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Paleosols Below the Ames Marine Unit (Upper Pennsylvanian, Virgilian, Conemaugh Group) in the Appalachian Basin, U.S.A.: Variability on an Ancient Depositional Landscape.

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PALEOSOLS BELOW THE AMES MARINE UNIT (UPPER PENNSYLVANIAN, CONEMAUGH GROUP) IN THE APPALACHIAN BASIN, U.S.A.: VARIABILITY ON AN ANCIENT DEPOSITIONAL LANDSCAPE

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ABSTRACT: A Vertisol-like paleosol complex, ranging from 3 to > 10 m thick, is developed below the Ames marine interval (Conemaugh Group, Upper Pennsylvanian) in the Appalachian Basin (eastern Ohio, western Pennsylvania, West Virginia, and adjacent parts of Maryland and Kentucky). Sub-Ames mudstones contain the following pedogenic features: very large slickensides, microsparitic calcite nodules, nodules or coatings of radial calcite spar, preserved soil microstructure, soil-compatible birefringence fabrics, and prominent mottling (commonly restricted to the lower part of the paleosolum). Soil formation comprised: (1) long-term pedogenesis in alluvial (and probably lacustrine) sediments, and (2) rapid development of Histosols (Harlem Coal) as much as 8 m thick encouraged by the approaching Ames transgression. Pedogenic carbonates in the sub-Ames interval at three localities yielded $\delta^{18}O$ values ranging from −6.18‰ to −1.21‰ PDB (average = − 4.02‰ PDB; s.d. = 1.42‰) and $\delta^{13}C$ values ranging −9.17‰ to −6.72‰ PDB (average = −8.12‰ PDB; s.d. = 0.59‰). A binary plot of these values suggests mixing (probably seasonal) of evaporative and meteoric effects on isotope partitioning. The stratigraphy of the Ames-Harlem Coal interval, the regional distribution and thickness of the Harlem Coal, and features of the sub-Ames paleosol show that the pre-Ames landscape had significant local relief (in the form of shallow paleovalleys with broad interfluves) along the western to northern margin of the Appalachian Basin (Ohio, southwestern Pennsylvania). The stratigraphic relationships of sub-Ames paleosols, the Harlem Coal-Ames marine unit interval, and the Ames marine unit itself are compatible with a significant effect of eustatic sea-level rise in this area. Greater regional tectonic subsidence was probably the strongest control on sub-Ames sedimentation and pedogenesis along the eastern to southern margin (south-central Pennsylvania, West Virginia, northeasternmost Kentucky), where there appears to have been very little relief. The morphology and stable-isotope geochemistry of sub-Ames paleosols are compatible with seasonally wet-dry climates, probably with moderate (~ 500-1000 mm) annual rainfall.

INTRODUCTION

During the Pennsylvanian, rivers draining the Appalachian orogenic belt prograded across the northern Appalachian (Dunkard) Basin, depositing sands and large volumes of mud on large, low-relief alluvial-deltaic plains (Callahan 1965; Sarg 1979; Donaldson et al. 1985). The basin was episodically covered by large lakes or by extensions of the Midcontinent or Central Interior Sea. The Ames marine unit (Fig. 1), representing the most widespread marine incursion, has been correlated over > 53,000 km² (Merrill 1988a). It records a single, relatively rapid and essentially synchronous, basinwide transgression produced by tectonism and/or glacioeustasy (Donahue and Rollins 1974; Sarg 1979; Al-Qayim 1983; Brezinski 1983; Brady et al. 1985; Saltsman 1986; Merrill 1988a, 1988b; Dennison 1989). Widespread paleosols (commonly with Vertisol-like features) appearing in sediments directly below the Ames marine unit (the "sub-Ames interval") permit an interpretation of regional pedogenesis relative to sedimentation, tectonics, and climate for a relatively well-constrained time period truncated by this widespread, synchronous event. Study of the sub-Ames paleosols also promotes a new model for coal (Harlem) deposition that is somewhat in opposition to the delta-lobe model. Comparison of the sub-Ames paleosols to Midcontinent U.S.A. analogs establishes the response of pedogenesis to differing paleogeographic, tectonic, and eustatic effects.

GENERAL STRATIGRAPHY

Dominant facies associations in the sub-Ames interval (Fig. 1) are: (1) dominantly high-chroma mudstones with local sandstones (Pittsburgh or Round Knob Redbeds); (2) strongly calcareous, low-chroma mudstones, locally associated with, or grading into, nonmarine limestones (Martin 1908; Swartz and Baker 1922; Flint 1965); (3) the Harlem Coal, and rarely a second, higher, thin carbonaceous shale to coal, the Ames Coal; and (4) low-chroma, noncalcareous to calcareous, underclays of the Harlem Coal; and (5) stratified sandstones, shaly sandstones, and/or shales, locally overlying the Harlem Coal in Ohio and western Pennsylvania. Numbers 1, 2, and 4 above all have pedogenic features, such as color horizonation and mottling, large slickensides (commonly in nested synformal-antiformal sets, as in modern Vertisols), carbonate nodules, and a lack of stratification. Sub-Ames paleosol profiles containing some or all of these facies range from 3.1 m at Loc. 12 (Figs. 2, 3, 6D) to 10.3 m at Loc. 16 (Figs. 2, 4, 6A), but most are 5–9 cm thick. Examinations of over 150 thin sections (taken at vertical intervals of ≤ 50 cm) verify pedologic affinities (soil micromorphology terminology follows Bullock et al. 1985).

Typical sub-Ames paleosol profiles along the northern to western basin margin in eastern Ohio and western Pennsylvania (Figs. 3, 5A) are developed in the mudstones of the Pittsburgh or Round Knob redbeds. Nonetheless, these paleosols are variable in their pedologic characteristics, and the overlying Harlem Coal and post-Harlem, pre-Ames stratified deposits are variable and discontinuous. Closely spaced outcrops and well cores (e.g., Avonmore coal field; Fig. 2) show that paleosol color, presence or absence of carbonate nodules, presence or absence of coal, and horizon and profile thickness can change markedly over a few kilometers (Joeckel 1993).

In many outcrops, both the Harlem Coal and the overlying sub-Ames clastic sediments are absent, and redbed paleosols extend upward to the base of the Ames marine unit (Figs. 1, 3, 5A), yet up to 11 m of stratified sandstones and shales overlie the Harlem Coal locally in eastern Ohio (Condit 1912; Stout and Lamborn 1924; Lamborn 1930; Sturgeon et al. 1958). The following downward sequence appears below the Harlem Coal, where it is present: (1) gray to dark gray, slickensided underclay (usually 1.0–1.5 cm thick) containing carbonaceous streaks, pyrite segregations, and roots, and usually consisting of one or two horizons with clear to gradual lower boundaries; (2) two to four horizons of reddish brown or dark reddish brown mudstone (each ~ 1–2 m) with carbonate nodules throughout, large slickensides (prominent in the uppermost horizon), and clear lower boundaries; (3) locally, an intervening mottled mudstone–sandy mudstone with a clear lower boundary; and (4) stratified sandstones or mudrocks. Where the Harlem Coal is absent (e.g., Locs. 2–5, 7–10; Figs. 3, 5), the sequence is similar, but the profile is usually somewhat thicker: (1) one to three light gray to dark gray, or greenish gray mudstone horizons (aggregate thickness usually ≤ 1.5 m) with slickensides and clear to gradual lower boundaries; (2) two to four reddish brown mudstone

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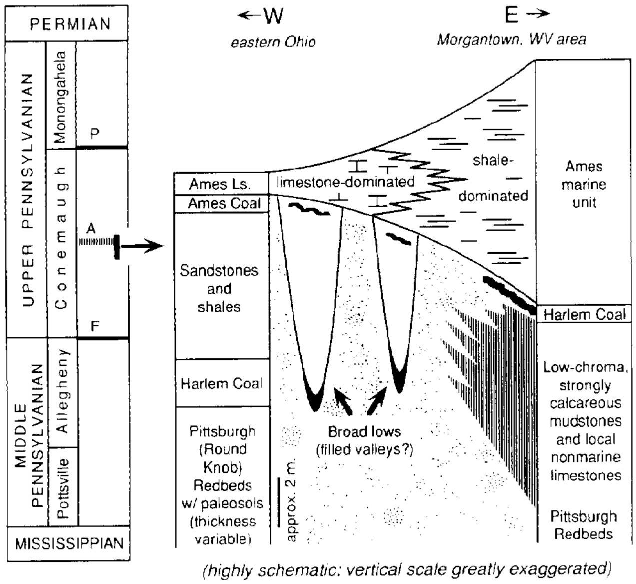

FIG. 1.—Highly schematic stratigraphic scheme for sub-Ames interval and Ames marine unit in northern Appalachian Basin, U.S.A. Section at left shows position of Ames marine unit (A) and sub-Ames interval (line with arrow) in Conemaugh Group, relative to upper Freeport Coal (F) at top of Allegheny Group and Pittsburgh Coal (P) at base of Monongahela Group. Schematic section at right shows detail of Ames and sub-Ames interval. Ames marine unit generally thickens and becomes carbonate-poor eastward. Harlem Coal is discontinuous in Ohio and Pennsylvania, and appears to have been deposited selectively in broad, shallow valleys or other lows.

horizons (each ~ 1.35–4.70 m thick) with carbonate nodules, large slickensides, and clear lower boundaries; and (3), stratified sandstones or mudrocks.

In contrast, along the southeastern basin margin (West Virginia and adjacent parts of southern Pennsylvania and western Maryland), paleosol profiles are developed in strongly calcareous mudstones as well as underlying redbeds (Fig. 5B). The downward sequence below the Harlem Coal is: (1) friable, gray or dark gray underclay < 1 m thick; (2) up to 8.8 m (usually 2–5 m) of resistant, strongly calcareous, low-chroma (light gray to dark gray) mudstone, with a clear to gradual (up to 20 cm) lower boundary; (3) one to three horizons of weak red to very dusky red (usually mottled at depth) mudstone (each 1.25–4.85 m thick), with abrupt to clear lower boundaries; and (4) stratified mudrock, sandstone or thin (< 50 cm) lacustrine limestones (Fig. 4: Locs. 16–19, 22, 23).

Overall, illite (~ 10 Å mineral) is the dominant clay-fraction mineral in sub-Ames mudstones (Joeckel 1993). Kaolinite and/or chlorite are present in lesser percentages. Localities 8, 10, 11, 12 show small to moderate amounts of mixed-layer "illite/smectite". Profiles under the Harlem Coal at Localities 11 and 12 contain large percentages of smectite (~ 14 Å mineral, expanding with glycolation), apparently weathered from illite.

