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INTEGRATION OF CHANNEL AND FLOODPLAIN SUITES, I. DEVELOPMENTAL SEQUENCE AND LATERAL RELATIONS OF ALLUVIAL PALEOSOLS[1]

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ABSTRACT: The lower Eocene Willwood Formation of the Bighorn Basin, northwest Wyoming, consists of about 770 m of alluvial rocks that exhibit extensive mechanical and geochemical modifications resulting from Eocene pedogenesis. Willwood paleosols vary considerably in their relative degrees of maturity; *maturity* is defined as stage of development as a function of the amount of time required to form. Five arbitrary stages are proposed to distinguish these soils of different maturities in the Willwood Formation. Stage 1 soils, the least mature, are entisols; stage 2 and stage 3 soils are intermediate in maturity and are probably alfisols; and stage 4 and stage 5 soils, the most mature, are spodosols. These stages are not only time-progressive elements of an in situ maturation sequence for Willwood soil formation, but, in the lateral dimension, they are also usually distributed sequentially.

Study of Willwood paleosols indicates that an inverse relationship exists between soil maturity and short-term sediment accumulation rate. The least mature Willwood paleosols formed in areas of relatively high net rates of sediment accumulation on 1) channel, levee, and crevasse-splay sediments of the proximal alluvial ridge, and 2) deposits filling large and small paleovalleys formed by major episodes of gullying (lowered baselevels). In contrast, the fine-grained sediments of the distal floodplain, where net sediment accumulation rates were relatively low, experienced development of much more mature soils. Soils of intermediate maturities occur in the order of their stage on intervening proximal floodplain and distal alluvial ridge sediments. Adjacent bodies of sedimentary rock that differ in their ancient soil properties because of distance from areas of relatively high sediment accumulation are denoted by the new term *pedofacies*.

The remarkable sequence of paleosols in the Willwood Formation clearly illustrates several important principles of soil-sediment interrelationships in aggrading alluvial systems that have broad application to other deposits. This is especially true in view of the widespread distribution of paleosols in nearly all ancient fluvial rocks. Further study of Willwood paleosols will not only enable precise lateral correlation of coeval alluvial sediments, and thereby fluvial sedimentary events, from the distal to the proximal realms of the floodplain but will also contribute to increasingly informative evaluations of the nature, tempo, and mode of alluvial succession.

INTRODUCTION

Most sedimentary basins adjoining mountainous regions throughout the world contain thick sequences of alluvial rocks. In the Rocky Mountain region of the western United States, alluvial deposits yield or are associated with significant reserves of coal, uranium, subsurface water, oil shale, gas, and trona, and knowledge of their geometries and origins is important economically as well as for academic interest. Many of these alluvial sequences are also dominated volumetrically by fine-grained clastics (silt, clay, and mud) that were deposited on ancient floodplains. Despite the commonly overwhelming percentage of floodplain as opposed to channel alluvium, floodplain sediments have habitually been ignored in both fluvial sedimentologic studies of the rocks themselves, and in more general modeling of alluvial systems.

Though few sedimentologists deny the potentially important role of floodplain sediments in evaluating ancient stream deposits, the realistic utility of these rocks in research has been hampered considerably by lack of field and laboratory methodologies to examine them. Sandstones deposited by channel systems generally contain large- and small-scale primary sedimentary structures that yield a great deal of information about the streams that formed them. Homologues of these sedimentary structures occur in modern stream-channel deposits and are quite amenable to modeling, both empirically by flume experiments and quantitatively by means of statistical analysis of facies ordering. In contrast, floodplain sediments are finer grained and commonly lack well-preserved sedimentary structures. Moreover, modern examples of overbank sediment are commonly obscured by vegetation, and both individual and composite depositional units in the overbank sequence are not only difficult to recognize in the field, they are nearly impossible to correlate laterally for any distance, or to relate to coeval channel deposits with any precision.

Soil survey studies and examinations of Quaternary soils have continued apace for more than a century, and paleosols have long been recognized in Tertiary alluvial rocks of the western United States (e.g., Schultz et al. 1955). However, as discussed elsewhere (Kraus and Bown 1986), their potential contributions to sedimentologic studies were overlooked due to the long-prevailing philosophy that paleosols are rarely preserved phenomena that 1) mark some major unconformities (e.g., Ritzma 1955, 1957; Pettyjohn 1966; Abbott et al. 1976), or 2) simply record pauses in what is otherwise a more or less continuous record of sediment accumulation (e.g., Allen 1974; Behrensmeyer and Tauxe 1982). Moreover, much of the philosophy of paleosols was developed by Quaternary workers who commonly described soil development in basically degrading regimes. It now appears that most ancient alluvial sequences contain numerous sequential (multistorey) paleosols (Chalyshev 1969; Bown and Kraus

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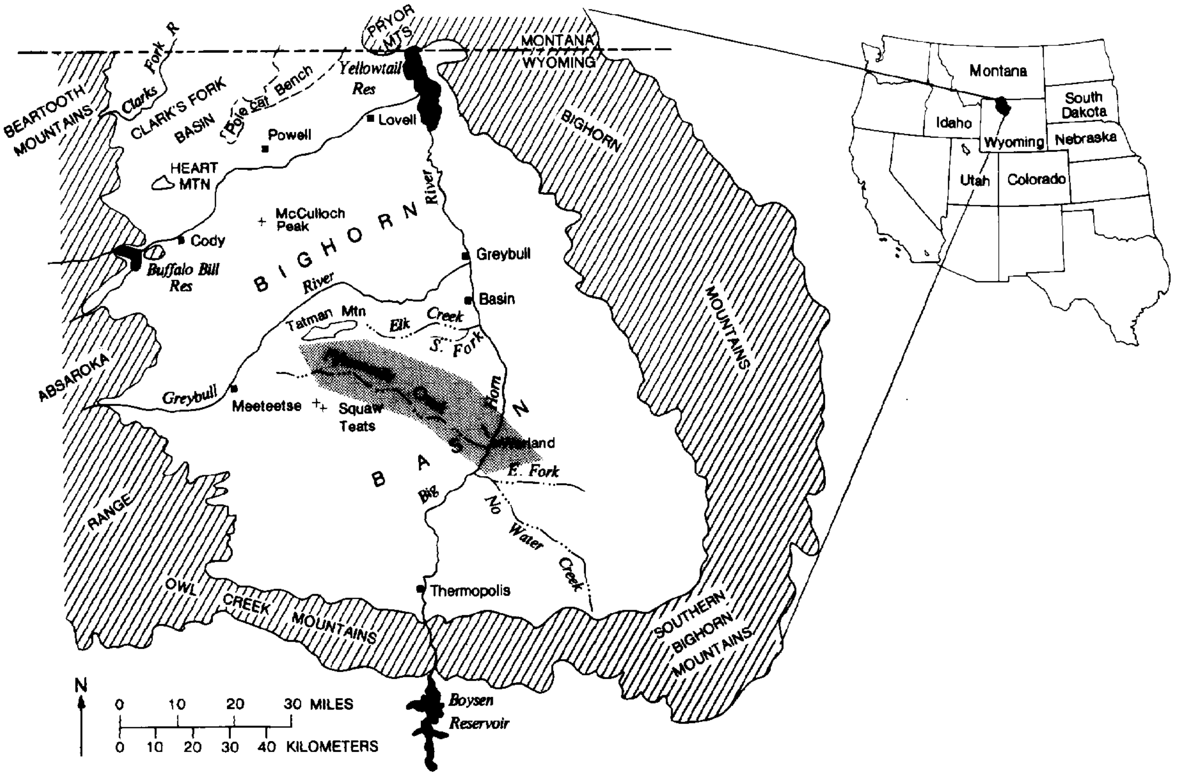


FIG. 1.—Map of the Bighorn Basin in northwestern Wyoming, showing study area (shaded).

1981a; Retallack 1983a, b; Kraus and Bown 1986) and that soil development, due to the very episodic nature of accumulation of alluvial sediment, is a normal part of the fluvial regime (Kraus and Bown 1986). Because many ancient alluvial soil profiles are easily recognized, exposed over broad areas, and formed almost instantaneously in terms of geologic time (in the range of 2,000–30,000 years), they offer a nearly ideal method of correlating deposits (and thereby sedimentary events) from the less active interchannel areas to the more active areas on and surrounding the alluvial ridge.

