FOSSIL SOILS AS GROUNDS FOR INTERPRETING LONG-TERM CONTROLS ON ANCIENT RIVERS[1]

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ABSTRACT: The main factors controlling fluvial systems are time, initial topographic relief, geology, climate, vegetation, base level, upland runoff, upland drainage network, hillslope morphology, downstream deliveries, channel behavior, and pattern of deposition. Similar factors control soil formation in drainage basins: climate, organisms, topographic relief, parent material, and time. Effects of these factors may be preserved as well or better in fossil soils of alluvial sequences, as in sedimentary structures, facies, and mineralogy of paleochannels. For example, former rainfall may be interpreted from depth to the top of the calcic horizon, from percent clay, from percent of different kinds of clay minerals, from quartz/feldspar ratio, from hue, and from identification of fossil soils.

Interpretation of the role of these factors in producing a particular stratigraphic section should take into account its resolution: the proportion of geological time represented (temporal completeness), of original sediment preserved (lithological completeness) and of original fossils preserved (paleontological completeness). Temporal and lithological completeness can be estimated by comparison with the most likely rates of sediment accumulation and most likely thicknesses (respectively) for pertinent sedimentary environments and time scales. Paleontological completeness can be estimated by comparing the preserved fossils with expectations based on former ecosystems indicated by fossil soils.

Likely controls and resolution of a sequence of Eocene and Oligocene fossil soils from Badlands National Park, South Dakota, were studied as a guide to the periodicity and causes of episodic sedimentation there. Short-term episodicity and filtering of sedimentation events of particular magnitude were apparent from superposition of paleosols, but resolution of the sequence was not sufficient to permit a detailed analysis of their individual causes. Long-term paleoenvironmental changes and four episodes of erosional downcutting could be recognized. All four occasions of landscape instability and erosion were times of drier climate and sparser vegetation than usual. Local uplift and supply of volcanic ash were contributing factors in some episodes of erosion. When allowances are made for time scales and completeness of sequences of fossil soils, they can be useful indicators of changes in former environment, biota, and fluvial regimen.

INTRODUCTION

"The history of any one part of the earth," as characterized by British paleontologist Derek Ager (1973, p. 100), "like the life of a soldier, consists of long periods of boredom and short periods of terror." This is especially true of fluvial sedimentary environments. Flood insurance would not be a very profitable business were it not that the odds are very much in favor of nothing happening for most of the time. Catastrophic events of sedimentation are episodic and occur during a small fraction of geological time. Much can be learned about such events from the nature of the sediment and especially its primary sedimentary structures and relationship to adjacent sediments. Turbidites and storm deposits (tempestites; following Ager 1974) are well known examples of recognizable event deposits, but neither of these reveal much of conditions between events of sedimentation. In fluvial sedimentary environments, a record of these conditions is not lost and gone forever. They may be interpreted from fossil soils formed on deposits of floods (inundites of Seilacher 1981) or other agents of deposition. Although much is known about soil formation, attempts to apply this information to the interpretation of ancient sedimentary environments are just beginning (Birkeland 1984; Retallack 1981). This late start may be due to the persistent agricultural and geographic emphasis of much modern soil science. There is also a conceptual bias, implicit in the very term *sedimentary rocks,* to consider sedimentation their most important attribute. In some cases erosion, surface modification, and subsurface alteration may have been more important to the ultimate appearance of the rock record.

Information from fossil soils may be useful for understanding many aspects of fluvial systems (Baker and Penteado-Orellana 1977; Brakenridge 1981), but in this article I will explore only three issues, here posed as questions. What were the relative roles of interacting environmental factors controlling fluvial systems? How complete are fluvial sedimentary sequences as a record of geological events? What are the duration, nature, and causes of episodic sedimentation?

This study arose from my desire to investigate more rigorously the general conclusions of my recent work on fossil soils of the Late Eocene to Oligocene, White River and Arikaree Groups, in the Pinnacles area of Badlands National Park, South Dakota (Fig. 1, Retallack 1983a, b). This is a classic area for studies of badlands erosion (Schumm 1962; Engelen 1973) and of the paleontology, biostratigraphy, and paleoecology of Oligocene fossil mammals (Clark et al. 1967; Webb 1977; Van Valkenburgh 1982; Prothero 1982; Prothero et al. 1982). Like many scenic, variegated, and red beds, this sequence is a pile of superimposed fossil soils (Fig. 2). These fossil soils and much of the data analyzed here are discussed in more detail elsewhere (Retallack 1983a, b).

FACTORS

Although there are several theoretical approaches to studies of soil genesis (Simonson 1959; Runge 1973), one of the most influential has been the factor-function approach of Jenny (1941). He codified the main factors in

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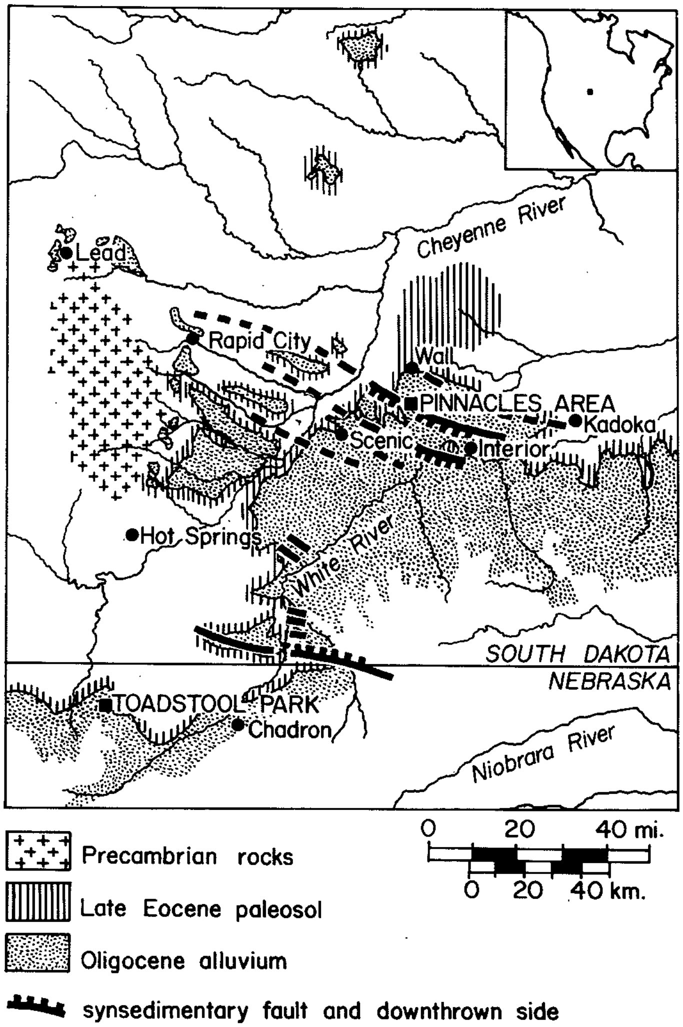

FIG. 1.—Outcrop of deeply weathered Late Eocene paleosols, Oligocene White River Group, synsedimentary faults, and mentioned localities in southwestern South Dakota and northwestern Nebraska (after Pettyjohn 1966; Clark et al. 1967).

soil formation: climate, organisms, topographic relief, parent material, and time. His early quantitative studies of these factors in the formation of specific soils and soil features have been widely imitated (Yaalon 1975). Such studies of modern and Quaternary soils provide a body of information, which can be used as a basis for interpreting environmental factors of the past from fossil soils (Retallack 1981, 1983a).

The factor-function approach has also been applied to understanding controls on modern rivers. Schumm (1977, 1981) considers that the main factors controlling fluvial systems are time, initial topographic relief, geology, climate, vegetation, base level, upland runoff, upland drainage net, hillslope morphology, downsteam deliveries, channel behavior, and pattern of deposition. Only a few of these factors can be effectively interpreted from primary sedimentary structures and channel morphology of ancient river sediments, but many of them can be interpreted from interbedded fossil soils. Such interpretations are explored in the following paragraphs.

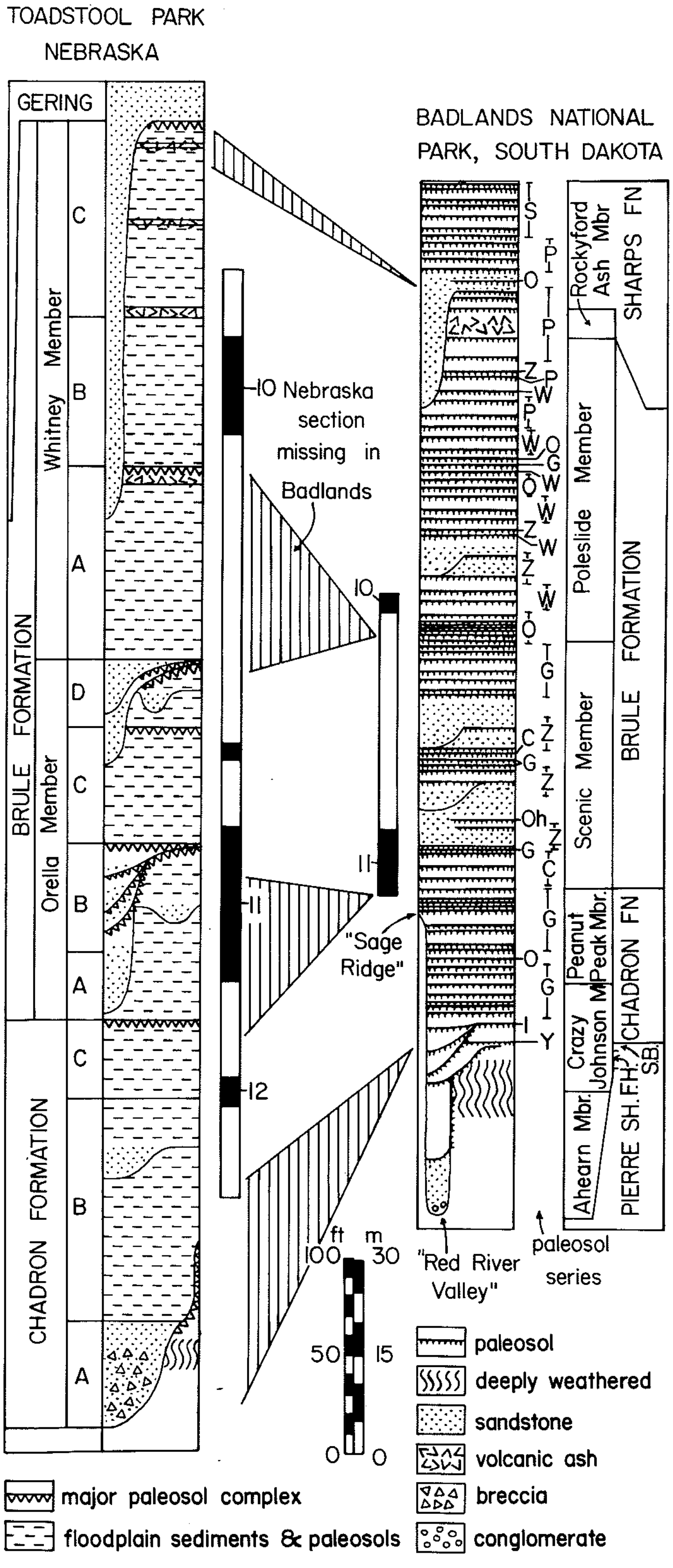

FIG. 2.—Geological sections of the White River and basal Arikaree Groups in Toadstool Park, Nebraska (left, after Schultz and Stout 1955) and in the Pinnacles area, Badlands National Park, South Dakota (right, after Clark 1937; Retallack 1983a, b), with paleomagnetic reversals and correlations (from Prothero 1982; Prothero et al. 1982). Only major paleosol complexes are shown in the Toadstool Park section; other paleosols there remain unstudied.

