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Geomorphology of a Pennsylvanian Land Surface: Pedogenesis in the Rock Lake Shale Member, Southeastern Nebraska

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GEOMORPHOLOGY OF A PENNSYLVANIAN LAND SURFACE: PEDOGENESIS IN THE ROCK LAKE SHALE MEMBER, SOUTHEASTERN NEBRASKA[1]

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ABSTRACT: Extensive, fresh exposures of reddish brown mudstones in the Rock Lake Shale Member in a quarry in southeastern Nebraska show pedogenic features (calcite glaebules, blocky spar crystallaria, peds, silt and clay- or micrite-filled pedotubules, slickensides, mottling, and overall horizonation) which indicate protracted subaerial exposure under increasingly arid conditions. The Rock Lake paleosol is bounded above and below by marine cyclothem deposits. Probable events represented by the paleosol are 1) clay and silt illuviation under humid conditions, 2) subsequent carbonate precipitation under progressively drier conditions, and 3) gleying of the A horizon during a marine transgression.

The Rock Lake paleosol developed on a flat and laterally extensive, semiarid to arid plain during a low stand of sea level. Examination of the Rock Lake at other localities (well cores and exposures) in nearby counties shows a distinct eastward facies change toward lower topography, earlier marine transgression, and arrested pedogenesis, which is consistent with transect direction from the Nemaha Uplift to the Forest City Basin.

INTRODUCTION

Missourian rocks in the Kansas-Nebraska-Iowa region contain reddish brown mudstones (Fig. 1) that have been interpreted in a pedogenic context (Schutter and Heckel 1985; Joeckel 1985). Prather (1985) and Watney (1980) described calcareous paleosols in red "shales" (mudstones) from cores of the upper Pennsylvanian Lansing-Kansas City Groups in western Nebraska and Kansas. Up to this time, no detailed, outcrop-based descriptions of paleosols in the Lansing-Kansas City interval appear in published literature. The purposes of this paper are 1) to describe in detail the features of a freshly exposed paleosol in the Rock Lake Shale Member (Stanton Formation, Lansing Group) and 2) to interpret its developmental history on a regional basis with data from well cores and other outcrops.

Detailed observations were made at three outcrops and on three well cores across a 50 km transect of Lancaster, Sarpy, and Cass counties in southeastern Nebraska (Fig. 2). Ongoing excavation in the Ash Grove Quarry near Louisville in Cass Co., Nebraska provides a pristine outcrop hundreds of meters across that exposes paleosol features clearly (Figs. 3, 4), therefore it is the best locality for in-depth analysis of lateral as well as vertical variation.

STRATIGRAPHY

In Nebraska, the Rock Lake Member of the Stanton Formation has been applied to a 1 to 2 m thick, reddish brown siltstone with an overlying greenish gray clayey shale which lies between the marine Stoner Limestone Member below and the marine South Bend Limestone Member above (Figs. 1, 3). The contact between the two subunits of the Rock Lake appears to be disconformable (non-gradational) throughout the study area, as is the contact between the Rock Lake and underlying Stoner Limestone. In all of the study localities except the Plattsmouth No. 1 well, the Rock Lake–South Bend contact is disconformable as well. The Rock Lake is a non-marine unit (an outside shale) that was deposited during the maximum regressive phase of the Stanton cyclothem (Heckel et al. 1979).

Although the formal stratigraphic names developed on outcrop have not yet been correlated to the subsurface sections studied by Prather (1985) and Watney (1980), the Rock Lake Shale is clearly a facies equivalent of the regressive "upper shale unit" subsurface lithofacies of Watney and Ebanks (1978).

The most significant stratigraphic aspect of the Rock Lake Shale is its position between the marine carbonates of the Stoner and South Bend Limestone members. These carbonates were deposited, respectively, during the regressive phase of the Stanton cyclothem and the succeeding transgressive phase of the South Bend cyclothem (Heckel et al. 1979). The thin shale in the upper Rock Lake records the drowning of the paleosol, presumably during the initial part of the South Bend transgression. The presence of a paleosol in a largely marine section indicates a significant eustatic drop in sea level (Heckel 1986), protracted subaerial exposure, and extensive alteration of sediment fabrics followed by a subsequent sea level rise and the drowning of the former land surface.

Since red mudstones are repeated throughout the Midcontinent Pennsylvanian section, paleosols in them could become important in determining the potential repeatability of geomorphic-pedogenic processes and features (perhaps they are a unique "pedofacies" *sensu* Bown and Kraus 1987; see Schutter and Heckel 1985). Individual cyclothem paleosols, such as the Rock Lake paleosol, provide a unique opportunity to study the emergence, evolution, and destruction of an ancient land surface having great lateral extent.

DESCRIPTION OF ASH GROVE QUARRY SECTION

The critical stratigraphic sequence (Figs. 3, 4) at the Ash Grove Quarry (ascending) is: 1) Upper Stoner thinly

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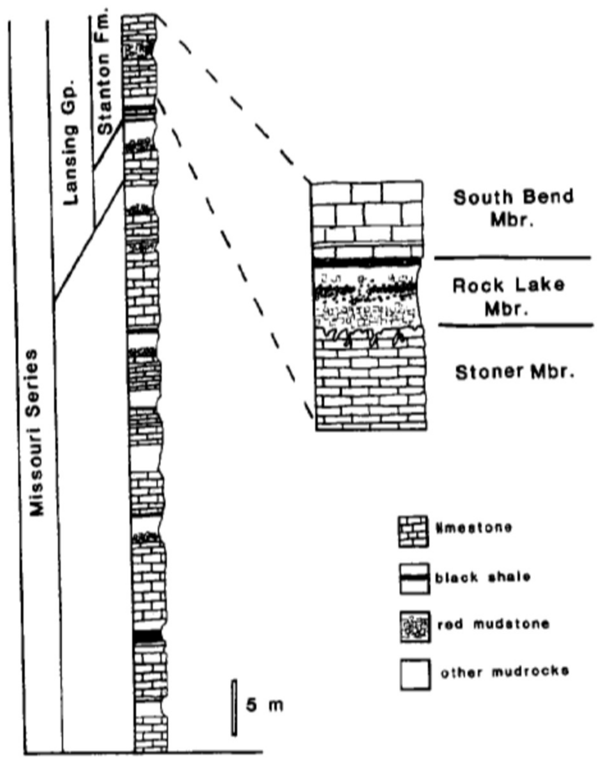

FIG. 1.—Missourian Series in Nebraska, after Burchett (1971); Stoner-Rock Lake-South Bend sequence is shown enlarged. Reddish brown mudstones with pedogenic features occur above many limestones throughout the section.

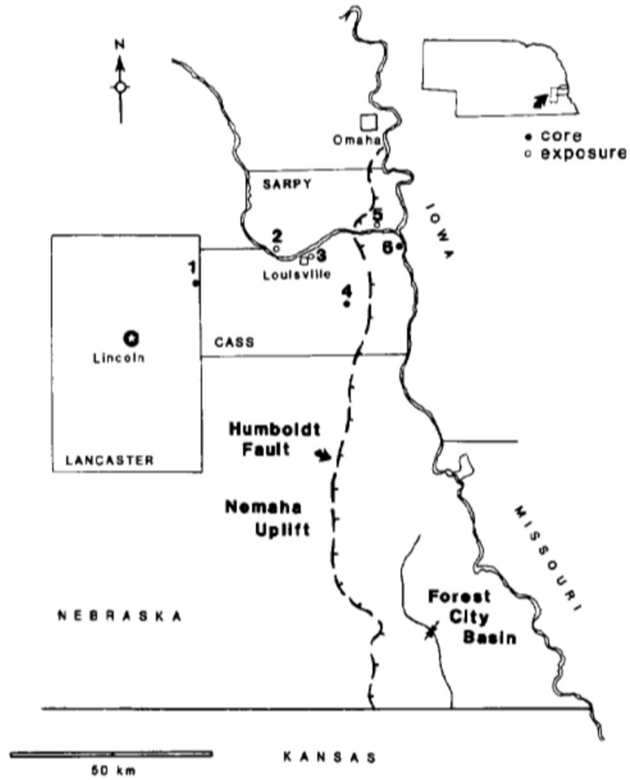

FIG. 2.—Map of study area. Numbered localities are as follows: 1) Midam No. 1 well (SE cor. sec. 1 T11N R8E), 2) Schramm State Park (NE¼ SE¼ NW¼ sec. 12 T12N R10E), 3) Ash Grove Cement Company Quarry (W½ NW¼ sec. 13 T12N R11E), 4) Amerada-Hess Schroeder No. 1 well (NE¼ SE¼ sec. 26 T11N R12E, 5) abandoned Sorenson Quarry (SE¼ SW¼ SE¼ sec. 28 T13N R13E), and 6) United Minerals Plattsmouth No. 1 well (E½ SE¼ SE¼ SE¼ sec. 7 T12N R14E). Structural features after Burchett (1971) and Burchett and Bolitho (1981).

laminated dolomitic micrite, little weathered, except for a subaerial exposure surface atop, 2) lower-middle Rock Lake Shale paleosol-containing dark reddish brown mudstone, 3) upper Rock Lake light greenish gray marine shale, and 4) biomicrite of the South Bend. Features present in 1 and 2 above identify a well-developed paleosol. Recognition and description of the well-developed and freshly-exposed paleosol at the Ash Grove Quarry in turn leads to a regional examination of features in the Rock Lake Shale, which follows in a subsequent section.