The 770-m-thick lower Eocene Willwood Formation in the Bighorn Basin of Wyoming (Figs. 1 and 2) is an exceptionally well-exposed alluvial deposit spanning about 3.5 Ma (Bown 1982) and containing numerous superposed profiles of alluvial paleosols. Earlier studies of these soils were largely concerned with their recognition and description (Neasham and Vondra 1972; Bown 1979; Bown and Kraus 1981a) and their classification (Bown and Kraus 1981a), as well as with the implications of alluvial paleosols in general for problems of time resolution in alluvial stratigraphy (Kraus and Bown 1986). The exposure of individual Willwood paleosols over wide areas in Bighorn Basin badlands (Fig. 2) has encouraged the examination of additional paleosol parameters that are more closely related to the alluvial system in the genetic sense and which are consequently of greater value to sedimentologists. These include temporal sequencing, lateral and vertical variability, and the corollary temporal, lateral, and vertical relations of the paleosols to different components of the ancient alluvial system.

In this paper we 1) present a brief resume of the nature of the soils and their maturation sequence, and 2) discuss the lateral relations and variability of Willwood paleosols and their relations to Willwood channel deposits. Part II (Kraus 1987) examines vertical sequences of Willwood paleosols and their relation to fluvial sedimentary events.

GENERAL ASPECTS OF WILLWOOD PALEOSOLS

Paleosols in the Willwood Formation are recognized on the criteria outlined by Neasham and Vondra (1972), Bown (1979), and Bown and Kraus (1981a). The most striking aspect of these paleosols in the field is distinctive color banding imparted to them by the redistribution and differential concentration and hydration or dehydration of ferric iron compounds in different parts of the profiles. Parent materials of Willwood paleosols consisted exclusively of alluvium that was dominantly mud (silt and clay) but included some sand layers. Although colored sandy units exist, they are rare; and it is the muds that are characterized by intense variegation with hues of yellow, orange, red, purple, and blue.

At least provisionally, more mature Willwood paleosols appear to be related to the order of soils comprising the spodosols (Soil Survey Staff 1975). This assignment is based on the presence of:

1) a well-developed A horizon that is generally made up of an eluviated (leached) albic zone (Ae horizon) and one or more organic-rich zones (Ao horizons, or epipedons);
2) a well-developed B horizon that is enriched in finely disseminated, interstitial, hydrated or dehydrated sesquioxides of iron and aluminum and, occasionally, oxides of manganese. These constituents, the soil plasma, locally occur as glaebules (Brewer and Sleeman 1964). One or more argillic (Bt) or calcareous (Bca) zones may or may not be present; and
3) a spodic zone, that is rich in organic carbon and aluminum and iron oxides. The spodic zone generally formed in the lower part of the A horizon or in the underlying upper part of the B horizon. In Willwood soils, the spodic horizon is commonly deep purple in color.

The A horizons of Willwood spodosols vary in thickness from about 10 cm to more than 1.5 m and in color from light ashy gray to bluish gray. Epipedons tend to be very dark gray. The most mature spodosols possess a complex B horizon that is generally purple near the top and grades downward to dark red, light red, and sometimes orange or yellow. The B horizons attain a maximum thickness of approximately 3 m. Because soils form very rapidly and to great depths on alluvial parent materials, C horizons, or zones of relatively unaltered parent alluvium, rarely survived Willwood pedogenesis and are almost never associated with the most mature spodosols. The A horizons of Willwood spodosols commonly contain immense lags of fossil vertebrate remains (Bown and Kraus 1981b) and numerous rhizoliths. A host of invertebrate trace fossils are variously distributed throughout the solum (Bown and Kraus 1983).

Retallack (written comm., 1982) has properly questioned the identification of Willwood paleosols as spodosols, preferring assignment to alfisols because of the relatively abundant nodular calcium carbonate (incipient calcrete) present in the lower parts of most profiles. Although the presence of calcium is believed to inhibit development of the spodic horizon, that horizon can form once carbonates have been leached from the upper part of the solum (Soil Survey Staff 1975). For the Willwood paleosols, it appears likely that most incipient calcrete development was related to the prevailing early Eocene alternating wet and dry seasons (Bown 1979) and that $CaCO_3$ translocation was accomplished relatively early in soil genesis. At present, the exact classification of the most mature Willwood paleosols is moot; they are either spodosols with the unusual attribute of calcium carbonate accumulations, or alfisols with the equally unusual development of spodic horizons (see Soil Survey Staff 1975, p. 96).

WILLWOOD SOIL MATURATION SEQUENCE

The attributes of the spodosols described briefly above are broadly characteristic of only the most obvious and best-developed examples of Willwood paleosols. Clearly, if all of the soils in the Willwood Formation were similar in character, they would be of limited value in understanding the complex lateral and vertical relationships between channel and overbank deposits. However, soil formation is a near-surface phenomenon occurring through time, and certain soils have had more time to develop than other soils of the same type. The detailed morphological and geochemical differences among these soils can be used to establish their relative maturity, where maturity of a particular kind of soil is defined as the relative length of time required to form the soil if all other variables (e.g., parent material, moisture, temperature, vegetation) remain relatively constant.

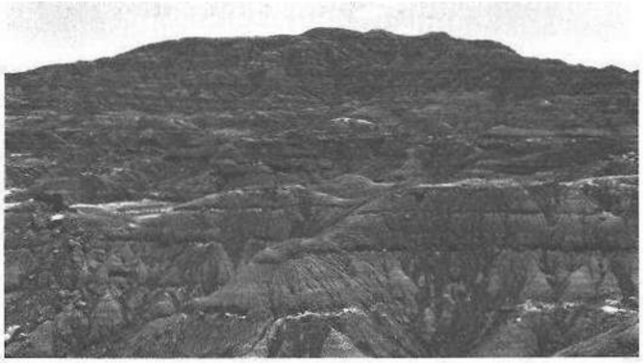
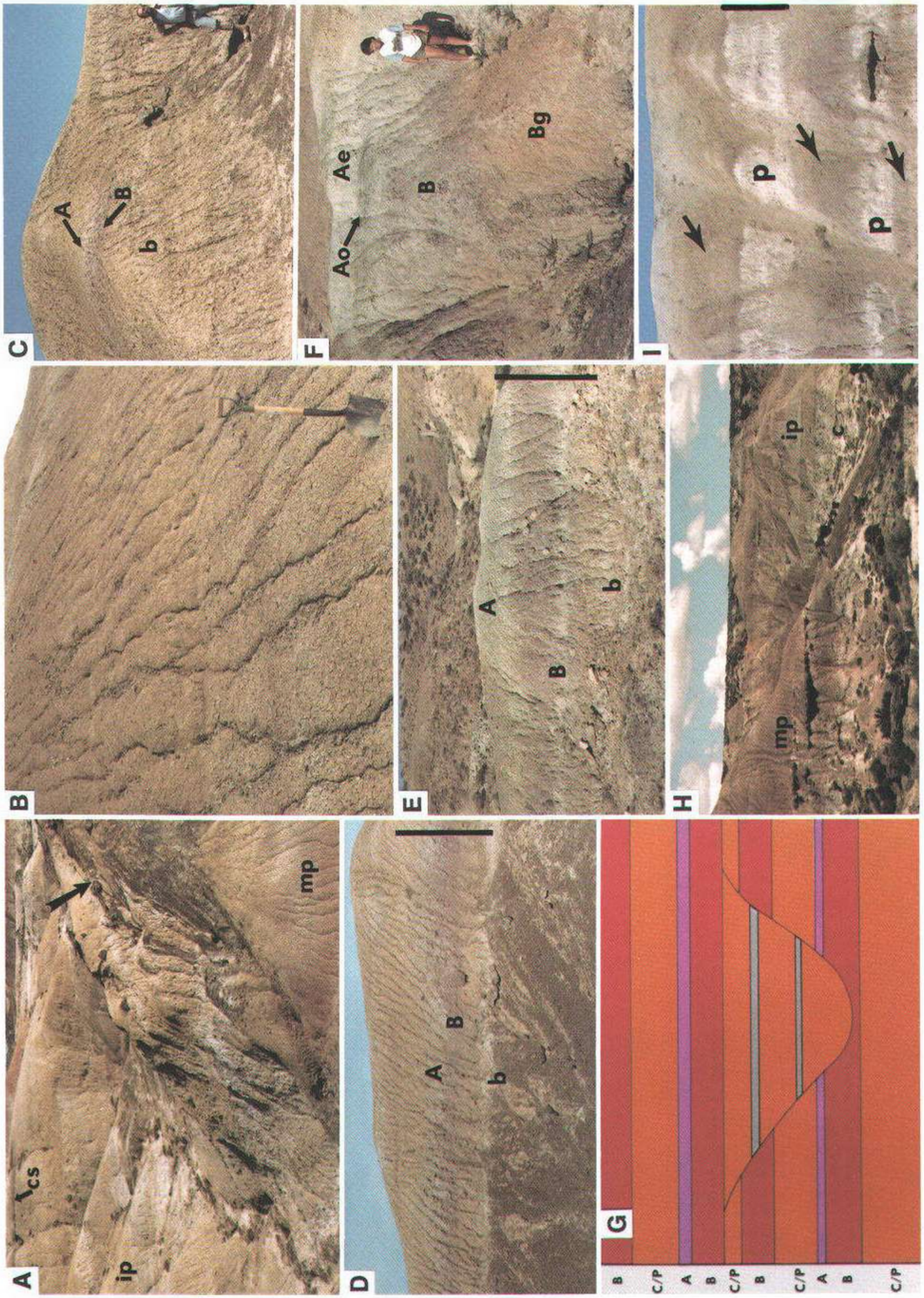


FIG. 2.—Exposures of the Willwood Formation on the north side of Sheep Mountain, Bighorn Basin, showing mudstone-dominated architecture and stressing the great vertical and lateral control available for studies of spatial variability in paleosols of the Willwood Formation. About 275 m of the upper part of the formation is illustrated.

