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Virgilian (Upper Pennsylvanian) Paleosols in the Upper Lawrence Formation (Douglas Group) and in the Snyderville Shale Member (Shawnee Group, Oread Formation) of the Northern Midcontinent, U.S.A.: Pedologic Contrasts in a Cyclothem Sequence

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VIRGILIAN (UPPER PENNSYLVANIAN) PALEOSOLS IN THE UPPER LAWRENCE FORMATION (DOUGLAS GROUP) AND IN THE SNYDERVILLE SHALE MEMBER (OREAD FORMATION, SHAWNEE GROUP) OF THE NORTHERN MIDCONTINENT, USA: PEDOLOGIC CONTRASTS IN A CYCLOTHEM SEQUENCE

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ABSTRACT: **Paleosols in the upper Lawrence Formation and in the Snyderville Shale Member (Virgilian) extend over an estimated area of over 14,000 km² in Nebraska, Iowa, Missouri, and Kansas. These paleosols, both within cyclothems, are: (1) critical indicators of nearly basin wide emergence (peak regression of the Midcontinent seaway) and geomorphic stability, and (2) useful stratigraphic markers. Both paleosols appear to be analogous to modern Vertisols: they have nested, synformal-antiformal sets (~ 4-10 m wide) of very large, intersecting slickensides. Also, some profiles of the upper Lawrence paleosol also have filled cracks extending to depths of 100+ cm. There are, however, significant differences between the paleosols: high-chroma coloration, strong preserved soil structure, and small iron oxide nodules (upper Lawrence) versus dominantly low-chroma coloration, weak to very weak preserved soil structure, and pyrite segregations (Snyderville). After a period of widespread subaerial exposure, each paleosol was drowned and slightly eroded by a marine transgression.**

The upper Lawrence shows a single paleosol across the study area. The paleosol is thickest and best-developed shelfward (northward) and shows topohydrosequence variation at two basinward localities in northeastern Kansas. Stratigraphic trends suggest an appreciable time differential in the south-to-north migration of the Toronto transgression. The Snyderville shows two welded paleosols in southeastern Nebraska and a single one elsewhere in the study area. Elsewhere in the Snyderville, there is local evidence for lowstand incision of streams and small lows that underwent little or no subaerial exposure. Snyderville paleogeography and pedogenesis, however, were markedly different from upper Lawrence paleogeography and pedogenesis. Contrasts between the two paleosols are likely to be related to intercycle changes in geomorphic conditions (driven by patterns of sedimentation, eustasy, and tectonics) and climate.

INTRODUCTION

The upper Lawrence Formation and the Snyderville Shale Member (Upper Pennsylvanian, Virgilian, Midcontinent, USA) provide an excellent opportunity to apply the interpretive utility of paleosols to cratonic cyclothems, particularly because they are parts of two closely successive cycles. Persistent marine units in the same succession (Figs. 1, 2) supply stratigraphic control across 450+ km and permit the placement of events, including pedogenesis, on an interpretive sea-level curve (Ball 1964; Toomey 1964; Burchett and Reed 1967; Troell 1969; Rascoe 1978; Heckel 1986).

The current state of knowledge of several late Missourian–Virgilian paleosols in the northern Midcontinent suggests that the upper Lawrence and Snyderville paleosols are the most prominent. They are readily traceable for ~ 150 km west-east and > 250 km north-south (to Waverly, Kansas, Locality 18: Figs. 2–4). Potentially correlative paleosols appear in scattered outcrops yet farther south (Fig. 2, Localities 19–22).

STRUCTURAL SETTING AND GENERAL STRATIGRAPHY

The Late Pennsylvanian Midcontinent basin consisted of the rapidly subsiding, clastic-dominated foreland basin of the Ouachita-Arbuckle orogenic belt (south-central Oklahoma) and a vast, carbonate-rich cratonic shelf extending north and west. The effects of major fluvial-deltaic systems (draining the orogenic belt—the main source of Douglas and Shawnee group clastics) and subsidence on Lawrence-Snyderville deposition become more apparent southward across eastern Kansas, where both units thicken and coarsen (Ball 1964; Toomey 1964; Troell 1969; Adler et al. 1971; Prichard 1975; Rascoe 1978). Subtle tectonism around the northern end of the Nemaha Uplift in southeastern Nebraska (Fig. 2) appears to have had local influence on sedimentation (Condra and Reed 1938; Adler et al. 1971; Fagerstrom and Burchett 1972) and pedogenesis (see Joeckel 1989).

The Lawrence Formation is a thick interval of shales, mudstones, and sands, locally containing a marine limestone (Amazonia Limestone Member; see Howe and Koenig 1961). Total thickness ranges from 5 m in Nebraska (Locality 1) to ~ 70 m at the Kansas-Oklahoma line (Ball 1964, fig. 4). The upper Lawrence Formation (the 2–3 m interval directly below the Toronto Limestone Member) typically contains a single paleosol developed in dominantly reddish mudstones (Figs. 3, 4). There is a < 1–10 cm gradation between the parent laminated mud shale and the overlying, massive, paleosol mudstone. In the northernmost localities, 0–170 cm of mud shale with very thin laminae or lenses of silt directly overlie the upper Lawrence paleosol (Figs. 3, 4). This unit represents marginal-marine conditions at the onset of the Toronto transgression (see Ball 1964, p. 252). In northeastern Kansas (Fig. 4; Localities 10–13), sediments between the Toronto and the upper Lawrence paleosol thicken to 3–6 m of thinly laminated very fine sandstone and shale (interpreted as tidally influenced sediments by Garbish et al. 1991). The paleosol beneath these thicker sediments is stratigraphically equivalent to the paleosol overlain only by the thin shale or mudstone farther north, although some north-south diachrony is certain.

In the northeastern Kansas and northward, the Snyderville Shale Member is a 2–6 m interval of dominantly grayish and greenish mudstone and siltstone. In far southern Kansas, it thickens to up to 25 m (Moore 1935) and turns dominantly reddish (Localities 19–22, Fig. 2). In southwestern Iowa, northwestern Missouri, and northeastern Kansas, the Snyderville usually contains a single paleosol underlain by the karstified Toronto Limestone. Direct observations (Localities 1, 3; Fig. 3) combined with interpretations of earlier descriptions (Condra 1927, 1930; Condra and Scherer 1939) indicate that two partially welded paleosols (an upper low-chroma paleosol and a lower high-chroma one) are developed in the slightly thicker Snyderville in southeastern Nebraska. Across the entire study area, the Snyderville paleosol(s) is usually overlain by a 3–75 cm grayish or greenish, marginal-marine shale with sharp upper and lower contacts.

The < 2 μm fraction in Lawrence and Snyderville paleosols and shales is uniformly dominated by illite and lesser chlorite (with minor kaolinite): it may have originally been smectite-rich, but evidence for widespread diagenetic illitization is equivocal. At a few localities there is a very slight broadening of illite {001} peaks up-profile that could be interpreted as pedogenic weathering of an original (detrital rather than diagenetic) illite-

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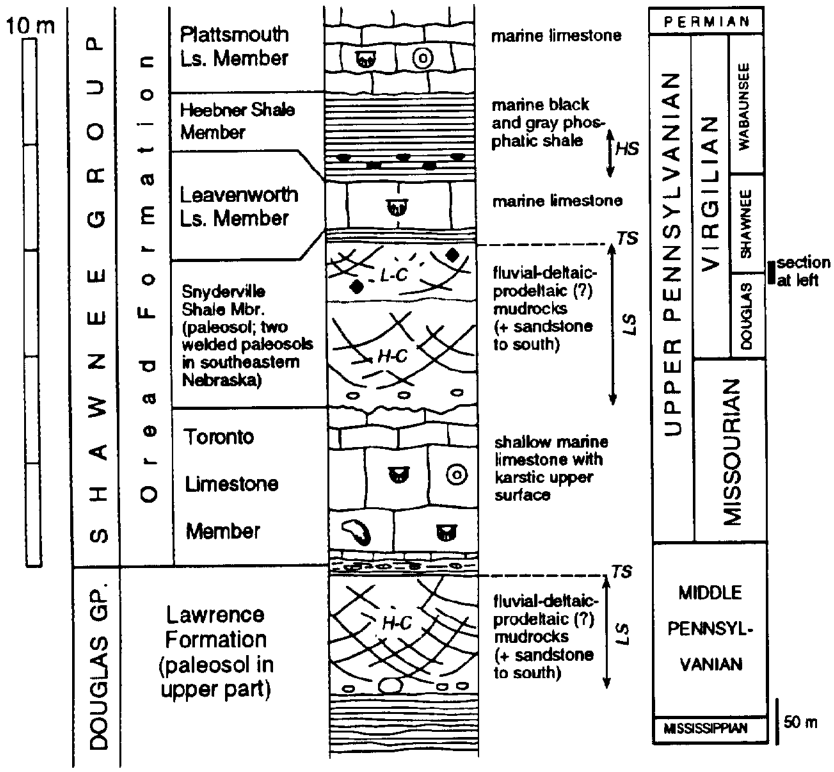

FIG. 1.—Stratigraphic section of the upper Douglas and lower Shawnee groups in northern shelf area of northern Midcontinent, U.S.A. (partially after Ball 1964; Burchett and Reed 1967; Troell 1969) Paleosols are developed in the upper part of the Lawrence Formation and in the Snyderville Shale Member. Marine transgressive surfaces lie atop each paleosol. Marine sediments in the Toronto, Leavenworth, Heebner, and Plattsmouth members are laterally extensive and readily recognized across the Midcontinent outcrop belt. Stratigraphic column at far right shows position of section in overall Pennsylvanian section of the northern Midcontinent; abbreviations are: H-C (high-chroma paleosol), HS (sea-level highstand deposits), L-C (low-chroma paleosol), LS (paleosol development at sea-level lowstand), TS (marine transgressive surface). See Figure 6 for key.

rich clay (cf. Schutter 1983), but generally there is no difference between paleosol and parent material clays.

