opinion that it is likely that the construction of the proposed SBH could affect the transport, erosion and deposition of sand on adjacent beaches and headlands. This could potentially include the permanent burial or the greater risk of an increased rate of erosion of significant National Heritage listed dinosaurian track-bearing surfaces and associated geological and cultural features at the southern end of Bungurunan (**Fig. 2, 7, 11, and 15B**) and the small south-east facing beach on Entrance Point (survey zone D; **Fig 23**).

We cannot see how these impacts can be avoided or mitigated if the construction of the proposed SBH facility in its current form were to go ahead. Trying to protect sections of beach or reef from sand loss or increased deposition would be futile. Artificial bollards or large boulders would do little to halt sand movement at the best of times, and the creation of larger, continuous artificial barriers (i.e., breakwaters) has its own problems; sections of Broome Sandstone would necessarily need to be buried, and the new structures would further exacerbate any existing sand transport issues that might stem from the construction of the proposed SBH and its breakwater. In short, it is hard to see how the introduction of a large-scale structure along this stretch of beach would not irreversibly change the existing patterns of littoral sand movement, the consequences of which would likely significantly impact on existing National Heritage values (i.e., dinosaurian tracks).

Shifting the position of the proposed SBH within survey zone C, to either the northwest or the southeast of Reddell Point Beach, would do little to avoid any impact on National Heritage values. Moving it the northwest might reduce the impact of the proposed entrance channel and adjacent spending beach on track-bearing surfaces in the southeastern corner of survey zone C, but tracks within the repositioned main footprint of the harbour and breakwater would still be effected, and tracks on Reddell Point could be placed under greater risk from permanent burial. Similarly, moving it to the southeast of Reddell Point Beach has a greater direct impact on track-bearing surfaces in the southeastern corner of survey zone C.

In order to avoid any significant impacts on National Heritage listed dinosaurian tracks and related geological features, we believe there are two options:

(i) Change the design of the SBH from that proposed in the preliminary concept diagram (**Fig. 3**);

(ii) Build it in a different location (which may also necessitate a new design).

Option 1: SBH design change

If the proposed location of the SBH is maintained, the only way any significant impacts on National Heritage values can be avoided is if the overall direct footprint of the proposed facility is greatly reduced. This could be achieved either by making it much smaller and reducing the size of both the harbour and the breakwater, or moving to a design that is farther offshore, such that the harbour area is not directly above the intertidal exposures of Broome Sandstone. Whether either of these options meets the requisite criteria for the SBH and/or is even feasible is not something we can comment on at this point. Any new design would need to be assessed on its own merits.

Option 2: SBH location change

The northern half of survey zone F and all of survey zone G seem to preserve little in the way of National Heritage listed dinosaurian tracks (**Fig. 29**). There are some sauropod tracks on detached blocks of Broome Sandstone close to the astronomical high tide mark (**Fig. 25**), but these could easily be moved (see below) without causing them any damage.. Survey zone G, between Broome Jetty and the KPA slipway, does not appear to preserve any dinosaurian tracks in the exposed sections of Broome Sandstone. As far as avoiding any significant impacts on National Heritage listed dinosaurian tracks and related geological features, this part of Entrance Point seems best suited to the construction of a SBH facility. The southern end of Simpson's Beach, north of survey zone G, also appears to have minimal intertidal exposure of the Broome Sandstone and may also be suitable, but we did not examine this area in any detail during the course of our July 2018 survey.

Moving the SBH facility to this location would likely have its own sets of location issues due to the close proximity of Broome Jetty and other KPA infrastructure (e.g., the slipway), and potential indirect impacts on adjacent track-bearing surfaces from changes to sand transport, particularly those within survey zone E (**Fig. 24A,B**), would also need to be carefully considered. But the overall impact on National Heritage values would likely be minimal. In terms of the impact on the natural aesthetics of the area, this part of Entrance Point is already partly developed, being situated close to the jetty and existing public boat launching facilities. The few sauropod tracks that do occur along the foreshore are on detached blocks and could be removed without causing any damage and placed on display in an interpretive centre or similar that could be located nearby (but see previous comments on other issues associated with the removal of tracks). In this way, the development would be seen in a much more positive light insofar as the area's dinosaurian tracks are concerned; the direct impact of the proposed SBH on National Heritage values would be minimal, and the tracks that are removed could be utilised in a way that helps promote the area for dinosaur-themed tourism. We feel this would be a good outcome.

