Exploring the sedimentary, pedogenic, and hydrologic factors that control the occurrence and role of bioturbation in soil formation and horizonation in continental deposits: An integrative approach

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ABSTRACT

Interpretation of paleosols involves deciphering the complex interplay between multiple biotic and abiotic processes. Previous ichnological research has shown that trace fossils, which record biotic influences on pedogenesis, are particularly useful for reconstructing physicochemical conditions during soil formation, which, in turn, can yield important data about paleoenvironment, paleohydrology, and paleoclimate. Our goal is to integrate ichnology with the substantial body of research that exists in the areas of sedimentology and pedology to present an integrative framework with which to interpret paleosols in the continental rock record. Tiering of traces is particularly prominent in terrestrial settings because the vertical distribution of soil biota is controlled largely by the groundwater profile. Interpretations of trace fossils are therefore facilitated by assigning traces to one of four moisture regimes: epiterraphilic, terraphilic, hygrophilic, and hydrophilic. The balance between deposition and pedogenesis is expressed by the paleosol profile, which can range from simple to compound, composite, or cumulative. The combination of sedimentation and pedogenesis, including groundwater-influenced bioturbation, can act to enhance or destroy horizonation within soils; these processes ultimately determine the paleosol characteristics that are preserved in the stratigraphic record. We illustrate our conceptual model with examples of multiple paleosol types that contain evidence of varying amounts of bioturbation attributable to crayfish.

INTRODUCTION

Trace fossils, studied via their architectural and surficial morphologies and the material that fills them, record information about the tracemaker and the physicochemical conditions of its surroundings (Bromley, 1996; Hasiotis, 2002). Deciphering the occurrence, depth, and tiering of plant and animal trace fossils in paleosols is paramount to interpreting the sedimentological, pedological, and hydrological conditions under which paleosols formed in continental deposits (Bown and Kraus, 1983; Hasiotis, 2002, 2007). This is particularly important for reconstructing the postdepositional histories of landscapes and the physicochemical conditions experienced by the organisms and soils, and recorded by sedimentary and pedogenic (i.e., biotic and abiotic) fabrics (Jenny, 1941; Hasiotis, 2004, 2008; Schaetzl and Anderson, 2005; Hembree and Hasiotis, 2007; Smith et al., 2008). Bioturbation in modern soils, particularly by animals, is known to be extremely effective at mixing sediment at and within the subsurface, and helping to build and destroy pedogenic structures and voids while playing a major role in nutrient cycling (Wallwork, 1970; Hole, 1981).

Herein we explore the hydrological, sedimentological, and pedological factors that control the spatial and temporal distribution of terrestrial and aquatic bioturbation that results in pedogenic fabrics and horizonation, and the physicochemical expression of organism-sediment interactions. Our objective is to demonstrate that trace fossils can be equally as powerful in reconstructing paleoenvironments and the depositional histories of continental sedimentary successions as marine trace fossils based on their occurrence, tiering, depth, and relation to the sedimentary facies (Figure 1). Despite the similarities between continental and marine trace fossils and their resultant bioturbation, their genesis and significance are distinctly different from each other because the specific organism behaviors and biophysicochemical conditions under which the traces formed are exclusive to each realm of deposition (e.g., Hasiotis and Bown, 1992; Hasiotis, 2002, 2008).

MATERIAL AND METHODS

Actualistic studies of the spatial and temporal distribution of terrestrial and aquatic organisms in continental environments provide the dataset from which we explore ichnopedologic fabrics—sedimentary fabrics that result from bioturbation and pedoturbation (Appendix A)(Hasiotis, 2007; Hasiotis et al., 2007, in press, and references therein). These and other actualistic studies were synthesized to understand how organisms interact with sediment to produce bioturbation that results in soils and horizonation through organism activity. Tracemakers of ichnofossils in paleosols are inferred from the trace fossil and its relationship to the sedimentary and pedogenic fabric. These interpretations are also made via comparison to similar structures found in modern depositional systems, continental environments, and pedogenically modified sediment that are analogous to the studied geologic deposits.

