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Tectonic and paleoclimatic significance of a prominent upper Pennsylvanian (Virgilian/Stephanian) weathering profile, Iowa and Nebraska, USA

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Abstract

A Virgilian (Stephanian) weathering profile up to 4 m deep, containing a paleosol (basal Rakes Creek paleosol) in the basal mudstone of the Rakes Creek Member and karstified marine sediments in the Ost, Kenosha, and Avoca members below, is restricted to southeastern Nebraska (specifically the Weeping Water Valley) and the Missouri River Valley bluffs of adjacent easternmost Iowa. This weathering profile, informally referred to as the Weeping Water weathering profile, disappears farther eastward into the shallow Forest City Basin in southwestern Iowa.

Weeping Water weathering profile features are prominent in comparison to other Midcontinent Pennsylvanian subaerial exposure surfaces, indicating prolonged subaerial exposure, relatively high elevation, and a marked drop in water table along the Nemaha Uplift in southeastern Nebraska. Eastward, on the margin of the Forest City Basin, the basal Rakes Creek paleosol and underlying karst are thinner and relatively poorly developed; paleosol characteristics indicate formation on lower landscape positions.

Comparative pedology, the contrasting of paleosol variability, morphology, and micromorphology between different paleosols in the same regional succession, provides a basis for interpreting the larger significance of the basal Rakes Creek paleosol. The stratigraphically older upper Lawrence and Snyderville paleosols in the same area are significantly different in patterns of lateral variability and overall soil characteristics. Weaker eustatic control and stronger tectonic activity may explain the greater west–east variability (and eventual eastward disappearance) of the basal Rakes Creek paleosol. Differences in soil characteristics between the Vertisol-like upper Lawrence and Snyderville paleosols and the non-Vertisol-like basal Rakes Creek paleosol appear to be due to climate change, particularly a shift from more seasonal to more uniform rainfall. This climate change hypothesis is compatible with overall Virgilian stratigraphic trends in the northern Midcontinent outcrop area.

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1. Introduction

1.1. General

A paleosol developed in the basal terrigenous mudstone of the Rakes Creek Member along with the karstified marine sediments of the underlying Ost Limestone, Kenosha Shale, and Avoca Limestone members constitute a weathering profile up to 4 m deep in the Weeping Water Valley of southeastern Nebraska (Figs. 1, 2). This weathering profile, informally called the Weeping Water weathering profile, can be traced eastward in diminished form into the Missouri River Valley on the Nebraska–Iowa border, but it essentially disap-

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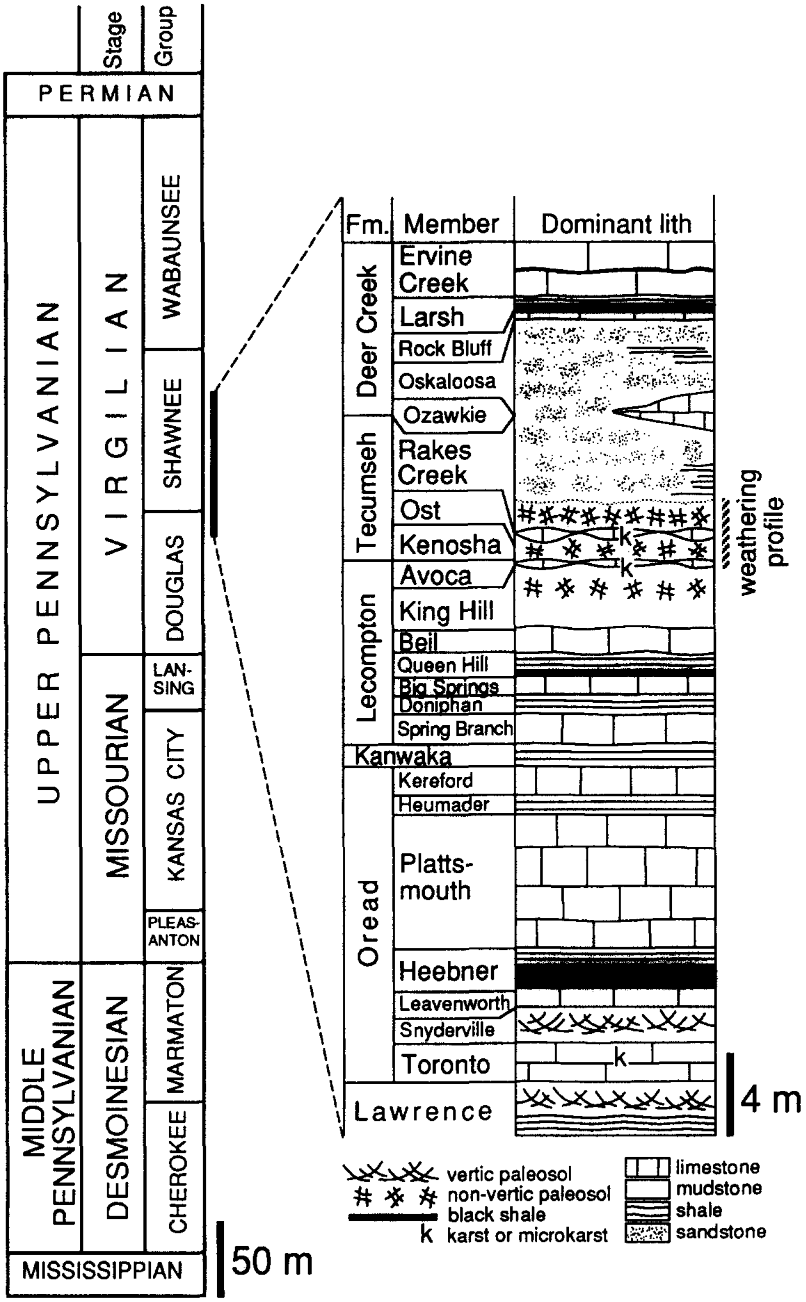


Fig. 1. Generalized stratigraphic section, for southeastern Nebraska, USA, of interval discussed in this paper. Paleosols are known in Lawrence Formation, Snyderville Member, and King Hill Member, as well as Rakes Creek–Ost interval, which includes basal Rakes Creek paleosol and karstified marine sediments underneath. Other non-carbonate units have not been studied in detail.

pears farther eastward into the Forest City Basin, a shallow intracratonic basin, in southwestern Iowa, USA (Fig. 2). The degree of development of pedogenic and sub-paleosol weathering features indicates a relatively intense and temporally significant period of subaerial exposure, yet one which was clearly limited in its geographic extent. The recognition of these facts is essential for the accurate and detailed reconstruction of Midcontinent USA basinal history (in terms of eustasy, tectonics, sedimentation, and paleoclimate) during Late Pennsylvanian time.

1.2. Terminology

I use the term "basal Rakes Creek paleosol" to refer to the ancient soil solum present in the basal mudstone of the Rakes Creek Member or Rakes Creek–Oskaloosa interval. This usage, while informal, is in violation of the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983) because it duplicates the name of a stratigraphic unit. In cyclothems and many other ancient sedimentary sequences, though, individual paleosols are limited to particular depositional units. Such paleosols, which formed on very low relief depositional surfaces, do not cross the contacts of different lithostratigraphic units, and therefore it is more convenient to give them informal names corresponding to lithostratigraphic unit names. Otherwise, one would be faced with the prospect of naming myriad paleosols, whose significance and interpretational value would probably be lost in the confusion.

I also use the term "Weeping Water weathering profile" to refer to the combined weathering profile that includes the basal Rakes Creek paleosol as well as pedogenically-modified mudstones and karstified marine sediments extending as far downsection as the Avoca Limestone Member (Fig. 1). Technically, this profile cannot be called a geosol according to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983) because it incorporates weathered materials (karstified limestones and calcareous shales) that are not strictly "pedologic soils." However, the choice of a name derived from a geographic locale (for the valley of Weeping Water Creek) is technically correct and also quite suitable because weathering features are developed best in that area. This profile incorporates a succession of materials which vary considerably in terms of their weathering characteristics, unit thicknesses, and degree of continuity or "welding." It is genetically significant as a discrete entity because it represents a relatively long and complex history of alternating deposition and weathering, some of which predates the development of the basal Rakes Creek paleosol.

2. Background

During Pennsylvanian time, sedimentary sequences representing variations of the classic North American cyclothem were deposited in the Appalachian, Illinois, and Midcontinent basins (Wanless and Shepard, 1936, Wanless, 1966, 1972; Ferm, 1970; Heckel, 1980). Particularly in the Midcontinent, these cyclothems have been interpreted as products of Milankovitch-driven (glacio-) eustatic cycles (Heckel, 1986, 1991). Indeed, estimations of the duration of Carboniferous depositional cycles do cluster within the Milankovitch time band, particularly about the 413 ka eccentricity period (Algeo and Wilkinson, 1988). The Weeping Water weathering profile actually lies between the deposits of two major marine cycles (Lecompton and Deer Creek cycles of Heckel, 1986), and is developed in the deposits of one intermediate marine cycle (Avoca) and one minor marine cycle (Ost) in the terminology of Heckel (1986).

The general pattern of sedimentation in the Midcontinent was constant throughout Pennsylvanian time. Alternating shallow marine carbonate and siliciclastic mudrock sedimentation dominated the vast distal shelf of southeastern Nebraska, southwestern Iowa, and adjacent parts of Kansas and Missouri, far north of the Ouachita–Arbuckle orogenic belt in Oklahoma and Arkansas and the deep foreland Anadarko Basin in central to western Oklahoma (Fig. 2). Clastic units thicken and commonly coarsen southward towards the Anadarko Basin, and carbonate units thin or pinch out entirely near the Kansas–Oklahoma line. Despite the continuance of this pattern through the Pennsylvanian, local stratigraphic variability indicates intrabasinal paleogeographic change between certain depositional cycles or sets of cycles.

