A paleopedological approach to the interpretation of terrestrial sedimentary rocks: The mid-Tertiary fossil soils of Badlands National Park, South Dakota

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ABSTRACT

Sedimentology is concerned with processes, environments, and products of sedimentation, whereas paleopedology is concerned with soil formation on these materials between times of sedimentation. Both approaches can contribute much to an understanding of ancient terrestrial environments.

Fossil soils can be recognized from irregular vertical tubular structures (fossil root traces and burrows), massive bioturbated layers with gradational contacts (soil horizons), complex cracking and veining (peds and cutans), and distinctive petrographic textures (sepic plasmic fabrics). In Badlands National Park, South Dakota, numerous other features, such as patterns of fossil-bone accumulation, horizons of calcareous nodules and layers, and local variations in mineralogy, and trace and major-chemical elements were also evidence of fossil soils. In the Pinnacles area of Badlands National Park, there are at least 87 successive fossil soils in 143 m of stratigraphic section.

Ancient soil formation is a kind of early diagenesis, which can be obscured by additional changes after burial of the soil (late diagenesis). In Badlands National Park, those few late diagenetic features identified did not seriously alter traces of ancient soil formation.

Fossil soils can be mapped and named in the field using the soil-mapping procedures of the U.S. Department of Agriculture. At least ten such nongenetic units (fossil soil series) can be recognized among fossil soils of the Pinnacles area of Badlands National Park. Each represents a particular ancient environment. In most cases, these fossil soil types could be identified within modern soil classifications, such as those of the U.S. Department of Agriculture and the Australian C.S.I.R.O. In addition, fossil soils can be evidence of past soil-forming factors, such as climate, organisms, topographic relief, parent material, and time of formation. Climatic interpretations from fossil soils may be useful confirmation of other data, although some immature or waterlogged soils reveal nothing of climate. The kind of former vegetation (such as woodland or grassland) can be interpreted from fossil soils, even where direct fossil evidence of its floristic composition is lacking. Fossil soils may be a guide to the degree, nature, and location of preservational biases of animal and plant fossils. Fossil soils can also be used to assess the degree of adaptation of associated fossil mammals, because they are evidence of vegetation independent of other fossils. From features of fossil soils related to waterlogging or drainage, it may be possible to assess paleotopographic changes, as well as some aspects of their tectonic control. Little-altered parent material is usually preserved under fossil soils. In some cases, as in the region of the South Dakota Badlands during the Oligocene, parent material appears to have been complexly interrelated with vegetation, climate, and fluvial regimen. Times of formation of fossil soils can be estimated by comparison with studies of modern soil formation. From such estimates, which for the sequence in the Pinnacles area of Badlands National Park appear to be crude but not

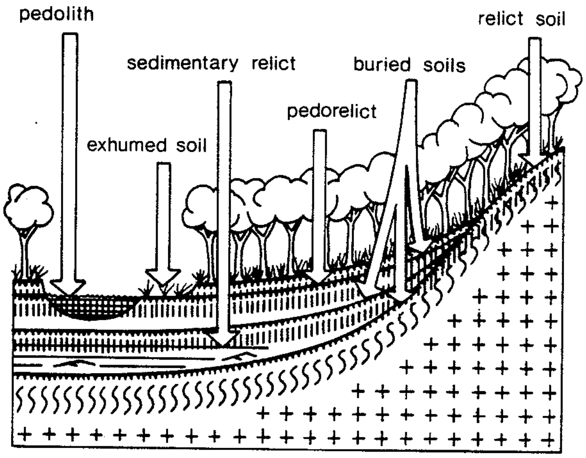

Figure 1. Important terms and concepts in the study of fossil soils (paleopedology).

Note: **this article represents a summary and introduction to the Geological Society of America Special Paper 193, *Late Eocene and Oligocene Paleosols from Badlands National Park, South Dakota,* by Greg J. Retallack.**

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unrealistic, the completeness and rates of sediment accumulation of different parts of a sequence can be compared, providing insights into changing factors in the long-term behavior of fluvial systems.

INTRODUCTION

Sedimentological models (or paradigms in the special sense of Kuhn, 1962) are now familiar to most geologists, because of their prominent place in university curricula, in the search for oil and gas, and in a burgeoning published literature (Friedman and Sanders, 1978, Chap. 1). By contrast, appropriate models for paleopedology are an integral part of soil science and allied environmental and agricultural sciences, but they have had little impact on the interpretation of the sedimentary rock record. In this paper, I attempt to outline a paleopedological approach to the interpretation of terrestrial sedimentary rocks and to indicate the kinds of interpretations that can be made from paleopedological evidence, using as an example a study of late Eocene and Oligocene fossil soils from Badlands National Park, South Dakota (Retallack, 1983).

The following simplified concepts and terms are basic to an understanding of paleosols or fossil soils (Fig. 1). In nonmarine sedimentary environments, sediment may be moved around by running water, wind, or gravity slides. Between episodes of deposition, this sediment and other exposed materials are altered chemically, physically, and by the action of colonizing microbes, fungi, plants, and animals, to form a soil. At an early stage of its formation, a soil may have numerous *sedimentary relicts*, which are sedimentary structures remaining from its deposition, such as bedding and ripple marks (Brewer, 1964). With further development, soil features, such as tubular structures from roots and burrows and recognizable soil horizons, become more pronounced. The materials involved in horizons vary with different kinds of soils. For example, in spodosols of the U.S. Department of Agriculture Classification (Soil Survey Staff, 1975), the A horizon is usually quartz-rich, sandy, and light-colored, because it is leached of humus, iron, and aluminum. These last may accumulate in the B horizon, which thus tends to be massive, dark, and red.

In subsiding river valleys of the sort in which many thick sedimentary sequences accumulate, soils are periodically covered by sediment. If a flood is especially catastrophic and 1 m or more of alluvium is deposited over a previous soil, then a new soil will form on the higher land surface, now separated from the *buried soil* (Birkeland, 1974). No longer a complex interface between an ecosystem and the earth's surface, buried or fossil soils are analogous to the skeleton of a fossil animal (Nikiforoff, 1943), from which some concept of the former thing often can be reconstructed. In addition to catastrophic floods, there are also numerous minor floods, from which only a few centimetres of sediment may be deposited. Many ecosystems can cope with this slight degree of disturbance and continue to grow and incorporate this material into the pre-existing soil, to form a *cumulative* soil (Birkeland, 1974). Renewed soil development on a sedimentary mantle of intermediate thickness (a substantial fraction of the soil thickness, about 10 cm to 1 m) may result in the overlap of the B horizon of a later soil with the A horizon of an earlier one. The remaining structures of the earlier A horizon in the later B horizon are examples of *pedorelicts*, a general term for soil features believed to have formed in a soil or fossil soil different from the one in which they are present (Brewer, 1964). This is not the same thing as a *relict soil*, a term used for soil profiles in which it appears that the same soil material has been modified by

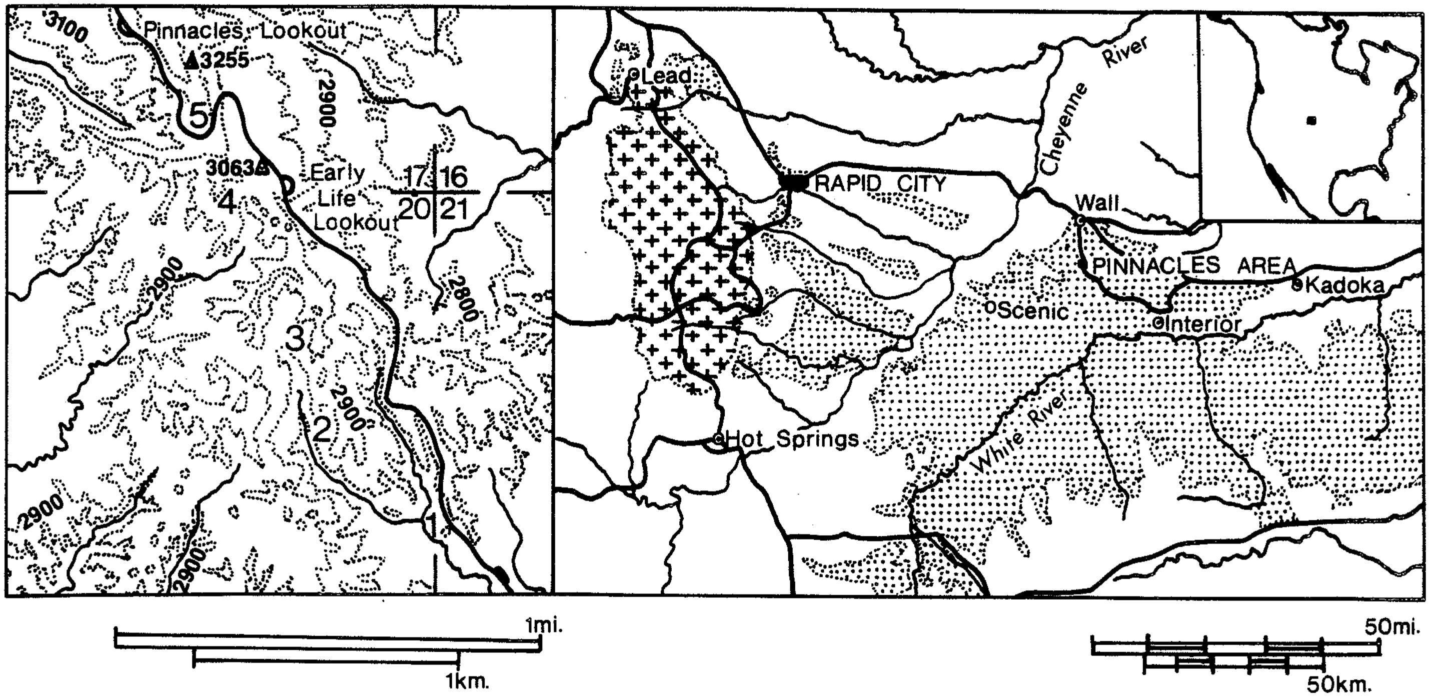


Figure 2. Location of measured section in the Pinnacles area (left), Badlands National Park, South Dakota (right), showing outcrop of late Eocene and Oligocene White River Group (stipple), Precambrian crystalline and metamorphic core of the Black Hills (crosses), U.S. highways (heavy lines), and major streams (thin lines). Areas 1 to 5 are localities where the detailed section (Fig. 5) was measured, with local sections combined by visual tracing of paleosols.

two or more different regimes of soil formation because the same parent material has remained at the surface while climate, vegetation, or other soil-forming factors changed. An *exhumed soil* is one buried and then uncovered by erosion, often at a much later time of different conditions (Birkeland, 1974). Whether a soil is relict or exhumed may be difficult to determine but may be settled by tracing the soil laterally to where the same land surface is buried (Ruhe, 1965). Both relict and exhumed and reburied paleosols for the most part occur at major geological unconformities, representing millions of years of geological time. Eroded soil material can accumulate to form a *pedolith* (in the sense of Gerasimov, 1971), a deposit with sedimentary organization, such as bedding or ripple marks, but with soil mineralogy and clast microstructure. Most sediment is ultimately derived from soil and so is pedolithic in a strict sense. However, in many sedimentary sequences, sediment from distant sources is distinct from locally eroded soil material, for which the term and concept of pedolith are useful.

