Journal of Sedimentary Research

Journal of Sedimentary Research, 2014, v. 84, 144–167
Research Article
DOI: http://dx.doi.org/10.2110/jsr.2014.8

DISTRIBUTION, PALEOENVIRONMENTAL IMPLICATIONS, AND STRATIGRAPHIC ARCHITECTURE OF PALEOSOLS IN LOWER PERMIAN CONTINENTAL DEPOSITS OF WESTERN KANSAS, U.S.A.

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ABSTRACT: **Cumulic paleosols in core from the Lower Permian (Asselian–Sakmarian) Council Grove Group of western Kansas contain a diverse suite of pedogenic features, including carbonate nodules, gleying, fossil burrows, rhizoliths, peds, and cutans. Abundant gleying, burrowing by organisms with a high soil-moisture requirement, and extensive plant growth are evidence of at least intermittently high soil moisture during this time. Paleosol character was strongly influenced by regional topography and paleogeographic position, as well as the climate changes accompanying hierarchical glacioeustatic cycles. The distribution of pedogenic features across formations also indicates a shift toward more humid conditions during a larger 3rd-order regression.**

Climatic variability during the interval of soil formation resulted in overprinting and close stratigraphic juxtaposition of both humid and arid climate indicators. Variability is likely the result of exposure to multiple 5th-order eustatic and climatic cycles during the lowstands of 4th-order cycles. Fifth-order cycles are expressed as lithologic changes in stratigraphically equivalent outcrops across the state, but lack of accommodation space prevented cycles from being expressed as differing lithologies in the study area. Biologic activity assisted in consolidation and stabilization of eolian and alluvially deposited sediments.

This study emphasizes that detailed, quantitative study of pedogenic features can reveal important paleoclimatic and paleoenvironmental information in otherwise lithologically similar paleosols. Close juxtaposition of opposing climatic indicators over intervals of known sea-level change adds evidence to the hypothesis of a link between sea-level change and climate change in the Early Permian. Pedogenic features thus support a semiarid or wetter climate for the midcontinent during the Early Permian.

INTRODUCTION

The purpose of this paper is to document the characteristics and distribution of trace fossils and other pedogenic features within Lower Permian (Asselian–Sakmarian) cyclothemic strata in western Kansas, USA and to interpret their paleoenvironmental and sequence stratigraphic implications. This study examines three formation-level lithostratigraphic units from the upper portion of the Council Grove Group that were deposited in a continental setting. The Speiser, Blue Rapids, and Easly Creek shales are units consisting mainly of fine sand- to silt-size sediments characterized by varying degrees of pedogenic modification, including prominent zones of gleying, rooting, and bioturbation composed of *Naktodemasis* isp. These features are a valuable source of paleoenvironmental information that can be used to reconstruct hydrologic and climatic conditions in continental settings during periods of soil formation (Kraus 1999; Retallack 2001; Hasiotis 2002; Hasiotis and Platt 2012).

Pennsylvanian and Permian strata in Kansas have long been recognized as cyclical in nature (Moore 1931, 1936) and have often been interpreted as the product of eustatic change driven by orbital forcing (Heckel 1977, 1986). Hierarchical, cyclic sedimentation patterns allow identification of multiple scales of sequences in Paleozoic strata of the midcontinent, which can be linked to both eustatic and climatic change (Miller and West 1993; Soreghan 1994; Miller et al. 1996; Soreghan 1997; Boardman and Nestell 2000). Outcrops showing smaller-scale lithofacies changes and repeated soil profiles in composite paleosols have been interpreted as 5th-order or 6th-order stratigraphic cycles—the meter-scale cycles of Miller et al. (1996) and punctuated aggradational cycles of Goodwin and Anderson (1985), and may represent time periods of 10–100 ky (Miller and West 1993, 1998; Boardman and Nestell 2000). These repeated 5th- or 6th-order sequences comprise longer-term 4th-order sequences (0.1–1 My) that are expressed as regional, formation-level lithologic units that are correlatable across Kansas and beyond. The change in distribution, thickness, and character of lithofacies in 4th-order cycles can, in turn, be linked to much longer 3rd-order (1–10 My) changes in global sea level (Busch and West 1987; Youle et al. 1994; Puckette et al. 1995).

The distribution and stratigraphic succession of ichnocoenoses (trace-fossil assemblages) and pedogenic features record environmental, hydrologic, and climatic changes that have the potential to preserve smaller-scale eustatic cycles in relatively homogeneous formations when major lithologic changes are not present. These features may also be the

Published Online: March 2014

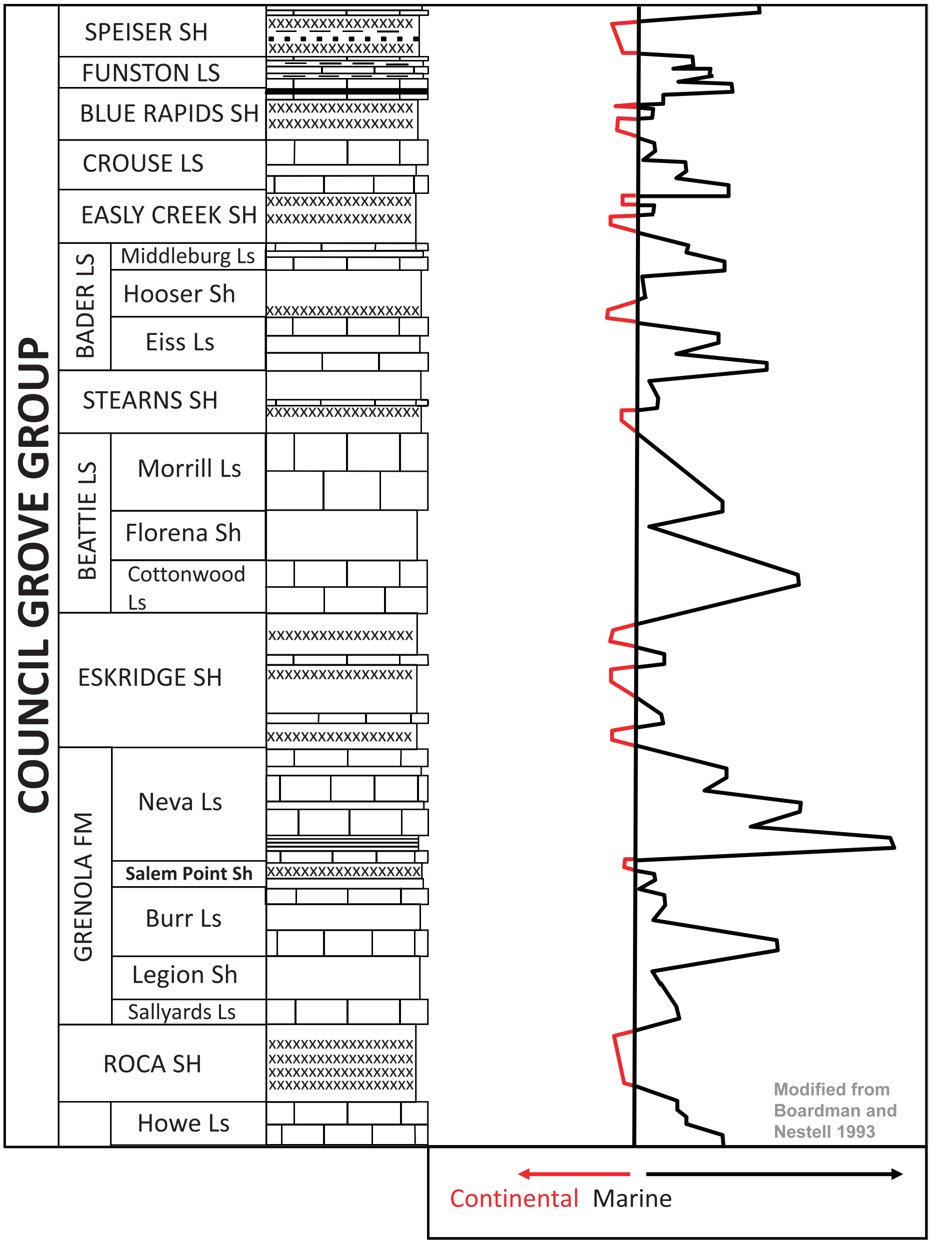


FIG. 1.—Stratigraphic column showing studied interval in Council Grove Group and generalized sea level. Modified from Boardman and Nestell (2000).

only indicators of environmental change within more recognizable larger order cycles. Although both outcrop and core of Lower Permian rocks in Kansas have been described (e.g., Miller and West 1993; Miller et al. 1996; Dubois et al. 2012), paleosol variability between outcrop and core has not yet been described in detail. Previous studies have not quantified the distribution of trace fossils and other pedogenic features with respect to changes in climate and sea level.

GEOLOGIC SETTING

The Lower Permian Council Grove Group is ~ 75 m thick, and consists of alternating marine and continental deposits divided into 14 formations and representing less than 10 million years of deposition (Baars 1990) (Fig. 1). The Council Grove Group is the principal source of petroleum from the highly productive Hugoton–Panoma gas field. Numerous studies of the stratigraphy, depositional environments, and paleoecology of formations in the Council Grove Group have been conducted (e.g., Mudge and Yochelson 1962; Lane 1964; Abdullah 1985; Schultze 1985; Miller and West 1993; Miller et al. 1996; Rankey 1997; Miller and West 1998; Boardman and Nestell 2000; Olszewski and Patzowsky 2003) but were limited mainly to outcrops in the eastern portion of the state.

Deposits of the Council Grove Group in Kansas are relatively flat lying, dipping shallowly to the west at roughly ~ 4 m per 1.6 km (13 feet per mile; 0.15 to 0.25 degrees), and outcropping in a north–south-trending belt near the city of Manhattan (Fig. 2). Current dip direction and magnitude are likely not reflective of original slope steepness during deposition, which was probably < 1 m per km and oriented to the south (Rascoe and Adler 1983; Olszewski and Patzkowsky 2003). In the study area, Permian deposits dip to the southeast as a result of subsidence associated with the Hugoton extension of the Anadarko basin, an asymmetric foreland–intracratonic basin that began activity in the late Cambrian, continued subsiding until the Pennsylvanian, and was mostly filled in by the middle Permian (Garner and Turcotte 1984; Sorenson 2005).

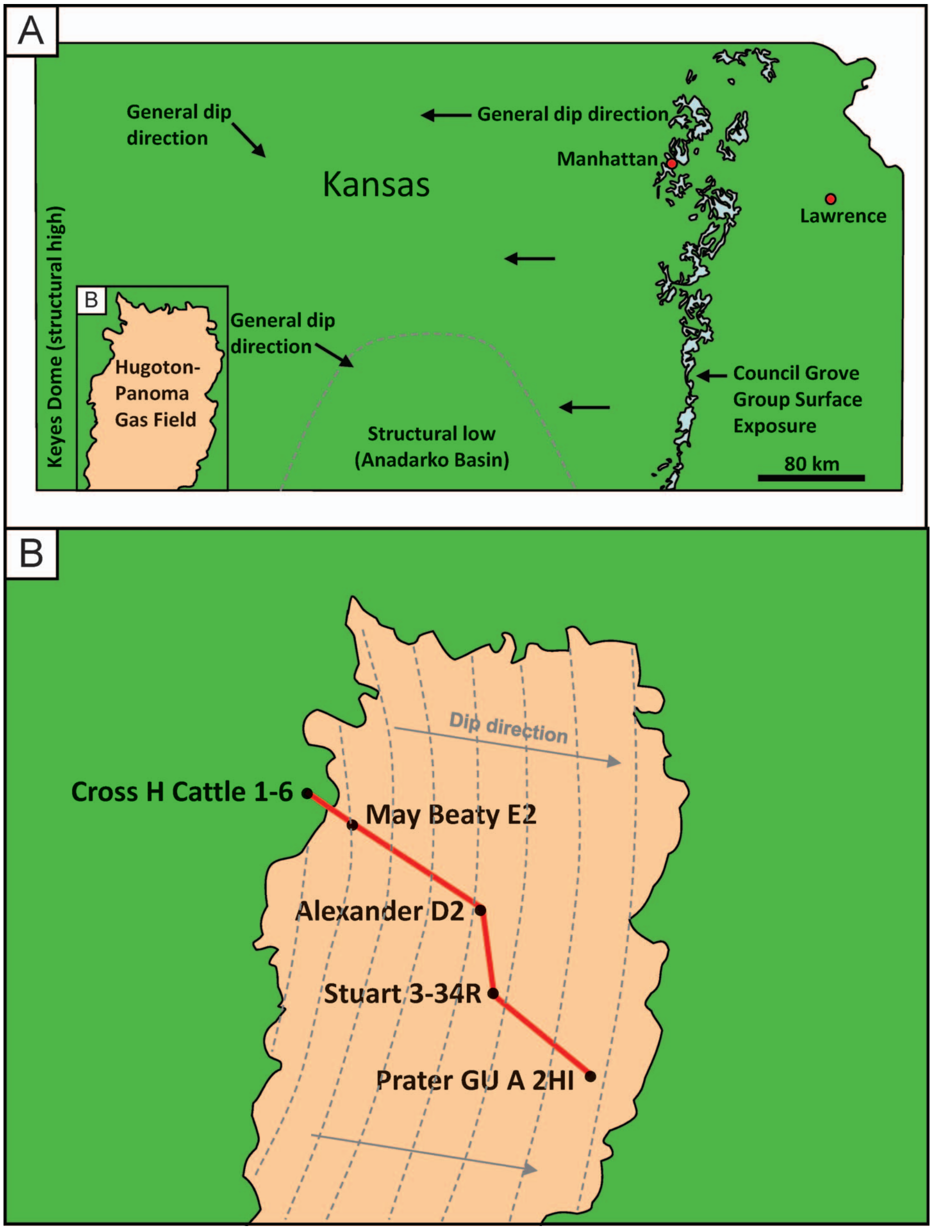


FIG. 2.—Map showing current geographic location of upper Council Grove group outcrops in Kansas, Hugoton–Panoma gas field, and location of core transect.