The significance of sub-Ames clay mineralogy is debatable. Pervasive diagenetic illitization of original smectites may well have occurred, but as yet there is no unequivocal evidence for it. Clay residues from large carbonate nodules from Loc. 8 were analyzed under the assumption that they might record original soil minerals in a diagenetically protected microenvironment, yet they were found to be essentially identical (illite, illite/smectite, and chlorite) to the host paleosol. Apparent weathering effects (production of expandable clays) under the Harlem Coal are equally problematic: they could long postdate the original pedogenic interval, as may be the case in certain other underclays (Rimmer and Eberl 1982).

DESCRIPTON

Ames Coal and Harlem Coal

The concept of the Harlem Coal has been debated outside of its type area in Carroll County, Ohio. Most authors (e.g., Berg and Glover 1976; Glover and Bragonier 1978; Sarg 1979; Fonner and Messina 1981a, 1981b; Fonner et al. 1981; Merrill and Lyons 1987) refer to the thick coal directly below the Ames marine unit in southwestern Pennsylvania, West Virginia, and western Maryland as the Harlem, yet others (Al-Qayim 1983; Flint 1965) have attempted to recorrelate it as the Ames Coal of Sturgeon et al. (1958). Very few published stratigraphic sections actually indicate two separate coals (Collins and Smith 1977; Al-Qayim 1983), and in these outcrops the lower (Harlem) is the better developed. The "traditional" Harlem Coal (i.e., the more common usage of the name) in eastern Ohio, western Pennsylvania, and West Virginia often directly overlies the sub Ames paleosol, whereas no data suggest a well-developed paleosol underneath the higher Ames Coal where two coals are present. The traditional Harlem clearly has a genetic link with the sub-Ames paleosol complex underneath it, recording the elevation of water table and base level (with the Ames transgression) on the pre-Ames landscape. Thus, the traditional concept of the Harlem reflects its true genetic stratigraphic significance.

In eastern Ohio and western Pennsylvania, the Harlem is notably discontinuous and ranges from a < 1 cm smut to an 80 cm coal (Loc. 26); in fact, the Ames limestone, the Ames limestone–Harlem Coal interval, and the Harlem Coal itself can vary significantly in thickness over distances of a few kilometers (Shaw and Munn 1911; Johnson 1925a, 1925b, 1929; Schaffner 1958, 1963; Glover and Bragonier 1978; DeLong 1969, 1972; Joeckel 1993). In contrast, the Harlem is more persistent on the eastern to southern margin of the basin (West Virginia and immediately adjacent areas), where it is 5–60 cm thick.

Pittsburgh or Round Knob Redbeds

These are thick (> 5 m), dominantly reddish or reddish brown, blocky weathering, noncalcareous to strongly calcareous, massive mudstones. Pedologic features include: (1) common, large, intersecting slickensides inclined 15–60° that form discernible synformal-antiformal sets 2–5 m wide in some cases; (2) common to many small slickensides; (3) common, sharp-margined, subrounded to rounded, 1–80 mm nodules of hard, fine-grained, light gray to light reddish brown calcitic carbonate; and (4) rare brecciation (relict soil structure). Mudstones are laterally persistent in much of western Pennsylvania (Johnson 1925a, 1925b; Hughes 1933), but locally in eastern Ohio they are partially cut out by stratified clastic sediments directly beneath the Ames and above the Harlem Coal. In the mudstones, high-chroma horizons predominate; low-chroma horizons are common but usually lie exclusively within 1.5 m of the base of the Ames marine unit. Low- and high-chroma transitions are marked by gradations rather than depositional contacts, evoking a pedochemical transition.

In thin section, high-chroma mudstones are up to 80% weakly to strongly impregnated with iron oxide (birefringence fabric is locally undifferentiated). Impregnative iron oxide commonly has a patchy distribution, producing roundish and equant to narrow and streak-like mottles with distinct to prominent margins (Fig. 7D). Distinct- to sharp-margined patches of unimpregnated matrix (low-chroma mottles) appear alongside or totally surround iron-oxide-impregnated zones. Several birefringence fabrics appear, but stipple- and mosaic-speckled and weak to strong parallel striated are the most common. A few isolated examples of circular striation, unistrial, and granostriated fabrics appear in many thin sections. Rarely, there are small to large (< 1.5 mm²) domains of unistrial fabric interpreted as domains of relict sedimentary fabric. The birefringence color of clays is light gray to yellowish gray, becoming yellowish red to bright red in zones rich in iron oxide. Very few to few (2–5%), subrounded to rounded, equant to prolate, pure nodules of iron oxide are always present. Iron oxide

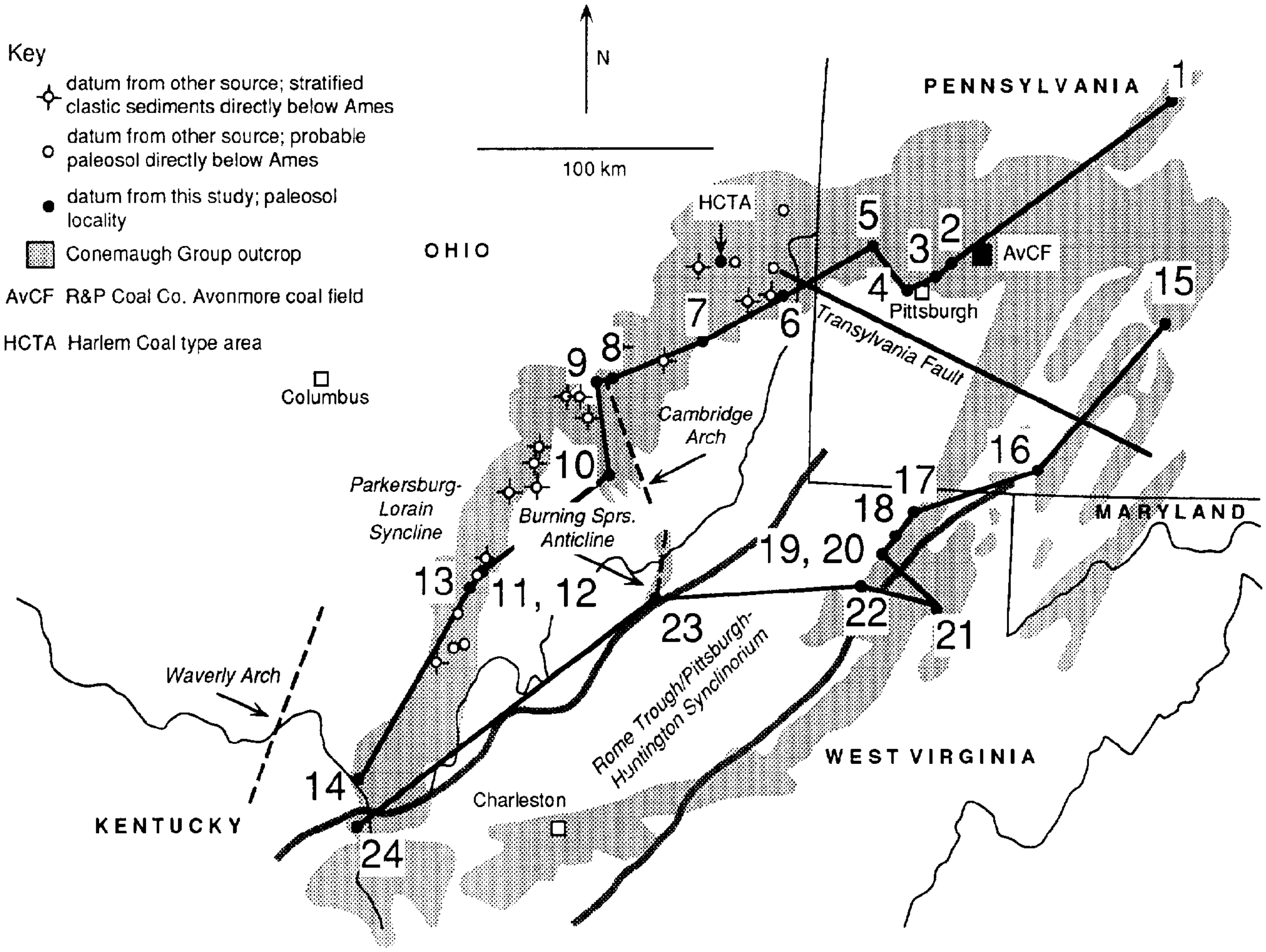

FIG. 2.—Conemaugh Group outcrop and associated structures in northern Appalachian Basin (in part after Collins and Smith 1977 and Hansen 1986). Note discontinuous distribution of non-paleosol facies (stratified sands and muds above Harlem Coal) directly below Ames marine unit interval. Numbered localities constitute northwestern (1–14) and southeastern (16–24) transects for sub-Ames paleosol profiles (see Appendix 1 and Joeckel 1993 for more data). Note discontinuous distribution of Harlem Coal in eastern Ohio.

and microsparitic carbonate nodules appear in elongate tracts or clusters, as in modern Vertisols, wherein similar nodules are redistributed by pedoturbation (Mermut et al. 1989).

Thin sections of low-chroma paleosol horizons (not underclays *sensu stricto*) above high-chroma horizons in the Pittsburgh or Round Knob Redbeds show massive fabric. Stratification is absent from thin sections in all but a single case, suggesting that original sedimentary fabrics were destroyed. Soil structure is absent as well, however; if originally present, it was destroyed by waterlogging and/or compaction. Microsparitic calcite nodules (30–8000 μm) form $\leq$ 15% of these mudstones; a very few have rough margins that appear to record partial dissolution. Weak crystallitic (scattered carbonate crystallites), stipple-speckled, and random striated birefringence fabrics dominate. Crystallitic *b* fabrics are rare in the uppermost few tens of centimeters of paleosol profiles, where stronger reticulate, cross-striated, or parallel-striated fabrics are visible, possibly because of very late-pedogenic leaching of carbonates under acid marshes or swamps, or to burial diagenetic leaching. Parallel-striated domains appear throughout low-chroma horizons, recording shear stress produced by wetting and drying (Nettleton and Sleeman 1985), which may have been accentuated by burial diagenesis (cf. Jim 1986). Granostriated fabric appears around large carbonate nodules. Clays have light yellowish gray or light brownish yellow to light yellow birefringence colors due to the lack of impregnative iron oxide.

Strongly Calcareous, Low-Chroma Mudstones

Thick (~ 5–7 m), moderately to very strongly carbonate-impregnated massive mudstones, associated with or grading into impure to pure limestones, appear underneath the Harlem Coal at and near the eastern to southern basin margin (Fig. 4: Locs. 16–19, 22, 23; Figs. 5B, 6A, B), where they have been referred to as the "Lavansville limestone" (Flint 1965) or (erroneously) the Ewing Limestone (Fonner et al. 1981). Strongly calcareous, low-chroma mudstones contain nodules or lithoclasts and/or intraclasts of micritic to finely microsparitic carbonate, diagonal stringers or sheets of micritic-microsparitic carbonate along slickenside planes (Fig. 6C), and/or thin beds of micritic to microsparitic, intraclastic or lithoclastic limestone containing ostracodes and/or mollusc fragments (which also appear sparsely in the mudstones). A few, small pyrite crystals are usually present throughout.