Time

Although the sequence of paleosols in Badlands National Park has been biostratigraphically, paleomagnetically, and radiometrically dated (Prothero et al. 1982), it is not yet possible to determine accurate ages of individual fossil soils. For this reason, not time, but stratigraphic level was used as the independent variable (or x-axis in Figs. 3–7, 9) in this analysis of factors controlling ancient riverine landscapes.

An additional inducement for using stratigraphic level is the episodicity and incompleteness of this sequence. Paleomagnetic, biostratigraphic, radiometric, and lithologic correlations with sections of similar age in nearby Nebraska (Prothero 1982; Prothero et al. 1982) reveal major breaks in sedimentation in the Pinnacles area of Badlands National Park, South Dakota (Fig. 2). These breaks correspond to times of widespread erosion and channel cutting, and to higher than usual extinctions, originations, and turnover of fossil mammalian genera (Schultz and Stout 1980; Prothero 1985). The breaks are marked by especially well developed and closely superimposed fossil soils, followed by fossil soils of a different kind. Major breaks are located at the boundaries of each of the following rock units: Late Cretaceous marine rocks, Late Eocene Slim Buttes Formation, Early Oligocene Chadron Formation, early Late Oligocene Scenic Member, mid-Late Oligocene Poleslide Member and late Late Oligocene Sharps Formation. Because of these major breaks, data considered here have been plotted as histograms or fitted with a line by regression for each unit (Figs. 3–7, 9).

Initial Relief

Initial relief is only partly discernible from the depth to former water table in fossil soils and from the depth of incision of paleochannels, both of which are discussed more fully under the heading of Base Level. Total relief from base level to the tops of adjacent hills and mountains at any one time or stratigraphic level, cannot be determined accurately. Some qualitative observations on likely changes in relief are outlined in the following paragraphs.

The Black Hills were in existence by Late Eocene time (about 40 m.y. ago) and provided a source terrain for the latest Eocene and Oligocene sequence deposited in Badlands National Park (Clark et al. 1967; Kirchner 1977). By latest Eocene time (deposition of Slim Buttes Formation), the metamorphic and granitic core of the Black Hills was already exposed to erosion, providing characteristic pebbles and heavy minerals to outwash now exposed in Badlands National Park. Streams draining an up-arched rim of Paleozoic rocks flowed in the same courses as modern streams draining the Black Hills. After Paleocene and early Eocene uplift and intrusion, the Black Hills appear to have been tectonically less active until well into Miocene time, where there is some evidence of volcanism about 10 m.y. before present (Kirchner 1977). It is likely that the Black Hills had attained an elevation comparable to that of the thickness of the eroded Cambrian to late Cretaceous sequence (at least 1,200 m according to Feldmann and Heimlich 1980) by Late Eocene, and that they maintained a comparable elevation during Oligocene time. Their present elevation (2,207 m at the highest point) was probably attained during Late Miocene to Recent time (Trimble 1980).

The thickest Eocene and Oligocene sequence within Badlands National Park is now confined to an asymmetric graben trending southeast from the Black Hills (Fig. 1). The northern boundary faults appear to be growth faults (Clark et al. 1967) and may have separated the broad, southeasterly sloping alluvial plain from slightly more elevated, rolling terrain to the north and east. To the southwest (now northeastern Nebraska) was a persistent area of large, easterly flowing streams, draining the southern Black Hills, as well as the Front Range of the Rocky Mountains, and perhaps other mountains farther west (Schultz and Stout 1955; Stanley 1976).

Geology

As already discussed, the domal structure of the Black Hills, ringed by cuestas of Paleozoic and Mesozoic rocks, probably imposed a concentric and radial pattern of drainage during the mid-Tertiary, much like that of the present. Southeast of the hills, streams flowed southeast, in part confined by subsidence of a large, asymmetric graben, a geologically controlled pattern of drainage very different from that prevailing at present.

Within the present area of Badlands National Park, the latest Eocene landscape was eroded into the smectitic and illitic Pierre Shale, capped in places by thin remnants of the overlying Fox Hills Formation. This landscape was probably rolling country with a topographic relief of at least 27 m, and perhaps with some low mesas formed on nearly flat-lying horizons of calcareous nodules in the Pierre Shale, and sandstones and siltstones of the Fox Hills Formation. The thick, strongly developed fossil soil formed on these materials and the overlying Slim Buttes Formation includes a sandy, eluvial (E) horizon with some sedimentary relict layers. This paleosol may have been more prone to sheet erosion than underlying clayey material.

The overlying Chadron, Brule, and Sharps Formations all have low and nearly uniform amounts of sand-sized material (Fig. 3A). This clayey and silty alluvium was very widespread by the time the upper Chadron Formation was deposited (Clark et al. 1967) and probably constituted the main geological control of mid-Tertiary fluvial sedimentation in Badlands National Park. This alluvium shows a marked decrease in the amount of clay (Fig. 3C) and an increase in the amount of silt (Fig. 3B) from Early to Late Oligocene. Considering the relationship between grain size and erodability established by (Hjulström 1939), flood plains were becoming more easily eroded with the passage of time.

Other methods of estimating contemporary flood-plain lithification from fossil soils are substantially in agreement with this general trend. The degree of development of a soil is not only related to the time available, but implies a degree of alteration of parent material. Some of these alterations, such as the formation of clay and calcareous cement, aid in armoring the flood plain against erosion. The proportion of the thickness of each rock unit occupied by paleosols of a given degree of development or by channel sandstone (Fig. 3D) is evidence of both generally decreased time for formation and increased disturbance of the flood plain from Early to Late Oligocene time. The categories of soil development used are those of Retallack (1984). Categories of calcareous cementation of soils (after those of Gile et al. 1966) show similar trends when plotted in this way (Fig. 3E). The calcareous horizons were largely below the surface of the soil. They represent the last line of resistance to erosion of the flood plain. Only occasionally, such as at the top of the Scenic Member, were paleosols found to have been completely eroded back to their petrocalcic horizon. These strongly developed horizons may have been critical in preserving underlying deposits from further erosion. Local lateral erosion of calcic horizons, seen where they were truncated by the cut bank of sandstone paleochannels, was much more common.

Climate

Many changes during soil formation involve chemical reactions in dilute solutions which are more critically affected by the amount of water than by its temperature, although high temperature and abundant water may have complementary effects in promoting soil formation. As a result, the effects of rainfall are more readily apparent from fossil soils than are the effects of temperature, although the two are not always easy to distinguish. Judging from identification and comparison of each of the fossil soils in the Pinnacles area of the Badlands National Park with modern soils (Retallack 1983b), there is a trend from humid Late Eocene to semiarid Late Oligocene climate, with some irregularities (Fig. 4A).

This general drying is supported by a number of other measures. The depth to the top of the calcic horizon in modern desert soils has been found to be directly related to the mean annual rainfall (Jenny 1941; Arkley 1963). This relationship does not necessarily hold for petrocalcic horizons (Kubiena 1970), but both become shallower within fossil soils higher in the sequence in Badlands National Park (Fig. 4B). The deep petrocalcic horizon shown for the paleosol at the base of the mid-Tertiary sequence is really a relict zone of calcareous nodules of the Cretaceous marine parent material, altered by deep weathering in a humid climate. Noncalcareous fossil soils of the lower Chadron Formation are evidence of more

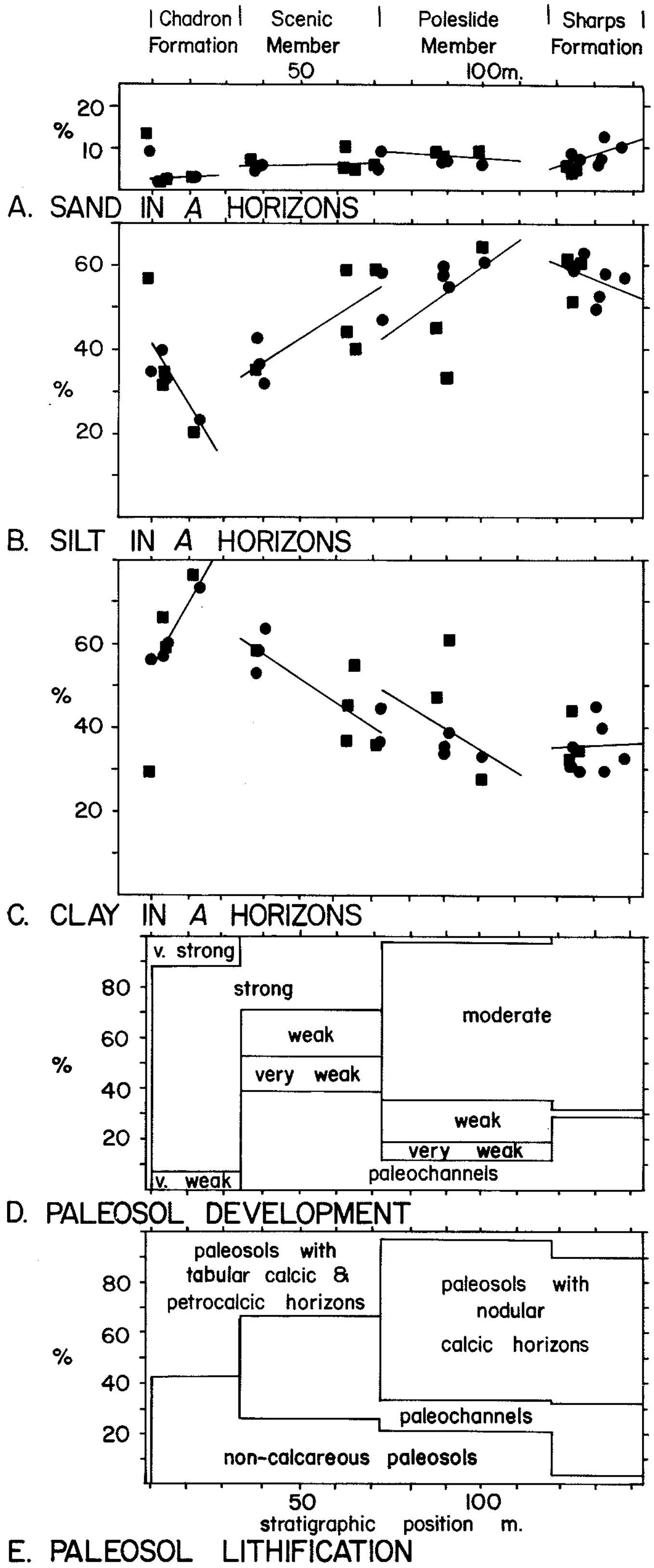

FIG. 3.—Quantitative estimates of changes in the nature of flood plains in a measured section in the Pinnacles area, Badlands National Park, South Dakota. Data of Figures 3A–C from point counting petrographic thin sections (Retallack 1983b). Paleosol development categories (after Retallack 1984) are very weak (root traces and much relict bedding), weak (A-C or Ck profiles), moderate (A-B-C or Ck at stage II), strong (as above with thick, red, clayey B or Ck at stages III or IV), and very strong (exceptionally thick, red, clayey or calcareous).

than 100 cm mean annual rainfall. The mean annual rainfall may have declined to as low as 50 cm by the time the top of the Scenic Member was deposited, and has been in the range of 45–50 cm for the Poleslide Member and 35–45 cm for the Sharps Formation, if Jenny's (1941) data for the modern Great Plains are used for calibration and negligible erosion and compaction are assumed.