Upper Stoner Limestone

The Stoner Member is a compact, non-fissile, thinly laminated micrite which contains very few or no body fossils and scattered dolomite rhombs (P. Holterhoff, pers. comm.). The uppermost 50 cm is stained pinkish grey (7.5YR 7/2—this and all subsequent colors are fresh, dry colors from the Munsell Soil Color Charts) and contains dense subvertical and horizonal vermicular root voids (0.1–5 cm in diameter and generally < 15 cm apart on bedding planes; Fig. 3B). The interpretation of these features as root voids is based on the following criteria: 1) sinuous morphology, 2) irregular branching, 3) variable diameter, which suggests systems of roots and rootlets, and 4) association with what appears to be a subaerial exposure surface. Dark reddish brown (5YR 3/3) mudstone identical to that in the overlying Rock Lake Member fills these root voids. Small (< 1 cm) sheet cracks, sparse polygonal mudcracks, and large (> 4 cm wide) irregular fissures filled with silt and clay are also present at the top of the Stoner. Small (1–3 mm in diameter) micrite breccia clasts are visible along the walls of larger root voids and fissures. There is a sharp contact between the Stoner and the overlying Rock Lake Member.

Rock Lake Shale Member

The upper 8 cm of the Rock Lake Shale is a thinly laminated gray (5YR 5/1) shale containing abundant small brachiopods and small fossil fragments. It has a sharp basal contact with the remaining 1.6 m of the member, which is paleosol-bearing claystone and siltstone (Figs. 4, 5). Description of the paleosol-bearing interval is in the soil literature style (i.e., in pedogenic horizons, not depositional units, and measured and described from the top of the soil downward), as follows:

0–8 cm (interpreted as a paleosol A horizon).—Light greenish-gray (5Y 6/1) noncalcareous siltstone consisting of spheroidal aggregates (Fig. 6A) averaging 0.5–4 cm in diameter, but as large as 10 cm. These spheroids are brittle and exfoliate crudely when struck but lack internal struc-

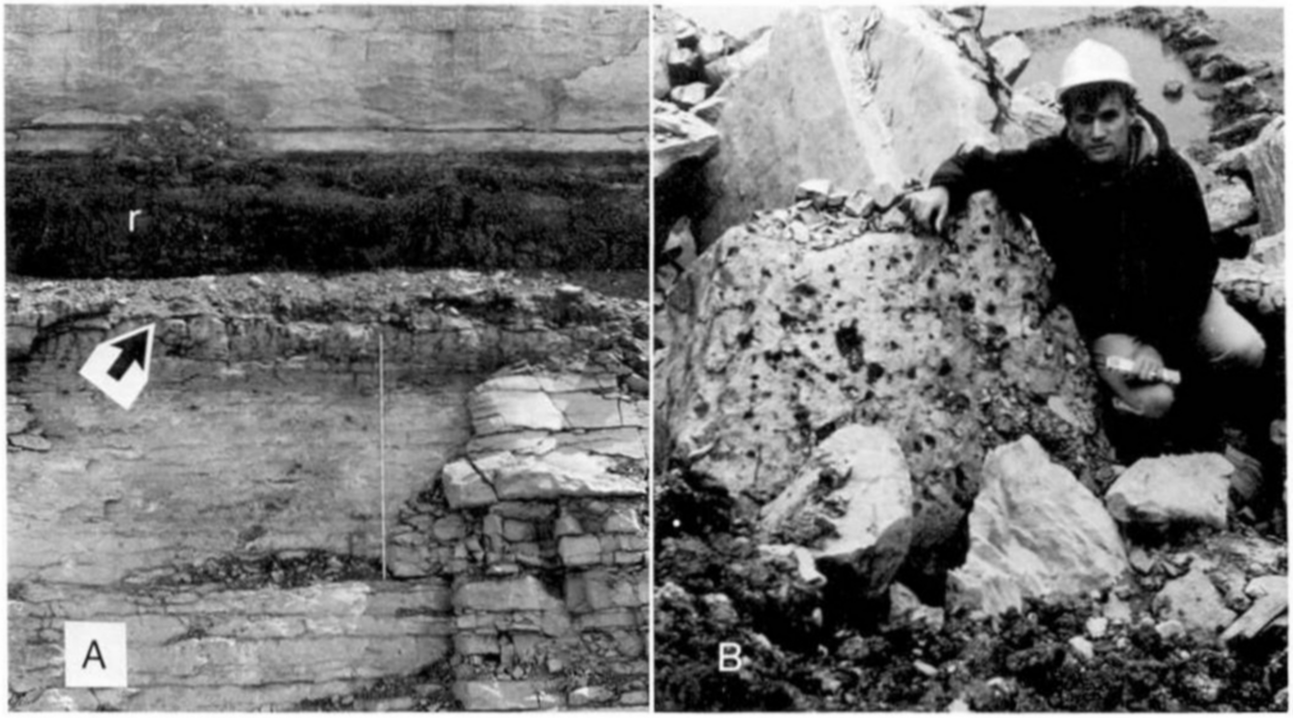

FIG. 3.—Rock Lake paleosol at Ash Grove Cement Company Quarry. A) Exposure of the Stoner Limestone (below) Rock Lake Shale (r) and South Bend Limestone (above). Arrow points to Rock Lake-Stoner contact, which is marked by dark staining and vertical root traces. Vague ledge near middle of Rock Lake is glaebule zone or calcrete. Scale rod is 2 m. B) Slab of top surface of Stoner Limestone, showing paleo exposure surface and cross sections of root traces; scale in author's hand is approx. 15 cm.

ture. Most of the spheroids at the upper contact are light greenish-gray, but there are areas where spheroids at the same level are weak red (10R 5/2) and contain abundant fine (< 0.5 mm in diameter), reddish gray (10R 6/1), vermicular mottles. In the middle of the horizon, many spheroids are light greenish gray on top and reddish brown (5YR 5/4 and 3/3) with fine, vermicular, light greenish gray mottles below. Beneath this zone the spheroids are reddish brown throughout. Pedogenic boundaries between greenish and reddish zones are always irregular and abrupt. Scattered small (< 1 cm), diffuse, micrite nodules (hereafter referred to as glaebules, after Brewer 1976, p. 258–259) are present throughout this horizon.

8–33 cm (intepreted as the upper part of a paleosol K horizon).—Reddish brown (5YR 5/4 and 4/3), massive, clayey siltstone blotched with diffuse, weak red (2.5YR 5/2–6/2) calcareous patches and large (> 1 cm) micrite glaebules. The entire horizon is well-indurated with calcite cement. Large (1 cm by up to 22 cm long) light greenish gray mottles and patches appear in the upper 5–10 cm of the horizon, and there are many unbranched or sparsely branching mud-filled pedotubules 0.5–1 cm in diameter throughout.

33–60 cm (interpreted as the lower part of a paleosol K horizon; i.e., a calcrete).—Reddish brown (5YR 5/3) and dark reddish brown (5YR 3/3) clayey siltstone with very abundant, reddish brown, brownish yellow (10YR 6/6), and light greenish gray spherical, micrite glaebules 0.5–2.2 cm in diameter (Fig. 6B). Some hand specimens from this horizon consist of almost completely intergrown glaebules separated by narrow (< 1 cm) mud-filled cracks; other areas consist of diffuse glaebules in a matrix of calcareous silty claystone. In outcrop, areas at a particular level vary from glaebule-packed and well-indurated to moderate concentrations of glaebules in a more friable calcareous matrix. The entire horizon weathers in slight relief and even produces small ledges in relatively fresh outcrop. The base of the horizon is indistinct but is marked by scattered vertical, yellowish brown, calcareous pedotubules about 1.5 cm in diameter and up to 15 cm long.

60–160 cm (interpreted as paleosol Bt and C horizons).—Dark reddish brown (5YR 3/3), vaguely blocky, clayey siltstone with abundant small (< 1 sq cm) subvertical and subhorizontal slickensides and large (> 5 sq cm) horizontal slickensides from about 90 to 110 cm. This same interval contains many small (0.5–1 mm in diameter), subvertical root channels partially filled or lined with clay cutans and marked by light greenish gray drab halos. The upper 20 cm of this horizon contains scattered micrite glaebules.

Micromorphology

The Rock Lake Shale displays peds, glaebules, crystallaria, and other pedogenic features, which can be verified and interpreted via petrographic thin sections (Fig. 7).