These sediments are uniformly gray to very dark gray and nonbedded, contain many intersecting oblique (30–55°) shear planes or slickensides, and weather into angular blocks, wedge-shaped aggregates, or large (up to

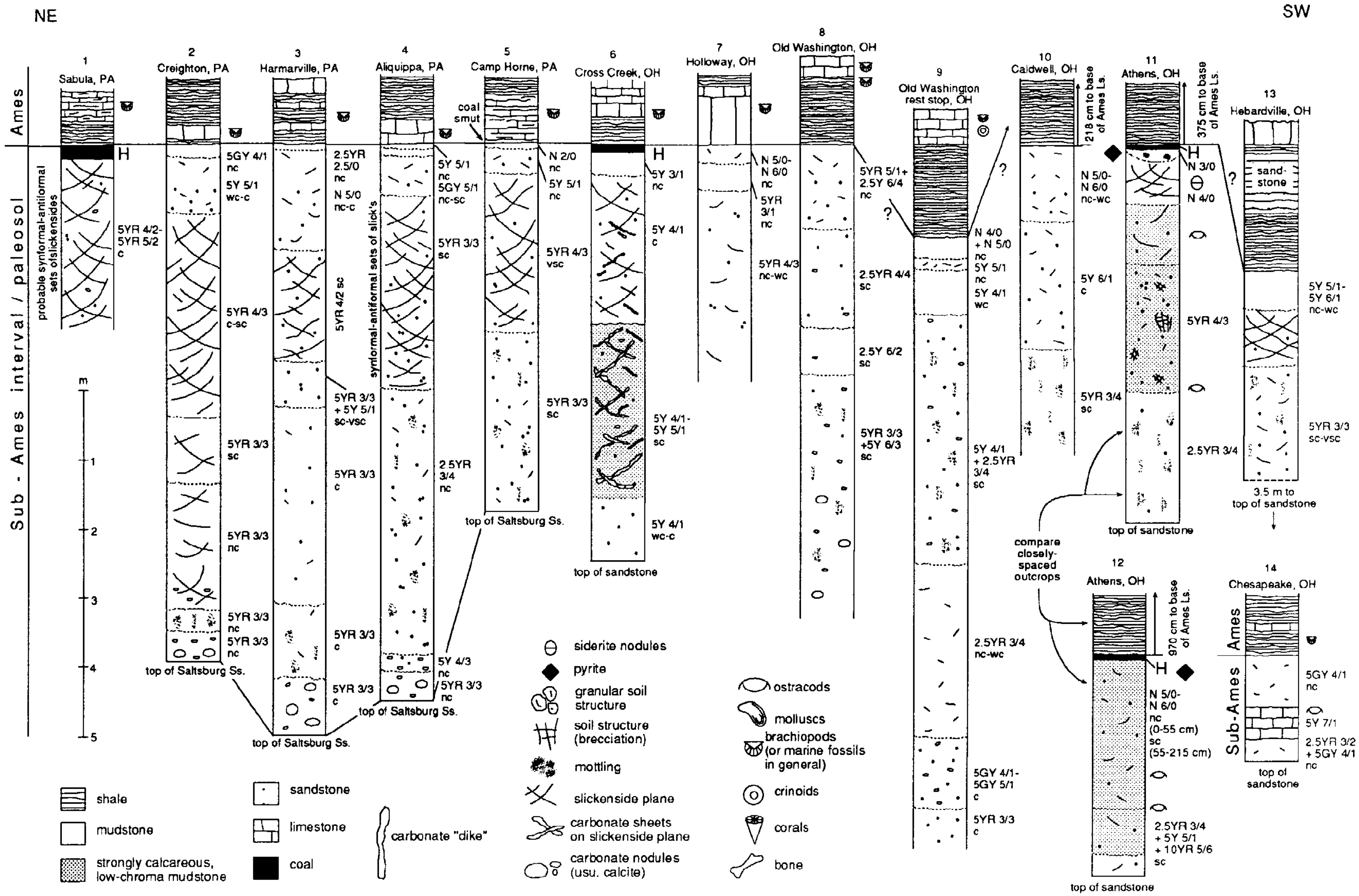

FIG. 3.—Transect of western to northern part of Conemaugh Group outcrop, showing variation in development of sub-Ames paleosol. Datum is contact between marine (Ames) and underlying nonmarine sediments. Note rare appearance of Harlem Coal, except where thick, pre-Ames clastics overlie it (Locs. 11, 12).

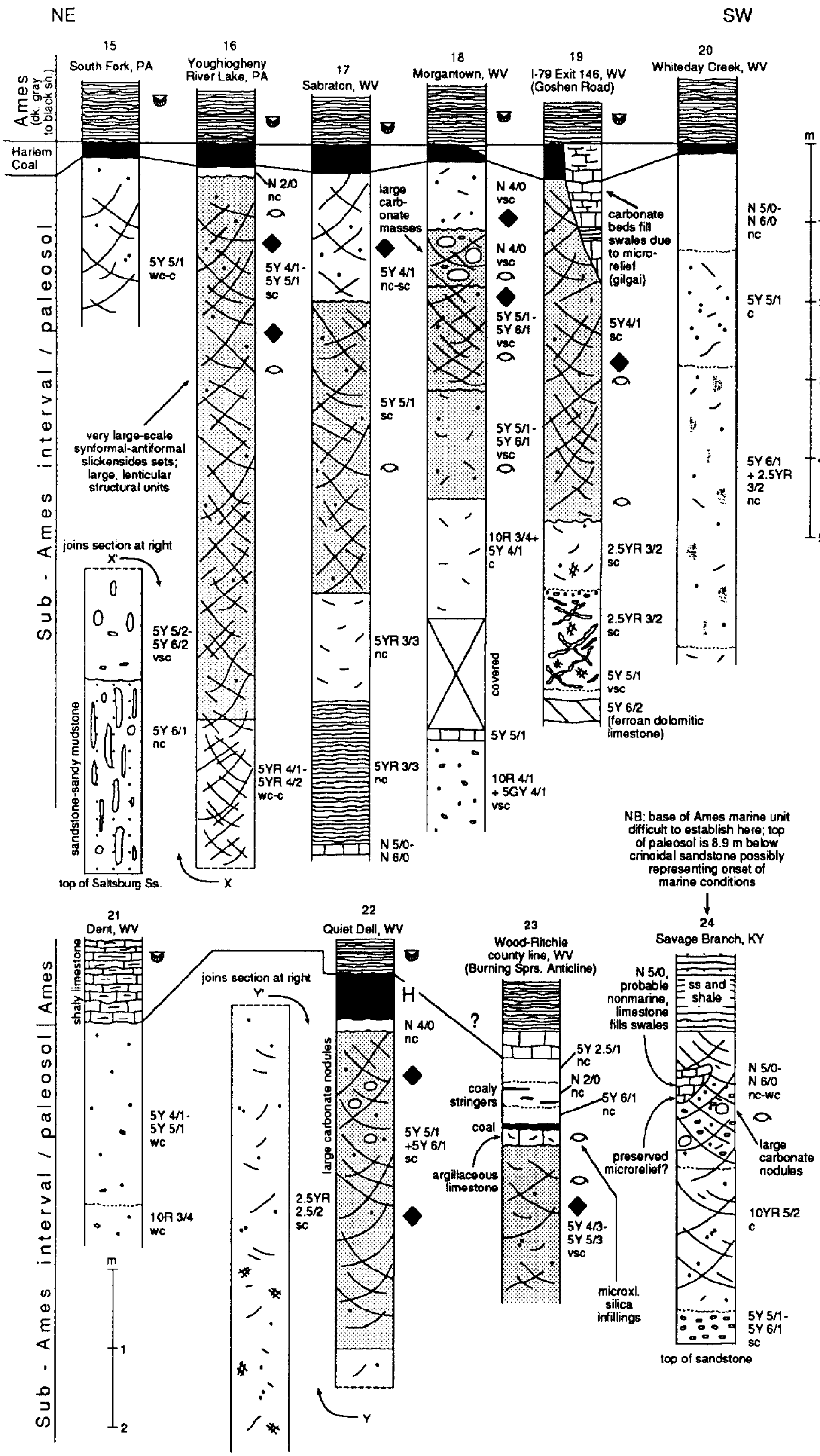

FIG. 4.—Transect of eastern to southern part of Conemaugh Group outcrop, showing variation in development of sub-Ames paleosol. Datum is contact between marine (Ames) and underlying nonmarine sediments. Note more consistent appearance of Harlem Coal than in Figure 3.

