Insect Ichnofossils in Palaeosols as a Diagnostic Feature

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Paleosols represent key elements in the analysis of non-marine sequences. They yield valuable information on stratigraphic discontinuities and unconformities, they can be utilized as marker beds for correlation and, finally, they are one of the most reliable paleoclimatic evidences indicating landscape stability. In cases where pedofabric is not evident or root traces are absent, insect trace fossils are powerful tools for recognizing paleosols and the subaerial exposure of deposits. Even when land arthropods colonized paleosols since the Ordovician, reliable insect trace fossils have been recorded in paleosols from the Cretaceous to the Recent. During the early Cretaceous appeared ecological key groups of insects, such as bees, aculeate wasps, ants, termites and different groups of beetles. In contrast with older ones, these insects construct or line the walls of their breeding or pupation chambers with organic matter, hence contributing to their cementation, early diagenesis, and their later preservation as trace fossils. In addition, these insects produced more complex structures, which can be compared in detail with modern ones, resulting in reliable attributions. Four ichnofamilies including ichnogenera attributed to breeding and pupation chambers of bees, wasps, ants, beetles, and termites were recognized until now in Cretaceous to Recent paleosols: Coprinisphaeridae, Celliformidae, Pallichnidae, and Krausichnidae. In older paleosols, the attribution to insects of trace fossils that are morphologically simple, and as such that can be produced by a wide range of invertebrates, or that are not comparable with insect modern ones may be a misleading procedure that may result in false paleoenvironmental interpretations.

Skolithos-Dominated Piperock in Non-Marine Environments and Their Significance in High-Resolution Analysis

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The Caturrita Formation Triassic red beds (Ladinian-Lower Norian sucession, Paraná Basin, southern Brazil) contain abundant vertical ichnofossils in low angle, trough cross-bedded fine-grained sandstones interpreted as crevasse splay deposits, forming a composite piperock. The ichnofauna of the lower and upper parts of the studied succession characterizes the Scoyenia Ichnofacies. Laterally spreading rhizoliths cap the lower part, suggesting extensive paleosol development and revealing a non-depositional period (S1 surface). Overlying S1, three packets of thickening, slightly coarsening and shallowing-upward recurrent cycles characterize the middle part of the sedimentary succession, bearing the Skolithos-dominated composite piperock. It is formed by the palimpsest preservation of an oldest S. linearis suite, an intermediate T. barretti monospecific suite, and a youngest, substrate-controlled, Skolithos cf. serratus monospecific suite. Skolithos cf. serratus is dominant, being closely spaced (~160 burrows/m^2), and having sharp, irregular boundaries with delicate scratch marks. Colonization started in softgrounds, maybe under subaqueous conditions, showing gradual substrate dessication, being S. cf. serratus produced in firmgrounds (S2 surface). Midge larvae and tiger beetles are assumed as Skolithos linearis and Skolithos cf. serratus tracemakers, respectively, while Taenidium barretti represents oligochaete burrows. Substrate dewatering and subaerial exposure played an important role in the non-marine piperock generation. The top of the middle part of sedimentary succession represents a depositional hiatus by non-deposition, reflecting low rates of erosion of firmgrounds. It suggests important environmental (climatic?) changes opening the colonization window to insects in exposed floodplains. Both S1 and S2 surfaces are interpreted as autocyclic, being useful for stratigraphic correlation in local scale.