Prominent paleosols appear in several Upper

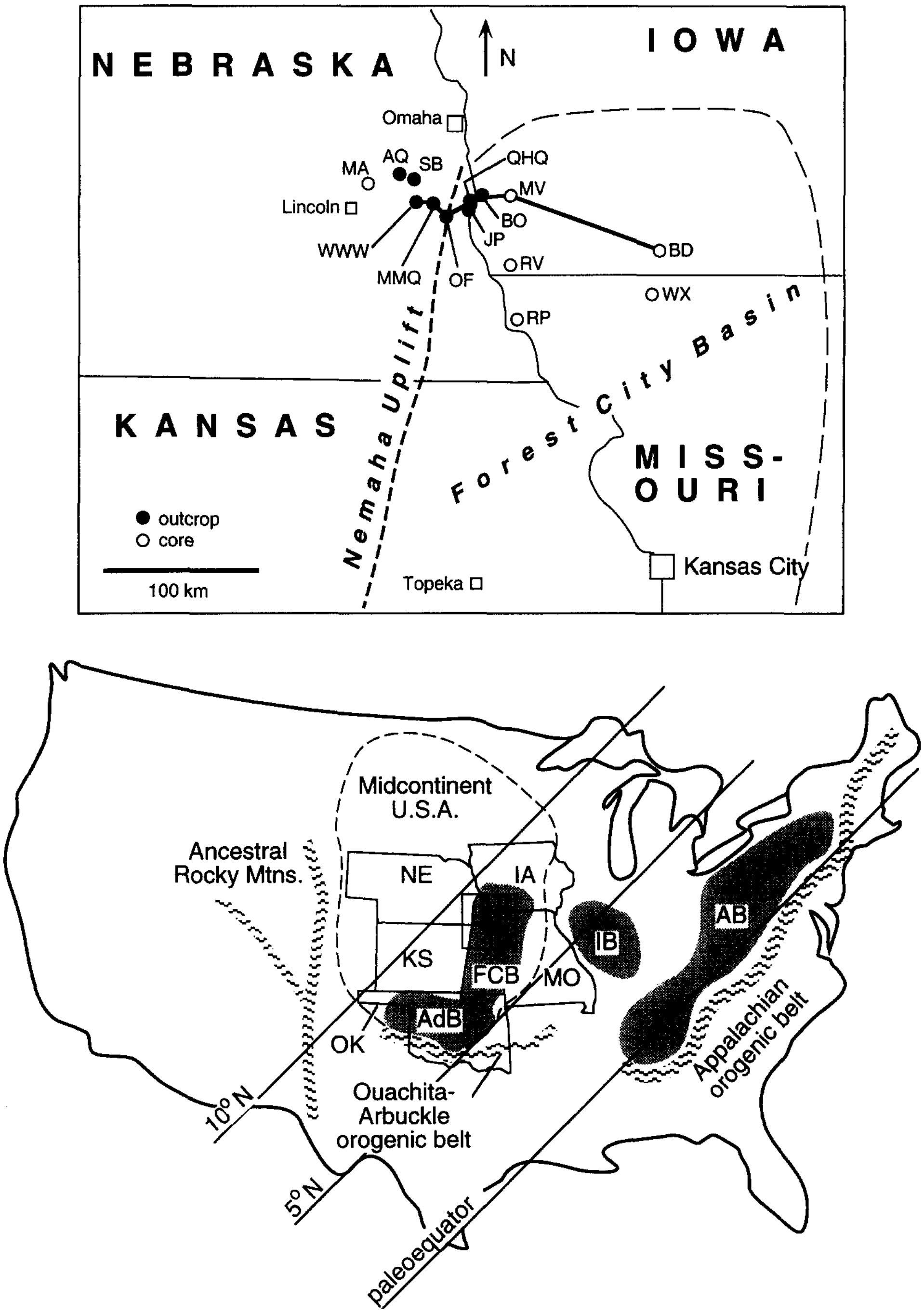


Fig. 2. Map of localities. *WWW*=Exposure on Weeping Water Creek (SE1/4 sec, 32, T11N R11E, Cass Co., NE); *MMQ*=Martin Marietta Quarry (NE 1/4 sec. 3, T10N R11E, Cass Co., NE) at Weeping Water; *OF*=Ost Limestone type section (SE1/4 sec. 34, T10N R12E, Cass Co., NE); *JP*=Jones Point (NW1/4 sec. 28, T10N R14E, Cass Co., NE); *QHQ*=Queen Hill Quarry (SW1/4 sec. 9, T11N R14E Cass Co., NE); *BO*=Burr Oak, IA (NW1/4 sec. 15, T71N R43W, Mills Co., IA); *MV*=well core near Malvern, IA (NW1/4 sec. 5, T71N R41W, Mills Co., IA); and *BD*=well core near Bedford, IA (SE 1/4 sec. 4, T67N R34W, Taylor Co., IA). Other localities in immediate vicinity showing upper Lawrence Formation and Snyderville paleosols are: Mid-Am well,

Pennsylvanian regressive facies units (particularly siliciclastic mudstones) on the shelf north of the orogenic belt, but their characteristics vary. There are two common, very broad morphological types of paleosols in Missourian and Virgilian rocks in southeastern Nebraska and adjacent areas: (1) those showing strong vertic features (particularly, synformal–antiformal sets of large, cross-cutting slickensides) and (2) those that lack vertic features (such as the basal Rakes Creek paleosol). In many cases, paleosols of the latter type contain a discrete horizon wherein carbonate nodules are concentrated, and/or a prominently fine to medium blocky-weathering subsoil.

Furthermore, significant variability also appears within some individual paleosol horizons, whereas others are relatively uniform. Paleosol variability appears in the form of differences in coloration, horizonation, degree of development, and solum thickness. A given paleosol within a cyclothem may not be uniformly expressed across large geographic areas, particularly around the northernmost margin of the Midcontinent outcrop belt (southeastern Nebraska, and adjacent parts of Iowa, Kansas and Missouri: see Joeckel, 1989, 1993). The basal Rakes Creek paleosol is a very clear example of non-uniform expression, yet a paleosol in the upper Lawrence Formation downsection (Fig. 1) is relatively uniformly expressed.

There are also major lithofacies changes in the stratigraphic interval containing the Weeping Water weathering profile (Fig. 1). The Tecumseh and upper Lecompton formations of the Shawnee Group were not correlated from northeastern Kansas to the Weeping Water, Platte, and Missouri valleys of southeastern Nebraska–southwestern Iowa until the late 1920's and 1930's (Condra, 1930; Condra and Reed, 1937, 1938; Condra and Scherer, 1939; Fig. 1), a situation that probably reflects the interpretive problems associated with the lithofacies changes in these units. In the process of this correlation, the originally uppermost members of the Tecumseh Formation (Rock Bluff Limestone and Larsh Shale, now included in the middle of the Deer Creek Formation) proved to be relatively consistent in general characteristics across the entire region (the Larsh is a laterally persistent "core shale" interpreted to represent sea-level highstand within the Deer Creek major cycle: Heckel, 1986, 1991). In contrast, strong lateral lithofacies changes were noted from the interval between the Beil Limestone and the base of the Rock Bluff Limestone, which includes the Weeping Water weathering profile (Condra, 1930; Condra and Reed, 1937; Burchett, 1971; Fagerstrom and Burchett, 1972). Most of the individual stratigraphic units (Kenosha, Avoca, Ost, Rakes Creek, Ozawkie, and Oskaloosa members) in this interval can vary considerably over as little as 0.5 km.

The nature of Pennsylvanian tectonism in the study area is still incompletely understood, although structural effects on sedimentation have been considered for some time (e.g., Condra and Reed, 1937). Based on facies changes and general structural patterns, Fagerstrom and Burchett (1972) interpreted gentle syndepositional uplift at the northeastern end of the Nemaha Uplift (i.e., the Nehawka Arch) during Rakes Creek–Oskaloosa deposition. These authors mapped a north–south shoreline along the eastern margin of the emerging Nehawka Arch during early Rakes Creek time.

3. Description of and associated units

Much of the detailed description of the Weeping Water weathering profile is based on fresh exposures and well cores in and around the Martin Marietta quarry (MMQ; Figs. 3A, 4A) at Weeping Water, Cass County, Nebraska, where the valley of Weeping Water Creek exposes Pennsylvanian bedrock over several kilometers. Eastward, the same strata crop out in the Missouri River Valley on the Nebraska–Iowa line.

Lancaster Co., NE (*MA*), abandoned quarry at Ashland, NE (*AQ*), abandoned quarry west of South Bend, NE (*SB*), and well cores from near Riverton, IA (*RV*) and Rockport (*RP*) and Wilcox (*WX*), MO (see Joeckel, 1993). Other abbreviations: *AB* = Appalachian Basin, *AdB* = Anadarko Basin, *FCB* = Forest City Basin, *IA* = Iowa, *IB* = Illinois Basin, *KS* = Kansas, *MO* = Missouri, *NE* = Nebraska, *OK* = Oklahoma. Paleogeography in part after Heckel (1980).

