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

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ABSTRACT

True substrates are defined as sedimentary bedding planes that demonstrably existed at the sediment-water or sediment-air interface at the time of deposition, as evidenced by features such as ripple marks or trace fossils. Here we describe true substrates from the Silurian Tumblagooda Sandstone of Western Australia, which have been identified by the presence of the surficial trace fossil *Psammichnites*. The examples are unexpected because they have developed along erosional internal bounding surfaces within a succession of cross-bedded sandstones. However, their seemingly counterintuitive preservation can be explained with reference to recent advances in our understanding of the time-incomplete sedimentary-stratigraphic record (SSR). The preservation of true substrates seems to be an inevitable and ordinary result of deposition in environments where sedimentary stasis and spatial variability play important roles. We show that the true substrates developed during high-frequency allogenic disturbance of migrating bedforms, forcing a redistribution of the loci of sedimentation within an estuarine setting, and subsequently permitting an interval of sedimentary stasis during which the erosional bounding surfaces could be colonized. These observations provide physical evidence that supports recent contentions of how sedimentary stasis and the interplay of allogenic and autogenic processes impart a traditionally underestimated complexity to the chronostratigraphic record of geological outcrop.

CHRONOSTRATIGRAPHY AND TRUE SUBSTRATES

It has been recognized for over a century that unconformities and sedimentary breaks riddle Earth's stratigraphic record at a variety of scales, such that two-dimensional (2-D) stratigraphic sections are fragmentary chronicles of elapsed geological time (Barrell, 1917; Sadler, 1981; Dott, 1983). Recently, a number of largely model-driven studies have explored the previously underappreciated causes and effects of this time-deficient SSR (Miall, 2015; Paola et al., 2018). Three recurring themes are:

(1) Ordinariness: The SSR preferentially records mundane rather than dramatic events (Jerolmack and Paola, 2010; Paola, 2016).

(2) Sedimentary stasis: The dominant sedimentation state under which the SSR accumulated was stasis; i.e., 'neither deposition nor erosion', rather than 'either deposition or erosion' (Ganti et al., 2011; Tipper, 2015; Straub and Foreman, 2018).

(3) Spatial variation: Any time gaps in one 2-D stratigraphic section of a basin fill were likely compensated by contemporaneous deposition of strata elsewhere within the same basin (Runkel et al., 2008; Reesink et al., 2015; Gani, 2017).

These emerging understandings have profound implications for how field geologists interpret the sedimentary rock record at outcrop, particularly in the consideration of bedding planes that reflect high-frequency, short-duration pauses between the deposition of beds below and above (Miall, 2016). If, as models predict, any spatially isolated expression of the SSR (e.g., a vertical section through a singular outcrop) is mostly a record of stasis, then bedding planes might potentially archive more time—and physical clues to the operation of the depositional environment—than the beds that they separate.

This is particularly the case for bedding planes that we here distinguish with the term "true substrates": fossilized sediment-water (or sediment-air) interfaces that are the plan-view equivalents of chronostratigraphic surfaces in vertical profile (i.e., synoptic or sampled topography; Ganti et al., 2013; Paola et al., 2018). Not all true substrates can be recognized as such (Dott, 1983), but many can, particularly where they maintain an original morphology from the time of deposition (e.g., ripple marks) or host surficial ichnologic, biotic, sedimentary, petrographic, or pedogenic signatures (e.g., Miall and Arush, 2001; Davies et al., 2017).

These true substrates provide high-resolution snapshots of tracts of ancient seafloors, river beds, or other substrates, yet their striking resemblance to transient modern equivalents can seem counterintuitive, provoking recurring questions as to how they were preserved in the rock record at all (Miall, 2015). In this paper, we utilize recent understandings of ordinariness, sedimentary stasis, and spatial variation to present a conceptual model in which preservation of true substrates, at outcrop scale, is inevitable because of the time-deficient nature of the SSR. This is grounded in original field observations of bedding planes that demonstrate that, contrary to some traditional assumptions, even erosional second-order cross-bedding bounding surfaces had the potential to persist as true substrates for intervals of stasis subsequent to their initial scour (bounding surface orders used are after Allen, 1983).