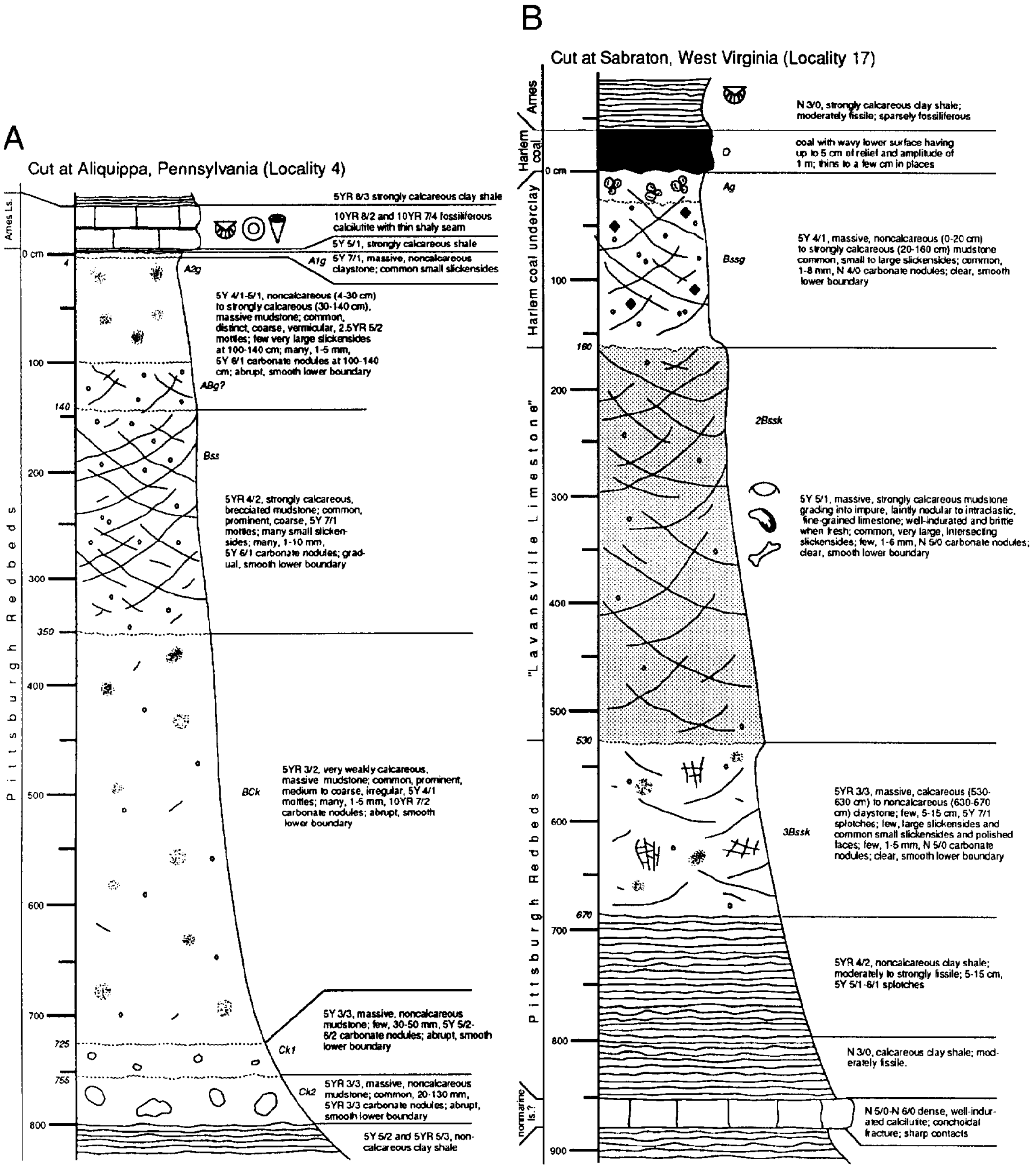

FIG. 5.—Detailed paleosol profiles illustrating paleosol characteristics common to A) western to northern and B) eastern to southern margins of the northern Appalachian Basin. Symbols as in Figure 3.

35 cm × 150 cm), lenticular units tilted ~ 20–30° (Loc. 16 only). At Loc. 19 (Fig. 6B), slickensides also form crude, synformal-antiformal sets with relict gilgai microrelief atop. These features indicate some affinity with modern Vertisols (Krishna and Perumal 1948; Dudal and Eswaran 1988; Joeckel 1994). Furthermore, the downward gradation over 2–20 cm in color and carbonate content gradation from strongly calcareous, low-chroma mudstones into high-chroma (Pittsburgh) mudstones is soil-like. Slickenside planes frequently cross this boundary, indicating a continuity of pedogenic processes.

Similar strongly calcareous, low-chroma (in a few cases oxidized) mudstones (~ 2–4.5 cm thick) also appear below the Harlem Coal and underclay in parts of Ohio (Locs. 6, 11, 12). In far northeastern Kentucky and adjacent Lawrence Co., Ohio (Locs. 14, 24), the sub-Ames paleosol contains many large carbonate nodules and/or discontinuous to contin-

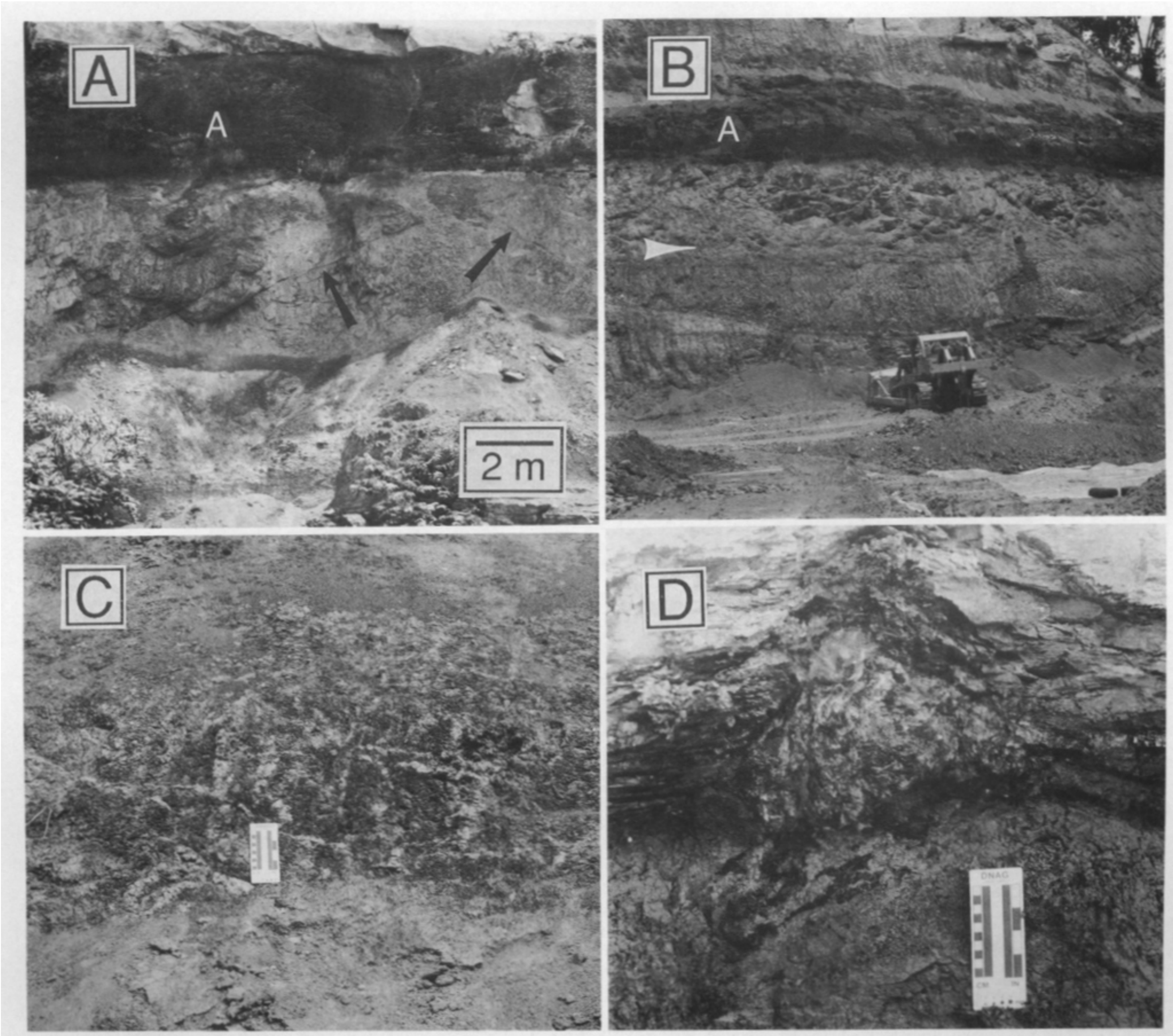

FIG. 6.—**A)** Stratigraphic section at Loc. 16; Ames marine unit (A) is ~ 5 m of dark gray shale overlying Harlem Coal (not visible) and sub-Ames paleosol. Synformal-antiformal, very large slickensides (a few are arrowed) appear in massive, strongly calcareous, low-chroma mudstone, approximately 7 m thick, which overlies Pittsburgh Redbeds. Saltsburg Sandstone (weak ledge low in photo) underlies sub-Ames interval. **B)** Stratigraphic section at Loc. 19. Ames marine unit (A) and Harlem Coal (at base of Ames marine unit, but not visible) over sub-Ames 5–6 m deep paleosol developed in strongly calcareous, low-chroma mudstones. A few, very large slickensides are visible (undulating fracture surfaces in exposure face). Bulldozer in foreground is approximately 3 m high. Lithologic discontinuity (arrow) separates this paleosol from another vertic paleosol underneath (in Pittsburgh Redbeds), to which it appears to be partially welded. **C)** Fine-grained calcite sheets along slickensides in redbeds deep in sub-Ames (sub-Harlem Coal) paleosol; exposure on exit ramp, just around hill from A above. DNAG scale in centimeters and inches. **D)** Pyritized and coalified stump in Harlem underclay at Loc. 11. Note draping of shale laminae over stump, indicating late pedogenic–very early diagenetic (pre-compaction) pyritization by infiltration of marine pore waters. DNAG scale in centimeters and inches.

uous beds of nonmarine limestone 40–50 cm thick. These limestones lack marine fossils and show evidence for periodic desiccation. In southern Pennsylvania and adjacent Maryland, similar limestones (with spirorbids and/or ostracodes) ≤ 2 m thick also appear locally, underneath the Harlem Coal (Martin 1908; Richardson 1934; Dutcher et al. 1959; Flint 1965). Thin (15–30 cm) beds of well-indurated, cracked, micritic or finely microsparitic, calcitic or ferroan dolomitic limestone directly underlie strongly calcareous mudstones in the Morgantown, West Virginia area (Figs. 4, 5). Such limestones have traditionally been considered nonmarine or "freshwater" (cf. Adams 1954).

Small-scale (≤ 3500 μm) brecciation, interpreted as ultrafine to very fine, subangular blocky soil structure, rarely appears (Locs. 11, 19, 22) in thin sections of strongly calcareous, low-chroma mudstones. In less calcareous zones, crystallitic birefringence fabrics (calcite crystallites throughout the mudstone matrix) dominate, but small (≤ 5 mm^2) domains of moderate to strong, clay-dominated (stipple speckled) fabrics are common. In carbonate-dominated domains, strong crystallitic birefringence fabrics characterize the matrix, and only a few (≤ 2%) domains of stipple-speckled fabric are present. Carbonate-dominated zones may actually contain a few veins or vugs infilled with clear, equant spar. Usually, there are a very few

