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Using Trace Fossils to Differentiate between Alluvial, Lacustrine, Eolian, and Marine Paleoenvironments

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This paper describes the how trace fossils can be used in conjunction with secondary sedimentary and pedogenic structures to differentiate the paleoenvironments of alluvial, lacustrine, and eolian systems from marine paleoenvironments. The type, distribution, and tiering of terrestrial and aquatic trace fossils are useful tools for deciphering continental environments in both outcrop and core. The trace fossils and paleosols are also important for interpreting subenvironmental settings within these deposits, as well as their paleohydrologic and paleoclimatic settings.

Trace fossils and trace fossil associations that are found commonly in marine deposits have been well documented and summarized in Hantzschel (1975), Ekdale et al. (1984), Pemberton (1992), and Pemberton et al. (2001). Much of this work encompasses the ichnofacies concept of Seilacher (1953, 1967), which identified associations of trace fossils that were recurrent through long intervals of geologic time and characteristic of a given set of environmental conditions. Only the *Scoyenia* ichnofacies was established for continental deposits (Seilacher, 1953, 1967), though others have tried to erect new continental ichnofacies (Buatois and Mangano, 1993, 1995; Buatois et al., 1998) and modify existing ichnofacies to include trace fossils in alluvial, lacustrine, and eolian deposits (Bromley and Asgaard, 1991). Publications at the monograph-scale that focus on continental trace fossils are very rare (Hasiotis et al., 1994; Hasiotis, 2002), though there has been an increase of published papers on this subject over the last twenty years (see references in Buatois et al., 1998; Hasiotis, 2002).

Understanding the distribution of burrowing organisms in modern continental settings allows for better identification and interpretation of ancient environments and the mechanisms that influenced the trace-making biota (Fig. 1). Continental organisms are terrestrial in habitat (above, on, and below the soil but above the water table), amphibious (restricted to shorelines), freshwater-aquatic (e.g., below the water table, rivers, lakes, and capillary water around grains), or hypersaline-aquatic (e.g., playa lakes). Modern terrestrial and aquatic organisms function primarily in a nitrogen-dominated atmosphere, living above, at, or below the freshwater-air or air-substrate interface. They also live in a variety of dry to variably moist substrates and freshwater to hypersaline aquatic environments, to which they are adapted and into which they burrow for all of the same reasons as marine organisms. Terrestrial and freshwater organisms are distributed vertically and laterally in continental depositional systems according to their physiological needs or tolerance to water, soil moisture, salinity, ecological associations with other organisms, and ultimately by climate. Plants, invertebrates, and vertebrates have different requirements for water or soil moisture, substrate consistency at the water-substrate interface, and the degree of ionic concentration and salinity within the water or substratum.

A four-part division of behavior categorizes ichnofossils into behavioral groups that indicate different space and trophic use as well as moisture zones of the groundwater profile, based on the distribution of extant organisms and their physiological requirements for water (Fig. 1). Organisms living above the water table in the uppermost parts of the soil-water profile down to the upper part of the vadose zone construct *Terraphilic* traces. They have low tolerance for areas of prolonged high moisture levels, can tolerate short periods of 100% soil moisture, and can live in areas with relatively little available water. This category also includes surface-dwelling and trackway-making organisms whose behaviors are termed *Epiterraphilic*. Organisms living within the upper, intermediate, and lower portions of the vadose zone with specific physiological and reproductive soil moisture requirements construct *Hygrophilic* traces. This category includes organisms living aboveground but that burrow to this level for reproduction. They obtain oxygen from the soil atmosphere rather than from groundwater or soil moisture. *Hydrophilic* traces are constructed by organisms that live below the water table within a soil and below the substrate in open bodies of water where the water table intersects the land surface like in rivers and lakes. These organisms obtain oxygen from the water. They can also use high levels of soil moisture to keep their gills wet for short periods of time. This category includes those organisms that burrow to depths below the water table and maintain the burrow's entrance at the surface.

The effect of burrowing organisms and plant roots on continental deposits above the water table results in soil development and measure the activity of organisms in soil-forming processes in modern and ancient environments. Organisms affect the substratum by mounding, mixing, forming voids, backfilling voids, forming and destroying peds. Burrowing organisms also regulate erosion as well as water, air movement, plant and animal litter, nutrient cycling, biota, and the production of special constituents. All of this activity plays a role in forming soil structures (e.g., platy, blocky, and prismatic peds), influencing redoximorphic conditions (e.g., red, green, yellow, purple mottling), and impacting porosity and permeability of the sediment.