THE TUMBLAGOODA SANDSTONE

The true substrates described here are seen in the upper part of Facies Association 3 (FA3) of the Silurian Tumblagooda Sandstone, Western Australia, deposited in the estuarine distal reaches of a braided fluvial system (Hocking, 1991; see the GSA Data Repository[1]). The strata are exceptionally well suited for the study of bedding planes because they crop out near-continuously, with negligible tectonic dip and only local faulting, along 15 km of coastal cliffs, with platform exposures of individual surfaces as much as 2000 m^2 in area.

FA3 consists of stacked, medium- to very coarse-grained sandstones that are ubiquitously trough cross-bedded, with a unimodal northwest-directed paleoflow (individual sets 0.1–1 m thick, 0.3–2 m wide). Sets either (1) are scalloped (Rubin, 1987) and separated by first-order bounding surfaces, recording subcritically climbing dunes (Allen, 1982), or (2) appear on bedding planes as wavy truncated foresets, suggesting supercritical climbing of larger 3-D dunes (Allen, 1982). The two types grade laterally into one another in places, indicating that they were sometimes amalgamated as larger compound dune forms. Trough cross-bed cosets are separated by well-exposed second-order bounding surfaces that are usually near-horizontally levelled (Fig. 1A), with few localized channelized scour pathways (1–3 m wide and oriented northwest-southeast) (Fig. 1B).

Some second-order bounding surfaces can be identified as true substrates because they host *Psammichnites* trace fossils (Fig. 1C): raised surface ridges with pronounced medial grooves, produced by a vagile animal

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[1] GSA Data Repository item 2018229, geological context and further high-resolution images of the Tumblagooda Sandstone bounding surfaces and trace fossils, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

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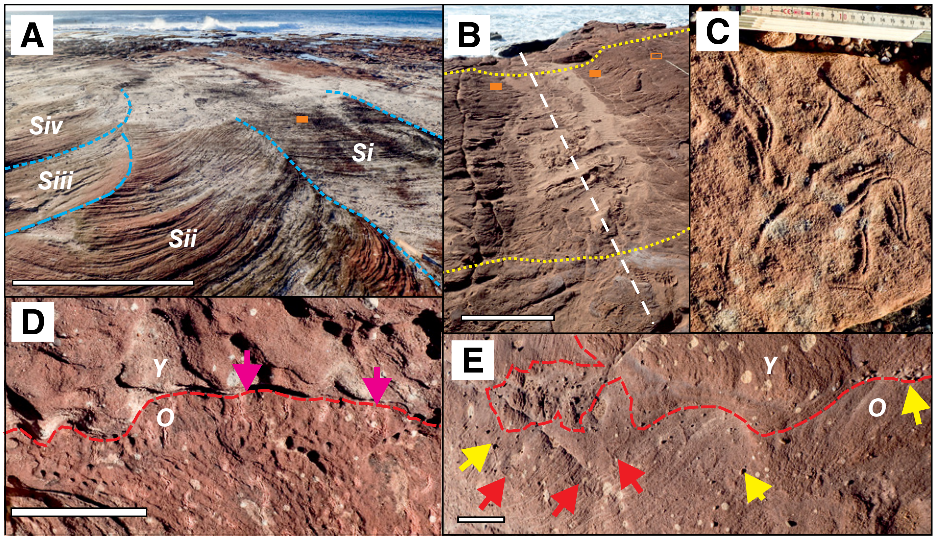