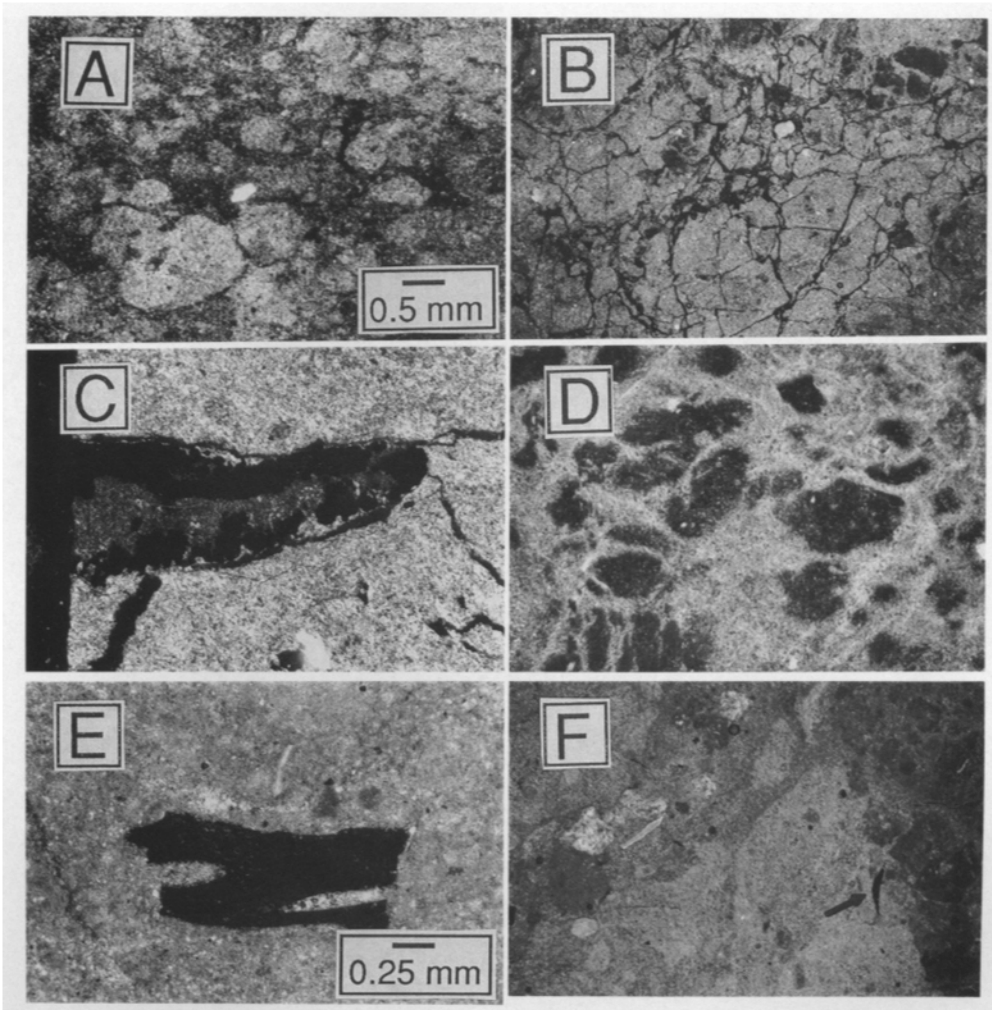

FIG. 7.—Micromorphology of sub-Ames paleosols. **A)** Granular structure in Harlem Coal underclay at Loc. 11 (vertical section 0–5 cm below upper surface of paleosol). Note organic material between granules. **B)** Subangular blocky structure in oxidized strongly calcareous mudstone with dark "veins" between peds impregnated with iron oxide at Loc. 11 (horizontal section 2.5 m below upper surface of paleosol). **C)** Pyritic feature (probably a root) infilled with late diagenetic microcrystalline silica from Loc. 12 (vertical section 35–40 cm below upper surface of paleosol). **D)** Patchy iron oxide impregnations (high-chroma mottles) in massive mudstone, 2.5 m below upper surface of paleosol at Loc. 13. Intervening bleached areas consist of stipple-speckled to weakly striated birefringent clay **E)** Bone fragment (vertebral centrum?) in strongly calcareous, low-chroma mudstone, Sabraton, West Virginia at Loc. 17 (transverse section 3 m below upper surface of paleosol). **F)** Nodular-intraclastic fabric of strongly calcareous, low-chroma mudstone at Loc. 19 (transverse section 1.02 m below upper surface of paleosol). Nodules and/or intraclasts of carbonate set in a mudstone matrix with speckled to striated and locally crystallitic birefringence fabric. Vertebrate fragment (scale?) indicated by arrow. Scales in A–D and F are 0.5 mm.

(< 5%) ostracode valves, bivalve mollusc fragments, and even small vertebrate fragments scattered throughout the matrix (Fig. 7E, F). Small (≤ 6 mm), rounded nodules of pure micrite or fine microspar (identical to those seen in more typical sub-Ames paleosol mudstones) or intraclasts and/or lithoclasts of finely microsparitic limestone are usually present, forming 10–15% of the sediment in some cases (Fig. 8E). Small pyrite crystals and framboids (≤ 2%) are scattered throughout the matrix, as are fragments of macerated organic matter.

Strongly calcareous low-chroma mudstones clearly have a pedogenic overprint, which is indicated by slickensides, local relict gilgai, spotty clay birefringence fabrics, rare soil structure, brecciation of preexisting carbonates, and precipitation of authigenic carbonate as nodules and sheets. Interpreting the depositional and subsequent pedogenic history of such unique sediments is difficult, but the presence of nonmarine fossil biotas, abundant carbonate, and nonmarine limestone lithoclasts or intraclasts indicate a lacustrine signature. Much clastic sediment was still present in the system, however, suggesting a combination of lacustrine and alluvial deposition over time. The resulting sediments underwent episodic wetting and drying, leading to brecciation and nodularization of carbonates and development slickensided cracks. Certain modern ephemeral lake muds have similar features (Schreiber et al. 1972).

Harlem Coal Underclays

Harlem Coal underclays are typically light gray to gray, but also contain discontinuous dark gray upper horizons (pod-shaped bodies a few meters long and < 40 cm thick) in some outcrops. These discontinuous horizons probably represent organic-matter-rich horizons in former soil microlows, which are common in wetter modern Vertisols (Neitsch et al. 1989; Williams and Touchet 1989; Wilding et al. 1991). Other features are: medium

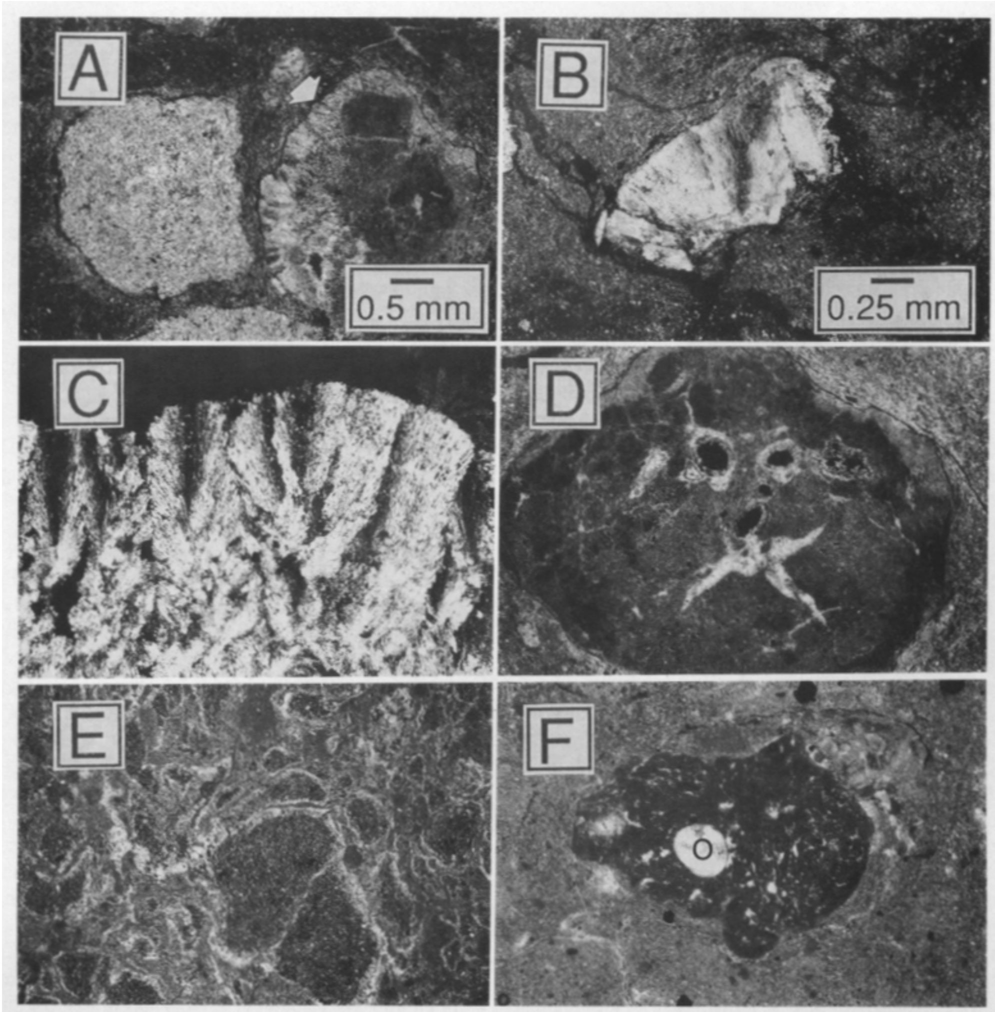

FIG. 8.—Micromorphology of sub-Ames paleosols. **A)** Microsparitic nodules: coarser in nodule on left and finer in nodule on right. Finer microspar nodule is impregnated with iron oxide and has partial coating of radial spar (arrow). Loc. 8, horizontal section 3 m below upper surface of paleosol. **B)** Fragment of radial spar; note extinction band (Loc. 4, 4 m below upper surface of paleosol). **C)** Radial spar coating from exterior of a large nodule; note extinction bands (Loc. 8, 4.5 m below upper surface of paleosol). **D)** Iron-oxide-impregnated microspar nodule with included iron oxide nodules (dark) and spar-filled cracks (Loc. 8, transverse section 3 m below upper surface of paleosol). **E)** Clay granules (relict peds?) and microsparitic carbonate matrix in dolomitic "dike" approximately 11.7–11.8 m below upper surface of paleosol (Loc. 16, vertical section). Note circumgranular cracks infilled with clear spar. **F)** Limestone intraclast with spar-filled ostracode (o), from strongly calcareous, low-chroma mudstone (Loc. 18, transverse section 3 m below upper surface of paleosol). Scales in **A** and **D–F** are 0.5 mm; scales in **B** and **C** are 0.25 mm.

to large slickensides, pyrite nodules or scattered crystals, carbonized and pyritized roots and stumps, carbonaceous streaks, and wavy, low-relief contact with the overlying coal (possibly an indicator of original soil microrelief). Moderately to strongly developed, loosely grouped to packed granules (50–1500 μm), sometimes grading into fine, rounded subangular blocky aggregates, appear in some Harlem Coal underclays (Fig. 7A). Packed granules grade laterally into massive or very faintly granular matrix with or without scattered, distinct granules. Individual granules are slightly reddish brown to brownish gray in plane-polarized light, because of an overall impregnation with organic material; many granules are partially coated or capped with brown to dark brown or opaque organic matter (Fig. 7A). A few granules have discrete hypocoatings presumed to be organic compounds. Stipple-speckled (common), weak to moderate cross-striated or parallel-striated (very rare), and unistrial (extremely rare, only in $\leq$ 1 mm^2 domains) birefringence fabrics appear in the granular underclays. A very few granules have discontinuous rims of birefringent clay at or near their margins, and there are isolated examples of continuously oriented rims of birefringent clay at granule margins (circular striated fabric). Clay birefringence colors are grayish yellow to bright yellow, but matrix birefringence is often partially masked by pervasive, impregnative organic material. At three localities, few ($\leq$ 5%) pyrite crystals ($\leq$ 800 μm) are scattered throughout the matrix or distributed in loose stringers between granules. Pyritized plant fragments or roots appear rarely, and a few of these have internal voids infilled with microcrystalline silica (Fig. 7C), as do carbonate nodules at other localities.