Production of clay in soils declines in more arid and cool climates (Jenny 1935). Data from paleosols in Badlands National Park (Fig. 4C) was plotted from grain-size counts of 500 points in petrographic thin sections of the most altered and clayey horizon of each paleosol (Retallack 1983b, Appendix 3). This was the B horizon in fossil soils with A-B-C profiles, and the A in A-C profiles. Although temperature decline may possibly account for the declining clay content in these paleosols, there are reasons to believe that paleoclimate was warmer than cool temperate in this region during the mid-Tertiary (Retallack 1983b). Considering Jenny's (1935) data, the effect of climatic drying was probably more pronounced than that of cooling in this sequence.

Not only the amount but the kind of clay also reflects a general drying trend (Fig. 4D). These data were culled from Schultz's (1961) mineralogical study of numerous samples (20 from the uppermost Cretaceous rocks, 19 from Chadron Formation, 26 from Scenic Member, 10 from Poleslide Member, and 7 from Sharps Formation), collected throughout southwestern South Dakota. A humid climate during deposition of the Slim Buttes Formation and development of soils on Cretaceous marine rocks is compatible with the abundance of kaolinite at that stratigraphic level. Clays in the overlying mid-Tertiary sequence were generally less leached of soluble cations, and consist largely of smectite, mixed-layer smectite, and illite. Within the Sharps Formation, illite becomes more abundant. These changes in clay minerology could be explained by less severe weathering with time, judging from the weathering sequence for colloidal minerals proposed by Jackson et al. (1948). Comparison of these data for southwestern South Dakota with those for clays formed on felsic igneous rocks of the eastern Sierra Nevada of California and Nevada (Barshad 1966) indicates former mean annual rainfall of less than 50 cm for the mid-Tertiary sequence.

Quartz/feldspar ratios, also estimated from point counting (Retallack 1983b, Appendix 4), are additional indications of declining rainfall from the Late Eocene to Late Oligocene (Fig. 4E). Very little feldspar resisted humid, acidic weathering during deposition of the Slim Buttes Formation and formation of associated fossil soils. Feldspar in the overlying mid-Tertiary sequence became generally more abundant as weathering became less severe in drier climates of the later Oligocene. Quartz/feldspar ratios show in a more accentuated fashion than changes

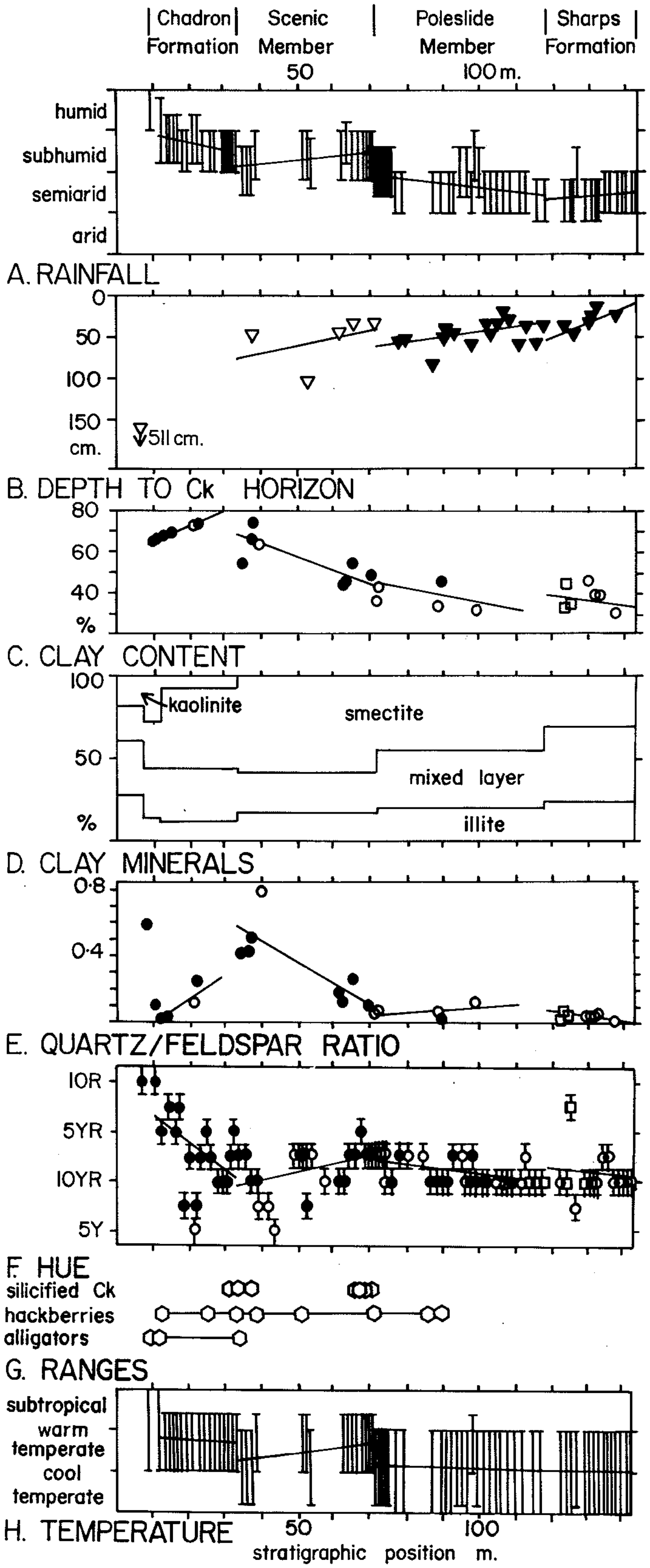

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FIG. 4.—Quantitative estimates of changing climate in a measured section of the White River and basal Arikaree Groups in the Pinnacles area, Badlands National Park, South Dakota. Open symbols in Figure 4B are petrocalcic horizons and closed symbols calcic horizons. In Figures 4C, E and F data are from B horizons (closed circles), upper A horizons (open circles), and lower A horizons (open boxes).

in the amount of clay, an increase in weathering of fossil soils at the top compared to the bottom of the Chadron Formation—the reverse of the general long-term trend. Variations in feldspar content within the Chadron Formation (noted by Clark 1937; Clark et al. 1967), and in clay content and quartz/feldspar ratios recognized here, could be indications of climatic changes of lesser magnitude than the long-term drying trend. Alternatively (and more likely), this was a time when volcanic ash first began to accumulate in this region, and quartz/feldspar ratios may reflect increasing predominance of ash compared to material derived from the Black Hills and from within the depositional system.

Although there is some evidence for a concomitant decrease in mean annual temperature of southwestern South Dakota during Oligocene time, it is not so well established as the drying trend already discussed. Comparison of fossil soils of Badlands National Park with modern soils provided a very broad range of paleotemperature for each fossil soil, and a correspondingly insignificant cooling trend (Fig. 4H).

The Munsell hue of each paleosol can be used as an indicator of paleotemperature (Fig. 4F). Hues were taken from the same horizons as data of Figure 4C, and are listed by Retallack (1983b, Appendix 2). In general, modern soils are reddest toward the equator (Birkeland 1984). Unfortunately, the degree of redness of soils, like the degree of clayeyness, is also related to time of formation and amount of rainfall (Ruhe 1965; Harden 1982), complications which seriously compromise interpretation of paleotemperature from hue. Color of fossil soils may also redden over several thousands of years of burial, as yellow and brown ferrihydrite or goethite are dehydrated to brick red hematite (Walker 1967). There is, however, reason to suspect that such alteration reaches a steady state within a million years or so (Birkeland 1984; Harden 1982). Although the hues of all the 30–40 m.y. old fossil soils of Badlands National Park may be redder than those of the original soils, relative differences in hue may still reflect paleoenvironmental change. In this sequence the most pronounced cooling and drying are indicated during the latest Eocene to earliest Oligocene, with a lesser climatic deterioration during mid-Oligocene time.

Better indications of cooling are provided by paleontological evidence. Fossil alligators became extinct in this region just above the base of the Scenic Member (Fig. 4G), where they are represented by an articulated skeleton of a small individual (Clark et al. 1967; South Dakota School of Mines, Geology Museum display). This is at a lower stratigraphic level than one would expect the general drying trend to have curtailed year-round flow of large streams. Living alligators survive seasonal droughts in Florida, but they cannot withstand temperatures lower than 20°C and are not found north of 30° latitude (Colbert 1964). Their disappearance from South Dakota may reflect climatic change from a subtropical to a warm, temperate climatic regime. Fossil pits of hackberries (*Celtis hatcheri,* Chaney 1925) were found from the base of the Chadron Formation to the middle of the Poleslide Member. Modern species of *Celtis* are widespread in semiarid to humid, tropical to temperate cimates, as far north as southern Quebec, Ontario, and Manitoba (Elias 1970). These trees are at least evidence of climates warmer than boreal. Other plant fossils of similar age from the Gulf Coast and from the Rocky Mountains to the west are evidence of a climatic cooling from subtropical to temperate during the Oligocene (Leopold and Macginitie 1972; Wolfe 1978; Daghlian et al. 1980).

Seasonality of climate is also difficult to ascertain. The presence of calcic and petrocalcic horizons is evidence of seasonally dry climate during deposition of most of the sequence. Seasons much more arid than usual may be indicated by gypsum or barite roses replaced by chalcedony (Osborn 1901; Sinclair 1921; Wanless 1923; Honess 1923) and by silicified petrocalcic horizons (Fig. 4G). There are growth rings in both freshwater clams (Cook and Mansfield 1933; Gries and Bishop 1966) and fossil wood (South Dakota School of Mines, Geology Museum specimens 377, 670) from these mid-Tertiary rocks. The harsh season was probably drier than usual and may also have been colder.

Vegetation

Only what botanists call a *plant formation,* such as woodland or savanna, can be interpreted from fossil soils. For example, Ultisols, Alfisols, and Spodosols of the U.S. Department of Agriculture classification (Soil Survey Staff 1975) are usually formed under woody vegetation such as forest, woodland, and heath. Grasslands form Inceptisols and Mollisols with characteristic granular soil structure (peds and cutans) and abundant, fine root traces. Scattered large root traces can be used to distinguish soils of savanna (grassland with scattered trees) from those of prairie (open grassland). Soils of early successional vegetation can be distinguished from those of prairie by the weak development of their profiles, and especially by the persistence of relict sedimentary structures, such as bedding and ripple marks.

