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Applying Ichnology to Sequence Stratigraphy – A Legacy of S. George Pemberton

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Summary

The rise of sequence stratigraphy marks one of the most important turning points in the analysis of sedimentary successions (*cf*. Miall, 2015 and Burgess, 2016 for discussions). It serves as a methodology that employs stacking patterns and key bounding surfaces to erect a framework for which the depositional facies of sedimentary environments can be mapped and interpreted in the context of paleogeography (Bhattacharya, 2011; Catuneanu *et al*., 2011). While debate may surround the actual origins of the concept (Pemberton *et al*., 2016), the modern sense of the framework was certainly well into its inception by the early 1980s. It probably should come as no surprise that many basic ichnological applications were already well established in the 1960s and 1970s, and merely awaited a suitable facies-driven stratigraphic framework through which the interpretive value of trace fossils could be harnessed. The pivotal ichnological contributions to sequence stratigraphy are: 1) the identification of stratigraphic discontinuities through the use of substrate-controlled trace fossil suites (or omission suites), and 2) recognition of subtle facies shifts marked by abrupt juxtaposition of non-adjacent softground trace associations. Within the Ichnology Research Group at the University of Alberta, George Pemberton spearheaded the supervision of a number of theses and post-doctoral research throughout the 1980s, 1990s and 2000s that focused on exploring these applications. This integration of ichnology with the sequence stratigraphic concept stands as a testament to Professor S. George Pemberton's scientific vision.

Substrate-Controlled Ichnofacies and Stratigraphic Omission

The concept of stratigraphic omission within paleontology has a long history, but historically was focused on temporal duration and the loss of biozones. By contrast, within the discipline of ichnology, omission was recognized to be closely associated with the changing rheology of the substrate into which biogenic structures are excavated (*e.g*., Bromley, 1975; Pemberton and Frey, 1985). Trace fossils that showed increasing rigidity of the substrate were recognized by a number of key features, including the preservation of bioglyphs along the burrow margins that recorded their excavation, such as scratch marks. Within the Seilacherian framework, these associations are regarded as "substrate-controlled ichnofacies", which mark substrate consistencies ranging from lithified substrates (*Trypanites* Ichnofacies) to firm, compacted but non-lithified substrates (*Glossifungites* Ichnofacies). Later, palimpsest excavations into coalified substrates were assigned to the *Teredolites* Ichnofacies (Bromley *et al*., 1984). It was not lost on early workers that such associations could be key in helping to resolve which facies intervals adhered to Walther's Law and which recorded juxtaposed successions separated by a stratigraphic break across which Walther's Law was contravened (*e.g*., Bromley, 1975; Pemberton and Frey, 1985; Vossler and Pemberton, 1988; Savrda, 1991; MacEachern *et* al., 1992; Taylor and Gawthorpe, 1993; Pemberton and MacEachern, 1995).

George Pemberton and his research group quickly proposed criteria that could be employed in identifying subsurface (core) expressions of these omission trace fossil associations, based on modern-day settings and outcrop occurrences:

1. Omission suites are by their nature palimpsest, and so cross-cut earlier softground, stiffground and/or firmground associations;
2. Most firmground and hardground structures record permanent domiciles, and so are typically infilled by physical sedimentation after abandonment (*i.e*., passively filled);
3. Substrates, being rigid, lead to burrows that are sharp-walled and unlined;
4. Burrow margins may contain bioglyphs such as scratch-marks that record the excavation of the structure using the hard parts of the animals (*e.g.*, claws, jaws, shell margins);
5. Suites tend to be dominated by vertical and subvertical structures, although these give way to more horizontal dwellings with increasingly distal depositional positions;
6. Many associations record long-lived substrates generally devoid of significant sedimentation, allowing multiple generations of colonizers. Correspondingly, burrow densities can be very high;
7. Omission traces typically are present in lithologies that would not or could not host such ethological grouping in their original softground states (*e.g*., open unlined vertical shafts within mudstones);
8. Omission burrows typically show little or no post-depositional compaction, particularly as substrates shift from stiffground through firmground to hardground conditions;
9. Omission traces may be associated with mineralized crusts and/or encrusting biota.