Although granular Harlem underclays superficially resemble pellet tonsteins (Diessel 1992), faunal activity and aggregative effects of organic matter almost certainly produced the underclay granular structure (as in modern near-surface soil horizons; Bullock et al. 1985). It is possible that this faunal activity dates to the late-pedogenic, syntransgressive perching of the water table associated with transgressive drowning (cf. Gardner et al. 1992). Nongranular (massive) underclay horizons either appear below horizons with strong granular structure or constitute the entire underclay. These horizons have moderate to strong parallel-striated and/or weak to strong cross-striated or reticulate-striated *b* fabrics (with light yellowish brown to yellow birefringence), again reflecting shear stress due to pedogenic shrink-swell and possible diagenetic compaction as well.

CARBONATE AND IRON OXIDE SEGREGATIONS

Carbonate features in sub-Ames paleosols consist of: (1) fine calcite crystallites in mudstone matrices, (2) typic calcitic micrite nodules, (3) geodic to septaric calcite microspar nodules (Fig. 8A), (4) radial calcite spar nodules (Fig. 8A–C), (5) compound calcitic microspar or calcitic microspar–iron oxide nodules (Fig. 8D), (6) irregular sheets or stringers of fine carbonate along slickenside planes (rare), and (7) dolomitic-calcitic subsoil "dikes" (very rare). Low-Mg calcite (3.02–3.03 Å) is the dominant carbonate mineral in sub-Ames pedogenic nodules, carbonate beds, carbonate sheets along slickenside planes, and nonmarine limestones. Concentrations of dolomite (2.88–2.90 Å) appear in subsoil "dikes" (Loc. 16) and in nonmarine limestones underlying paleosols (Loc. 19). One such limestone (Loc. 19) is mostly ferroan dolomite. Generally, all nodules are subrounded to rounded and sharp-margined, a condition probably resulting from cyclic pedoturbation (e.g., Mermut and Dasog 1986).

Micrite nodules are rare in paleosols of the sub-Ames interval, and aside from crystallite size, they are very similar to nodules composed of very fine microspar. Microspar nodules ($\leq$ 5 cm in diameter) are much more common and consist of equigranular xenotopic (mosaic-like) microspar grading into macrospar (aggrading neomorphism is apparent in some nodules). These nodules are particularly common in mudstones of the Pittsburgh or Round Knob redbeds. Nodules range from being nearly free of iron oxides to iron-oxide-banded to so thoroughly impregnated with iron oxide that they are nearly opaque. This entire range is commonly seen within one thin section. Septaric veins of clear, commonly equant, coarse microspar or macrospar are usually present in the interiors of nodules, and in high-chroma mudstones, one or two concentric bands of iron oxide are commonly present in the veins. Commonly, spar veins are truncated by the margin of a nodule, demonstrating at least one period of abrasion (possibly via pedoturbation) after the final precipitation of void-filling spar. Microcrystalline silica is typically present as a final stage of intranodular void filling. Identical microcrystalline silica infillings in pyritic features from Harlem underclays and in ostracode valves from limestones atop the sub-Ames paleosol suggest that silica precipitation is a burial diagenetic phenomenon. Microspar nodules in the sub-Ames paleosols may represent neomorphism after micrite during seasonal wet periods of only a few weeks to a few months (cf. Sehgal and Stoops 1972; Sobecki and Wilding 1983). Neomorphism may have also been encouraged by pedoturbation (cf. Wieder and Yaalon 1982). Vein-filling calcite spar within nodules probably precipitated directly from soil solution (cf. Wieder and Yaalon 1982; Drees and Wilding 1987; Monger et al. 1991).

Radial calcite (Fig. 8A–C), found at seven localities, consists of $\leq$ 200 μm, needle-like, prismatic crystals grouped in flower-bouquet-like bundles (250–1500 μm) showing sweeping extinction. The morphology of radial spar strongly suggests growth into open space within unconsolidated sediment (i.e., soil). It appears as: (1) common, discontinuous outer coatings around microspar nodules, (2) rare subrounded masses that are clearly fragments of much larger precursor nodules, verifying a pre-burial origin (Fig. 8B), and (3) very rare rounded nodules composed entirely of radial spar forming a continuous (360°) fabric. Drees and Wilding (1987) found similar coatings of prismatic calcite crystals with iron oxide banding in modern soils from Texas. These modern calcite crystals grow normal to nodule surfaces into inter-nodular spaces (intermittently filled with water). Sub-Ames radial spar is interpreted to have formed in the same way; regular cycles of soil shrinking and swelling would have facilitated cracking, providing extranodular voids for crystal growth.

Compound nodules in sub-Ames paleosols consist of a few, small calcite microspar (and in some cases, iron oxide) nodules in a matrix of microspar and, rarely, radial macrospar. The association of iron oxide features (banding, staining, coatings, or discrete nodules) with carbonate nodules in sub-Ames paleosol profiles is analogous to certain soils (notably some Vertisols) of the semiarid to arid tropics. In these soils, precipitation of carbonate and iron oxide in the deeper part of the solum results from seasonal or long-term climatic water-table fluctuation (Sehgal and Stoops 1972; Kooistra 1982; Nettleton and Sleeman 1985). Matrix carbonate in the sub-Ames paleosol nodules is non-cathodoluminescent to very weakly cathodoluminescent, but spar cements in small voids within carbonate or iron oxide–carbonate nodules show up to 30 oscillatory bands (dull-orange-luminescent, weakly luminescent, and nonluminescent), which possibly record changes in soil Eh (hence also Fe and Mn mobility) related to water-table fluctuation.

Irregular sheets (1–7 cm thick, 20–120 cm long) of hard, light gray to white, micritic to finely microsparitic carbonate (grading into stringers of irregular, subrounded nodules) appear along intersecting slickenside planes in the sub-Ames paleosol profiles at Locs. 6 and 19 (Fig. 6C). They contain a few sand or silt grains and a few clay-filled vugs, but otherwise are relatively pure, and therefore appear to be displacive in origin. A thin section of one sheet (Loc. 6) showed septaric (*sensu* Bullock et al. 1985) veins infilled with clear, equant spar, verifying that carbonate precipitation took place before significant burial (i.e., while overburden pressures were still low enough to allow radial cracking), as a result of carbonate precipitation from groundwater in very late stages of pedogenesis.

Dolomitic-calcitic subsoil "dikes" (vertical sheets or masses of carbonate, up to 5 cm × 100 cm, filling joints or desiccation cracks) appear in the lowermost 400 cm of a sub-Ames profile at Loc. 16 (Fig. 4). They consist mostly of fine ($\leq$ 20 μm), equigranular xenotopic microspar, but approximately 5–20% of the material consists of $\leq$ 1400 μm clots of micrite, which are partially surrounded by curving (circumgranular) cracks (Fig. 8E). Approximately 10–40% of the dike material is subangular blocky or rounded subangular blocky fragments (< 3000 μm; probably ultrafine to very fine peds) of birefringent clay or silty clay , also surrounded by cracks infilled with coarse microspar. The "dikes" appear to be deep-solum features associated with groundwater (cf. Joeckel 1994).

Small iron oxide nodules ($\leq$ 10%) appear in most thin sections of high-chroma sub-Ames mudstones; they are much less common (0–2%) in low-chroma mudstones. The dominant type is usually $\leq$ 500 μm in diameter, sharp-margined and strongly impregnative to pure. Weakly or moderately impregnated halos surround a few iron oxide nodules in some thin sections. Siderite nodules, crystallites, or iron oxide pseudomorphs appear in sub-Ames paleosols (Loc. 4, 9, 11; see Joeckel 1993), but they are extremely rare. At Locs. 4 and 13, there are rare (< 2%), 50–200 μm, iron oxide pseudomorphs after pyrite.

In several thick, high-chroma-dominated profiles lacking a well-developed Harlem Coal, there are large, weakly iron-impregnated calcite nodules or compound carbonate–iron oxide nodules deep in the profile. Subrounded, 5–10 cm compound iron oxide nodules with included nodules of dense, finely microsparitic (< 10 μm), equigranular xenotopic calcite appear in the lower 1.4–3.4 m of sub-Ames profiles at Locs. 2 and 3. Segregations of interstitial iron oxide are common in the calcite microspar nodules found in high-chroma horizons, and small (20–300 μm) subrounded nodules of iron oxide are included within the microspar. Veins of clear, equant calcite spar crosscut both calcite microspar and iron oxide phases. Subrounded, 1–15 cm nodules of dense, hematite-rich microsparitic calcite appear in the lower 2.0 m of profiles at Locs. 4 and 8. These large nodules contain a few, small, included iron oxide nodules.

STABLE ISOTOPE (C, O) GEOCHEMISTRY

Calcite from pedogenic nodules in the sub-Ames interval at Locs. 4, 8, and 19 (Fig. 9) yielded $\delta^{18}O$ values ranging −6.18‰ to −1.21‰ PDB (average = −4.02‰ PDB; standard deviation = 1.42‰) and $\delta^{13}C$ values ranging −9.17‰ to −6.72‰ PDB (average = −8.12‰; standard deviation = 0.59‰ PDB). Calcite spar from veins within nodules have $\delta^{18}O$ in the same range as the nodule matrix (−2.96‰ to −2.44‰ PDB), but slightly lower $\delta^{13}C$ (−10.07‰ to −7.8‰ PDB), probably indicating separate geochemical events.

At each locality, the lowest $\delta^{18}O$ values in nodule carbonates are from deeper in the profile than the highest $\delta^{18}O$ values, but overall there is no consistent trend with increasing depth. Evaporative effects (which concentrate $\delta^{18}O$) would have been strongest near the soil surface and weakest deep in the solum, but nodules would have been mixed through profiles by pedoturbation. The trend shown by carbonate from pedogenic nodules seems to indicate that individual nodules are composites of crystallites formed at different times during the year (i.e., through a range of soil moisture; Lohmann 1988).