The late Eocene and Oligocene White River and lower Arikaree Groups of Badlands National Park, South Dakota (Fig. 2), are particularly appropriate as an example of the study of fossil soils, because of the long history of controversy over their likely paleoenvironment and particularly over the presence of fossil soils in them. This area is best-known for abundant and diverse fossil mammal remains, striking examples of badland erosion, and spectacular scenery of gray-green, pink, red, orange, and white color-banded pinnacles, razorback ridges and steep runneled slopes (Figs. 3, 4). In about 150 yr of research on the origin of these deposits, almost every conceivable nonmarine paleoenvironment has been considered, but there is now general agreement that these are deposits of an extensive alluvial plain (Wanless, 1922, 1923; Clark and others, 1967). Fossil soils in these and correlative deposits in adjacent states have been casually mentioned by many (Hatcher, 1893, p. 212; Matthew, 1901, p. 357; Darton, 1903, p. 33; Galbreath, 1953, p. 16; L. G. Schultz, 1961; Stout, 1978; C. B. Schultz and Stout, 1980), but serious attempts to study them (C. B. Schultz and others, 1955; Harvey, 1960) have attracted bitter criticism (Clark, *in* Clark and others, 1967). In my own opinion (defended in more detail elsewhere; Retallack, 1983), the presence of numerous paleosols in these and other deposits can no longer be seen as a matter of controversy, but rather as an assumption on which to base more detailed interpretations.

RECOGNIZING FOSSIL SOILS

One problem with the recognition of paleosols or fossil soils is the purely semantic question of defining them. The main difficulty here arises not from their fossil nature, but from concepts of modern soil, which may be quite different for engineers, agriculturalists, geologists, and soil scientists (Ruhe, 1965; Hunt, 1972). I prefer to broadly define soils as the material on the surface of a planet or similar body, altered by physical or chemical weathering, the action of organisms, or all of these. Such a definition includes surficial materials that have been called (loosely, according to some authorities) Martian and Lunar soils, and it also brings within the domain of paleopedology such things as Precambrian paleosols. For the study of all of these materials, pedological approaches and concepts may be appropriate and productive.

The most diagnostic features of fossil soils younger than Silurian are fossil root traces, preserved in their place of growth. Actual fossil root material is found preserved only in fossil soils that were highly reducing and waterlogged. In oxidized fossil soils, root traces may be filled with soil material contrasting with their immediate matrix, or with other materials, such as crystalline calcite or chalcedony. Unlike burrows, which also may be present, root traces taper and branch downward, are very irregular in width and direction, and commonly have a concertinalike outline because of the compaction of the surrounding matrix. Soil horizons are also diagnostic of fossil soils, although these vary in nature for different kinds of soils. They may be layers that are conspicuously organic, leached, reddened, nodular, crystalline, or clay-rich compared to overlying or underlying layers. Two features of soil horizons useful for field recognition are their usual gradational contacts from one horizon to another below the sharply truncated upper surface of the fossil soil, as well as their generally massive and bioturbated appearance. Horizons develop progressively with the obliteration of original sedimentary, metamorphic, or igneous textures of the parent material. The characteristically complex system of cracks and associated filling or altered material (cutans) and natural clods of material defined by them (peds) are also diagnostic of soils and fossil soils. Finally, sepic plasmic fabric (in the sense of Brewer, 1964) is a characteristic fabric of petrographic thin sections of soils and fossil soils viewed under crossed nicols, in which areas of randomly oriented, flecked clay are separated by zones of highly birefringent, oriented clay.

Applying these various criteria for fossil soils to the late Eocene and Oligocene deposits in the Pinnacles area of Badlands National Park, it was possible to recognize 87 successive paleosols in 143 m of stratigraphic section (Figs. 4, 5). Such sequences of fossil soils are not unusual, as has been shown by studies of Eocene fossil soils in Wyoming (Dorf, 1964; Bown and Kraus, 1981a, 1981b) and of Pleistocene fossil soils

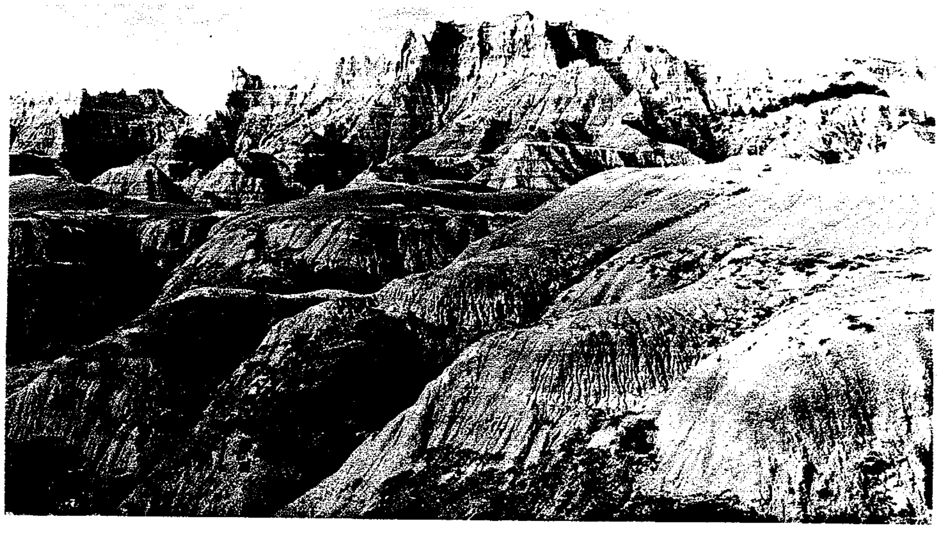
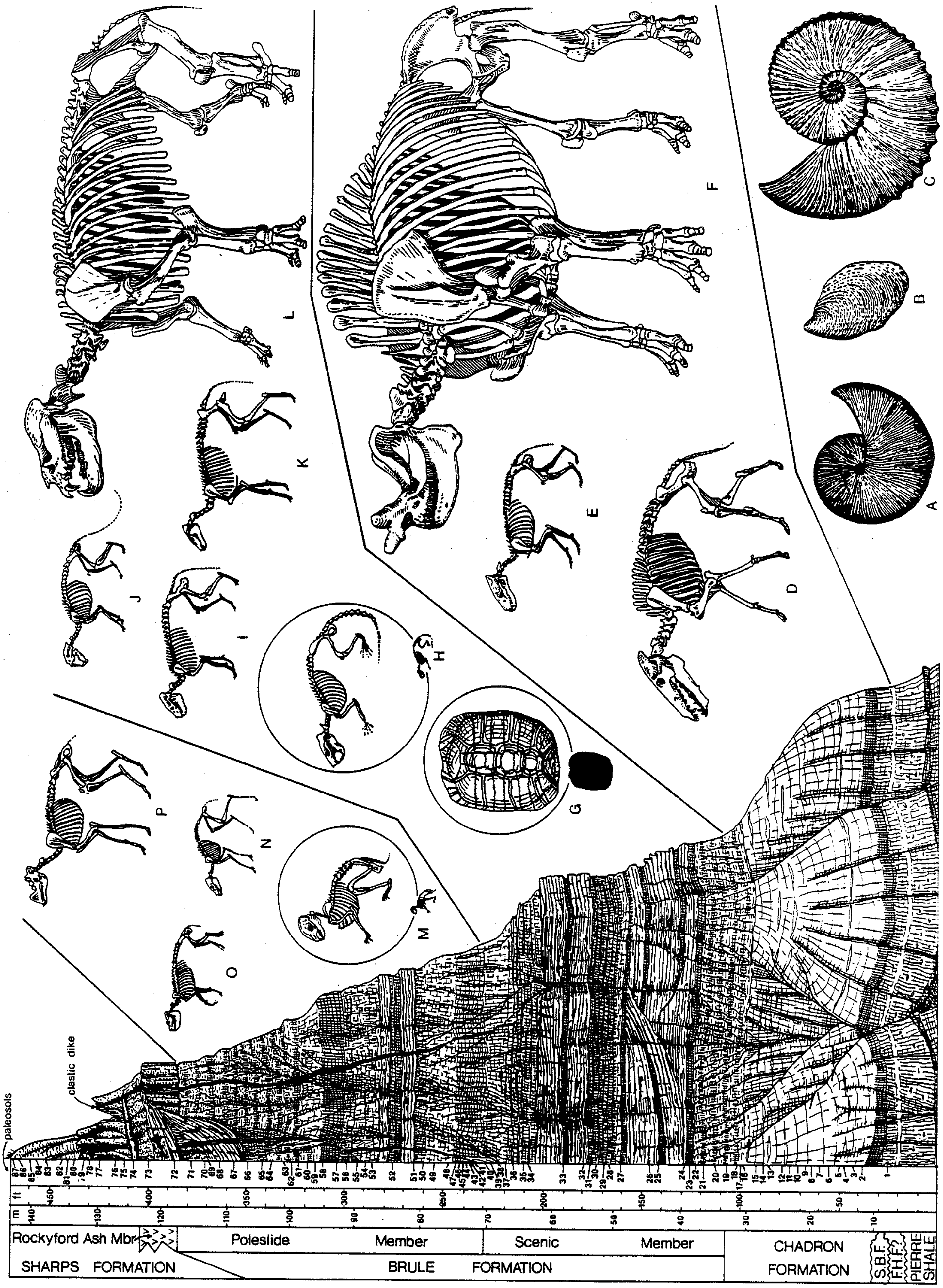