Closer examination of Willwood paleosols reveals that the obvious, well-developed examples comprise only a small percent of the whole paleosol spectrum. The remainder consists of numerous soils that resemble the very well-developed soils to varying degrees and some that appear to lack any similarity whatsoever. By first examining soils with the most obvious and thickest profile development and working backwards through the more similar to less similar soils, it is evident that nearly all Willwood paleosols were on the way to becoming the same kind of soil, but they simply represent different stages of development (i.e., represent different maturation stages). The most mature (stages 4 and 5) are relegated, with the qualifications observed above, to the spodosols. Following Retallack (written comm., 1982), some of the less mature varieties, in which spodic horizons have not had the time or opportunity to develop (stages 2 and 3; Figs. 3C, D, 4, 5A), probably are alfisols; that is, soils with an ochric epipedon, an argillic horizon, and moderate to high base saturation. They are distinguished from the spodosols by the absence of a spodic horizon above the argillic horizon (Soil Survey Staff 1974, p. 96). The least mature Willwood soils are entisols that sometimes have an ochric epipedon, but have few if any well-developed horizons (Figs. 3A, B, 4, 5A).

The maturation stages 1 through 5 (Figs. 3–5) were proposed by Bown (1985a, b) as a tentative scheme for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identifying near end members (stages 1 and 5) and landmarks in between (stages 2–4) in a continuous, nondiscrete, and intergraded developmental sequence of Willwood soil formation. As such, it is extremely difficult or impossible to specify a particular maturation stage for each individual paleosol, even though it is possible to relate these paleosols to their closest counterparts in the maturation sequence. Identifying the maturation stage of different paleosols is important for two reasons. First, establishment of a general maturation sequence permits lateral changes in Willwood paleosols to be easily identified, and then soils of different maturity can be related to their position on the alluvial plain, specifically proximity to the channel. Second, when vertical sequences of multistorey paleosols are examined, successive (temporal) changes in soil maturation can be documented and used to determine changes in short-term sediment accumulation rates (see Kraus 1987) and/or climatic succession. Because most geologic time in alluvial regimes represents soil formation (i.e., neither active sediment accumulation nor active erosion took place; Kraus and Bown 1986), almost all ancient alluvial sequences contain a paleopedologic record of alluvial activity in both time and space, in addition to the record provided by channel deposits. Paleosols are also excellent general indicators of paleoclimate and thereby offer a method of attaining climatic controls independent of frequently inadequate paleontologic means. For analysis of the lower Eocene Willwood Formation and its lateral and vertical successions of paleosols, it is useful to elaborate on the maturation sequence that was originally outlined by Bown (1985a, b).

Stage-1 Paleosols

As observed above, the parent material for all Willwood paleosols was alluvium; coarser alluvium (sand and sandy silt) near the stream channels, and finer alluvium (mud with some fine sand) more distal to the channel belt. Where relatively unmodified, parent material is gray or greenish gray in color, commonly retains original stratification, and generally shows some bioturbation by invertebrates or plants (rhizoliths). Stage 1 (Figs. 3A, B; 4, stage 1; 5A) represents the development of an entisol in which orange or yellow mottles first appeared. These mottles consist of zones enriched in hydrated ferric iron oxides (limonite, goethite, lepidocrocite) that sometimes coalesced to form tabular orange or yellow beds (Fig. 3A, B). Where present, these beds have diffuse upper and lower contacts and commonly are streaked or mottled with light red (Figs. 3B; 4B; stage 1). Red areas are zones of local dehydration of ferric iron compounds which probably formed during episodic lowering of the groundwater table. Glaebules rich in manganese (MnO_2) sometimes occur near the bottom of stage-1 paleosols, and small to large calcrete ($CaCO_3$) glaebules also developed at this very early stage.

Bioturbation of stage-1 paleosols is generally intense and as great as that observed in more mature soils. This is probably because continual pedogenesis destroyed or obfuscated the burrows themselves and only the last few generations of burrows are ever well preserved. *Edaphichnium lumbricatum* (Bown and Kraus 1983), an earthworm trace fossil (Fig. 6), is especially abundant. Zones rich in organic carbon are first observed in stage 1; however, these do not seem restricted to any particular part of the solum. All textural horizons appear to be depositional (sedimentary relict) in origin and are distinguished from the Bt horizons of more mature soils by their retention of relict bedding. In the upper 200 m of the Willwood Formation in the southern Bighorn Basin, stage-1 paleosols are commonly pink rather than yellow or orange (Fig. 3B) and contain 1–4-cm-thick streaks of dark red color. However, like soils of this stage lower in the formation, there is no distinct horizon formation.

The presence of abraded $CaCO_3$ glaebules in lag deposits of many Willwood channel sandstones attests to the lower Eocene origin of these structures (Bown and Kraus 1981a, fig. 5). Abundant glaebules in stage-1 and stage-2 paleosols indicate that much of the carbonate accumulated very early (probably most was formed by stage 2 or early in stage 3; Fig. 3C, D), allowing later development of the spodic horizon so characteristic of the more mature paleosols (some stage 3 and all stage 4 and 5 soils). Glaebular $CaCO_3$ is as abundant in some stage-1 and stage-2 paleosols as in any later stage (Fig. 3C).

Stage-2 Paleosols

Stage-2 Willwood paleosols differ from those of stage 1 principally in the first obvious, though incipient, horizon formation in the profile. An eluvial Ae horizon is

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FIG. 3.—Relationship of Willwood paleosol maturation stages to areally differing parts of the floodbasin. A) Levee deposits in middle part of Willwood Formation with immature stage-1 paleosols (ip) situated in scour (base marked by arrow) cut into sequence of mature paleosols (mp). cs = carbonaceous shale. B) Levee deposits in upper part of Willwood Formation upon which stage-1 paleosols are developed. C) Sequence of distal levee deposits with several stage-1 paleosols, punctuated by A, upper B (B), and lower B (b) horizons of a stage-2 paleosol (alfisol). Note lag of abundant calcium carbonate glaebules at man's feet. D) Proximal floodplain deposits showing stage-3 paleosol (alfisol) development. Note accumulation of calcium carbonate nodules and segregation of B horizon into purple, dark red, and light red components. Bar is 5 feet (1.52 m). E) Stage-4 paleosol (spodosol) developed on distal floodplain sediments. Note increased thickness of A horizon and purple component of upper B horizon. Bar is 5 feet (1.52 m). F) Stage-5 paleosol (spodosol) on distal floodplain alluvium. Note great thickness of A horizon and purple upper B horizon (b), and division of A horizon into a clearly defined eluvial (Ae) horizon and organic carbon-rich epipedons (Ao). G and H) Schematic (G) and actual (H) examples of relative soil maturity in scours. G depicts a paleogully system excavated in a sequence of relatively mature floodplain soils and filled with younger floodplain deposits upon which relatively immature soils developed. In H a crevasse channel (c) is cut into floodplain deposits with relatively mature paleosols (mp). Levee deposits filling the top of the crevasse scour are characterized by immature (Stage-1) soil development (ip). I) Three successive stage-4 paleosols (spodosols) separated by crevasse splay sands, constituting unaltered soil parent materials (p). B horizons shown by arrows. Bar is 5 feet (1.52 m).