Figure 1. Bounding surfaces and *Psammichnites* in Facies Association 3 (FA3) of Silurian Tumblagooda Sandstone, Western Australia, with first-order surfaces in blue, second-order surfaces in red; orange boxes mark *Psammichnites* patches. A: Four truncated cross-bed sets (*Si–Siv*) deposited by subcritically climbing dunes. B: Channelized scour cut into cross-stratified sets (white line shows channel axis). Yellow lines show topographic relief; open orange box is enlarged in E. C: *Psammichnites* cross-cutting truncated foresets. Scale is in centimeters. D: Plan view of younger (*Y*) set on top of older (*O*) set: *Psammichnites* on top of *O* buried under second-order bounding surface at base of *Y*. E: Plan view of a set (*Y*) with patchily preserved pebble lag (yellow arrows) at its lower second-order bounding surface, on top of older set (*O*) of truncated, *Psammichnites*-hosting (red arrows) cross-strata. Scale bars: 1 m in A and B, 10 cm in D and E.

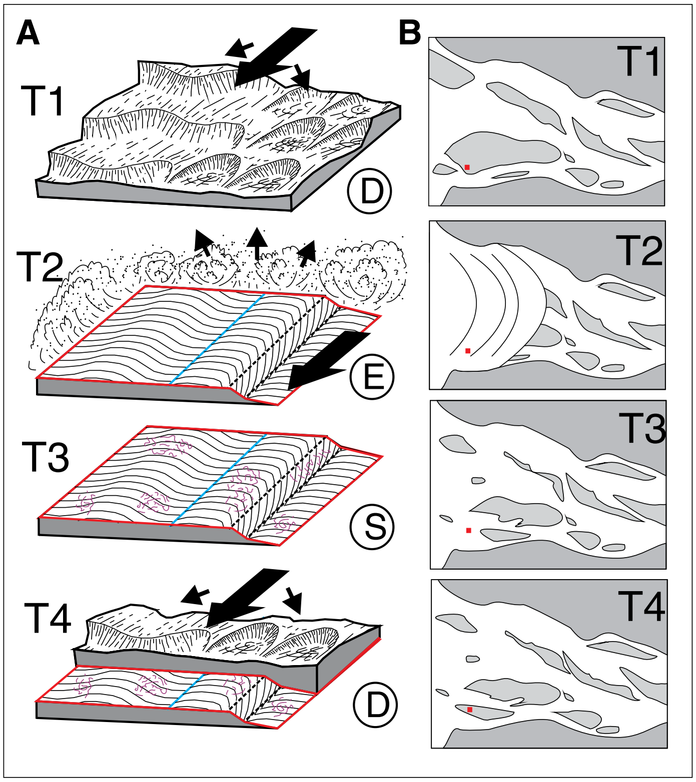

Figure 2. Depositional model showing development of cross-strata, bounding surfaces, and *Psammichnites*. A: Changing appearance of substrate at different time intervals. Large arrows show direction of sediment transport, small arrows show sediment deposition or removal from the substrate. Development of 1st-order (blue) and 2nd-order (red) bounding surfaces are highlighted. Time 1 (T1): Deposition (D) state creates cross-strata within amalgamated fluvial-estuarine dunes; potential time taken for creation of preserved sedimentary signature (TC) is minutes to hours. T2: Erosion (E) state levels and scours 2nd-order bounding surface through storm-surge wave action, with channel developing as waves recede; TC is minutes to hours. T3: Stasis (S) state permits *Psammichnites* organism colonization; TC is hours to years. T4: Deposition state creates overlying cross-strata, not preceded by erosion; TC is minutes to hours. B: Location of states shown in A (red box), relative to hypothetical wider estuarine environment. Spatial distribution of active subaqueous dune barforms is instantaneously shuffled between T1 and T3 in areas affected by T2 storm surge; elsewhere, barforms experience steady passage. Time duration of regional conditions: T1 = years; T2 = hours; T3 = hours to years; T4 = years.