In thin section, the upper, spheroidal horizon has little discernable structure, except for a few sinuous channels

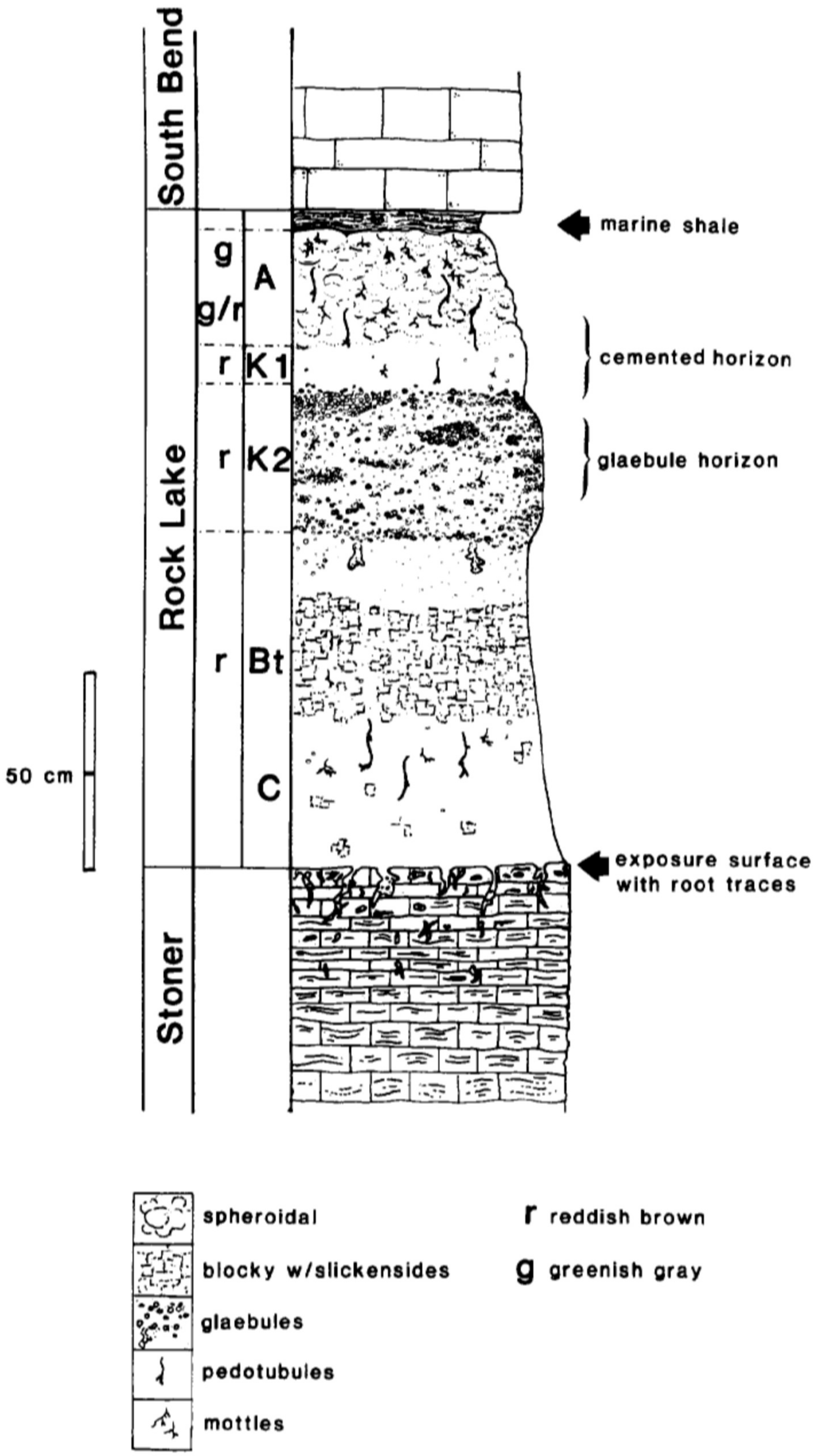

FIG. 4.—Diagram of critical stratigraphic sequence at Ash Grove Quarry, showing Rock Lake Shale and its associated pedogenic features, with soil horizons (upper case) tentatively assigned.

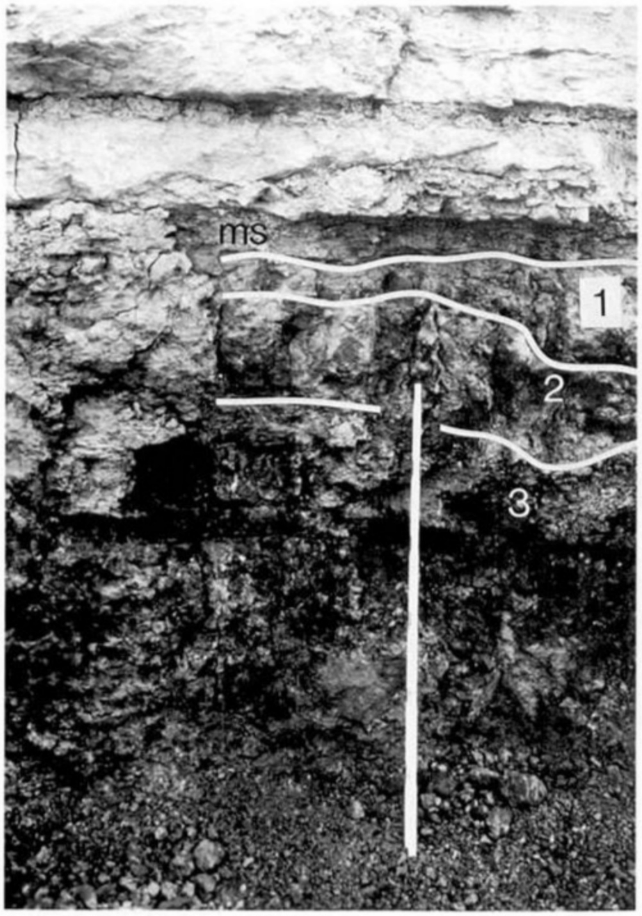

FIG. 5.—Rock Lake paleosol at Ash Grove Quarry. The marine shale (ms) of the Rock Lake Member overlies the spheroidally-weathered A horizon (1). Massive cemented zone or hardpan (2) overlies glaebule horizon (3). Note overall blocky texture of lower part of paleosol and abundance of small glaebules; also note large, sinuous root trace barely visible just above and to right of top of 1 m scale rod.

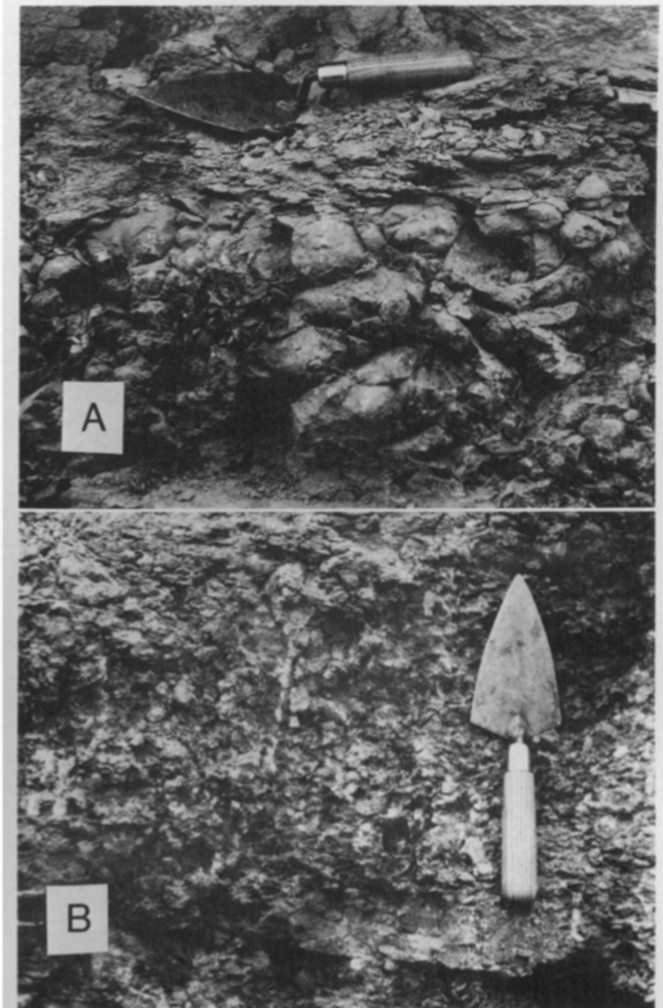

FIG. 6.—Features of Rock Lake paleosol at Ash Grove Quarry. Trowel is approx. 20 cm long. A) Spheroids in A horizon in sharp contact with overlying fissile marine shale upon which trowel lies. B) Glaebule horizon weathering as a ledge with glaebules (white), and large pedotubule (dark vertical line) about 15 cm left of trowel.

50–100 μm wide lined with greenish iron-clay cutans. Mottles that appeared sharp in hand specimen are usually diffuse in thin section, although a few are clearly delineated in cross section by circular greenish or reddish ferrans. The matrix is silt dominated ("silasepic fabric" of Brewer 1976, p. 310), consisting of quartz and muscovite grains with regular clotted-appearing accumulations of clay. A very few small (about 375 μm across), angular, reddish, clayey peds are visible (Fig. 7A). Micrite glaebules in this horizon are diffuse ("orthic glaebules" of Brewer 1976, p. 275), whereas glaebules from lower in the profile have sharp boundaries and can be removed from the matrix as discrete entities ("disorthic glaebules" in the usage of Wright 1982).

The glaebule horizon (33–60 cm) displays a distinct suite of pedogenic microstructures. Three spatially adjacent (and genetically related) phases of carbonate enrichment (i.e., glaebule development) are apparent: 1) a non-glaebular phase, 2) an orthic glaebule phase, and 3) an orthic-disorthic glaebule phase.