Kansas in the Late Pennsylvanian and Early Permian was roughly centered in the Pangean supercontinent, and located slightly north of the equator (Scotese 2002; Blakey 2012). Overall high sea levels led to repeated flooding and exposure of the continental interior. Pennsylvanian and Permian depositional environments in Kansas were especially sensitive to climatic and eustatic variations due to their setting on a broad, shallow, gently dipping carbonate ramp, which resulted in regionally extensive cyclothem deposition (Heckel 1977; Puckette et al. 1995; Mazzullo 1998; Olszewski and Patzkowsky 2003; Feldman et al. 2005). The Hugoton area was adjacent to the eroding Ancestral Rocky Mountains to the northwest (Rascoe and Adler 1983; Johnson 1989; Boardman and Nestell 2000), which likely provided a source for much of the clastic sedimentation in the region (Soreghan et al. 2002). In the Hugoton basin, an inverse relationship exists between the thicknesses of limestone and continental units, where limestones thicken basinward and continental deposits thicken towards the hinterland, with a concomitant thinning in marine limestones. This pattern can be seen in the selected core transect (Fig. 3).

BACKGROUND

Stratigraphic Cycles in Kansas Paleozoic Strata

The late Paleozoic strata of the midcontinent have played an important role in the evolution of the cyclothem concept. Cyclothems were initially proposed by Moore (1931), and the term was coined by Wanless and Weller (1932), who defined it as "a series of beds deposited during a single sedimentary cycle" in reference to Pennsylvanian rocks of Illinois. The definition was later modified to define a specific succession of rocks bounded by unconformities, which is the generally accepted definition today (Weibel 2004). Moore (1936) was the first to apply the term to the midcontinent area, and Heckel (1977) defined the classic Kansas type cyclothem based on the Pennsylvanian and Permian outcrops in the eastern part of the state.

Wanless and Shepard (1936) initially postulated glacioeustatic change as the mechanism responsible for cyclic sedimentation. Elias (1937) proposed an alternate explanation wherein cycles were the product of local epiorogenic effects rather than global sea-level change.

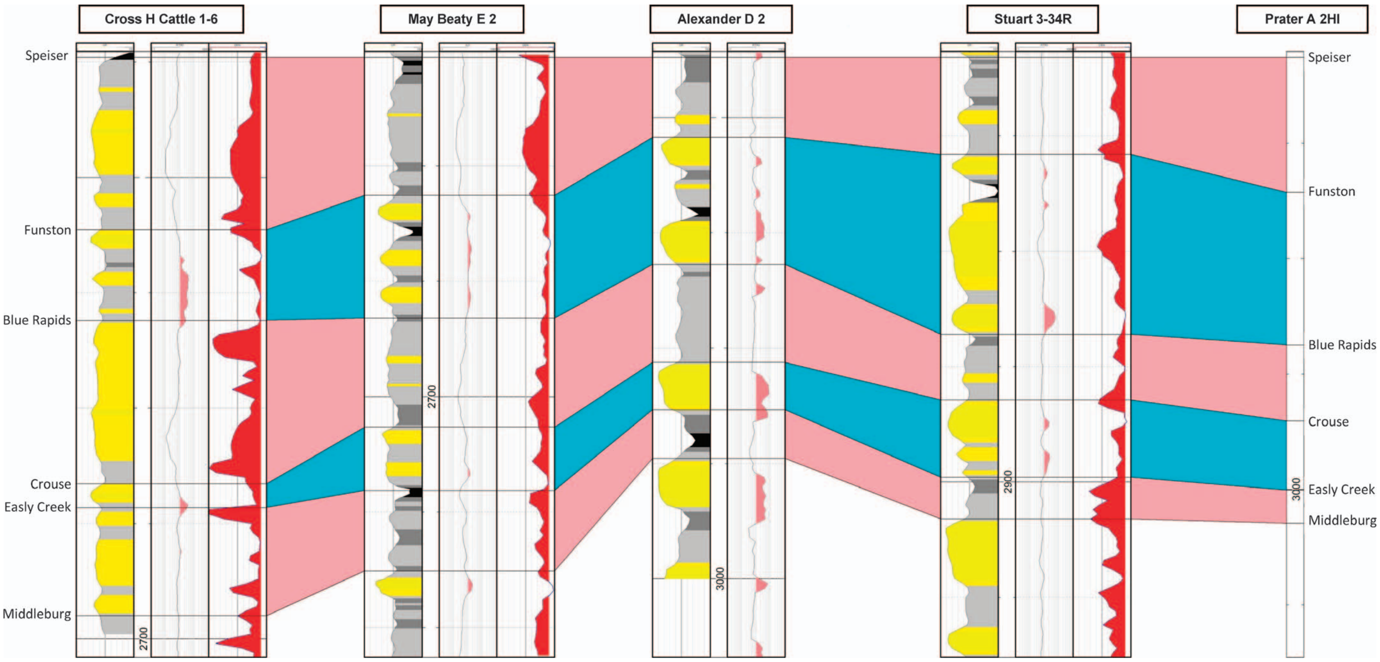


FIG. 3.—Cross section of core transect used in this study, showing formation tops and Gamma ray, induction, and density-porosity electric logs.

Diastrophism or periodic tectonism remained the favored mechanism behind cyclic sedimentation for many years. Correlation of hypothetical sea-level curves in other midcontinent basins in the 1950s and 1960s, especially Schenk's (1967) recognition of black shales as continuous across large areas, led to a resurrection of the eustasy model. Currently, the most widely accepted mechanism for cyclothem deposition is a combination of eustatic and climatic change driven by orbital forcing.

Cyclothems are still considered a useful concept, but the advent of sequence stratigraphy has made the term somewhat obsolete. Modern research has focused on both the lithologic sequence and the nature of the bounding surfaces, referencing cyclothems in a historic sense and applying sequence stratigraphic principles to cyclic strata (e.g., Miller and West 1993, 1998; Mazzullo et al. 1995; Puckette et al. 1995; Mazzullo 1998; Boardman and Nestell 2000; Olszewski and Patzkowsky 2003; Feldman et al. 2005; West et al. 2010).

Puckette et al. (1995) examined upper Council Grove core in the Oklahoma panhandle and interpreted the depositional setting and sequence stratigraphic context of each formation-level unit. They interpreted the lower sections of upper Council Grove limestones as small-scale transgressive systems tracts in 4th-order sequences, upper limestones as highstand or forced-regression systems tracts, and paleosols (redbeds) as lowstand systems tracts. The uppermost formations in the Council Grove were interpreted as being part of a larger, 3rd-order regressive-sequence set. Lithologies seen in Oklahoma Council Grove core were similar to those seen in the Hugoton area.

Olszewski and Patzkowsky (2003) also attempted to put the stratigraphic architecture of cyclothems into a sequence stratigraphic framework. In their model, the smallest-scale depositional sequence consists of very thin units composed of alternating carbonate and clastic couplets, which are interpreted to be very thin fifth-order sequences. Fourth-order sequences can be inferred from the stacking patterns and changing lithologies of 5th-order cycles, and are bounded by unconformities. These 4th-order composite sequences are generally equivalent to Heckel's Kansas-type cyclothem.

Cyclicity and Climate Change

Perlmutter et al. (2007) emphasized the link between orbital cycles, climate change, and paleolatitude. Most paleoclimatic and paleogeographic reconstructions agree that Upper Pennsylvanian and Lower Permian strata in the midcontinent were deposited near the paleoequator, under variable climatic conditions with seasonal variations in rainfall (e.g., Miller et al. 1996; Rankey 1997; Kessler et al. 2001). Other authors, however, differ in their interpretations of how specifically climate change relates to eustasy. The Council Grove Group, in particular, has been the focus of numerous hypotheses regarding the relationship between sea level and climate in the Permian.

Miller and West (1993) recognized that the carbonate to clastic alternations within 5th-order sequences cannot be explained by eustatic change alone. They proposed a model wherein eustasy was accompanied by a concomitant change in regional paleoclimate. Eustatic lowstands (glacial maximums) corresponded to periods of weakened monsoonal intensity that allowed warm, moist subtropical airmasses to carry moisture farther into the continental interior, thus increasing weathering and erosion, which favored deposition of clastics and the formation of paleosols. Eustatic highstand deposits (glacial minima) corresponded to stronger monsoon intensity, diverting moisture to subtropical latitudes and causing increased aridity near the equator, which led to deposition of thin carbonates. The cycles delineated by these surfaces can be considered parasequences rather than sequences.

Olszewski and Patzkowsky (2003) also examined climate changes associated with midcontinent cyclothems. They also favored an interpretation by which transgressive carbonates were deposited during the most arid conditions. Marine siliciclastics, deposited during highstand, represent the most humid climates. Paleosols formed during lowstand and subaerial exposure, and represent a transition from wetter to drier conditions. They cited the transition from vertic to calcic paleosols in the Speiser Shale as evidence for increasing aridity as conditions began to move toward those that favored limestone deposition.

The paper by Dubois et al. (2012) is one of few studies to examine core from the Hugoton basin, including several of the same cores that are described in this study. In their model, continental units are the product of concurrent loess deposition and pedogenic modification during sea-level lowstands. Windblown silt and fine-grained sand sourced from the Ancestral Rocky Mountains were stabilized by soil development—including bioturbation and rooting—resulting in siliciclastic aggradation that reduced available space for carbonate deposition landward during sea-level rise. Their interpretations support a climate pattern that is opposite to that of Miller et al. (1996), favoring an interpretation where most arid climates occurred during falling sea level and eolian deposition, with maximum lowstand and aridity occurring in roughly the center of continental intervals. Rankey (1997) applied the same climate model—drier lowstands and wetter highstands—to examples of both 4th-order and 5th-order cycles, although Miller et al. (1996) noted that the two cycle scales would not necessarily have the same climate signature. Limestones and the upper portions of continental units are interpreted as having been deposited during the wettest time periods during sea-level rise. No lithologic changes that could be interpreted as representing smaller-scale cycles (i.e., a series of discrete exposure surfaces or thin limestones) are seen in the Hugoton cores.

Fifth-Order Cycles in Council Grove Group Outcrops

Miller and West (1993) and Miller et al. (1996) provided detailed stratigraphic sections of measured Council Grove Group outcrops in Riley County, Kansas, ~ 480 km (300 miles) northeast of the Hugoton Basin (Fig. 4). Although individual formations are correlative across the state, the character of paleosol-bearing units in outcrop sections is noticeably different than that seen in core. Most notably, the Speiser, Blue Rapids, and Easly Creek shales contain thin limestones that separate each formation into a series of paleosol profiles. Miller and West (1993) noted the spatial extent of intraformational lithologic changes within Upper Council Grove Group outcrops, and recognized them as small, 5th-order cycles.

The Easly Creek Shale in outcrop is lithologically heterogeneous, containing limestone, mudstone, and siltstone (Miller and West 1993). The lower section lies above the Middleburg Limestone, and contains pedogenically modified mudstone clasts and gypsum crystals. The overlying interval is characterized by mudstone containing thin, sandier intervals with evidence of soft-sediment deformation. A unit of thin limestone containing rhizoliths overlies this sequence. Above these thin carbonates are decimeter-scale siltstone beds containing blocky and columnar ped structures, capped by a distinct exposure surface.

The Blue Rapids Shale is separated into four smaller units, each containing a variegated mudstone showing evidence of pedogenic modification with a marine carbonate at the base (Miller and West 1993). The lowest sequence is interpreted to represent a complete individual soil profile. The next overlying sequence is similar: both of these intervals record a transition from blocky peds at the base to columnar ped structures near the top of each mudstone unit. Above these are two additional limestone to mudstone sequences, the lower of which contain mudstone with prominent pseudoanticlines. In the Speiser Shale, four distinct sequences can be recognized (Miller and West 1993), at least three of which can be correlated in outcrop across multiple counties (Cunningham 1989). The lowermost sequence rests atop the Funston Limestone and is composed of red- and green-banded clastics with abundant ped structures and rhizoliths. The next sequence begins with a carbonate mudstone with rhizoliths, overlain by greenish-gray mudstone. This unit, in turn, is overlain by another mudstone with peds, pseudoanticlines, and compacted rhizoliths. The uppermost sequence in the Speiser Shale is composed of a limestone at the base, followed by grey mudstone. Other authors report additional continental features of the Speiser Shale, including ephemeral ponds (Hembree et al. 2004) and the presence of lungfish (*Gnathoriza*) and lysorophid aestivation burrows (Cunningham 1989; Schultze 1985; Hembree et al. 2004; Hembree et al. 2005).

METHODS AND MATERIALS

Five 3-inch cores were used for this study from Grant, Kearny, and Hamilton counties in Kansas—Cross H Cattle 1–6 (API 15-075-20543), May Beaty E2 (API 15-093-20134), Stuart 3-34R (API 15-067-21415), Alexander D2 (API 15-067-20338) and Prater Gas Unit A 2HI (API 15-175-20250). Core were selected to form a roughly northwest-to-southeast transect trending down dip into the Hugoton extension of the Anadarko basin across approximately 80 km (50 miles), with varying distances between individual core (Fig. 2).

The three uppermost continental units in all wells, the Speiser, Blue Rapids, and Easly Creek shales, were selected for study. This study focuses on certain quantifiable characteristics of paleosols that may provide additional insight into paleoenvironment and paleoclimate of the Hugoton area in the Early Permian (Figs. 5, 6). Trace-fossil morphology, ichnotaxonomy, and modern analogs were discussed in earlier papers (Counts and Hasiotis 2009), and Dubois et al. (2012) qualitatively catalogued pedogenic features.

In each core, continental units were analyzed with regard to selected pedogenic features, including trace fossils (Table 1). These features were chosen because they provide substantial paleoenvironmental information, are the most macroscopically visible, and are also present in modern soils, thus allowing these methods to be easily replicated in future studies. Grain-size estimates for each interval, environmental interpretations in stratigraphic columns, and general descriptions of carbonate units, were based on work by M.K. Dubois. Pedogenic features were quantitatively indexed using a modified version of Folk's (1951) visual estimation chart. Indices were created by measuring the percentage of each feature covering the slabbed core face for every 15 cm (6 in) interval of core. The purpose of this process was twofold: 1) it allowed pedogenic modification to be quantified, and 2) it allowed the distribution of pedogenic features to be easily visualized. Each of the primary indicators of pedogenesis—bioturbation, rooting, soil carbonate, and gleying, as well as an index for displacive diagenetic anhydrite—were measured to create an index of soil features. This resulted in over 2,500 individual measurements in 77 m (total 254 ft) of core. Each pedogenic characteristic, along with the core name, lithology, and depth interval, were entered into a spreadsheet so that data could be organized and crossplotted to show relationships between variables. Pedogenic features were plotted by depth for each core (Figs. 7–11), and the total percentage of each formation covered by each individual feature was calculated (i.e., total area of the core face in square inches between formation boundaries divided by the total area covered by a particular pedogenic feature) (Fig. 12). Pedogenic features were also crossplotted by grain size so that any relationship to lithology could be seen (Figs. 13). Indices, qualitative descriptions, and interpretations were used to correlate individual features across core within known formation boundaries. Attempted correlations were based on the presence, absence, and abundance of pedogenic features, along with their stratigraphic position and lithology. Other pedogenic features were qualitatively noted (Figs. 5, 6, Table 1). Discrete trace fossils were also measured where possible. For each visible trace fossil, the diameter and length were measured, and orientation was noted for a separate study.