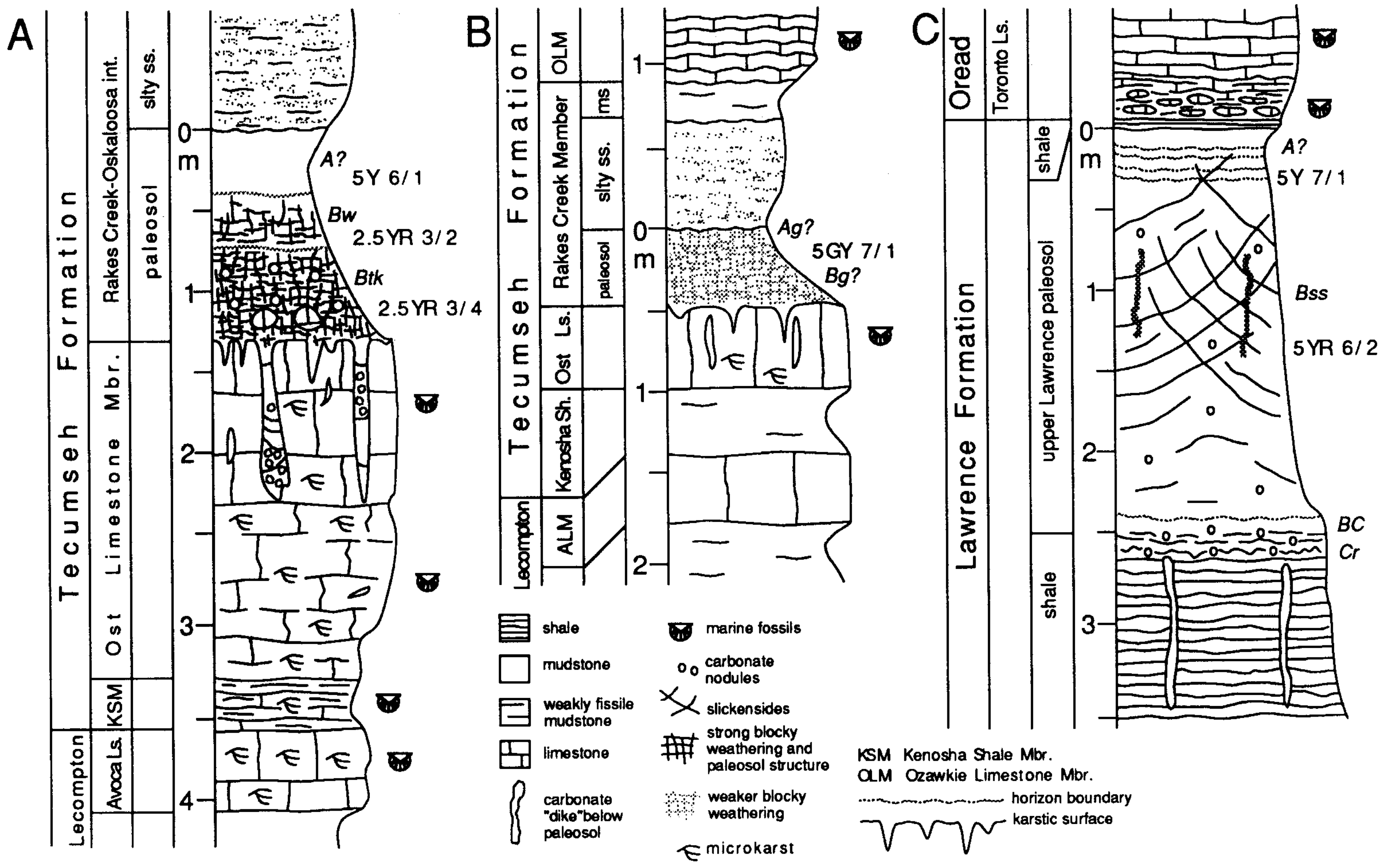


Fig. 3. Profiles of (A) in the Martin Marietta Quarry (MMQ), Weeping Water Valley, NE; and (B) eastward at the western edge of the Forest City Basin at Burr Oak, IA, compared with (C) representative profile of upper Lawrence Formation paleosol from near South Bend, Nebraska (SW1/4 sec. 15, T12N R10E, Cass Co., NE). Note west–east trend from deeper, strongly horizonated basal Rakes Creek paleosol with strong karst underneath to shallow, poorly horizonated basal Rakes Creek paleosol with weak karst. Also note strong contrast between "Alfisol-like" basal Rakes Creek paleosol in Weeping Water Valley and stratigraphically older Vertisol-like upper Lawrence paleosol in same geographic area.

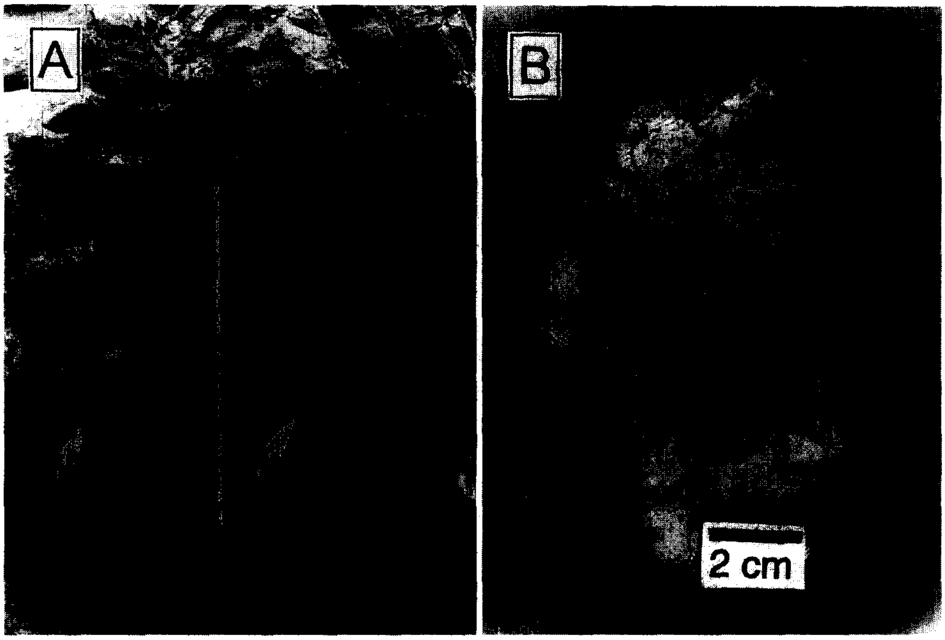


Fig. 4. A. At MMQ, Weeping Water Nebraska, showing paleosol with light-colored surface horizon grading into overlying very fine sandstone near top of photo and darker-colored subsurface horizons above underlying Ost Limestone with karst pipes (two are marked by arrows). Leveling rod is 1.5 m long. B. Strong development of reddish brown mud-filled microkarst cracks in lower 10 cm of Ost Limestone at same quarry.

3.1. *Rakes Creek–Oskaloosa sandstone*

Martin Marietta Quarry and Weeping Water Valley

In the Weeping Water Valley, the Rakes Creek and Oskaloosa members are indistinguishable due to the absence of the Ozawkie Limestone Member, which separates the two units elsewhere (Fig. 1). The Rakes Creek–Oskaloosa interval (sensu Burchett, 1971) in the Weeping Water Valley consists of a 5–9 m silty, very fine sandstone and an underlying thin (~0.5–1.5 m, but usually 1–1.3 m) paleosol-bearing mudstone. The clay fraction (<2 μm) of the basal mudstone is uniformly dominated by illite and lesser chlorite, with minor kaolinite—a very common clay mineral assemblage for Pennsylvanian mudrocks in the northern Midcontinent. The upper (sandstone) unit is mostly unfossiliferous, massive, and friable; it is light gray to pale yellow (5Y 7/2-7/3) in outcrops, but light gray (N 7/0 or 5Y 7/1) in cores. The basal 1–3 m of the sandstone contain many $\leqslant 1$ mm planar laminae of slightly darker mud. A few of these laminae are convoluted or disrupted, recording fluid escape and faunal burrowing. The upper 20–50 cm interval of the sandstone unit (directly underneath the Rock Bluff Limestone) is darker and contains $\leqslant 2$ mm mud laminae as well; locally, it also contains simple vertical burrows, a basal pelleted zone, brachiopod valves, or carbonized plant fragments.

The Rakes Creek sandstone records a somewhat anomalous introduction of a large volume of coarser-grained sediment into southeastern Nebraska and southwestern Iowa. Thick sandstones are very rare in the Kansas City to Shawnee groups along the northernmost Midcontinent Pennsylvanian outcrop (although they eventually increase in abundance in the overlying Wabaunsee Group; Fig. 1).

Missouri River Valley

Along the Missouri River bluffs (and southward into northeastern Kansas), the Rakes Creek and Oskaloosa members are separated by the Ozawkie Limestone (for more detail on this unit, see Fagerstrom and Burchett, 1972). Overall, the

Rakes Creek fines eastward, becoming shalier into Iowa. In the Missouri Valley, the Oskaloosa Member locally contains a zone of thinly interlaminated (possibly flaser-bedded), mud and sandy silt (sometimes mudcracked), in its upper 1.5 m, with beds of mudstone and shale below. This zone of interlaminated mud and sandy silt probably represent some form of marine tidal deposition. The Oskaloosa Member becomes even sandier eastward in a core from near Bedford, Iowa (Fig. 2).

3.2. *Basal Rakes Creek mudstone and paleosol*

Martin Marietta Quarry and Weeping Water Valley

In the Martin Marietta Quarry, the paleosol in this mudstone can be grossly subdivided into three horizons (Figs. 3A, 4A). Intervals for these horizons are presented as depths below the paleosol surface (as in descriptions of modern soils).

The upper horizon (~0–40 cm; probably mostly or entirely the original A horizon) is gray (5Y 5/1-6/1) massive-weathering, noncalcareous, siltstone grading downward into silty mudstone. In the uppermost 10 cm of this horizon there are a few, slightly sinuous, subhorizontal to subvertical stringers of light gray to pale yellow very fine sand that represent disrupted stratification, as burrows or cracks filled with sediment infiltrating from above. In one well core, there are also discrete fragments of the overlying sandstone, recording soft-sediment deformation as a result of partial liquefaction of the upper paleosol horizon shortly after burial.

Micromorphologically, the upper paleosol horizon ranges from massive (i.e., well-mixed, with no trace of coherent sedimentary laminae) to very weakly soil-structured and exhibits only moderately birefringent, weakly speckled to very weakly parallel striated birefringence fabrics (Fig. 5A, B). It includes a very few (<5%), 20–1000 μm long aggregates of strongly oriented (unistrial) clay, which are very likely relict fragments of pedoturbated sedimentary laminae (although a few could be fragments of pedogenic clay coatings). Clay aggregates in the upper ~15 cm of the paleosol are pale yellow in plane polarized light (PPL), but those below this level and in subjacent horizons are both yellow and dark reddish (i.e., relatively strongly impregnated with iron oxides, despite the surrounding iron-depleted matrix); this probably indicates that major segregation of iron oxides occurred prior to burial diagenesis (although subsequently this iron must have undergone some diagenetic changes). The lower boundary of the upper horizon is smooth and gradual (~7 cm wide), and marked by distinct, fine to coarse, vermicular mottles.

The middle horizon of the paleosol (~40–70 cm; corresponding approximately to an original Bt horizon) is dusky red to dark red (2.5YR 3/2-4/2) with about 20–30%, irregular, dark gray (N 4/0) mottles. It exhibits weak to strong subangular blocky structure (peds ranging ~100 × 100–1500 × 4000 μm in thin-section), and also weathers in a strong blocky fashion (Fig. 5A). There are very few (<5%), small (2–30 mm), equant, sharp-margined, micritic to finely microsparitic carbonate nodules.