The non-glaebular phase consists of reddish, silty clay, with angular blocky peds separated by coarse, blocky spar-filled circumgranular cracks ("crystallaria" of Brewer 1976, p. 283; see my Fig. 7B). Carbonate-impregnated peds are present, and grade into the orthic glaebule phase.

The orthic glaebule phase consists of reddish to brownish micrite with much included silt, grading laterally into carbonate-impregnated clayey peds (75–3,000 μm wide) in various stages of disaggregation. The smaller peds are frequently rounded, even pellet-like, but the larger peds are consistently angular or subangular in form. Circumgranular cracks 100 μm wide appear between peds and have a primary fill of micrite overlain by coarse, blocky spar (Fig. 7B); calcite silt grains are occasionally included in spar crystals. Smaller intragranular cracks extend through the sides of peds and appear to be the mechanism of ped decomposition, as peds in various stages of shat-

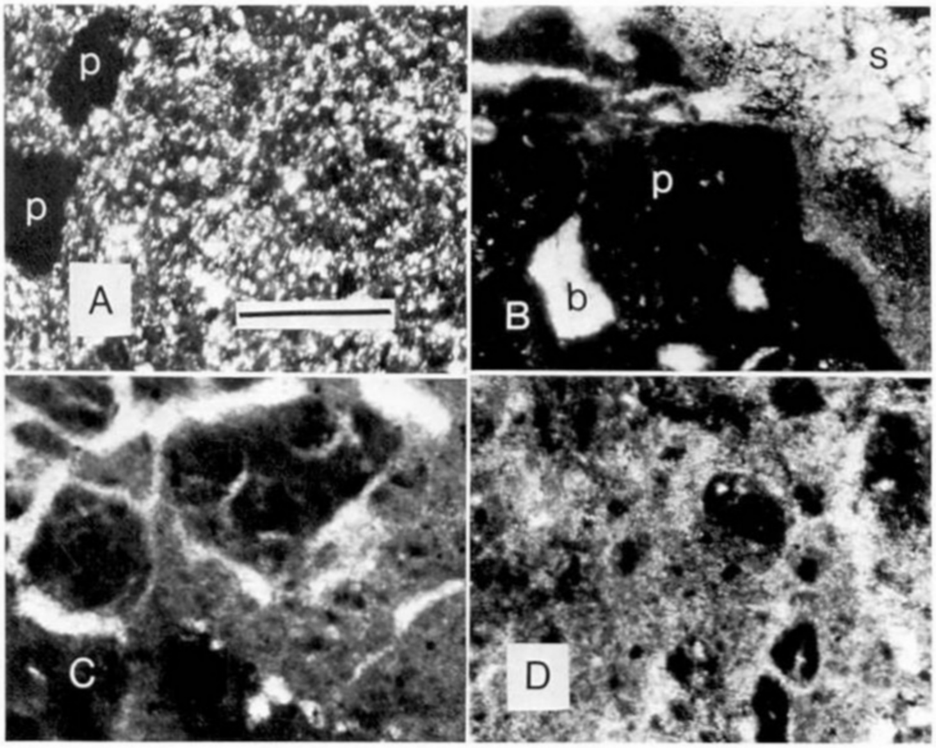

FIG. 7.—Micromorphologic features of Rock Lake paleosol at Ash Grove Quarry; scale bar represents 0.5 mm for all photos. A) Silty, greenish A horizon with two relect, reddish, clay-rich peds or granules (p); crossed polarizers. B) Large ped (p) in K horizon developing internal vugs filled with spar (b), and surrounded by planar voids (crystallaria) filled with micrite and blocky spar (s). C) Peloidal micrite in the disorthic phase of the K horizon; note incipient peloids surrounded by spar-filled circumgranular cracks. D) Structure of a micrite-filled pedotubule from the base of the K horizon, showing small, reddish, clay granules (dark) in a yellowish matrix of micrite, carbonate silt, and quartz silt.

tering are visible. Larger calcite-impregnated peds have internal vugs 75–1,125 μm long filled with blocky spar.

The orthic-disorthic glaebule phase is brownish to grayish clotted to peloidal (Fig. 7C) micrite with a few included silt grains and small (75–125 μm in diameter), rounded clay granules. Individual clay granules are discrete and are surrounded by spar-filled circumgranular cracks. Some were clearly fractured and the two resulting fragments offset by spar growth in intragranular cracks. The grayish micrite of this phase is almost completely devoid of clay granules but does contain similarly-sized micrite peloids which are also surrounded by spar-filled circumgranular cracks. Spar-filled vugs 75–1,125 μm long are present in the grayish micrite, as are large (625 μm wide) fractures filled with a combination of calcite silt, micrite peloids, and blocky spar. In vertical section, micrite-dominated zones (i.e., disorthic nodules when viewed in hand specimen) may be separated by multiple sets of subhorizontal, clay-lined stylolites 25–50 μm wide.

Calcareous pedotubules from the base of the glaebule-rich zone consist of an unsorted mixture of yellowish micrite, calcite silt, silt, and clay with a few large, carbonate-impregnated peds and some small, egg-shaped clayey granules (Fig. 7D). The individual pedotubule cross-sectioned for microscopic examination had a vertical fracture filled with very large (375 μm wide) blocky spar crystals containing calcite silt inclusions.

Mineralogy

The clay fraction (< 0.002 mm) from the A and B horizons of the Rock Lake paleosol was analyzed by automated x-ray diffraction (including potassium and glycerine treatments) and a Perkin-Elmer thermal analysis at the National Soil Survey Laboratory (Lincoln, Nebraska). Diffraction graphs of clays from the A horizon yielded approximately equal relative peak sizes for montmorillonite-chlorite, montmorillonite, and kaolinite; a larger illite-mica peak; and smaller quartz and hematite peaks. The mineralogy of the B horizon is similar, except that there is relatively less kaolinite and no quartz in the clay fraction. However, thermal analysis showed an increase in total clay-fraction kaolinite from 21% in the A horizon to 26% in the B horizon. Elemental analysis detected minor amounts (approximately 10%) of hematite in both the A and B horizons. In both the A and B horizons the dominant constituent of the silt-sand fraction is quartz, but mica is also present; no feldspars were detected.

OBSERVATIONS FROM OTHER LOCALITIES

Cores and outcrops elsewhere in southeastern Nebraska provide a regional assay of pedogenic features in the Rock Lake Shale (Fig. 8), the interpretation of which can be grounded in observations from the key section at the Ash Grove Quarry. These cores and outcrops show some divergences in features from the Ash Grove Quarry section; such divergences illuminate geomorphic variability across the region during the Pennsylvanian.

Upper Stoner Limestone

The upper Stoner Limestone consistently has an exposure surface, but its character changes slightly from locality to locality. Root traces filled with reddish brown silt and reddish staining on the micrite, comparable to

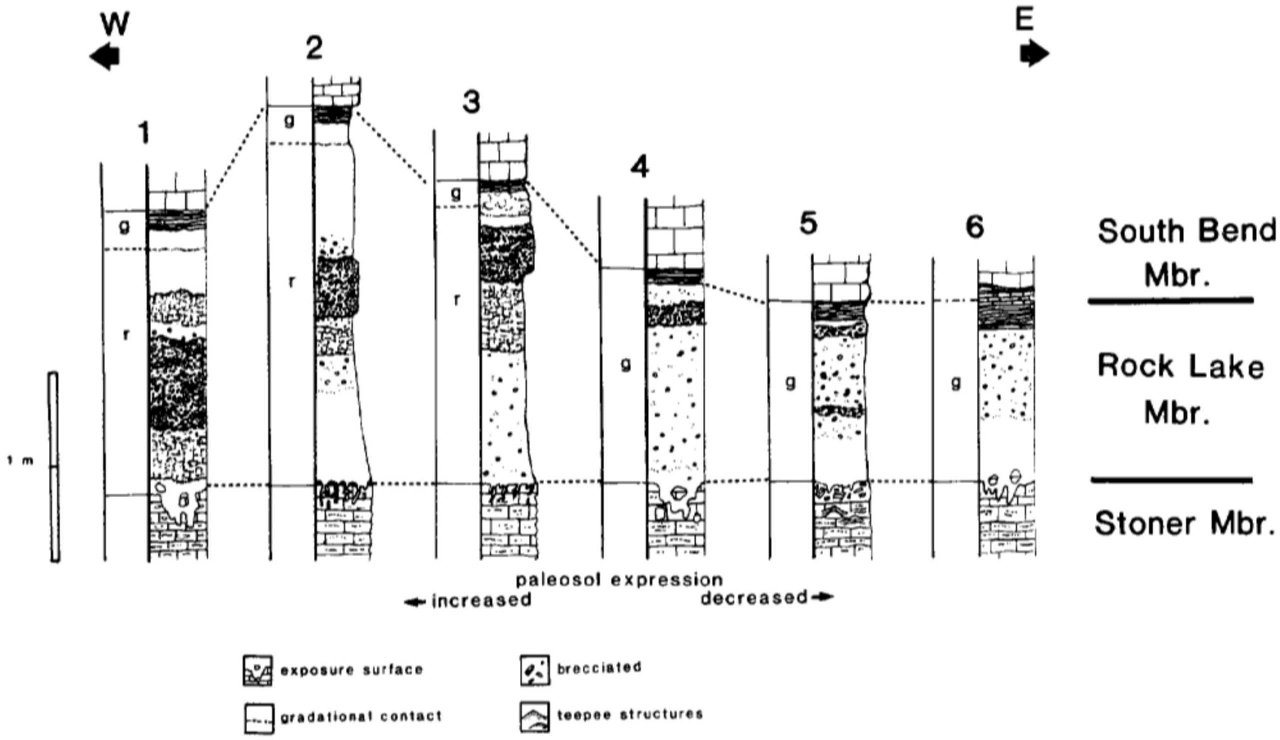

FIG. 8.—Regional variation in Rock Lake paleosol and associated depositional units. The numbers of localities are as given in Figure 2. Western localities show a well-developed calcrete in an overall reddish profile, whereas those to the east show increasingly sparse glaebules in a more greenish profile. Soil development appears to have been interrupted by transgression earlier in the eastern part of the study area.