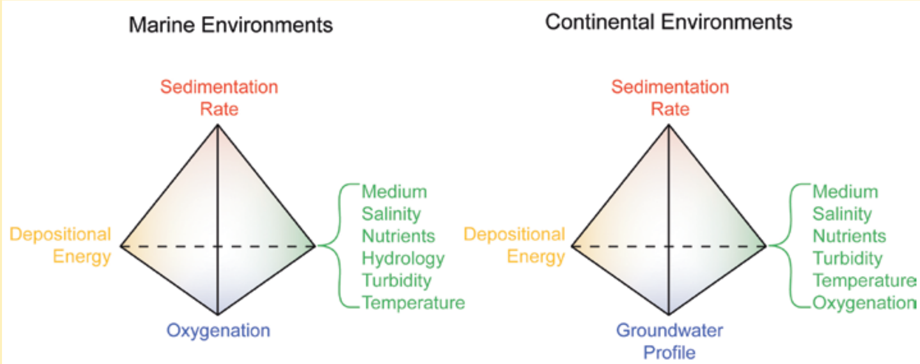

Figure 1: Tetrahedra illustrating the major physicochemical controls on trace-making organisms in marine and continental environments. Though parallel in many respects, the major difference between the two is the role of the groundwater profile and subaerial exposure in continental environments that allows soil formation to take place.

We integrated the concepts from several major reviews on processes that link various aspects of pedogenesis to sedimentation and pedoturbation (i.e., both biotic and abiotic aspects), bioturbation to sedimentation, and bioturbation to pedogenesis (Jenny, 1941; Wallwork, 1970; Hole, 1981; Johnson et al., 1987; Kraus, 1999; Schaetzl and Anderson, 2005; Hasiotis, 2002, 2007; Hasiotis et al., 2007). We used Hasiotis (2004, 2007, and references therein) to understand how the spatial and temporal distribution of the hydrologic regime and groundwater profile effect terrestrial and aquatic organisms and communities. We used Kraus (1999, and references therein) to recognize the interplay between sedimentation and pedoturbation under nonsteady and steady state conditions of deposition to produce soils of various developmental stages and pedogenic fabrics. We used Johnson et al. (1987, and references therein) to comprehend the production and destruction of horizonation in soils due to biotic and abiotic pedoturbation through time

DEVELOPING AN INTEGRATIVE APPROACH TO DECIPHER ICHNLOGIC PATTERNS IN PEDOGENICALLY MODIFIED DEPOSITS

Organism Tiering and Moisture Regimes

Organisms in terrestrial and aquatic environments are distributed vertically in sediments and soils based on biological and physicochemical characteristics with respect to their affinity for water (Cloudsley-Thompson, 1962; Wallwork, 1970; Whittaker, 1975; Glinski and Lipiec, 1990; Hasiotis, 2007; Hasiotis et al., in press). This vertical distribution is referred to as tiering, which also takes place in the marine realm (Bromley, 1996; Hasiotis, 2002). Modern and ancient traces can be assigned to one of four moisture regimes based on the space occupied, trophic use, and moisture zones of the groundwater profile, which behaviorally classifies the tracemaker as 1) epiterraphilic—organisms living on the surface, 2) terraphilic—organisms living above the water table to the upper vadose zone, 3) hygrophilic—organisms living in the vadose zone, or 4) hydrophilic—organisms living below the water table within a soil or living in aquatic settings and make traces on or below the sediment surface in open bodies of water (Hasiotis 2000, 2004, 2008). This moisture-regime classification is based on the well-established concept that moisture is a major control on the distribution of soil fauna (Cloudsley-Thompson, 1962; Wallwork, 1970; Hasiotis 2002, 2008; Hasiotis et al. 2007, in press; Counts and Hasiotis, 2009). Even though Bromley et al. (2007) questioned the methods of Hasiotis (2004), an abundance of life history studies of modern tracemakers demonstrate that moisture levels control the behavior, depth, distribution, and reproductive success of continental organisms (Appendix A; Hasiotis 2008).

Terrestrial environments, in contrast to aquatic environments, exhibit the overall greatest depth of tiering (Figure 2), based on studies of modern plant, invertebrate, and vertebrate traces (Hasiotis et al., in press). The depth, diversity, and abundance of organism traces are controlled mostly by the groundwater profile and climate, which is measured by temperature, precipitation, seasonality, solar insolation, and controlled by continentality, latitude, wind patterns, and orographic effects (e.g., Jenny, 1941; Thornthwaite and Mather, 1955; Birkeland, 1999). These subaerial bioturbation patterns are distributed between up to all four zones of moisture-regime behavior and play a major role in sediment mixing that leads to the construction and destruction of soil structures and horizons (e.g., Thorp, 1949; Hole, 1981; Halfen and Hasiotis, 2010).

