

Using Process Ichnology to Refine Interpretations of Sedimentary Rocks

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Several characteristics of ichnofossils and ichnofossil assemblages are ideally suited to elucidate depositional stress in sedimentary environments. These include: 1) the distribution of trace fossils; 2) the diversity and range of ethological aspects of the ichnogenera; 3) the presence or absence of burrow linings; 4) size; and, 5) the degree of deformation of laterally associated traces. When these parameters are coupled with sedimentological data, trace fossils proffer high-resolution interpretations of the prevailing depositional conditions that lend insights into both physical and chemical (i.e., physico-chemical) stresses. To this end we employ a range of modern and ancient examples of the aforementioned ichnological characteristics to deduce sedimentary process-revealing interpretations.

1. Spatial Distribution

The spatial distribution of trace fossils primarily reflects the degree of stability and temporal persistence of physico-chemical conditions in a sedimentary environment. Trace fossils can be distributed (i) homogeneously, (ii) regularly heterogeneously, or (iii) sporadically heterogeneously (e.g. Gingras et al. 2007; MacEachern et al 2007). Thorough, homogeneously distributed bioturbation is generally associated with readily available food and oxygen, and slow, continuous sedimentation. This is mainly the result of the time-averaged shifting of regularly heterogeneously distributed infaunal communities (and their tier positions) within a depositional environment. Continuous, highly burrowed media is a dominant feature of many shelfal to offshore deposits.

In other sedimentary environments, such fabrics are entirely subordinate. Generally speaking, lower bioturbation intensities are not congruent with homogeneous trace fossil distributions. Regularly heterogeneous trace fossil distributions result from predictably recurrent variability in local physico-chemical parameters. Depositional environments characterized by regular and uneven colonization are influenced by tidal, seasonal to annual, or longer-term climatic cycles. Regular heterogeneous distributions most commonly are expressed as bioturbated beds interbedded with unburrowed or sparsely burrowed media. Sporadically heterogeneous distributions, on the other hand, are the result of persistent spatio-temporal variability in physico-chemical conditions. Bioturbation intensities in such settings are variable in such cases, and may span the full range of BI values rather unpredictably. There are a number of sedimentary environments characterized by episodic sediment erosion and/or deposition, most notably estuaries and deltas. Variable chemistry of the depositional waters may also play a role in developing sporadically occurring trace-fossil suites.

2. Diversity

Trace-fossil diversity is commonly taken to be a reflection of the degree of physico-chemical stress, wherein highly diverse suites record optimal conditions and low-diversity suites are considered indicative of environmental stress (MacEachern et al. 2007). Diversity is optimal in depositional settings characterized by well-oxygenated marine waters, variable substrate consistencies, generally reduced deposition rates, and variable but abundant food resources (e.g., suites of the *Cruziana* Ichnofacies). If any of these parameters are compromised, a shift in the diversity of ichnogenera present will be observed.

3. *The Significance of Burrow Linings*

Certain ichnogenera are defined by the presence of burrow linings. Some are prone to the development of linings, and others may display linings locally but lack them elsewhere (Zorn et al. 2010). Organisms may choose to line their burrows for a variety of reasons, and care must be taken in assessing the environmental parameters being reflected. The most commonly cited explanation for burrow linings is to compensate for reduced substrate consistency and burrow-margin stability. This is not always a valid interpretation, however. In many situations, burrow linings may reflect other organism-environment responses. Additional purposes of a lining include burrow-margin lubrication, maintenance of water saturation levels, waste stowage, symbiotic associations with bacteria, passive reaming or reprobation, and accumulation of a biogenic deposit. Some traces are regularly associated with strongly heterolithic intervals and are invariably lined with a single layer of clay (e.g., *Teichichnus*, *Diplocraterion habichi*, and *Lingulichnus*) or multiple layers of clay and silt (e.g., *Cylindrichnus*). In such instances, burrow stability, lubrication of the burrow interior, and/or bioturbation in the presence of pronounced water turbidity variously explain the occurrence of localized mud-rich spreite or linings.

4. *The Significance of Burrow Diameter*

Diminution is a first-order response to chemical stress and occurs in salinity-stressed environments and oxygen-poor settings (Pemberton et al, 1982; Savrda and Bottjer, 1989). Discerning brackish-water-induced diminution from low-oxygen diminution can be challenging. Salinity-stressed trace-fossil assemblages generally comprise simple, facies-crossing forms such as *Cylindrichnus*, *Planolites*, *Thalassinoides*, *Arenicolites*, *Skolithos*, and cryptobioturbation. Oxygen-stressed environments have been identified by the domination of a very low-diversity of very small trace fossils, such as *Chondrites* (suggesting facultative diminution).

5. *The State of Burrow Deformation*

The style and amount of distortion of trace-fossil assemblages are determined by the cohesiveness of the bottom-sediment, sedimentation rate, stability of the local sediment pile, and local sediment-stabilizing influences such as biolamination. Burrow deformation spans a continuum from essentially undeformed structures through to completely obscured biodeformational structures. The preservation of unlined trace fossils (in full relief) suggests that the sediment was compacted prior to bioturbation and was somewhat cohesive at the time of burrow emplacement (Pemberton and Frey, 1985). Differential compaction of trace fossils *versus* the matrix results from bioturbation in a slightly to moderately cohesive substrate. The preservation of distinct burrow structures is reduced dramatically in soupy substrates.

Additionally, trace fossils may be penecontemporaneously deformed on dipping depositional surfaces, forming *en echelon* burrows bent in the same direction (Gingras and Bann, 2006). This has been used as a creep indicator on tide-influenced point-bar deposits, and possibly for some delta-front settings.

Interpreting the Sedimentary Record

Ichnological observations that relate diversity and distribution trends, characteristics of the burrow linings, the size ranges of trace fossils, and the presence of penecontemporaneous deformation, stand to substantially improve sedimentary interpretations. In particular, these observations provide direct evidence of the: (1) consistency or variability of physical processes and chemical conditions; (2) availability and distribution of food resources; (3) consistency of the colonized substrate; (4) overall levels of salinity and oxygenation; and, (5) the stability of depositional surfaces. Many of these interpretations cannot be derived utilizing physical sedimentary structures alone. Neoichnological research holds the promise of building the ichnological process-response models essential for refining existing depositional facies models.

Where process ichnology is fully integrated with sedimentological analyses, high-resolution interpretations of the sedimentary record can be achieved.

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