LAWRENCE FORMATION PALEOSOL

Lawrence paleosol thickness ranges from 156 to 264 cm in northeasternmost Kansas (Locality 9), southeastern Nebraska, southwestern Iowa, and northwestern Missouri. In this same area, preserved soil structure is also most apparent. Paleosol thickness decreases to as little as 100 cm basinward, where soil structure is overall less prominent.

The upper Lawrence paleosol is dominantly dusky red, reddish brown, dark reddish brown, or (rarely) weak red. The upper 30–100 cm (very rarely the upper 90–220 cm) are commonly light gray to gray, or light greenish gray to greenish gray, with an abrupt to clear ($\leq$ 3 cm wide), smooth (very rarely irregular) lower boundary. Faint mottling appears in the upper parts of profiles, sometimes directly at the boundary between the low-chroma and high-chroma horizons. These mottles are probably pedogenic, because it appears that iron in the upper part of the profile was reduced during the Toronto marine transgression. A few, small (1–5 mm), roundish, diffuse-margined, gray or greenish-gray mottles appear deeper in profiles, sometimes around small iron oxide nodules or iron-oxide-coated carbonate nodules. These mottles overprint soil structure, indicating their formation after lithification.

Paleosol Macrofeatures

Slickensides.—Very large (a few to several meters long), intersecting slickensides are the most striking characteristics of upper Lawrence Formation paleosol (Figs. 5A, 6, 7). These slickensides are (1) restricted to paleosol profiles, (2) nested in 3–11 m (commonly 4–6 m), bowl-shaped, synformal sets with intervening "peaks", (3) best developed below 30 cm depth, (4) vertically spaced at 3–40 cm (spacing increases below 100–150 cm), (5) inclined 15–45°, and (6) uniformly polished, with well-developed < 1–3 mm grooves. In a few cases, very dark-gray to dark-reddish-brown or reddish-gray metallic coatings of hematite appear on slickenside surfaces. Colors characteristic of superjacent horizons are also smeared on slickensides deep in the profiles, recording translocation of soil material.

In outcrop, very coarse, angular blocky to wedge-shaped aggregates (up to 15 cm wide) delineated by slickensides parallel the coarsest structure present in the original soil. At Locality 8, intersecting slickensides define large lenticular structural units (30 cm × 100 cm to 50 cm × 160 cm) with long axes tilted 20–40° (as in modern Vertisols; Krishna and Perumal 1948). Profiles also contain common to many, smaller slickensides throughout. Parent materials contain a few, isolated, large slickensides or common, smaller slickensides, to depths of up to 170 cm below the base of the overlying paleosolum.

Filled Cracks.—Elongate infillings (of slightly darker mud with included peds) after former soil cracks appear in a few profiles. At Locality 3, a few 1–4 cm wide, slightly undulating, vertical infillings of dusky-red (10R 3/2-4/2) mud appear in the pinkish-gray to reddish-gray (5YR 6/2-5/2) paleosol and penetrate to depths of 50–100 cm below the top of the paleosol. Strong brecciation (soil structure) appears within 5 cm of these features. Similarly, gray or greenish subvertical streaks (0.1–1 cm wide and up to 50 cm long) appear in the upper parts of paleosol profiles at Localities 3 and 5 (Fig. 3).

Soil Structure.—Four fabrics appear in hand specimen: (1) brecciated; (2) faintly brecciated, flecked, or veined; (3) streaked (very rare); and (4) massive (Fig. 6C). Brecciated and massive fabrics are by far the most common. These fabrics represent relict soil structure and demonstrate a morphological continuum. Brecciated fabric, characteristic of the thickest and most strongly developed profiles in the upper Lawrence, is a mosaic of small (1–25 mm), loosely to closely fitted, subangular (rarely angular or rounded subangular) blocky peds surrounded by "veins" (infillings) of darker mudstone (Fig. 5B). Larger (> 3 mm) peds are compound. Peds

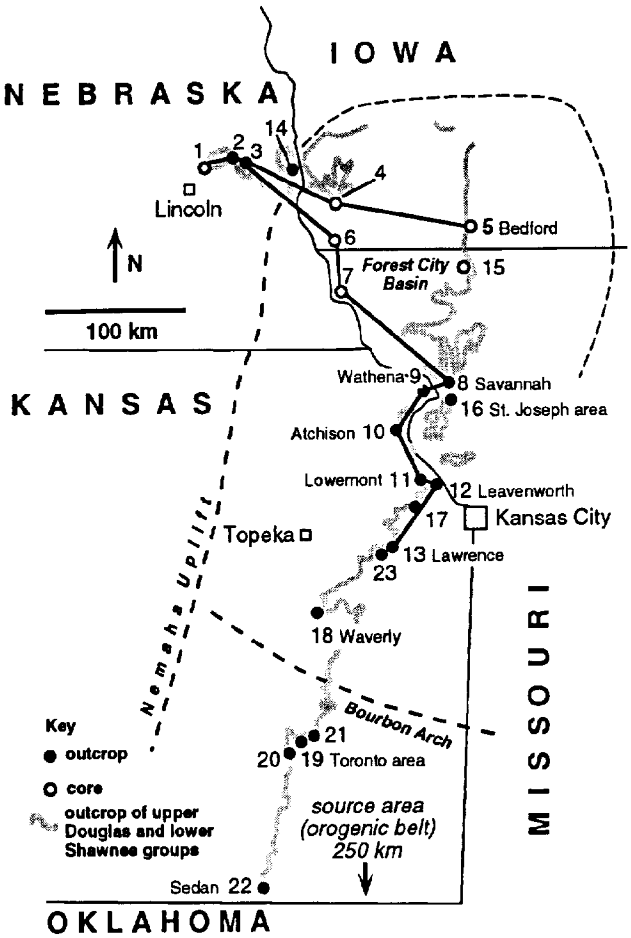

FIG. 2.—Map of upper Lawrence and Snyderville paleosol localities. Outcrop belt of upper Douglas and lower Shawnee groups in Iowa, Nebraska, Missouri, and Kansas (trend of Oread Escarpment) is shaded. Solid lines indicate transects (see Figs. 3, 4). For full locality information, stratigraphic section descriptions, and keyed petrographic descriptions see Joeckel (1993).

are commonly pinkish red, very pale brown, or light gray in a reddish brown matrix, or reddish brown in a dark-reddish-brown matrix. Brecciation is prominent along large slickensides, implying a very close link between wetting and drying cycles and the development of structure in the deeper part of the subsoil. Fine "veins" between peds are usually reddish, but may turn gray to light gray below 200 cm. Veins commonly contain fine carbonate nodules, iron oxide nodules, and granular to subangular blocky aggregates (all reworked by pedoturbation) in weakly to strongly iron-oxide-impregnated silty clay or silt.

Faintly brecciated, flecked, or veined fabrics represent weak soil structure. Such fabrics show weakly differentiated subangular blocky peds or few to common veins in a largely massive matrix. Streaked fabric (rare), consists of indistinct, 20–30° streaks, 1–5 mm wide, that are in some cases associated with prolate granular or elongate, rounded subangular blocky peds. The long axes of these peds are parallel to the streaks. The oblique "grain" of this fabric suggests soil movement along and between slickensides during soil wetting-drying cycles. Massive fabric appears most commonly at the tops of profiles (i.e., within low-chroma zones) or in the middle to lower parts of profiles that otherwise show strong brecciation fabrics. Profiles in the southern (basinward) part of the study area, however, are dominated by massive fabric.

Parent material several tens of centimeters below the paleosolum is thinly (< 1 mm) and laminated. Upward, lamination becomes discontinuous, broken, or slightly convoluted (in conjunction with the appearance of carbonate nodules) 10–20 cm below the paleosolum. A few clay-filled cracks (1–4 mm wide) cut across lamination in this zone.

Relict Lamination.—Relict sedimentary lamination within the upper 75 cm of a few upper Lawrence profiles records intermittent sedimentation late in the history of the soil. Relict fragments of stratified sediment also appear in thin section (see discussion below) at various positions in profiles. At Locality 3, isolated, discontinuous, planar to slightly convoluted, subhorizontal, clay-rich laminae 1–3 mm thick appear in the uppermost 10 cm of the profile. At Locality 8, an undulating 6 cm layer of clay and silt laminae (with marine fossils) appears at 68–75 cm but grades into the adjacent well-mixed massive mudstone.

Carbonate Features.—Carbonate features in upper Lawrence profiles consist of: (1) fine ($\leq$ 20 μm) calcite crystallites throughout the matrix (usually lacking in the parent shales); (2) 1–30 mm, equant to prolate, sharp-margined, calcitic nodules distributed throughout the profile; (3) small to large cylindroids (2–6 cm × 19–70 cm) or rounded, horizontally compressed masses (~ 10–50 cm in diameter); (4) < 10 cm discontinuous beds of calcitic and/or dolomitic carbonate (Fig. 5D); and (5) vertically elongate "dikes" of calcitic and dolomitic carbonate just below the paleosolum (Fig. 5C). Slickenside planes can also be zones of preferential carbonate cementation: in some cases cementation is post-Pennsylvanian (it overprints soil fabric), but in others it may be original because no such relationship is visible and dolomite is present. The nodules, masses, and beds are nearly pure carbonate, indicating that they grew displacively in unconsolidated sediment (soil). Furthermore, large nodules, cylindroids, masses, and beds are concentrated in a very distinct horizon at or just above the contact between the paleosol and the parent material (except at Locality 12, where there are large carbonate cylindroids throughout the profile), indicating a strong genetic significance arising from the original permeability contrast between soil and parent material.

Subsoil dikes consisting of fine calcite and dolomite with sheaths and infillings of slickensided clay appear at Localities 3, 7, and 8 (Figs. 3, 4). Disc-shaped septaric (*sensu* Bullock et al. 1985) nodules (with clay-filled cracks) are associated with the dikes at Locality 3. The dikes are light gray or greenish, 3–10 cm wide and up to 165 cm long, and are spaced at intervals of approximately 50–150 cm. They represent precipitation of carbonate in joints produced by desiccation of the parent material. Slickensided clay infillings/sheaths indicate sub-solum mass movement due to water-table fluctuation. The origin of the dolomite in the dikes and nodules is debatable.