Aquatic environments exhibit the shallowest tiering depth, which is restricted to the hydrophilic zone. The depth of burrowing and feeding in freshwater rivers and lakes is controlled mostly by bottom-water oxygen, redox conditions in the sediment, and the size and ability of an organism to modify its microenvironment (Fisher, 1982; McCall and Tevesz, 1982; Ward, 1992; Hasiotis, 2002). The relative permanency of an aquatic environment and absence of subaerial exposure limit the penetration and mixing depth of bioturbation, which also prevents the movement of physicochemical constituents and formation of secondary structures typical of soils and paleosols.

Thus, a community of organisms that inhabits a landscape at any one moment in space and time will exhibit different behaviors representative of each moisture regime that reflect the groundwater profile under a particular climatic and hydrologic regime. The resultant depths of burrowing and rooting behaviors (Figure 2) through time (i.e., seasonal and annual activities) will mirror the development of soil horizons and their inherent pedogenic fabrics.

Interplay of Sedimentation and Pedoturbation: How Bioturbation is Expressed

Soil formation, and thus paleosol formation, is the result of the interplay between the sedimentation regime, hydrologic regime, pedoturbation, and the traditional soil-forming factors (Figures 2–3A). Together, they control the sediment accumulation rate and stacking pattern of finer grained vs. coarser grained sediment and the relative duration of soil formation (Bull, 1991; Kraus, 1999 and references therein). When combined with nonsteady and steady state deposition in alluvial systems, a variety of soil categories are produced (Figures 3–4). A paleosol representing pedogenesis in a body of sediment during a period of landscape stability—i.e., no substantial deposition or erosion—is considered