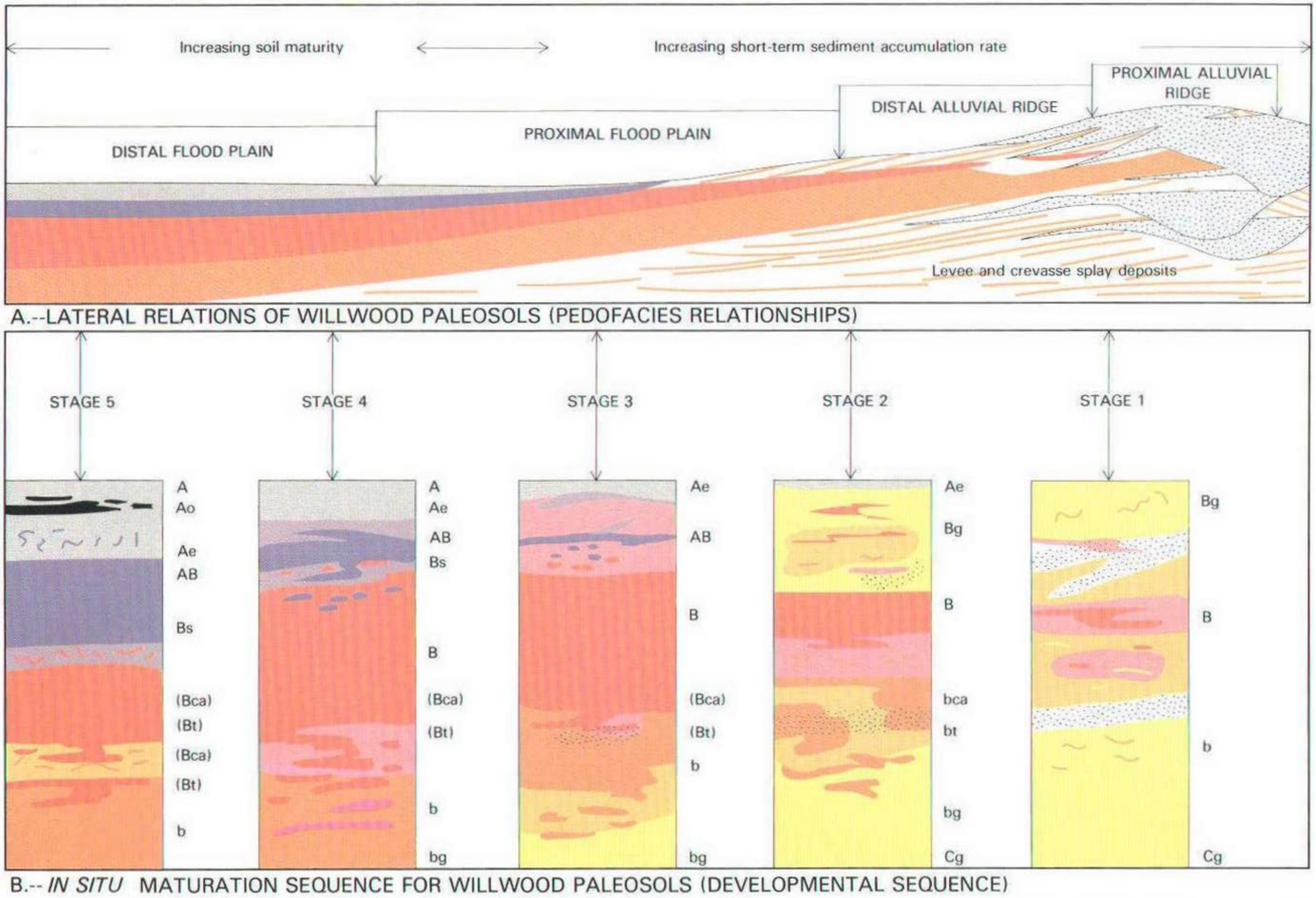


FIG. 4.—Diagram showing A, lateral relations of Willwood paleosols to different parts of the floodbasin, with respect to B, stages 1–5 of the Willwood soil maturation sequence. A is diagrammatic and not to scale; B represents simplified versions of actual paleosols. The entire sequence depicted in A is a single pedofacies. A = A horizon; Ae = eluviated zone in A horizon; Ao = epipedons in A horizon; AB = A–B transition; B = upper B horizon; Bg = gleyed upper B horizon; Bs = spodic zone in upper B horizon; (Bca) = calcrete in upper B horizon; (Bt) = clay enrichment in upper B horizon; b = lower B horizon; bca = calcrete in lower B horizon; bg = gleyed lower B horizon; bt = clay enrichment in lower B horizon; Cg = gleyed C horizon.

commonly present in some part of the upper solum (generally at the top; Figs. 3C, 4B), and is underlain by a reddish upper B horizon (Fig. 3C) or by a gleyed and then a reddish upper B horizon (Fig. 4B, stage 2). The reddish zone was formed by continued accumulation of iron oxides below the Ae horizon, coupled with prolonged better drainage of the upper part of the developing profile. Better drainage permitted increased dehydration of the iron oxides; however, color boundaries separating the incipient A horizon and different colors of the B horizon remain diffuse. In some stage-2 paleosols, the upper part of the B horizon consists of an upper dark red zone and a lower light red zone, reflecting dehydration of discrete parts of the profile containing different amounts of translocated iron (Fig. 4B, stage 2).

An orange or yellow lower B horizon, rich in Fe and Al oxyhydrates, is invariably present beneath the redder upper B horizon. The color probably reflects the proximity of the groundwater table at the time of formation. Small Fe and Al-rich glaebules are distributed throughout the B horizon (Fig. 5A) and calcrete glaebules (where present at all) approach their maximum abundance at one or several levels in the lower B horizon. Calcrete development is generally more significant by stage 2 than originally thought by Bown (1985b, p. 22). Zones rich in translocated clay (Bt horizons) are first recognizable in stage 2, and these zones commonly underlie zones rich in $CaCO_3$ glaebules. In many instances, the formation of clay-rich pans beneath calcretes is consistent enough to suggest that the buildup of pedogenic carbonate was related to the inability of the carbonate to move downward out of the system past the impermeable pans. Continued carbonate accumulation was perhaps facilitated by lateral groundwater movement (see, e.g., Brammer 1968). Elsewhere, however, $CaCO_3$ glaebules are abundant throughout the profile (including the A horizon). Instances of this rather more pervasive dispersion of soil carbonate were possibly caused by an apparent rise of the water table through the sediments as they accreted (see discussion of hydromorphic soils, below) and reflects superimposed (composite) soil profiles (Bown and Kraus 1981a, fig. 10).

Stage-2 paleosols vary considerably in the nature and thickness of B-horizon development. Whereas most Willwood paleosols at this stage of maturity possess very thin (5–20 cm), reddish upper B horizons above considerably thicker yellow or orange lower B horizons (Fig. 3C), some stage-2 paleosols are characterized by little or no A horizon and about equally thick upper (red) and lower (yellow or orange) parts of the B horizon. As will be discussed further, proximity to the coeval channel belt affects the type of soil encountered; this B horizon variability could well be related to subtle differences in the parent alluvium.

Stage-3 Paleosols

Stage-3 paleosols (Figs. 3D, 4B, 5A) are distinguished from those of stage 2 by the first well-defined profile horizon formation and by the first important buildup of soil plasma constituents and illuvial clay in the evolving B horizon. The A horizon had invariably formed by this stage, although generally only the Ae is present. Its contact with the upper part of the B horizon is diffuse. The upper part of the B horizon, marked by dark and light red tabular zones (Fig. 3D), is now considerably thickened because it expanded markedly downward at the expense of the yellow or orange lower B horizon. All of the B is enriched significantly in translocated Fe and Al sesquioxides, much of which is now in the form of glaebules. As in stage 2, these compounds are largely dehydrated in the upper part of the B and largely hydrated in the lower part, although considerable mottling exists at contacts. Textural horizons (where present) are more obvious and are exemplified by extensive slickensiding, clay trains, cutans on skeleton grains, and clay-lined vugs.