In addition to core, outcrops of the Speiser and Blue Rapids shales near Manhattan, Kansas were reconnoitered in order to examine the section for discrete pedogenic features, and specifically for trace fossils. These outcrops, however, have been thoroughly described in detail by numerous authors (e.g., Miller and West 1993; Miller 1994; Miller et al. 1996; Mazzullo 1998; Boardman and Nestell 2000; West et al. 2010, and many others), so measuring numerous sections was unnecessary.

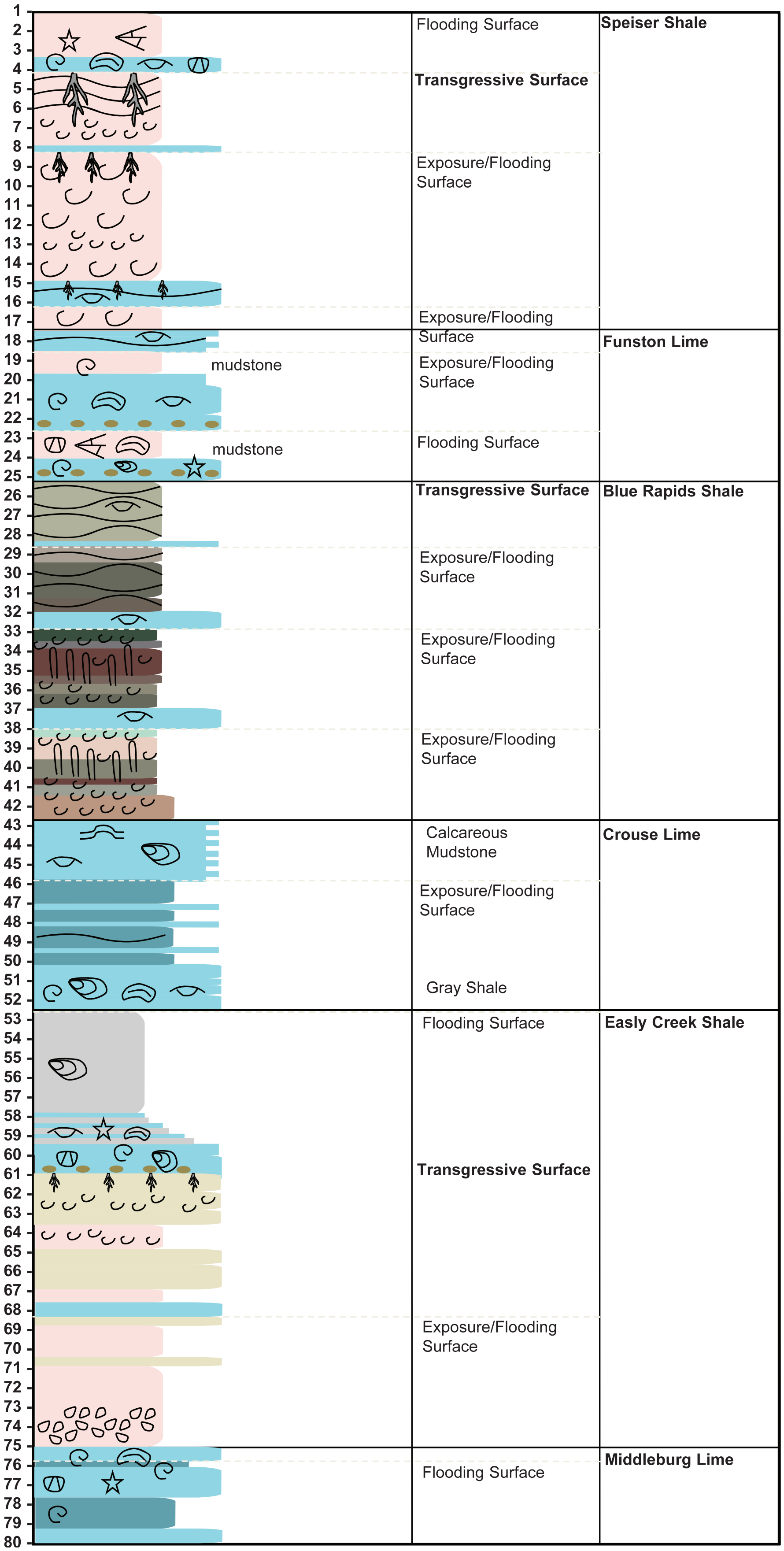
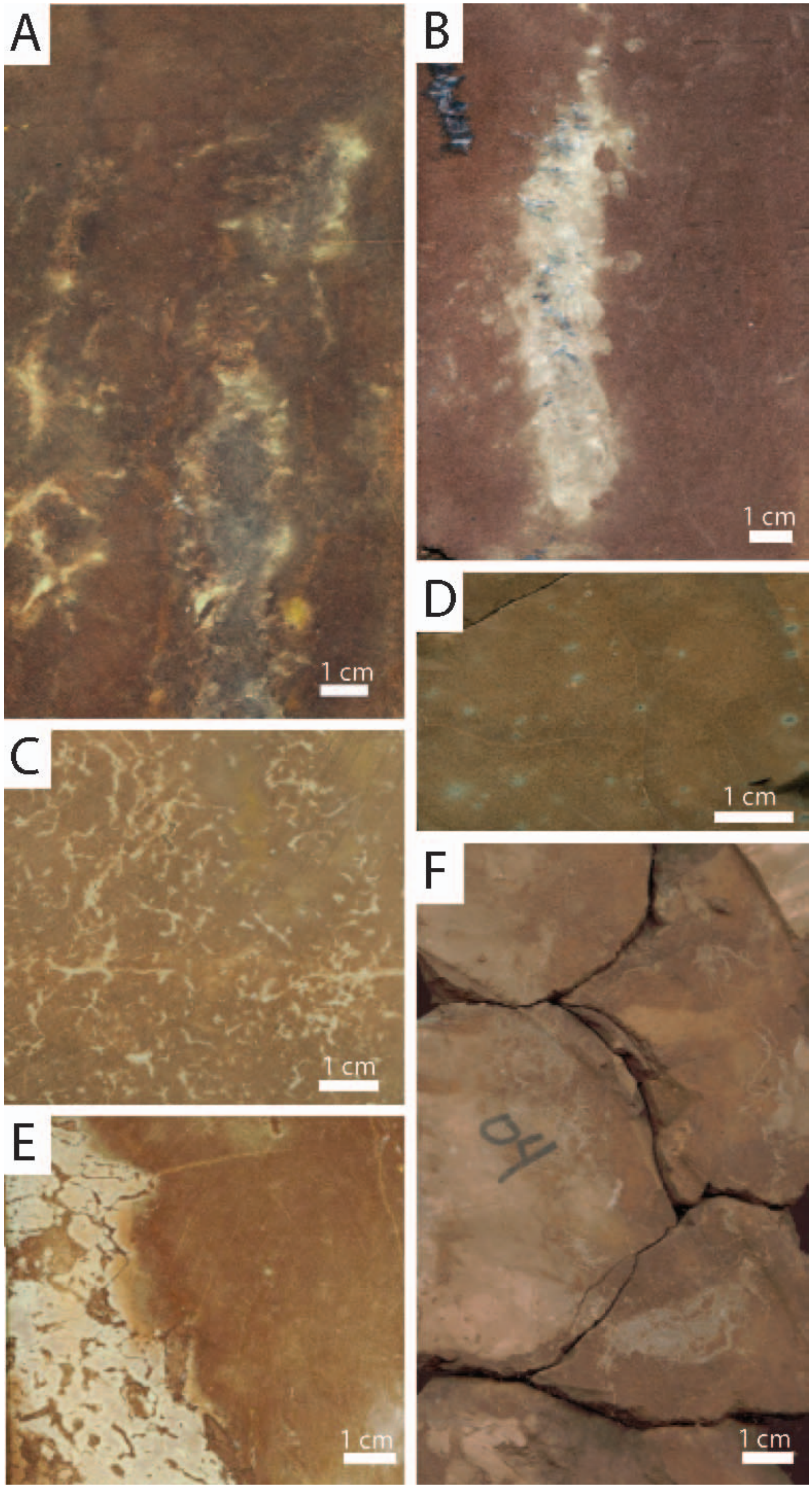


FIG. 4.—Composite upper Council Grove outcrop section as described by Miller and West (1993). Vertical scale same as described core in Figures 9–13.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SPATIAL AND STRATIGRAPHIC DISTRIBUTION OF OBSERVED PALEOSOL CHARACTERISTICS

All formations studied consist primarily of fine- to coarse-grained siltstone and very fine-grained sandstone with interbedded, intermittent, clay-rich intervals of varying thickness. These formations are separated by carbonate units of various lithologies. Coarser grain sizes are more common in stratigraphically higher formations (Dubois et al. 2012). Siltstones and sandstones of the Council Grove Group generally are weakly cemented by cryptocrystalline iron oxide, which fills the greater part of the existing pore space (Fig. 14). Calcite cements are also common, although not as ubiquitous as iron oxide cement, and are most abundant in sediments adjacent to overlying or underlying limestones. Iron oxides typically result in rocks that are dark red to brown red in color, with increasing amounts of calcite causing increasingly lighter shades of red.

Several zones in paleosols are composed of similar or identical lithologies but are light green to light gray in color. These zones are interpreted as the product of gleying. Green or gray sediments, when combined with other evidence of pedogenic activity, are often described as gleyed zones, as these colors are indicative of a reducing environment (Sheldon and Tabor 2009). At least some degree of gleying is present in all formations in all core. Notably, gleying is present usually in the uppermost portions of all continental intervals. The lowermost formation studied, the Easly Creek Shale, is generally thinner than the overlying continental units and does not contain any discernible pattern of gleying other than a narrow band at the top of the formation. In addition to gleying at the formation top, both the Speiser and Blue Rapids shales show a distinct interval of gleyed sediments in a roughly correlative interval near the upper middle of the formation. The Speiser Shale also contains a higher incidence of gleyed strata near the base. On a larger scale, the total percentage of gleyed strata in each formation increases upward from the Easly Creek Shale to the Speiser Shale (Fig. 12A). Increased gleying also shows a strong correlation with finer-grained deposits (Fig. 13A).

Upper Council Grove Group paleosols also contain numerous associations of discrete, centimeter-scale carbonate nodules, but bedded or massive carbonate is rare. Individual nodules exceeding the width of the core were absent, and nodule size remained fairly consistent throughout the studied interval. Core was thus seen as displaying a representative suite of nodule sizes. Nodules are present and patchily distributed in all formations, although definitive correlative zones in paleosols are not present. The Speiser Shale contains concentrations of carbonate nodules ranging from the lower to the upper parts of the formation, with little consistency between cores. In the Blue Rapids Shale, the most significant concentration of carbonate nodules is in the most basinward core, the Prater A 1; other cores contain only small quantities of nodules 1.0–1.3 m (3–4 ft.) below the formation top. The Easly Creek Shale, however, contains significant amounts of carbonate nodules dispersed throughout each core along the transect. No significant trend in distribution of carbonate nodules is seen between formations, although the Easly Creek Shale generally contains less carbonate than the overlying formations (Fig. 12B). Carbonate nodules are also more likely to be present in finer grained rocks, with the exception of muddy siltstones (Fig. 13B).

Overall, rhizoliths are also common throughout the studied intervals. Rhizoliths are often preserved as gleyed rhizohalos that surround the original root cast, which is preserved in some places as carbonaceous debris. Rhizolith morphologies are highly variable, ranging from a large, single taproot, to very small, isolated, carbon-filled traces, to fine networks of thin interlocking tubules. Rhizoliths are present in all cores and are most abundant in the upper halves of continental intervals. In the Speiser Shale, rhizoliths can be correlated in a zone 0.6–1.3 m (2–4 ft) thick approximately 3 m (10 ft) from the top of the interval. Rhizoliths are present both above and below this zone but are much less frequent. In the Blue Rapids Shale, rhizoliths are present near the top of the formation in the most landward core (Cross H Cattle) and are present but sparse in the most basinward (Prater), while cores in between these two locations show little or no rhizoliths. In the Easly Creek Shale, rhizoliths are more common than in all other formations and are distributed throughout the formation. Overall, rhizolith abundance decreases stratigraphically upward in successive formations, with the Easly Creek Shale recording the highest percentage of rhizoturbation and the Speiser Shale the least (Fig. 12C).

Trace fossils are common in Permian paleosols in the form of adhesive meniscate backfilled burrows (AMBs). AMBs in Permian paleosols, including the traces and sections described here, were referred to the newly erected ichnogenus *Naktodemasis* (Smith and Hasiotis 2008), and a possible new ichnospecies (Counts and Hasiotis, in preparation) based on their unique internal morphology. No other ichnospecies or type of trace fossil was observed in continental units in any of the studied core. Traces are often visible as high-contrast, brick-red burrow outlines and meniscate fill in gleyed zones, or lighter-colored burrows in red-oxidized sediment. Almost all continental siltstone and sandstone of the upper Council Grove Group show some degree of mottling, which is likely related to bioturbation. Visible bioturbation in the Speiser Shale is concentrated ~ 3.6–5.5 m (12–18 ft) from the top of the formation, although much of the formation has likely been completely bioturbated. While most of the deposits appear homogeneous, reaction with dilute HCl reveals a mottled appearance created by differential carbonate cementation within and around ghost burrows. Near the bottom of the Speiser Shale, however, there is a higher incidence of gleyed sediments with faint horizontal laminations. The Blue Rapids and Easly Creek shales contain fewer assemblages of trace fossils than the Speiser Shale; the amount of visible bioturbation increases in each successively higher formation (Fig. 12D). Traces are also more likely to be more common in coarser grain sizes (Fig. 13D), an observation reported in Dubois et al. (2012) but not statistically quantified.