The changing proportions of each recognizable kind of former vegetation for the mid-Tertiary sequence of Badlands National Park has been estimated from the stratigraphic thickness occupied by corresponding fossil soils (Fig. 5A). Interpretations of vegetation are defended in detail elsewhere (Retallack 1983b). Although there were several vegetation types at any one time, vegetation became more and more open from Late Eocene to Late Oligocene time. Paleosols at the base of the mid-Tertiary sequence were forested. Open woodlands appeared during deposition of the Chadron Formation, and savanna during deposition of the Scenic Member. Savanna was prominent during deposition of the Poleslide Member, and the first paleosols of open grasslands appeared in its upper part. The Sharps Formation contains almost entirely fossil soils of open grassland.

A useful index of vegetation density in fossil soils formed under savanna is the proportion of a line transect (20 cm was used) in the upper portion of the fossil soil occupied by large (more than 3 mm in diameter) root traces with drab haloes (Fig. 5B). The two most likely explanations for drab-haloed root traces are that they are a reflection of the original chemical microenvironment of the living root or that they are zones of reduction associated with anaerobic decay of roots after burial of the soil (Retallack 1983b). I currently favor the latter interpretation, but in either case they represent the last crop of trees before burial. The density of drab-haloed root traces was not measured in fossil soils with red B and drab E horizons. In these fossil soils drab mottles become more abundant in the upper B horizon and coalesce to form the E horizon. These were scored as 100% (in Fig. 5B). The positions of fossil soils with abundant, fine root traces, but lacking large, drab-haloed root traces, have been plotted as 0% (in Fig. 5B). Fossil soils of this kind in the Chadron Formation and Scenic Member were all early successional soils, but those higher in the sequence mostly represent open grasslands. These were the culmination of a long-

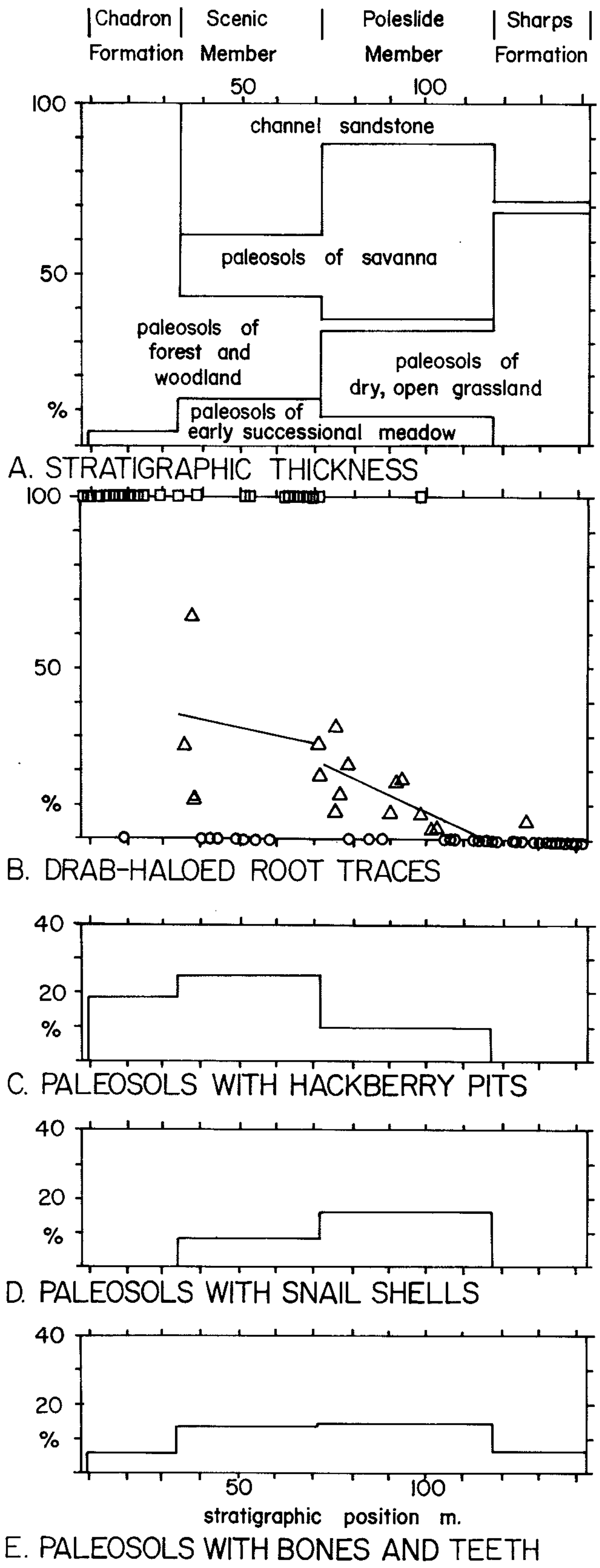


FIG. 5.—Quantitative estimates of changing vegetation and animals in a measured section in the Pinnacles area, Badlands National Park, South Dakota. Different symbols in Figure 5B indicate drab A horizons (boxes), scattered, large, drab-haloed root traces (triangles), and A horizons with fine root traces but lacking large, drab-haloed ones (circles).

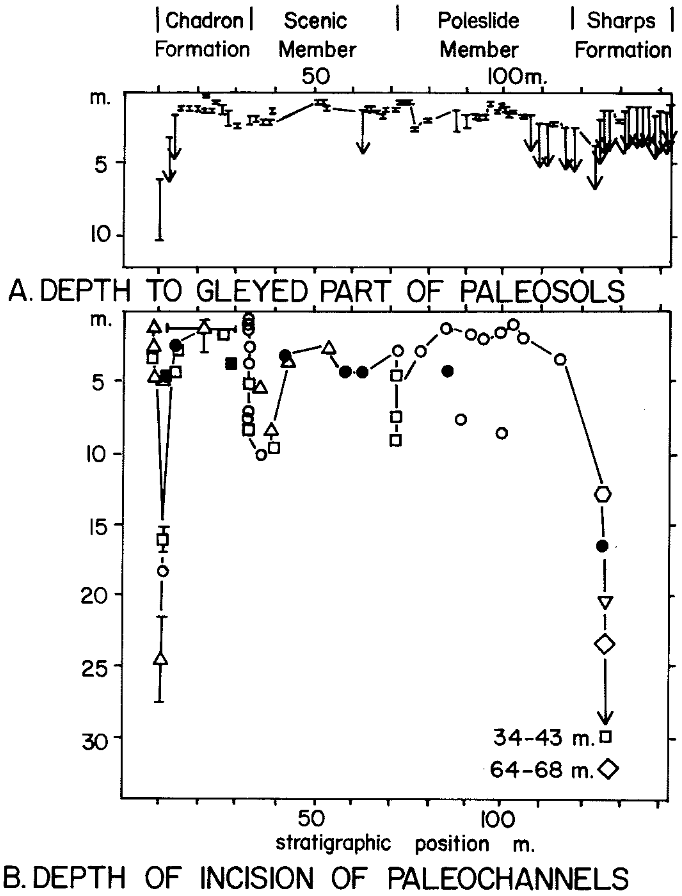


FIG. 6.—Quantitative estimates of changing base level in a measured section in the Pinnacles area, Badlands National Park, South Dakota. Sources of data for Figure 6B are Wanless 1923 (open circles); Schultz and Stout 1955 (open squares); Harvey 1960 (open diamonds); MacDonald 1963 (open octagons); Clark et al. 1967 (upright open triangles); Harksen 1974 (inverted open triangles); and Retallack 1983a, b (closed circles).

term trend of increased spacing of trees in savannas of progressively younger age.

Changes in vegetation can also be argued from paleontological evidence, such as the proportion of paleosols containing hackberry pits (Fig. 5C), land snails (Fig. 5D), and bones and teeth (Fig. 5E). Preservational biases in these data are discussed in detail elsewhere (Retallack 1984). Pits of hackberry (*Celtis hatcheri,* an ulmaceous tree) provide independent evidence for trees during deposition of the Chadron and Brule Formations, and for their subsequent rarity. Large land snails (*Pseudolisinoe leidyi*) have a similar stratigraphic distribution to open woodland and savanna, and may have been dependent on these environments. The diversity, and dental and limb structures of mammalian remains found throughout the mid-Tertiary sequence, are comparable to those of faunas of much more open vegetation than existed in western North America during Eocene time (Clark et al. 1967; Webb 1977).

Base Level

The term *base level* is used here, in the classical sense of Barrell (1917), as the level to which landscapes tend to be reduced by erosion. One approximation of base level in fossil soils is provided by traces of ancient water tables. Both base level and water table fluctuate to some extent; daily, seasonally, and on longer time scales. In addition, water tables are not as flat as the name would imply; they tend to follow the landscape (Buol et al. 1980). Below the water table there is little weathering, and there may be gley minerals or colors. The development of soil structure (peds and cutans), some kinds of soil micromorphology (sepic plasmic fabric), and of fossil roots and burrows are all dramatically curtailed below the water table.

Fluctuation of water table within the fossil soil developed on the unconformity with Late Cretaceous marine rocks was mostly between the level where calcareous nodules of the parent material appear to be dissolved, reprecipitated, and ferruginized, and the level where yellow, weathered C horizon of this fossil soil gives way to fresh, gray Pierre Shale. In other fossil soils of the mid-Tertiary sequence, water table was assessed to have been seldom higher than the calcic or petrocalcic horizon and seldom lower than the next underlying gray-green clay layer, clasts, or mottles. From these data (Fig. 6A), periods of low water table appear concentrated at the boundaries of each of the rock units. This is independent evidence for the major periods of erosional downcutting already discussed. There were times of exceptionally low water table during deposition of the uppermost Slim Buttes Formation and Poleslide Member. The uppermost Chadron Formation and Scenic Member were deposited at times of lower than usual water table.

Another indication of fluctuations in base level is the depth of incision of sandstone paleochannels, here (Fig. 6B) combining my own observations in the Pinnacles area with those of Harksen (1974) near Cedar Pass, of Clark et al. (1967) largely within Badlands National Park, of Wanless (1923) in the western part of the Park, of MacDonald (1963) in the area around Wounded Knee, and of Schultz and Stout (1955) and Harvey (1960) farther south in northwestern Nebraska. The magnetostratigraphic and biostratigraphic correlations of Prothero (1982; Prothero et al. 1982) and the type sections of the various rock units (Harksen and MacDonald 1969) were carefully considered in relating these measurements from far afield to a particular stratigraphic level in the Pinnacles area. Because much of the thicker sequence in northwestern Nebraska and farther southwest in South Dakota is not represented by rock in the Pinnacles area, many of the paleochannel depths measured in those areas have been plotted along erosional disconformities in the sequence in the Pinnacles area. Paleochannels from all areas are evidence of erosional episodes of valley and stream cutting near the boundaries of each rock unit.

Upland Runoff

By this factor, is meant the amount of water and sediment load moved within the upland drainage system (Schumm 1981). This could not be determined from the lowland sequence studied.

Upland Drainage Net

By this is meant the density of the network of upland streams, as well as their channel shape, gradient, and pattern. As for upland runoff, this could not be determined from the sequence in Badlands National Park.