Lateral Variability

Shelfward, long (~ 0.1–0.3 km) cuts at shelfward Localities 2, 3, and 8 show no significant lateral variation, and well cores show only a reddish or reddish-brown paleosol in the upper Lawrence. Basinward, however, there are at least two clear examples of lateral variation in profile development in the upper Lawrence paleosol. A roadcut 0.6 km long (Locality 12) shows a greenish-gray paleosol (under a lens of coaly shale) grading laterally into a slightly higher gray to very dark-gray and locally dark-reddish-brown paleosol containing common carbonate nodules, large slickensides, and large carbonate sheets with slickensides on them (Fig. 7). This 40 m gradation represents a 0.6 m differential in topography. At Locality 13, a similar transition takes place over < 3 km and with 1.3 m of apparent relief. Paleotopography and lateral variation in these examples is comparable to modern soil landscapes (e.g., Wilding et al. 1991; Favrot et al. 1992).

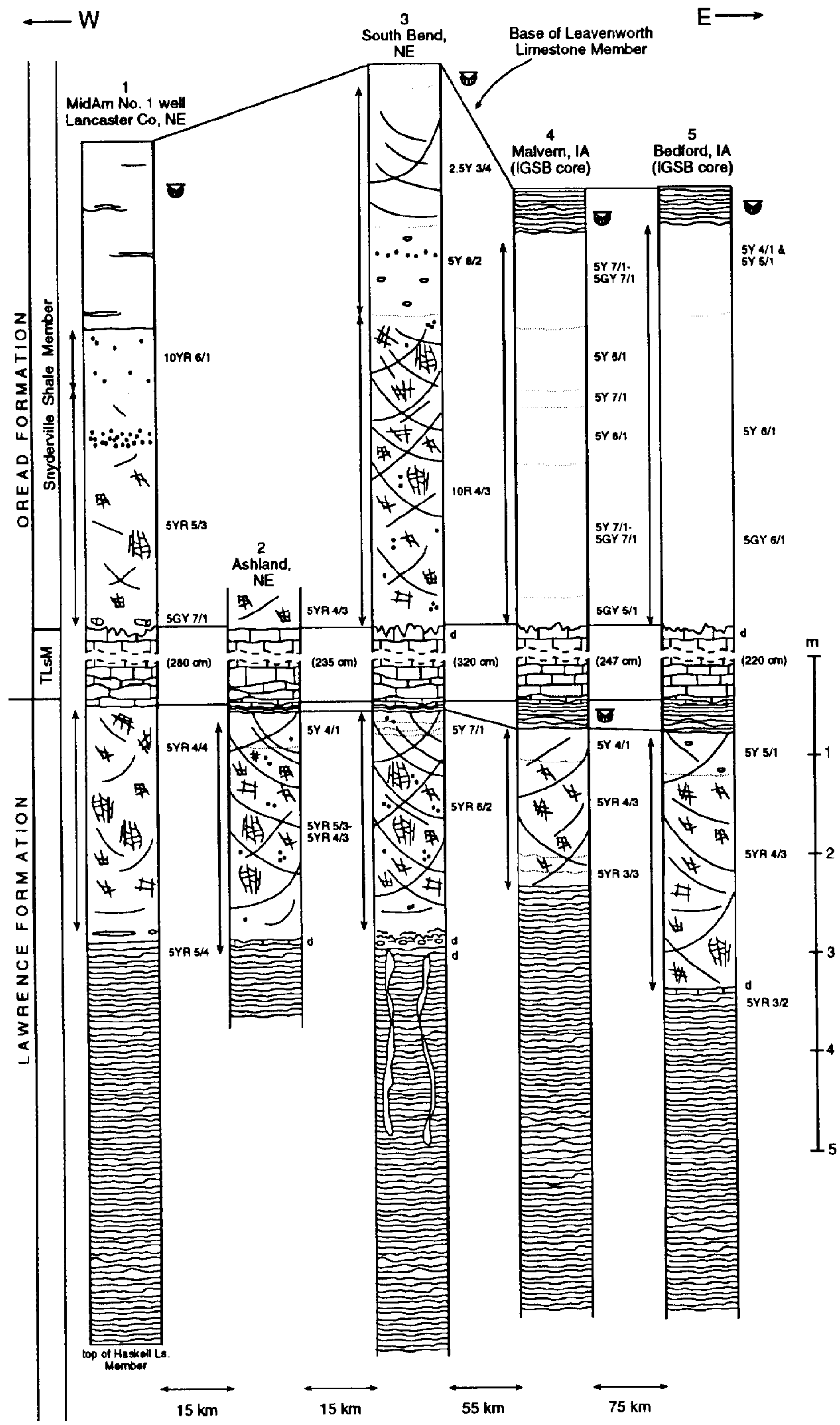

FIG. 3.—West-east transect of upper Lawrence and Snyderville paleosols in northernmost shelf area of northern Midcontinent, USA Paleosols (double-headed arrows) are consistently present in upper part of Lawrence Formation and in Snyderville Shale Member. Part of Toronto Limestone Member has been omitted from each graphic section; measurements in parenthesis to right of Toronto position indicate total thickness of that unit (not amount omitted). See Figure 6 for key.

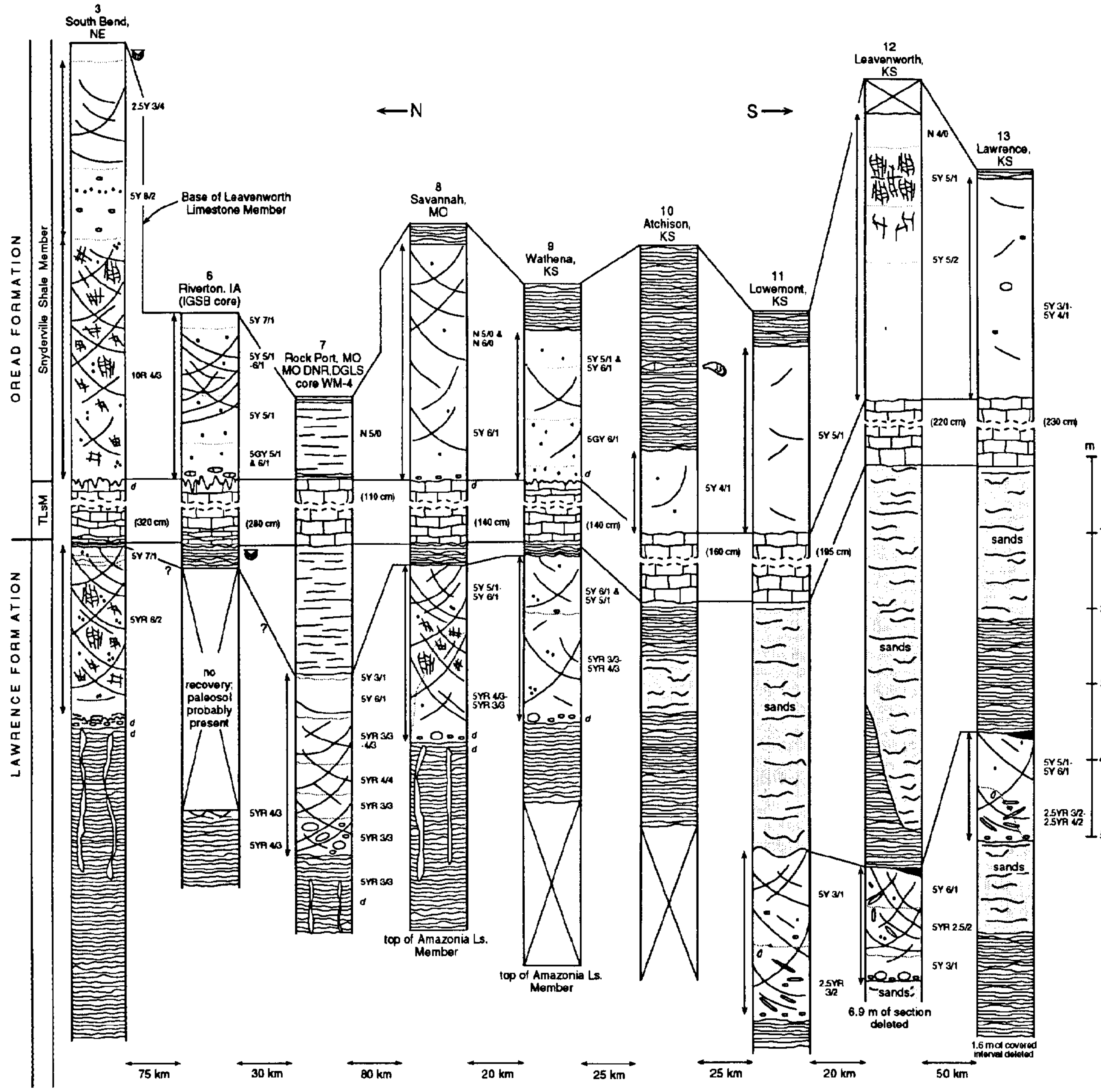

FIG. 4.—North-south transect of upper Lawrence and Snyderville paleosols in northern Midcontinent, USA. A paleosol (double-headed arrow) in the upper part of Lawrence Formation, prominent in Nebraska-Iowa area (see Fig. 3) is overlain by stratified sands and muds (interpreted as estuarine tidal sediments) in northeastern Kansas. Paleosol in Snyderville Shale Member (double-headed arrow) is persistent except at Rock Port, Missouri (well core), where it is replaced by marine sediments. Part of Toronto Limestone Member has been omitted from each graphic section; measurements in parenthesis to right of Toronto position indicate total thickness of that unit. See Figure 6 for key.