Anhydrite crystals of varying size are found scattered throughout the section. Anhydrite is distributed patchily and is often found only as star-shaped, bladed crystals, though it may be concentrated into denser areas with higher concentrations of crystal aggradations. Although bedded anhydrite is rare, most crystals are displacive and, thus, must have been formed before significant compaction and lithification. Anhydrite occasionally forms the core of rhizoliths. The exact timing of anhydrite formation is difficult to ascertain, but it must have been shortly after

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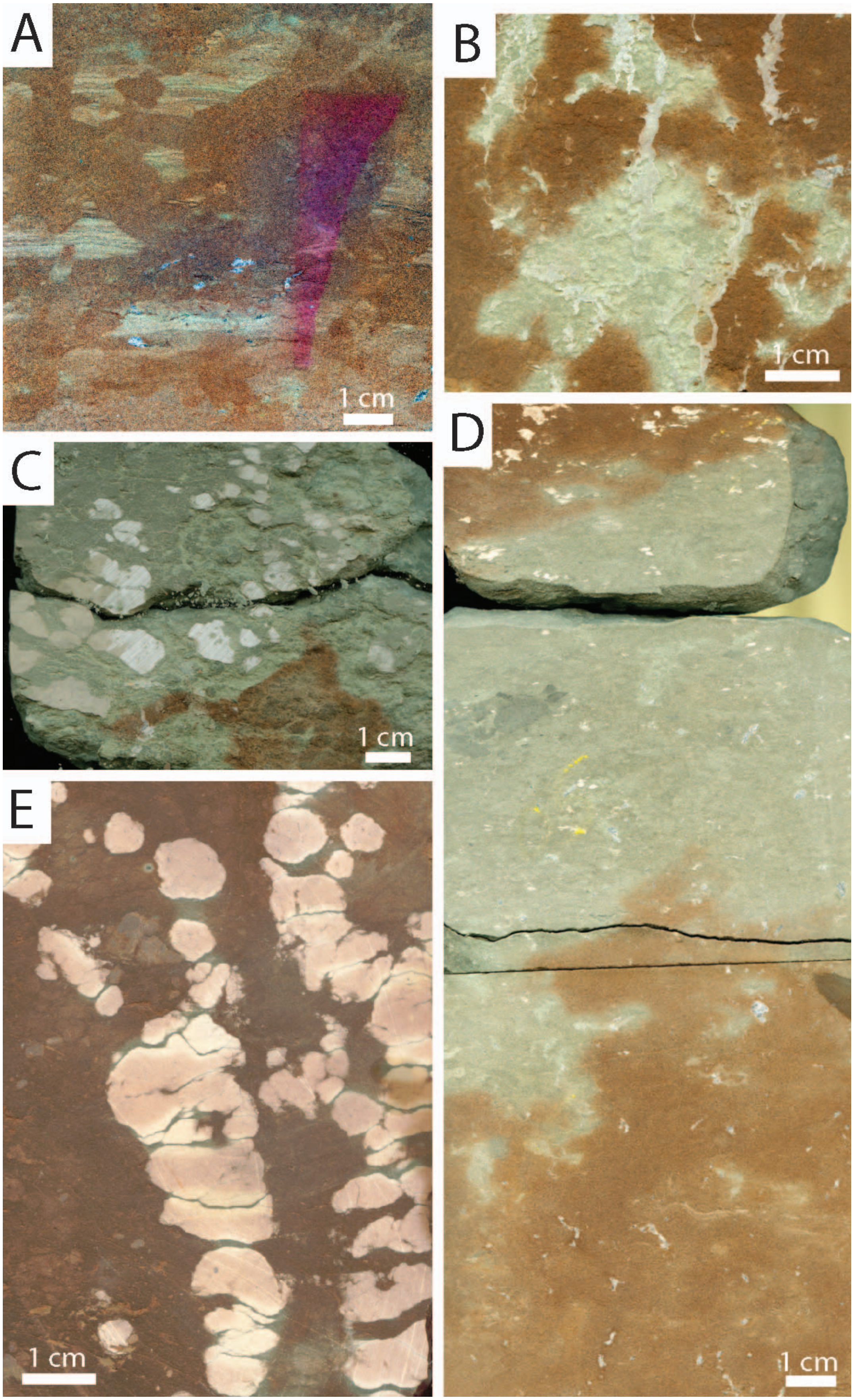
FIG. 5.—Soil features in upper Council Grove Group paleosols, showing a variety of rhizolith morphologies and ped structures. **A)** Large vertical rhizolith with multiple redoximorphic halos; Cross H Cattle 787 m (2582 feet). **B)** Vertical, anhydrite-filled rhizolith surrounded by faint *Naktodemasis* burrows within the rhizohalos; Cross H Cattle Cross H Cattle core, 791 m (2596 feet). **C)** Fine network of small rhizoliths; May Beaty E 2, 829 m (2723 feet). **D)** Small, isolated rhizoliths with carbonaceous interiors and gray reduced halos; D Alexander, 905 m (2970 feet). **E)** Subvertical network of small, branching rhizoliths; Stuart 3-34R, 897 m (2942 feet). **F)** Ped structures in core-breaks in core face follow clay-rich cutans along ped surfaces; Prater, 946 m (3104 feet).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deposition. Like bioturbation, anhydrite is most common in stratigraphically higher formations and in coarser grain sizes (Figs. 12E, 13E).

DISCUSSION

Paleoenvironmental and Paleoclimatic Significance of Paleosol Characteristics

Pedogenesis is a complex process based on the interaction of the prevailing climate, local organisms, topographic relief, parent lithology, and time of exposure (Jenny 1941). The paleosols, their stratigraphic architecture, and their internal characteristics preserve sufficient soil features to reconstruct at least some of these parameters for the Lower Permian of western Kansas, which are useful in larger-scale paleoecological, paleogeographic, and paleoclimatic reconstructions.

Analysis of Upper Council Grove deposits in the studied cores supports the assertion that these units are cumulic paleosols formed mainly from the deposition of silt- and sand-size particles throughout the time interval of soil formation. Deposition rates were likely high enough that the exposure surface was aggrading; continual deposition ensured that sediments were buried below the pedogenic window (the time and depth over which soil formation occurs) before significant maturation could occur. However, deposition was not so fast that pedogenesis was completely arrested; the two were likely co-occurring. These deposits would likely be classified as Inceptisols if found in modern environments, based on the lack of horizonation and incipient soil structures, but absolute rates of pedogenesis cannot be determined from the current data set. Lithologies in thin section bear a resemblance to modern loess deposits (Dubois et al. 2012), indicating a possible eolian origin for sediment deposition. Subaqueous processes of deposition, including periodic overland sheet flow, cannot be ruled out; all continental units are generally lacking in primary sedimentary structures that would provide clues as to the initial mechanism of deposition. This is most likely because they have been completely bioturbated. General patterns of lithologic change can still be discerned, however; coarsest grain sizes are typically concentrated near the middle of each formation, indicating closer proximity to the source area or increased energy of deposition during times of lowest sea level. Across formations, the upward trend of increasing coarser sediment may indicate a longer-term shift in the relative position of the Hugoton Basin toward the source area, proposed by some to be the Ancestral Rocky Mountains (e.g., Dubois et al. 2012).

The combination of pedogenic features and trace fossils in the studied interval indicates an environment with a variable climate that was capable of supporting an ecosystem containing plant and animal communities. Such communities require more rainfall than is currently seen in modern arid climates, which have an upper limit of 380 mm per year MAP. We therefore favor an interpretation wherein precipitation in the Early Permian of the Midcontinent reached a minimum of several hundred millimeters per year, the approximate range of modern semiarid climates (Peel et al. 2007). The repeated occurrence of features supporting this interpretation across multiple formations indicates that environmental conditions were relatively similar over time, but variations in their abundance indicate a change from drier to wetter conditions within the observed stratigraphic interval.

Gleying

Gleying is the product of bacterially mediated iron reduction in soil minerals from Fe^{3+} to Fe^{2+}, a process that can occur only in anaerobic conditions (Retallack 2001). Gleyed zones in both modern and ancient soils are usually colored green or gray and are often caused by complete water saturation or high concentrations of organic matter (Vespraskas 2004). Gleying should therefore be more common in finer-grained sediments, which are more likely to retain water due to decreased porosity and increased capillarity. Gleying in waterlogged soils can happen relatively quickly, with color change occurring in as little as five years (Vespraskas et al. 1999). Extensive gleying in continental sediments is, thus, an indicator of precipitation in areas with poor drainage, high subterranean water tables, topographic lows with ponded water, and/or subaqueous anoxic environments, including lakes, marshes, or ponds (Sheldon and Tabor 2009). Soils dominated by gleying, or Gleysols, are distributed worldwide in a wide range of climates, but are dominant in tropical regions near the equator (0° latitude) and in subpolar and temperate regions in Eurasia and North America (~ 60° latitude) (Driessen et al. 2001). Although the relationship between Gleysol formation and mean annual precipitation has not been quantified, gleying is notably less common in arid regions like the Middle East, North Africa, and Australia (Micheli et al. 2006). The abundance of gleying within Council Grove Group paleosols is partially due to the differences in drainage ability of different soil lithologies. In many cases, though (e.g., in the Speiser Shale, Cross H Cattle core at ~ 2591 feet, in the Speiser and Easly Creek shales, May Beaty core, ~ 2628 and ~ 2724 feet), gleying occurs in close proximity to oxidized sediment with no visible change in grain size. These types of gleying are likely not the result of poor drainage, but instead are interpreted to be associated with high subterranean water tables, which may in turn be related to smaller scale sea-level fluctuations that are not recorded by lithologic change. Since at least some of these intervals are tentatively correlative, it is less likely that they are simply the result of local topographic variation. Fifth-order sea-level rise may have led to an overall rise in base level and, thus, decreased the distance from surface to the top of the water table. Gleying at formation tops is also likely due to a raised water table resulting from higher base level as sea level rose in the transgressive portion of each 4th-order cycle. Gleying at the base of the Speiser Shale is probably due to a remnant high water table as sea level fell from the preceding highstand. In addition to base-level changes, eustatic change was likely accompanied by changes in regional climate (e.g., Miller et al. 1996; Olszewski and Patzkowsky 2003). The interval of time during which soil formation occurred was likely subject to multiple smaller-scale climate cycles that favored either drier or wetter conditions, resulting in gleyed and oxidized intervals in close proximity to one another. Aggradation was, therefore, slow enough to allow climate changes to be recorded in the soil before it was buried too deeply. Gleying increases up section from the Easly Creek Shale to the Speiser Shale, as does the proportion of coarser-grained sediments; this likely indicates increasingly high water tables or wetter climates as sea level fell during the larger-scale, 3rd-order cycle that encompasses much of the Upper Council Grove Group. The abundance of gleying in coarser-grained intervals suggests that increased water

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FIG. 6.—Additional soil features in upper Council Grove Group paleosols, showing primary sedimentary structures, soil carbonate, and gleying. **A)** Remnant horizontal laminae interrupted by later bioturbation; Stuart 3-34R, 859 m (2820 feet). **B)** Patchy, mottled intervals of gleyed silt, not associated with other soil features; Stuart 3-34R, 886 m (2906 feet). **C)** Carbonate nodules in gleyed interval, indicating variable soil moisture; D Alexander 907 m (2977 feet). **D)** Larger, discrete area of gleyed sediment reflecting greater extent of iron reduction; Cross H Cattle 824 m (2704 feet). **E)** Vertical strings of round soil carbonate nodules associated with minor gleying Stuart 3-34R, 909 m (2982 feet).

Legend			
	Naktodemasis burrows (AMB)		Coated grains
	Rhizoliths		Echinoderms
	Peds and cutans		Algal laminae
* * *	Anhydrite		Brachiopods
G G G	Gleying		Bivalves
	Chert	- - - -	Discontinuity surface
	Bryozoans	P P P	Peloids
	Ostracods		Encrusting fauna
	Rip-up clasts		Fusulinids
	Carbonate nodules		Phylloid algae
	Horizontal laminations		Ripple marks

saturation was not a product of changing depositional environment, but rather a climatic shift toward wetter conditions.

Pedogenic Carbonate

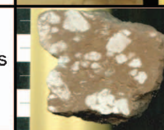
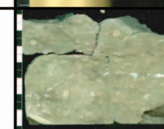
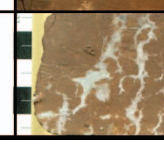
Pedogenic carbonate nodules in paleosols are the product of subaerial carbonate precipitation. Calcium carbonate typically enters soils as windblown particulate matter or dissolved calcium in rainwater (Royer 1999). Soil carbonate forms as carbonate minerals are leached from overlying A horizons and percolate downward during rainfall, and are then reprecipitated in B horizons (Reeves 1976). The presence of carbonate nodules is, thus, an indicator of soil maturity. Pedogenic carbonate is also thought to be an indicator of dry or seasonal climates, since it requires both rainfall and periodic evaporation in order to form (Retallack 1994). In the Midcontinent of the USA, modern soils contain carbonate only in areas where annual precipitation falls below 500–600 mm (Retallack 2001), although they may be found less commonly in environments with $>$ 1000 mm (Aslan and Autin 1998; Royer 1999). Marion (1989), however, estimated that $CaCO_3$ precipitation would cease at a mean annual precipitation $<$ 37 mm in the American Southwest.