Integrating Ichnology, Sedimentology and Sequence Stratigraphy to Delineate Incised Fluvio-Estuarine Valleys and Shoreface-Offshore Complexes in an Early Palaeozoic Basin of Northwest Argentina

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The Upper Cambrian-Tremadocian Santa Rosita Formation of Cordillera Oriental (northwest Argentina) reveals a series of transgressive-regressive cycles punctuated by incision of fluvio-estuarine valleys. Ichnologic models of marginal- and shallow-marine environments were originally based on Mesozoic units and need to be calibrated in order to be useful for Paleozoic reservoirs. Open-marine, wave- and storm-dominated deposits range from the shelf to the upper shoreface. Alternating and contrasting energy conditions due to repeated storm events superimposed on fairweather sediments were among the key controlling factors for ichnofossil distribution and preservation. The fairweather assemblage is the most diverse and includes the more varied behavioral strategies, containing *Archaeonassa*, *Arthrophycus*, *Bergaueria*, *Cruziana*, *Diplichnites*, *Dimorphichnus*, ?*Gyrolithes*, *Gyrophyllites*, *Monomorphichnus*, *Palaeophycus*, *Phycodes*, *Planolites*, *Rusophycus* and *Trichophycus* (*Cruziana* ichnofacies). The storm-related assemblage is monospecific (*Skolithos*), representing the *Skolithos* ichnofacies. Ichnofossils also occur in transgressive tide-dominated estuarine valley deposits that overlie fluvial facies along the valley axis. No trace fossils are recorded in the inner estuary, where salinity values were probably too low. Middle estuarine deposits are mostly unbioturbated; only arthropod trackways (*Diplichnites*), vertical burrows (*Skolithos*), and horizontal vermiform burrows (*Palaeophycus*) rarely occur in tidal rhythmites. The presence of trackways in middle estuarine deposits may reflect the ability of some marine arthropods to periodically migrate inland. The highest ichnodiversity is restricted to the outer zone of the estuary, representing near-normal marine conditions. The outer estuarine ichnofauna consists of trilobite trace fossils (*Cruziana*, *Rusophycus*, *Monomorphichnus*), vertical burrows (*Skolithos*, *Diplocraterion*, *Conostichus*) and feeding structures (*Teichichnus*, *Planolites*).

Characterization of a Sandy Tide-Dominated Incised Valley Fill System Using Ichnofabric Analysis: Woollybutt and East Spar Fields, Barrow Sub-Basin, Western Australia

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Seismic data from the Barrow Group in the Barrow Sub-basin reveals the presence of a NE-trending incised valley fill system with an anomalously thick section in the East Spar and Woollybutt fields, and dramatic thinning of the section laterally on adjacent interfluves to the east and west. This model is supported by evidence from palynology, FMI and core data. Ichnofabric analysis is crucial in (1) accurately characterising the different facies associations within the incised valley and, in particular, (2) accurately determining degrees of marine influence within the channelised strata.

A series of stacked fluvially and tidally distributary channel fill strata, overlain by fully marine middle shoreface, lower shoreface and shelfal sediments, dominate the succession. For example, *Teichichnus*-dominated ichnofabrics characterise delta front sandstones associated with intense fairweather bioturbation, while more distal delta front strata are characterised by heterolithics with *Ophiomorpha*, *Teichichnus* and *Phycosiphon*. The channel fills comprise multiple fining-upward packages of coarse to medium, trough cross-bedded and planar stratified, with thick clay drapes and dense colonisation by very large, robust-walled *Ophiomorpha nodosa*. Colonisation within tidally influenced channels is interpreted. In contrast, the fluvially dominated channel fills are non-bioturbated and locally display rootlet horizons towards their tops.

A series of backstepping, sharp-based shoreface sandstones are recognised towards the top of the study interval, associated with progradation of a shoreline across the marine portions of the valley fill. Dense colonisation by firmground *Skolithos* and *Diplocraterion*, cross-cutting a background mottled ichnofabric with *Ophiomorpha*, is evident. The sandbodies represent detached forced regressive shoreface sandstones deposited during stillstands prior to major transgression and deposition of the Mardie Greensand and subsequent Muderong Shale. The incised valley fill itself is a compound fill comprising multiple episodes of channel incision associated with falls in relative sea level.