The effect of ancient burrowing organisms resulted in paleosols that are preserved in the geologic record since the Ordovician. Paleosols are not deposits. They are the result of postdepositional modifications of deposits within alluvial, eolian, lacustrine, and transitional environments. This view of paleosols is contrary to the approach taken by other ichnologists who treat paleosols as a separate kind of environment or ichnofacies. Pedogenesis modifies nearly all surficial deposits. It occurs at different rates and with different results based on the magnitude and frequency of depositional events, distance from sediment source, parent material, position and fluctuation of groundwater profile, inherent local topography, composition of biotic communities, and the climate with regard to temperature and precipitation. The broad range of soil types and conditions in continental environments produces a high degree of spatial heterogeneity, resulting in juxtaposed microcosms, each with unique physical, chemical, and biologic properties. Consequently, paleosols cannot be used as a subdivision or potential ichnofacies.

Although the position of the ancient water table is not preserved in the rock record, its position is approximated through sedimentologic (primary and secondary sedimentary structures), ichnologic (burrow and root depths; tiering), and paleopedologic (mottling, ped structure, micromorphology, texture, and soil geochemistry) evidence. The depths of traces, their crosscutting relationships with other traces, or tiering, and their decrease in abundance within a profile approximate the position of ancient soil-moisture zones and the water table. These traces occur in deposits whose primary and secondary sedimentary structures or pedogenic features preserve characteristics of the environment in which the organism was burrowing. Integration of physical, biogenic, and chemical evidence provides information about the paleohydrology. In turn, ichnologic evidence is linked with other physical and geochemical evidence to interpret the climate at a particular time and place.

The effect of burrowing organisms and plant roots on deposits below the water table or in areas where the water table intersects the ground surface is minimal compared to subaerial and marine settings. Bioturbation is typically very shallow and burrowing patterns are simple. The decrease of O_2 and high levels of CO_2 and other products of anoxia in bottom waters and sediment preclude organisms deeply penetrating into the substratum. Also, lacustrine organisms are already submerged in water and do not need to burrow deeply to obtain moisture or food. Most lacustrine systems are short lived and fluctuate dramatically in breadth, depth, salinity, and water quality over short intervals geologically. These conditions have likely led to dramatically different burrowing behaviors of lacustrine organisms compared to those behaviors of marine burrowing organisms.

Thus, the vertical and lateral distribution of trace fossils can also be used to indicate the development of immature to mature paleosols in terrestrial and aquatic deposits. This is especially true for environmental settings where the activities of burrowing organisms outpaced pedoturbation (i.e., abiotic soil modifications). Trace fossils and their various architectural components (e.g., shafts, tunnels, chambers, and plant root patterns) also indicate infrequent, gradual, or rapid accumulation of terrigenous sediment based on the development and intensity of resultant ichnofabrics. Since soils are formed by both biotic and abiotic processes, ichnofabrics as defined for trace fossil patterns in marine deposits cannot be directly applied to most bioturbation patterns in continental deposits. Low concentrations of easily recognizable roots and the shafts, galleries, cells, and chambers of trace fossils in deposits with abundant primary sedimentary structures indicate immature paleosols due to a relatively rapid sedimentation rate. Relatively moderate concentrations of poorly- to well-defined roots and shafts, galleries, cells, and chambers in deposits with little to no primary sedimentary structures and presence of pedogenic features indicate variably mature paleosols due to a variably slow to moderate sedimentation rate. High concentrations of poorly preserved roots and shafts, galleries, cells, and chambers in deposits with no primary sedimentary structures and the presence of pedogenic features indicate mature paleosols due relatively to a slow sedimentation rate or relatively long hiatus in deposition.

Substrates where pedoturbation outpaces bioturbation lack appreciable evidence of bioturbation. Instead, these deposits contain well-developed subangular, blocky peds and prismatic structures, as well as distinct color mottling patterns. The traces of plants and animals are destroyed for the most part by the expansion and contraction of clay minerals due to wetting and drying of the substrate. Also, the downward accumulation of clay minerals into thick horizons precludes many types of organisms from burrowing deeply. It is in these clay-rich soils (paleosols) that organisms inhabit fractures or constructed their burrows that are destroyed by the action of shrinking-swelling clays.