SNYDERVILLE SHALE MEMBER PALEOSOL

The Snyderville paleosol or paleosol complex contrasts markedly with the upper Lawrence paleosol (Table 1, Fig. 6A, B). It is very dark gray to light gray, olive gray, and greenish gray to light greenish gray where one paleosol is present (the darkest colors are limited to the uppermost horizons). Where two partially welded paleosols are present in Nebraska, the upper one is similarly low-chroma but the lower one is a high-chroma soil almost identical to the upper Lawrence paleosol. Shelfward (north of Locality 18; Figs. 3, 4), pedogenic effects are usually evident through most of the Snyderville (total unit thickness is usually 2.5–4 m, and paleosola are usually 2.5–3.7 m thick). The underlying Toronto Limestone always shows microkarst (except where the Snyderville paleosol is weak or absent) and regional, partial dolomitization. Microkarst consists of subvertical to horizontal, elongate (1–20 mm × ≤ 150 mm) to irregular, gray or greenish mud-filled voids, appearing to depths of 30–120 cm below the top of the Toronto.

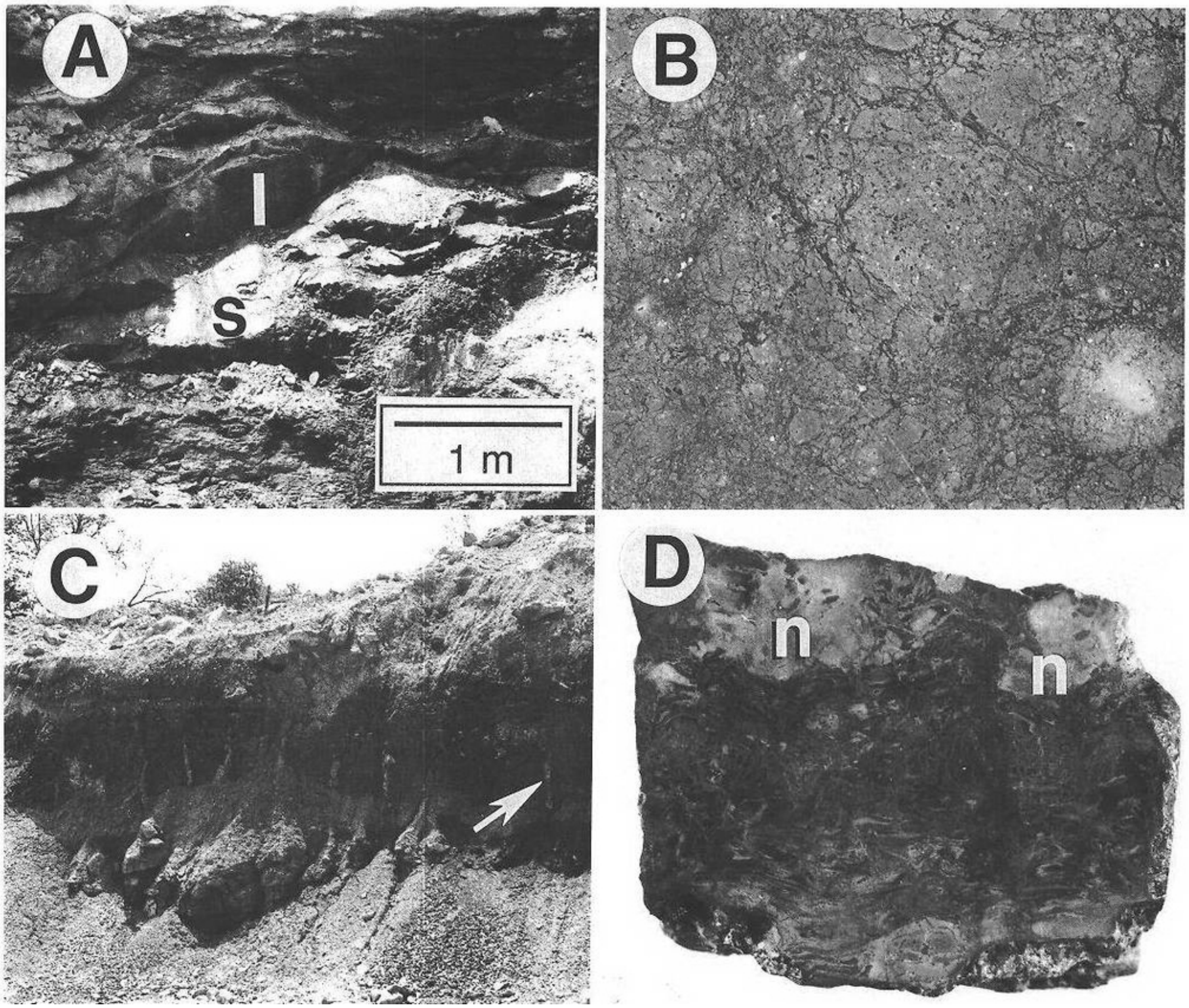

FIG. 5.—Features of upper Lawrence paleosol. **A)** Large lenticular structural units (e.g., "l") between slickensides (e.g., "s"), Locality 8. **B)** Preserved soil structure (brecciated fabric) from Locality 3 (actual size). **C)** Dolomitic "dikes" (e.g., white arrow), vertical sheets of dolomitic carbonate, under paleosolum (base of which is represented by white line) at Locality 8. Weak ledge just above talus slope is Amazonia Limestone Member. **D)** Vertical polished slab of laminated mudstone parent material immediately beneath paleosolum, ~ 240–250 cm below paleosol surface), at Locality 3. Dolomitic nodules (n) displace and disrupt sedimentary laminae, indicating that they are likely to be synpedogenic features.

At Locality 3 (Figs. 2, 3), the Snyderville (6 m thick) contains two paleosols split by an 80 cm siltstone. The upper paleosol is relatively thin (160 cm), pale yellow (2.5Y 7/4) and structureless and contains pyrite, but the lower one is thicker (300 cm) and weak red (10R 4/3), and has well-developed soil structure and small iron oxide nodules. Both contain very large, intersecting slickensides. Two such paleosols are present within the Snyderville at several localities in southeastern Nebraska. At the other extreme, Snyderville lacks a paleosol southward in Missouri at Locality 7, and it contains only a thin (110 cm), very weakly developed paleosol (overlain by 250 cm of marine shale) at Locality 10 (Fig. 4). These cases probably evidence local lows (possibly structural: Locality 7 lies near the old axial trend of the Forest City Basin).

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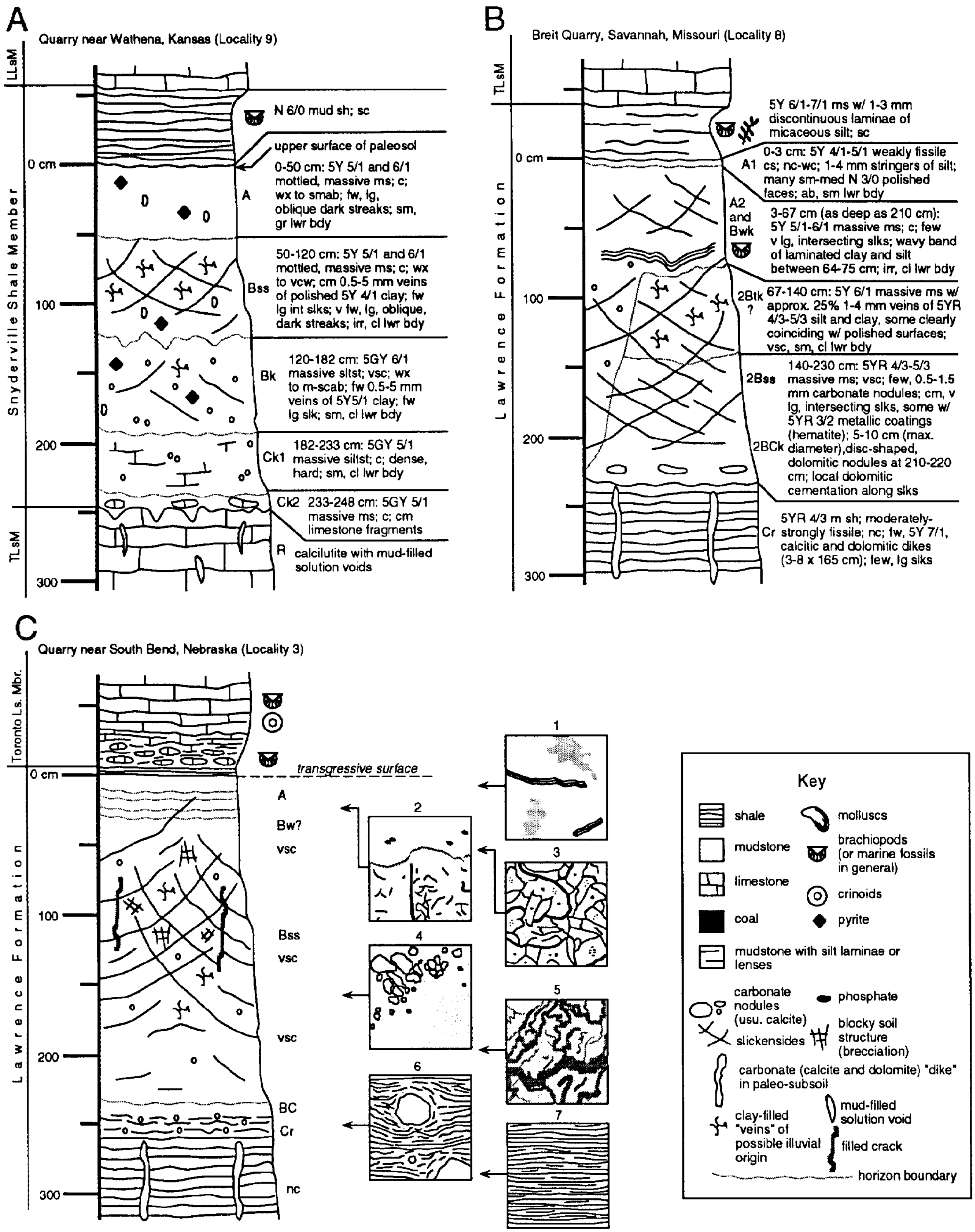
FIG. 6.—**A)** Profile of Snyderville paleosol at Locality 9. **B)** Profile of the upper Lawrence Formation paleosol at Locality 8. **C)** Profile of upper Lawrence Formation paleosol at Locality 3. Fabrics of mudstones illustrate type of soil structure or lamination at various levels in the profile. (1) Massive mudstone with few, discontinuous or broken, relict clay laminae. (2) Transition between low-chroma horizon with weak structure to high-chroma horizon with strong structure. (3) Well-developed brecciation fabric (preserved peds). (4) Massive mudstone with few, isolated (in this case, carbonate-impregnated) peds. (5) Massive mudstone with well-developed low-chroma veining. (6) Laminated mudstone with laminae disrupted by dolomitic carbonate nodules. (7) Laminated mudstone. Boxes represent approximately 2 cm × 2 cm vertically oriented cut surfaces. Abbreviations: cs (claystone), ms (mudstone), sltst (siltstone), nc (noncalcareous), c (calcareous), sc (strongly calcareous), vsc (very strongly calcareous), fw (few), cm (common), sm (small) med (medium), lg (large), slks (slickensides), wx (weathers), gr (gradual), cl (clear), sm (smooth), irr (irregular), lwr (lower), vcw (very coarse wedge-shaped blocks), smab (strong medium angular blocky), m-scab (moderate to strong coarse angular blocky).



