Incomplete but intricately-detailed: The inevitable preservation of true substrates in a time-deficient stratigraphic record

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GEOLOGICAL CONTEXT OF THE TUMBLAGOODA SANDSTONE

The Tumblagooda Sandstone is a 1210 meter-thick (at outcrop) succession of strata composed almost entirely of medium- to coarse-grained sandstones, with mudrocks and conglomerates making up <1% of the unit. It was deposited at the intersection of the Southern Carnarvon and Perth Basins, and presently crops out over an area of >7000 km² in a number of well-exposed coast and gorge sections around Kalbarri, Western Australia (Figure S1). The age of the unit is debated as it is largely unfossiliferous (it contains one unique euthycarcnoid fossil, Kalbarria brimmellae: McNamara and Trewin, 1993) and contains no directly dateable indicators. It has been cited as Ordovician (Mory et al., 1998) on the basis that limestones from the base of the Dirk Hartog Group (DHG) yield Llandovery (early Silurian) conodonts, within subsurface cores from a set of wells located 100-400 km north of the nearest Tumblagooda Sandstone outcrop, and that the DHG in these cores overlies a sandstone that has been interpreted to be the Tumblagooda Sandstone (although no there is no data between the Tumblagooda outcrop and the cores to confirm that the sandstones in each instance are the same unit). A Silurian age for the Tumblagooda Sandstone appears far more likely based on multiple lines of circumstantial evidence (McNamara, 2014), and it may be contemporaneous with deposition of parts of the DHG to the north.

The unit is formally subdivided into four facies associations (FA1-FA4, Figure 1; Hocking, 1991) that are distinguished from one another by sedimentary architecture, lithology, paleocurrent variance and trace fossils. The upper part of FA3, which crops out largely in coastal sections, is the focus of this paper. Other facies associations crop out inland and consist of NW-directed coarse-grained fluvial sandstones (FA1), medium-grained sandstones exhibiting slightly bidirectional palaeoflow, tidal sedimentary structures, and a diverse arthropod trace fossil assemblage (FA2), and medium-coarse-grained cross-bedded sandstones characterized by intense Skolithos piperock ichnofabrics and rare laminated siltstone horizons (FA4). A recent interpretation of FA2 can be found in Bradley et al. (2018). Aside from the examples discussed in
the paper, true substrates are also common in FA2 (see examples illustrated in Hocking, 1991: for example, their figures 26, 30, 44).

Figure S1. Geological context. A. Map showing five localities where Psammichnites-colonized surfaces have been identified: bedrock over area shown is all Tumblagooda Sandstone. B. Generalized stratigraphic log of the Tumblagooda Sandstone, showing distribution of its constituent facies associations, paleocurrent data, and continuously exposed stratigraphic intervals at the study localities. C. Example sedimentary log from Red Bluff, showing recurrence interval of identified Psammichnites horizons. Top of log = top of FA3.
FACIES ASSOCIATION 3

FA3 accounts for c. 280 meters of the Tumblagooda Sandstone and consists entirely of stacked, medium to very coarse-grained, trough cross-bedded sandstones with frequent pebbly horizons, and foresets indicating a strongly unimodal paleoflow to the northwest (mean 299°, n=347). The upper part of FA3 (approximately 1100-1120 meters from the base of the formation) is the focus of this study because it is particularly well-exposed as extensive bedding planes and three-dimensional outcrop of negligibly-dipping strata, within coastal cliffs immediately to the south of Kalbarri (Figure S1). Trace fossils are fewer in number and diversity than the underlying FA2, but a low diversity ichnofauna of Planolites, Psammichnites and Skolithos increase in their frequency of occurrence up-section towards the overlying FA4. The first of these traces to appear, stratigraphically, are Psammichnites – in the instances described here these occur stratigraphically lower than their first association with the other burrows. Psammichnites was previously reported from the succession under the names Aulichnites (Trewin and McNamara, 1994; McNamara, 2016) and Didymaulichnus (Hocking, 1991). Its most likely tracemaker was a mollusk (Mángano and Rindsberg, 2003).