feeding at negligible depth below the sediment-water interface (Mángano and Rindsberg, 2003). The traces are <5 mm in width, variable in length (usually <10 cm, but up to 1 m), and grouped in unevenly distributed patches as straight, sinuous, or looping forms, cross-cutting the erosionally clipped foresets of underlying cosets. *Psammichnites* can be seen to be directly overlain by sandstone cross-strata (Fig. 1D) and, in at least two examples, by toeset pebble lags (Fig. 1E). The relief of the surficial traces is consistently <2 mm, meaning that they are visible only in low-angle light on bedding planes and have no visually discernable structure in vertical bed profiles (in part due to the homogenous, granular nature of their host sandstones). In addition to uncertainty from irregular outcrop morphology, these factors combine to make it impossible to confidently correlate colonized surfaces over wide areas. However, *Psammichnites* exist with certainty on at least 20 distinct second-order bounding surfaces, and the colonized surfaces may be closely spaced (two discrete surfaces are seen within 1 m vertically at two sites). The presence of *Psammichnites* has no apparent relationship to the size of individual sets, and they are seen on both subcritically and supercritically climbing foresets. The trace fossils prove that their host bounding surfaces are true substrates because (1) *Psammichnites* are surficial constructions on the primary substrate, the creation of which required an interval of sedimentary stasis (allowing time for faunal colonization), and (2) colonized surfaces are concordant with the synoptic topography, whether level or inclined (e.g., on channelized scour margins).

POST-SCOUR STASIS ON CROSS-BEDDING BOUNDING SURFACES

Many numerical and flume-tank models of cross-bedding are predicated on the understanding that the formation of bounding surfaces and that of cross-beds are coupled, with scour occurring during bedform passage when successive iterations of migrating dunes subcritically climb over and truncate one another (Allen, 1982; Rubin and Hunter, 1982). In such a model, the surfaces recording true substrates are most likely to be individual foresets, representing instantaneous iterations of migrating lee faces. However, the colonized erosional bounding surfaces in FA3 prove that even constructed boundaries (*sensu* Ganti et al., 2013) can have persisted in time as true substrates.

This counterintuitive observation is explainable by the recognition that stratigraphically successive cosets (each a product of a state of deposition in the local system) must have been genetically separated from both one another and the intervening second-order bounding surfaces (each a product of a state of erosion followed by a state of stasis), implying high-frequency allogenic erosional disturbance of autogenic bedform migration (terms used *sensu* Hajek and Straub, 2017). While such generalized disturbances can be expected to yield similar stratigraphic signals regardless of sedimentary environment, our favored interpretation for FA3 (see the Data Repository) involves the erosional clipping of estuarine bars by high-frequency allogenic wave action (e.g., during storm surges) (Fig. 2). Wave-levelling of 3-D dunes (and scoured drainage channel development during wave retreat) would have instantaneously shifted the loci of concentrated flow and deposition within the estuarine setting (e.g., Fruergaard et al., 2013). This allogenically triggered spatial shuffling would have resulted in localized patches where the sedimentation state had shifted from deposition to erosion to stasis within a matter of hours. The duration of the ensuant stasis (i.e., the time taken for deposition to reestablish at the same locality) would have depended on how long it took newly established bedforms to migrate to the same tract of scoured, colonized substrate. The evidence for such a history shows that the FA3 cross-bedding developed under a hybrid of variability-dominated and deposition-dominated models of dune preservation (Reesink et al., 2015) (Fig. 3).