A
Quarry near Wathena, Kansas (Locality 9)
LLsM
Snyderville Shale Member
TLsM
0 cm
100
200
300
N 6/0 mud sh; sc
upper surface of paleosol
A
0-50 cm: 5Y 5/1 and 6/1 mottled, massive ms; c; wx to smab; fw, lg, oblique dark streaks; sm, gr lwr bdy
Bss
50-120 cm: 5Y 5/1 and 6/1 mottled, massive ms; c; wx to vcw; cm 0.5-5 mm veins of polished 5Y 4/1 clay; fw lg int slks; v fw, lg, oblique, dark streaks; irr, cl lwr bdy
Bk
120-182 cm: 5GY 6/1 massive sltst; vsc; wx to m-scab; fw 0.5-5 mm veins of 5Y5/1 clay; fw lg slk; sm, cl lwr bdy
Ck1
182-233 cm: 5GY 5/1 massive siltst; c; dense, hard; sm, cl lwr bdy
Ck2
233-248 cm: 5GY 5/1 massive ms; c; cm limestone fragments
R
calcilutite with mud-filled solution voids
B
Breit Quarry, Savannah, Missouri (Locality 8)
TLsM
Lawrence Formation
0 cm
100
200
300
5Y 6/1-7/1 ms w/ 1-3 mm discontinuous laminae of micaceous silt; sc
A1
0-3 cm: 5Y 4/1-5/1 weakly fissile cs; nc-wc; 1-4 mm stringers of silt; many sm-med N 3/0 polished faces; ab, sm lwr bdy
A2 and Bwk
3-67 cm (as deep as 210 cm): 5Y 5/1-6/1 massive ms; c; few v lg, intersecting slks; wavy band of laminated clay and silt between 64-75 cm; irr, cl lwr bdy
2Btk ?
67-140 cm: 5Y 6/1 massive ms w/ approx. 25% 1-4 mm veins of 5YR 4/3-5/3 silt and clay, some clearly coinciding w/ polished surfaces; vsc, sm, cl lwr bdy
2Bss
2BCk
140-230 cm: 5YR 4/3-5/3 massive ms; vsc; few, 0.5-1.5 mm carbonate nodules; cm, v lg, intersecting slks, some w/ 5YR 3/2 metallic coatings (hematite); 5-10 cm (max. diameter), disc-shaped, dolomitic nodules at 210-220 cm; local dolomitic cementation along slks
Cr
5YR 4/3 m sh; moderately-strongly fissile; nc; fw, 5Y 7/1, calcitic and dolomitic dikes (3-8 x 165 cm); few, lg slks
C
Quarry near South Bend, Nebraska (Locality 3)
Toronto Ls. Mbr.
Lawrence Formation
0 cm
100
200
300
transgressive surface
A
Bw?
vsc
Bss
vsc
vsc
BC
Cr
nc
1
2
3
4
5
6
7
Key
shale
mudstone
limestone
coal
mudstone with silt laminae or lenses
carbonate nodules (usu. calcite)
slickensides
clay-filled "veins" of possible illuvial origin
molluscs
brachiopods (or marine fossils in general)
crinoids
pyrite
phosphate
blocky soil structure (brecciation)
carbonate (calcite and dolomite) "dike" in paleo-subsoil
mud-filled solution void
filled crack
horizon boundary

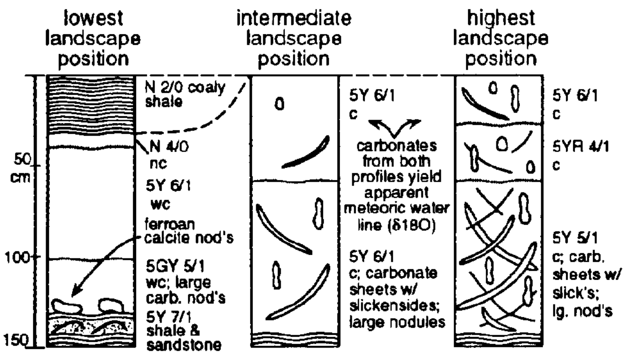


FIG. 7.—Lateral variation in upper Lawrence paleosol at north end of east wall of cut at Locality 12 (near Leavenworth, Kansas). Transition from low-chroma paleosol under coaly shale-filled swale or channel (left) to low-chroma paleosol with carbonate nodules and carbonate sheets along slickensides (middle), to even more carbonate-rich and slickensided paleosol with reddish near-surface horizon (right) takes place over 40 m and represents approximately 60 cm of microrelief. Transition (continuous in outcrop) is presumed to represent part of an ancient topohydrosequence trending from low, very poorly drained soil (beneath swale) to slightly higher, better-drained soil.

TABLE 1.—*Features of modern Vertisols and other vertic soils as analogs for features in upper Lawrence Formation (L) and Snyderville Member (S) paleosols*

Color: Reddish (5YR) modern Vertisols (as L) exist (Gile and Grossman 1979; Crenwelge et al. 1981), but grayish Vertisols (5Y, 10YR; similar to S) are more common (Calhoun et al. 1988; Harris 1989; see Appendix V in Joeckel 1993).

Maximum solum thickness: Modern Vertisol sola 202–229 cm thick (Crenwelge et al. 1981; Sehgal and Bhattacharjee 1988; Neitsch et al. 1989) are comparable to both L and S.

Intersecting slickensides (L, S): Diagnostic of Vertisols (Soil Survey Staff 1990); gilgai cycles range 3–25 m in modern Vertisols (Dudal and Eswaran 1988; Wilding et al. 1991).

Deep cracks (L): Diagnostic (Soil Survey Staff 1990); range 0.5–150 mm wide (Crenwelge et al. 1981; Hawando 1984; Harris 1989; Pillai-McGarry and Collis-George 1990a, 1990b). Infillings (≤ 4 cm wide; usually in upper 100 cm of profile) are found in Vertisols, vertic Mollisols, and associated Alfisols (e.g., Dudal 1965; Cotton 1971; Guckian and Garcia 1979; Crenwelge et al. 1981; Hawando 1984; Guckian 1988; Dudal and Eswaran 1988; Harris 1989). Infillings also appear along slickensides (as S).

Small iron (and manganese segregations (L): Common (Thorp et al. 1960; Dudal 1965; Harris 1989; Mowery and Bower 1978), and in associated Alfisols (e.g., Cotton 1971; Mowery and Bower 1978; Harris 1989).

Metallic coatings on slickensides (L): Noted in a Sudan Vertisols (Dudal 1965).

Clustered soil nodules (L, S): Noted in Indian Vertisols (Mermut and Dasog 1986).

Marine fossils (L): Noted in Vertisols and vertic Mollisols in Texas (Guckian and Garcia 1979).

Paleosol Macrofeatures

Slickensides.—Very large slickensides (not always prominent, because of diminished outcrop quality) are essentially identical to those in the upper Lawrence paleosol. At Locality 12, a series of darker, bowl-shaped features (~ 3–6 m wide, up to 2 m deep) is faintly visible in the Snyderville paleosol. They are probably analogous to the microlows of some modern Vertisols (Dudal and Eswaran 1988). Large (1–4 m), oblique dark streaks (richer in organic material and trending parallel to adjacent slickensides, which are in some cases coated with dark-gray polished clay, appear between 100 and 300 cm in several Snyderville profiles in northeastern Kansas and adjacent Missouri. They suggest translocation of soil material, via pedoturbation, from similarly dark-colored overlying horizons.

Soil Structure.—Soil structure is significantly weaker than in the upper Lawrence paleosol. Low-chroma Snyderville profiles are dominated by massive or veined fabrics with very faint to faint mottling. Strong brecciated fabric is well developed in the Snyderville paleosol only in the reddish lower paleosol at Locality 3.

Subvertical and sinuous to zig-zag veins are prominent in many Snyderville profiles, mostly in the interval 40–180 cm below the paleosol surface. They are < 1–20 mm wide (mostly ≤ 5 mm) and extend up to 200 mm. In most cases, they are noticeably darker than the surrounding material, and consist of polished clay and fine intercalations of silt. Larger veins contain reworked weak peds or granules and small carbonate nodules. A few veins show offsets along their lengths, indicating post-infilling mass movement within the soil.

Relict Lamination.—Small fragments of laminated clay or clay and silt (visible only under the microscope) appear below 200–250 cm (see discussion below).

Carbonate Features.—Few sharp-margined carbonate nodules (3 cm in diameter) appear in Snyderville profiles. They are dominantly calcite micrite, but some are dolomitic deeper in the profile. Snyderville mudstones are usually calcareous to very strongly calcareous due to dispersed fine (< 20 μm) calcite crystallites. Weathered fragments of the underlying Toronto appear in the lowermost parts of several profiles.