The lowermost horizon (~70–130 cm; originally a Btk horizon) of the paleosol is dusky red to dark reddish brown (2.5YR 3/2-3/4), exhibits strong subangular blocky structure, and likewise weathers in a prominently blocky fashion. There are abundant clay-enriched polished faces along the faces of these blocks and also along vertical fracture planes, (as large as 500 mm^2). There are 15–20%, small (2–30 mm), equant, sharp-margined, micritic to finely microsparitic carbonate nodules, some of which trail off into sheets of fine prismatic spar that coat surrounding peds. Thin sections show that the few very large (up to 9 cm) carbonate "nodules" in the lower part of this horizon are actually weathered fragments of the underlying Ost Limestone.

Missouri River Valley

The basal mudstone and paleosol of the Rakes Creek grades from dominantly reddish westward to greenish gray or light greenish gray (5GY 6/1, 7/1) in the Missouri Valley, as it thins from about 1.2 m at Queen Hill Quarry on the Nebraska side to 0.45 m near Burr Oak, Iowa (Fig. 3B). Here it is relatively unhorizonated (possibly consisting of an Ag and Btg or Bg horizon, now rendered indistinguishable), but still blocky-weathering and

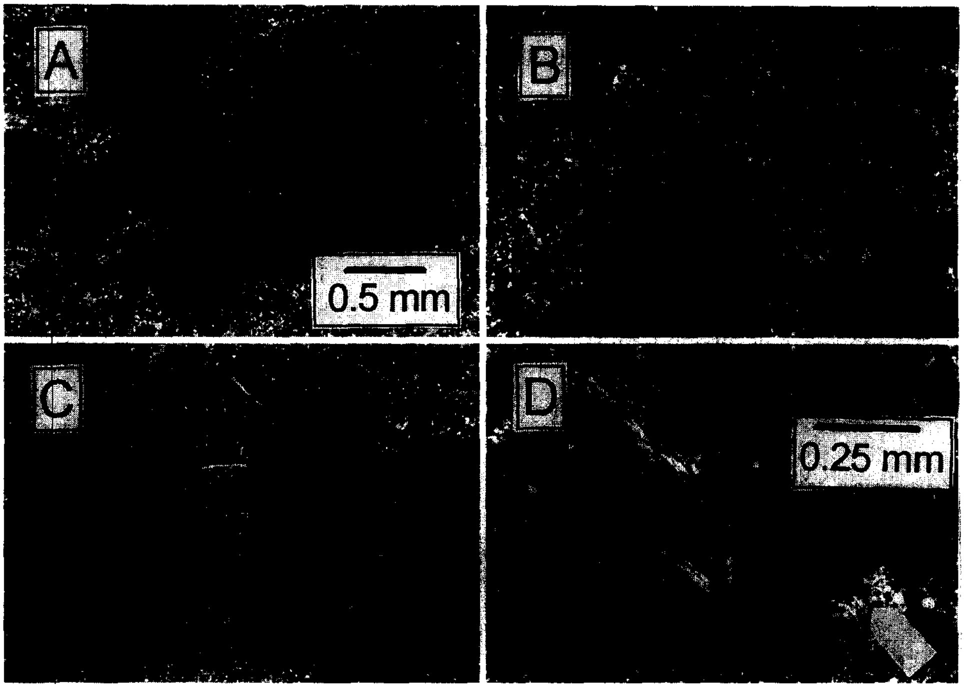


Fig. 5. Micromorphology of basal Rakes Creek paleosol at MMQ. A. Strongly developed soil structure in middle horizon, showing iron oxide-impregnated blocky peds (*p*). B. Massive siltstone of upper horizon of paleosol (note contrast with A); darker areas are unevenly ground parts of thin section. C. Thick clay coating (marked by arrows) along vertical void between iron oxide-impregnated peds. D. Thin coating of clay with strong preferred parallel orientation and layered appearance, apparently around root channel; note distinct termination of feature (arrow). Scales in A, B, C are the same.

showing a few polished faces. The upper 10–20 cm in exhibit platy- to spheroidal weathering.

Forest City Basin, southwestern Iowa

Difficulties in correlation due to facies changes become apparent in Iowa Geological Survey Bureau well cores from near Riverton and Bedford, Iowa. However, the basal Rakes Creek paleosol, by any correlation, is notably absent. The apparently correlative intervals in these cores consist of marine shales.

3.3. Ost Limestone Member

Martin Marietta Quarry and Weeping Water Valley

The Ost Limestone Member in this area underwent regional, immediately post-depositional (Pennsylvanian) weathering: it is readily recognized in the Weeping Water Valley by its well-developed karstic features (Figs. 4A, 6) and tendency to weather yellowish. By Midcontinent Pennsylvanian standards, the development of karstic features in the Ost is extreme, although within the outcrop area, the strongest manifestation of karst is limited to the Weeping Water Valley. Karstic features in the Ost consist of: (1) a pervasive, three-dimensional network of fine microkarst "veins" (silt- and clay-filled cracks, Fig. 4B), which occupy an estimated 10–25% of rock volume; (2) regularly interspersed, vertically-oriented solution pipes (Fig. 4A), locally occupying as much as 10–20% of the volume of the unit; and (3) a few, poorly-defined shallow depressions up to 50 cm deep and 120 cm in diameter. While consistently karstified, the Ost shows greater than twofold variation in thickness (0.8–2 m) over less than a kilometer in the Weeping Water Valley, indicating considerable lateral heterogeneity in the original depositional environment (see discussion of Avoca Limestone Member). In the Weeping Water Valley, the Ost and Avoca members represent pulses of shallow marine carbonate sedimentation. Locally, these phases were not interrupted by major clastic sedimentation and exposure during Kenosha Shale time.

At MMQ, the Ost is a micritic to finely microsparitic, locally peloidal, limestone containing 20–30% marine fossil fragments (brachiopods, fusulinids, bryozoans, echinoderms, ostracods, and molluscs). In older quarry exposures and natural outcrops, relatively unweathered parts of the Ost are white to light gray with strong brown and reddish yellow stains. Zones around and below karst pipes and adjacent to microkarst veins are conspicuously colored in exposures, ranging from very pale brown to yellow, but this coloration is notably absent in well cores. The white to light gray parts of the outcropping Ost are consistently calcite-dominated (< 10% dolomite), whereas the brownish or yellowish parts in exposures contain ~35–75% dolomite. Furthermore, calcitic areas are coherent and well- indurated, but dolomitic areas are soft to friable and earthy. Dolomitization, yellowish color, and softening are associated with proximity to the modern land surface and ongoing surface exposure. Pennsylvanian weathering, however, cannot be dismissed as an ultimate contributing factor because of the very clear geometric relationship between well-weathered, yellowish, dolomitic parts of the Ost and karstic features, particularly solution pipes.

Where it is thickest (~2 m) in exposures at MMQ, the Ost can be subdivided into three horizons, the differentiation of which is presumed to be due mostly to Pennsylvanian weathering. The upper horizon (~80 cm thick) consists of dominantly gray (5Y 6/1), well-indurated, fossiliferous, calcitic, micritic and very finely microsparitic (crystallites ⩽10 μm) limestone. This horizon contains many throughgoing karstic solution pipes. In well cores, this part of the Ost is also finely microsparitic, locally showing partial nodularization, circumgranular cracking (with associated precipitation of clear, equant spar), and evidence for aggrading neomorphism. In outcrops, the upper surface of the Ost as well as zones along karst pipes, are softer, yellow (10YR 8/8), and dolomitic. On further exposure, the upper horizon as a whole weathers into 1–20 cm, subangular to subrounded blocks with intervening, weakly platy-weathering zones.

The middle horizon of the outcropping Ost (~80 cm thick) is dominantly very pale brown (10YR 8/2) and yellow (10YR 8/8), fossiliferous, dolomitic and calcitic, finely (~5–20 μm) microsparitic limestone that weathers friable to moderately indurated. In thin-section, the fabric of this horizon consists of a few, "floating," rounded masses or clots of micrite with diffuse margins (~500–1250 μm wide) grading into progressively coarser dolomitic microspar (indicating aggrading neomorphism). There are many dark reddish brown mudstone-filled veins, and the softest parts of this horizon lie around the basal termini of solution pipes: this relationship seems to verify a partial Pennsylvanian origin for the characteristics of mineralogy and physical resistance, as the karst pipes are definitely Pennsylvanian in age.

The lower horizon (~40 cm) in outcrop is dominated by friable-weathering, earthy, yellow (10YR 7/8) dolomitic, finely microsparitic limestone with 15–30% reddish brown mudstone-filled microkarst veins up to 1 cm wide. In well cores and very fresh quarry exposures, the middle and lower horizons are difficult to distinguish, as both are light gray (~N 7/0), micritic to finely microsparitic limestone with common microkarst and planar to circumgranular cracks infilled with clear, equant spar.

Karstic features. Subvertical to vertical, fine, microkarst veins in the Ost are dominantly ⩽2 mm wide, 50–300 mm long, whereas horizontal veins are mostly ⩽7 mm wide, ⩽200 mm long, and have vertical spacings of 3–15 mm (usually ⩽5 mm). Horizontal veins are generally parallel to bedding, but they also undulate gently and vary in width along their lengths. Both types of veins are locally larger, particularly in the lower part of the Ost (Fig. 4). Most microkarstic features are infilled with dusky red (2.5YR 3/2) calcareous mudstone, a few with gray (5Y 5/1), or greenish gray (5GY 5/1) calcareous mudstone (more common with depth). In thin-section, many infillings have clearly segregated clay laminae (20–250 μm thick) and silt laminae (40–500 μm). Clay laminae are moderately to strongly impregnated with iron oxide and exhibit unit extinction due to strong parallel orientation of clay particles. Thus, the infilling events were discrete in that they brought in suspensions of fully dispersed clay (which sedimented in discrete layers of well-oriented particles) or silt, rather than undispersed sediment.