Carbonate nodules found in paleosols are displacive and thus formed before significant lithification of the matrix. They are also associated with root traces, have a rounded morphology with a microcrystalline matrix. These characteristics are consistent with subaerially formed pedogenic carbonate nodules. Since the physical processes responsible for pedogenic formation of carbonate remain relatively constant through time, modern precipitation limits to paleosols containing carbonate nodules can be reasonably applied. In modern environments, calcic soil formation occurs at a range of between 40 and 1100 mm per year. While this range is relatively large, carbonate nodules are less common on either extreme, in both the most arid environments (e.g., Sahara-type deserts) and the more tropical and temperate areas that receive higher amounts of rainfall. Most soil carbonate in these studies forms in areas with a mean annual precipitation of between 100 and 800 mm per year (Marion 1989; Retallack 1994; Royer 1999). It is likely, therefore, that the Early Permian of southwestern Kansas likely had an average rainfall within this range. Methods used to quantify mean annual precipitation based on depth to the Bk (carbonate-rich) horizon are not applicable here due to the cumulative nature of the paleosols in question; however, future studies may be able to further refine this range using geochemical methods (e.g., those described in Sheldon and Tabor 2009). Most pedogenic carbonate in the upper Council Grove Group is nodular, indicating that it was not able to develop fully into massive or layered beds. This also indicates either suboptimal conditions for pedogenic carbonate formation or rapid aggradation that buried incipient nodules before significant development. No indices have been published quantifying the relationship between soil carbonate morphology and MAP. The distribution of carbonate nodules in vertical stringers indicates continual aggradation of the soil surface and associated rising of the Bk horizon. The percentage of carbonate nodules in the coarser sediments of each formation decreases stratigraphically upward, potentially indicating a change to increasingly wetter climates in which carbonate precipitation is not favored. Although there are other factors that influence the precipitation of soil carbonate, such as time, local topography, and parent material (Schaetzl and Anderson 2005; Retallack 2005) there is no evidence that these are substantially different for the stratigraphic intervals examined in this study.

Rhizoliths

Root traces, or rhizoliths, reflect colonization of exposed sediments by land plants. Plant colonization occurs in a wide range of environments and climates, but it requires at least some amount of moisture in the soil.

TABLE 1.—*Pedogenic features indexed for this study, and their significance.*

Pedogenic Feature	Description	Interpretation	Environmental and Climatic Implications	Photograph
Trace fossils	*Naktodemasis*; Variably oriented, cylindrical burrows with tortuous axes and meniscate backfill	Burrows produced by subterranean insects and larvae	Abundance of burrows indicates adequate soil moisture for organism survival (likely between 20-40%). Semiarid to temperate climate.	
Rhizoliths	Downward-branching, vertical structures often with gleyed haloes and carbonaceous or mineral-filled interiors	Root structures produced by land plants	Adequate soil moisture and insolation for plant colonization; gray rhizohalos indicate perched water tables (Kraus and Hasiotis, 2006)	
Carbonate nodules	Irregular or spheroidal $CaCO_3$ nodules, often in vertical stringers	Subaerially formed soil carbonate, or caliche	Generally dry conditions with seasonal moisture variability; arid to semiarid climates with 37-1000 mm MAP (Retallack 2001, Royer, 1999)	
Gleying	Green or gray sediment; reduced (ferric) Iron in matrix. As mottles, discrete zones, or associated with burrows and root traces	Prolonged periods of subsurface saturation and anoxia	Poor soil drainage, high water tables, low topography; adequate precipitation to recharge shallow groundwater; uncommon in arid climates (Vespraskas et al., 1999; Driessen et al. 2001)	
Peds	Blocky or columnar aggregates of soil, often bounded by cutans	Repeated shrinking and swelling of clay-rich soils	Seasonal soil-moisture variability; higher clay content in sediment (Retallack, 2001)	
Cutans	Clay-rich boundaries or skins of ped structures	Repeated shrinking and swelling of clay-rich soils	Formed by finer-grained material falling into open voids; seasonal moisture variability (Retallack, 2001)	
Anhydrite	Displacive, crystalline mineral growth, often in vertical strings or star-shaped, bladed crystals.	Diagenetic mineral formed during shallow burial	May form in previously open voids such as rhizoliths, occludes porosity (Dubois et al. 2012)	

Abundant rhizoliths can also be an indicator of increased plant growth in an area. The amount of vegetation cover in modern environments is directly affected by the amount of effective precipitation, which is a relationship between the amount of true precipitation and the degree of evaporation (Barry and Chorley 2009). In order for plant growth to occur, soil moisture must be continually above the permanent wilting point, the point at which plants can no longer recover from desiccation. This varies for both plant type and soil composition (Tolk 2003), but even at wilting point, soil moisture is $> 0\%$ due to both hygroscopic water on particle surfaces and a small amount of capillary water held in micropores that is unavailable to plants. In modern desert environments, growth of grasses begins in climates with a mean annual precipitation of $\sim$ 20 mm, and trees at $\sim$ 100 mm (Ward 2009). Although plant communities have changed in structure through geologic time, similar moisture tolerances to modern communities are reasonable to assume. Abundant rhizoliths in paleosols, therefore, may indicate sustained levels of mobile water in the soil over the time of soil formation, which can occur over a span of decades to millennia. The continual presence of plants and soil moisture can thus be an indicator of semiarid, temperate, or tropical climates, as sparse vegetative cover is typical of xeric or arid climates (e.g., Ward 2009). However, the specific composition and ecology of ancient plant communities cannot be determined from rhizolith assemblages alone, and the absolute time spans of formation of most paleosols cannot be precisely determined.

Plant communities colonized Council Grove Group soils repeatedly and over a wide area; rhizoliths are present in all formations studied and throughout the core transect. Rhizolith abundance shows no clear relationship to lithofacies and grain size, indicating that such other factors as soil moisture and sedimentation rate controlled plant distribution in continental settings. Rhizoliths are proportionately more abundant in the Easly Creek Shale, and less common in the Speiser Shale. Conditions became less favorable for plant growth over the Easly Creek Shale to Speiser Shale time span, possibly due to poorer drainage as evidenced by increased gleying and fewer carbonate nodules. Individual plants, however, may have been widely spaced: rhizoliths usually form less than 10% of the total area of the core face and are most often found as isolated traces. The lack of ubiquitous rhizoturbation indicates that although plant communities did not always dominate the landscape, they were repeatedly present throughout the upper Council Grove interval. The continued presence of flora provides additional evidence that soil moisture was likely higher than modern arid environments, where plant growth is more limited, e.g., B climates as defined in the Koppen system (Trewartha 1982). The absence of rhizoliths, however, can also be attributed to the destruction by *Naktodemasis*.

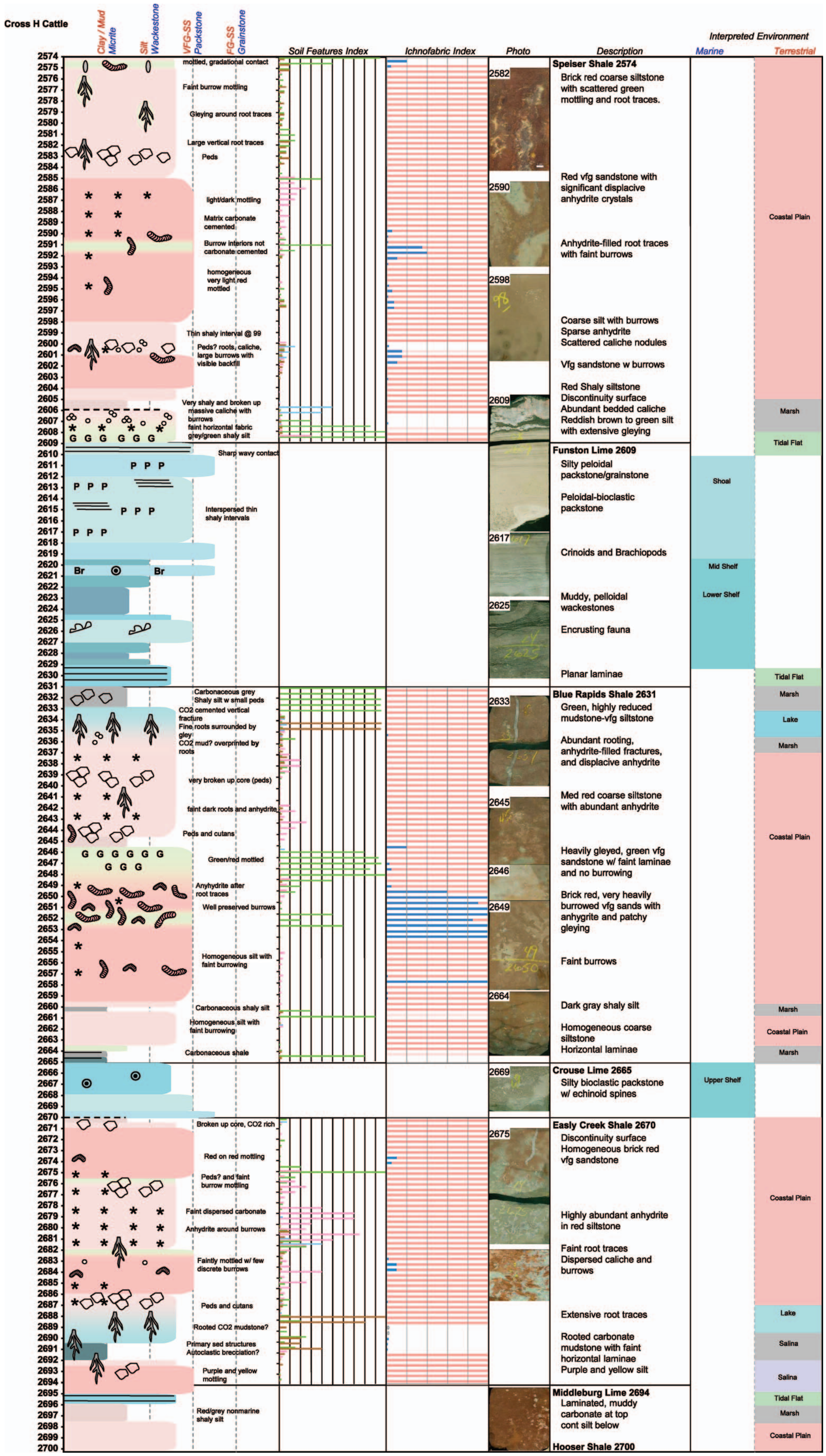


FIG. 7.—Stratigraphic column, detailed descriptions, representative photographs, interpreted sea-level curve, and depositional environments for the Amoco Cross H Cattle core, API 15-075-20543.

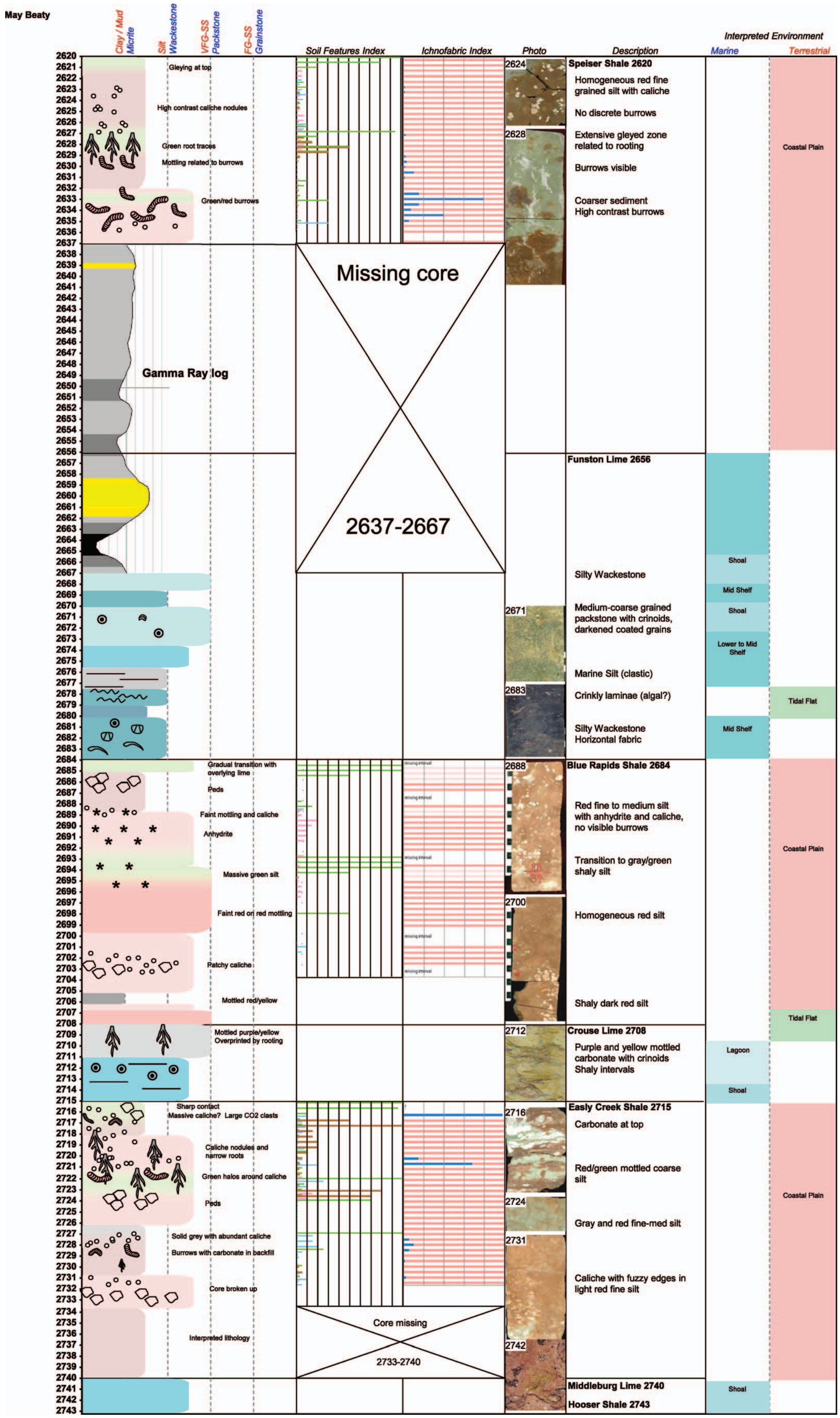


FIG. 8.—Stratigraphic column, detailed descriptions, representative photographs, interpreted sea-level curve, and depositional environments for the Amoco May Beaty E 2 core, API 15-093-20134.