CONCLUDING REMARK

The dinosaurian tracks of the Broome Sandstone represent a peerless part of Australia's natural and cultural heritage. The inclusion of these tracks and associated geological features in the West Kimberley National Heritage Area was more than warranted, and every effort should be made to ensure their ongoing conservation, particularly for stretches of coastline that are likely to receive increased visitation. The Reddell Point–Entrance Point area is one such place. With proper management there is potential for major flow on benefits for tourism and for local indigenous groups, as well as ongoing scientific research. We look forward to working with Broome Shire, the WA Department of Transport, the Kimberley Port Authority, the Dinosaur Coast Management Group, Nyamba Buru Yawuru and other indigenous groups (e.g., Goolarabooloo), and the greater Broome community to promote and manage this unique area.

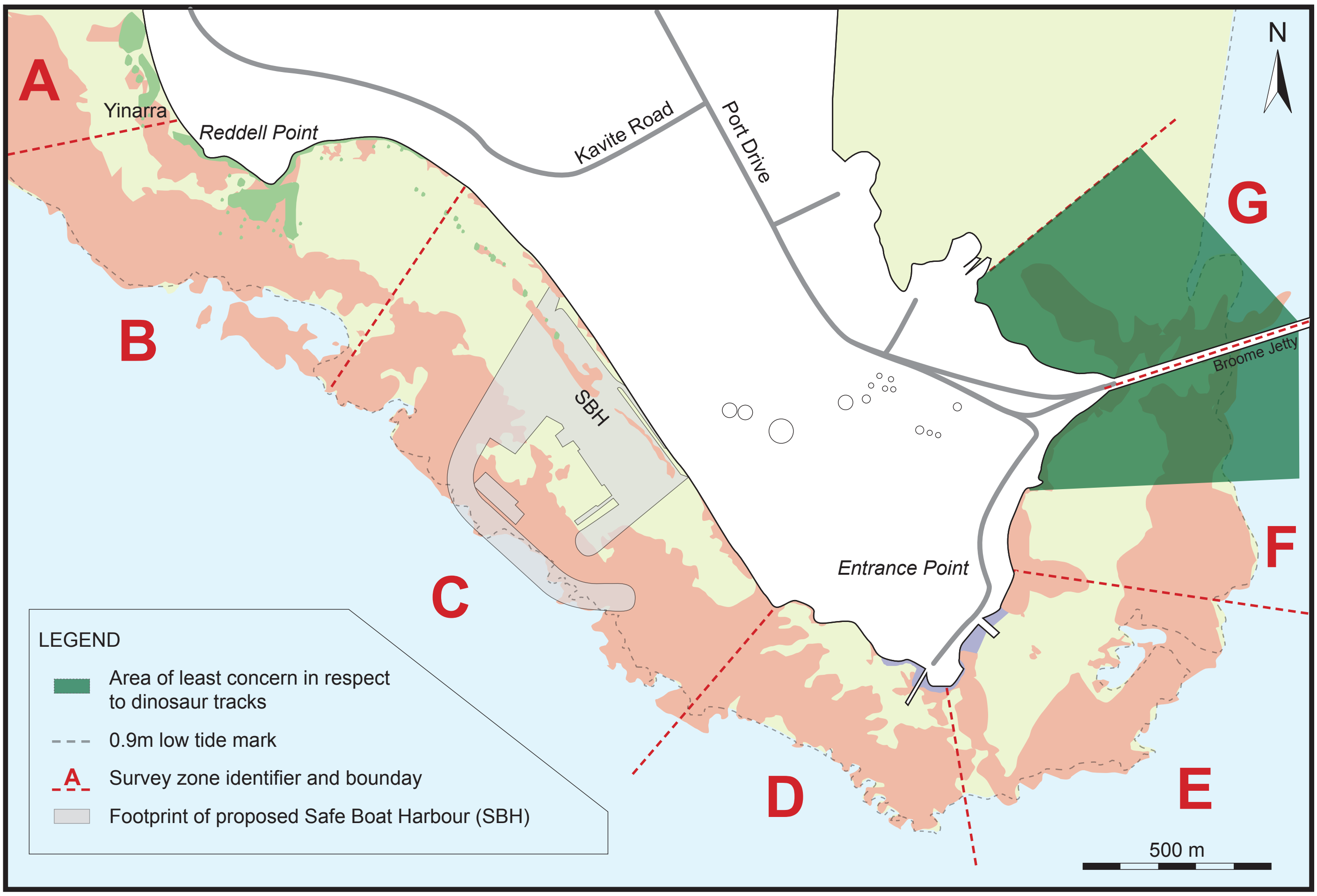

Figure 29: Schematic map of the survey area denoting the 'area of least concern' (green polygon) with minimal impact on in situ National Heritage listed dinosaur tracks.

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6. SUPPLEMENTARY INFORMATION

Shape data showing survey zones, exposures of National Heritage listed Broome Sandstone and dinosaur track-bearing surfaces, and an alternative site (an ‘area of least concern’) have been sent to SoB as .kml files.