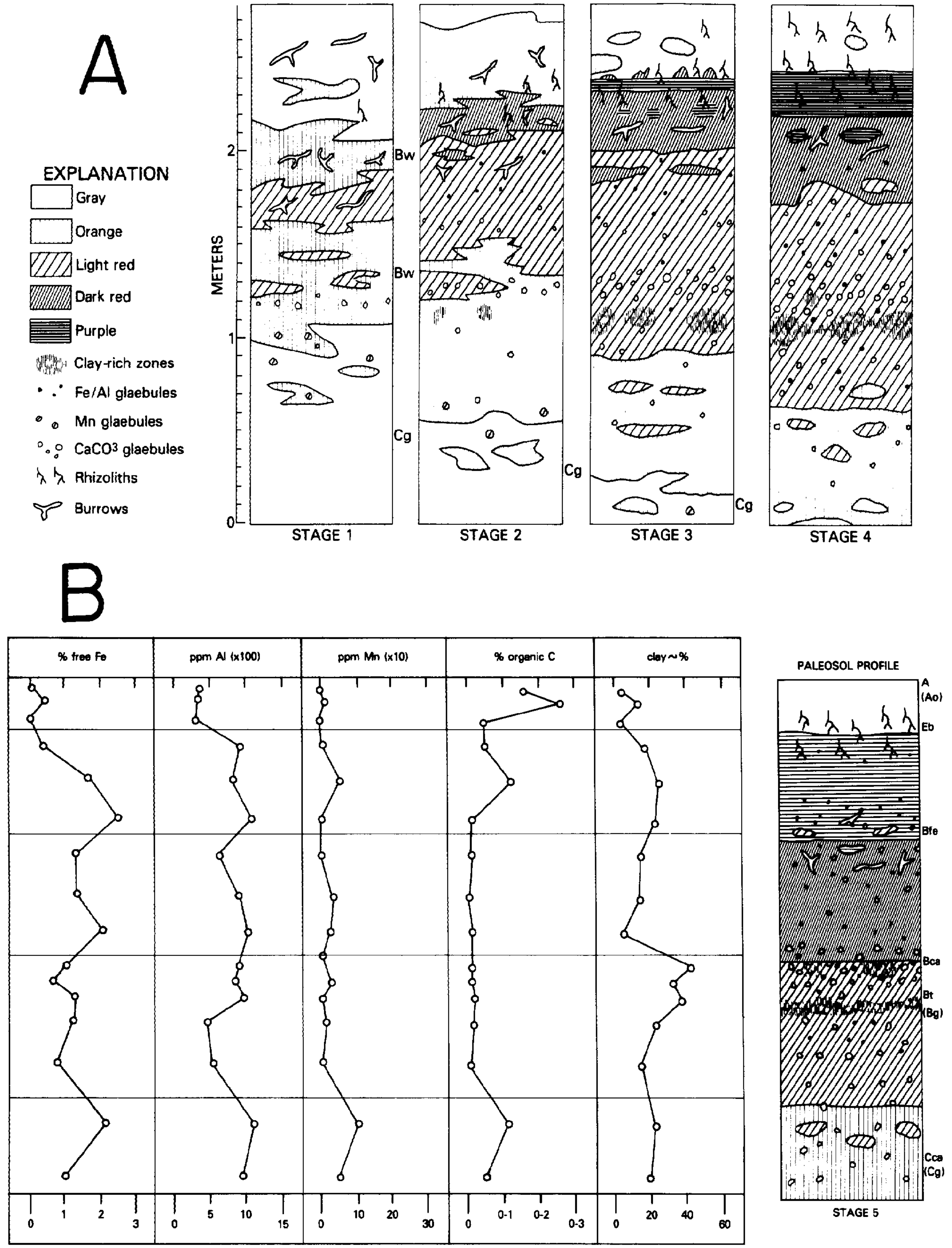
The uppermost part of the B horizon displays a purple color in stage 3 (Figs. 3D, 4B), although exposure of fresh surfaces reveals that this color is imparted by purple mottles in red mudstone. Weak spodic zones are sometimes developed in the purple upper B horizon. Although purple color was originally attributed to an admixture of organic carbon in the upper B horizon or to the large grain size of interstitial hematite (Bown 1985b), further analyses indicate that neither of these parameters alone necessarily produced purple color. Nonetheless, purple pigmentation invariably developed first in the upper part of the plasma-enriched profile and increased in importance in later maturation stages.

It appears that near maximum calcrete accumulation in the lower solum was accomplished early in stage 3. Calcrete glaebules attained their maximum size (8 cm long in diameter) and abundance in certain stage-2 and stage-3 paleosols. Although additional carbonate buildup occurred in maturation stages 4 and 5, it was probably minimal. In no instance does carbonate accumulation exceed the stage II of Gile et al. (1966).

Stage-4 Paleosols

The eluvial A horizon (Ae), in some cases developed as early as stage 2, is quite thick in stage-4 Willwood paleosols (Figs. 3E, 4B, 5A). Organic carbon also accumulated to a noticeable extent in some stage-4 soils, where it may form vague epipedons. Eluviation of clay from the A horizon was virtually complete by this stage, and, as a result, the Ae horizon is significantly coarser than subjacent horizons. Correspondingly, diffuse clay-rich zones up to 40 cm thick are present in the red and yellow parts of B horizons, and these do not appear to be appreciably thicker or richer in stage-5 soils.

Paleosols of maturation stage 4 also differ from those of stage 3 in the downward thickening of the purple uppermost B horizon at the expense of the top of the underlying dark red upper B (Figs. 3E, I, 4B). Likewise, the bottom of the dark red portion of the upper B horizon thickened downward, in this case at the expense of the top of the lower light red part of the upper B, as well as the yellow or orange lower B. In many stage-4 paleosols of the upper 300 m of the Willwood Formation, all of the lower B horizon is light red and few areas of visible hydrated iron oxides remain in the profile. There is an


A
EXPLANATION
Gray
Orange
Light red
Dark red
Purple
Clay-rich zones
Fe/Al glaebules
Mn glaebules
CaCO3 glaebules
Rhizoliths
Burrows
METERS
0
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STAGE 1
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0
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PALEOSOL PROFILE
A
(Ao)
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(Bg)
Cca
(Cg)
STAGE 5

overall decrease in the degree of mottling in B horizons from stage-3 to stage-4 paleosols, but all horizons are mottled to some extent.

Accumulations of iron and aluminum oxides in the B horizon appear to have reached their peaks early in stage 4, and this is commonly accompanied by an increase in the size and variety of Fe and Al-rich glaebules. That these oxides continued to accumulate significantly after the carbonate buildup passed its peak is indicated by nodular encrustations of hematite on many calcrete glaebules in stage-4 and stage-5 paleosols.

The most notable advance in soil development between stages 3 and 4 is the appearance of a well-defined spodic horizon (Fig. 4B, stage 4), which is typified by the association of aluminum oxides with organic carbon, generally accompanied by a significant proportion of iron oxides. They are invariably formed in the zone bounded by the A/B contact at the top and by the base of the uppermost purple B horizon. Spodic zones appear in certain advanced stage-3 paleosols, but there they are irregular and impersistent. In Willwood paleosols, spodic horizons may be single or multiple and vary from a few centimeters to more than 25 cm in thickness. It is on the basis of spodic horizon development that stage-4 and stage-5 (and some stage-3) Willwood paleosols are assigned to the Spodosol Group; stage-2 and most stage-3 paleosols are probably alfisols. Classification of these ancient soils is therefore a function of their positions in the maturation sequence, as was implied by Hutton (1951) and Rieger and Juve (1961) for soils formed on Recent loess and by Mohr et al. (1972) for tropical red, brown, and yellow soils.

Stage-5 Paleosols

By definition, stage-5 Willwood paleosols (Figs. 3F, 4B, 5B) represent the most mature stage of paleosol development in the Willwood Formation. Whereas stage 4 marks the first epipedon development, the first good spodic horizon formation, and the maxima for translocation of clay and soil plasma, stage 5 is distinguished from stage 4 principally by stronger epipedon development (good Ao horizons, Fig. 3F) and by greatly increased thicknesses of the A and uppermost B horizons. In some stage-5 paleosols, organic carbon accumulation in the A horizon is 0.8 percent dry weight and imparts a streaky charcoal color to the epipedon (Fig. 3F). The stage-5 A horizon appears to have gained some of its thickness (up to 1.5 m) by further leaching of minor units of sediment deposited on the soil surface. In consequence, there are zones in some stage-5 A horizons which are relatively rich in hydrated iron oxides although the great incidence of organic carbon prevents red pigmentation. Nonetheless, an appreciable amount of hematite does occur in mature soil A horizons in the form of reddish purple nodules that streak red (Variety #7 of Bown 1979). Generally, these form encrustations on fossils or around other organic remains. A horizons of Willwood paleosols, especially the more mature varieties, are commonly rich in vertebrate remains that accumulated through time on the surfaces of the ancient soils (Bown and Kraus 1981b).