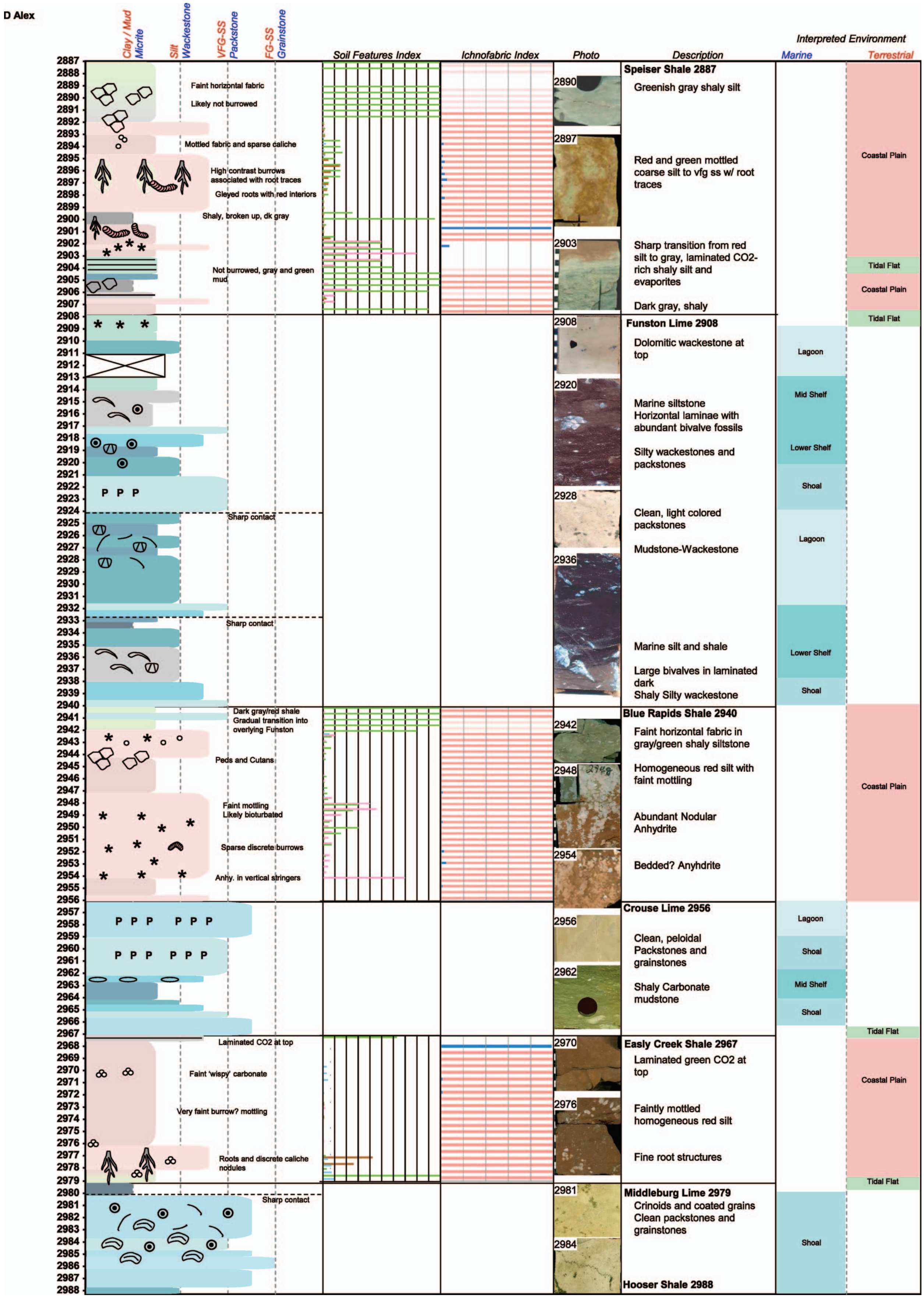


FIG. 9.—Stratigraphic column, detailed descriptions, representative photographs, interpreted sea-level curve, and depositional environments for the Cities Service Alexander D 2 core, API 15-067-20338.

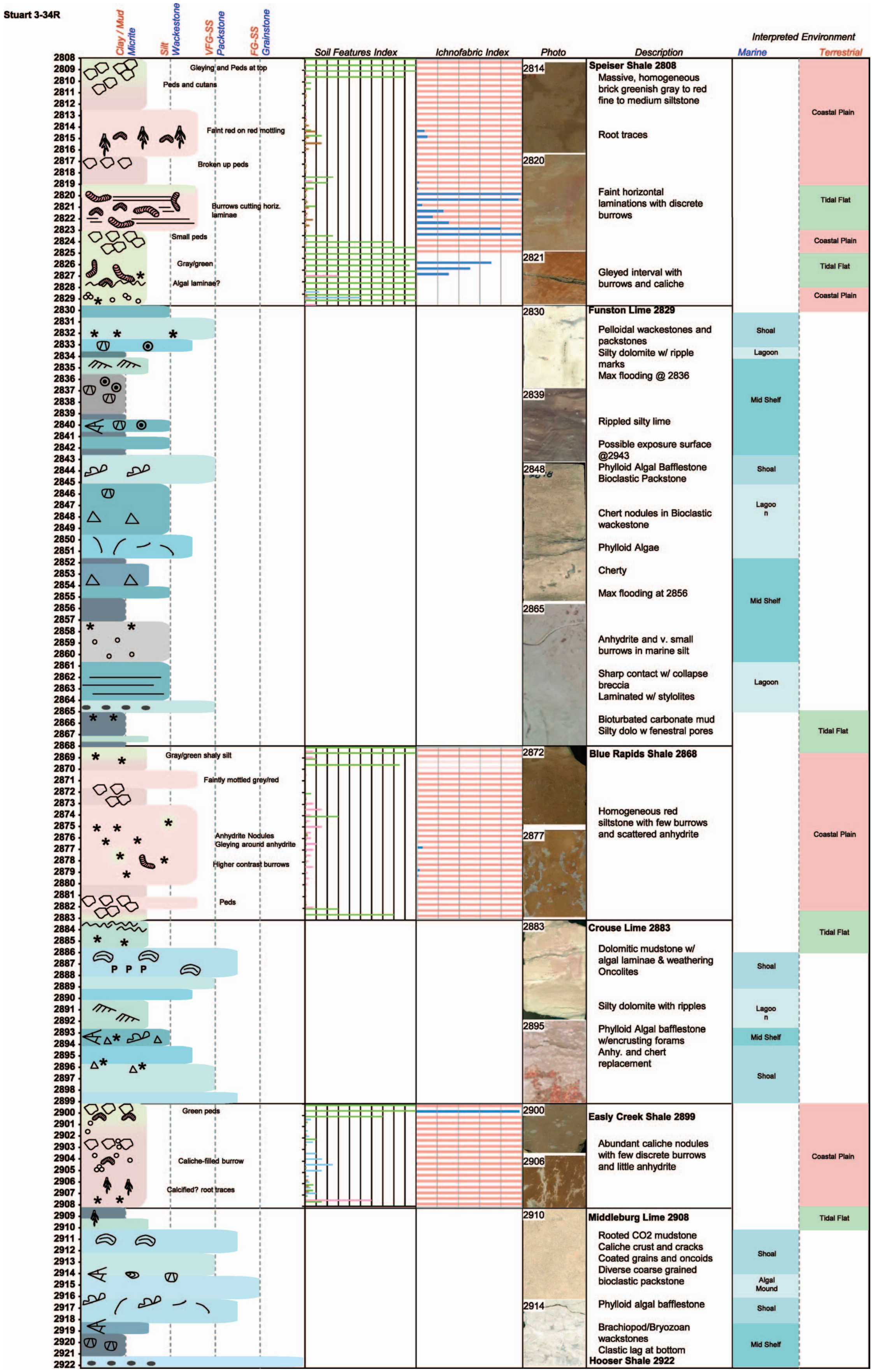


FIG. 10.—Stratigraphic column, detailed descriptions, representative photographs, interpreted sea-level curve, and depositional environments for the Pioneer Stuart 3-34R core, API 15-067-21415.

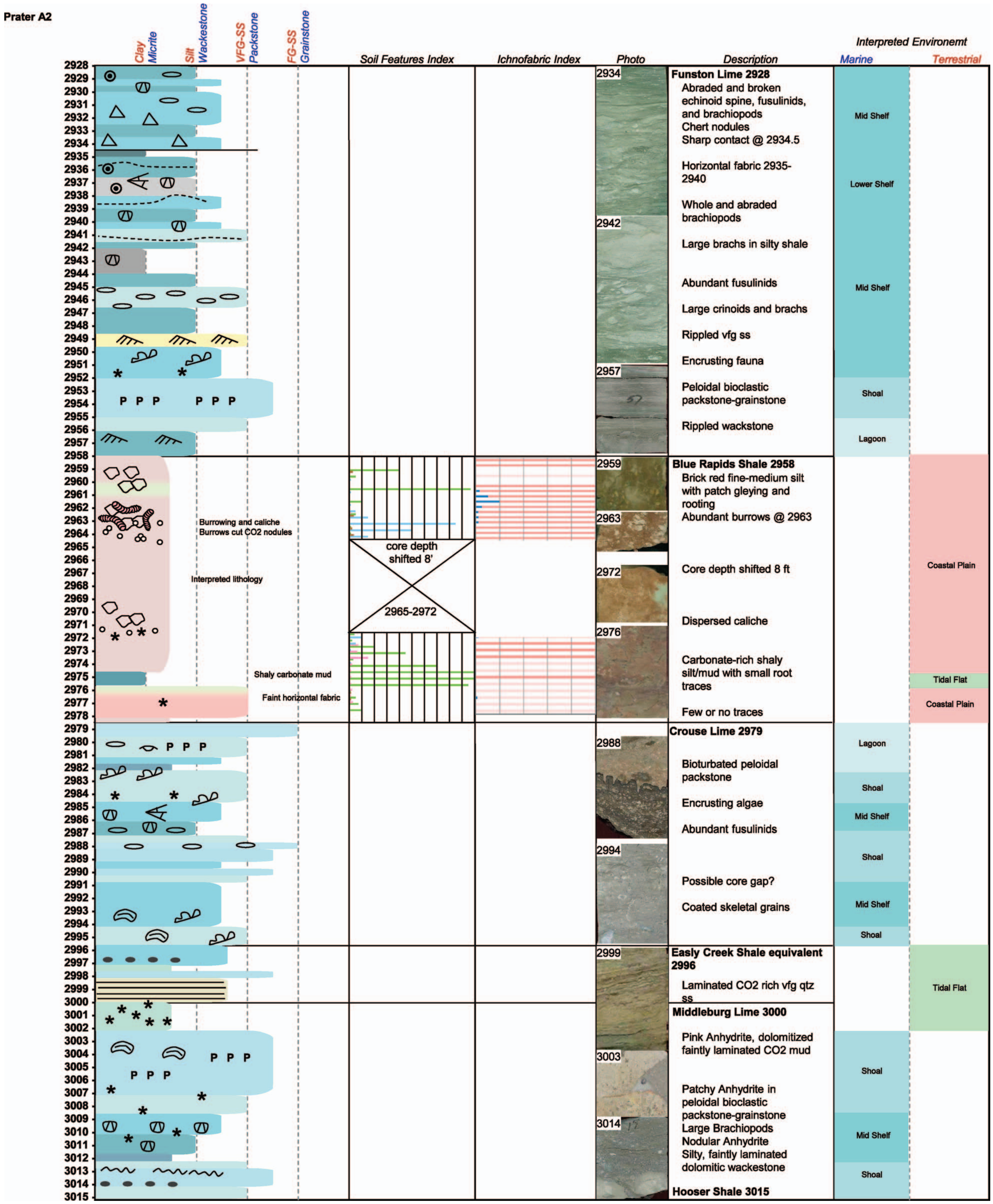


FIG. 11.—Stratigraphic column, detailed descriptions, representative photographs, interpreted sea level curve, and depositional environments for the Amoco Prater Gas Unit A 2HI core, API 15-175-20250.

Trace Fossils

Meniscate backfilled trace fossils in paleosols are likely formed by the burrowing action of fossorial insects or insect larvae (Smith and Hasiotis 2008; Counts and Hasiotis 2009). Insects may feed on the roots of plants or on detrital organic material within the soil (Vittum et al. 1999). Experiments with extant subterranean insects show that these organisms have a very low tolerance for soil moisture outside of a relatively narrow range. Chafer beetle larvae, dung beetles (order Coleoptera), cicada nymphs, and soil bugs (order Hemiptera) have all been shown to be

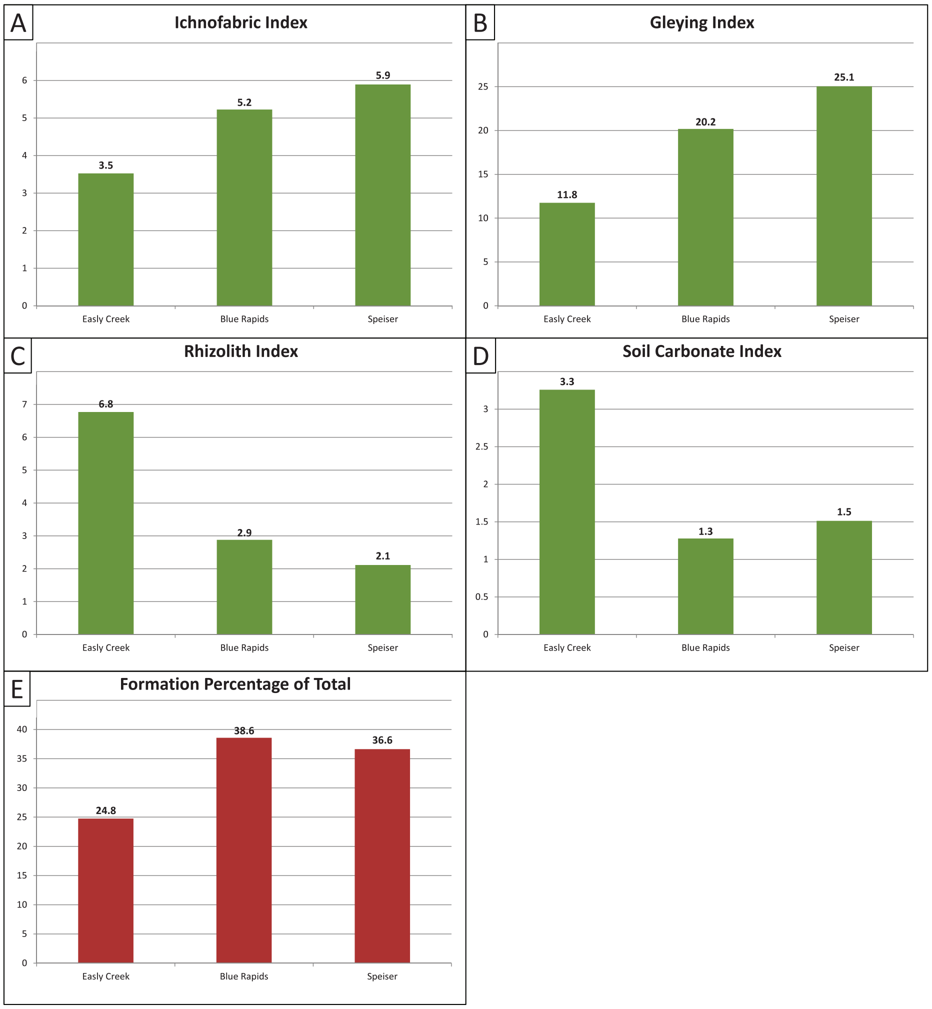


FIG. 12.—Bar charts showing total percentage of pedogenic features in each formation. Percentages shown are the total area of the core face covered by each soil feature, divided by the total slab area in each formation.

susceptible to desiccation (Counts and Hasiotis 2009; Smith and Hasiotis 2008; Brussaard and Slager 1986; Willis and Roth 1962, respectively). Although individual species have different tolerances in different soil compositions and field capacities, most of these insects show increased survival, preference, or reproduction at a moisture range of approximately 18–40% by weight (Willis and Roth 1962; Potter 1983; Potter and Gordon 1984; Villani and Wright 1990; Vessby 2001; Riis et al. 2005). Many modern fossorial insects have a multiyear life cycle, most of which is spent underground. We interpret extensive assemblages of backfilled trace fossils in cumulic paleosols, therefore, to indicate that environmental conditions remained favorable with enough adequate moisture to support multiple generations of insect populations.