Hillslope Morphology

Changes in base level have resulted in preservation of low-lying parts of several erosional landscapes. Some of these in northwestern Nebraska have been surveyed over small areas (less than four map sections) by Harvey (1960). Paleotopography below the Chadron Formation in western Badlands National Park has been contoured by King and Raymond (1971). Compared to higher parts of these landscapes, the preserved fluvial terraces and gullies are unlikely to be reliable indicators of regional slope angles, slope lengths, and profile forms.

Downstream Deliveries

As conceived by Schumm (1981), this factor includes the amount of water and sediment supplied by the river, either from upstream, or farther downstream, to a large depositional basin. Only sediment supplied to the Badlands area is considered here. The mid-Tertiary sequence of Badlands National Park was formed within a broad river valley (zone II of Schumm 1981) rather than a large depositional landscape, such a piedmont or delta (zone III).

Fossil soils in the Pinnacles area are formed on three different kinds of parent material: far-traveled alluvium, airfall volcanic ash, and material eroded from soils close at hand. The amount of far-traveled alluvium supplied to the flood plain was approximated by the percentage of

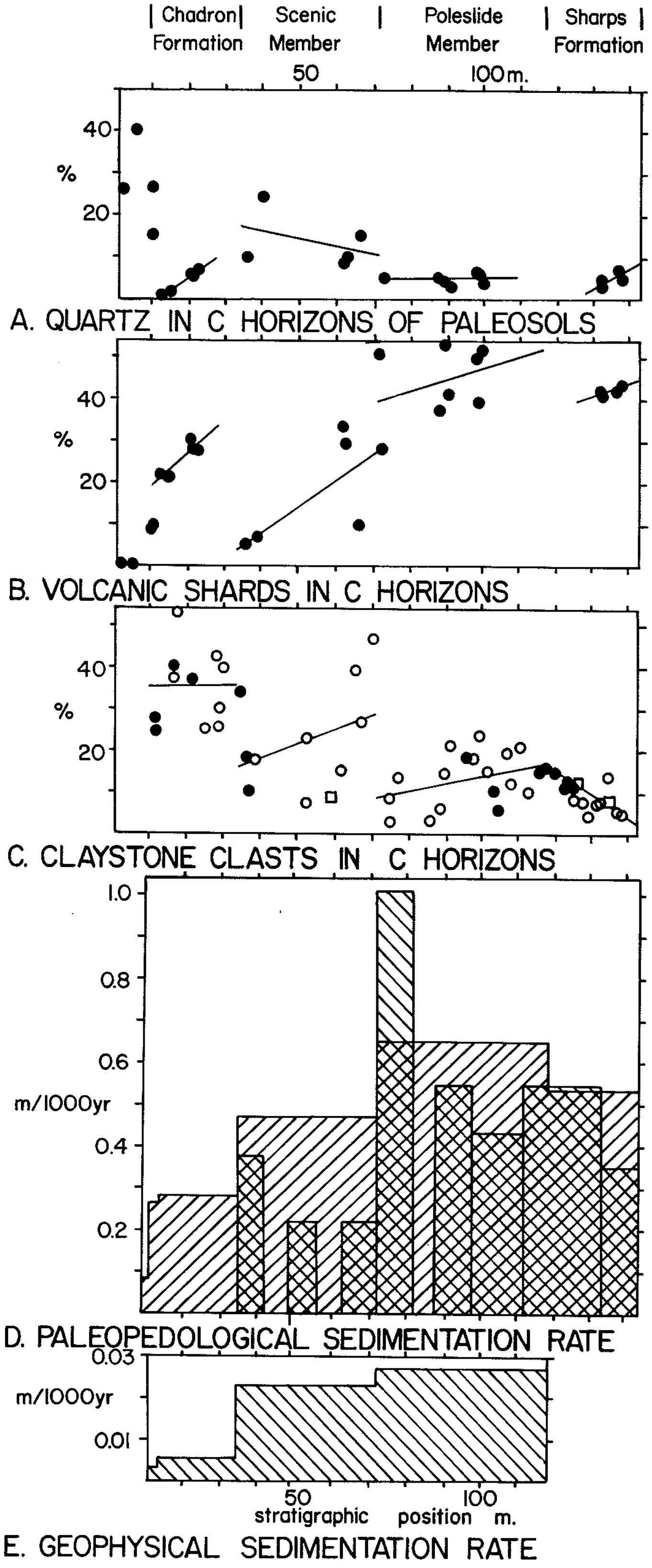


FIG. 7.—Quantitative estimates of changing rates and nature of sedimentary materials accumulated in a measured section in the Pinnacles area, Badlands National Park, South Dakota. Symbols in Figure 7C are for claystone clasts in matrix of claystone (closed circles), of micrite (open circles) and of channel sandstone (open boxes). Right sloping and cross-hatched pattern in Figure 7D represent estimates for selected stratigraphic intervals other than formal rock units.

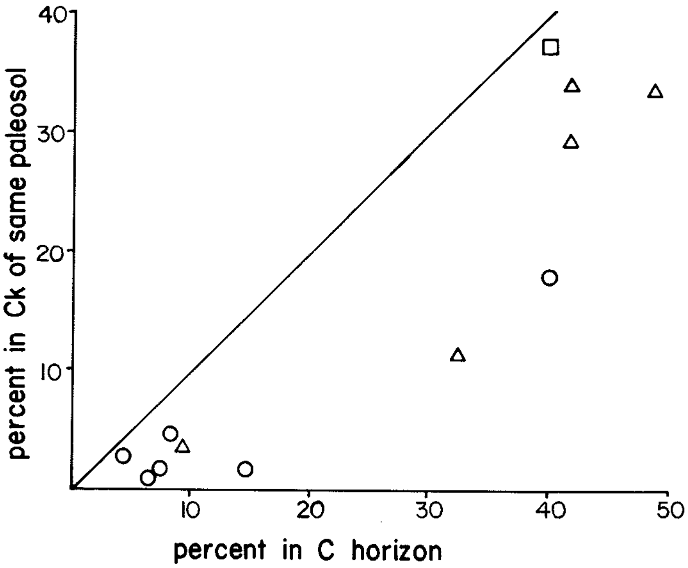
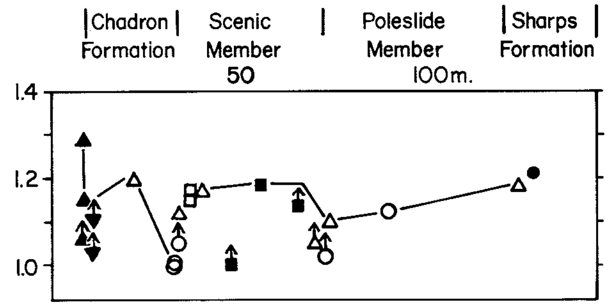


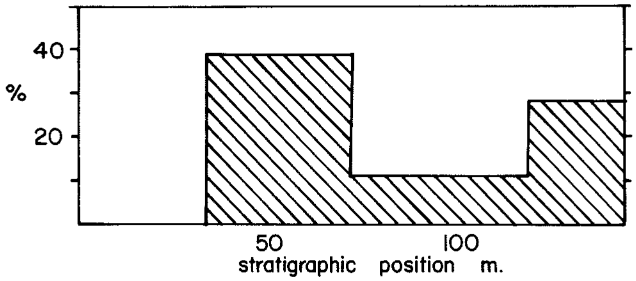
FIG. 8.—Percent clay clasts (boxes), volcanic shards (triangles), and quartz (circles) in noncalcareous subsurface (C) horizons, compared to calcareous (Ck) horizons of the same paleosol: illustrating variable replacement (distance away from line of no change) with micrite (based on point-counting data of Retallack 1983b).

quartz in the least altered (C) horizon of fossil soils (Fig. 7A), as estimated by counting 400 points in petrographic thin sections (Retallack 1983b, Appendix 4). Only noncalcareous parts of the C horizons were used because there is a noticeable depletion of quartz in calcic and petrocalcic horizons compared to adjacent clayey parts of the same fossil soil (Fig. 8). This can also be observed from the common embayment or partial replacement of quartz by micrite, widespread in calcic and petrocalcic horizons of soils (Estaban and Klappa 1983). Some quartz may have come from the Late Cretaceous Pierre Shale and Niobrara Chalk, which may contain 25% of this mineral of fine silt size or smaller (Schultz 1961). After deposition of the Chadron Formation, when most of these local Cretaceous rocks were covered, older crystalline, metamorphic, and sedimentary rocks of the Black Hills became the main source of quartz for the mid-Tertiary sequence in Badlands National Park.

Fluctuations in the supply and preservation of airfall volcanic ash have been approximated by percentage of volcanic shards in the C horizons of fossil soils (Fig. 7B), again estimated by point counting. Unlike the amount of quartz, which is low and uniform, volcanic shards vary greatly in abundance. They became increasingly important during the deposition of the Chadron Formation and Scenic Member, and are predominant within the Poleslide Member and Sharps Formation. This was in part climatically controlled; volcanic ash was less weathered to clay in the soils formed in more arid climate.



A. SINUOSITY OF PALEOCHANNELS



B. THICKNESS OF PALEOCHANNELS

FIG. 9.—Changing nature of paleochannels in a measured section in the Pinnacles area, Badlands National Park, South Dakota. Sources of data are Wanless 1923 (open circles), Clark 1937 (closed, inverted triangles), Ritter and Wolff 1958 (closed boxes), Seefeldt and Glerup 1958 (open boxes), Harvey 1960 (open triangles), King and Raymond 1971 (closed triangles) and Retallack 1983a, b (closed circles).

Although mid-Tertiary alluvium of Badlands National Park has been referred to as claystone, fresh rock samples are more commonly claystone breccia (Retallack 1983b, Fig. 4). The color, mottling, texture, and microstructure of claystone clasts betray their origin as resorted fragments of soils. The density of clasts in those fossil soils in which they were readily visible was measured in the field by the percentage of a 20-cm-long transect which they intersect (Fig. 7C). This is an estimate of the degree to which rivers were reworking their own flood plain as a source of sediment. In general, the degree of reworking declined from the Late Eocene to Late Oligocene. The proportion of far-traveled alluvium also declined in the face of great influxes of volcanic ash.

Also relevant to understanding downstream deliveries of materials is the rate at which the sequence accumulated. Rates of sediment accumulation can be calculated from the thickness of sequences and estimates of the time during which they accumulated (Fig. 7D–E). In this case, both paleomagnetic and radiometric correlations provided by Prothero (1982; Prothero et al. 1982), as well as addition of estimates of the time for development of individual fossil soils, were used for the age of sequences (Retallack 1983b, 1984).

Because of limitations on dating the time of formation of modern soils and because of incompleteness of this sequence, rates estimated from fossil soils are an order of magnitude greater than those estimated from paleomagnetic data. Nevertheless, paleopedological and paleomagnetic estimates vary proportionally, and can be used to compare changing rates between rock units (Retallack 1984). Rates based on fossil soils are especially useful for comparing changes in rates between parts of the sequence not amenable to paleomagnetic or radiometric dating. Such estimates reveal declining rates of sediment accumulation as each of the rock units of the upper portion of the sequence was deposited (Fig. 7D). This same result can be seen also from the lesser development of fossil soils at the base of the Scenic Member, Poleslide Member, and Sharps Formation and their better development near the tops of these units.