Figure 3. The Pinnacles area, Badlands National Park, South Dakota. For formation names, see Figure 4.



paleosols
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Rockyford Ash Mbr
SHARPS FORMATION
Poleslide Member
Scenic Member
BRULE FORMATION
CHADRON FORMATION
S.B.F.
F.H.F.?
PIERRE SHALE

Figure 4. Late Cretaceous, late Eocene, and Oligocene formations and fossils of Badlands National Park. A–C, Late Cretaceous molluscs: A, *Hoploscaphites nicolleti,* ammonite (after Waage, 1968); B, *Tenuipteria fibrosa,* bivalve (after Speden, 1970); C, *Discoscaphites cheyennensis,* ammonite (after Kauffman, 1977). D–F, early Oligocene mammals: D, *Archaeotherium mortoni,* pig-like entelodon (after Scott, 1940); E, *Hyaenodon horridus,* creodont (after Scott, 1895b; species name from Mellett, 1977); F, *Menodus giganteus,* titanothere (name after Clark and others, 1967, this species is better known as *"Brontops robustus"* and after Scott, 1941). G–L, early late Oligocene tortoise and mammals: G, *Stylemys nebrascensis,* land tortoise (after Hay, 1908); H, *Ischyromys typus,* squirrel-like rodent (after Wood, 1937); I, *Merycoidodon culbertsoni* (after Scott, 1940); J, *Hoplophoneus primaevus,* sabre-toothed cat (modified from Scott and Osborn, 1887); K, *Mesohippus bairdi,* three-toed horse (after Scott, 1941); L, *Metamynodon planifrons,* amphibious rhinoceros (modified after Osborn and Wortman, 1895). M–P, mid-late Oligocene mammals: M, *Palaeolagus haydeni,* archaic rabbit (after Wood, 1940); N, *Leptomeryx evansi,* chevrotain-like ruminant (after Scott, 1940); O, *Leptauchenia decora,* oreodon (after Sinclair, 1910); P, *Protoceras celer,* deer-like ruminant (after Scott, 1895a). All mammals and tortoise 0.007 times natural size, with enlargements in circles 0.04 and marine molluscs 0.4 times natural size.

in Czechoslovakia (Morrison, 1976). In the Badlands, not only field observations, but also associated laboratory studies confirmed the presence of many paleosols.

Numerous fine (1 to 2 mm diam) root traces were seen in the surface horizons of all the paleosols and are probably the remains of grasses and other herbs, as well as small tree roots. The most striking large root traces consisted of a central clay-filled, calcitic or chalcedonic, tubular structure as much as 3 cm in diameter, surrounded by a drab halo of comparable width. This halo of gray-green soil matrix surrounded the root trace and separated it from reddish or yellowish soil matrix of the same petrographic texture. These drab-haloed root traces were all of a size and depth of penetration comparable to tree roots. Many were also found in fossil soils including large superficial disruptions which were possibly holes left by wind throws of trees. Large drab-haloed root traces were also consistently found in association with fossil hackberry (*Celtis,* an ulmaceous tree) endocarps ("stones" or "pits") and with large proportions of arboreal and browsing (rather than grazing) fossil mammals. There are several plausible hypotheses for the origin of drab haloes around large fossil root traces (Retallack, 1983). According to the three most likely proposals, the halo could represent (1) the reducing effect of perched surface water in a waterlogged soil; (2) the rhizosphere, or chemical microenvironment of the living root and its associated halo of mucigel, microorganisms, and soil water; or (3) the result of the anaerobic decay of roots in ground water after burial. Only in one kind of fossil soil (Ogi Series) did the drab halo also include an iron-manganese halo, suggestive of waterlogging. The reddish color and lack of fossil pollen, spores, leaves, fructifications, wood, or other organic matter in these deposits are indications that these soils were mostly oxidizing and dry. Thus, drab haloes for the most part represent either the rhizophere or areas of anaerobic decay after burial. By either of these interpretations, drab-haloed root traces record the distribution of plants living just prior to burial, because roots and their rhizospheres decay rapidly in oxidizing dry soils. Drab-haloed root traces appear to be useful guides to the density of living roots just before burial, and they provide evidence for distinguishing forest, woodland, parkland, and savanna vegetation of the past.

A number of paleontological observations are additional evidence of fossil soils in Badlands National Park. These paleosols appear to have been too oxidizing to preserve the abundant vegetable fodder that supported the diverse mammal populations of the region, except for common endocarps of hackberry fruits (*Celtis hatcheri,* Chaney 1925). The endocarps of living hackberry (*Celtis occidentalis*) contain substantial amounts of biogenic calcium carbonate (24.9% to 64.2% by dry weight of the whole fruit) and silica (2.4% to 7%; Yanovsky and others, 1932; Lanning, 1961). Similar composition of the endocarps of the fossil species would have ensured their preservation over associated organic matter in all but the most acidic and highly alkaline of dry oxidizing soils. The selective preservation of only tissues that were originally mineralized, such as stony parts of plants and bones of mammals, appears to be a characteristic feature of sequences composed mainly of oxidized reddish fossil soils. Aquatic invertebrate fossils have been found locally in the White River Group (Meek and Hayden, 1876; Wanless, 1923, p. 204; Cook and Mansfield, 1933; Gries and Bishop, 1966; Clark and others, 1967; Lemley, 1971), but the most common and widespread invertebrate fossils are land snails [*Pseudolisinoe leidyi* (Hall et Meek) Wenz 1923], which were the only fossil invertebrates found in the Pinnacles area (Fig. 5). Among vertebrate remains also, aquatic forms such as fish and turtles are rare and restricted in occurrence, compared to abundant land tortoises and mammals. Several paleontological excavations have revealed articulated skeletons, even groups of skeletons, on restricted horizons, with associated evidence of rodent gnawing, predation, insect scavenging, "marking" with excreta, and chipping and flaking of bone from ancient surficial weathering (Sinclair, 1921; Wanless, 1923; Clark and Guensberg, 1970; Clark and others, 1967). As would be expected from its chemical composition and from observation of bones in modern soils (Watson, 1967; Glob, 1969), bone was most abundant in weakly developed, calcareous paleosols, which presumably were alkaline. Bone was also common in strongly and moderately developed, calcareous paleosols, and in weakly developed and moderately calcareous paleosols. No bone was seen in noncalcareous (presumably acidic) paleosols, regardless of their being strongly or weakly developed. Finally, concentrations of burrow-like irregularities on the tops of many paleosols and elongate nodules (perhaps burrow fills or krotovinas) in other paleosols constitute trace fossil evidence for periods of nondeposition and soil formation.

Beneath the popcorn-weathered surface of the White River Group, these deposits are extensively cracked, veined, and slickensided, and they include much intraformational claystone breccia (C. B. Schultz and others, 1955; Clark and others, 1967). In many cases, these features are the remains of original natural aggregates of soil (peds) and of clay skins and modified surfaces (cutans), voids, and cracks. Many of the claystone intraclasts were probably resorted from surficial peds of older soils within the drainage basin, because some of these clasts contain mottles like those of undisturbed fossil soils nearby. Sepic plasmic fabric is a characteristic petrographic texture of pedal soils in thin section (Brewer, 1964) and was also found widely in fossil soils of the White River and lower Arikaree Groups.

Many of the fossil soils of Badlands National Park contain calcareous layers

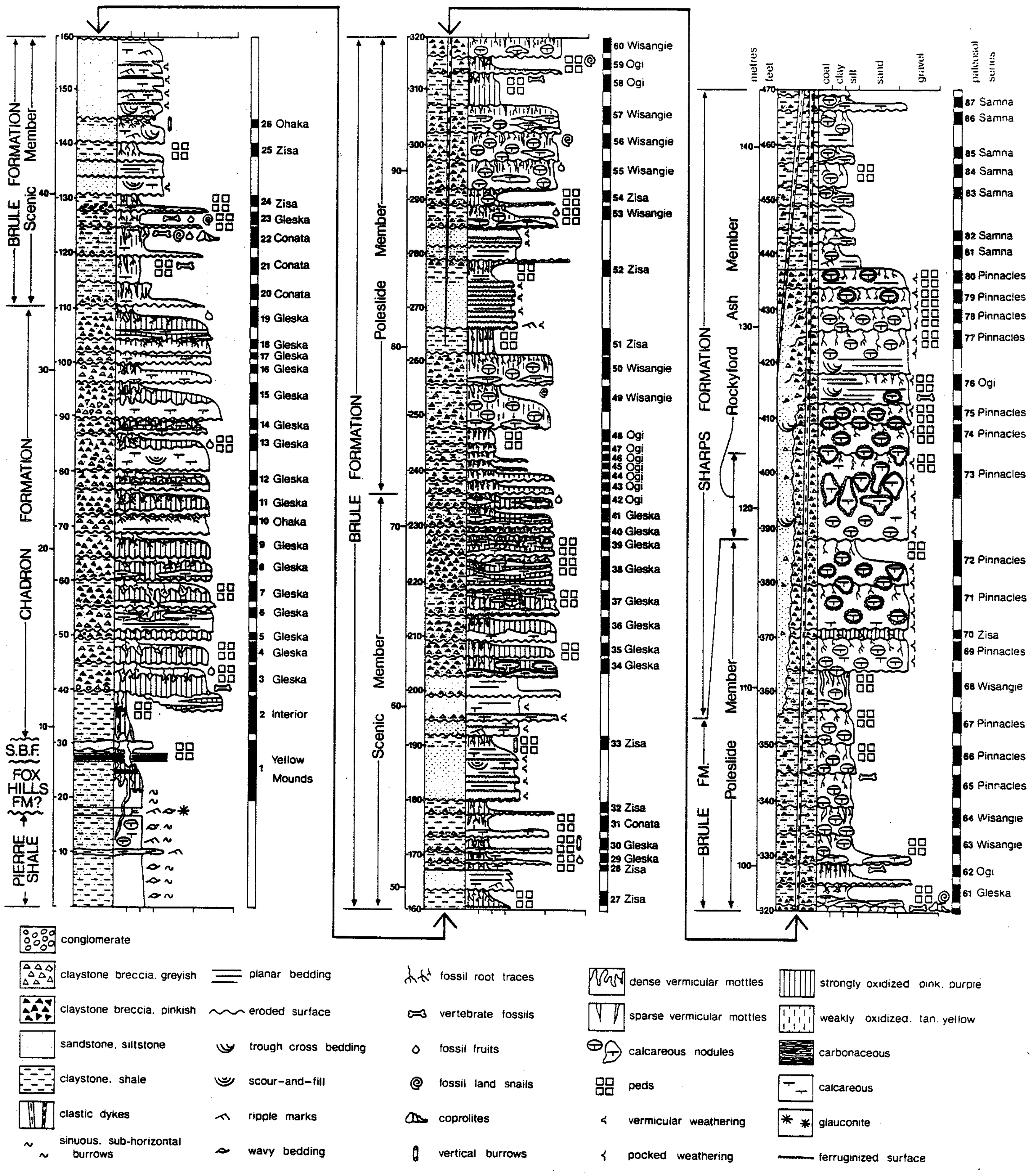

Figure 5. A sequence of paleosols in the Pinnacles area, Badlands National Park, South Dakota. Abbreviation S.B.F. is the Slim Buttes Formation.