similar features seen at the Ash Grove Quarry, can be observed westward at Schramm Park. Farther west, in the Midam No. 1 core, the upper 30 cm of the Stoner is light greenish gray (5GY 5/1) and contains sheet cracks and large solution cavities filled with greenish gray (5GY 5/1) silt; the uppermost 5 cm is a zone of micrite fragments comparable to the "regolith" described by Prather (1985).

At the localities east of Ash Grove Quarry, the exposure surface is still visible. In the Schroeder No. 1 core the upper Stoner is light gray (2.5Y 7/2) and contains large (12 cm wide and 8 cm deep) solution cavities, small cracks, and possible small root traces filled with greenish-gray (5GY 5/1) silt. The upper 30 cm of the Stoner in the Plattsmouth No. 1 core is similar, and has a zone of micrite rubble atop it. A significant variation in the expression of subaerial exposure is present in the upper Stoner at the Sorenson Quarry, where it is a light brownish gray (2.5Y 6/2) laminated micrite containing teepee structures (15 cm wide and 7 cm high) and spar-filled birdseyes. The micrite is overlain by a 5-cm cemented breccia of subrounded, laminated micrite rip-up clasts 0.5–10 mm across. Atop this breccia is an exposure surface evidenced by subvertical cracks and vugs, as well as small hollows, filled with greenish-gray silt.

Rock Lake Shale

Westward in the Midam No. 1 core and at Schramm Park (Fig. 9) the Rock Lake is very similar to its exposure at the Ash Grove Quarry. Both localities show a well-developed horizon of intergrown glaebules (Fig. 8). The glaebule horizon in the Midam core is particularly well-cemented in places, and contains features that appear to be "stacked" glaebules similar to those noted by Blodgett (1988, p. 112) in the Triassic Dolores Formation; Blodgett interpreted these features as rhizocretions. A 15 cm massive, carbonate-cemented horizon overlies the glaebule horizon in the Midam core, where carbonate infillings between peds ("boxwork") are present both in the A horizon above the cemented zone and below the glaebule horizon. A carbonate-cemented zone is not present above the glaebule horizon at Schramm Park, although the equivalent horizon is massive and brittle. A massive, light greenish gray gleyed zone about 10 cm deep is present at the top of the A horizon in the Midam core and at Schramm Park, but the color of the remainder of the unit is reddish brown (5YR 4/3, 4/4, or 5/3) in both sections.

Eastward in the Schroeder No. 1 core, at the Sorenson Quarry, and in the Plattsmouth No. 1 core, the Rock Lake shows a distinct change in color, glaebule distribution, and horizonation. At all three of these localities, the unit is a coarsely blocky to massive, greenish gray (5GY 5/1 or 6/1) to dark greenish gray (5GY 4/1) siltstone. Glaebules are small (< 1 cm in diameter) and yellow (10YR 7/8) at the Sorenson Quarry or pinkish gray (5YR 7/2) in the cores. Glaebules are clustered, but not abundant nor strongly intergrown, in a 20 cm horizon 30 cm below the paleosurface in the Schroeder core and in a few bands near the top of the paleosol in the Sorenson Quarry; small (< 5 mm) glaebules are scattered throughout the upper 50 cm of the Rock Lake in the Plattsmouth

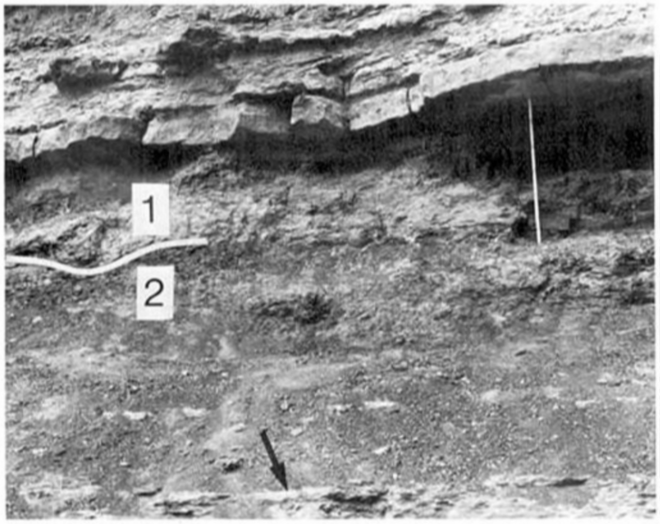

FIG. 9.—The Rock Lake Shale at Schramm Park, Sarpy County, Nebraska. A brittle, noncalcareous horizon that weathers in slight relief (1) overlies the weathered glaebule horizon (2). Arrow near lower center denotes top of Stoner Limestone. Light-colored band visible under overhanging South Bend Limestone above (1) is the gleyed part of the A horizon. Scale rod is 1 m.

core. In the Schroeder core and at the Sorenson Quarry, there are diffuse, reddish brown (5YR 5/8) or reddish gray (5YR 4/2) mottles below the glaebule horizons, but the Rock Lake in the Plattsmouth core is completely greenish gray.

In the eastern part of the study area, the Rock Lake–Stoner contact is as much as 25 m lower (based on modern topography) on the east side of a "zone of faulting or steep dip" (the Humboldt Fault, *sensu* Burchett and Bolitho, 1981) bounding the Nemaha uplift discussed by Burchett (1971); the localities which show the distinct pedofacies change to greenish gray color and the reduction of glaebule abundance (described above) are either near this line (Schroeder No. 1) or east of it (Sorenson Quarry and Plattsmouth No. 1). All localities in the Louisville area (including as well the Rock Lake, Carter, Goodrich, Meadow, and Stone Products Quarries described by Burchett 1971) and westward, show a dominantly reddish brown color and prominence of glaebules.

INTERPRETATION OF THE PALEOSOL

Comparison with Other Paleosols

In general, the pedogenic features of the Rock Lake Member at the Ash Grove Quarry are very similar to features described in calcareous paleosols (interpreted as Aridosols and Vertisols) from a variety of stratigraphic intervals and geographic locales. There appears to be a clear and predictable association of pedogenic features in calcrete-bearing paleosols which, in turn, compares well with some modern analogs.

Watney (1980) and Prather (1985) described orthic and disorthic micrite glaebules, crystallaria, pedotubules, and peds from subsurface Lansing–Kansas City interval paleosols developed in reddish brown mudstones. The same suite of features occurs broadly in certain modern soils and Pleistocene calcrete-bearing paleosols (Esteban and Klappa 1983). Wright (1982) described nearly identical calcrete-bearing paleosols in greenish, mottled mudrocks in the Visean (early to middle Mississippian) Llanelly Formation in Wales. Wright, Watney, and Prather all noted dissolution features underlying the various paleosols; Prather found up to 1 m of regolith development on carbonates at the base of the paleosol he studied. In this respect, the Rock Lake paleosol is different, as it is developed completely within a depositional unit and underlain by an exposure surface that shows some weathering but not extensive, deep regolith development. Due to the low degree of chemical weathering at the top of the Stoner Limestone and the relative thickness of the Rock Lake Shale, it appears that Rock Lake is not, as a whole, an *in situ* residue from the weathering of the underlying Stoner micrites.

Allen (1986) summarized the characteristics of Old Red (Devonian) calcrete paleosols from southern Britain, detailing the co-occurrence of micrite glaebules, crystallaria, root traces, and slickensides (features also present in the Rock Lake paleosol) in oxidized fluvial mudrocks. Allen proposed a genetic sequence for soil development on Old Red floodplains (1986, p. 63) involving a gradual increase in glaebule density followed by the development of well-cemented laminar horizons above the glaebule-rich horizon, and culminating in a mature calcrete profile containing features indicating repeated dissolution and reprecipitation of calcite. Allen's genetic sequence is virtually identical to that proposed by Gile et al. (1966) for "K-horizon" development in modern soils.

Genesis of the Paleosol

Development of the Rock Lake paleosol appears to have involved several processes: 1) reddening of the host mudrock, 2) illuviation of silt and clay through the profile via root channels and, possibly, intrapedal voids, 3) protracted calcite precipitation, first producing the glaebule-rich horizon and then an overlying massive, cemented zone, and 4) saturation and subsequent gleying of the permeable upper horizon during a marine transgression.