Pyrite.—Small (≤ 2 mm) pyrite crystals, clusters of crystals, or elongate (up to 3 mm) trains (as if precipitated along an elongate feature void or root) are always present in low-chroma mudstones in Snyderville paleosols. In contrast, the high-chroma mudstones that dominate the upper Lawrence paleosol never contain visible pyrite.

MICROMORPHOLOGY

Soil Structure

Upper Lawrence peds are small (< 4 mm), generally subangular blocky, and not impregnated or weakly to moderately impregnated with iron oxide (Fig. 8C, D, E). Moderately iron-oxide-impregnated peds (less common) have an undifferentiated birefringence fabric (see Bullock et al. 1985) and indicate at least some preburial segregation of iron oxides. Other peds have very weak to weak crystallitic, or weak stipple-speckled birefringence fabrics. Larger peds are usually compound. Granular peds (< 1200 μm), found rarely in larger infillings or as loose clusters, may be fecal.

Veins between aggregates in upper Lawrence paleosols are approximately 10–3000 μm wide, and they are moderately to strongly impregnated with red or reddish-brown iron oxide (possibly of burial diagenetic origin). Moderately to strongly birefringent streaks of yellowish-red (in crossed polarizers) clay appear roughly parallel to the margins of some aggregates and partially surround them (Fig. 8C). In upper Lawrence profiles in the shelfward part of the study area, and in the lower Snyderville paleosol at Locality 3, a few (usually ≤ 5%, but up to 10%) discrete and continuous coatings (50–200 μm thick) of moderately birefringent, red (weakly to strongly iron-oxide-impregnated) or reddish-gray (weakly iron-oxide-impregnated) clay with strong preferred parallel orientation appear in a few veins (Fig. 8E). Such features are likely to be illuvial, possibly even the results of clay neoformation. Some veins are filled entirely with birefringent clay, but most also contain iron oxide-impregnated silty clay or silt. A few infillings consist of silt alone (Fig. 8D).

While low-chroma profiles of the Snyderville paleosol do not show well-developed soil structure, infillings are common in many profiles, ranging from patches or bands (not sedimentary laminae) of medium to coarse silt, to clay- and silt-filled "veins" (small infillings) like those found in upper Lawrence profiles, to 10–200 cm dark streaks. The bands and patches of silt (which have diffuse to distinct margins) trend perpendicular or oblique to the horizontal plane, and are therefore unlikely to be sedimentary features. They are similar to better-defined infillings that contain both clay and silt, so they are best interpreted as older pedogenic infillings, although some may be faunal burrows. Dark-colored veins and digitate features, which appear at the junction of a few to several veins, each having a different orientation, commonly appear in hand specimens from the

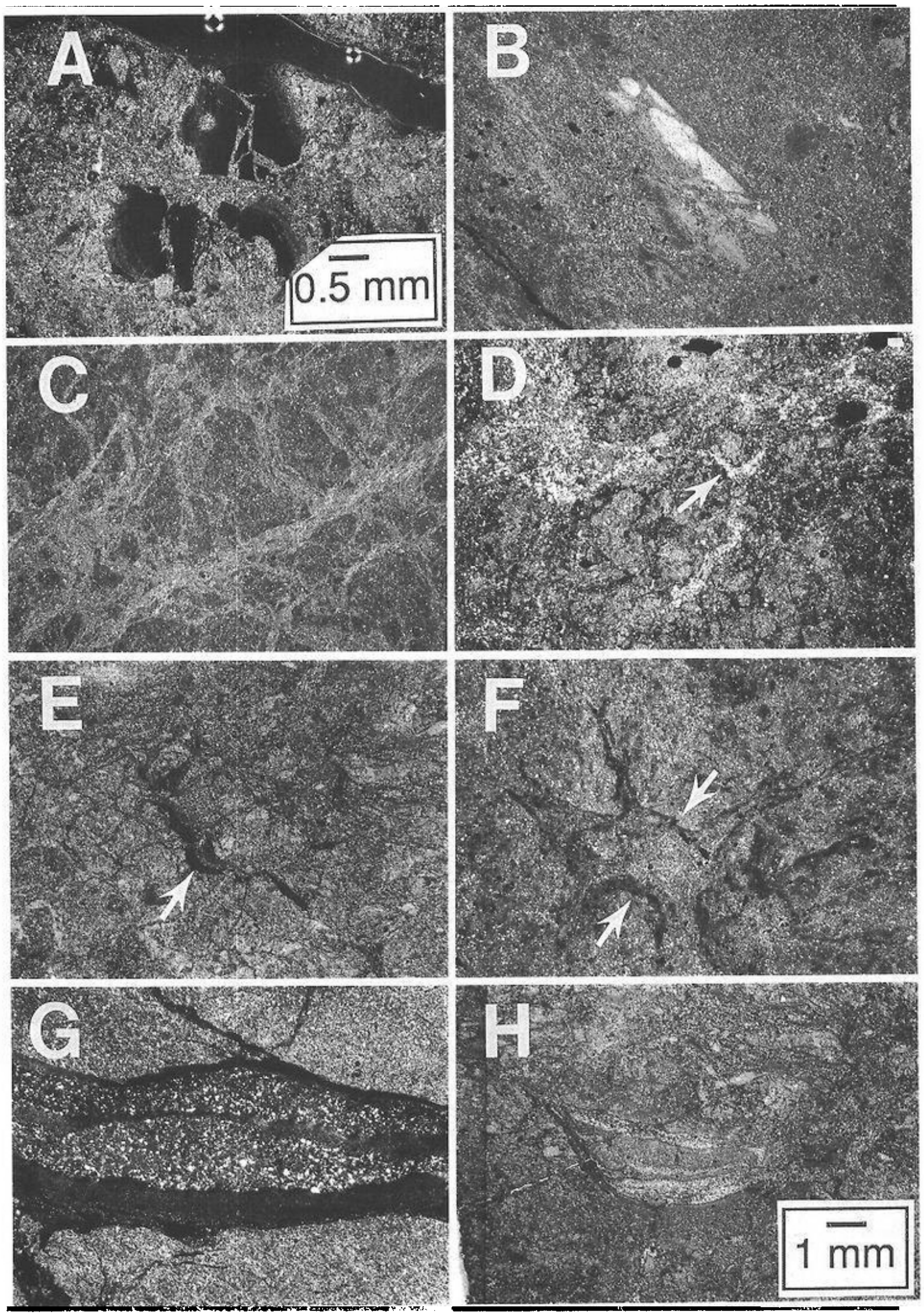


FIG. 8.—Micromorphology of upper Lawrence and Snyderville paleosols. **A)** Laminated relict sedimentary fragments moderately to strongly impregnated with iron oxide, approximately 55 cm below top of upper Lawrence paleosol at Locality 3 (transverse section). **B)** Fragment of a sedimentary lamina with unistrial fabric, about 185–190 cm below top of Snyderville paleosol at Locality 8 (vertical section). **C)** Brecciated fabric in horizontal section, approximately 215 cm below upper surface of paleosol at Locality 3 (near South Bend, Nebraska). Note weakly iron-oxide-impregnated aggregates (dark) and intervening "veins" containing strands of birefringent clay. **D)** Infillings of silt (arrow) between peds; note overall strong structure (peds highlighted by iron oxide "veins". Approximately 25–30 cm below top of upper Lawrence paleosol, Locality 3 (vertical section). **E)** Large, probably pedogenic, clay coating from approximately 220 cm below top of lower Snyderville paleosol at Locality 3 (vertical section). **F)** Digitate feature (arrowed) that probably represents five or six coalesced illuvial clay coatings along former void walls; silt fills interior (vertical section, approximately 75–80 cm below upper surface of paleosol; Snyderville paleosol, Locality 9). **G)** Vein-like feature infilled with iron-oxide-impregnated clay having strong parallel orientation (dark, including dark strand in middle) and silt; this feature may represent synpedogenic or postpedogenic movement of material in suspension (vertical section 69–74 cm below top of upper Lawrence paleosol, Locality 8). **H)** Large, bowl-shaped infilling composed of clay layers (with strong preferred orientation parallel to the margins of the feature) and silt layers (vertical section, 220–225 cm below upper surface of lower Snyderville paleosol at Locality 3). Same scale for **A–G**.

paleo-subsoils of Snyderville profiles (Fig. 8F). The veins are 50–500 μm-wide infillings of moderately to strongly birefringent clay or silty clay. Likewise, the digitate features (some > 4000 μm wide) are former vugs infilled with clay and silt. The two types of features are intimately related and probably are illuvial. Large ($\leq$ 10 mm wide), elongate, dark-colored infillings in Snyderville profiles usually contain concentrations of small carbonate nodules and coarse silt to very fine sand. The overall dark color of many Snyderville features appears to be due to incorporated organic material.

Much larger infillings appear in a few profiles, but they were rarely captured in thin sections. They represent deposition in large subsoil voids, probably after an extended period of desiccation (Fig. 8H).

Clay Fragments

Fragments of moderately to strongly birefringent clay with strong, continuous, preferred parallel orientation appear in small numbers (usually $\leq$ 5% but up to 15%) in both paleosols (Fig. 8A, B). These fragments are commonly prolate and subangular to subrounded, and are 350–6000 μm long. In the upper Lawrence paleosol and in the lower Snyderville paleosol at Locality 3 they are commonly dark red (with red or yellowish-red birefringence) due to impregnation with iron oxide, probably before or during pedogenesis, whereas a few clay fragments in the upper Lawrence paleosol and all clay fragments in the Snyderville profiles examined are not impregnated with iron oxide and have dull to bright yellow birefringence colors. Very fine carbonate crystallites (usually $\leq$ 4 μm) may be present within the clay fragments in both paleosols. In the uppermost part of the upper Lawrence paleosol and in the lower part of the Snyderville paleosol at Locality 9, prolate clay fragments form long, horizontal to oblique trains, indicating that they are relict sedimentary laminae (Fig. 8B). Subrounded fragments of interlaminated silt and clay 400–2300 μm long in the upper Lawrence paleosol at Locality 3 are probably sedimentary relics as well. A few of the clay fragments deep in the upper Lawrence paleosol and in the lower Snyderville paleosol at Locality 3 lie near illuvial clay coatings, suggesting that they are remains of coatings displaced by pedoturbation. Some fragments of laminated clay and silt may be remnants of surface crusts or thicker stratified deposits originally laid down when the soil surface was flooded. Large, laminated infillings (as in the lower Snyderville profile at Locality 3) seem to be the result of the same process (as in modern Vertisols; Mohr et al. 1972, p. 319–320; Kooistra 1982, p. 76–77; Nettleton and Sleeman 1985).