and nodules, arranged in horizons with a predictable relationship to the rest of the containing paleosol. Wanless (1923) and Stanley and Benson (1979) convincingly argued that these are original soil features on the basis of a variety of evidence: the usual lack of aquatic fossils, lacustrine bedding, or varving within these limestones; the uncrushed nature of skulls, tortoise shells and other hollow groups of bones within the nodules compared to those in surrounding claystone; the greater abundance of weatherable minerals within the nodules compared to surrounding matrix; the observed truncation of calcareous horizons by the cut bank of sandstone paleochannels; and the presence of similar calcareous clasts within intraformational breccias of paleochannels. In addition, the continuation of drab-haloed root traces extending through the nodules from the adjacent matrix is evidence that the nodules were present at the time of soil formation.

Three kinds of calcareous horizons were recognized in the White River and lower Arikaree Groups. The soft, powdery layers in the lower Chadron Formation were probably calcic horizons (in the terminology of Soil Survey Staff, 1975). The thin, purple-stained, partly silicified calcareous stringers of paleosols in the upper Chadron Formation and Scenic Member of the Brule Formation were probably indurated calcareous pans, like the petrocalcic horizons of some modern aridland soils (Flach and others, 1973). Rounded calcareous nodules of paleosols in the Poleslide Member of the Brule Formation and in the Sharps Formation are similar to caliche of modern soils, although none appear to have been better developed than stage II of Gile and others (1966).

Spectacular color banding, for which the scenery of Badlands National Park is renowned, is also to a great extent a product of ancient soil formation. The prominent uniform red bands of the Scenic Member (the "igaposome facies" of Clark and others, 1967, or Zisa Series of Retallack, 1983) include fine root traces and so are paleosols, but they show little profile development and numerous sedimentary relicts. Their bright color is attributable mainly to their noncalcareous composition, compared to other deposits at the same stratigraphic level. Their reddish color is also in part probably inherited from coeval or slightly older clayey soils of similar smectitic mineralogy, and certainly not from remnants of kaolinitic late Eocene paleosols or similar soils of remote source regions (as suggested by Clark and others, 1967). Subtle, gradational, and mottled color banding of other parts of the Badlands appears to be more directly a consequence of soil formation. This is best expressed in Gleska Series paleosols, which have a gray-green A horizon passing gradationally downward into a massive pink or purple B horizon. Clay mineralogy, chemical analyses, and the proportion of grains of different size and mineralogy, as well as the presence of clay skins (argillans) in the B horizon of these paleosols, are all evidence for the soil-forming process of lessivage, in which the B horizon is enriched in sesquioxides and clay that have been washed out of the A horizon (Retallack, 1983).

Mineralogical and chemical analyses of selected paleosols revealed additional evidence that they were, indeed, fossil soils. All four paleosols sampled showed surficial depletion of K_2O and P_2O_5 in proportion to their degree of development. These plant nutrients are characteristically depleted in the surficial layers of soils and have been used to recognize Quaternary paleosols (Smeck, 1973; Marshall, 1977). All four paleosols also showed a higher and sharper 15 Å smectite peak in their upper horizons, relative to lower horizons, where smectite appears to be poorly crystalline, perhaps interlayered with illite. Comparable distributions of smectites have also been found in some modern soils (Marshall, 1977, p. 208). The four paleosols also showed abundances of clay and other minerals, as well as chemical variation within the profile comparable with the degree and kind of development seen in the field. As is the case for trace elements in modern soils (Aubert and Pinta, 1977), the most important factor in their distribution in Badlands paleosols appears to have been the nature of parent material. Variation of trace elements within the four paleosol profiles is also closely parallel to that of modern soils (Retallack, 1983).

Many of these features, such as the distribution of bone and color banding, seem unremarkable, if not enigmatic, features of the sequence from a sedimentological perspective. From a paleopedological perspective, these features not only assume a new meaning but constitute independent lines of evidence for the presence and nature of fossil soils. A variety of other previously enigmatic rock types, such as red beds, variegated beds, cornstone, ganister, tonstein, underclay, and fireclay are also turning out to be (at least in part) fossil soils (Retallack, 1981).

PROBLEMS WITH DIAGENESIS

Part of the problem with the concept of diagenesis for the study of fossil soils is semantic. Soil formation itself is a kind of early diagenesis. For example, it is often stated (from a sedimentological perspective) that red beds form by the diagenetic alteration of minerals containing iron, for which there is compelling and indisputable petrographic evidence (Walker and others, 1967, 1978). From a paleopedological perspective, the problem becomes a matter of whether this alteration took place during soil formation (early diagenesis) or after burial of the soil (late diagenesis). For red beds including fossil soils, it is likely that the original oxidation and formation of yellow or brown ferric oxyhydrate minerals occurred during soil formation, but that the reddening of the deposits occurred during late diagenetic alteration of these minerals to the brick-red mineral hematite (this last was documented by Walker, 1974, 1976). For paleoenvironmental studies of fossil soils, clear distinction between early and late diagenesis is important, because the former is evidence of ancient soil conditions, whereas the latter is not.

To some extent, problems of late diagenetic alteration of fossil soils can be mitigated by the deliberate emphasis placed here on nongenetic mapping and naming of fossil soils, on structures observable in the field, and on micromorphology, which are less critically affected by late diagenesis than are the chemical and mineralogical composition of fossil soils. It is still necessary, however, to carefully consider each feature of fossil soils, in order to establish whether it is chemically and pedologically consistent with other features of the fossil soil. Critical evidence for the time of origin of a particular feature may come from its relationship with unequivocally original features, such as fossil root traces and burrows (Retallack, 1983). A number of common late diagenetic modifications of fossil soils, such as the late diagenetic reddening discussed above, are emerging from current research (Retallack, 1981). These need to be addressed with special care.

The few late diagenetic alterations recognized in the White River and lower Arikaree Groups have not obscured the abundant evidence of ancient soil formation already discussed. From strontium isotopic and petrographic studies of these and associated deposits (Stanley and Benson, 1979; Stanley and Faure, 1979), their widespread calcite and smectite cements appear to have formed at about the same time as the sediments and to remain in chemical equilibrium with modern ground water. The nature of grain packing and preservation of volcanic shards in sandstones is evidence that compaction during burial was slight (Stanley and Benson, 1979). Late diagenetic modification of these deposits appears confined to local and minor precipitation of opal, chalcedony, uranium minerals, gypsum, analcite, and pyrite, and the formation of clastic dikes, these last perhaps giant dessication cracks of a post-Oligocene desert playa (Retallack, 1983).

MAPPING AND NAMING FOSSIL SOILS

Fossil soils have been used extensively for stratigraphic correlation of Quaternary sediments. Each fossil soil usually has been called a "soil," for example, the Sangamon soil (American Commission on Stratigraphic Nomenclature, 1961), and also "geosol" (Morrison, 1968) or "pedoderm" (Brewer and others, 1970). In my opinion, the term "land surface" would be more straightforward and appropriate, because the named object is usually a mappable ancient surface, with its catenae of different kinds of fossil soils varying laterally according to regional differences in climate, organisms, parent material, topography, and time of formation. Senior and Mabbutt (1979) also proposed using the formal term "profile" for naming relict soil horizons or deeply weathered rock units of uncertain relationships and origin.

A different system of naming is needed for the paleoenvironmental interpretation of fossil soils, either laterally on an ancient land surface or on successive ancient land surfaces in a stratigraphic section. What is needed is a system of names for particular kinds of fossil soils as opposed to pedostratigraphic units. Such a system of names would be analogous to facies as opposed to

TABLE 1. INTERPRETED PALEOSOL SERIES OF THE WHITE RIVER AND LOWER ARIKAREE GROUPS IN THE PINNACLES AREA, BADLANDS NATIONAL PARK, SOUTH DAKOTA

Series	Age	U.S.D.A. 1975 soil	Stace and others 1968 soil	Northcote 1974 PPF
Samna	Latest late Oligocene	Ustollic	Chernozem eutrandept	Um5.11
Pinnacles	Latest late Oligocene	Calciorthid	Gray-brown calcareous	Gc2.12
Wisangie	Mid-late Oligocene	Andic ustochrept	Solonized brown soil	Gc2.12
Ogi	Latest Oligocene	Fluvaquentic eutrochrept	Wiesenboden	Uf6.13
Ogi	Mid-late Oligocene	Fluvaquentic eutrochrept	Wiesenboden	Uf6.13
Zisa	Late Oligocene	Fluvent	Alluvial	Uf1.41
Conata	Early late Oligocene	Andic ustochrept	Solonized brown soil	Gc2.22
Ohaka	Early late Oligocene	Andaquept	Alluvial	Uf6.61
Ohaka	Early Oligocene	Andaquept	Alluvial	Uf6.61
Gleska	Early late Oligocene	Petrocalcic paleustalf	Red-brown earth	Gn3.95
Gleska	Early Oligocene	Udic paleustalf	Red-brown earth	Gn3.95
Interior	Early early Oligocene	Paleudalf	Red podzolic	Dr5.21
Yellow Mounds	Late Eocene	Paleudult, paleustult, or palexerult	Yellow podzolic	Dr5.41

Note: this table has been summarized from Retallack (1983).