These characteristics, some of which are shown in Figure 1, could be employed to predict the presence of a stratigraphic discontinuity. Implicit in these ichnological associations was that regardless of the cause(s) of the stratigraphic omission, colonization of the discontinuity occurred in a marine or marginal marine setting. More problematic, however, was the differentiation of those omissions of autogenic origin from those of allogenic origin. Allogenically formed discontinuities fundamentally bound systems tracts and have more regional extent, allowing partitioning of the stratigraphic succession into genetically related packages. Gingras *et al*. (2000, 2001) demonstrated that discontinuities recording longer temporal gaps tended towards much firmer substrates (firmground to hardground) whereas shorter-lived discontinuities, such as autogenic erosion surfaces along the cutbanks of tidal creeks and channels, tended to less firm (*e.g*., stiffground) colonized substrates, based on some quantitative investigations of omission surfaces at Willapa Bay, Washington. Stiffground burrows could be seen to be more susceptible to compactional deformation during burial, providing a possible means of differentiating autogenically related omission from more pronounced allogenic omission.

However, the most apparent means of differentiating autogenic omission from allogenic omission appears to reside with the juxtaposition of facies across the discontinuity. It is clear from the many studies of discontinuity-bound successions that one of the hallmarks of allogenically induced shifts in deposition is the juxtaposition of markedly different depositional environments across such surfaces that contravene Walther's Law. Facies analysis that relies on ichnology integrated with sedimentology has been shown to be exceedingly valuable in discerning these paleoenvironmental juxtapositions. It was through this technique that Pemberton *et al*. (1992) were able to show the abrupt juxtaposition of brackish-water sedimentary facies (*e.g*., central basin mudstones) over open marine offshore mudstones along the estuarine incised valley margin within the Viking Fm of the Crystal Field. From these early examples have come numerous comparable integrated ichnological and sedimentological studies that showcase pronounced facies juxtapositions during base level fall and base level rise (*cf*. MacEachern *et al*., 2012 for a review). The literature is replete with examples of forced regressive shoreface and delta deposits overlying regressive surfaces of marine erosion and deep-water conduit fills of submarine canyon margins during base level fall, as well as tidal ravinement with estuarine onlap of valley margins and wave ravinement across earlier subaerial unconformities associated with base level rise. As the sequence stratigraphic models have been refined, ichnological applications have followed suit, and continue to contribute to the discrimination of discontinuities and characterization of their associated systems tracts.

Future of Ichnology in Sequence Stratigraphic Analysis

As is the case for nearly all areas of ichnology, there is a continued need for the neoichnological study modern environments, particularly to better characterize omission associations related to base level rise. The work of Gingras *et al*. (2000 and 2001) represents one of only a few such studies, and alone led to a major advance in our assessment of autogenic *vs*. allogenic discontinuities, which is crucial for discerning systems tracts. A better knowledge of where firmgrounds are likely to occur needs to be established. Are estuary margins more prone to firmground exposure than subtidal estuary channel margins? In open coastal settings, does the character of the backshore (*e.g*. eolian-dominated *versus* salt-marsh-dominated) have an influence on the development and preservation of burrowed firmgrounds? One can anticipate further such advancements in the sequence stratigraphic use of ichnology through the study of modern estuarine valleys, transgressively ravined shorelines, evaluating the spatial variability in the characteristics of discontinuities, *etc*.

Additional ancient examples must be investigated, and previously studied intervals re-evaluated in light of the continued development of the sequence stratigraphic concept. This is particularly true with respect successions associated with periods of base level fall and the differentiation of forced regressive *vs*. lowstand surfaces. Subtle upward changes in ichnological suites of otherwise similar facies should also be viewed from the perspective of discerning subtle “depositional conformities” that correlate to discontinuities (*e.g*., identification of correlative conformities and basal surfaces of forced regression).