Like some peds, iron-oxide-impregnated clay fragments probably contained iron oxides prior to pedogenesis, because they are sometimes surrounded by iron-poor materials. Moreover, the parent Lawrence shales are reddish brown. Some diagenetic alteration of iron oxides must have occurred in both paleosol mudstones and parent shales, but there is no evidence that the original soil was anything but a high-chroma soil.

Birefringence Fabric (B-fabric)

The dominant birefringence fabric of most thin sections from both paleosols is crystallitic fabric, due to ubiquitous micrite and microspar-sized crystallites of calcite and, in some Lawrence profiles, dolomite as well. This fabric overprints other fabrics, commonly parallel-striated. Thus, much of the fine carbonate may be burial diagenetic in origin. Stipple-speckled fabrics also appear in Snyderville siltstones or silty mudstones.

Iron Oxide Nodules

A few (< 10%) small (usually < 500 μm), strongly impregnated to pure, equant to prolate, smooth-margined nodules of dark-reddish-brown to black (XPL and PPL) iron oxide with a few included silt grains are present in all of the reddish upper Lawrence paleosol samples described in thin section, as well as in samples from the reddish lower Snyderville paleosol at Locality 3. They are absent in the other low-chroma Snyderville profiles. These nodules sometimes appear in loose clusters or elongate tracts, or reworked in the infillings of large veins (thus verifying their original pedogenic origin). Iron oxide nodules, as well as iron oxide impregnations in carbonate nodules, indicate periods of low Eh (due to water-table fluctuations), during which iron was mobilized in solution (Nettleton and Sleeman 1985; Sehgal and Stoops 1972).

Carbonate Nodules

A few ($\leq$ 10%), small ($\leq$ 3000 μm), micritic to finely microsparitic (crystallites $\leq$ 8 μm) calcitic carbonate nodules are present in all upper Lawrence and Snyderville paleosol profiles. These nodules are subrounded to rounded, and most are typic (having an undifferentiated internal fabric and regular, sharp external boundaries; Bullock et al. 1985), although a very few are geodic (having an internal void, in these cases usually filled with microspar; Bullock et al. 1985). In the upper Lawrence paleosol, a few of the typic and geodic carbonate nodules are moderately to strongly impregnated with reddish-brown iron oxide, or have hypocoatings of iron oxide 10–300 μm thick.

Low-Mg calcite (3.017–3.034 Å) dominates in carbonate features from both paleosols. Equigranular xenotopic microsparitic (or, rarely, micritic) dolomite and ferroan dolomite (2.888–2.916 Å) appear lower in the paleosola, within nodules and "dikes". Thin sections of these features show domains of micritic calcite and/or dolomite surrounded by dolomitic microspar. One shows aggrading neomorphism, suggesting that the coarser dolomite is a secondary product after an original, very fine-grained calcite or dolomite. Geometric relationships indicate that the most iron-rich dolomite represents the last stage of carbonate precipitation. Similarly, Sobecki (1980) found both authigenic calcite (3.013–3.033 Å) and dolomite (2.907–2.918 Å) in modern Mollisols on the subhumid Texas Gulf Coast.

Fossils

At Locality 3, five vertebrate bone and scale fragments were found in thin sections of the upper Lawrence paleosol. Mollusc and arthropod (trilobite?) fragments appear in carbonate nodules (probably in this case a highly altered limestone) at the base of the upper Lawrence paleosol at Locality 5. Brachiopod, mollusc, and echinoderm fragments appear very rarely in the upper parts of a few upper Lawrence and Snyderville profiles.

STABLE ISOTOPES (C, O)

Micritic to finely microsparitic carbonate from calcite and dolomite nodules in both paleosols yields $\delta^{18}O$ values ranging from -5.46 to 1.16‰ PDB (av. = -1.87‰ PDB, s.d. = 1.90) and $\delta^{13}C$ values ranging from -8.43 to -2.56‰ PDB (av. = -5.22‰ PDB, s.d. = 1.90; Fig. 9). Petrographic observations and the lack of evidence for high diagenetic temperatures or deep burial in the northern Midcontinent suggest that these nodules are likely to preserve original isotopic signatures. Most of the data points show a trend that seems to be dominated by evaporation (increasing $\delta^{18}O$ values). Several samples, (many from dolomitic nodules), yielded particularly high $\delta^{18}O$ values (-1.00‰ to $+1.00$‰ PDB). There is no consistent trend with depth; nodules were probably translocated by pedoturbation. Paleosol micritic carbonates from Locality 12 (see line in Figure 9) appear to be products of meteoric water-soil reactions instead of evaporation (relatively constant $\delta^{18}O$ but variable $\delta^{13}C$; Lohmann 1988), indicating that carbonate was precipitated in a saturated profile, a situation compatible with the dominance of low-chroma coloration and the topographically low position of the paleotopohydrosequence at this Locality (Fig. 7). Fine crystallites in the mudstone matrix lie within or barely outside

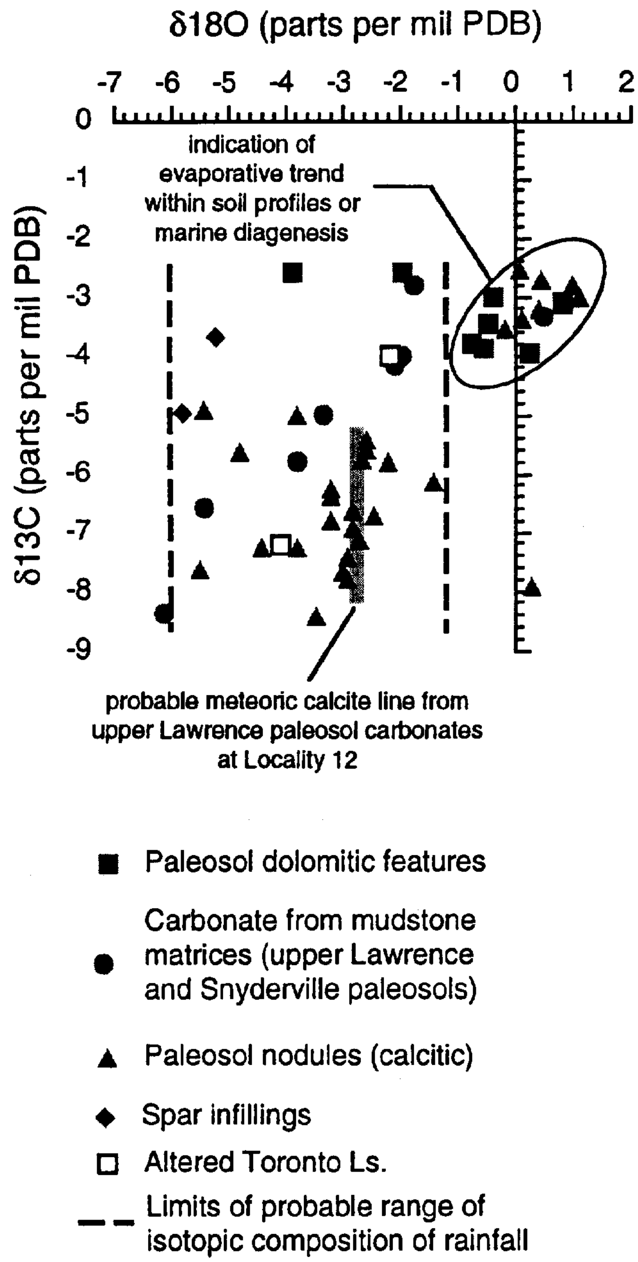


FIG. 9.—Carbon and oxygen isotope values (‰ PDB) for calcite and dolomite samples microdrilled out of carbonate nodules from upper Lawrence and Snyderville paleosols (see Joeckel 1993 for data and sample descriptions).

the range of values from carbonate nodules from the same localities. Thus, somewhat contrary to petrographic observations, they cannot readily be distinguished as a burial-diagenetic phase.

Overall, the range of $\delta^{13}C$ values from Lawrence and Snyderville paleosols probably indicates a significant component from land plants in soil CO_2 (Driese et al. 1992). Using the modifications of Cerling's model (Cerling 1991) outlined by Mora et al. (1993, fig. 22), the $\delta^{13}C$ values from the paleosols indicate atmospheric pCO_2 in the approximate range of 2750–3500 ppmV, which overlaps three other estimated ranges of Carboniferous pCO_2 provided by Mora et al (1993, fig. 22). However, values from such nodules apparently overestimate atmospheric pCO_2 somewhat (Mora et al. 1993).

Assuming minimal diagenetic alteration of isotopic signatures, a cluster of points between about −2 and −3‰ $\delta^{18}O$ (Fig. 9) reflects the composition of the bulk of Lawrence-Snyderville precipitation. Mean $\delta^{18}O$ values for brachiopods from the Oread Formation in Kansas are about −1‰ to −2‰ (Grossman et al. 1993). Thus, barring strong vital effects on brachiopod carbonate (Grossman et al. 1993, p. 1290), $\delta^{18}O$ values from the paleosols are little depleted relative to Late Pennsylvanian marine waters in the same area. Therefore, close proximity to the Midcontinent seaway source of meteoric water seems to have been the overriding control on the $\delta^{18}O$ composition of carbonates in both paleosols.