Five different brachiopods from the Ames Limestone (Loc. 8) yielded a tight range of $\delta^{18}O$ values from −4.05‰ to −3.49‰ PDB, yet corresponding $\delta^{13}C$ values ranged widely, from −3.72‰ to 2.34‰ PDB (Fig. 9A, B). These samples appear to represent a meteoric alteration trend, and it is likely that the original Ames marine $\delta^{18}O$ was, perhaps, two per mil higher (Lohmann 1988, fig. 2.8). Thus, nodular carbonates from the sub-Ames paleosols are slightly to moderately depleted relative to hypothetical contemporary marine waters. Hypothetical pre-Ames and post-Ames meteoric calcite lines (Fig. 9B, C) differ by about two parts per mil, possibly indicating (1) greater distance from marine source waters during pre-Ames times, (2) increased evaporative effects (drier climate) during post-Ames times, and/or (3) higher temperatures during post-Ames time. Both lines, however, are in the range of values expected for coastal meteoric waters (Hays and Grossman 1991). Using the modifications of Cerling's model (Cerling 1991) outlined by Mora et al. (1993, fig. 22), $\delta^{13}C$ values from the paleosols indicate atmospheric pCO_2 in the approximate range of 1150–1900 ppmV (S. Driese, personal communication, 1993), probably somewhat of an overestimate (Mora et al. 1993).

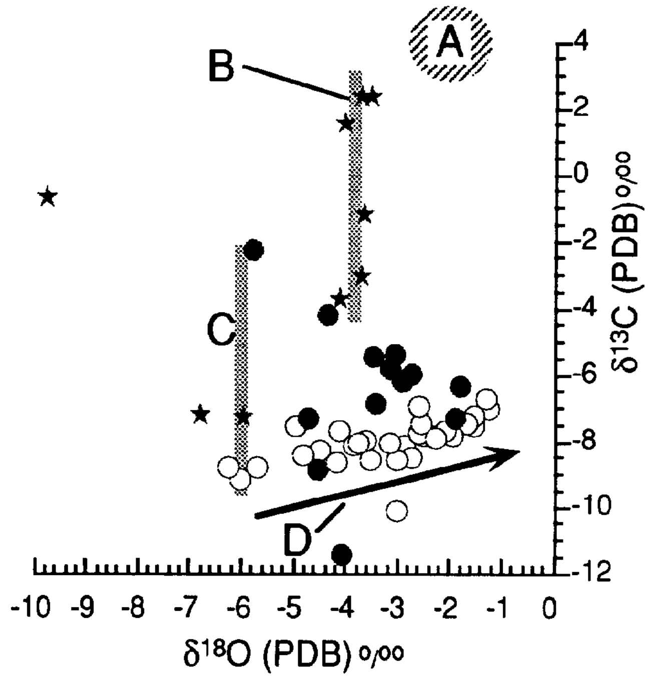

FIG. 9.—Plot of stable isotopes (C, O) from sub-Ames paleosols (see Joeckel 1993). **A)** Probable approximate composition of original Late Pennsylvanian marine waters (Lohmann 1988). **B)** Immediate post-Ames meteoric alteration trend based on six samples from five brachiopods from the Ames limestone at Locality 8. **C)** Probable pre-Ames transgression meteoric line based on composition of lowest $\delta^{18}O$ values from sub-Ames pedogenic nodules. **D)** Trend line for sub-Ames pedogenic nodules indicating mixing of meteoric and evaporative influences.

DISCUSSION AND INTERPRETATION

Pedogenic History

Macro- and micromorphological features in sub-Ames mudstones indicate the genesis of Vertisol-like soils under variable drainage conditions in alluvial to lacustrine muds (e.g., Nettleton and Sleeman 1985; Dudal and Eswaran 1988; Mermut et al. 1989). The paleosols were moderately developed soils in that they formed under a weak to moderate regime of chemical weathering under markedly seasonal rainfall, but their signature of subaerial exposure is pervasive in the sub-Ames interval. Multiple sedimentary and pedogenic events can be deciphered immediately at a few outcrops, but are less readily apparent elsewhere due to strong, ongoing pedogenic overprinting during pre-Ames times (processes such as wetting-drying, water-table fluctuations, and carbonate and iron mobilization-precipitation). The Harlem Coal indicates a major, local to regional change to poorly drained conditions and the development of shallow to deep Histosols. Considering the stratigraphic relationships of the sub-Ames paleosols, the Harlem Coal, and the Ames marine horizon, the most likely scenario for this drainage change would be the ponding of drainage and the perching of water tables in response to rise of base level with the approach of the Ames transgression.

Slickensides, so common in sub-Ames profiles, appear to have an optimal and relatively shallow depth ($\leq$ 2 m) of formation in modern soils (Yaalon and Kalmar 1978). Thus, paleosol profiles several meters thick with large slickensides throughout may have formed through ongoing sedimentation. In a few profiles (e.g., Loc. 16; Fig. 6A, B), though, individual slickenside sets extend downward for as much as 5 m, suggesting that pedogenic slickensides can form to great depths (even across discontinuities in parent material) over long periods of time (cf. Schreiber et al. 1972). In most sub-Ames profiles, slickensides are concentrated in relatively shallow horizons, whereas water-table features (extensive mottling, hematite-calcite nodules) are concentrated in subjacent horizons. Such profiles, relatively common on the western margin of the basin, may also represent surfaces that are geomorphically more stable because of the balancing of tectonism and sedimentation.

Both iron oxide and carbonate were mobile in sub-Ames paleosols, but probably at different seasons. Compound carbonate-hematite nodules, iron-oxide-bearing microspar, and visible iron oxide bands in void-filling spar cements demonstrate this point. The restriction of large carbonate or carbonate-hematite nodules to the deeper horizons reflects the necessity of their formation below the zone of strong pedoturbation and yet still within the zone of water-table fluctuation (> 1.5–3.0 m). Water-table fluctuations and resultant soil Eh fluctuations may also be indicated by cathodoluminescent bands in spar cements within nodules and rare siderite features and iron oxide pseudomorphs after siderite and pyrite. Isotopic data from paleosol carbonates indicate a mixing of evaporative and meteoric effects compatible with seasonal rainfall.

Histosols atop the sub-Ames paleosols were originally several tens of centimeters to several meters thick, and were not uniform in their drainage characteristics or chemistry (Lewis 1986; Kneller and Lewis 1988). By comparisons with Quaternary coastal-plain or coastal peats (Lyon and Goldthwait 1934; Hussey 1959; Anderson 1964; Frankel and Crowl 1961; Fairbridge and Newman 1968), the thicker Harlem peats probably accumulated much more rapidly than the precursor mineral soils had previously formed. Harlem underclays, and probably to some degree the strongly calcareous, low-chroma mudstones as well, reflect the surficial gleying of precursor mineral soils with the perching of water tables in response to sea-level rise. Peats may also have accelerated the weathering of underclay clay minerals. Harlem peats and the upper parts of Harlem underclays accumulated iron sulfides in a terminal pedogenic or very shallow burial environment as marine pore waters entered the system (as in drowning soils along modern coastlines; Wada and Seisuwan 1988; Rabenhorst and Haering 1989; Gardner et al. 1992).

Sedimentary History and Paleogeography

On the western to northern margin of the basin (eastern Ohio and much of western Pennsylvania), the sub-Ames interval resulted from alluvial sedimentation on a low-relief coastal plain that was well drained until the onset of the Ames transgression. Vertisol-like soil complexes were produced; these remained relatively well drained until the Ames transgression, but water tables fluctuated seasonally or over longer periods of time. The discontinuous nature of the Harlem Coal across eastern Ohio (and western Pennsylvania), as well as the general characteristics and stratigraphic position of sub-Ames paleosols where the Harlem Coal is absent, suggest that several meters of relief existed on the sub-Harlem surface there (sub-Ames landscape variation has also been noted by Caudill et al. 1992). I propose that this relief determined the lateral variability (drainage characteristics, thickness, color, horizonation, etc.) of pre-Ames soils and the Harlem peat. Peat was deposited selectively in low-lying areas (perhaps very broad, shallow valleys that intersected the Ames shoreline) in response to a relative rise in sea level at the onset of the Ames transgression. In these low-lying areas, water tables rose or were perched by ponded terrestrial drainage, formerly relatively well-drained soils became waterlogged and were partially gleyed, and up to 8 m of peat (assuming a 10x compaction factor) were deposited. Local fluvial-estuarine systems then deposited up to 11 m of stratified sands and muds atop the peat in the drowned valleys as sea level continued to rise or paused, but soils remained subaerially exposed and relatively well-drained longer in the broad, low-relief interfluves, until the Ames transgression flooded the entire landscape. This model differs from the traditional delta-lobe model for Appalachian coal deposition (e.g., Risek et al. 1994) in that it envisages a relict, deltaic-alluvial coastal plain subjected to periodic deposition, persistent regional subaerial exposure, slight dissection, then valley filling, then deposition of thick peats (in broad valleys rather than on or between delta lobes) and, finally, basinwide drowning. Significant eustatic influence is implicit in this model (cf. Demarest and Kraft 1987; Haq 1991), rather than autocyclic (delta switching) and/or tectonic controls alone.

On the eastern to southern margin of the basin (West Virginia and adjacent parts of southwestern Pennsylvania, western Maryland, northeastern Kentucky, and southernmost Ohio), however, the interpretive history of the sub-Ames interval is different. In the early stages of soil evolution (lower Pittsburgh Redbeds), relatively well-drained Vertisol-like soils developed on flat alluvial plains, as in areas to the west. However, poorer drainage (interpreted from the predominance of low-chroma colors in the upper part of the sub-Harlem paleosol interval) eventually dominated. Intermittent, shallow lakes were present, but pedogenic overprinting (mainly the effects of repeated wetting and drying) continued. Rising or perched water tables, produced late in soil evolution in response to the initiation of the Ames transgression, prompted peat deposition (Harlem Coal). Transgression led to the eventual infiltration of sulfate-rich marine pore waters, precipitating pyrite in both peats and the underlying mineral soils. Not coincidentally, the Harlem Coal appears to be more continuous in much of this area than in most of eastern Ohio and western Pennsylvania. Furthermore, the nature of the Ames transgression, particularly in northern West Virginia, Fayette and Somerset counties, Pennsylvania, and westernmost Maryland, also appears to have been very different from that on the western to northern basin margin. The Harlem Coal is usually overlain directly by thick (up to 10 m), very dark gray to dark gray, fossiliferous Ames shales. The pre-Ames landscape on the eastern margin of the basin must have been flat, with shallow ($\sim$ 2 m) depressions associated with soil microrelief (as at Loc. 19).