Channel Behavior

The morphology of river channels and the nature of sediment they carry are additional factors controlling fluvial deposition. Some aspects of the nature of sediment in the flood plain and of valley morpholgy have already been discussed, so remarks are here confined to channel morphology.

In this region of superb outcrops, sinuosity of paleochannels may be measured directly from the distance between two points around bends divided by the direct distance, measured both along contours of paleovalleys (King and Raymond 1971) and along mapped paleochannels (Wanless 1923; Seefeldt and Glerup 1958; Ritter and Wolff 1958; Harvey 1960; field mapping by author). Paleochannels mapped by Harvey (1960) are in northwestern Nebraska and others are in the western portion of Badlands National Park. Stream sinuosity was initially high during erosion of some parts of the Late Cretaceous sequence (Fig. 9A). It fell to low levels during initial accumulation of the Chadron Formation, the Scenic Member, and Poleslide Member, but returned to intermediate levels after each phase of low sinuosity.

There are also changes in the proportion of the sequence occupied by channel sandstone (Fig. 9B). Not only does the Scenic Member contain more channel sandstone in a vertical sequence than older rock units, but these sandstones are more laterally persistent. Sandstone paleochannels within the Chadron Formation are asymmetric and limited laterally by steeply cut banks. The paleochannel within the lower Sharps Formation in the Pinnacles area, as well as farther west near Cedar Pass, is also asymmetric, but its cut bank is less steep.

From these considerations, the likely pattern of channels at different stratigraphic levels can be interpreted within the classification of Schumm (1981). During deposition of the Chadron Formation and erosion of the landscape which it filled, streams were probably of the sinuous, suspended-load type (pattern 13 of Schumm 1981), although some may have had a mixed-load, sinuous pattern (8 of Schumm). For the remainder of the sequence, neither suspended-load nor bed-load streams are likely. Those of the Scenic Member appear to have ranged from mixed-load, island-braided, with a straight course (10 of Schumm) to mixed-load, loosely sinuous, with or without braid bars (7–9 of Schumm). Streams during deposition of the Poleslide Member and Sharps Formation were probably mixed-load and loosely sinuous

(7–8 of Schumm), only occasionally with braid bars (9 of Schumm).

Pattern of Basinal Deposition

By this factor, Schumm (1981) intended the relationship of stream deposition to other depositional subenvironments in a large, sedimentary basin, such as a deltaic coast. As ably argued by Hatcher (1902), there is very little evidence of deposition of the Badlands sequence in lakes: laminated shales are very rare. For much of the sequence measured in the Pinnacles area, calcic and petrocalcic horizons are evidence of dry seasons during which streams, as well as lakes and ponds, were probably dry, or very shallow and temporary. Although volcanic ash was introduced on the wind, it does not appear to have been reworked by wind. Apart from the very thick Rockyford Ash Member of the Sharps Formation, volcanic shards appear to have been weathered within fossil soils. No eolian dunes or ripples were seen. During the mid-Tertiary, Badlands National Park appears to have been a broad valley (a region of transportation or zone II of Schumm 1981), in which streams were much more significant than other agents of deposition.

COMPLETENESS

Before interpreting the role of these factors in the historical development of the mid-Tertiary sequence in Badlands National Park, it is well to consider the resolution of the sequence. At what level can the preserved sequence be considered a reasonably complete record of the past? Several different kinds of completeness may be considered.

Temporal completeness is, ideally, the proportion of time during which a rock unit accumulated, actually represented by events of sedimentation. Sadler (1981) has devised a method of estimating temporal completeness by comparing the rate of sediment accumulation determined for a particular sequence with rates usual for similar sedimentary environments and time spans. Such estimates can be used to compare rock units as well as to estimate their temporal resolution.

Lithological completeness is here defined as the proportion of sediment preserved in a sequence compared to what was formerly available in the sedimentary environment. Fluvial sediments are especially incomplete in this sense, because much sediment is transported out of the drainage basin. Additional losses of potential rock record occur during compaction, intrastratal solution, and other diagenetic modification of sedimentary rocks. An approximation for lithological completeness used here for the fluvial sequence of Badlands National Park was gained by comparing the thickness of particular alluvial sequences with the expected thickness of sediments in lakes or terrigenous continental shelves, accumulated over the same time span (using data from Sadler's 1981 compilation). The use of comparable time spans partially negates biases arising from diagenetic modification. Compared to rivers, lakes and terrigenous shelves are assumed to be more closed systems.

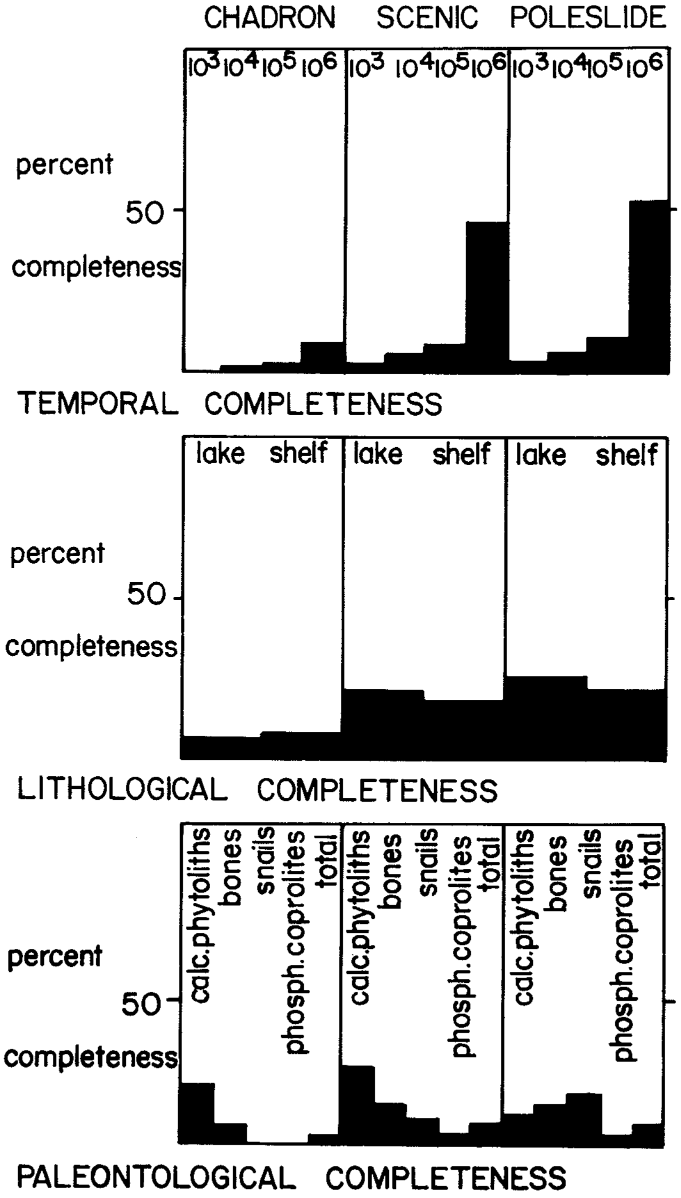


FIG. 10.—Temporal, lithological, and paleontological completeness at various time spans (in years) of selected rock units in the Pinnacles area, Badlands National Park, South Dakota (after Retallack 1984).

Finally, paleontological completeness is defined as the proportion of fossils preserved in a sedimentary sequence compared to what was once available. This is a very small fraction indeed, but estimates which are proportional from one rock unit to another may be gained by making some simplifying assumptions (Retallack 1984). Each fossil soil can be assumed to have supported life which would yield at least some fossils of the following categories: siliceous and calcareous phytoliths, pollen and spores, leaves and fructifications of plants, land snails, bones and teeth, and coprolites. In a "complete" sequence, each paleosol would yield each of these kinds of fossil. In practice, certain kinds of fossils are preserved in certain kinds of soils; for

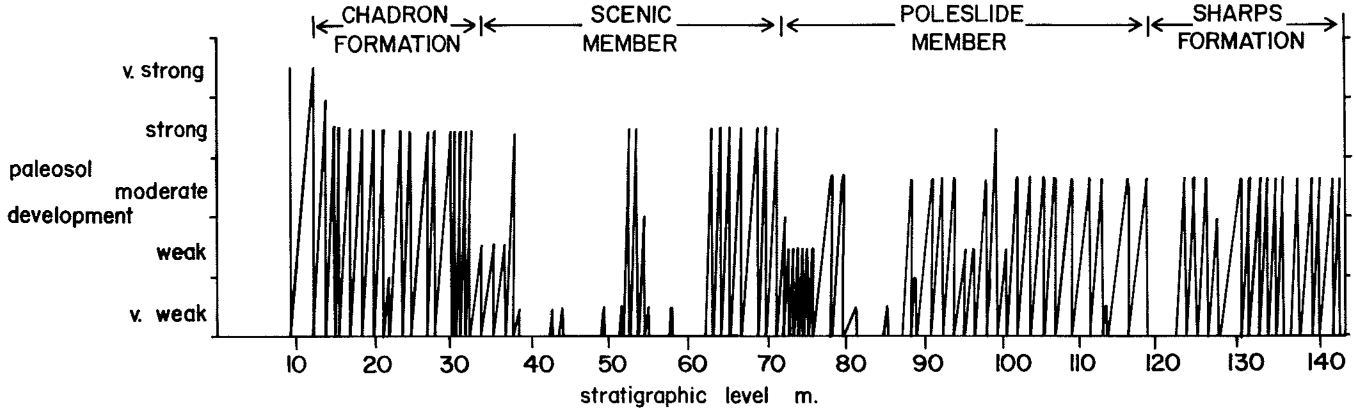


FIG. 11.—Degree of development (using categories of Fig. 3) of successive paleosols in a measured section in the Pinnacles area, Badlands National Park, South Dakota.

example, bone in alkaline, but not acidic soils. The proportion of fossil soils containing a given category of fossils provides a rough estimate of paleontological completeness.

Estimates of these various kinds of completeness for the sequence in Badlands National Park are shown in Figure 10. The data on temporal and paleontological completeness are discussed in more detail elsewhere (Retallack 1984). Temporally and lithologically the Chadron Formation is less complete than the Scenic Member, and the Scenic Member less complete than the Poleslide Member. The Chadron Formation appears paleontologically less complete than the Scenic and Poleslide Members, and fossils of the Scenic Member may be a slightly better record of past life than those of the Poleslide Member. These results also confirm that the entire sequence is very incomplete. It may be adequate for analyses of the causes of erosion or environmental change at time scales of 10^6–10^7 years, but not for factors controlling the superposition of individual fossil soils, at time scales of 10^1 to 10^4 years. Such long-term paleoenvironmental changes as can be recognized must be interpreted from less (probably much less) than a quarter of the sediment originally influenced by them. While the Scenic Member appears to have the most representative fossil record of the sequence, it is only of use in considering long term (10^6 to 10^7 yr) paleoenvironmental or evolutionary change, rather than shorter-term events, such as speciation (probably only 10^3 to 10^5 yr). Increasingly sophisticated estimates of factors controlling fluvial sedimentation, of the causes and nature of episodic sedimentation, and of completeness may be devised in the future. It is not anticipated, however, that this sequence can reasonably be interpreted at levels much finer than the rock units used here.