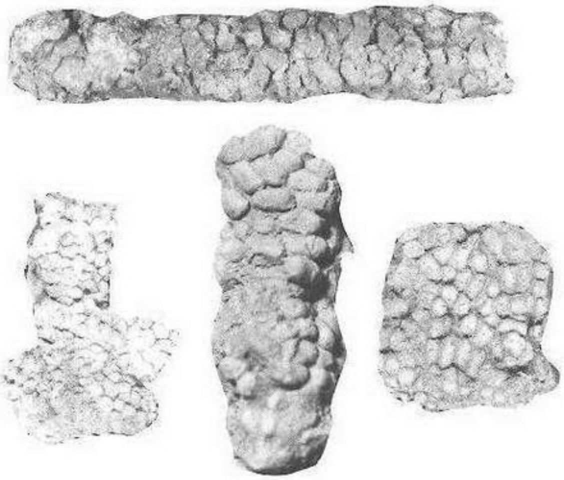

FIG. 6.—Specimens of the trace fossil *Edaphichnium lumbricatum* (Bown and Kraus 1983), fecal-pellet-filled burrow casts of an earthworm abundant in stage-1 and stage-2 paleosols developed on levee deposits in the Willwood Formation (natural size).

In certain stage-4 and stage-5 paleosols, the A horizons show dark yellow streaks (Fig. 3I). This local coloration is attributed to postpedogenetic modification caused by the introduction of iron into the A horizon during the development of younger soils. The eluviated mature A horizon is coarser than the underlying B horizon and probably acted as a conduit for groundwater as water tables were elevated following additional sedimentation. Iron arrived in the soluble ferrous state and was oxidized and hydrated following withdrawal of subsurface water from that part of the column.

Thick albic A horizons (up to about 90 cm) formed in stage-5 paleosols by downward expansion into the purple uppermost B horizon. This was probably accomplished by partial reduction of the concentrated ferric iron oxide in the presence of organic carbon, and removal of some of the iron by near-surface water gleying (see section on hydromorphic soils, below). A horizons that seem to have increased their thicknesses in this manner exhibit zones containing pipes or balls of purple- and gray-mottled mudstone in the upper part of the purple mudstone, now comprising the basal A horizon as well as the uppermost part of the B horizon (AB).

←

FIG. 5.—Diagrams illustrating A, incidence of soil coloration, glaebules, and trace fossils in maturation stages 1–4 of Willwood paleosols; and B, incidence of these attributes with respect to the distributions of mobilized iron, aluminum, manganese, organic carbon, and clay in a stage-5 Willwood spodosol. A = A horizon; (Ao) = epipedons in A horizon; B = B horizon; Bca = calcrete in B horizon; (Bg) = gleyed B horizon; Bt = clay enrichment in B horizon; Bfe = iron enrichment in B horizon (maximum); C = C horizon; Cca = calcrete in C horizon; Cg = gleyed C horizon; Eb = eluviated (albic) zone in A horizon.

The purple bed is also very thick in stage-5 paleosols, sometimes 1.5 m or more (Fig. 3F). The thickness was generally caused by progressive downward expansion of purple coloration into former red zones; however, in certain stage-5 soils that underwent a great deal of incremental profile buildup through depositional additions, the purple color expanded upward as well. The red moiety of the upper B horizon is also thicker in stage 5, and it is only in rather wet soils (identified by large numbers of MnO_2 glaebules and pervasive mottling of the lower solum) that a yellow or orange lower B horizon was retained (Figs. 3F, 4B, 5B).

Whereas coloration at the A/B and B/b (upper and lower B horizons) boundaries is diffuse and is accompanied by thick, strongly mottled zones in stages 2–3, these horizons of stage-4 and especially stage-5 paleosols are typified by much sharper color boundaries. Though some interhorizon mottling is always present at these contacts, it is generally restricted to zones only a few centimeters thick. This phenomenon reflects less mottling in general within the B horizons of more mature Willwood soils and the purple and dark red moieties of the B horizons of stage-4 and stage-5 spodosols locally contain no visible mottles whatsoever.

The succession of major developments in the evolution of Willwood soil profiles is briefly summarized as follows:

Stage 1.—No horizon formation; yellow or orange mottling, occasional development of yellow or orange beds with reddish streaks; color contacts diffuse; $CaCO_3$ accumulation initiated. Interpreted as *entisols* (Figs. 3A, B, 4A, 5A).

Stage 2.—First incipient horizon formation; Ae present but thin; red B horizon, sometimes darker red at top; color contacts diffuse; significant clay and plasma translocation initiated; $CaCO_3$ accumulation rapid (where present). Interpreted as *alfisols* (Figs. 3C, 4B, 5A).

Stage 3.—Marked horizon formation; Ae present and relatively thick; B horizon purplish at top, dark and/or light red in middle, yellow or orange at bottom; incipient, impersistent spodic zones sometimes present at top of B horizon; color contacts diffuse; significant plasma translocation, much concentrated as glaebules; clay translocation near peak (late stage 3); $CaCO_3$ translocation at peak (early stage 3). Interpreted as *alfisols-spodosols* (Figs. 3D, 4B, 5A).

Stage 4.—Profound horizon formation; Ae thick and first Ao distinguishable; eluviation of clay from Ae complete and declining elsewhere; all parts of B horizon thickened greatly; Al and Fe sesquioxide translocation at peak; overall decrease in mottling and color contacts more discrete; well-defined spodic horizon(s). Interpreted as *spodosols* (Figs. 3E, I, 4B, 5A).

Stage 5.—Profound horizon formation; Ae horizon thick and Ao horizon(s) well developed; A and upper B horizons much thicker than in stage 4; mottling less important, rare in many B horizons and color contacts sharp; very well defined and thick spodic horizon(s). Interpreted as *spodosols* (Figs. 3F, 4B, 5B).

Other Soils

The Willwood Formation consists of a great many discrete, three-dimensional packages of sediment, tens to hundreds of meters thick, that intergrade with one another both vertically and laterally over different areas of the Bighorn Basin (Bown 1979; Wing and Bown 1985). Internally, these packages differ considerably in parameters such as mud/sand ratio, sandstone geometry, carbonaceous shale occurrence and geometry (Wing 1980), and, naturally, characteristics of their contained paleosols. Bown (1979) named two such homotaxic packages the Sand Creek facies and the Elk Creek facies and, although this study is based primarily on those two named packages, it appears to be applicable to other, perhaps less clearly understood suites of Willwood paleosols (see Kraus 1987). Even though nearly all Willwood paleosols in the study area seem to fit one of the maturation stages defined earlier, a few examples deserve additional consideration.

Hydromorphic (Gley) Paleosols.—As observed above, the lower portions of the B horizons of many Willwood paleosols are enriched in hydrated iron and aluminum oxides and exhibit pervasive mottling. This phenomenon simply reflects the proximity of that lower part of the solum to the ancient groundwater table. However, certain paleosols show strong mottling in the upper part of the B horizon as well, even in stage-4 or stage-5 examples in which the extent of mottling is generally less. Moreover, extensively mottled (even leached) tabular horizons are also known in the upper part of the solum in some Willwood soils. These mottled areas and/or horizons of mottles and leaching are commonly associated with accumulations of calcium carbonate glaebules that have rounded surfaces, in contrast to the sharp, rugose surfaces of most of these structures. Brammer (1968) noticed similar rounded calcrete glaebules in Recent Indo-Gangetic alluvium and attributed their development to partial decalcification in saturated alluvial soils in the presence of decomposing organic matter.

More or less continuous saturation of the Willwood paleosols (gleying—see Bridges 1978; Buurman 1980) is also suggested by the mottling in which red iron oxides were partly reduced and removed in solution in the presence of organic carbon. This process produced gray mottles and, in areas of only partial iron depletion, the yellow hydrated iron oxides limonite and lepidocrocite. McKeague (1965), Moore (1974), and Meyer (1976) also believed that such mottling is primary and forms under only periodic hydromorphic soil conditions (pseudogleying), in which mottled parts of the solum undergo alternating phases of wetting and drying (Robinson 1949). The effect of wetting is redistribution of organic carbon in the soil, commonly along ped boundaries or root channels, such that local areas of reducing conditions are formed (e.g., Bloomfield 1951; Page 1964; Freytet 1971; Moore 1974). Mottling confined to the B horizons of the Willwood paleosols probably resulted from groundwater gleying or pseudogleying, whereas in instances in which the A horizon is also affected, the involvement of surface water gleying or pseudogleying may be indicated (but see discussion of yellow zones in A horizons of stage-5 paleosols, above).