The solution pipes are irregularly tube-shaped to inverse funnel-shaped (1–30 cm in diameter and 5–90 cm deep). Horizontal spacing ranges from 15 to 70 cm for the larger, continuous pipes. Pipes are usually infilled with dusky red to dark reddish brown (2.5YR 3/2-3/4), calcareous mudstone or breccia, but also (rarely) with gray (5Y 5/1) or greenish gray (5GY 5/1) calcareous mudstone (Fig. 6), particularly at depth, probably indicating a redox boundary associated with water table position. Several pipe infillings are stratified, indicating that the pipes must have remained partially open in a near-surface environment for some length of time, filling incrementally rather than instantaneously. Stratified infillings consist of 2–35 cm layers or lenses of reddish brown (2.5YR 4/4) breccia and 4–12 mm layers of dark reddish brown (2.5YR 3/4) mud dipping up to 10° (Fig. 6).

Breccia layers in karst pipe fills consist mostly of mudstone and limestone fragments (Table 1). The largest limestone fragments contain spar-filled circumgranular and elongate cracks, and irregular tracts of microspar also seen in the host limestone, suggesting that exposure and meteoric alteration of the Ost began before extensive extensive karstification. The breccia matrix appears to be dark reddish brown (2.5YR 3/4) or dark red (2.5YR 3/6) calcareous mudstone in hand specimen, but thin sections show that the it actually consists of deformed, rounded, mudstone aggregates (very likely reworked soil peds) dominantly $\leqslant 500$ µm in diameter. Generally, breccia layers are either moderately sorted and contain only fine (<500 µm) clasts or they are dominated by much larger (>2000 µm) clasts. Weak stratification within breccia layers is indicated by a very strong tendency for prolate limestone clasts to be oriented with their long axes horizontal.

In thin-section, mud layers within karst pipe infillings actually contain as many as twelve 200–6300 µm micro-graded (fining-upward) laminae (Fig. 6). Each lamina consists of a basal layer of coarse silt and/or very fine to medium sand-sized breccia clasts (mudstone, shale or clay, and limestone), grading upward through clayey silt and silty clay, and then into a 30–200 µm layer of pure, strongly oriented clay. Micro-grading in mud laminae probably resulted from sudden introduction of sediment suspensions and subsequent slow settling, possibly after major throughflow events in the vadose zone below the soil solum.

Missouri River Valley

At Burr Oak, Iowa, the Ost is a micritic and finely microsparitic limestone with common, vertical and horizontal cracks infilled with clear, equant spar (producing an overall brecciated appearance).

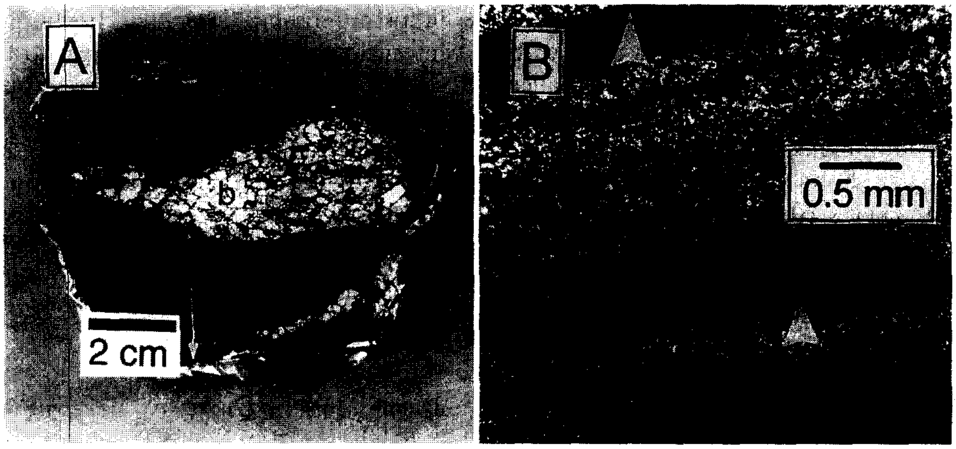


Fig. 6. A. Karst pipe infilling from MMQ. Note limestone breccia lens (*b*) and zone consisting of several bands of fining-upward laminae (arrow). B. Fining-upward laminae from zone within arrow in A. Arrowheads indicate tops of two fining-upward laminae.

Table 1
Clast types in karst pipe breccias within Ost Limestone at Martin Marietta Quarry, Weeping Water, Nebraska

Description of clast type	Size (μm)	Interpreted origin	Range of estimated abundance (%)
Light gray (PPL; 5Y 7/1 or 5GY 7/1 in hand specimen)/very light brown (XPL) mudstone, subrounded, equant-prolate	30 × 50–500 × 10,000	Reworked low-chroma soil peds	10–70
Slightly granular-appearing, dark reddish-brown (2.5YR 3/4 in hand specimen) mudstone matrix	10 × 20–300 × 600 (individual granules)	Deformed (crushed) reworked, high-chroma soil granules	30–65
Light gray (PPL; 2.5Y 7/4 in hand specimen)/light brownish gray micrite and fine microspar (weathered) or fossiliferous micrite; mostly subrounded, prolate; largest fragments are rounded, equant	70 × 100–3000 × 7000	Fragments from surrounding, synchronously weathered Ost Ls.	20–50
Slightly abraded marine fossil fragments	<2000	Dissolved out of surrounding Ost Ls.	⩽5
Very well-oriented (showing sweeping extinction) reddish brown or pale yellow clay; rounded, equant-prolate	10 × 20–200 × 250	Fragments of relict sedimentary clay laminae or of soil argillans (less likely)	<5
Reddish brown stratified clay and/or silty clay and/or silt; subrounded-rounded, prolate	50 × 250–250 × 3500	Fragments of relict sedimentary laminae (shale fragments)	<5

Microkarst "veins" persist in Missouri Valley exposures of the Ost, but they are infilled exclusively with light grayish green (5GY 7/1) mud. Vertical karst pipes, also infilled exclusively with light grayish green mud, are also much smaller (0.5–2 × 7–20 cm) than at MMQ, and also lack clearly stratified infillings. Within the Missouri Valley, the Ost shows greater than fourfold variation in thickness (0.45–2.3 m: Condra and Reed, 1938; R. Burchett, University of Nebraska Conservation and Survey Division, IANR, pers. comm.).

Forest City Basin, southwestern Iowa

The Ost is very difficult to differentiate in the cores from near Riverton and Bedford, Iowa, whereas Oskaloosa and Ozawkie members, as well as the Larsh and Queen Hill black "core" shales above and below, are readily identifiable. Thus, it is possible to determine approximately correlative lithostratigraphic intervals. In both cases, the interval approximately equivalent to the Ost consists of gray, calcareous to very strongly calcareous, fossiliferous shale, possibly including a thin calcilutite in the Bedford, Iowa core (see description of Avoca limestone). There is no evidence of any subaerial exposure within or above the marine shale intervals: the Bedford core calcilutite has microkarst, but there is no paleosol above it.

3.4. Kenosha Shale Member

Martin Marietta Quarry and Weeping Water Valley

At the Martin Mariette quarry, the Kenosha Shale (~30–50 cm thick) is weakly distinguished from the Ost and Avoca limestone members above and below, essentially grading between the two. It is a pale red (2.5YR 6/2), thinly (2–3 mm) and crudely laminated, fossiliferous (many crinoid fragments and brachiopods), shaly calcilutite or strongly calcareous shale. The unit underwent strong weathering during the Late Pennsylvanian, indicated by the many fine (≤2 mm wide) microkarstic veins, infilled with dusky red (2.5YR 3/2) mudstone.

The Kenosha shows considerable lateral variation, just as does the Ost Limestone Member. In the Weeping Water area it varies from the very strongly calcareous, microkarstified marine shale previously described to a 1 m+, reddish brown, massive, terrigenous mudstone over a distance of less than 0.5 km. Where the Kenosha is a terrigenous mudstone, evidence suggests that there was a discrete period of weak pedogenesis after its deposition and before the deposition of the overlying Ost Limestone (hence also before development of the basal Rakes Creek paleosol). Where the Kenosha is a calcareous, shaly unit gradational between overlying and underlying carbonates, microkarst appears to extend uninterrupted from the Ost to the Avoca. Thus, weathering during Rakes Creek time very probably overprinted earlier pedogenic signatures in the underlying Kenosha and Avoca members, resulting in a welded weathering profile.

Missouri Valley

Now very poorly exposed in this area, earlier workers (Condra, 1930, p. 32; Condra and Reed, 1938, p. 10; R. Burchett, Conservation and Survey Division, University of Nebraska–Lincoln; pers. comm.) described the Kenosha as a 1.8–2.3 m reddish brown and greenish gray mudstone on the Nebraska side of the valley. By inference from certain exposures and well cores in the Weeping Water area, this mudstone is likely to have shown at least some pedogenic features. Eastward at Burr Oak, Iowa, the Kenosha is a 40 cm, light greenish gray (5GY 7/1) massive mudstone. The variations in the thickness and character of the Kenosha from the Weeping Water Valley to the Missouri Valley underscore the complex history of repetitive deposition and pedogenesis in the Beil-Rock Bluff interval.

Forest City Basin, southwestern Iowa

The Kenosha cannot readily be identified in the Riverton and Bedford cores, due to difficulty in correlating the Ost and Avoca limestones.

3.5. Avoca Limestone Member

Weeping Water Valley

Where thickest in exposures at the MMQ, the Avoca Limestone consists of (in stratigraphic order): (1) A 50 cm, reddish gray (10R 6/1) dense, fossiliferous calcilutite containing about 10-20% fine microkarst veins infilled with reddish brown (2.5YR 4/3) mudstone; (2) An 8 cm, gray (N 6/0 or 5Y 6/1), calcareous shale containing 10–15% microkarst veins infilled with reddish brown (2.5YR 5/3) mudstone; and (3) a 27 cm, light gray (10YR 7/2) calcilutite with very weak microkarstic features, grading downward into light gray and pale red (2.5YR 6/2) shaly calcilutite. Overall, the Avoca Limestone weathers yellow (2.5Y 7/6) and parts of it become very friable like the Ost Limestone. Over less than 50 m at MMQ, the Avoca thins to as little as 40 cm and changes in lithologic composition as well. In one face exposed temporarily at MMQ, both the Ost and the Avoca filled a shallow depression with a lower surface sloping about 2°. This depression was incised into the underlying King Hill Member, and both the Ost and Avoca members thinned from its axis outward. Common depressions of this sort, possibly ravinements produced during the Avoca transgression, probably explain Ost-Avoca variability as a whole.