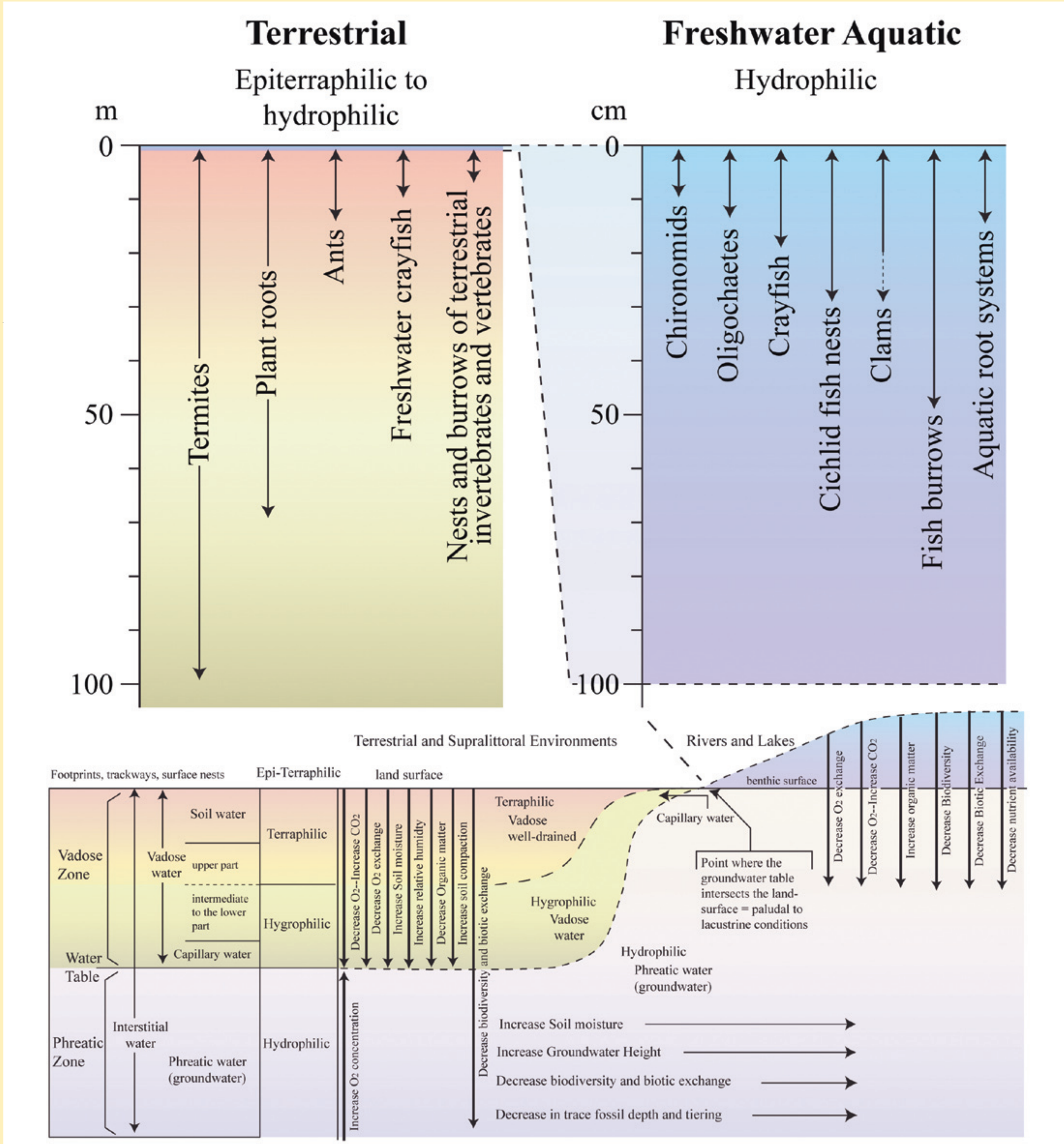

Figure 2: Schematic of the spatial distribution of the groundwater profile, physicochemical controls, behavioral categories, and their effects on tiering in conterminous terrestrial and freshwater aquatic environments. In general, the deepest tiered and penetrative organisms and their biogenic structures are in terrestrial settings; the shallowest are in freshwater settings. The spatial and temporal distribution of these components as well as the tiering depth and distribution of trace fossils, however, are also influenced strongly by the sedimentation rate, including the frequency and magnitude of flooding, and the major soil-forming factors. All together, these factors influence the degree of pedoturbation experienced by the sediment cover of the landscape. Modified from Hasiotis (2007) and Hasiotis et al. (in press).

a simple paleosol (Kraus and Aslan, 1993). Alluvial paleosols, however, are often complex and can be viewed as the result of a balance between sedimentation and pedogenesis (Kraus 1999). Rapid, nonsteady deposition produces vertically stacked, weakly developed soils separated by minimally weathered sediment, preserved as compound paleosols. Composite paleosols exhibit partly overlapping profiles that result from rates of pedogenesis that outstrip sedimentation rates. Steady deposition of small increments of sediment that become