Extensive mottling that is restricted to a few specific paleosols in a vertical sequence of otherwise similar paleosols almost certainly reflects generally wetter soil conditions. The varying dampness of the Eocene soils doubtlessly influenced the composition and distribution of the ancient flora and fauna. At some fossil localities in the lower part of the Willwood Formation, in which hydromorphic soils are prevalent, the vertebrate fauna contains an unusually high representation of *Arfia* (Creodonta), *Esthonyx* (Tillodontia), *Diacodexis* (Artiodactyla), *Homogalax* (Perissodactyla), *Ectocion* (Condylarthra), ischyromyid rodents, lizards, *Allognathosuchus* (Crocodilia), and turtles (Bown 1979).

Aside from its formation by gleying and pseudogleying, processes associated with the normal development of Willwood soil profiles under seasonal rainfall (Bown 1979, 1980; Bown and Kraus 1981a), the mottling seen in nearly all Willwood soil profiles still appears too pervasive to be explained by typical soil-forming conditions. The overall aggradational nature of the Willwood system probably placed an important role in producing this phenomenon. As increments of sediment were gradually added to the alluvial sequence and accommodated by basin subsidence, older soil profiles were buried and moved below the groundwater table. These buried soils probably underwent additional, perhaps lengthy, extrapedogenic hydromorphy when they became horizons of groundwater saturation. Because nearly all soil processes have been characterized by observations made on modern soils, there is no adequate term for this phenomenon that is defined here as *accumulative hydromorphy.*

As noted above, Bown (1979) described two geographically distinct packages of Willwood rocks in the southern Bighorn Basin, the Elk Creek and the Sand Creek facies. Briefly, the Elk Creek facies is typified by mature paleosols with deeply colored purple and brick red B horizons in which a great deal of pedogenic calcrete accumulated. These soils are associated with a relatively high proportion of channel sandstones (ribbons and sheets), cemented by calcium carbonate. In contrast, the homotaxic Sand Creek facies is characterized by mature soils having lighter pastel purple and mottled purple and orange B horizons with no calcium carbonate accumulation but with an appreciably greater proportion of manganese and hydrated iron and aluminum glaebules. Sand is somewhat less abundant in the Sand Creek facies, which is dominated by thin ribbon sandstones generally lacking in carbonate cement.

Wing and Bown (1985) also described rocks of the Fort Union Formation exposed near the town of Basin (Fig. 1) that are partly equivalent in age to those of the Sand Creek facies and the lower part of the Elk Creek facies of the Willwood Formation. In that area, Fort Union rocks are typified by a large volume of unmodified parent alluvium and several stage-1 and a few stage-2 paleosols, indicating less complete soil development associated with generally wetter soil conditions. Willwood rocks of the Clark's Fork Basin (Kraus 1985, 1987) also differ from those of the Sand Creek and Elk Creek facies. It appears, therefore, that coeval soil development was variable in different geographic areas of the same basin and that, in sum, hydromorphic characters of Willwood paleosols result from a combination of pedogenic, depositional, and geographic factors.

Alfisols.—As noted above, stage-2 and some stage-3 Willwood paleosols (those which exhibit $CaCO_3$ buildup but without spodic horizons) are perhaps best assigned to the alfisols. Stage-4 and stage-5 paleosols are probably spodosols, but they are unusual examples in which $CaCO_3$ was redistributed prior to development of the spodic horizon. In the Sand Creek facies, where there is no carbonate buildup of any kind, stage-4 and stage-5 paleosols are spodosols without qualification.

Another kind of soil, perhaps also referable to the alfisols, increases in importance through the upper 250 m of the Willwood Formation in the study area. The soils possess thin to thick purple and brick red upper B horizons but lack well-defined A horizons and lower B (b) horizons. They are invariably rich in lower solum accumulations of calcium carbonate glaebules. In the uppermost 100–150 m of the section, these soils generally have no purple component to the upper B and consist for the most part of thick, "naked" brick red B horizons. A weak spodic horizon or, more commonly, spodic zones, are present in some examples where a purple upper B horizon exists, but they are never found where this part of the profile is absent. Bown (1979) and Bown and Kraus (1981a) determined that the generally drier character of younger Willwood paleosols was probably related to overall basinal drying that accompanied the structural closure of the southern Bighorn Basin by rapid elevation of the Owl Creek Mountains (Fig. 1). It follows that the change in abundance from mature spodosols to mature alfisols upward in the Willwood section is likewise related to establishment of a drier climate. Drier conditions were also heralded by a decrease in both abundance and diversity of fossil primates and insectivorous mammals (see Bown 1980), an increase in diversity among artiodactyls and perissodactyls, a decrease and then increase in megafloral diversity (Wing 1980), and correlative changes in sediment deposit geometries (Bown 1979; Wing 1980).

LATERAL RELATIONS OF WILLWOOD PALEOSOLS

Lateral Maturation Succession

We have described how paleosols in the Willwood Formation can be roughly divided into several different types and, within the most prevalent group of these ancient soils (the alfisol-spodosol complex) a relative sequence of soil maturation is established. But why did all of the soils not go to completion; that is, why are not all Willwood paleosols stage-4 or stage-5 paleosols? Clearly, something happened to arrest further development along the maturation sequence. Possible causes seem to be limited to climatic change, erosion, and deposition. Appreciable climatic change is not suggested by the megafloras; furthermore, even very rapid climatic change would probably merely alter the course of soil development rather than abruptly halt its progress. More importantly, laterally adjacent Willwood paleosols, which are contemporaneous and thus developed under the same general climatic conditions, vary from stage 1 through stage 5. Erosion is an important process for arresting soil development, especially in degradational regimes, but this process can hardly have been a significant factor in an ancient alluvial sequence containing hundreds of well-preserved paleosols.

For paleosols of the Willwood Formation, as well as those contained in other thick alluvial sequences, the mechanism responsible for arresting soil-profile development is probably deposition. Although it is clear that relatively minor influxes of sediment are rather easily incorporated into the upper sola of developing soil profiles, large increments of new sediment can bury the evolving soil to depths beyond the near-surface physical and chemical processes that are responsible for soil formation. In these instances, the old soil is buried and becomes a paleosol, and pedogenic processes start anew on the fresh sediment. It follows that in areas where rates of net sediment accumulation are relatively rapid, more soil development is halted in relatively early stages of maturity and the superposed paleosols are dominated by immature forms. The corollary is also true; areas of the alluvial plain characterized by relatively slow sediment accumulation rates are typified by more mature soil profile development.

Interchannel or overbank environments can be simply subdivided into areas of more active and more passive sedimentary activity, depending on whether they are proximal or distal to the channel, respectively. Both particle size and short-term sediment accumulation rate decrease with distance from the channel belt (Bridge and Leeder 1979). The most coarse grained (fine sands and silt) and thickest deposits accumulate as levees directly adjacent to the channel (see, e.g., Alexander and Prior 1971), and these are commonly cut by crevasse feeder channels also filled by sands and silts (Singh 1972). In large part, the deposition of levees is responsible for development of the alluvial ridge, or the elevated portion of the alluvial plain occupied by an active channel. Beyond the levees are floodplain areas (sensu Collinson 1978) that are characterized by low rates of sediment accumulation and dominantly fine-grained sediment (silt and clay), although influxes of coarser sediment are episodically brought onto the floodplain by crevasse splays.

Levee, crevasse-channel, and crevasse-splay deposits (Fig. 3A, C, H) comprise a volumetrically significant part of the Willwood Formation. Willwood levee deposits consist of fine or very fine sandstones that are thinly interbedded with siltstones. Unless obliterated by bioturbation, small-scale cross lamination is the characteristic sedimentary structure. The levee deposits are preserved either laterally to channel sandstones or, more commonly, directly above or below a channel sandstone. In some examples, the strata display a primary dip that is usually subtle (2 to 4 degrees) but can be as much as ten degrees. Levee deposits commonly abound with fossil vertebrates, some of which are very complete and well preserved. They are additionally characterized by the eggshells of birds, abundant trace fossils of earthworms (Oligochaeta, Fig. 6), concentrations of invertebrates (see Hanley 1985), and distinctive cylindrical calcite nodules that probably replaced the stumps of trees that grew along the channel margin and then rotted (Kraus 1985).

Willwood crevasse-channel deposits (Fig. 3H) are coarser-grained than levee deposits, and characteristic sedimentary structures include large-scale cross stratification and horizontal stratification in addition to small-scale cross lamination. Other criteria, suggested by Bridge (1984) to distinguish crevasse channels, also typify the Willwood examples and include a channelized shape, coarsening-upward sequences, and paleocurrent trends oblique to the flow of the main channel. In addition, Willwood sandstones interpreted as crevasse-feeder channel deposits commonly contain lag deposits of invertebrate fossils (see Hanley 1985), and, in some exposures, these channels cut through proximal levee deposits.