Iron present in the Rock Lake is most likely detrital in origin and arrived at the locale of deposition in close association with the clay fraction. Although dewatering of goethite to form pigmentary hematite can occur in later diagenesis (Buol et al. 1980), the reddish brown color of the Rock Lake is probably due to subaerial ageing of fine-grained iron hydroxide to hematite under a warm, well-drained, subaerial regime during the Pennsylvanian (see Walker 1967 and Turner 1980, p. 63–64 for a discussion of this phenomenon in fine-grained sediments). Reddish brown or red colors are characteristic of many modern Aridosols and presumably result from *in situ* development of poorly crystalline hematite (Nettleton and Peterson 1983, p. 191).

Silt/clay illuviation through the paleosol is evidenced by silt and clay-filled pedotubules, root channel argillans, and, probably, the increase in clay below the glaebule-rich horizon. Abundant small slickensides in the 90–110 cm interval (which has been interpreted as an older paleosol Bt horizon) are not necessarily direct evidence for clay illuviation, however, because they are the direct result of stress orientation. In any case, illuviation to this lower horizon had to occur before the plugging of the glaebule-rich horizon by calcite.

In the argillic horizons of modern Aridosols, stress cutans (i.e., pedogenic slickensides) are produced by repeated swelling and shrinkage associated with wetting and drying (Nettleton and Peterson 1983, p. 177). According to Nettleton and Peterson, true illuviation argillans, as well as the peds which bear them, may be destroyed by repeated shrink and swell in Aridosol B horizons. The clay mineralogy of the Rock Lake paleosol is compatible with an interpretation of such activity. The vaguely blocky texture of the horizon beneath the glaebule-rich horizon at Ash Grove Quarry is compatible with the absence of coherent peds in the B horizons of fine-textured modern Aridosols. Another possible mechanism of clay orientation in the Rock Lake paleosol would be the downward displacive effect of the expanding glaebule-rich horizon. Such a mechanism could explain the presence of large horizontal slickensides. Reeves (1976) mentioned slickensides within (though not below) modern calcretes and attributed them to stresses created during expansive calcite precipitation.

The presence or absence of illuvial clays in modern Aridosols have been a subject of disagreement among pedologists for many years, mostly because of the lack of ped argillans in many Argid argillic horizons. However, most authorities interpret such argillic horizons as illuvial, albeit relict late Pleistocene, features (Nettleton and Peterson 1983, p. 188–189). Nettleton and Peterson (1983, p. 190) estimated that 2,200–4,600 yr are required for the formation of argillic horizons in Aridosols on fine-grained parent materials (i.e., like the Rock Lake Member host). Some of the kaolinite in the hypothesized Bt horizon may be neoformed, because there is a slight increase in kaolinite from the A horizon to the B horizon. Kaolinite in similar modern soils formed on probable aeolian dust in Greece is probably in part the product of alteration of 2:1 silicates (Macleod 1980).

If the horizon below the glaebule-rich horizon is a true argillic B horizon then, by analogy with interpretations of modern Argids, it must be a relict feature dating from a wetter period earlier in the development of the paleosol. Such a wetter period could have been due to the original proximity of the locality to the regressing seaway; continued regression later in the development of the paleosol, by withdrawing the coastline, might have decreased rainfall. This interpretation is a gross oversimplification of complex paleogeographic-paleoclimatic patterns (involving latitudinal position, oceanic and atmospheric circulation, and relief features), but it expresses the very real possibility that some aspects of climate on newly-emergent Pennsylvanian land surfaces were influenced directly by the overall transgression-regression mechanism.

Extensive precipitation of carbonate above the Bt horizon is not unusual for a longer-lived soil profile; Bown and Kraus (1987) noted concentrations of carbonate nodules (Bca horizons) immediately above Bt horizons in Eocene Willwood Formation paleosols from Wyoming.

The glaebule horizon above the old Bt horizon is an incipient K horizon (*sensu* Gile et al. 1965). Carbonate precipitation in analogous modern Aridosols occurs at or near the common depth of wetting (Nettleton and Peterson 1983, p. 194). Gile et al. (1966) hypothesized that carbonate precipitation in modern finer-grained soils begins as filaments and ped coatings, later as increasingly dense glaebules, and finally as laminae. In the four-stage genetic sequence of Gile et al. (1966; subsequently modified, as in Machette 1985), the Rock Lake paleosol is in Stage III of development for fine-grained calcic soils: dense, indurated nodules with internodular cement. Plugging of soil pores is complete at the end of Stage III; plugging is inferred for the Rock Lake calcrete because the horizon immediately above the glaebule-rich horizon is heavily cemented with calcite, suggesting that downward-moving solutions were concentrated there and that calcite cement was precipitated to form a hardpan.

Disorthic and orthic glaebules in the Rock Lake calcrete are spatially adjacent and laterally intergrading; therefore, a genetic relationship between them can be inferred. Wright (1982) interpreted disorthic glaebules in the Llanelly Formation as products of: 1) simulataneous calcite precipitation and clay dissolution (although he had no direct evidence for this), and 2) physical displacement of nodules from the host mudrock by argillopedoturbation. Allen (1986) also hypothesized argillopedoturbation as an important process in Old Red Sandstone paleosols. Clay and silt dissolution may have taken place in the Rock Lake calcrete, since these constituents gradually disappear through the three phases of development. However, the close proximity of the non-glaebular, orthic, and orthic-disorthic glaebule phases tends to refute the necessity of argillopedoturbation in the production of glaebules with more distinct boundaries and few inclusions of siliciclastic host material. In short, the disorthic subphase of the Rock Lake calcrete is probably a product of clay dissolution and *in situ* host claystone displacement, although some argillopedoturbation may have occurred. Observable displacive effects of calcite precipitation include: 1) spar growth between peds, which actively shatters them, 2) separation of micrite peloids via accumulation of carbonate in circumgranular cracks and vugs, and 3) dispersion of silt grains in a micrite groundmass ("floating grains" of Goudie 1983, p. 106). Dissolution of calcite along stylolites between nodules was probably a late diagenetic event associated with much later subsurface compaction of the host mudrock.

What was the source of carbonate for calcrete development in the Rock Lake? The parent mudrock was probably not strongly calcareous (as indicated by the lack of carbonate in the middle-lower part of the Rock Lake), but thick carbonates are within 2 m below of the paleosol surface. Upward movement of groundwater laden with dissolved calcite seems unlikely, however, in the light of

1) significant calcite precipitation above the plugged or nearly plugged glaebule-rich horizon, 2) the occurrence of most pedogenic carbonate precipitation well above the contact with underlying Stoner carbonates, and 3) the presence of what is interpreted as an older Bt horizon below the extensive development of calcrete.

An eolian mechanism of carbonate dust accumulation at the soil surface seems more plausible. Crocker (1946), Hutton and Leslie (1958), Ruhe (1967, p. 60), Reeves (1976, p. 103), Nettleton and Peterson (1983, p. 209), and Machette (1985, p. 7–8) envisaged aeolian dust as a major source of soil carbonate, citing examples of accumulations of carbonate dust via rainfall and eolian fallout in Australia and the southwestern U.S. This mechanism of carbonate accumulation, commonly called the "*per descensum* model," involves the accumulation of carbonate on a surface by wind and rain, followed by leaching and reprecipitation deeper in the soil over a period of thousands of years (Machette 1985). Such a mechanism is compatible with the Rock Lake paleosol because 1) the host material was apparently noncalcareous, 2) the zone of major carbonate accumulation is within the profile and well above the underlying micrites of the Stoner Member, 3) the profile at Ash Grove Quarry appears to have been cemented from the bottom up (rather than from the top down, as might be expected in a "*per ascensum*" model), and 4) it is likely that extensive carbonates were subaerially exposed in North America during sea level lowstands of the Missourian (witness the exposure surface at the top of the Stoner), and hence could have provided ready sources of carbonate dust.

Calcareous pedotubules near the base of the glaebule-rich horizon may represent pipes, analogous to those mentioned by Reeves (1976, p. 56–57) and Esteban and Klappa (1983, p. 9), through which materials were moved via suspension, collapse, and solution to create a distinct fill. A hypothesized sequence of pedogenic events is presented in Figure 10.

The formation of spheroidal structures in the A horizon at the Ash Grove Quarry is difficult to explain. They are clearly *in situ* features and may be the result of weathering under a late regime of plant types in a mesic environment promoted by transgression (witness the few, large, greenish root traces that penetrate the top of the glaebule horizon), repeated wetting and drying, or both. Relict reddish peds seen in thin section suggest that the A horizon was originally reddish and probably had granular structure before alteration during the final phase of pedogenesis.

Classification

The Rock Lake paleosol, where well-developed in the western part of the study area, is definitely an Aridosol, due to the presence of a petrocalcic horizon within 1 m of the paleosurface (Soil Survey Staff 1975, p. 155). During the development of the glaebule horizon, yearly rainfall may have been within the range of 40–60 cm (as is the case for modern calcretes, in general: Goudie 1983, p. 93). At the Ash Grove Quarry, its expression is similar to that of modern Petrocalcic Paleargids, which may have both argillic and petrocalcic horizons (although the latter is usually beneath the former; Soil Survey Staff 1975, p. 167).