Missouri Valley and Forest City Basin, southwestern Iowa

The Avoca does not contain karstic features in any known Missouri Valley exposures, and it is difficult to differentiate in the Riverton and Bedford, Iowa cores. It is probably represented by a fossiliferous, calcareous shale in the Riverton core and by microkarsted, light gray (5Y 7/2) calcilutite in the Bedford core. Actually, there are two calcilutites (41 cm and 66 cm thick), separated by a 38 cm greenish gray (5Y 6/1) mudstone, in the Bedford core. The upper calcilutite could be correlative with the Ost Limestone of the Weeping

Water Valley in Nebraska. The microkarst in the Bedford core may thus represent an exposure event at least partially coeval with the Weeping Water weathering profile in Nebraska.

4. Paleosol micromorphology: clay segregations

Clay segregations are common and in the basal Rakes Creek paleosol in the Weping Water Valley (Fig. 5C, D). Observations polled from soil scientists called attention to the similarity of these 290 Ma features to clay coatings in modern soils and Late Pleistocene paleosols. While some of the basal Rakes Creek paleosol clay segregations are very clearly fabric elements produced by stress orientation, many likely had an illuvial origin. The following features are characteristic of this probable illuvial clay (PIC), and were used as criteria for its identification: (1) sharp boundaries with adjacent matrix, (2) position along the walls of infilled voids, (3) thickness generally >50 μm (up to ~400 μm thick), (4) lateral continuity (up to 7000 μm long), (5) strong preferred parallel orientation, and (6) vaguely layered appearance. PIC color is light reddish brown or very light reddish yellow (PPL) and reddish yellow or yellow (XPL). Assuming that PIC is in fact pedogenic, the occurrence of yellowish PIC with very little or no iron oxide impregnation, frequently amidst soil material that is iron oxide impregnated to various degrees, again suggests that much segregation of iron oxides took place before burial diagenesis, even before the cessation of pedogenesis (possibly even in the parent material before pedogenesis). PIC bodies are elongate coatings along what appear to be former root voids and digitate vugs, which appear to have been situated between adjacent peds in the original soil. While the clay itself is assumed to have been physically translocated from an upper horizon, it could also be neoformed clay (i.e., newly precipitated in-situ).

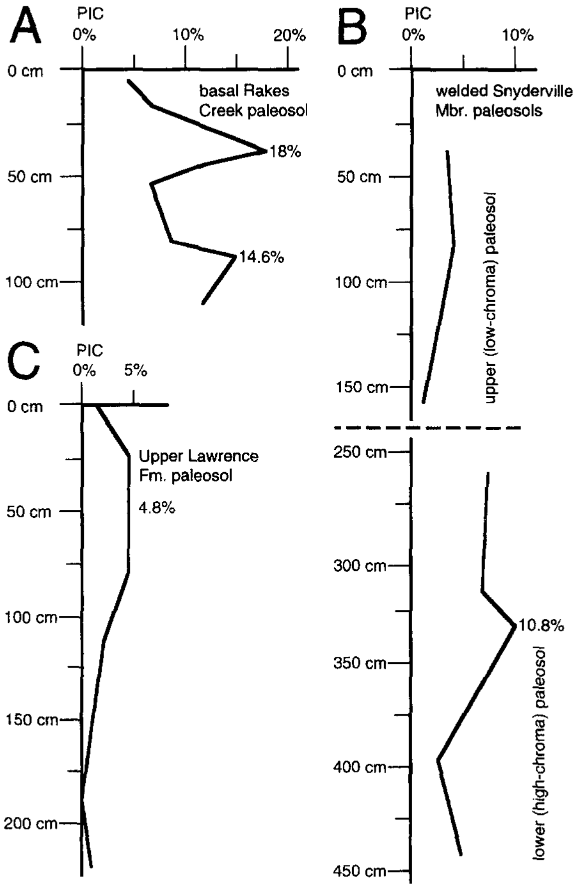


Fig. 7. Probable illuvial clay (PIC) percentages estimated from 500 counts per thin section: basal Rakes Creek paleosol at MMQ (A), welded Snyderville Member paleosols at locality SB in Fig. 2 (B), and upper Lawrence paleosol at locality SB (C). Note apparent relative abundance of PIC in basal Rakes Creek paleosol.

Point-counts show that PIC ranges up to 18% in the basal Rakes Creek paleosol, as opposed to a maximum of ~5% in the upper Lawrence Formation paleosol and ~10% in the Snyderville Member paleosols down-section but in the same geographic area (Fig. 7). The estimates for the upper Lawrence and Snyderville paleosols may actually be somewhat inflated, as PIC features are less prominent than in the basal Rakes Creek paleosol, leading to a tendency to relax distinguishing criteria somewhat in counting.

5. Discussion

5.1. Weathering profile genesis and burial

The Weeping Water weathering profile indicates a substantial period of exposure and water-table depression in the Weeping Water Valley region of southeastern Nebraska during marine regression at the close of the Ost minor depositional cycle. As basal Rakes Creek paleosol and Ost karst features appear to be continuous, the most parsimonious hypothesis regarding their genesis is that there was a single episode of exposure and weathering during early Rakes Creek time that produced both. The resulting weathering profile, however, eventually incorporated what appear to be pre-Rakes Creek weathering features in the Kenosha and Avoca members. During the early Rakes Creek pedogenic episode, the development of relatively strong soil structure and the intra-profile movement of clay were prominent processes in the development of the basal Rakes Creek soil, as was karstic carbonate dissolution and meteoric diagenesis simultaneously in the underlying Ost Limestone. Eastward, subaerial exposure was briefer or, locally, never initiated.

Soil development in early Rakes Creek time was truncated by the deposition of the overlying silty sand. The overall eastward fining in the Rakes Creek-Oskaloosa interval and the westward thinning of the Ozawkie Limestone Member possibly indicate a western and/or northern component in the source for this silty sand, but its depositional environment is unclear. Presumably, this silty sand represents the first phase of deposition associated with rising sea level at the onset of the succeeding Deer Creek marine cycle. Fagerstrom and Burchett (1972) interpreted it as a deltaic deposit, but currently available data indicate nothing particularly diagnostic in its geometry and sedimentary characteristics. Alternating thin mud and silt or sand laminae in the lower Rakes Creek–Oskaloosa interval at Weeping Water, Nebraska and in the Oskaloosa Member at Queen Hill Quarry in the Missouri Valley are compatible with (but by no means diagnostic of) marine tidal influence. Brachiopods in the uppermost 50 cm of the Rakes Creek–Oskaloosa interval in the Weeping Water area definitely indicate marine influence by at least the end of Rakes Creek–Oskaloosa time.