Together, trace fossils and paleosols indicate the presence of discontinuity surfaces that were formed by varying degrees of pedogenesis, helping to differentiate alluvial from lacustrine and marine paleoenvironments in outcrop and core. The patterns in bioturbation and degree of pedogenesis also are useful in identifying and interpreting subenvironments with alluvial and eolian deposits. For example, channel, levee or bank, crevasse- or -splays, and proximal and distal floodplain environments contain several different types of trace fossil associations dominated by one or more types of trace fossils (see Fig. 1). Although each environment is interpreted from vertically and laterally related sedimentary units with distinct sedimentary structures, many of the trace fossils were constructed in these units under different environmental and hydrologic conditions than those that existed during deposition. Trace fossil associations present during or shortly after an extrachannel depositional event record hydrophilic and hygrophilic behaviors that indicate water-table levels at or above the surface with turbid to clear-water conditions. Depending on the frequency and magnitude of the extrachannel event, the original trace-making communities are displaced by communities with greater numbers of terraphilic and hygrophilic behaviors due to lower overall soil moisture and water-table levels subsequent to the event. These trace fossils overprint and destroy the original hydrophilic and hygrophilic trace fossils, and help promote the formation of pedogenic features.

These patterns in bioturbation and pedogenesis can also be used to distinguish intervals in lacustrine and marine deposits that have been subaerially exposed to form immature to mature paleosols with imperfectly to well-drained conditions in the substratum. Lower burrow densities indicate greater sedimentation rates or higher water tables, as well as chemically inhospitable substrates directly adjacent to or in internally drained basins and evaporative lakes. Palustrine carbonates or peat swamps form where high water tables and standing water persist for long periods of time with little or no terrigenous input. Relatively higher sedimentation rates and high, standing water tables above the substratum produce thick intervals of lacustrine mudstones and siltstones and very thin sandstones with very little bioturbation. The near lack of bioturbation in many types of lacustrine deposits can be attributed to high rates of sedimentation and salinity or alkalinity of the water and bottom sediments. The occurrence of mottled, subhorizontal burrows and shallow, dense rhizoliths in thin sandstones within these lacustrine deposits likely represents temporary episodes of local freshening of the saline or alkaline lake waters that allowed infaunal organisms and shallowly rooted plants to occupy the substrate in proximal lacustrine environments. This activity is also attributable to the lowering of lake level. Greater densities of subvertical and subhorizontal burrows and roots within an interval in lacustrine-dominated strata indicate longer periods of subaerial exposure and surface stability due to sediment bypass and the lowering of lake level that allows pedogenesis and more diverse and deeply penetrating bioturbation.