DISCUSSION AND INTERPRETATION

Soil Morphology and Genesis

Both paleosols very strongly resemble modern Vertisols (Table 2), as would be expected on the low-relief, low-latitude (but not equatorial; see Heckel 1980) coastal plains they record. Intersecting slickenside sets and different, co-occurring paleosol fabrics in both paleosols are particularly reminiscent of modern Vertisols, in which soil mass movement and structural modification occur due to cycles of wetting and drying under seasonal rainfall (Dudal and Eswaran 1988). The association of illuvial argillans with fragments of well-oriented clay in some profiles records infrequent episodes of illuviation under stabler, wetter conditions and subsequent pedoturbation resulting from wetting-drying (and subsequent shrink-swell) cycles, as in some modern Vertisols (Nettleton and Sleeman 1985). Likewise, large dark streaks in Snyderville profiles resulted from the downward translocation of soil material along slickenside planes during pedoturbation.

Paleosol dolomite, particularly in the upper Lawrence, is somewhat problematic, yet it may illuminate ancient pedogenic processes. While this dolomite could be of burial-diagenetic or relict-marine origin (cf. Mora et al. 1993), modern pedogenic dolomite does exist and is thought to result from: (1) frequent wetting-drying cycles, including water-table fluctuations, (2) Mg^{2+} concentration after localized precipitation of low-Mg calcite, or (3) climatic drying (Sherman et al. 1947, 1962; Rostad 1975; Sobecki 1980; Hutton and Dixon 1991; Sobecki and Karathanasis 1987; Botha and Hughes 1992). Thus, dolomite in upper Lawrence subsoil nodules and dikes could be a product of cycles of soil wetting and drying (already postulated from other vertic soil features) within the zone of water table fluctuation. High $\delta^{18}O$ values from paleosol dolomite are compatible with early marine-influenced diagenesis of calcite or, possibly, with evaporation-dominated pedogenic dolomite precipitation.

Paleosols and Basin History

Given their geologic setting (low-gradient, periodically flooded cratonic basin) the ultimate controls over the development of both paleosols would have been: (1) eustasy (apparently the overriding control on Midcontinent cyclothems; Heckel 1980, 1986, 1991) and the location and migration of major facies tracts, (2) tectonism (gentle uplift and subsidence, e.g., Fagerstrom and Burchett 1972), and (3) climate (cf. Cecil 1990). By their lateral continuity and prominence, both paleosols are of immediate utility as stratigraphic markers indicating particularly widespread subaerial exposure and geomorphic stability, a condition highly compatible with eustatic sea-level lowstand (Haq 1991). Localized fluvial downcutting on the shelf between the Toronto and Leavenworth transgressions (Ball 1964, p. 361–362) supports this interpretation. The occurrence of two major exposure events just before the Heebner sea-level highstand (Heckel 1986, 1991) seems particularly compatible with a glacioeustatic mechanism. Both paleosols developed during lowstand exposure of the northern Midcontinent shelf and evolved relatively uninterruptedly after an initial pulse of deposition (i.e., the last phase of a depositional cycle) until the basin-wide Toronto and Leavenworth transgressions (combined with subsidence) resumed sedimentation. Resumed sedimentation resulted in burial of the paleosols by thin transgressive sediments, which probably infilled shallow ravinement surfaces, at least in the northern part of the study area. Other than this basic scenario, however, the histories of the two paleosols differ significantly.

Post–upper Lawrence paleosol sedimentation prompted by the Toronto transgression and encouraged by greater subsidence rates, indicated by marked southward unit thickening, began earlier in the Atchison-Leavenworth-Lawrence, Kansas area than farther north/shelfward. Sediments deposited atop the paleosol in this area probably record estuarine-drowned valley systems (cf. Lanier et al. 1993). The differential in solum thickness, horizonation, and degree of structure development from north to south are wholly compatible with different duration of subaerial exposure. Thus, while tidal sediments were being deposited in eastern Kansas, the area to the north remained emergent and pedogenesis continued, producing a more strongly developed profile. Eventually, even this area was drowned by the Toronto transgression. Disrupted relict stratification in the upper parts of upper Lawrence paleosol profiles may indicate relatively slow cessation of pedogenesis during burial by migrating littoral facies tracts.

There is no comparable southward thickening of clastic deposits directly above the Snyderville paleosol, and its degree of development does not show north-south changes analogous to the upper Lawrence paleosol in the same area. There were local lows (Localities 7 and 10) showing little or no pedogenesis, yet northward (in southeastern Nebraska) there is a thick, complex profile in the Snyderville. There was probably a supplemental terrigenous sediment source and local tectonism (at the northern Nemaha Uplift–Forest City Basin margin) in the latter area during Snyderville time, fostering two distinct periods of deposition and soil development. The first episode involved a well-drained landscape, topographically high relative to areas east and south and the second a poorly drained one like that represented by the Snyderville elsewhere. Thus, the genesis of the Snyderville landscape was strikingly different from, and indeed independent of, the genesis of the upper Lawrence landscape, despite the development of both landscapes in the same region and during closely successive depositional cycles.

The striking overall contrast in color between the two paleosols could be attributed to differences in parent materials or diagenesis, yet sources of sediment for both paleosols were not likely to have differed appreciably (except possibly in southeastern Nebraska, but there is a reddish, Lawrence-like mudstone in the basal Snyderville there anyway), and it is difficult to imagine major differences in diagenetic history between two units separated by only a few meters of limestone. Rather, the combination of color and morphological contrasts (Table 1) strongly suggests an original contrast in soil moisture: drier during upper Lawrence time and wetter during much of Snyderville time (especially outside of Nebraska). Similar contrasts are apparent between different Vertisols (Uderts and Usterts) on the same modern coastal plains (e.g., Guckian and Garcia 1979; Crenwelge et al. 1981; Guckian 1988; Neitsch et al. 1989). The regional consistency of contrasting features in the paleosols, however, indicates that the differences between them are due to a factor(s) of greater magnitude than local landscape variability, namely climate and/or regional geomorphology (a function of tectonics and sedimentation patterns balanced against eustatic sea-level change). Higher or more seasonally consistent rainfall during Snyderville time, and/or the development of an extensive, very low, poorly drained Snyderville coastal plain (with the contributing factor of shallow Toronto bedrock) are hypotheses that parsimoniously explain the overall differences in paleosol features.

Less net sedimentation relative to subsidence (the Snyderville is a relatively thin unit) and the probable association of lower north-south (yet, at some point, higher west-east) basinal gradients during Snyderville time

TABLE 2.—*Comparison of upper Lawrence (L) and Snyderville (S) paleosols*

Similarities:

Sets of prominent (L) or distinct (S), very large, intersecting slickensides.
Overprinting of other b-fabrics by crystallitic b-fabric visible in thin section.
Small calcitic nodules throughout profile.
Dolomite (S: rare small nodules or L: common large segregations) in lower paleosolum illuvial argillans in some thin sections; fragments of well-oriented clay in many.

Differences:

Upper Lawrence Formation Paleosols	*Snyderville Shale Member Paleosols*
• high-chroma (reddish to reddish brown); upper, low-chroma horizon(s)	• low-chroma (grayish to greenish gray); darker streaks and "bowls" in subsoil
• developed in mudstone over shale with large, vertical carbonate "dikes"	• developed in mudstone or siltstone over limestone with microkarst
• mudstone/shale atop paleosol grades upward into overlying marine limestone	• mudstone/shale atop paleosol has sharp contact with overlying marine limestone
• strong soil structure in several profiles	• soil structure very weak or absent
• iron oxide nodules present; pyrite absent	• iron oxide nodules very rare or absent; pyrite present throughout profile
• greenish gray or yellowish streaks on slickensides in subsoil	• dark gray or very dark gray streaks (organic-material-rich) present in subsoil
• significant, noncyclic lateral variability represented in two long outcrops in northeastern Kansas	• lateral variability not noted; cyclic "bowls" at same outcrops as left; two welded soils in southeastern Nebraska

are likely to have had a strong impact on the geomorphic differences between the two successive soil landscapes. Also, different rates and magnitudes of sea-level rise associated with the approach of subsequent transgressions might have had different geomorphic effects on two such low-gradient (cf. Fagerstrom and Burchett 1972) surfaces, thereby contributing to the eventual characteristics of the paleosols. The Leavenworth-Heebner transgression was definitely more extensive than the Toronto transgression (Heckel 1986). It was probably more rapid as well: there is little or no gradation between the shale above the Snyderville paleosol and the Leavenworth Limestone or between the Leavenworth and the Heebner black shale, while the shale above the upper Lawrence paleosol grades markedly into the basal Toronto shaly limestone. If this was the case, there would have been relatively less time for the "remodeling" of Snyderville soil landscapes (which can, however, be inferred from two basinward Lawrence exposures) or coastal geomorphic and depositional systems ahead of the transgression. A slower and less extensive Toronto transgression might have allowed pronounced landscape "remodeling" leading to major north-south differences in paleosol characteristics, local topohydrosequence variation, and variability in transgressive facies overlying the paleosol.

SUMMARY AND CONCLUSIONS

Characteristics of both paleosols are consistent with the (glacio-) eustatic model of cyclothem deposition (Heckel 1980, 1986, 1991). Long-distance lateral variation in the upper Lawrence amounts to a north-south "mega-" chronosequence overlapped by markedly different transgressive sediments southward than northward. The Snyderville paleosol, somewhat more variable west-east than north-south, essentially represents a west-east "mega-" topohydrosequence, apparently influenced by gentle tectonism. Overall geomorphic differences between the two paleolandscapes, though, were probably the product of tectonics, eustasy, and sedimentation combined. The paleosols may also indicate a trend from lower and/or more seasonal rainfall trending toward higher and/or less seasonal rainfall. If the glacioeustatic model is correct, possible Milankovitch-driven climatic changes and the geomorphic effects of sea-level change would probably have had some degree of temporal overlap, making a final assay of specific causes difficult. Nonetheless, detailed study of inter-cycle variability in Midcontinent Pennsylvanian paleosols (or paleosols in similar sequences) should prove to be a valuable source of information for the detailed reconstruction of basin history.

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