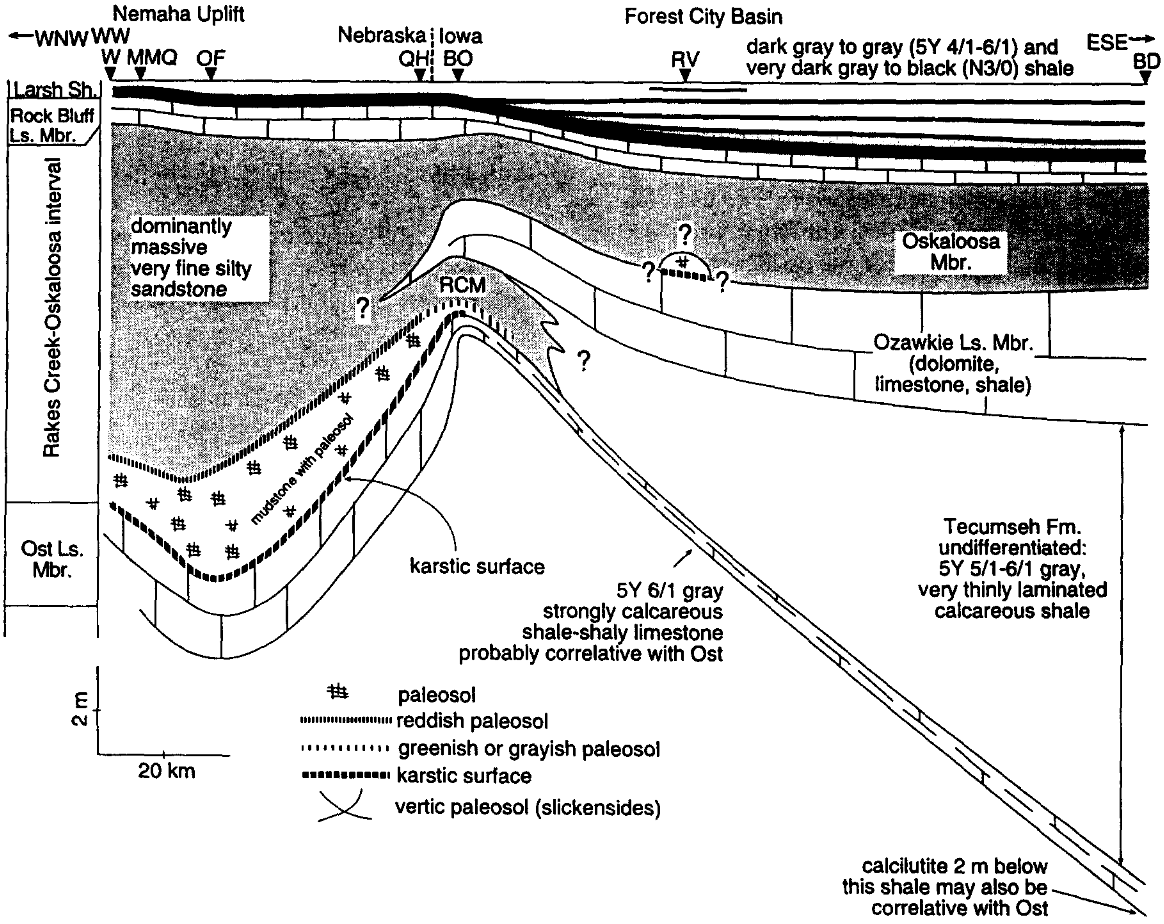
5.2. Comparative paleopedology

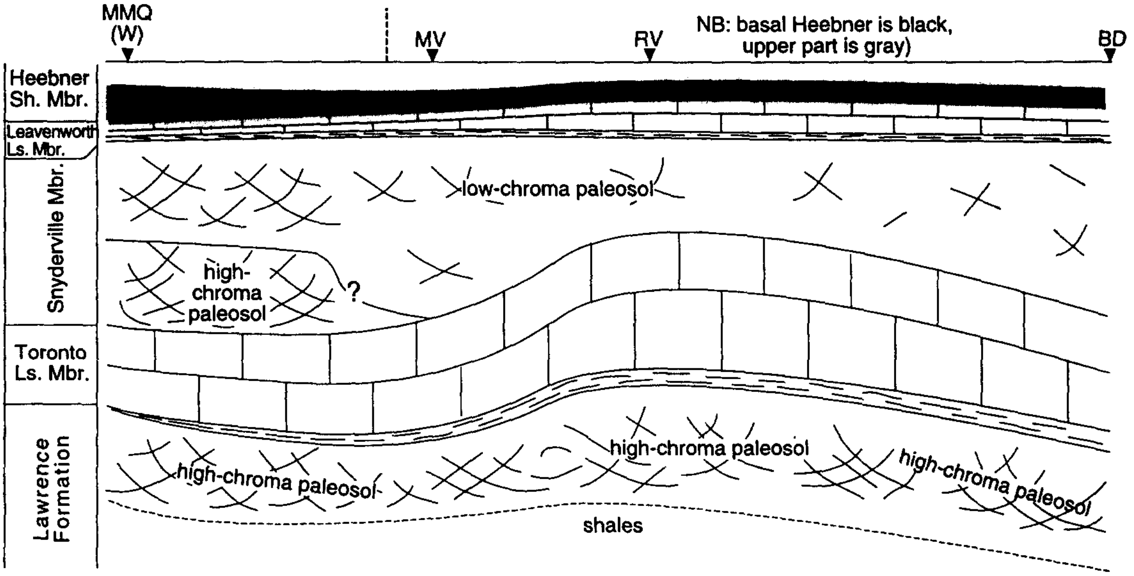
Comparison of the basal Rakes Creek paleosol to other Virgilian (Stephanian) paleosols in the same area reveals temporal variation in tectonism, sea-level cycles, and climate. There are significant morphological differences between the basal Rakes Creek paleosol and the next two well-documented major paleosol intervals down-section, the Vertisol-like Snyderville and upper Lawrence paleosols (Joeckel, 1993, in press). These differences appear at single-exposure to regional scales.

The upper Lawrence paleosol is essentially uniform across the study area (Figs. 2, 8). The Snyderville is similarly widespread, but shows west–east lateral variation, and whereas the upper Lawrence paleosol is developed in the upper part of a thick shale, the Snyderville paleosol lies atop the karstified Toronto Limestone Member (Joeckel, 1993, in press). Nonetheless, both of the upper Lawrence and Snyderville paleosols (1) have prominent sets of intersecting, very large slickensides, (2) lack strongly fine to medium blocky-weathering subsoil horizons with concentrations of carbonate nodules in discrete horizons, and (3) contain relatively few PIC features.

In contrast, the basal Rakes Creek paleosol exhibits: (1) pronounced west–east lateral variation (Fig. 8), including its eventual eastward disappearance; (2) strongly fine to medium blocky-weathering subsoil horizons, and consistent strong soil structure in thin-section; (3) common carbonate nodules (some are actually lithorelicts from the underlying limestone), which are concentrated in the subsoil; (4) relatively common PIC features; and (5) more strongly developed underlying karst (the Ost-Kenosha-Avoca karst is locally almost 3 m deep, but the Toronto karst is less than 1 m deep.

The Rakes Creek, upper Lawrence, and Snyderville paleosols all developed on depositional landscapes in the same subregion of a low-gradient cratonic basin within a comparatively short interval of time. The differences between these paleosols could be due to: (1) the timing, extent, and geographic origin of major influxes of clastic sediment; (2) rates and magnitudes of sea-level change (Heckel, 1980, 1986, 1991); (3) syndepositional tectonism or compaction (Fagerstrom and Burchett, 1972; Gay, 1989), and (4) climatic change (Cecil, 1990), probably linked with sea level change. Thus, explanatory hypotheses can be formulated to explain differences in both regional


Nemaha Uplift
←WNW WW
W MMQ OF
Nebraska Iowa
QH BO
Forest City Basin
RV
dark gray to gray (5Y 4/1-6/1) and very dark gray to black (N3/0) shale
ESE→
BD
Larsh Sh.
Rock Bluff Ls. Mbr.
Rakes Creek-Oskaloosa interval
Ost Ls. Mbr.
dominantly massive very fine silty sandstone
RCM
?
mudstone with paleosol
Oskaloosa Mbr.
Ozawkie Ls. Mbr. (dolomite, limestone, shale)
karstic surface
5Y 6/1 gray strongly calcareous shale-shaly limestone probably correlative with Ost
Tecumseh Fm. undifferentiated: 5Y 5/1-6/1 gray, very thinly laminated calcareous shale
2 m
20 km
paleosol
reddish paleosol
greenish or grayish paleosol
karstic surface
vertic paleosol (slickensides)
calcilutite 2 m below this shale may also be correlative with Ost


MMQ (W)
MV
RV
NB: basal Heebner is black, upper part is gray)
BD
Heebner Sh. Mbr.
Leavenworth Ls. Mbr.
Snyderville Mbr.
Toronto Ls. Mbr.
Lawrence Formation
low-chroma paleosol
high-chroma paleosol
?
high-chroma paleosol
high-chroma paleosol
high-chroma paleosol
shales

variability and general pedologic characteristics between the Rakes Creek and upper Lawrence and Snyderville paleosols.

5.3. Tectonism and eustasy

In this study, it is particularly noteworthy that the basal Rakes Creek paleosol is laterally variable and that it disappears eastward into the Forest City Basin. In comparison, the Snyderville paleosol is laterally variable but continuous eastward and the upper Lawrence paleosol is both continuous eastward and relatively invariable. The variability and disappearance in the basal Rakes Creek paleosol indicates an eastward decrease in original elevation and incomplete subaerial exposure of the Forest City Basin during the post-Ost regression. Three factors could account for this regional phenomenon: (1) active uplift of the Nehawka Arch during Rakes Creek time, (2) an increased differential in compactional subsidence across the Nemaha Uplift and Forest City Basin in Rakes Creek time relative to upper Lawrence-Snyderville time, and (3) a weak post-Ost regression that exposed only the Weeping Water, Nebraska-Burr Oak, Iowa area, versus region-wide exposure during upper Lawrence and Snyderville times (Figs. 8, 9). Evaluating the potential effects of these three factors on basal Rakes Creek soil development is difficult.

According to Chamberlain and Lemish (1980), the Forest City Basin formed at the close of the Mississippian, but minor tectonic activity in the form of minor faulting and gentle folding, continued, and even gradually increased, through the Pennsylvanian. Earlier workers (Fagerstrom and Burchett, 1972), concluded that active (but subtle) tectonism influenced the appearance and migration of facies tracts during Rakes Creek time. The strong development of Ost-Kenosha-Avoca karst westward from the margin of the Forest City Basin and the apparently continuous, though slight, eastward thickening overlying highstand deposits (Larsh Shale) lend some credence to this hypothesis, although unit thickening could also be due to greater syndepositional compactional subsidence. The thicknesses of the Queen Hill-Larsh and Heebner-Queen Hill intervals, however, actually decrease at the western margin of the Forest City Basin (near the Nebraska–Iowa line) relative to sections both east- and westward (Figs. 8, 9). The basal Rakes Creek paleosol is a low-chroma paleosol in this area of thinning, though, most likely indicating that it was originally topographically lower than areas to the west (where a well-horizonated, high-chroma paleosol persists), yet higher than areas to the east (where no paleosol is present). This thinning of units at the western margin of the basin is thus somewhat contradictory to facies distributions and paleosol characteristics. This thinning may due to enhanced gravitational compaction over a pre-existing structure, which has been documented elsewhere in Midcontinent U.S.A., most notably on the Nemaha Uplift in eastern Kansas (Gay, 1989). Nonetheless, evidence for differential compaction is much less clear in the underlying interval (Figs. 8, 9A,C,D), which should show a matching trend. Some form of sediment bypass may have taken place at the margin of the Forest City Basin, but this scenario seems unlikely given the spatial scale involved. In the end, a hypothesis of subtle tectonism cannot be rejected, but the overall structural effects (including both tectonism and differential compaction) on Late Pennsylvanian cyclothem deposition and pedogenesis are clearly complicated.

Heckel (1986), on the other hand, illustrates differing magnitudes of Midcontinent sea-level cycles during the Late Pennsylvanian and the effect of cycle magnitude on the distribution of facies. The Ost and Avoca sea-level cycles were not major cycles and the regressions associated with them did not completely expose the study area. The post-Snyderville Heebner cycle, however, is considered a major cycle in Heckel's (1986) scheme.

Fig. 8. Interpretative cross-sections of intervals bearing the Weeping Water weathering profile, including the basal Rakes Creek paleosol (above), and the upper Lawrence and Snyderville paleosols (below). Datum in each case is the top of the overlying black phosphatic ("core") shale (see Heckel, 1991). Note stronger west–east variablity in paleosol and associated units in Rakes Creek–Oskaloosa interval.