From Ichnofabric to Reservoir Model – a Tide Dominated Delta Front Succession from the Lajas Formation, Neuquen Basin, Argentina

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The Lajas Formation of the Neuquen Basin consists of a thick succession of tide-dominated deltaic reservoirs. Such depositional settings are becoming increasingly commonly recognised and form impportant reservoirs offshore Norway, S. China Sea and in S. America. Previous work on the Lajas Formation has described the delta top palaeoenvironments in some detail. This presentation is focussed on the delta front setting. Detailed facies architectural studies have been undertaken, which utilise ichnofabric analysis and high resolution sequence stratigraphy. This architectural data has, in addition, been used as the basis for creation of a reservoir model which honors the outcrop data to a high degree.

Using Traces Fossils in Deepwater Deposits to Interpret Palaeoenvironments and Facies Distributions: Examples from Angola Slope Deposits, Block 15, West Africa

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Trace fossils are an invaluable tool for understanding better the local and regional depositional environments of reservoir and non-reservoir rocks in higher order sequences. Although lithofacies analyses are used to interpret depositional environments, many are not well constrained because most lithofacies can occur in multiple settings and associations. Trace fossils can be used as proxies to understand paleoenvironmental and paleoecological conditions in deep-water settings. The diversity, abundance, tiering depth, and ichnofabric indicies of trace fossils can be used to evaluate the (1) frequency and magnitude of deep-water depositional and erosional events, (2) surfaces of erosion and amalgamation that produce dewatered, compacted substrata, (3) relative duration(s) of hiatuses, (4) bottom water oxygenation and turbidity, (5) overall rate of sedimentation, and (6) depositional environments in slope and basin settings.

Trace fossil associations demonstrate the presence of unique paleoenvironmental settings and bottom-water conditions. For example, deep-water firm grounds assigned to the more typical shallow-water Glossifungities ichnofacies are easily recognized by burrows with sharp walls and spreite excavated in dewatered and compacted sediments. These burrows remain open and are later filled, often with multiple fill episodes by sediments of various grain sizes. In other instances, areas with high, episodic rates of muddy turbidity current deposition have little or no penetrative bioturbation. Most traces in these environments are small, fine surface trails. On the other hand, environments where sedimentation was lower, in event frequency and magnitude, have trace fossil associations that are more diverse, penetrative, with higher ichnofabric indices.

Applied Ichnology for Advanced Facies Models of Shallow Marine, Deltaic and Coastal Successions

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The facies characteristics of shallow marine and coastal environments are largely determined by the complex interplay and relative importance of wave energy, tidal flux, storm influence, and fluvial-sediment input. Ichnology constitutes a powerful tool for fingerprinting these processes, particularly when integrated with sedimentological and stratigraphic analysis. Trace fossils are biogenic sedimentary structures, strongly facies controlled, and temporally long ranging, making them ideal for facies analysis. Ichnofossils are also readily observable at outcrop and core scales, making their identification and interpretation as routine as physical sedimentary structures.

The ichnofacies paradigm is exceptionally well poised to offer critical information about the conditions operating during deposition (e.g., softground ichnofacies) or during the development of stratigraphic discontinuities (e.g., substrate-controlled ichnofacies and palimpsest softground suites). Ichnofacies stand as one of the most elegant but most widely misunderstood and mis-used concepts in sedimentology. Softground ichnofacies have been refined to include proximal, archetypal and distal expressions, permitting high-resolution subdivision of successions deposited in environments such as strandline shorefaces and deltas. Models addressing brackish-water induced stresses, substrate consistency changes, O2 reductions, and energy variations on bioturbation have enhanced the identification and subdivision of estuarine incised valley, embayment, and interdistributary bay deposits. Current work on the effects of hypopycnal-induced water turbidity, hyperpycnal discharge, freshets, fluid mud deposition, heightened depositional rates, and storm events on infauna help to identify the deltaic ichnological signal, and elucidate the relative importance of waves, tides and fluvial discharge. Ultimately, such models could be applied to along-strike variations in linked depositional systems, enhancing paleogeographic reconstructions.