PRESERVATION OF POST-EROSIONAL TRUE SUBSTRATES

The preservation of delicate *Psammichnites* traces immediately underneath "high-energy" deposits of pebble lags and cross-bedded sandstone is counterintuitive, but actual. Where other true substrates with delicate and detailed surface components have been observed in the rock record, their preservation has commonly been seen as unusual because it is perceived that the deposition of overlying sediment should have inevitably been associated with erosion. Studies of features such as trace fossils, casts of soft-bodied organisms, or adhesion marks have commonly invoked enhanced biological or chemical substrate stability (with more or less actualistic causes, depending on the age of the strata) to explain their preservation (e.g., Jensen et al., 2005; Sarkar et al., 2011; Tarhan et al., 2016; Sappenfield et al., 2017). However, there is no physical evidence for chemical or biological stabilization of the FA3 *Psammichnites,* and modern analogue suggests that any stabilization by interstitial biopolymers would have been limited, as the initial scour of host substrates would have reset biosediment systems to an immature recovery state (Chen et al., 2017). The form of the traces was likely maintained by secretions of mucus by the tracemaker, but this would only provide adhesion of internally constituent sand grains and not cohesion of the whole substrate (Dorgan et al., 2006).

Here we show that recent advances in our understanding of how the sedimentary rock record accumulates can explain the preservation of the FA3 *Psammichnites*. These remove the need to require surface stabilization for the preservation of any delicate or detailed structures on true substrates. Figure 4 presents a conceptual model demonstrating why true substrate preservation is inevitable due to spatial variability in any depositional environment. True substrates should be expected to be encountered in the field because any bedding plane, observed exposed in an outcrop, records only a finite spatial cell of the original depositional environment (presently non-observable due to having been eroded away or being concealed within the body of the outcrop). In the original environment, spatial variability was prevalent for both sediment accumulation and flow conditions. Considering the latter, any individual flow event could have waned both spatially and temporally, its intensity successively falling below critical velocities for erosion, transport, and deposition of a given sediment grain size. As waning flow passed over multiple finite spatial cells of a substrate, each cell would have experienced one of four sedimentation states at any given point in time: either (1) erosion, (2) deposition, (3) local stasis (i.e., coeval with upstream erosion, downstream deposition, and overriding transport), or (4) regional stasis (quiescence between flow events). Even with just two flow events, variable in their inception points, durations, and spatial extents and buffered by intervals of regional stasis, any randomly located finite spatial cell would have experienced one of at least nine possible sequences of the four sedimentation states. In the illustrated example (Fig. 4), three end-result sequences include a transition from

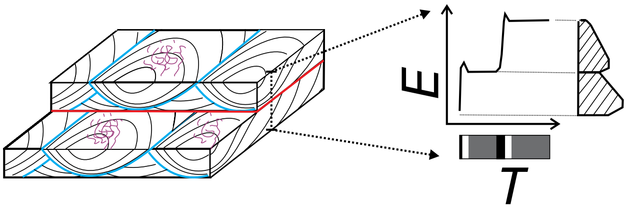

Figure 3. Block diagram showing stratal expression of events in Figure 2 (*Psammichnites* [purple], 1st-order [blue], and 2nd-order [red] bounding surfaces are highlighted). Graph shows how bed elevation (E) changed during time of deposition (T) and a resultant 2-D stratigraphic profile. Bar at bottom shows time recorded as strata (black), stasis time recorded by trace fossils (gray), and missing time (white).