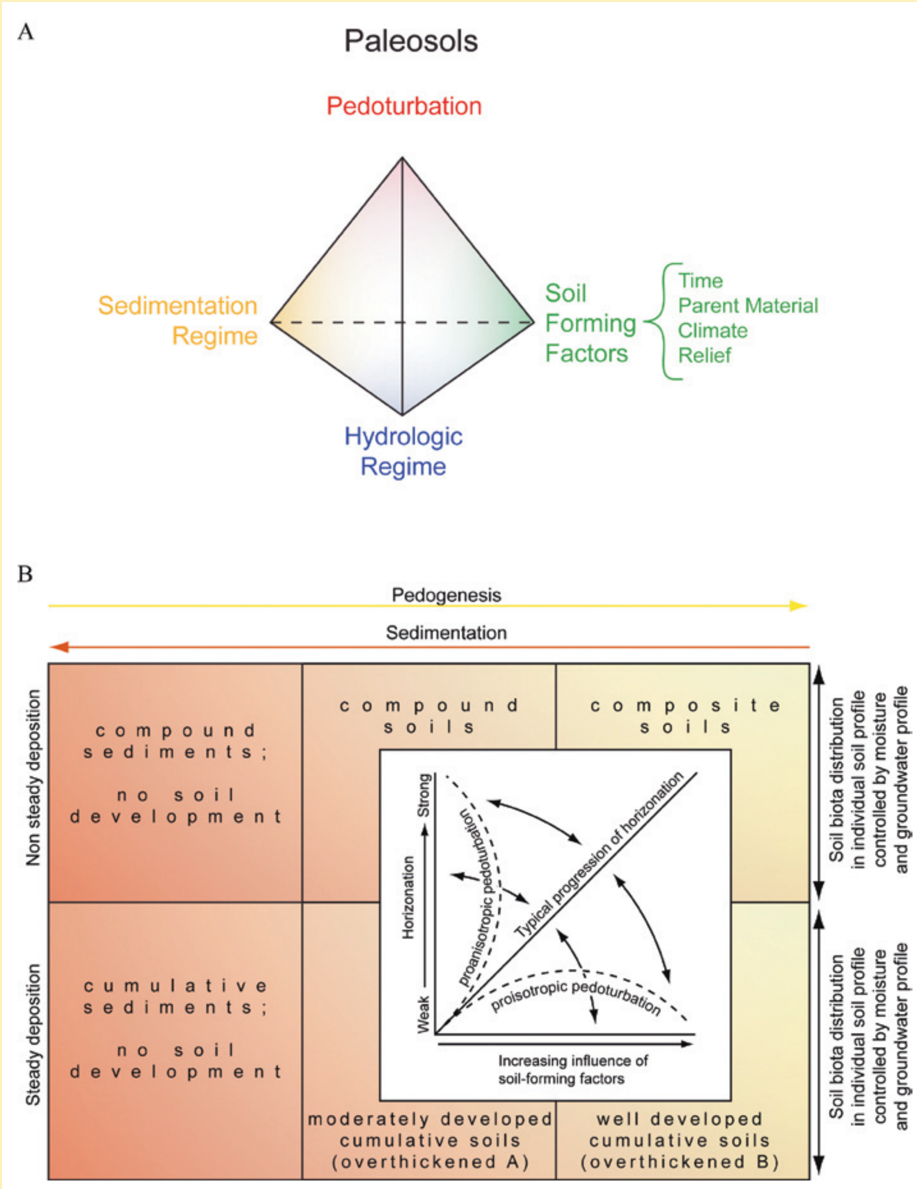

Figure 3: Controls on pedogenesis and horizonation reflected by bioturbation patterns in poorly to well-developed paleosols. The expression of trace fossils in paleosols is the result of the interplay between the local abiotic soil-forming factors, sedimentation and hydrologic regimes, and pedoturbation (see also Figure 2). The balance between sedimentation and pedoturbation under nonsteady and steady deposition will produce no soils, or compound, composite, or cumulative paleosol profiles. The degree and depth of biotic and abiotic pedoturbation will produce soils with either few horizons (proisotropic) or many well defined horizons (proanisotropic). The depth and degree of horizonation of soils is also influenced strongly by the groundwater profile. Modified from Johnson et al. (1987) and Kraus (1999).

incorporated into a soil profile by pedogenesis results in cumulative (Kraus 1999), cumulate (Marriott and Wright 1993), or cumulic (Retallack 2001; Smith et al. 2008) soils and paleosols.

In general, the depth, density, and diversity of trace fossils will create bioturbation patterns that follow the same degree of soil development as expected for simple, compound, composite, and cumulative soil (paleosol) profiles based on the same controls, with a few caveats. Simple paleosols formed over short time spans (10^0-10^2 years) will have relatively low diversity, low to high abundance, low to high density, and mostly shallow to few deep burrows (Figure 4A). This pattern reflects the lack of time available for a variety of different moisture-regime inhabiting organisms to colonize and exploit the landscape. The dominant fabric in these soils will be that of the parent material, i.e., primary bedding. These same soils formed over relatively longer durations (10^3-10^6 years) could display a range of bioturbation patterns: relatively low to high diversity, low to high abundance, low to high density, and shallow to deep burrows. When bioturbation diversity, abundance, and density are observably high, the dominant fabric is patterned after the activity of animals and plants produced by multiple generations of activity (Figure 4E). Lower intensities of bioturbation are expressed at the expense of pedogenic fabrics in which diversity, abundance, and density of bioturbation is masked by one or more soil structures (Figure 4F) (Johnson et al., 1987).

Bioturbation patterns in composite and cumulative soil profiles will also be distinct from one another in general. Composite paleosols, for the most part, will have several tiers of trace fossils and/or bioturbation textures indicative of shallow subsurface and deeper subsurface communities welded without preservation of any original primary bedding (Figure 4B). These patterns might be reflective of A, AB, and/or B horizons of thicknesses typical for each horizon (Birkeland, 1999; Kraus, 1999; Retallack 2001). Cumulative soil profiles will have over-thickened bioturbation patterns reminiscent of A, AC, AB, or B horizons that reflect continual bioturbation patterns and similar moisture regime conditions through time (Figure 4C–D).