The depositional environment of FA3 has previously been interpreted as either a continental braided fluvial system (Trewin and McNamara, 1994; Evans et al., 2007) or the marine-influenced distal reaches of a fluvial system (Hocking, 1991). We consider the latter interpretation the most likely because, although it has a unimodal NW flow and lithology that matches that of the fluvial strata within FA1 (Hocking, 1991), the vertical increase in ichnological signatures (vastly pre-dating other known non-marine burrows; Minter et al., 2016) suggests increasing marine influence in the water column, even though there is little sedimentological evidence for marine currents. The interpretation also fits with the fact that FA2, which separates FA1 and FA3, was deposited under a strong marine influence (Bradley et al., 2018), and that FA3 passes upwards into the fully marine FA4. Further, flow seems to have been perpendicular to the paleo-coastline (as indicated by bidirectional currents and wave-ripple crestlines in FA2; Figure S1), although FA3 lacks evidence for emergence (e.g., adhesion ripples), which are very common in FA2. FA3 was thus most likely deposited in a fully submerged setting: the unimodal flow suggests physical dominance of fluvial flow (or, less likely, strongly ebb-dominated tidal flow), but within partially marine waters that
permitted the sporadic colonization of the sands by epifaunal and infaunal burrowing organisms. A wide estuarine setting is plausible, but this is a cautious conclusion because there is an absence of diagnostic evidence for any incised valley at the scale of the outcrop. This environmental setting, and the presence of a marine burrowing ichnofauna from a time when such burrows are unknown elsewhere in the global rock record (or even along fluvial bounding surfaces of FA1 of the Tumblagooda Sandstone) is the basis for our tentative interpretation of the *Psammichnites* bounding surfaces being the result of allogetic forces in the form of elevated wave action (as opposed to fluctuations in fluvial discharge). Storm surges would be the most likely trigger of such increased wave action further into the Tumblagooda estuary.

**FURTHER EXAMPLES OF *PSAMMICHNITES* COLONIZED SURFACES**

Figure S2 provides an expanded version of Figure 1 in the main text. Figures S3-S17 show further examples of *Psammichnites* colonized bounding surfaces, and sedimentary and outcrop characteristics, of the upper part of FA3. Note that this is not a complete catalogue of all occurrences – this selection is chosen because the traces are best visible in low-angle light, and are not all apparent on photographs that were taken in the field.
Figure S2. Bounding surfaces in the field. A. Four truncated cross-bed sets (Si-iv) deposited by subcritically climbing dunes. Green box marks Psammichnites patch. B. Undulose appearance of truncated foresets of supercritically climbing dunes on the same surface as in A. C. Channelised erosive scour cut into cross-stratified sets (white line = channel axis). Yellow line shows topographic relief to bedding plane, green boxes mark Psammichnites patches, yellow box enlarged in E. D. Detail of Psammichnites on truncated foresets. E. Irregular surface, due to recent erosion, showing plan view of a younger set (Y) with a patchily-preserved pebble lag (yellow arrows) at its lower 2nd order bounding surface (red line), overlying top of older set (O) consisting of truncated, Psammichnites-colonized (red arrows) cross-strata. F. Plan-view of younger (Y) set of cross-bedding conformably overlying older (O) set, on margin of channel shown in C: Psammichnites on top of O can be seen to be buried (arrows) under the 2nd order bounding surface (red line) at the base of Y. G-H. Profile view looking west (G) and plan view looking north (H) of same outcrop, showing position of Psammichnites patches (green boxes) on tops and sides of three-dimensional original erosional topography and bounding surfaces. 1st-order (blue) and 2nd-order (red) bounding surfaces, and recent erosional contact between sets (yellow) highlighted. Numbers refer to relative age of cross-bedsets (S1 = oldest) and
bounding surfaces (e.g., BS1, BS1i). Yellow box in H shows area enlarged in E. Locations: Jake’s Point (A-B), Mushroom Rock (C, E), Red Bluff (D, F-H). Scale bar: 1 m (A-C, H), 10 cm (E-G).

Figure S3. Typical exposure of FA3 between Red Bluff and Pot Alley
Figure S4. Psammichnites on truncated foreset tops – location shown in orange box in Fig 1A/S2A, Jake’s Point.

Figure S5. Psammichnites on truncated foreset tops – Jake’s Point.
Figure S6. Psammichnites on truncated foreset tops – Jake’s Point.

Figure S7. Psammichnites on truncated (supercritically-climbing) foreset tops – Jake’s Point.
Figure S8. Detail of Psammichnites on truncated foreset tops – Jake’s Point.

Figure S9. Psammichnites in sandstone horizon immediately underlying pebble lag (see Fig. S10: pit marks show where pebbles rested on top of burrowed surface) – Mushroom Rock.
Figure S10. Pebble lag overlying Psammichnites horizon shown in Fig. S9 – Mushroom Rock.

Figure S11. Psammichnites on truncated foresets making up channel margin, shown in main text Figure 1B – Mushroom Rock.
Figure S12. Psammichnites on truncated foresets making up channel margin, shown in main text Figure 1B – Mushroom Rock.

Figure S13. Detail of channel margin (synoptic topography) possibly scoured during retreat of storm surge waves (shown in main text Figure 1B). Locations of Figs. S11 (pink) and S12 (green) circled. Further Psammichnites patch at feet of APS.
Figure S14. Context of main text Figure 1D – Mushroom Rock.

Figure S15. Dense Psammichnites on truncated foreset, highlighted by upper orange box in Fig. S2G, Red Bluff
Figure S15. Psammichnites along synoptic topographic scour into truncated foresets – oblique angle of image in Fig. 1D/S2F, Red Bluff.

Figure S16. Detail of Psammichnites in lower orange box shown in Fig. S2G. Red Bluff
REFERENCES CITED IN APPENDIX