TABLE 1. (*Continued*)

Vegetation	Fauna	Climate
Grassland	Not known within National Park; possibly rabbit (*Palaeolagus*), beaver (*Palaeocastor*) and deer-like ruminant (*Nanotragulus*), or others as in Pinnacles Series	Warm-cool temperate, seasonally dry, semi-arid
Grassland	Only beavers (*Palaeocastor, Capacikala*) found in National Park; possibly also horse (*Miohippus*), rhinoceros (*Hyracodon, Diceratherium*), oreodon (*Desmatochoerus, Cyclopidius*), camel (*Oxydactylus*) and deer-like ruminants (*Nanotragulus*)	Warm-cool temperate, seasonally dry, semi-arid
Savanna woodland, trees scattered	Deer-like ruminant (*Protoceras*), anthracothere (*Elomeryx*), horse (*Miohippus*), rhinoceros (*Subhyracodon*), beaver (*Agnotocastor*) and entelodon (*Archaeotherium*); probably also (in part) oreodon (*Leptauchenia*), horse (*Mesohippus*) and peccary (*Perchoerus*)	Warm-cool temperate, seasonally dry, semi-arid
Streamside swale trees, aquatic and semi-aquatic herbs	Lizard (Lacertilia), mole (Talpidae?), small rodents (*Domnina, Tamias, Proheteromys, Hitonkala, Plesiosminthus*) and large entelodon (*Dinohyus*): possibly also others as in Pinnacles Series	Warm-cool temperate, seasonally dry, semi-arid to sub-humid
Interfluve lowland, seasonally swampy, with trees, aquatic and semi-aquatic herbs	Mainly rabbits (*Palaeolagus* and less common *Megalagus*) and deer-like ruminants (*Leptomeryx* and less common *Hypisodus*); probably also (in part) oreodon (*Leptauchenia*), horse (*Mesohippus*) and peccary (*Perchoerus*)	Warm-cool temperate, seasonally dry, semi-arid to sub-humid
Streamside swale, early successional herbs	No bones seen; probably a similar fauna to that of the latest Ogi Series during the latest late Oligocene, the Wisangie Series during the mid-late Oligocene and Gleska Series during early late Oligocene	Soil not diagnostic for climate
Savanna woodland, trees weakly clumped to scattered	Mainly rabbits (*Palaeolagus*, 26%), squirrel-like rodents (*Ischyromys*, 23%) deer-like ruminants (*Leptomeryx*, 21%, and *Hypertragulus*, 17%) and cursorial rhinoceros (*Hyracodon*, 8%)	Warm to cool temperate, seasonally dry, semi-arid to sub-humid
Streamside bar; with early successional herbs	No bones seen; similar to matrix of alligator skeleton; probably a similar fauna to Gleska Series during the early late Oligocene	Soil not diagnostic for climate
Marshy clearing, herbs only	No bones seen; similar to matrix of a described "titanothere graveyard"; probably a similar fauna to that of the Gleska Series during the early Oligocene	Soil not diagnostic for climate
Streamside gallery woodland	Mainly oreodon (*Merycoidodon*, 31%), horse (*Mesohippus*, 24%), squirrel-like rodent (*Ischyromys*, 9%) and rabbit (*Palaeolagus*, 5%); also abundant land turtle (*Stylemys*) and aquatic rhinoceros (*Metamynodon*)	Subtropical to warm temperate, seasonally dry, sub-humid
Widespread open woodland	Probably mainly pond and river turtle (*Graptemys*), titanothere (*Menodus s.l.*), rhinoceros (*Trigonias, Hyracodon, Caenopus*), horse (*Mesohippus*), entelodon (*Archaeotherium*) and oreodon (*Merycoidodon*)	Subtropical to warm temperate, seasonally dry, sub-humid to humid
Widespread woodland	Probably at least rhinoceros (*Hyracodon*), horse (*Mesohippus*), and creodont (*Hyaenodon*)	Subtropical to warm temperate, seasonally dry, sub-humid to humid
Hillside forest	Not known in National Park; possibly horse (*Epihippus*), tapir (*Colodon*), oreodon-like ruminants (Agriochoeridae) and deer-like ruminants (Leptotragulinae)	Subtropical to warm temperate, seasonally dry or cool, humid

formations, and to fossil associations as opposed to biozones of conventional stratigraphy. The soil mapping units of the U.S. Department of Agriculture (Soil Survey Staff, 1951, 1962) have proven useful and effective (Retallack, 1977a, 1977b, 1983) for several reasons. The most useful unit is the soil series, especially for reconnaissance mapping of fossil soils in the field. These units are named after localities, for example, the Pinnacles Series paleosols. As for other kinds of geological units, it is useful to name a type profile, or unit stratotype, in the terminology of Hedberg (1976). Specific paleosols can be named from the texture of their A horizons, for example, the Pinnacles silty clay paleosol, or they can be named from other features. Different paleosol series can also be grouped into broader units (paleosol associations) on the basis of similarity of parent material or other features. These names do not imply anything of the nature or origin of the paleosols and are not dependent on modern soil classifications, the criteria of which cannot always be recognized in paleosols or unequivocally distinguished from late diagenetic modifications. There is thus little confusion between paleosols defined in different areas or studies. Finally, the units already have been defined and accepted by soil scientists.

In the Pinnacles area of Badlands National Park, ten paleosol series were recognized (Fig. 5, Table 1) in order of stratigraphic appearance for thick, very strongly developed, sandy, yellow/red paleosols (Yellow Mounds Series); thick, very strongly developed, clayey, gray/red paleosols (Interior Series); strongly developed, clayey, gray/pink paleosols (Gleska Series); very weakly developed, clayey, gray-green paleosols (Ohaka Series); weakly developed, silty, tan paleosols (Conata Series); very weakly developed, silty, red paleosols (Zisa Series); weakly developed, silty, orange paleosols with iron-manganese–haloed root traces (Ogi Series); moderately developed, ashy, and light-colored paleosols with caliche nodules and sparse, large, drab-haloed root traces (Wisangie Series); moderately developed, ashy, light-colored paleosols with caliche nodules and fine root traces only (Pinnacles Series); and moderately developed, ashy, dark brown paleosols with caliche nodules (Samna Series). The qualitative scale of soil development used here is from Birkeland (1974, p. 23).

DESCRIBING FOSSIL SOILS

Each fossil soil represents a distinctive kind of ancient terrestrial environment, the nature of which is best interpreted after a systematic field and laboratory examination. There is no substitute for detailed field observations. For example, evidence that calcareous nodules are in place and contemporaneous with soil formation in Wisangie Series paleosols of the Poleslide Member of the Brule Formation is the way in which large drab-haloed root traces pass through them from the surrounding soil matrix.

Detailed petrographic studies are also useful for describing fossil soils, especially considering the great amount of information now available on the micromorphology of modern soils (Brewer, 1964; Stace and others, 1968; Kubiena, 1970). The standard petrographic procedure of point-counting thin sections for proportions of sand, silt, and clay, and for mineralogical content, is a useful method for quantifying profile development. From this kind of examination of three paleosols found in the Scenic Member of Badlands National Park (Fig. 6), clay enrichment of the B horizon is most pronounced in the Gleska clay silty variant paleosol, less marked in the type Conata clay, and absent in the type Zisa clay. In the Conata and Gleska paleosols, there was some illuviation of clay from the A horizon, as indicated by field and petrographic evidence of clay skins, but some of the clay enrichment also could have been due to weathering of volcanic shards and (to a lesser extent) feldspars.

Determination of clay mineralogy by X-ray diffraction or other means is also useful, although clays are so notoriously susceptible to late diagenetic alterations that it is difficult to be certain of the original mineralogy. In the case of the White River and Arikaree Groups, there is strontium isotopic and other evidence that smectite is original (Stanley and Benson, 1979; Stanley and Faure, 1979). The predominantly smectitic composition of most of the paleosols in the Pinnacles area of Badlands National Park (excepting the Yellow Mounds and Interior Series) is compatible with other evidence, such as calcareous nodules and horizons, that these were alkaline soils of moderate to high cation exchange capacity and base saturation.

Soil scientists routinely base interpretations on analyses of selected "free elements," that is, amorphous or simple oxides extractable by reagents such as sodium dithionite. Such chemical analyses also have