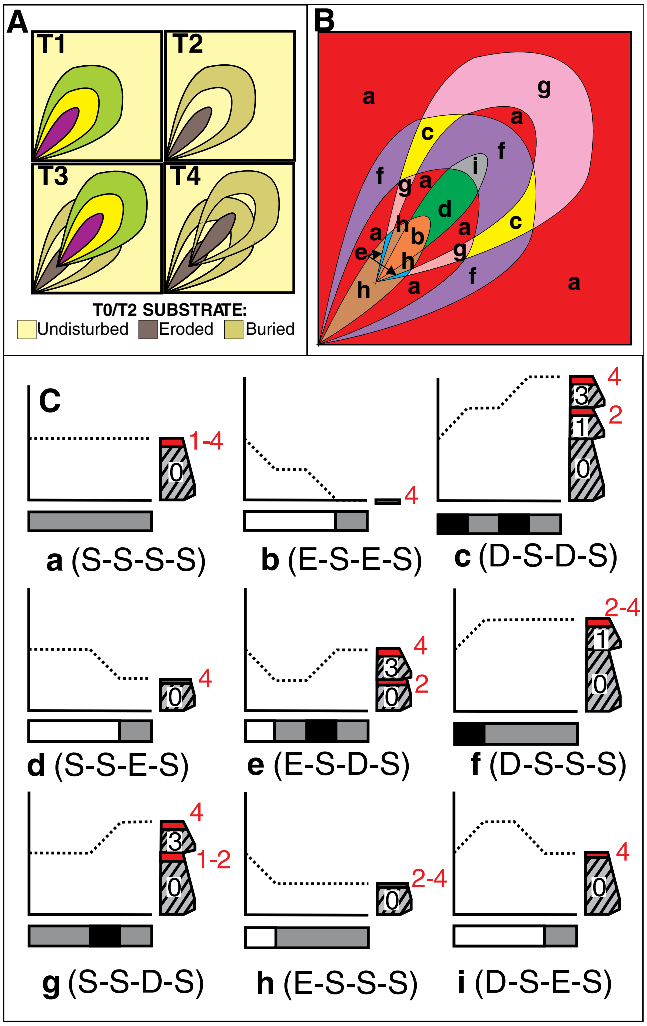

Figure 4. Conceptual model illustrating inevitability of true substrate preservation due to spatial variability within two discrete waning flows. A: Plan view of region experiencing two radially dissipative flow events waning through critical velocities necessary for erosion (purple), transport (yellow), and deposition (green), with offset inception points and buffered by intervals of regional stasis. Flow events occur at time intervals T1 and T3, and regional stasis at T2 and T4, with cumulative sedimentary effects on antecedent T0 substrate. B: Map of regional substrate showing how any internal finite spatial cell has experienced one of nine different combinations (a–i) of sequential states of erosion, deposition, and stasis between time intervals T1 and T4. C: Regional variability in resulting stratigraphic expressions immediately after T4 (time-elevation plots, as in Fig. 3, for each area shown in B). Letters show sequence of erosion (E), deposition (D), and/or stasis (S). Numbers show when strata were deposited (black) or duration of stasis during which time signatures could be imparted to true substrates (red). True substrates are shown in red on stratigraphic columns.

stasis to deposition without intervening erosion, permitting the potential interment of true substrates. As any 2-D stratigraphic profile at outcrop is a stacked record of multiple finite spatial cells (aggrading under different sequential combinations of sedimentation states), the inevitable occasional preservation of true substrates thus appears to be an extended example of the "strange ordinariness" (Paola et al., 2018) of the time-incomplete SSR.

CONCLUSIONS

Recent advances in the modeling of how strata record time can be used to frame field observations of sedimentary rocks in the field. A recognition of the importance of sedimentary stasis, the ordinariness of the rock record, and spatial variability within depositional environments can be combined to indicate that the counterintuitive preservation of true substrates may be inevitable, and that it is unnecessary to invoke mechanisms of substrate stabilization to explain it.

Conversely, the colonized second-order bounding surfaces of FA3 are also an instance where field observations have implications for the parameters that can be incorporated into future modeling, namely:

(1) While stasis time is conventionally considered to not be preserved (Tipper, 2015), the existence of true substrates supports contentions that this is a simplification (Paola et al., 2018). While the duration of stasis and the order of events that occurred during stasis can only be approximated, where true substrates can be confidently recognized in the field, they provide definitive proof of instances (and the minimum recurrence interval) of stasis.

(2) The importance of autogenic processes in the creation of the sedimentary record (Hajek and Straub, 2017) is complicated by sporadic interference from high-frequency allogenic processes, which can be as "ordinary" as autogenic processes on depositional time scales (Dott, 1983). These have the potential to spatially shuffle sedimentation states, instantaneously, within a depositional environment. This process has likely rendered a level of complexity to the time-incompleteness of the SSR, which requires assessment on an outcrop-by-outcrop basis.

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