Trace-fossil assemblages in Permian paleosols are interpreted to be the work of insects or insect larvae that lived in the soil vadose zone for an extended period of time, based on morphological similarities with modern burrows (Smith and Hasiotis 2008; Counts and Hasiotis 2009). The association between trace fossils and rhizoliths provides additional evidence for this hypothesis; many modern fossorial insects feed on plant roots and organic matter disseminated in the soil (Counts and Hasiotis 2009, and references therein). By using these modern insects as analogs, the approximate range of soil moisture in Permian sediments can be deduced from the moisture tolerances of these organisms. Like their modern counterparts, the constructors of *Naktodemasis* would have been susceptible to desiccation and could not have survived even limited amounts of time in completely dry sediments. Permian sediments, thus, likely retained some amount of water even during the dry season. Conversely, sediments unlikely were completely saturated for long periods of time, since many fossorial insects cannot survive in fully subaqueous conditions. Ambient soil moisture was, therefore, likely most often within this range in upper Council Grove Group paleosols. The lack of visible primary sedimentary structures in the majority of continental units suggests that sediments have been completely bioturbated during pedogenesis. Inorganic pedoturbation is also possible, and it is likely that some degree of the homogeneity of these intervals is the result of mixing by illuviation or shrinking–swelling of clays. Most abiotic processes, however, leave other indicators of their presence (e.g., ice wedges, graded bedding due to mass movement, etc.), which are absent in the section. Although multiple generations of organisms repeatedly colonized these soils, visible burrow assemblages are likely only the most recent generation of burrowing. Decreased abundance of traces upward throughout the studied section may be related to increasing soil moisture content through time, as evidenced by increased gleying and decreased pedogenic carbonate. Burrowing activity is also more common in coarser grain sizes; traces that are indicative of higher soil moisture would be expected to be most abundant in the sediments deposited during wetter climates. Previous research has interpreted the climate during the deposition of these and closely related sediments (i.e., those in nearby areas, or stratigraphically close formations) as ''more arid,'' ''relatively arid,'' ''semiarid,'' etc. (e.g., Miller and West 1993; Mazzullo et al. 1995; McCahon and Miller 1997; Rankey and Farr 1997; Kessler et al. 2001;

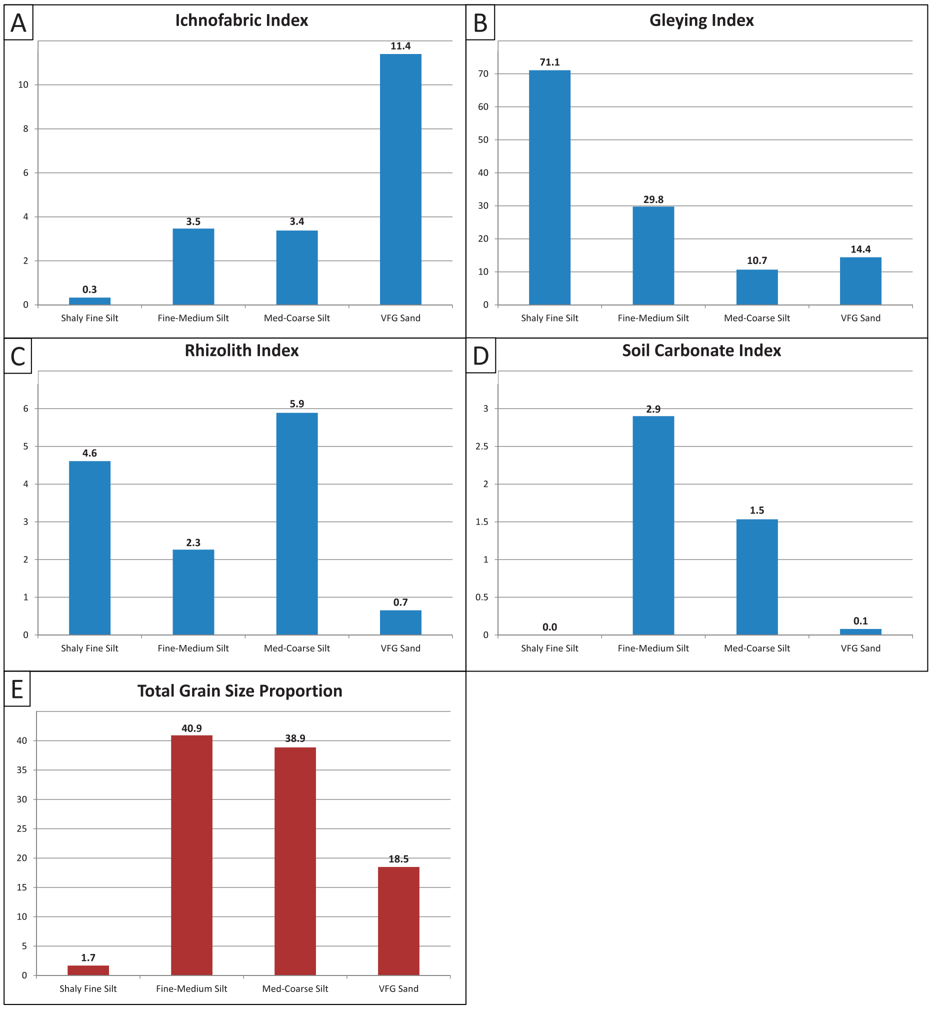


FIG. 13.—Bar charts showing total percentage of pedogenic features in each of the four major lithologies in paleosols. Percentages shown are the total area of the core face covered by each soil feature, divided by the total slab area determined to consist of each particular lithology, regardless of core or formation.

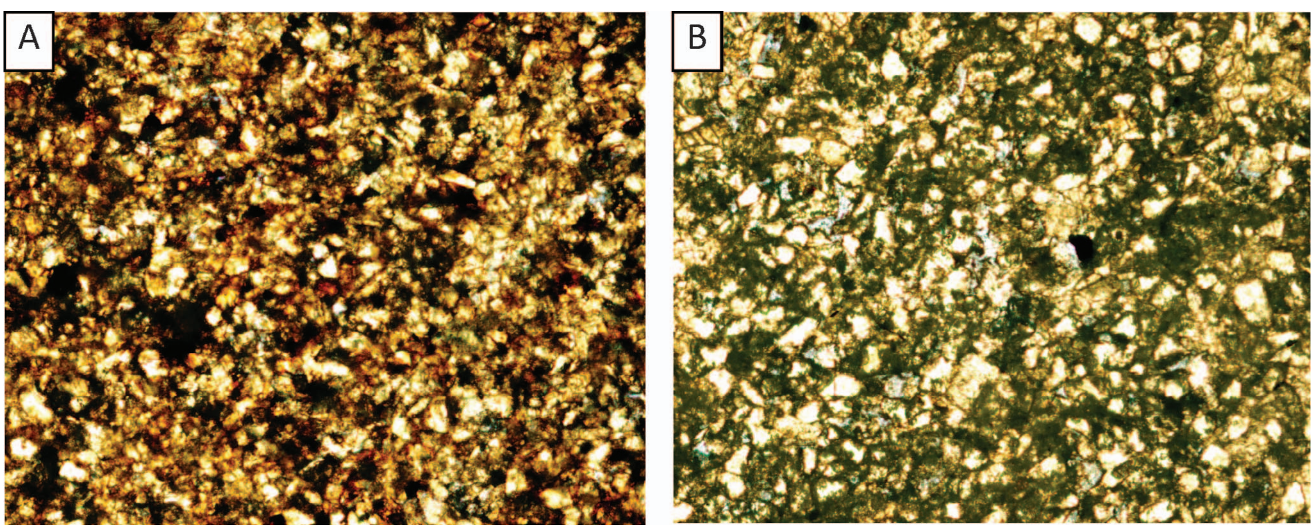


FIG. 14.—Thin section photos showing general nature of iron-oxide-cemented siltstone, the most common lithology in Council Grove Group paleosols. **A)** Oxidized sediment, Cross H Cattle 2716.2, PPL 10X, **B)** gleyed sediment, Cross H Cattle, 2651.5, PPL 10X.

Olszewski and Patzkowsky 2003), and are even directly interpreted as "arid" (Puckette et al. 1995). Regardless of previously hypothesized climates, large numbers of insect burrows in paleosols are not suggestive of arid conditions (Hasiotis et al. 2012). The pedogenic features described in this study suggest a semiarid or wetter climate for the Hugoton area during the Early Permian.

Peds

Blocky peds and their associated cutans are present in both outcrop and core. Outcrop exposures also occasionally contain prismatic peds and gilgai structures, forming vertisols that are not seen in core. Vertisols are found today only in temperate to tropical latitudes, typically in hot climates, and form only in soils with greater than 30% clay content and shrink–swell potential (Driessen et al. 2001; Retallack 2001). Blocky peds also reflect shrinking and swelling clays, but to a lesser degree than prismatic ped structures. Both ped structures are representative of climates with fluctuating seasonal moisture conditions (Brady and Weil 1999; Schaetzl and Anderson 2005). Due to the nature of core exposure, the distribution of peds was not examined in this study.

Hugoton-Area Depositional Mechanisms and Stratigraphic Architecture

Evidence of soil moisture in paleosols suggests that mechanisms other than eolian deposition were responsible for initial sedimentation of silts and fine sands in continental units. Modern semiarid environments with higher amounts of precipitation contain at least some proportion of sediment deposited through overland flow, when rivers and streams overtop natural levees or the boundaries of incised channels in low-relief areas during flooding events (Leopold et al. 1964). Our observations of paleosols are consistent with contributions from both sheetflood and eolian deposition; coarser grain sizes may have been deposited during higher-energy flooding events, with fine silts being deposited by wind action or reworked from lower-energy environments in the fluvial cycle. Alluvial and eolian depositional mechanisms have been proposed for the similar paleosols, such as the underlying D-zone in the Lansing–Kansas City Groups (Prather 1985). The sediments described here are interpreted as having been continually bioturbated and pedogenically modified both during and after deposition, creating cumulative paleosol profiles without well-defined horizons. Although sedimentation and pedogenesis were co-occurring, sedimentation rate high enough to build thick successions of compound paleosols in some areas (e.g., processes described in Krauss 1999 and Hasiotis and Platt 2012).

Isopach mapping of continental units shows a clear increase in thickness landward (Fig. 3). Extensive subaerial burrowing and plant colonization may have an impact on stratigraphic architecture; biostabilization of the landscape by these organisms likely played a role in the updip aggradation and thickening of continental units (as hypothesized by Dubois et al. 2012). Updip portions of the clastic wedges that form continental units are thicker and coarser overall, since they were deposited closer to sediment source areas. The decreasing relief of the coastal plain setting slowed the deposition of sediment as fluvial energy decreased in the hinterland. Accommodation for subsequent cycles was created by subsidence associated with the Hugoton basin, which was an isostatic response to sea-level change and was relatively consistent across the region (Johnson 1989). The alternating clastic–carbonate wedge architecture of the area is thus a function of biostabilization, variation in sedimentation rate, depositional environment, and subsidence.

Regional Changes in Cyclothems

The internal changes in continental units over the ~ 480 km (~ 300 mile) span between core and outcrop represent fundamentally different mechanisms of soil formation in the two areas (Fig. 15; see comment). Outcrop paleosols contain distinct exposure surfaces at the base of thin limestones and are not interpreted as cumulic. Each of the stacked paleosols seen in outcrops was likely formed through pedogenic modification of existing marine clastics that were deposited during 5th-order cycles. This mechanism of paleosol formation is also well known in other midcontinent cyclic strata, e.g., the underlying Pennsylvanian Roca Shale (Rankey and Farr 1997). Since these cycles are likely related to global sea-level change, evidence of 5th-order cyclicity should be present in the Hugoton area as well. The lack of internal, cyclic changes in lithology in continental units in core, however, suggests that the Hugoton area was less sensitive to these smaller-scale sea-level changes. Stratigraphic variations in pedogenic features in Hugoton-area sediments are evidence that the parameters affecting soil formation change significantly over the time interval during which each unit was formed. These variations in soil characteristics may be related to differences in water-table height or climate change, which in turn may be influenced by 5th-order cycles. These variations, however, lack the regularity that would indicate a strong relationship to cyclical sea-level change.