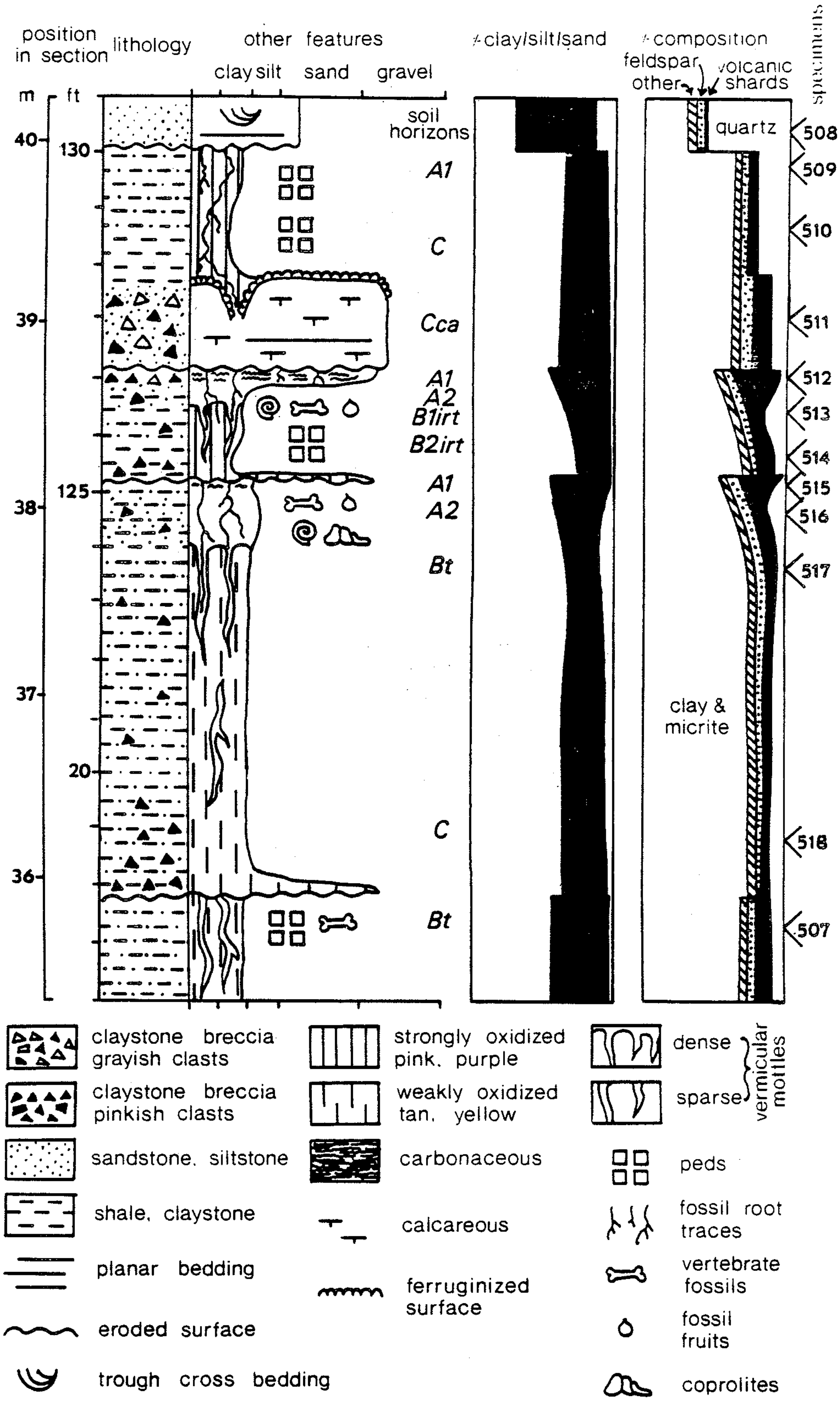

Figure 6. A detailed stratigraphic section of the Conata eroded phase (bottom), type Conata clay (lower middle), Gleska clay silty variant (upper middle), and type Zisa clay (top) paleosols (numbers 21 to 24 of Fig. 5) in the lower Scenic Member of the Brule Formation, Pinnacles area, Badlands National Park, South Dakota.

been used in studies of paleosols of Tertiary age (Johnson, 1977; Bown, 1979; Singer and Nkedi-Kizza, 1980), but their usefulness is diminished by the possibility of late diagenetic leaching, expulsion with pore water, or recombination of these elements. In the Badlands study, as well as in the other studies of Tertiary paleosols cited above, late diagenetic alterations are unlikely to have been significant, but if the geochemistry of much older and altered paleosols is to be meaningfully addressed, then appropriate geochemical approaches will have to be devised. To this end, I decided to explore the use of whole-rock major- and trace-element analyses and molecular weathering ratios. The ratios are explained by Jackson and Sherman (1953) and Vinogradov (1959) and analyses and ratios for a variety of modern soils were tabulated by Marbut (1935). Petrographic study of Badlands fossil soils revealed varied parent materials, mixed from volcanic ash fall, resorted soil material, and distantly derived alluvium. The kind of parent material was found to exert systematic biases into the chemical analyses and ratios, but overprinted on these effects were also discernible effects of soil formation. For example, the soil-forming process of lessivage in Gleska Series paleosols, suspected from petrographic and field evidence already discussed, was confirmed by the slight down-profile increase in total iron and surficial increase in silica (Retallack, 1983).

IDENTIFYING FOSSIL SOILS

Identification of a fossil soil within a classification based on modern soils often carries the implication that it formed in a similar environment. The classifications of the U.S. Department of Agriculture (Soil Survey Staff, 1975) and of the Australian Commonwealth Scientific and Industrial Research Organization (C.S.I.R.O.) (Stace and others, 1968), and the nongenetic key of Northcote (1974), represent a variety of different approaches to soil classification and were applied successfully to paleosol series recognized in Badlands National Park (Table 1). Some fossil soil series can be identified more accurately and within finer subdivisions of a particular classification than others. Fossil soils should not be strained to fit particular categories within a classification, because some, notably those formed under different atmospheres during the early Precambrian, appear to have been extinct kinds of fossil soils (Retallack, 1981).

Any identification of a fossil soil with comparable modern soils is necessarily tentative because many of the usual diagnostic criteria are not preserved. The nature of soil horizons is the basis of many classifications of modern soils. Horizons of fossil soils, however, may be more red and hematitic (Walker, 1974, 1976), less rich in organic carbon (Stevenson, 1969), or more gleyed (Roeschmann, 1971) than they were before burial, because of these common late diagenetic changes. The important criteria of original Eh and pH of a fossil soil are also difficult to assess, although there is some correlation of Eh and pH with mineral composition of soils (Baas-Becking and others, 1960). Reduced fossil soils or horizons are drab colored (bluish or greenish gray), carbonaceous, or contain minerals such as pyrite or siderite. Leached or A2 horizons may also be drab or light gray, but in formerly oxidized soils they are noncarbonaceous and lack these minerals. Oxidized soils and fossil soils or horizons are reddish in color and have minerals such as ferrihydrite, goethite, and hematite. Soils and fossil soils or horizons of low or acid pH are noncalcareous. Those of high or alkaline pH are progressively more strongly calcareous in proportion to their alkalinity. Very alkaline soils (pH 9 to 10) may be mineralized with zeolites, gypsum, and other evaporite minerals. Cation exchange capacity and base saturation are very difficult to determine from fossil soils but were probably higher in fossil soils with smectite clays than in those with kaolinite. The coefficient of linear extensibility (COLE), or degree to which a wetted soil expands, cannot be determined directly, although resulting gilgai structures may be preserved, notably in Oligocene paleosols in Texas (McBride and others, 1968) and in a 2.2-b.y.-old Precambrian paleosol in Transvaal, South Africa (Button, 1979). These criteria, and other lines of evidence already discussed, were used to identify paleosols from Badlands National Park (Table 1).

INTERPRETING FOSSIL SOILS

The concept of soil formation as a function of climate, organisms, topographic relief, parent material, and time of formation was most succinctly expressed by Hans Jenny (1941). Since the publication of his influential book, much has been learned about the factors of soil formation, although quantification of the multivariate relationship that he proposed is still a long way off. One aim of paleopedology is to use information on modern soil formation in a uniformitarian way to interpret environments of the past. Environmental reconstruction is also a common aim of sedimentological studies, and a combination of these with other geological approaches can yield surprisingly detailed reconstructions (Fig. 7; see also others of Retallack, 1983). Fossil soils of Badlands National Park provided evidence for a variety of different aspects of late Eocene and Oligocene environments of the Great Plains.

Climate

The latest Eocene Yellow Mounds silty clay loam is a strongly developed paleosol that is surprisingly rich in kaolinite, microcline, and quartz, compared to the underlying smectitic Cretaceous marine shales and overlying smectitic White River and lower Arikaree Groups. This and the presence of fossil alligator and soft-shelled turtle at comparable stratigraphic horizons elsewhere in South Dakota (Bjork, 1967) are evidence that, for a long time, climate in this area was humid and subtropical to warm temperate. The overlying Interior clay paleosol is also noncalcareous, but overlying Gleska Series paleosols have progressively better-differentiated calcareous horizons higher in the sequence. This is an indication of declining mean annual rainfall, which was within the subhumid range during the early Oligocene. Severe droughts during the early late Oligocene are indicated by the petrocalcic horizons and chalcedony pseudomorphs of barite or gypsum roses in some Gleska Series paleosols. Climate also may have cooled to temperate, because hackberry endocarps become increasingly common and only rare small alligators persisted during the early late Oligocene. By mid-late Oligocene time, climate was arid and caliche nodules were widespread in soils. From the relationship between depth to caliche nodules and rainfall given by Jenny (1941, 1980), annual rainfall may have been about 400 to 500 mm for late late Oligocene Pinnacles and Samna Series paleosols. Alligators did not persist during the mid-late Oligocene, and so climate also

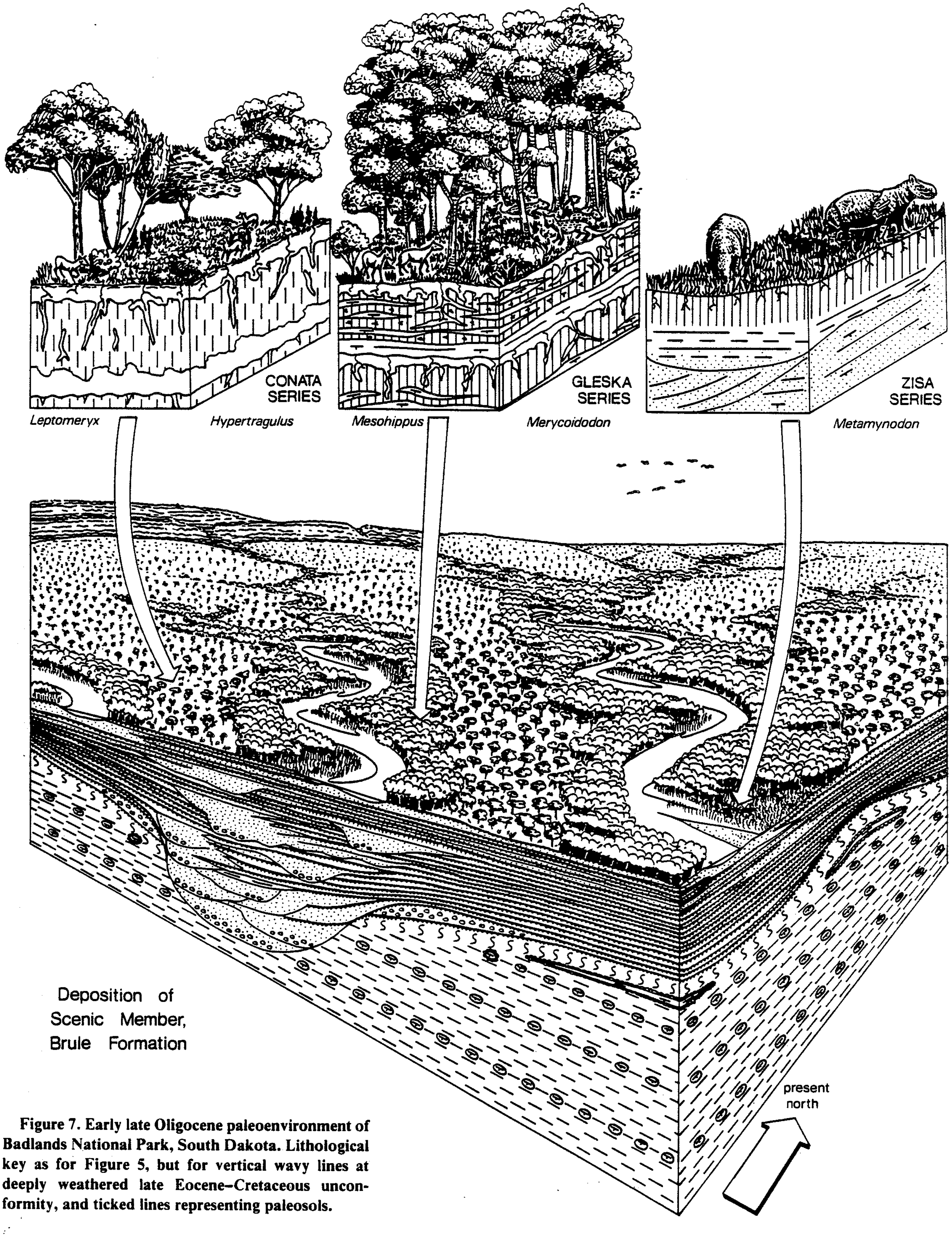

Figure 7. Early late Oligocene paleoenvironment of Badlands National Park, South Dakota. Lithological key as for Figure 5, but for vertical wavy lines at deeply weathered late Eocene–Cretaceous unconformity, and ticked lines representing paleosols.

may have cooled. Not only the evidence indicated, but also identification of the paleosols within modern soil classifications (Retallack, 1983) confirms these climatic changes. These interpretations lack precision because climate is only one of a number of soil-forming factors.