Johnson et al. (1987) examined different pedogenic processes, including bioturbation, which act to enhance horizonation (proanisotropic pedoturbation) and destroy horizonation (proisotropic pedoturbation) through time. Proanisotropic pedoturbation may reflect longer duration simple and composite pedogenic conditions in which multiple horizons are developed (e.g., Figure 4B). Proisotropic pedoturbation may reflect cumulative pedogenic conditions in which bioturbation (including root patterns) form continuous patterns without any indication of horizonation or over-thickened horizons, which may be relatively immature or mature depending on the balance between sedimentation and pedoturbation (Figure 4C–D); these patterns may or may not form composite pedogenic sequences in alluvial packages.

Figure 4 is composed of examples of continental deposits that were pedogenically modified by crayfish bioturbation, and are interpreted in using the integrated concepts described here. Figure 4A shows pedoturbation by shallow (~50 to 60 cm deep) but complex crayfish burrow system of shafts, tunnels, and chambers attributed to *Camborygma* *symplokonomos* in interbedded siltstone and mudstone (Hasiotis and Mitchell, 1993). The host sediment still exhibits some of its primary bedding and was interpreted as a floodplain paleoenvironment in a fluvio-lacustrine setting (see also Dubiel and Hasiotis, 2011). The crayfish burrows suggest a high water table that would have been 30-40 cm deep; the number of burrows suggests a relatively short-lived landscape. This succession would be interpreted as a simple paleosol that, if multiple simple paleosols were stacked one atop the other, the entire complex would qualify as a compound paleosol in which crayfish burrowing acted to produce proanisotropic pedoturbation and begin the process of horizonation. Figure 4B exhibits stacked successions of interbedded siltstone and sandstone pedogenically modified primarily by moderately deep (~60 to 90 cm) and simple crayfish burrows attributed to *Camborygma eumekenomos* (Hasiotis and Mitchell, 1993). The host sediment exhibits no primary bedding, tabular to columnar structures, rhizoliths, and nondistinct small-diameter burrows, and was interpreted as a channel-levee-floodplain paleoenvironment in a fluvial setting (Hasiotis and Honey, 2000). The crayfish burrows suggest fluctuating water-table levels. The succession represents composite paleosols with partly overlapping profiles resulting from nonsteady deposition where pedogenic rates outstrip sedimentation rates. Bioturbation patterns acted to produce proanisotropic pedoturbation and encourage horizontation. Figures 4C and 4D depict outcrops that contain hundreds of thousands or more crayfish burrows of 2 to 4 m depths, attributed to *Camborygma eumekenomos* (Hasiotis and Mitchell, 1993), that represent multiple generations of activity. The host sediment exhibits no primary bedding, tabular to columnar structures, as well as rhizoliths and *Naktodemasis*, in which no definitive bed boundaries are present within the 6 m interval; these successions are interpreted as proximal to distal floodplain paleoenvironments with fluctuating water table levels (Dubiel et al., 1992; Hasiotis et al., 1993). Each outcrop represents cumulative paleosols produced by steady deposition of small increments of sediment that became incorporated into the soil profile where pedogenic rates outpaced sedimentation rates, while the soil biota incorporated new material. Crayfish bioturbation acted to produce proisotropic pedoturbation so that no distinct horizonation could form; Figure 4C represents an accumulation akin to an A horizon characterized by little modified sediment, whereas Figure 4D represents an accumulation akin to a B horizon in which sediment is the form of glaebules of hematite, maghemite, and simple clays.