Greater attention must be paid to composite discontinuities that record amalgamation of surfaces of different origin. Many low-accommodation settings appear to be characterized by such composite surfaces, but criteria for their identification are generally lacking. In the siliciclastic realm, for example, hardground surfaces are probably more commonly associated with transgression across previous subaerial unconformities. Case studies that seek to explore the characteristics and colonization of such surfaces would be of great value in showcasing what we should be looking for in the rock record.

Integrated ichnological and sedimentological facies models need to be more closely tied to the mapping and characterization of discrete systems tracts preserved between bounding discontinuities, if we should ever hope to develop high-resolution paleogeographic reconstructions and explain preserved depositional architectures.

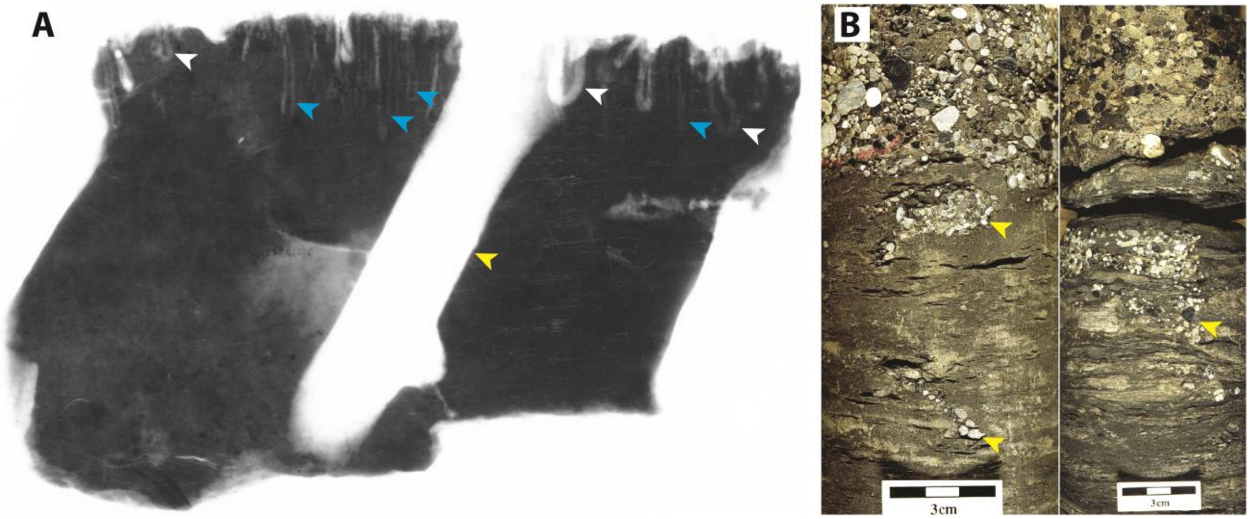

Figure 1. (A) An X-radiograph of a modern *Glossifungites* Ichnofacies-demarcated omission surface from Willapa Bay, Washington, USA. This omission surface was cut by wave erosion. A large *Thalassinoides*,

made by the mud shrimp *Upogebia pugettensis,* is indicated with a yellow arrow. *Arenicolites,* made by amphipods (*Corophium volutator*), are indicated with white arrows. Gracile *Diplocraterion,* constructed by the small worm *Polydora* sp., are shown with blue arrows. Burrows were active and not yet passively infilled. A mottled palimpsest burrow fabric is cross-cut by the active burrows. (B) A Cretaceous example (Cardium Fm), showing a transgressively modified subaerial unconformity characterized by firmground *Thalassinoides* (yellow arrows) of the *Glossifungites* Ichnofacies, which cross-cuts the original softground burrow fabric.

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