EPISODICITY

Before the advent of accurate data on the timing of events of deposition, sedimentation was widely considered to be cyclical. Familiar examples range from point-bar cycles (Allen 1965) to glacio-eustatic cyclothems (Heckel 1977) and the tectonosedimentary "pulse of the earth" (Grabau 1940). In geomorphology, the erosional cycle of Davis (1899) with its youthful, mature, and senile stages of valley and river form, is widely known. Quantitative studies of the repetition of sedimentary facies, such as Markov Chain analysis (Miall 1973), have seldom demonstrated strictly cyclical sedimentation. Graphs of Quaternary temperature change (Shackleton and Opdyke 1973) and of Phanerozoic sea-level change (Vail et al. 1977) are no longer plotted as the hypothetical sinusoidal waves formerly used to convey such an idea (Barrell 1917). Quantitative studies of changes in landscapes (Thornes and Brunsden 1977) and in rivers (Schumm 1977) indicate that sedimentation is more productively considered to be episodic. Fossil soils, as much as the sediments themselves, can be important clues to the periodicity, nature, and causes of episodic sedimentation.

Superposition of Fossil Soils

A conspicuous expression of episodic sedimentation is the way in which fossil soils may be found one on top of another in long sedimentary sequences (Dorf 1964; Morrison 1976; Retallack 1983a, b). At face value, this appears to be a record of periodic destruction and sedimentation over former ecosystems and their soils.

Episodicity of the mid-Tertiary sequence of Badlands National Park may be examined by considering the degree of development (according to a scale of Retallack 1984) of fossil soils at each stratigraphic level (Fig. 11). The primary cause of strong soil development is a long time of uninterrupted soil formation. Since both clayey argillic (Bt) and calcic (Ck) subsurface horizons are equally acceptable as indexes of development, other factors such as climate and vegetation do not appreciably bias this measure as an estimate of time. While the pattern of development is not perfectly cyclical, neither is it random. There are some long successions of fossil soils whose degree of development is comparable at the resolution of the scale used. If the probability that a fossil soil of given development is succeeded by a fossil soil of similar development is assumed to be equal to the probability that the degree of development of the next fossil soil will be different, as in tossing a coin ($P = 0.5$), then successions of more than 7 similar fossil soils have a probability of occurring by chance less than 0.01 times. Such successions occur at the top of the Chadron Formation (8 fossil soils, $P = 0.004$), Scenic Member (7, $P = 0.008$), Poleslide Member (7), and Sharps Formation (11, $P = 0.005$).

Such successions of similar fossil soils are probably not just coincidence, but can be interpreted as evidence that significant retarding factors are filtering events of sedimentation preserved in the rock record. Crowley (1984) has presented a stochastic model indicating the action of such filters on sedimentation rate. Sedimentation rate may be controlled by such factors as subsidence or vegetation. With low rates of subsidence or dense vegetation, only a record of the most powerful floods will be preserved. With high rates of subsidence or sparse vegetation, there will be a record of floods of lesser discharge. In general, the more powerful the retarding factors, the greater the magnitude of sedimentary events overcoming them and the longer the recurrence interval of these events. The Badlands sequence can be seen as a record of destabilizing events with recurrence intervals of as little as 5 to 100 yr, but mostly of a few thousand (Poleslide Member and Sharps Formation) to many thousands of years (Chadron Formation and upper Scenic Member). It remains uncertain, because of incompleteness of the sequence, whether these destabilizing events were floods alone or a rare concurrence of a number of perturbing factors, such as changes in vegetation and climate. Fossil soils, nevertheless, are evidence of the periodicity of disruption and of the relative magnitude of events of sedimentation.

The magnitude of sedimentary events is a difficult area in the interpretation of sedimentary environments. Different workers may interpret the same deposit as the product of surf or storm, depending on their Cuvierian or Lyellian leanings. Selley (1970) had a similar dichotomy of interpretation in mind in his preference for explaining deposition in terms of common events intrinsic to a particular depositional system (autocyclic), rather than in terms of rare catastrophic events extrinsic to the system (allocyclic). The opposite point of view argued by Dott (1983) is an indication that the tide of opinion is turning again. Using fossil soils it may be possible to gain estimates of likely recurrence intervals and magnitudes of sedimentary processes. In the Badlands, the Chadron Formation and upper Scenic Member was deposited by disruptive events with a periodicity of 10^3 to 10^4 yr, perhaps as short as the altithermal climatic maximum or perhaps as long as Pleistocene glacial and interglacial stages. The lower Scenic and Poleslide Members include some deposits representing sedimentary events of the magnitude of 5 to 100-yr floods. The upper Poleslide Member and Sharps Formation is mostly a record of events with a periodicity of 10^3 to 10^2 yr—comparable to the Little Ice Age of the middle of the present millenium or to Pleistocene interstadials. The causes of superposition of individual fossil soils in this mid-Tertiary sequence may never be known in as much detail as these Quaternary climatic changes or flood-recurrence intervals. A detailed understanding of superposition of individual fossil soils is best derived from sequences of better resolution, such as the sequence of Quaternary fossil soils preserved in Czechoslovakian loess (Morrison 1976).

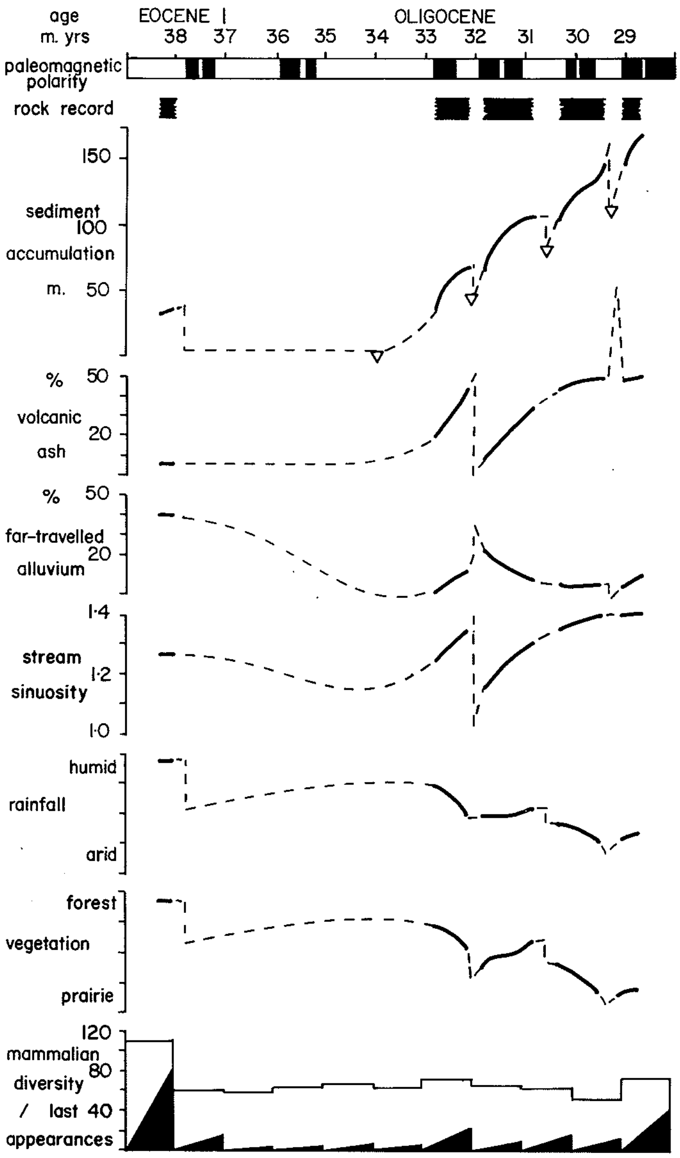


FIG. 12.—Factors controlling fluvial deposition in a measured section in the Pinnacles area, Badlands National Park, South Dakota. Data mostly generalized from Figures 3–7 and 9, with paleomagnetically based time scale and mammalian data from Prothero (1982, 1985) and Prothero et al. (1982). Dashed lines are inferred and triangles represent observed limit of downcutting.

Cutting and Filling

Although the ultimate causes of each event of sedimentation in the mid-Tertiary sequence of Badlands National Park are uncertain, the data presented on factors controlling fluvial sedimentation have sufficient resolution in unravelling causes of long-term (10^5 to 10^6 yr) episodes of alluviation punctuated by erosion and down-

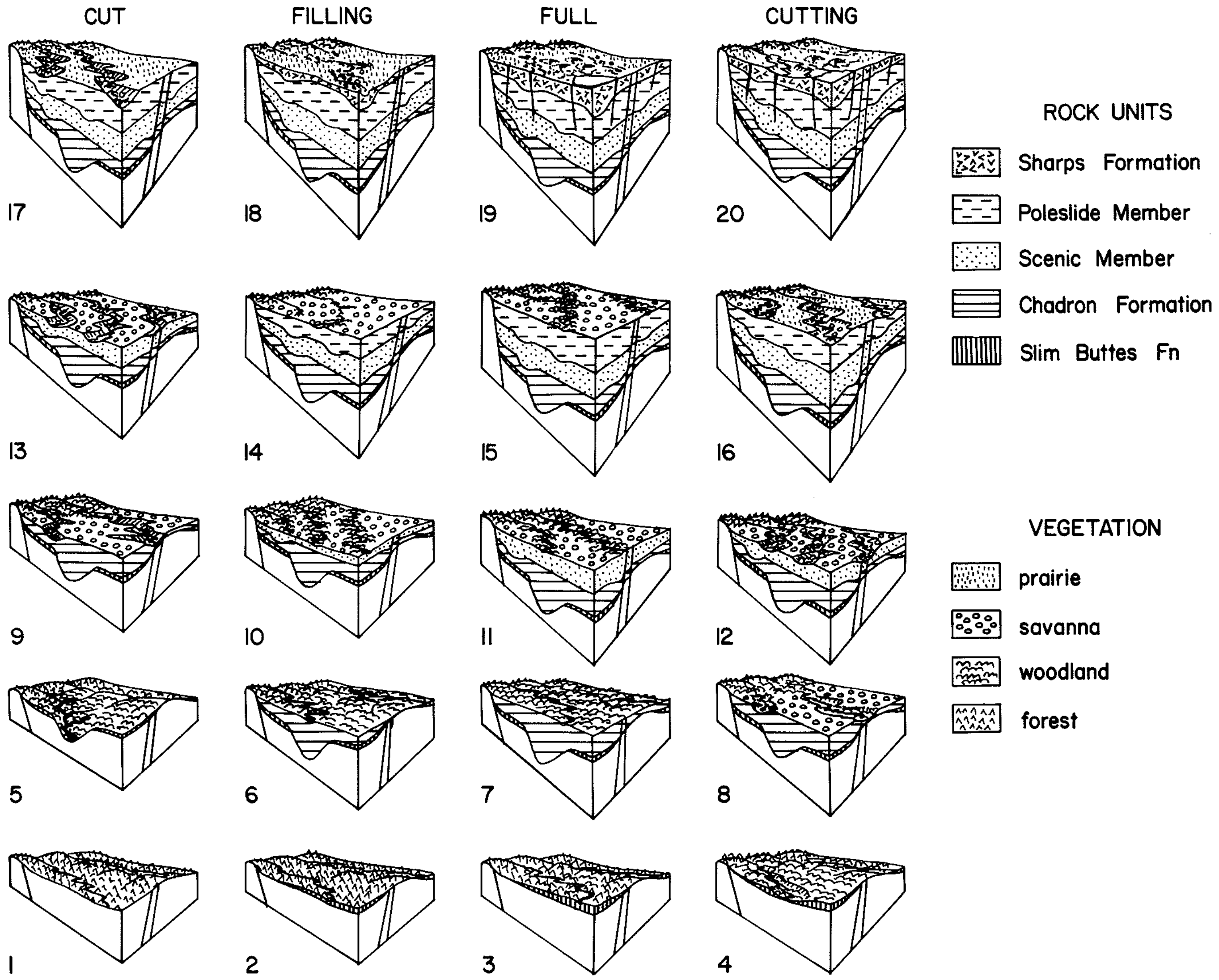


FIG. 13.—A reconstruction of changes in vegetation and landscape during Late Eocene to Oligocene cutting and filling cycles which produced the six major rock units now exposed in Badlands National Park, South Dakota.