Considering gradational changes in climatically sensitive features from one paleosol to another, gaps in time between paleosols, and local paleoenvironmental effects, it is difficult to detect sudden or cyclical climatic changes. The change from an ultisol to an alfisol at the base of the sequence may seem abrupt, but both are exceedingly well-developed fossil soils representing many thousands, if not millions, of years of soil formation. Considering these long breaks in the rock record, these two fossil soils reveal nothing concerning the rapidity of climatic changes associated with the so-called "Terminal Eocene Event" (Cavelier and others, 1981), which occurred at about this time. There also may be a major disconformity near the base of the Scenic Member, as indicated by the truncated ranges of mammalian fossils in this area (Prothero, 1982) and perhaps also by relict petrocalcic horizons (Figs. 5, 6). If there were abrupt climatic changes or climatic cycles, then they appear to be unrecorded within this and numerous other disconformities. Perhaps soil formation occurred always at one stage of a climatic cycle, a model discussed for these deposits by C. B. Schultz and Stout (1980) and in general terms by Sadler (1981).

Organisms

The distribution of large, drab-haloed root traces, the thickness and continuity of A2 horizons, and comparisons with modern soils are all evidence that the Yellow Mounds silty clay was forested, the Interior clay wooded, and the Gleska Series paleosols vegetated by open woodland. Only hackberry endocarps remain as direct fossil evidence of these trees, and, as discussed previously, these are probably a misleading guide to the floristic composition of Eocene and Oligocene vegetation in the area of Badlands National Park. Only what botanists call a "plant formation" can be interpreted from fossil soils, and for these I have followed the classification of Daubenmire (1968, p. 251).

Gleska Series paleosols are abundant in the Chadron Formation, indicating that woodlands were widespread during the early Oligocene. Only occasionally were they interrupted by streams or marshy clearings with weakly developed soils (Ohaka Series) vegetated by herbaceous plants. In the Scenic Member of the Brule Formation, Gleska Series paleosols are consistently found overlying or underlying channel sandstones of small tributary streams. Weakly developed Zisa Series paleosols are usually near or interbedded with these stream deposits. Conata Series paleosols, with intermediate development and irregularly scattered drab-haloed root traces, are separated from channel deposits by Gleska Series paleosols. The early late Oligocene mosaic of vegetation during deposition of the Scenic Member thus included early successional herbaceous vegetation in streamside swales, extensive gallery woodland beside streams and savanna, a vegetation of scattered trees with intervening areas of bunch grasses, forbs, and small shrubs in the interfluves (Fig. 7). Similar conclusions were reached by Clark and others (1967) on the basis of mammal fossils found at this stratigraphic level. During mid–late Oligocene time (deposition of the Poleslide Member), there were meadows in streamside swales (Zisa Series), extensive savanna woodlands (Wisangie Series), and in low-lying, perhaps seasonally swampy interfluves, savanna with many shrubs and perhaps also bulb-bearing and taprooted herbs (Ogi Series). In the late late Oligocene Sharps Formation, large drab-haloed root traces are found only in periodically waterlogged savanna woodland paleosols (Ogi Series) associated with sandy paleochannels of streams entrenched as much as 18 m into underlying deposits. Only fine root traces were seen in the shallow, A–C horizon fossil soils (Pinnacles and Samna Series) of former high terraces and flood plains. Root traces and patterns of cracks and veins (peds and cutans) in these paleosols indicate that Pinnacles Series paleosols supported scattered bunch grasses and shrubs, whereas Samna Series paleosols supported more continuous cover, perhaps also slightly wetter and more lush, although the vegetation of both was still more clumped and less lush than much modern prairie and meadow grassland.

There were also comparable changes in mammalian fossils preserved in paleosols and associated sediments of Badlands National Park. Instead of interpreting paleoenvironments only from mammalian fossils (as done by Clark and others, 1967), it is now possible to assess mammalian evolution and migration by comparing the degree of adaptation of species or faunas (their functional morphology) with paleoenvironments independently assessed from fossil soils. It is also possible to assess local differences in the preservation of mammal fossils (taphonomy). With regard to taphonomy, it is clear from this study in Badlands National Park that some fossil soils preserve much bone, whereas others do not. In the Scenic Member of the Brule Formation, both Conata and Gleska Series paleosols contain abundant bone, including articulated skeletons. From my own study of fossil soils at several localities comprehensively collected by Clark and others (1967), it appears that death assemblages accumulating under gallery woodlands during the early late Oligocene consisted mainly of oreodon (*Merycoidodon,* 30%) and horse (*Mesohippus,* 24%), and under savannas of interfluves they consisted mainly of rabbits (*Paleolagus,* 26%) and deerlike ruminants (*Leptomeryx,* 21%, and *Hypertragulus,* 17%). Both environments were also littered with numerous tortoise shells (*Stylemys*), which were not included in the statistics.

Behrensmeyer (1981) discussed and compared these data from the Scenic Member with those from her studies of the preservation of bones in comparable modern environments and alkaline soils of the Amboseli Basin, Kenya. As guides to habitat preferences and communities of living mammals, the Amboseli bone accumulations are poor, but not unrealistic for large (more than 15 kg body weight) animals. In cases of comparably exceptional preservation, such as in the Scenic Member, complicating factors such as seasonal migrations and size-related preservational biases confound exact reconstruction of mammalian populations, and only a general impression of communities of large mammals is attainable.

By contrast, almost no bone was seen in Gleska Series paleosols of the Chadron Formation in the Pinnacles area, presumably because these soils were not sufficiently alkaline for the preservation of bone. Fossil mammalian remains, usually poorly preserved and disarticulated, are found in paleochannels and associated sediments (Clark, 1937; Clark and others, 1967). These fossils are an extremely biased sample of original mammalian populations.

Thus, each kind of fossil soil is a unique taphonomic situation as well as evidence for a particular paleoenvironment. It has long been recognized that mammalian fossils are a biased record of past mammalian life, but the question has remained, how biased? Evidence from fossil soils is providing some insights into the degree, nature, and location of the biases. Detailed studies of bone preservation in different kinds of soils and fossil soils are needed to quantify and substantiate these observations.

With regard to functional morphology, evidence from fossil soils may be used to break the chain of circular reasoning that Gould and Lewontin (1979) labeled the "Panglossian Paradigm." It is no longer necessary to assume that organisms were optimally adapted to their environment. The degree to which organisms were maladapted to their environment can be assessed by comparison with independent evidence of environments from fossil soils. Diverse savanna-adapted faunas appear to have been well-suited to savanna and streamside gallery woodlands during the late Oligocene deposition of the Brule Formation (Fig. 7). Vertebrate paleontologists have proposed for a long time that these savanna-adapted forms migrated into the Great Plains from elsewhere before and during the early Oligocene deposition of the Chadron Formation (Osborn, 1910; Clark and others, 1967; Emry, 1981). Migration, rather than evolution in place, is also indicated by the precocious appearance of these savanna-adapted forms at a time of extensive woodlands, as is evident from fossil soils in the Chadron Formation. More surprising are changes in fauna during the late late Oligocene, when extensive steppe or prairie is indicated by fossil soils of the Sharps Formation. There are some corresponding changes in the fauna of the Sharps Formation (MacDonald, 1963, 1970) compared to the fauna of the underlying Poleslide Member—smaller animals within several evolutionary lineages, more animals with clear adaptations for burrowing, and many animals with dentition approaching subhypsodont. On the other hand, high diversity, persistence of most elements of the so-called "White River Chronofauna" (of Emry, 1981, p. 569), including long-necked camels, and the lack of fully hypsodont dentition, are all indications that this fauna was not as completely adapted to steppe as some Pliocene and modern faunas discussed by Gregory (1971). Prairie habitats indicated by these fossil soils were local and temporary, because savanna was again widespread during the Miocene (MacGinitie, 1962; Thomassen, 1979). Local and temporary steppe environments probably provided important selection pressures for the evolution of prairie-adapted faunas of the late Tertiary.

Topographic Relief

Local paleotopographic maps can be constructed from spot heights on fossil soil surfaces, as has been done for paleosols in the White River Group in nearby Nebraska by Cyril Harvey (1960). Paleotopography also can be assessed from indications within paleosols of ancient water tables. For example, reduced minerals such as siderite in fossil soils of oxidizing atmospheres younger than about 1 b.y. are almost always the result of waterlogging. From these two paleopedological lines of evidence, together with evidence from paleochannels of the depth of channel incision and sinuosity, and evidence from stratigraphic mapping, it may be possible to assess paleotopographic changes in terrestrial sedimentary basins.