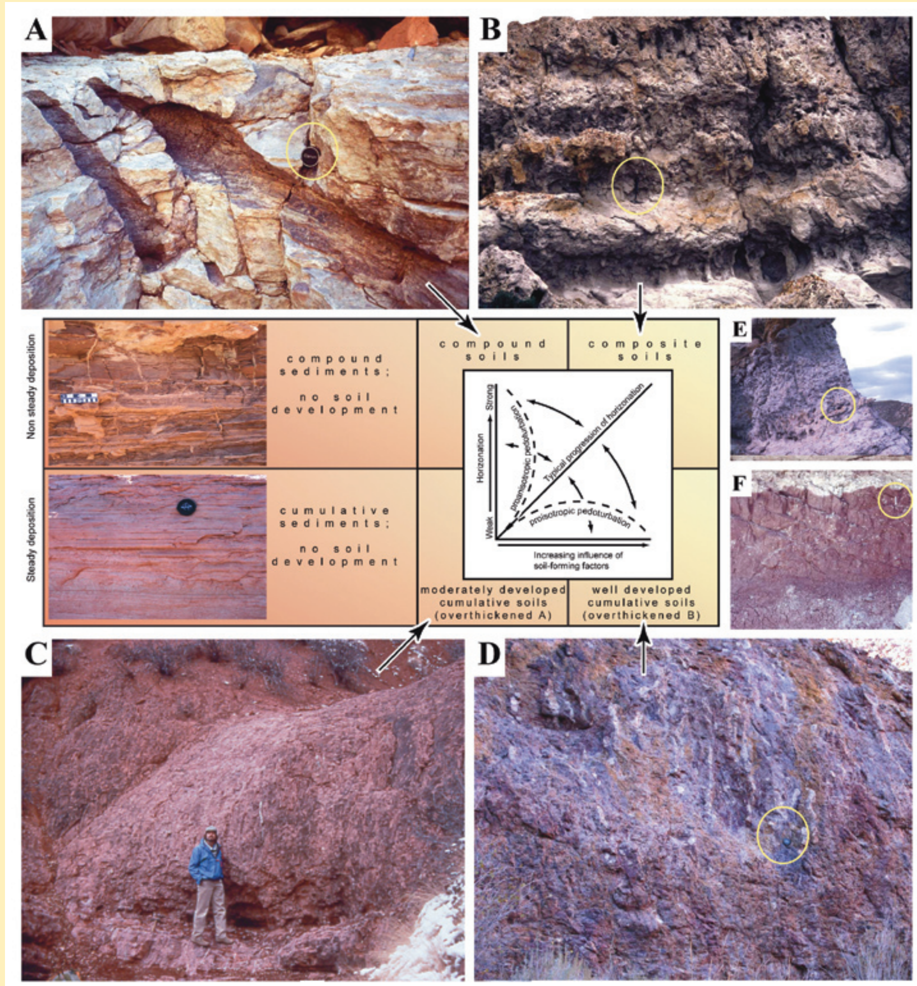

Figure 4: Crayfish bioturbation patterns as related to sedimentation and pedoturbation rates in nonsteady and steady state deposition. Compound sediment example from the upper part of the Moenkopi Formation, Fry Canyon, Utah; note sand-filled desiccation cracks; scale 15 cm. Cumulative sediment example from the lower part of the Salt Wash Member of the Morrison Formation, Montezuma, Utah; lens cap 5 cm. A) Owl Rock Member of the Chinle Formation, Stevens Canyon, Utah; lens cap 5 cm. B) Paleocene Fort Union Formation, Castle Gardens, Wyoming; rock hammer ~35 cm. C) Chinle Formation, undifferentiated, Eagle Basin, Dotesero, Colorado; person ~1.5m tall. D) Mottled Strata of the Shinarump Member, Chinle Formation, Professor Valley, Moab, Utah; lens cap 6 cm. E) Paleocene Fort Union Formation, Washakie Basin, locality 12, Wyoming; rock hammer ~40 cm. F) Paleovertisol with little visible bioturbation in the Petrified Forest Member, Petrified Forest National Park, Arizona; scale 10 cm.

SUMMARY

Continental trace fossils record organism behaviors that contributed to the depth and degree of pedogenesis, and are informative for interpreting paleosols when integrated with interpretations of the sedimentologic, hydrologic, and pedologic histories of the sedimentary succession. Bioturbation is one of the five major soil-forming factors, whose depth, distribution, and amount of time active in the soil is controlled by the sizes and behaviors of organisms, zonation of the groundwater profile (soil moisture and water table levels), and type and seasonality of climate. Combining continental bioturbation patterns with the patterns of sedimentation and pedoturbation enables a tripartite approach to interpreting the ichnopedogenic landscape that unites the controls on the development of soils (preserved as paleosols) in relation to the frequency and magnitude of sedimentation events, biotic and abiotic pedogenesis, and groundwater profile through time in alluvial basinal settings. Pairing the approach of

Johnson et al. (1987) with that of Kraus (1999) incorporates sedimentation and erosion—i.e., landscape evolution—with the soil-forming processes responsible for features preserved in paleosols. Ichnofossils record organismal behaviors that contributed to the depth and degree of pedogenesis, and are informative for interpreting paleosols because soil moisture and water table levels control the distribution of soil biota.

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