REGIONAL SYNTHESIS

Three points summarize the significant regional aspects of the Rock Lake Member and associated units: 1) the upper Stoner exposure surface is laterally extensive, 2) the paleosol in the Rock Lake is best developed west of the Humboldt Fault and is increasingly poorly developed eastward towards the extrapolated axis of the Forest City Basin (Figs. 2, 8), and 3) the contact between the paleosol-bearing mudstone and marine shale within the Rock Lake is consistently sharp, as is the Rock Lake-South Bend contact (except at Plattsmouth).

Features such as thin lamination, fenestral voids, mudcracks, scattered dolomite crystals, and teepee structures, together with the rarity of body fossils, suggest that the upper Stoner was deposited on a broad, arid or semiarid tidal flat (after Shinn 1983; Scoffin 1987) along the margin of a shrinking epicontinental sea. The brecciated micrite atop the Stoner at the Sorenson Quarry indicates early cementation followed by erosion and redeposition in the intertidal zone. Region-wide exposure of the Stoner surface led to slight weathering: microkarst development, oxidation, and colonization by plants. The Rock Lake Shale was deposited atop this surface.

A possible origin for some of the sediment of the Rock Lake is as eolian dust deposited on a low, newly-emergent plain, a hypothesis also advanced for the Stranger Shale in southwestern Iowa (Goebel, Bettis, and Heckel, 1989). Recent literature interpreting modern reddish, fine-grained soils in arid or semiarid coastal regions supports this hypothesis. Red soils overlying coastal limestones in the Bahamas and Bermuda are developed in probable eolian dust deposits (Syers et al. 1969; Bricker and Mackenzie 1971), and eolian origins have been proposed for "terra rossa" soils in the circum-Mediterranean area (Pye 1987, p. 170). Deposition of all or part of the Rock Lake as intertidal muds (Russell 1974) or from fluvial sediment plumes extending into shallow marine environments (S. R. Schutter, pers. comm.) are possible alternate hypotheses. A floodplain origin for the Rock Lake is unlikely given the fairly uniform, sheetlike aspect of the unit and the absence of channels and coarser deposits.

After deposition in some environment, the Rock Lake was exposed subaerially for an appreciable period, and soil development was initiated across the area.

Pedogenesis advanced the farthest in a genetic sequence in the Louisville area and west, where the paleosol is well-horizonated and the calcrete is thick (Fig. 8). The glaebule horizon is well-represented at the Ash Grove Quarry, Schramm Park, and in the Midam No. 1 core. The glaebule horizon is farthest below the paleosurface at Schramm Park, suggesting the possibility of continued incremental deposition of dust and/or localized variability in the depth of wetting. A cemented horizon (hardpan) is present above the glaebule horizon at the Ash Grove Quarry and in the Midam No. 1 core, but not at Schramm Park (Fig. 9).

There are at least three possible explanations for the

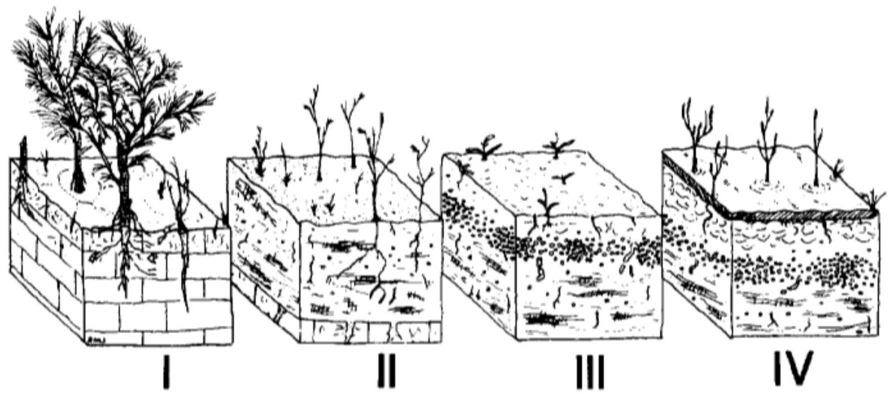

FIG. 10.—Hypothetical developmental sequence for the Rock Lake paleosol at Ash Grove Quarry. The Stoner Limestone was subaerially exposed and colonized by plants (I) prior to the deposition of the Rock Lake Shale. During and after deposition of the Rock Lake Shale, initial clay/silt illuviation occurred, and pedality was established (II). Continued carbonate precipitation led to the development of a calcrete (III), and the entire profile was gleyed and inundated during a marine transgression (IV).

absence of a cemented horizon at Schramm Park: 1) Quaternary, or perhaps Pennsylvanian, leaching of carbonates out of the Rock Lake (the glaebule horizon has a weathered appearance, and the glaebules are chalky), 2) lack of formation, perhaps due to local permeability of the underlying glaebule horizon during the Pennsylvanian, or 3) the brittle, ledge-like horizon (Fig. 9) above the glaebule horizon is a fragipan dating from another (humid) episode of pedogenesis during the Pennsylvanian. Fragipans are compact, brittle horizons that occur within 40–80 cm of the surface in silty soils (e.g., those derived from eolian dust) of humid regions, and they do not form below carbonate-rich horizons or in calcareous parent materials (Soil Survey Staff 1975, p. 42–43). The interpretation of the brittle zone as a Pennsylvanian feature, and not merely a result of overall diagenetic compaction, depends upon its tendency to weather in relief. Such differential weathering, which is not due to any existing cement, suggests development of a compact, brittle horizon before compaction of the unit as a whole. The position of the brittle horizon above a horizon of carbonate enrichment, the apparent absence of significant carbonate accumulation in the upper 80 cm of the Rock Lake at Schramm Park, and the weathered appearance of the glaebule horizon (suggesting some leaching of carbonate) are potentially compatible with a fragipan interpretation. If there is a fragipan at Schramm Park, then it represents a return to humid conditions before the South Bend transgression.

Transgression led to the gleying of at least part of the Rock Lake soil profile, either directly, by saturation with marine water, or indirectly, by the raising of local water tables in advance of inundation. Gleying proceeded deepest in the east, where permeability was high due to incomplete development of the calcrete, and where inundation/saturation arrested soil development relatively early (westward, the Rock Lake surface remained topographically high and the soil profile matured). Swift (1968) described gleying of glacial till by humic acids from salt marshes in Nova Scotia, where active landward migration of nearshore facies occurs and a small-scale disconformity (a ravinement: a surface produced by shoreline wave erosion) marks the plane of marine transgression. This modern transgressive situation, and others provided by Swift (1968), is reminiscent of events interpreted from the upper Rock Lake. However, there is no evidence suggesting erosion of a significant part of the Rock Lake paleosol—perhaps the South Bend transgression was too fast to either accumulate or remove significant amounts of sediment, or wave erosion during the transgression was limited to the removal of hypothetical marsh sediments deposited (atop the Rock Lake) at the leading edge of the landward-moving transgressive facies belt.

In general, the study area was a low, flat-lying plain during the development of the Rock Lake paleosol, yet regional relief was clearly sufficient to influence pedogenesis. Missourian paleotopography in the area was probably a relict feature of the tectonic activity responsible for the Forest City Basin. There is no evidence for pronounced uplift of the western part of the study area during the formation of the Rock Lake paleosol, because the Stoner-Rock Lake-South Bend sequence proceeds westward intact. Contemporaneous compaction of the Forest City Basin sequence may have maintained downwarping in the eastern part of the study area, however, and contributed to any relict topography.

BIOTIC IMPLICATIONS

In the context of literature on modern soils and the bulk of descriptions of calcrete-bearing paleosols, some features of the Rock Lake paleosol can be interpreted with a degree of confidence. Certain other aspects stimulate intriguing, but currently unanswerable, questions.

The nature of the plant community(s) on the Rock Lake paleosol at the Ash Grove Quarry during various stages in its development is unknown. Root traces suggest that abundant, relatively large, plants colonized the exposure surface atop the Stoner Limestone, but presumed root channel pedotubules in the overlying Rock Lake have smaller diameters and are appreciably less dense. Drab halos around root traces are more abundant in the interpreted Bt horizon but are still patchy in distribution. Throughout the paleosol there is no direct evidence (e.g., large, coherent root trace systems) for colonization by large arborescent forms. The pool of possible colonizers (pteridosperms, lycophytes, conifers, etc.) would be radically different than that in a modern arid or semiarid region today (mostly xerophytic angiosperms, including grasses); plants may even have been absent from the paleosurface by the time the calcrete was fully developed.

Presumably, the flora of the Rock Lake paleosurface differed significantly in appearance from Pennsylvanian coal forest floras. Contemporaneous rocks in eastern Kansas yield remains of conifers (the Garnett flora, including *Walchia*) that are traditionally considered "upland" forms (Rothwell and Mapes 1988). Perhaps the Missourian red mudstone paleosols were the "upland" sites of Midcontinent floras; Schutter and Heckel (1985) hypothesized that conifer savannas occupied parts of the Missourian plains of the Midcontinent. The small, single root traces and pedotubules suggest low annuals or perennials, but it seems somewhat unlikely that such plants were conifers.