This distinctive sedimentary history is hypothesized to have been the result of closer proximity to a structural low, the axis of what remained of the foreland basin at that time. Net Conemaugh subsidence rates were higher in this area (Arkle 1974; McKee and Crosby 1975, plate 8A; Collins 1979; Al-Qayim 1983). Faster subsidence would have (1) tended to subdue relief by encouraging aggradation, but not localized downcutting; (2) promoted high water tables in sub-Ames soils, producing the widespread, thick low-chroma upper parts of sub-Ames profiles; (3) encouraged the development of lakes; (4) provided more accommodation space for Harlem peat accumulation; and (5) accommodated more detrital sediment during and after the Ames transgression, thereby limiting carbonate production in that part of the Ames sea (as opposed to eastern Ohio). Al-Qayim (1983), in fact, concluded that the facies distribution and thickness of the Ames marine interval in West Virginia was strongly affected by tectonism. The appearance of similar stratigraphic trends in northeasternmost Kentucky (Loc. 24 area) also supports syndepositional tectonic movement, associated with the "Pittsburgh–Huntington Synclinorium" (Merrill 1988a).

Comparison with Contemporaneous Midcontinent, U.S.A. Analogs

Compared to the Ames, approximately contemporaneous Midcontinent pedogenic intervals (Joeckel 1989, 1994; Joeckel and Joeckel 1994) are thinner (by $\geq$ 50% in most cases), less stratigraphically complex (although not necessarily less well developed), and devoid of thick, widespread coals. A single complex of paleosols in the Appalachian Basin (such as the Ames) may, in fact, correspond to multiple, discrete, marine-deposit-bounded paleosols in the Midcontinent. Distinct differences between the northern Midcontinent and the Appalachian Basin explain these contrasts: (1) About three times as many marine incursions entered the Midcontinent than entered the Appalachian Basin, so intervals of pedogenesis were likely to have been more frequent but briefer than in the latter. (2) Many of the Midcontinent incursions appear to have been of equal magnitude to the Ames, which is the largest of a few incursions in the Late Pennsylvanian of the Appalachian Basin. Eustasy was the overriding control on Midcontinent deposition (Heckel 1980, 1986). (3) At least the eastern to southern margin of the Appalachian Basin was in a more active tectonic setting (foreland basin) than the northern Midcontinent, and this probably was conducive to extensive peat deposition. (4) The main source of clastic sediment in the Appalachian Basin ran approximately parallel to the basin axis and was also close to the basin axis (thereby promoting terrestrial conditions), whereas in the Midcontinent, the Ouachita–Arbuckle orogenic belt lay far to the south of the vast northern Midcontinent shelf. Observations made in this study indicate that about 30% of the Conemaugh Group is likely to have some form of pedogenic overprint, as opposed to about 10% in time-equivalent strata in the Midcontinent.

Paleoclimate and Time

A few general points address the issue of pre-Ames climate: (1) Sub-Ames paleosols lack massive accumulations of near-surface pedogenic carbonate characteristic of drier climates. (2) Nonetheless, Vertisol-like features in sub-Ames profiles are compatible with seasonal rainfall (cf. Sigleo 1983; Dudal and Eswaran 1988; Cecil 1990). (3) Stable isotope values ($\delta^{18}O$) from carbonate nodules in three sub-Ames profiles are also compatible with seasonally wet-dry conditions. (4) The deeper parts of sola, however, had to be saturated enough at some time to promote mobilization and reprecipitation of iron in nodules and mottles. A pre-Harlem Coal climate with moderate (most likely 500–1000 mm/yr, and probably > 750 mm/yr), seasonal rainfall is compatible with these observations. A large body of data shows that modern massive pedogenic carbonates (lacking in sub-Ames paleosols) develop in areas receiving < 500 mm/yr (Goudie 1983), and that at > 1000 mm/yr plinthite (rather than non-hardening mottles of the sort in sub-Ames paleosols) begins to appear if soil temperatures are consistently > 0°C (Joeckel 1991). Furthermore, stratigraphic relationships indicate that the primary impetus for the eventual development of the Harlem Coal could have been the ponding of drainage and the perching of water tables at the onset of the Ames transgression, rather than greatly increased rainfall. Higher rainfall or a decrease in rainfall seasonality (or both) may indeed have accompanied the Ames transgression, but this is not a testable hypothesis given the kinds of data now available. Great paleoclimatic differences between the Appalachian Basin and the Midcontinent are untenable on the basis of paleosols alone, unless the presence of thick coals in the Appalachian Basin, by itself, indicates episodic wet (> 1000 mm/yr) and equable climates.

The temporal significance of the sub-Ames paleosols is more difficult to address. Modern Vertisols (simple sola) probably range in age from 0.5 to 30 ka (Parsons et al. 1973; Scharpenseel and Pietig 1973; Mermut and Dasog 1986). Complex sola of various types on modern subtropical coastal plains and marine terraces have been dated at 20–250 ka (Bleeker 1983; Vepraskas and Wilding 1983; Merritts et al. 1991; Markewich et al. 1987, 1989). If Milankovitch-driven glacioeustasy played a significant role in Late Pennsylvanian Appalachian Basin sedimentation, then marine invasions of the basin would be expected at intervals of at least 200,000–400,000 yr (probably longer, because only a few major marine incursions entered the basin). Thus, by indirect comparison, the sub-Ames paleosols are likely to represent time intervals on the order of 10^4–10^5 yr.

SUMMARY AND CONCLUSIONS

A thick, dominantly Vertisol-like paleosol complex is present below the Ames marine unit across the Appalachian Basin, indicating basin-wide subaerial exposure before the Ames transgression. Stratigraphic data and the characteristics of sub-Ames paleosols suggest that the pre-Ames landscape had shallow paleovalleys and low, well-drained interfluves on the western to northern margin of the basin. The upper to middle (and sometimes lower) parts of sub-Ames paleosol profiles in this area are characterized by very large, intersecting slickensides indicating wet-dry cycles. The middle to lower parts of many sub-Ames profiles show mottling and other features attributable to Eh changes associated with fluctuating water tables. Regional tectonism probably influenced deposition and pedogenesis in the sub-Ames interval on the eastern to southern margin of the basin, a more geomorphically uniform area of low relief that was probably undergoing slightly faster subsidence. Paleosol profiles here show evidence for periods of poor drainage and lacustrine influence and, finally, more uniform Harlem peat development with the approach of the Ames transgression. Pre-Ames climate as a whole was seasonally wet-dry (estimated at 500–1000 mm rainfall per year). Paleosol data alone do not explicitly support a major climate change in association with Harlem peat deposition. Rather, drainage modification ahead of the Ames transgression seems more likely as a major causative factor in peat deposition. Limited $\delta^{18}O$ data are compatible with a shift towards drier and/or warmer climate during immediate post-Ames time, but many more data will be necessary to test this hypothesis. Comparison of contemporaneous northern Midcontinent and Appalachian Basin paleosols provides two broad models for soil development in a stratigraphic succession: (1) several thin, simple soils lacking thick, widespread coals, and bounded by thick marine strata (tectonically subdued, eustatically controlled northern Midcontinent) versus (2) thick paleosol complexes, capped by thick, widespread coals over large areas, and truncated by relatively thin marine deposits (more tectonically influenced, less eustatically controlled Appalachian Basin).

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APPENDIX

SELECTED SUB-AMES PALEOSOL LOCALITIES

For full locality information and measured sections, see Joeckel (1993). **Loc. 4**: Cut on E side of PA Hwy. 60 ~ 1 km S of Aliquippa, PA exit ramp (Exit 10) and ~ 1.6 km S of Green Garden Rd.; Hopewell Township, Beaver Co., PA (USGS Aliquippa, PA 7.5 min. quad.). **Loc. 6**: Cut just W of Cross Creek on U.S. Hwy. 22, ~ 0.5 km W of exit to Wintersville, Jefferson Co., OH (USGS Smithfield, OH 7.5 min. quad.). **Loc. 11**: Outcrop behind parking lot for University Mall, Athens, OH; ~ 1.7 km W on old Hwy. 50 from new Hwy. 32/50 overpass near Della Rd. Approximate location is NW1/4 SW1/4 NE1/4 sec. 34, T5N R13W, Athens Co., OH (USGS Athens, OH 7.5 min. quad.). **Loc. 12**: Hillside (hill 902 ft MSL) above entrance ramp to Hwy. 50/32 eastbound (also exit for State Street and Columbus, OH) in Athens, OH, ~ 0.8 km SW of sewage treatment plant along Hocking River (on Ohio University campus) and ~ 0.5 km E of radio tower (USGS Athens, OH 7.5 min. quad.). **Loc. 13**: Cut on N side of U.S. Hwy. 50, ~ 0.5 km N of Hebardville, Athens Co., OH (USGS The Plains, OH 7.5 min. quad.). **Loc. 14**: Cut on N side of new OH Hwy. 7 bypass between Symmes Creek Rd. and Tallow Ridge Rd., Chesapeake, Lawrence Co., OH (USGS Huntington, WV-OH 7.5 min. quad.). **Loc. 16**: Exposure in spillway of Youghiogheny River Lake ~ 1 km SSW of Confluence, Somerset Co., PA (USGS Confluence, PA 7.5 min. quad.). Section measured near center of cut. **Loc. 17**: Cut along Sabraton, WV entrance ramp onto I-68 (USGS Morgantown South, WV 7.5 min. quad.). **Loc. 18**: Cut on U.S. Hwy. 119 at Morgantown Motel, Morgantown, WV; 0.2 mi (0.3 km) from junction with Hwy. 857, and ~ 3.2 km from intersection with Pleasant Street in Morgantown (USGS Morgantown South, WV 7.5 min. quad.). **Loc. 19**: Cut along exit ramp from I-79 at Exit 146 (Goshen Rd.), Clinton Township, Monongalia Co., WV (USGS Morgantown South, WV 7.5 min. quad.). **Loc. 22A**: Cut ~ 0.1 km. W of I-79 (southbound) exit ramp to Stonewood and Nutter Fort, WV (Exit 115); ~ 0.2 km SW of junction of I-79 and Hwy. 20 near Quiet Dell, Harrison Co., WV (USGS Mount Clare, WV 7.5 min. quad.). **Loc. 22B**: Cut along S-bound entrance ramp at I-79 Exit 115, Harrison Co., WV (USGS Mount Clare, WV 7.5 min. quad.). **Loc. 24A**: Cuts on both sides of U.S. Hwy. 23 between Catlettsburg and Burnaugh, KY; 2.2–2.8 km N of intersection with Route 757 West (USGS Burnaugh, KY-WV 7.5 min. quad.). **Loc. 24B**: Cut atop hill between Catlettsburg and Burnaugh, KY on U.S. Hwy. 23, NW of Savage Branch bridge and ~ 3.8–4.2 km N of intersection with Rt. 757 West at Whites Creek (USGS Burnaugh, KY-WV 7.5 min. quad.). **Loc. 26** (Harlem Coal type area): Myers Mining Company pit near junction of Peach Rd. and Apollo Rd. (W1/2 NE1/4, sec. 9 Lee Township), Carroll Co., OH (USGS Carrollton, OH 7.5 min. quad.).