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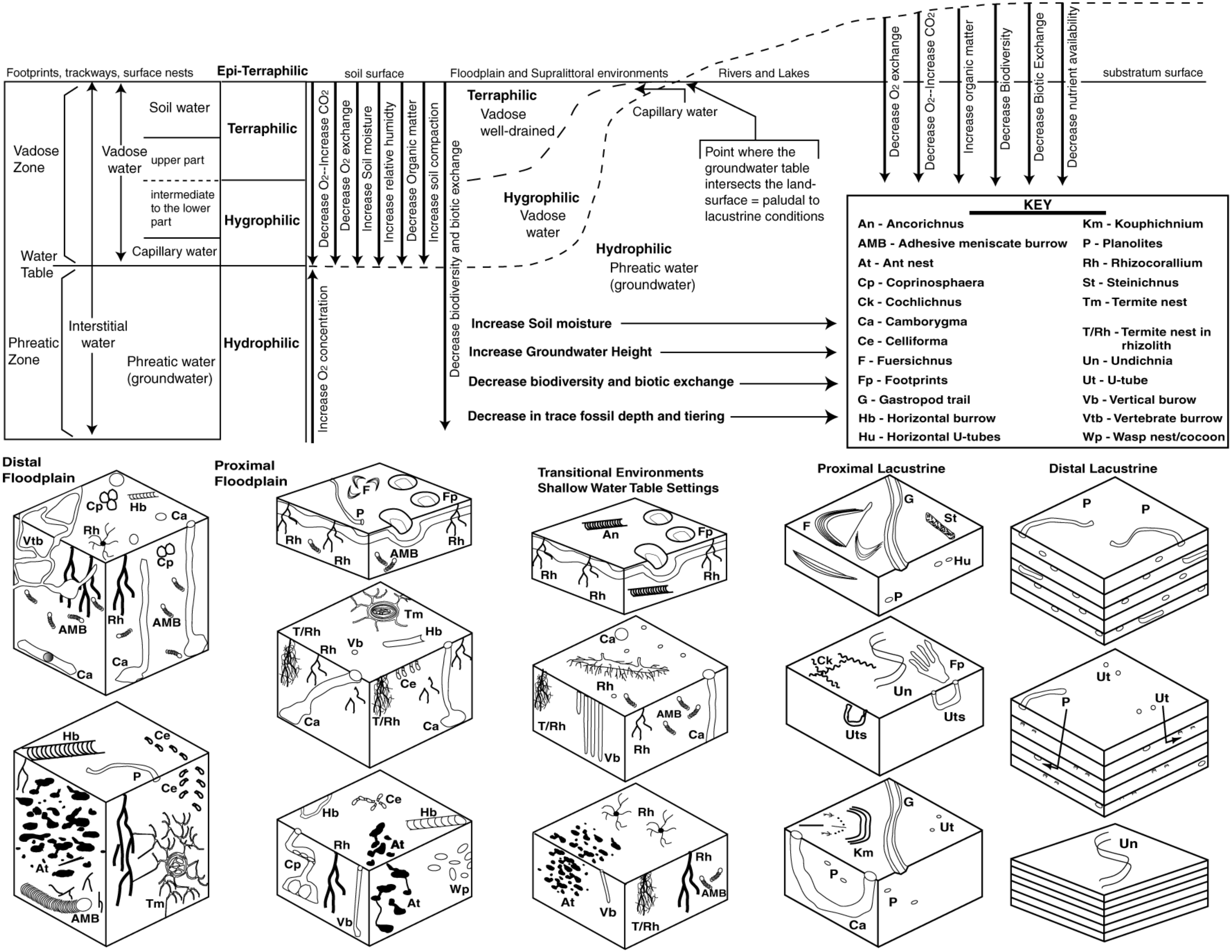
Footprints, trackways, surface nests
Epi-Terraphilic
soil surface
Floodplain and Supralittoral environments
Rivers and Lakes
substratum surface
Vadose Zone
Vadose water
Soil water
upper part
intermediate to the lower part
Capillary water
Water Table
Phreatic Zone
Interstitial water
Phreatic water (groundwater)
Terraphilic
Hygrophilic
Hydrophilic
Decrease O2--Increase CO2
Decrease O2 exchange
Increase Soil moisture
Increase relative humidty
Decrease Organic matter
Increase soil compaction
Decrease biodiversity and biotic exchange
Increase O2 concentration
Terraphilic
Vadose well-drained
Hygrophilic
Vadose water
Hydrophilic
Phreatic water (groundwater)
Capillary water
Point where the groundwater table intersects the land-surface = paludal to lacustrine conditions
Decrease O2 exchange
Decrease O2--Increase CO2
Increase organic matter
Decrease Biodiversity
Decrease Biotic Exchange
Decrease nutrient availability
Increase Soil moisture
Increase Groundwater Height
Decrease biodiversity and biotic exchange
Decrease in trace fossil depth and tiering
KEY
An - Ancorichnus
AMB - Adhesive meniscate burrow
At - Ant nest
Cp - Coprinosphaera
Ck - Cochlichnus
Ca - Camborygma
Ce - Celliforma
F - Fuersichnus
Fp - Footprints
G - Gastropod trail
Hb - Horizontal burrow
Hu - Horizontal U-tubes
Km - Kouphichnium
P - Planolites
Rh - Rhizocorallium
St - Steinichnus
Tm - Termite nest
T/Rh - Termite nest in rhizolith
Un - Undichnia
Ut - U-tube
Vb - Vertical burow
Vtb - Vertebrate burrow
Wp - Wasp nest/cocoon
Distal Floodplain
Proximal Floodplain
Transitional Environments Shallow Water Table Settings
Proximal Lacustrine
Distal Lacustrine
Cp
Hb
Ca
Vtb
Rh
Cp
AMB
Rh
AMB
Ca
Ca
Hb
Ce
P
Ce
At
Tm
AMB
F
Fp
P
Rh
Rh
AMB
Rh
Tm
T/Rh
Hb
Vb
Rh
Ce
Ca
T/Rh
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Km
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P
Ca
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P
Ut
Un