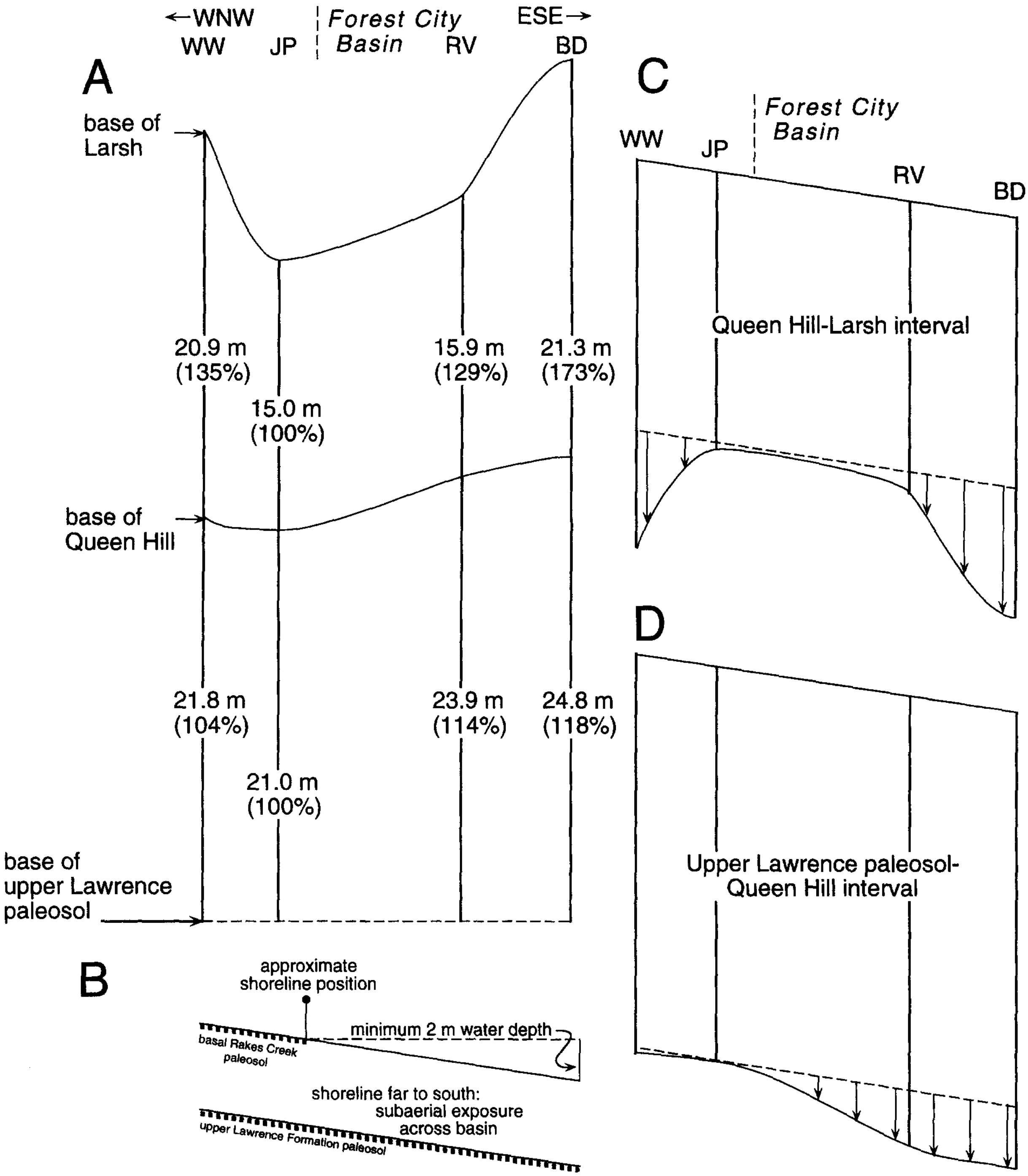


Fig. 9. Thickness variation in key intervals across the study area, interpreted as product of differential tectonism. (A) Simple thickness diagram using base of upper Lawrence paleosol as datum (see Fig. 1), with percentages relative to minimum thickness for each interval. Upper Lawrence paleosol–Queen Hill interval is more uniform in thickness (21.8–21.0–23.9–24. 8 m, with maximum only 118% of minimum) than Queen Hill–Larsh interval. Weeping Water section (*WW*) is composite of MMQ exposures and well drilled on site in May, 1994; Jones Point section (*JP*) is composite Jones Point–Plattsmouth, Nebraska section from Condra and

Some eustatic effect on soil–landscape development must be accepted, given the bulk of data supporting a eustatic mechanism for Midcontinent cyclothem deposition.

5.4. Paleoclimate

The contrast in general pedologic features between the Rakes Creek and upper Lawrence and Snyderville paleosols cannot simply be a matter of intrabasinal gradients and landscape position because the characteristics of the three paleosols are consistent. Strong vertic features do not appear in any basal Rakes Creek profile, and there are no upper Lawrence or Snyderville profiles with characteristics like the basal Rakes Creek paleosol. There is something of a parallel in the perceived evolutionary sequence of Vertisols and vertic Alfisols on modern landscapes (Dudal and Eswaran, 1988), which probably has a subtle climatic control, namely slight oscillations between more seasonal and less seasonal subhumid climates. Cecil (1990) has already suggested Late Pennsylvanian oscillations between humid subtropical and semiarid climates in the Appalachian Basin, which was positioned near the paleoequator (Fig. 2). The area examined in the current study would have been at a higher latitude than the Appalachian Basin (Fig. 2), and therefore may have been subject to even more intense climate cycles. Therefore, I hypothesize that the transition from Vertisol-like soils (upper Lawrence and Snyderville paleosols) to more "Alfisol-like" paleosols (basal Rakes Creek) resulted from a trend from more seasonal to less seasonal rainfall, and possibly a trend towards increased annual rainfall as well.

Currently, there is no evidence for truly extreme climatic changes in the upper Douglas and lower Shawnee groups of the northern Midcontinent. Coals in this interval, more common southward in Kansas, are thin and their distribution appears to be determined by local drainage conditions rather than paleoclimate. Clay mineral assemblages of the paleosols are highly similar: illite- and chlorite-dominated, with minor kaolinite. Such assemblages have been considered both original/detrital (e.g., Schutter, 1983) and diagenetic by different authors. Attempts at determining illite polytypes, in order to assay the potential effects of diagenetic illitization of hypothetical original smectite, have so far been inconclusive. However, in both the Rakes Creek sandstone and the basal Rakes Creek paleosol, scanning electron microscopy shows abundant partially dissolved feldspar grains—a potential source of K^+ ions for the illite–smectite transition. Thus, there is a significant possibility that the illite-dominated clay mineral assemblage in the basal Rakes Creek paleosol as well as other Midcontinent Upper Pennsylvanian paleosols, was originally smectitic, and probably more or less uniform through time.

The hypothesized climatic shift interpreted from paleosols is compatible with larger-scale trends. In the Appalachian Basin, Cecil (1990) interpreted the Missourian–Virgilian climate trend as an early peak in climatic drying followed by a return to slightly wetter, but oscillating, climates in the Virgilian. The overall trend in Midcontinent Pennsylvanian paleoclimate has not yet been evaluated in anything approaching the same comprehensive manner, yet regional stratigraphic trends provide the means for such an evaluation. In the Waubaunsee Group of southeastern Nebraska and

Reed (1938). (B) Basal Rakes Creek paleosol and upper Lawrence paleosol landscapes reconstructed with basinward slopes of 2 inches/mile (0.032 m/km) as calculated by Fagerstrom and Burchett (1972) from dimensions of Ozawkie Limestone stromatolites. Rakes Creek shoreline, where basal Rakes Creek paleosol disappears, is placed just east of Missouri River Valley. Minimum water depth basinward at Bedford, Iowa would have been 2 m. Upper Lawrence landscape, in contrast, was exposed subaerially basinwide (shoreline was probably far south in Oklahoma, see Joeckel, 1993), indicating much greater eustatic effect on soil development. (C) Reconstructed Queen Hill-Larsh interval, given maintenance of a 0.032 m/km basinal slope throughout deposition. Dotted line represents hypothetical constant subsidence and equal deposition across basin. Solid line below dotted line represents actual sediment thickness measured downward from hypothetical basin slope; downward-pointing arrows indicate potential greater subsidence or, in WW-JP area, filling of accommodation space by Rakes Creek–Oskaloosa clastic wedge. (D) Diagram for upper Lawrence paleosol–Queen Hill interval constructed in same manner as C. Note gradual increase in subsidence basinward and less differential subsidence relative to C.

adjacent areas (Fig. 1), coals and sands are far more common and limestones are thinner and less numerous than in the underlying Shawnee and Douglas groups, and, for that matter, the Lansing and Kansas City groups as well (Burchett and Reed, 1967; Burchett, 1977). This pattern in the vertical distribution of facies can logically be interpreted as the product of an overall shift towards wetter climates towards the end of the Pennsylvanian, probably beginning in Shawnee Group time. Further data will be needed to test and refine this hypothesis.

6. Summary and conclusions

(1) Paleosol and karst features, intensely developed relative to other Midcontinent Pennsylvanian subaerial exposure surfaces, indicate that there was prolonged subaerial exposure, high elevation relative to areas eastward, and a relatively marked drop in water table west of the Forest City Basin margin in southeastern Nebraska (particularly in the Weeping Water Valley) during Rakes Creek time. Intermittent very shallow marine conditions and subaerial exposure had dominated since at least the time of King Hill deposition, leading to the production of a complex weathering profile in mudstones, calcareous shales, and limestones.

(2) Eastward on the margin of the Forest City Basin, the basal Rakes Creek paleosol developed under conditions of lower landscape position and higher water table; both the paleosol and the underlying karst are less well developed than they are westward, probably indicating a diminished period of subaerial exposure as well. Farther eastward into the basin, the basal Rakes Creek paleosol disappears, although correlative karst may be present locally.

(3) The west–east differential in the Weeping Water weathering profile must be a result of areally limited, eustatically-controlled subaerial exposure enhanced by subtle tectonism. Intense karst development in the Ost Limestone confined to a relatively small area of southeastern Nebraska contrasts with less intense, but more widespread, karst in the Toronto Limestone below and more widespread paleosol development in both the upper Lawrence Formation and the Snyderville Shale (which, in both cases, resulted from very widespread marine regressions). Relatively weaker eustatic control and possible tectonism explain the localization of the basal Rakes Creek paleosol and the very strongly developed karst underneath it. The differential in the thickness of the Queen Hill-Larsh interval relative to the upper Lawrence paleosol-Queen Hill interval, and the west–east facies variation in the Rakes Creek-Oskaloosa interval are compatible with changing patterns of syndepositional tectonism.

(4) The difference between Vertisol-like paleosols down-section and the more "Alfisol-like" basal Rakes Creek paleosol is related to slight shifts in paleoclimate, probably a shift from more seasonal to more uniform rainfall. Changes in paleosol characteristics and facies distributions in the Upper Pennsylvanian of the Midcontinent provide a means for interpreting large-scale paleoclimate trends.

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