The Yellow Mounds silty clay loam paleosol forms a paleotopographic surface with a mappable relief of at least 25 m (Clark and others, 1967). Calcareous nodules of the Cretaceous parent material of this soil appear to have been partly corroded even at depths of 5 m in the fossil soil, and no pedogenic gley minerals were seen. Water table was certainly deeper than 6 m, and probably deeper than 27 m, which is the thickness of the yellowish leached uppermost Pierre Shale in some parts of South Dakota (Pettyjohn, 1966). This and the latest Eocene to earliest Oligocene Interior clay paleosol were soils of a rolling hilly terrain of moderate relief. In contrast, early Oligocene Gleska Series paleosols have oxidized B horizons, but their C horizons are usually drab. Water table was probably within about 1 m of the surface. This and sinuous paleochannels of the Chadron Formation, the cut banks of which are no more than 3 m deep, are evidence of a broad, low-gradient flood plain. During the early late Oligocene, water table may have been comparably high in Gleska Series paleosols, but there is less evidence of it, probably because of declining mean annual rainfall. In the Pinnacles area, paleochannels of this age are no more deeply incised than 1 to 2 m and appear to have been loosely sinuous with some braided reaches. This may have been on account of sparser vegetation than previously. It is less likely to have been due to steeper stream gradients, because local topographic relief was low. During the mid–late Oligocene, there is some evidence of surficial gleying in the clayey Ogi Series paleosols. Other paleosols of this age have abundant caliche nodules and other evidence of dry climate, but no evidence of water tables, which were at least deeper than 2 m. Paleochannels of the Poleslide Member are incised as much as 2 m and are more sinuous than those of the Scenic Member. Thus, relief remained low. During the late late Oligocene deposition of the Sharps Formation, there is also some evidence of surficial waterlogging in streamside Ogi Series paleosols, and perhaps also in some Samna Series paleosols, but evidence of high water table is again lacking. Paleochannels at this stratigraphic level are sinuous but incised as much as 19 m into underlying deposits. This was a dry landscape of extensive elevated grassy flood plains dissected by wooded stream gullies and their associated terraces.

Parent Material

The sedimentary or other material on which fossil soils form (their parent material) is usually preserved in a mildly altered form in their C horizon. Only by reference to the parent material as a starting condition can the degree and nature of soil development be assessed. For example, the massive, red, noncalcareous kaolinitic B horizon of the Yellow Mounds silty clay loam paleosol is impressively well-developed compared to the smectitic shales and calcareous nodules of its parent material. In the overlying White River and lower Arikaree Groups, there are three main kinds of parent material: (1) volcanic ash fall, (2) resorted soil material, and (3) far-transported alluvium. These are mixed in different proportions that are complexly interrelated with paleoenvironmental changes.

Resorted soil material, in the form of claystone intraclasts (former soil peds) predominates in parent material of Gleska Series paleosols of the Chadron Formation.

There is a fairly even mix of ash fall, resorted soil material, and far-transported alluvium in the Scenic Member of the Brule Formation. Ash forms most of the parent material of paleosols in the Poleslide Member of the Brule Formation and Sharps Formation. These changes within the sequence are not entirely due to increased amount and frequency of volcanic eruptions, because only the Rockyford Ash Member is preserved without extensive alteration in soils, and the nature of shards and their smectitic alteration products are uniform throughout the White River and lower Arikaree Groups. Nor does it seem that tectonic changes alone caused variation in the supply of alluvium from the Black Hills to the west, because changes in paleotopography and paleochannels, while noticeable, are not striking. Instead, these changes in parent material are probably a consequence of decreasing stability of the landscape under increasingly sparse vegetation and increasingly dry climate, conclusions independently reached by Clark (1975). Volcanic ash and alluvium were deeply weathered under a wooded stable landscape of confined, meandering alluvial channels during the early Oligocene. Both sheet erosion and flooding probably were more severe in a landscape of savanna woodlands and loosely sinuous and braided streams of the late Oligocene.

Time

Relative time for development of a fossil soil can be assessed from the degree of expression of soil features compared to relict sedimentary features. Birkeland (1974, p. 23) devised a useful qualitative scale of soil development. Quantitative estimates can be gained by comparison with studies of modern soil development and usually require classification of the fossil soil. For strongly developed fossil soils, such estimates are only minimum times for formation, because soil development proceeds to a steady state after which additional changes are slow and difficult to detect (Birkeland, 1974, p. 130). For example, the Yellow Mounds silty clay loam paleosol is similar to ultisols in the southeastern United States on land surfaces that are at least 10,000 yr old, perhaps several million years old (Cady and Daniels, 1968; Buol and others, 1973, p. 292; Birkeland, 1974, p. 6; Soil Survey Staff, 1975). A comparable minimum time is probably also represented by the Interior clay paleosol. Gleska Series paleosols have well-differentiated A and B horizons probably representing at least 5,000 yr of soil development (Buol and others, 1973; Soil Survey Staff, 1975). Judging from radiometric and geomorphological evidence for the age of Pleistocene calcareous layers (Gile and others, 1966; Williams and Polach, 1971), the calcic horizons of some Gleska Series paleosols (stage III of Gile and others, 1966) probably took at least 4,000 yr to form and the petrocalcic horizons 6,000 yr or more. Caliche horizons are not so well-developed (stage II of Gile and others, 1966) in Wisangie, Pinnacles, and Samna Series paleosols, but indicate 4,000 yr or more of soil formation. Conata Series paleosols contain no recognizable sedimentary relicts, and considering their moderate development and carbonate accumulation, by comparison with similar modern inceptisols (described by Buol and others, 1973; Gile and others, 1966), they probably represent a depositional hiatus of at least 2,000 yr. Ogi Series paleosols are also bioturbated and massive in appearance but could represent as little as 100 yr. Sedimentary relicts are prominent in both Zisa and Ohaka Series paleosols, which show little profile development beyond formation of some surficial soil structure and abundant fine root traces. A conservative minimum figure of 5 yr was used for these paleosols in the calculations of ensuing paragraphs.

From a paleopedological perspective, the White River and lower Arikaree Groups in the Pinnacles area are very incomplete on time scales varying from 10^0 to 10^6 yr. Additional time may have been unrecorded in paleosols subsequently incorporated within the recognizable paleosol profiles. Such sequences may be appropriate for studying long-term dynamics of fluvial systems (at the scale of graded and cyclical time of Schumm, 1977) or long-term coevolutionary changes of vegetation, mammals, and environment. Such sequences are not, however, adequate for studying events of geologically short duration such as speciation (considering that durations may be only 10^3 to 10^4 yr for biological species and 10^6 yr for mammalian paleontological species, according to Schopf, 1981) or climatic fluctuations on the time span of Pleistocene Glacials and Interglacials (10^3 to 10^5 yr, Hays and others, 1976).

From the minimum times of a number of paleosols in a sequence and the thickness of the sequence, it is possible to calculate a rate of sediment accumulation. Such a computation involves a number of (perhaps unrealistic) assumptions: (1) that no or few prior paleosols have been overprinted by the paleosols visible; (2) that there has been little significant erosion and destruction of paleosols; (3) that once a soil gained a given degree of development, it was covered by another unit of sediment; and (4) that long diastems are located between rather than within the sequences used for calculations. Even so, rates calculated for the White River and lower Arikaree Groups in the Pinnacles area were close to median rates calculated for comparable time spans in fluvial systems by Sadler (1981) and showed relationships from one rock unit to the next similar to rates calculated from paleomagnetic and radiometric estimates of the age of the rocks. Rates calculated from paleosols thus may be useful for comparing changes between different parts of a sequence.

Considering paleomagnetic and radiometric dating of time, time rock, magnetic and rock units represented in Badlands National Park (McDowell and others, 1973, as corrected by the method of Dalrymple, 1979; Van Couvering and others, 1981; Prothero and others, 1982), it is possible to calculate rates of sediment accumulation for the sequence in the Pinnacles area. These are very low rates of sediment accumulation, because such sequences of fossil soils are demonstrably incomplete and probably include disconformities additional to the recognized fossil soils, and because rock units probably do not correspond exactly with chronostratigraphic units. Such rates are also highly artificial averages, because there is evidence in the Scenic Member of increments of 50 cm or so of sediment at a time, completely entombing large skeletons and skulls and sealing them off from further surficial weathering (Clark and others, 1967).

Paleomagnetically and radiometrically estimated rates of sediment accumulation for the Pinnacles area are 0.0047 mm/yr for the Chadron Formation, 0.023 mm/yr for the Scenic Member, and 0.027 mm/yr for the Poleslide Member. By contrast, rates estimated from paleosols in the Chadron Formation are 0.28 mm/yr, for the Scenic Member, 0.47 mm/yr, and for the Poleslide Member, 0.65 mm/yr. Although the rates estimated from fossil soils are much higher than those estimated from paleomagnetic and radiometric ages, they show comparable changes from one unit to another and, moreover, they can be used to compare subdivisions of a unit not amenable to radiometric or paleomagnetic dating. For individual successions of paleosols not counting stream channel deposits, the lower Scenic Member of interstream savanna paleosols yields a rate of 0.38 mm/yr; the middle Scenic Member of nearstream woodland paleosols, a rate of 0.22 mm/yr; and the upper Scenic Member of nearstream woodland paleosols, a rate of 0.22 mm/yr. Such data are additional evidence for the control of erosion and sediment accumulation by vegetation. In the Poleslide Member, fossil soils constitute evidence of increasingly dry climate and increasingly sparse savanna vegetation, with correspondingly higher rates of sediment accumulation than during deposition of the Scenic Member. Despite the fact that vegetation became more sparse as the Poleslide Member accumulated, rates calculated from the lower Poleslide Member are higher (1.06 mm/yr) than those for the upper Poleslide Member (0.50 mm/yr). This is probably not due to changes in rates of local or regional subsidence or uplift; there are no more-gleyed paleosols or more deeply incised paleochannels, nor appreciably more alluvium from the source terrain. The Poleslide Member does have much more abundant and well-preserved volcanic shards than the Scenic Member has, and the increased rates of sediment accumulation may have been due to increased supply of volcanic ash. Rates of sediment accumulation remained high during deposition of the Sharps Formation and were greater near the Rockyford Ash Member and associated paleochannels (0.56 mm/yr in interval 111–113 m) than away from them (0.35 mm/yr in the clayey sequence of Samna Series paleosols).

CONCLUSIONS

Fossil soils are proving to be abundant and widespread in numerous terrestrial sedimentary sequences, and scientific methodologies appropriate for their study are being devised. Fundamental to their use in the interpretation of Earth history is a working familiarity with basic conceptual models of how soils fit into sedimentary systems and with the kinds and scope of interpretations that can be made from fossil soils. It is to these ends that I dedicate this summary and prospectus of a detailed study of Eocene and Oligocene fossil soils of Badlands National Park, South Dakota.

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