Several factors may influence the reasons that fifth-order cycles do not consistently affect Hugoton-area paleosols. Our observations support the model proposed by Dubois et al. (2012), wherein biostabilization of the landscape results in topographic aggradation and reduced accommodation. Positive relief created through aggradation prevented all but the largest sea-level changes from affecting updip sediments. Although small-scale (5th-order) sea-level fluctuations occur, little or no accommodation exists to allow for extensive flooding and limestone deposition like that seen in outcrop. Neither is there space for the marine clastics that form the basis for outcrop paleosols to be deposited during late-stage highstand and early regression (Fig. 15B). Additionally, the lack of *Naktodemasis* burrow assemblages in outcrop may indicate that little or no biostabilization took place. Topographic relief could not be created in the outcrop area, inasmuch as the lesser degree of biologic activity would not have allowed significant stabilization and aggradation. The abundance of *Naktodemasis* burrows in Hugoton area indicates that enough moisture was present in sediments to support plant growth, soil-biota life cycles, and biostabilization of the landscape via pedogenesis, resulting in the building of relief. Future sequence stratigraphic models should incorporate extensive burrowing, aggradation, and reduced accommodation in the updip portions of continental cycles. The uniform nature of continental formations in core, however, is also likely a function of geographic position on the broad, low-relief ramp. The overall Hugoton area was likely located farther from the basin center than outcrops, decreasing the influence of sea level on the area, while experiencing greater sediment input from the source area (i.e., the Ancestral Rocky Mountains). In addition, the Hugoton basin most likely had a steeper slope than the outcrop area to the east due to higher rates of subsidence in the tectonically active basin (Johnson 1989). Small changes in sea level would, thus, have affected a smaller spatial area than the flatter passive margin to the east, which had little large-scale tectonic activity.

Implications for Early Permian Paleoclimate

Although existing paleoclimate models are based on data sets from a broad geographical and spatial range, our more detailed observations can lend support to specific aspects of models proposed by others (e.g., Miller and West 1993; Miller et al. 1996; Rankey 1997; Soreghan 1997; Olszewski and Patzkowsky 2003). Many of these and other studies favor an interpretation of a drier or "relatively arid" climate during this time but do not specify exactly which climate classification they prefer. Our observed characteristics of continental units in the Upper Council Grove

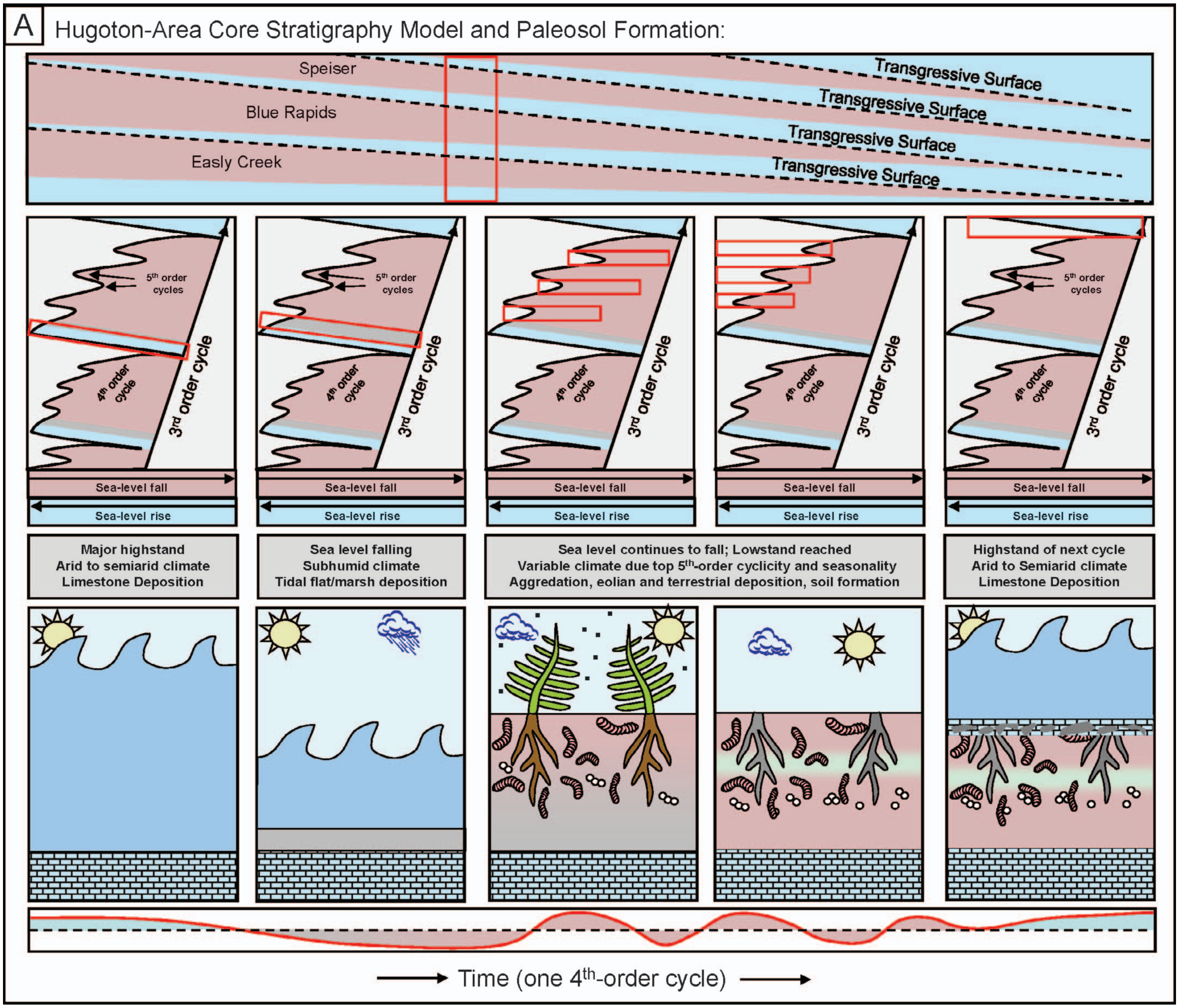


FIG. 15.—Cycle hierarchies recorded in paleosols, and hypothesized mechanisms of soil formation in upper Council Grove Group paleosols in both Eastern Kansas outcrops and Hugoton-area core. Outcrop model modified from Miller et al. (1996). Although sea-level change was consistent in both areas, 5th-order cycles are not visible in the Hugoton area as lithologic changes due to paleogeographic differences. Soil formation was also different in each area, with outcrop paleosols being the result of pedogenic modification of marine clastics, and Hugoton-area soils accumulating and aggrading throughout the interval of subaerial exposure.

Group suggest that paleosol formation took place while climate was semiarid at times, but was interspersed with other, wetter climates as well. Juxtaposition of soil features interpreted to represent both high and low amounts of soil moisture indicates climatic variability within the time interval of soil formation. These interpretations are consistent with the model proposed by Miller et al. (1996), wherein 5th-order lowstands are coincident with wetter climates, and 5th-order highstands are coincident with dry conditions. During the time of formation of each cumulative paleosol, several of these smaller cycles would have occurred. The observed pedogenic characteristics are thus a result of the climatic variability between the lowstand and highstand portions of these 5th-order cycles, as well as the slower change from semiarid to monsoonal climates over the course of 4th-order cyclothems. The difference between wetter lowstand and drier highstand climates on both 4th-order and 5th order time scales likely contributed to pedogenic variability more so than seasonal variations in monsoonal time periods.

Given the intraformational climate variability, our interpretations suggest that the Permian climate during deposition of Hugoton-area continental units was more complex than simply "relatively arid" or "semiarid." We note the strong influence of climate variability on deposition and pedogenesis. If climate change was occurring at 5th-order time scales in outcrops 300 km to the east, then some degree of climate cyclicity would also be seen in Hugoton area, regardless of the particular depositional environment, paleogeography, or ramp position. The interpretations of Dubois et al. (2012) do not take into account climatic variations on these time scales. Our studies show that models of cyclic climate change need to incorporate cycle hierarchies and more rapid variations in climate in order to fully explain observed pedogenic features.

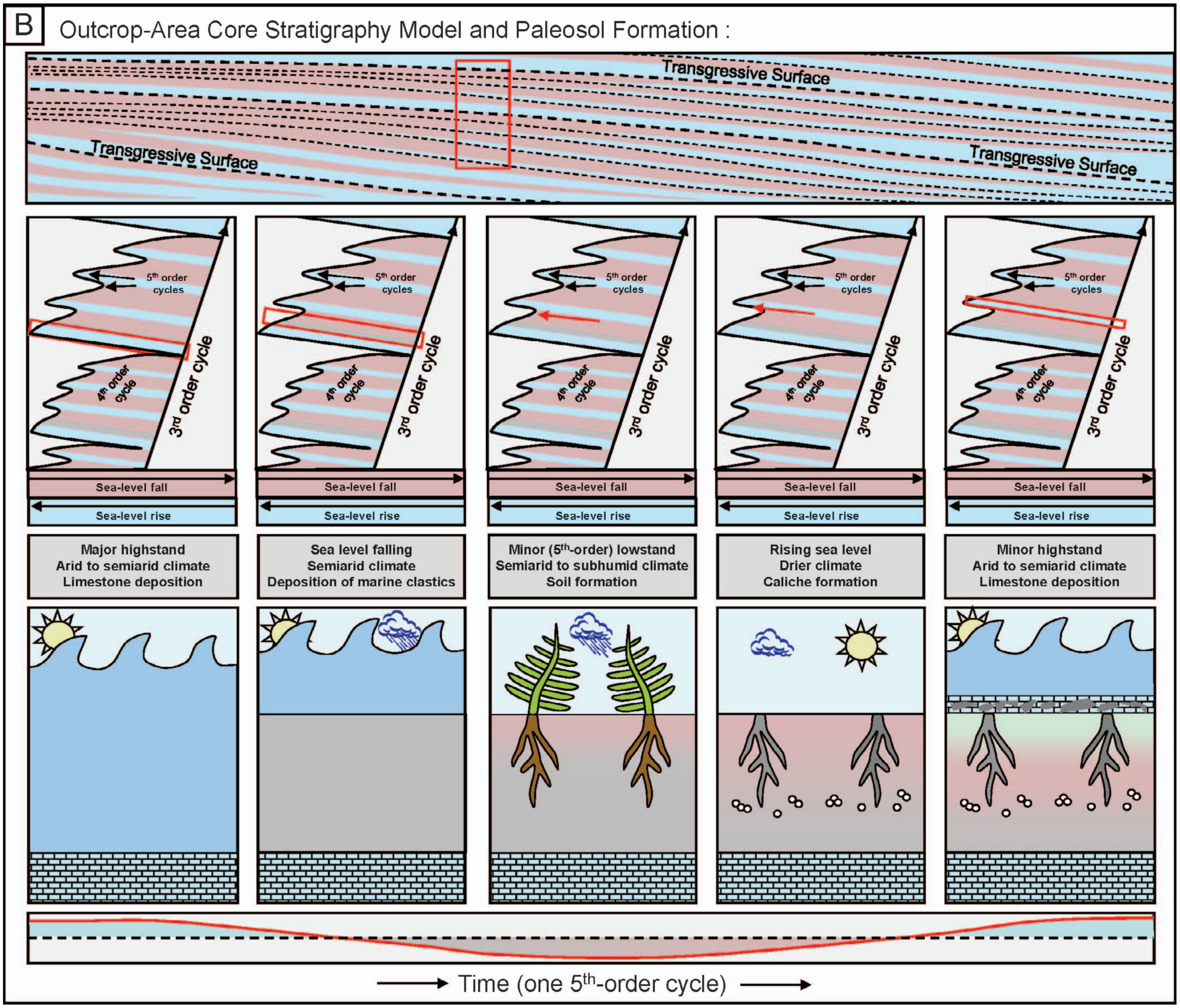


FIG. 15.—Continued.

These smaller-scale cycles may play an important role in determining the characteristics of cumulic paleosols. Although our detailed observations cannot address the climate moisture levels of highstand phases, they support an overall semiarid climate during lowstand. Even during the drier portions of 5th-order cycles, soil moisture would have had to be high enough to support the continued presence of stable communities of organisms. Sedimentation and pedogenesis may have alternated with climate as the predominant soil-forming factors, with sedimentation having a greater contribution in drier times, and pedogenic alteration in the wetter.

Changes in paleosol features across formations are also indicative of climate change, but on a larger scale. The Speiser Shale has been interpreted as the terminal end of a larger 3rd-order cycle that encompasses most of the Council Grove Group (Boardman and Nestell 2000). Trends in paleosol features across continental units from the Easly Creek to the Speiser Shale can, thus, be used to determine climatic response to 3rd-order sea-level regression during late-stage highstand. Both gleying and total bioturbation increase stratigraphically upward across the formations studied; we interpret this as evidence of increasing soil moisture as sea level fell over 3rd-order time scales. Additionally, pedogenic carbonate, an indicator of climates where precipitation is less than evapotranspiration, is proportionally less abundant in the Speiser and Blue Rapids shales than in the underlying Easly Creek. This increase in soil moisture is likely related to a more humid climate and not increasingly higher water tables, in that falling sea level would have lowered overall base level. Generally coarser grain sizes in the Speiser Shale also could indicate increased contribution from overland flow, since coarser grain sizes require higher energy for deposition and may not be eolian in origin. Our observations support the interpretation that larger-scale regressions are coincident with changes to a more humid or seasonal climate with increased precipitation.

CONCLUSIONS

Permian continental deposits in Hugoton core are interpreted as cumulative paleosols that are the product of continual aggradation and pedogenic modification of both windblown and floodplain silts and very fine sands. Paleosol characteristics, including trace fossils, rhizoliths, carbonate nodules, and gleying, indicate a variable, seasonally wet climate in the western interior of Pangea. By comparing trace fossils to modern analogs, Hugoton-area paleosols are thought to have consistently contained adequate soil moisture to allow for continued survival of infauna. Soil features are not consistently distributed throughout continental units, and cannot be tied directly to smaller scale cyclicity, but are ultimately the product of climate variability related to smaller, 5th-order cycles. Differences in character between outcrops and core reflect different mechanisms of soil formation that are related to both the time scales of formation, the paleogeographic setting, and the presence of topography-building organisms that reduce accommodation space in the Hugoton basin. Our observations indicate that a semiarid climate during deposition of continental units is supported for the Hugoton area. This study also underscores the need to account for cycle hierarchies and intracycle climate variability when reconstructing paleoclimates.

ACKNOWLEDGMENTS

This research was supported by the University of Kansas Joseph M. Patterson scholarship, a University of Kansas summer field research award, the American Association of Petroleum Geologists Raymond C. Moore Memorial Grant, and a Geological Society of America research grant. The authors wish to thank Drs. Robert Goldstein at the University of Kansas and Lynn Watney of the Kansas Geological Survey, as well as Dr. Keith Miller of Kansas State University and an anonymous reviewer for helpful reviews of this manuscript.

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Received 24 October 2012; accepted 1 October 2013.