CONCLUSIONS

The Rock Lake paleosol formed on a laterally-extensive plain under climatic conditions varying from humid (during the formation of a Bt horizon at the Ash Grove Quarry) to semiarid (during the precipitation of calcite glaebules). Drier conditions prevailed and left a strong signature. Paleotopography affected regional pedogenesis, resulting in reddish color and well-developed horizons of calcite glaebules in the higher western part of the study area and greenish color and poorly developed, sparse carbonate glaebules in the lower, eastern part.

Developmental time for the Rock Lake paleosol is an intriguing issue but escapes immediate resolution. Based on modern examples, an absolute minimum developmental time of 5,000 yr can be hypothesized (Nettleton and Peterson 1983, p. 198). Exposure surface longevity could have been appreciably longer; Machette (1985) found that Stage III calcic soils in New Mexico ranged in maximum age from 100,000 to 500,000 yr. A developmental time of 4,000 to 50,000 yr could probably be accomodated in Heckel's (1986) estimation of 235,000–400,000 yr for major depositional cycles during the Pennsylvanian in the North American Midcontinent. Thus, an "outside shale" with a well-developed paleosol may represent an appreciable portion of the total time involved in a complete depositional cycle.

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REFERENCES

Allen, J. R. L., 1986, Pedogenic calcretes in the Old Red Sandstone facies (late Silurian–early Carboniferous) of the Anglo-Welsh area, southern Britain, *in* Wright, V. P., ed., Paleosols: Their Recognition and Interpretation: Princeton, N.J., Princeton University Press, p. 58–86.

Blodgett, R. H., 1988, Calcareous paleosols in the Triassic Dolores Formation, southwestern Colorado, *in* Reinhardt, J., and Sigleo, W. R., eds., Paleosols and Weathering through Geologic Time: Geol. Soc. Am. Spec. Paper No. 216, p. 103–121.

Bown, T. M., and Kraus, M. J., 1987, Integration of channel and floodplain suites, I: Developmental sequence and lateral relations of alluvial paleosols: Jour. Sed. Petrology, v. 57, p. 587–601.

Brewer, R. A., 1976, Fabric and Mineral Analysis of Soils: New York, Krieger Publishers, 482 p.

Bricker, O. P., and Mackenzie, F. T., 1971, Limestones and red soils of Bermuda: Discussion: Geol. Soc. Am. Bull., v. 81, p. 2523–2524.

Buol, S. W., Hole, F. D., and McCracken, R. J., 1980, Soil Genesis and Classification: Ames, Iowa, Iowa State Univ. Press, 404 p.

Burchett, R. R., 1971, Guidebook to the geology along portions of the lower Platte River Valley and Weeping Water Valley of eastern Nebraska, Univ. Nebraska Conservation and Survey Div., 39 p.

Burchett, R. R., and Bolitho, M. R., 1981, Structure of the Elmont Limestone in central Otoe County, Nebraska, *in* Burchett, R. R., ed., Regional Tectonics and Seismicity of Eastern Nebraska, Annual Report July 1980–June 1981: published report NUREG/CR-2411 prepared for Nuclear Regulatory Commission by Nebraska Geol. Sur., p. 2–13.

Crocker, R. L., 1946, Post-Miocene climatic and geologic history and its significance in relation to the genesis of major soil types of South Australia: Commonwealth Sci. Ind. Res. Org. Bull. No. 193, 56 p.

Esteban, M., and Klappa, C. F., 1983, Subaerial exposure environment, *in* Scholle, P. A., Bebout, D. G., and Moore, C. H., eds., Carbonate Depositional Environments: Am. Assoc. Petroleum Geologists Mem. No. 33, p. 1–95.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1965, The K horizon: A master horizon of carbonate accumulation: Soil Sci., v. 99, p. 74–82.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Sci., v. 101, p. 347–360.

Goebel, K. A., Bettis, E. A., and Heckel, P. H., 1989, Upper Pennsylvanian paleosol in Stranger Shale and underlying Iatan Limestone, southwestern Iowa: Jour. Sed. Petrology, v. 59, p. 224–232.

Goudie, A. S., 1983, Calcrete, *in* Goudie, A. S., and Pye, K., eds., Chemical Sediments and Geomorphology: London, Academic Press, p. 93–131.

Heckel, P. H., 1986, Sea-level curve for Pennsylvanian eustatic ma-

rine depositional cycles along midcontinent outcrop belt, North America; Geology, v. 14, p. 330–334.
HECKEL, P. H., BRADY, L. L., EBANKS, W. J., AND PABIAN, R. K., 1979, Field guide to Pennsylvanian cyclic deposits in Kansas and Nebraska: Guidebook Series No. 4, Kansas Geol. Sur., 79 p.
HUTTON, J. T., AND LESLIE, T. I., 1958, Accession of non-nitrogenous ions dissolved in rainwater to soils in Victoria: Australian Jour. Agricultural Resources, v. 9, p. 492–507.
JOECKEL, R. M., 1985, A possible pedogenic origin for features of "red shales"—Shawnee Group (Pennsylvanian—Virgil Series), Cass County, Nebraska (abstr.): Proc. Nebraska Acad. Sci., 95th Ann. Meeting.
MACHETTE, M. N., 1985, Calcic soils of the southwestern United States, *in* Weide, D. L., ed., Quarternary Geology of the Southwestern United States: Geol. Soc. Am. Spec. Paper No. 203, p. 1–21.
MACLEOD, D. A., 1980, The origin of the red Mediterranean soils in Epirus, Greece, Jour. Soil Sci., v. 31, p. 125–136.
MUNSELL COLOR COMPANY, 1975, Munsell Soil Color Charts, 1975 Edition: Baltimore, Md., Kollmorgen Corporation.
NETTLETON, W. D., AND PETERSON, F. F., 1983, Aridosols, *in* Wilding, L. P., Smeck, N. E., and Hall, G. F., eds., Pedogenesis and Soil Taxonomy II: The Soil Orders: Amsterdam, Elsevier, p. 165–215.
PRATHER, B. E., 1985, An upper Pennsylvanian desert paleosol in the D-zone of the Lansing-Kansas City Groups, Hitchcock County, Nebraska: Jour. Sed. Petrology, v. 55, p. 213–221.
PYE, K., 1987, Aeolian Dust and Dust Deposits: London, Academic Press, 334 p.
REEVES, C. C., 1976, Caliche: Origin, Classification, Morphology, and Uses: Lubbock, Tex., Estacado Books, 233 p.
ROTHWELL, G. W., AND MAPES, G., 1988, Vegetation of a Paleozoic conifer community, *in* Mapes, G., and Mapes, R. H., compilers, Regional Geology and Paleontology of Upper Paleozoic Hamilton Quarry Area in Southeastern Kansas: Field trip guide for 22nd Ann. Mtg. South-central Sec. Geol. Soc. Am., Lawrence, Kan., p. 213–224.
RUHE, R. V., 1967, Geomorphic surfaces and surficial deposits in southern New Mexico: State Bur. Mines Min. Res./New Mex. Inst. Mining and Tech. Mem. No. 18, 65 p.
RUSSELL, J. L., 1974, Comparison of two Late Paleozoic red shales of the Midcontinent region: Lincoln, Neb., [unpubl. Ph.D. diss.]: Univ. of Nebraska – Lincoln, 289 p.
SCHUTTER, S. R., AND HECKEL, P. H., 1985, Missourian (early late Pennsylvanian) climate in Midcontinent North America: Internat. Jour. Coal Geol., v. 5, p. 111–140.
SCOFFIN, T. P., 1987, An Introduction to Carbonate Sediments and Rocks: Glasgow, Blackie, 274 p.
SHINN, E. A., 1983, Tidal flat environment, *in* Scholle, P. A., Bebout, D. G., and Moore, C. H., eds., Carbonate Depositional Environments, Am. Assoc. Petroleum Geologists Mem. No. 33, p. 171–210.
SOIL SURVEY STAFF, 1975, Soil Taxonomy: Soil Conservation Service, U.S. Dept. Agri., Agri. Handbook No. 436, 754 p.
SWIFT, D. J. P., 1968, Coastal erosion and transgressive stratigraphy: Jour. Geol., v. 76, p. 444–456.
SYERS, J. K., MOKMA, D. L., JACKSON, M. L., DOLCATER, D. L., AND REX, R. W., 1969, Eolian sediment influence on pedogenesis during the Quaternary: Soil Sci., v. 107, p. 421–427.
TURNER, P., 1980, Continental Red Beds: Contributions to Sedimentology 29: Amsterdam, Elsevier, 562 p.
WALKER, T. R., 1967, Color of Recent sediments in tropical Mexico: A contribution to the origin of red beds: Geol. Soc. Am. Bull., v. 70, p. 917–920.
WATNEY, W. L., 1980, Cyclic sedimentation of the Lansing–Kansas City Groups in northwestern Kansas and southwestern Nebraska: Kansas Geol. Sur. Bull. No. 220, 70 p.
WATNEY, W. L., AND EBANKS, W. J., 1978, Early subaerial exposure and freshwater diagenesis of Upper Pennsylvanian cyclic sediments in northern Kansas and Southern Nebraska (abstr.): Am. Assoc. Petroleum Geologists Bull. (Abstracts), v. 62, p. 570–571.
WRIGHT, V. P., 1982, Calcrete paleosols from the Lower Carboniferous Llanelly Formation, South Wales: Sed. Geol. v. 33, p. 1–33.