Cumulative Willwood levee and crevasse-channel sequences are as much as 15–20 m thick, and both their thickness and lateral extent (up to 10 km) are roughly proportional to the sizes of the associated channel system. These deposits form a distinctive alluvial ridge that, because of decreasing grain size and sediment thickness away from the channel margin, can be subdivided into a *proximal alluvial ridge* and a *distal alluvial ridge* (Fig. 4A).

Willwood floodplain sequences are dominated by mudstones and siltstones deposited from suspension during flooding episodes. The mudrocks are interspersed with thin, very fine sandstone units that are tabular and laterally extensive. These units have undergone intense bioturbation that has masked any sedimentary structures. These very fine sandstones probably represent distal crevasse-splay or distal levee deposits. The proximal and distal floodplain regions of the Willwood alluvial plain (Fig. 4A) are distinguished by the degree of penetration of these areas by these fine sandstones. The *proximal floodplain* contains some proportion of crevasse-splay sand, whereas the *distal floodplain* is generally devoid of these deposits. Floodplains for some of the larger Willwood channel systems often exceeded 20 km in breadth.

As noted above, certain paleosol profiles in the Willwood Formation are exceedingly rich in fossil vertebrate remains (Bown and Kraus 1981b) and about 600 of the most important of these soil accumulations of fossils were traced laterally to establish their relative stratigraphic positions in a master section of the formation. In the course of this endeavor, the paleosol profiles were observed to change gradually, though considerably, in both appearance and internal character in the lateral dimension. Because these changes are repetitive in several sections they are highly predictable. Although actual field relations are considerably more complicated than those depicted in Figure 4A, the general lateral succession of paleosol maturation stages occurs as illustrated. The least mature soils are those of the proximal alluvial ridge and the most mature occur on the distal floodplain. There is a gradual and continuous progression from stage-1 through stage-5 soil maturities on the intervening floodplain. Although the relationship of soil maturity to sediment accumulation rate is therefore an inverse one, as suggested previously by Leeder (1975) for pedogenic carbonates, it seems obvious that lateral variability arises from complex, interrelated factors and not accretion rate alone. In addition to the sediment accumulation rate, particle size (Bridge and Leeder 1979) produces laterally variable parent material for soil development. Furthermore, soil moisture and the type of vegetation and fauna vary with distance from the channel.

Because time must be equalized for accurate correlation across the alluvial system, it is consistent that several immature soils in a thick deposit of alluvial ridge sediments occupy the same time of formation as does one or a few more mature soils on a thinner sequence of sediment on the distal floodplain. This equalization of time immediately complicates the rather simple schematic portrayal of paleosol-sediment relationships illustrated in Figure 4A; however, it is now possible to correlate rather disparate active and passive areas of the Willwood alluvial plain with some precision. This procedure has important implications for elucidating the Willwood alluvial system in the lateral sense (as discussed here) and vertically (Kraus 1987). Both are important if we are to understand the dynamics of alluvial systems in general and their relation to geologic time.

Initially, Bown (1985a, b) believed that the lateral changes in Willwood soils outlined here were related to catena development; that is, lateral variability in soils resulting from their relative positions on hillslopes (see, e.g., Milne 1935; Gerrard 1981; Birkeland 1984). However, true catenas differ considerably from the lateral relations characteristic of Willwood paleosols and most other paleosols that formed in thick alluvial successions. These relations deserve additional consideration.

Conclusion: The Pedofacies

Just as sedimentary rocks exhibit lateral changes in their characteristics, soil properties vary laterally in response to areally differing environmental conditions. Most commonly described is the *catena* (Milne 1935), which refers to a lateral continuum of morphologically different soils that have formed on a hillslope and thus reflect their specific topographic position. Soil development varies with local relief because of different microclimatic and drainage conditions as well as downslope translocation of soil constituents. Because catenas form on hillslopes, inherent to the concept is the fact that pedogenic development accompanies a geologically lengthy period of nondeposition or net degradation.

In contrast to catenas, cumulative soils receive episodic influxes of sediment (parent material) as pedogenesis progresses. Lateral variability also develops in cumulative soils, but it has commonly been attributed to parent material variation, including the rate of parent material accumulation and its grain size. Described examples of lateral change in cumulative soil properties are best studied in loess systems (see references in Ruhe 1973). Recent workers (e.g., Kleiss 1973; Kleiss and Fehrenbacher 1973; Ruhe 1973) have stressed the complexity of loess soils and the various interrelated factors that doubtlessly contributed to areally variable soils. These include particle size of the parent material and the amount of water passing through each soil.

With few exceptions, studies of lateral change in soil properties have focused on soils developed on hillslopes or in loess landscapes rather than in alluvial systems. Nonetheless, laterally adjacent but morphologically different paleosols are widespread in the alluvial Willwood Formation of Wyoming. The ancient alluvial record usually reflects lengthy periods of episodic sedimentation; consequently, most alluvial paleosols are cumulative in nature. Furthermore, because most lateral variability we see in Willwood paleosols arises from proximity to the active channel rather than topographic position, most alluvial paleosols are best compared to the loess examples cited above rather than to the catena concept. This is not to imply that true paleocatenas are not preserved and are not recognized in alluvial sequences. Base-level changes can produce geologically lengthy episodes of erosion and concomitant landscape changes during the accumulation of an alluvial sequence (Kraus and Bown 1986). If soils that developed on the resultant local relief are then buried due to renewed fluvial sedimentation, the unconformity that forms will be marked by a paleocatena.

Soil workers employ various terms to describe soil variability related to the length of pedogenesis (chronosequence; e.g., Jenny 1941; Vreeken 1975) or to parent material (lithosequence; e.g., Miles and Franzmeier 1981); however, for describing lateral variability in cumulative soils or paleosols, such terms suffer from several drawbacks. Use of the term *sequence* to refer to lateral change is confusing because of the temporal connotations of that word to sedimentologists. Moreover, the facies concept, which was formulated to describe lateral change in sedimentary rock units, is perfectly applicable to lateral changes in unconsolidated or cemented sediment arising from areally different pedogenic processes. Thus, the term *pedofacies* is proposed to denote *laterally contiguous bodies of sedimentary rock that differ in their contained laterally contiguous paleosols as a result of their distance (during formation) from areas of relatively high sediment accumulation.* Pedofacies are bounded vertically by the tops and bottoms of all of these laterally contiguous soils that are developed sequentially in the lateral dimension. In the Willwood Formation, areas of rapid sedimentation were the channel belts. Although the term *facies* has been used and misused in numerous ways since its introduction (Gressly 1838), the examples of Middleton (1978) and Walker (1984) are followed and pedofacies is used to refer to the contained soils or paleosols themselves, rather than to an abstract set of features characteristic of the soils or paleosols. Pedofacies is also used in a stratigraphically unconfined sense rather than for subdivisions of a specified stratigraphic unit (see following paper by Kraus regarding uses of the pedofacies).

The facies concept has been applied to soils and soil stratigraphy in a very limited sense by workers including Richmond (1962) and Morrison (1967). "Soil facies" refers to lateral changes in *geosols,* which are the basic formal unit of pedostratigraphy and are defined as ". . . a body of rock that consists of one or more pedologic horizons developed in one or more lithostratigraphic, allostratigraphic, or lithodemic units and [is] overlain by one or more formally defined lithostratigraphic or allostratigraphic units" (North American Stratigraphic Commission 1983). This stratigraphically confined definition of soil facies greatly restricts utility of the facies concept for soils and paleosols. Recognized geosols are few in number and the numerous multistorey paleosols that comprise alluvial units such as the Willwood Formation do not qualify as geosols. Thus, they are not contained in the concept of "soil facies." As Walker (1984) pointed out, Gressly (1838) originally defined facies in a stratigraphically unconfined way; thus, there is no historic precedent to confine facies stratigraphically in soils or paleosols. Furthermore, the facies concept is most useful when vertical sequences of facies can be described and used to interpret controls on deposition (e.g., Walker 1984; also see Kraus 1987). Only stratigraphically unconfined facies can be used in this manner.

In summary, lateral changes are expected to develop in alluvial soils, and these primarily reflect distance from the channel belt. The term *pedofacies* is proposed to describe these morphological changes, and it is defined in a concrete and stratigraphically unconfined sense. The term *pedofacies* is preferred to *soil facies* because of the stratigraphically confined meaning of the latter term and, thus, its limited geologic utility.

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