cutting. Periods of erosion are marked by changes in the nature of fossil soils, by thinner units of sediment separating fossil soils, by greater surficial erosion of fossil soils and by unusually deep incision of sandstone paleochannels between each of the rock units recognized (Figs. 2, 6). Paleomagnetic, radiometric, and biostratigraphic correlation of the sequence in Badlands National Park with rocks of similar age in nearby northwestern Nebraska (Prothero 1982; Prothero et al. 1982) has revealed a thicker sequence there, including deeply incised channels at the same stratigraphic levels as disconformities in Badlands National Park. Prothero's (1985) compilation of mammalian diversity (boxes in Fig. 12) and extinctions (black triangles in Fig. 12) is an indication that at least two of these periods of erosion were times of crisis for animals living in this area. Periods of erosional downcutting appear to have been times of landscape instability after some kind of geomorphic threshold was exceeded. A consideration of likely factors involved in each erosional episode reveals that each was different in some way (Figs. 12, 13).

The period of erosion between formation of the strongly developed fossil soil on the Slim Buttes Formation and accumulation of the overlying Chadron Formation was probably not due to uplift in the area of deposition, because it involved a change to higher sedimentation rate. Nor was it due to uplift in the source area because the proportion of far-traveled alluvium (quartz) declined. Increased subsidence in the area of deposition is also unlikely because this was a time of regional valley cutting. Although volcanic shards first appear in the sequence at about this level, they are rare and usually very weathered. The supply of ash was not sufficient to overwhelm weathering of ash to clay in soils of the flood plain, so it is unlikely to have been significant in causing increased rates of sediment accumulation. This leaves the effect of climatic drying and, consequently, sparse vegetation, as the principal cause of this downcutting.

The transition from the Chadron Formation to the Scenic Member was also a time of change from wetter to drier climate, denser to sparser vegetation, better to lesser developed fossil soils and lower to higher sediment accumulation rates. Although the effect of drier climate and sparser vegetation is in evidence as before, a contributory uplift or other destabilization of the source area cannot be ruled out. This would account for the increase in far-traveled alluvium (quartz) in the C horizons of paleosols, and for the low sinuosity and coarse bedload of paleochannels in the Scenic Member.

Another climatically induced threshold of the stabilizing capability of vegetation may have been exceeded at the transition between the Scenic and Poleslide Members. There was a change to more open vegetation, with climatic drying. Substantial tectonic movement or change in rate of subsidence in either area of deposition or the source terrain can be discounted on the same grounds as indicated for the transition between the Slim Buttes and Chadron Formations. Both increased supply and less severe weathering of airfall volcanic ash may have been significant contributing factors to the destabilization of the landscape.

The transition between the Poleslide Member and Sharps Formation is more completely preserved than other boundaries between rock units. Correlation with thicker Nebraskan sequences reveals a comparably complete record of this transition (Fig. 2). Many of the estimated paleoenvironmental factors in the Pinnacles area (Figs. 3A–C, 4A–C, E–H, 5B, 6A, 7A–C) do not show pronounced change over this interval. Again, vegetation became sparser in a drier climate, but a critical geomorphic threshold may have been crossed by sudden influx of the thick and little-weathered Rockyford Ash Member of the Sharps Formation.

These cutting and filling episodes vary in likely causes and in scale. Even larger-scale cutting and filling episodes in Tertiary alluvium of the Great Plains are discussed by Schultz and Stout (1980). Superposition of fossil soils represents episodicity at a much smaller scale.

Some of the erosional episodes recognized here are synchronous with global episodes of marine regression (Vail et al. 1977), of eolian deposition (Janacek and Rea 1983), and of climatic cooling, as estimated from isotopic (Berger 1982) and paleobotanical data (Wolfe 1978). The close agreement of fossil soils of the Czechoslovakian loess and oxygen isotopic variation in foraminiferal tests of the deep sea, as independent records of Pleistocene climatic change, has been demonstrated by Morrison (1976). When allowances are made for different time scales and completeness, long sequences of fossil soils, such as those of Badlands National Park, are also useful indicators of paleoenvironmental change.

CONCLUSIONS

Although this study is based on the mid-Tertiary sequence in Badlands National Park, the approach employed could be applied to many other comparable sequences of fossil soils. Such sedimentary sequences are controlled by complex interactions of a number of different factors. The effects of some of these factors, such as the nature of downstream deliveries and fluctuations in water level, may be interpreted from the structures and composition of sedimentary deposits. These and other factors, such as climate and vegetation, may be interpreted from associated fossil soils. Evidence from paleosols and paleochannels combined may provide an impressive array of constraints for understanding how fluvial sedimentary sequences are put together. Reasonable numerical models for ancient fluvial systems remain a goal for the future, but some understanding of the way in which alluvial deposits accumulate can already be gained by comparing sequential changes in environmentally sensitive features of fossil soils, as I have attempted in this study. As more is learned about the formation of particular modern soil features, more and better information will be gleaned from sequences of paleosols.

Fossil soils are particularly useful as evidence of episodic sedimentation. Some event deposits, such as turbidites, provide a detailed record of changing conditions during deposition. Flood deposits (inundites) capped by fossil soils, are also event deposits. These, however, may provide evidence of conditions during sedimentation, as well as during the long intervals between floods. Conceivably, storm deposits (tempestites) capped by hardgrounds in limestones of shallow-marine shelves could be analyzed in a similar way to the paleosol-capped flood-deposits studied here.

Detailed histories of changing environments can and have been interpreted from sequences of Pleistocene paleosols, which can be dated within time spans of a few thousands or tens of thousands of years. For older sequences, such as the mid-Tertiary succession of paleosols described here, temporal resolution of individual paleosols and imprecision of paleoenvironmental indicators were not sufficient for consideration of paleosol-by-paleosol paleoenvironmental changes or episodicity. There are however, varying scales of episodic sedimentation. Cutting and filling cycles over periods of about 2 million years are evident in the Badlands sequence. Each erosional event is marked by strong disconformities and erosionally truncated, strongly developed, and overlapping paleosols. Each erosional event also truncates trends in paleoenvironmentally sensitive features of paleosols underlying it. From consideration of these features, each cutting cycle appears to have been initiated by climatic drying and consequent sparser vegetation. Uplift of the source terrane and exceptional influx of volcanic ash contributed to downcutting in some cases. Such sequences of pre-Quaternary paleosols can provide evidence for controls on episodic sedimentation on time scales greater than individual-event deposits. The multifactor analysis of such sequences attempted here could be applied to test other explanations for long-term, episodic sedimentation conventionally thought to be controlled by tectonic activity (for example, in Tertiary alluvium of the western U.S.) or by changes in sea level (for example, in Pennsylvanian cyclothems of the mid-continental U.S.).

Some of the climatic changes revealed by this particular

TABLE 1.—*Factors controlling fluvial sedimentation and the various measures used in this paper to quantify them, where possible*

	Measures Used in This Paper	Text-Figure
Time	stratigraphic level (used as dependent variable for other factors)	3–7, 9
Initial relief	filled paleorelief	2
Geology	locus of deposition	1
	flood-plain grain size, % sand in paleosol A horizons	3A
	flood-plain grain size, % silt in paleosol A horizons	3B
	flood-plain grain size, % clay in paleosol A horizons	3C
	flood-plain lithification, % paleosols in qualitative development classes	3D
	flood-plain lithification, % paleosols with different classes of calcareous horizon	3E
Climate	rainfall from identifications of paleosols with modern soils	4A
	rainfall from depth to top of calcic (Ck) horizon	4B
	rainfall from % clay in most altered horizon of paleosols (B, upper or lower, or A)	4C
	rainfall from % kinds of clay in each rock unit	4D
	rainfall from quartz/feldspar (mineral weathering ratio) in most altered horizon	4E
	temperature and rainfall from hue of paleosols	4F
	temperature from stratigraphic range of selected fossils and features	4G
	temperature from identification of paleosols with modern soils	4H
Vegetation	plant formations typical of modern soils analogous to the paleosols	5A
	% density of large, drab-haloed root traces in line transects	5B
	% paleosols with hackberry (a kind of tree) endocarps	5C
	% paleosols with fossil land snails	5D
	% paleosols with bones and teeth	5E
Base level	depth to water table indicated by gley features in paleosols	6A
	depth of incision of paleochannels	6B
Upland runoff	not determined	
Hillslope morphology	not determined	
Downstream deliveries	% quartz in lowest (C) horizon as estimate of far-transported alluvium	7A
	% volcanic shards in lowest (C) horizon as estimate of volcanic airfall	7B
	% claystone clasts in lowest (C) horizon as estimate of resorted soil material	7C
	sediment accumulation rate based on estimates of time for formation of paleosols	7D
	sediment accumulation rate based on paleomagnetic and radiometric estimates of time	7E
Stream behavior	paleochannel sinuosity measured from maps	9A
	% of measured section occupied by paleochannels	9B
Pattern of basinal deposition	not quantified	

study of paleosols (for example, at about 32 and 38 m.y. before present) coincide in time (within the limits of current resolution) with climatic changes revealed by studies of fossil floras of the Pacific Northwest and changes in the oxygen isotopic composition of foraminiferal tests in the Pacific Ocean. Sequences of paleosols may provide valuable supporting evidence for paleoenvironmental change, but the interpretation of this evidence is not always easy. Abrupt truncation of paleoenvironmentally sensitive features of paleosols may reflect conditions deteriorating beyond a geomorphic threshold that is peculiar to a particular sedimentary system. Between these erosional events there are successions of very similar paleosols. These may represent a balance between stabilizing forces (such as vegetation) and destabilizing forces (such as floods of a critical magnitude), in a kind of dynamic equilibrium. The degree of external forcing (such as climatic deterioration) required to upset this balance and initiate periods of severe erosion may have varied considerably with local conditions. Thus, in principle, the various lines of evidence for paleoenvironmental conditions need not coincide exactly in time. As the quality of these disparate lines of evidence improve, there is hope not only for understanding what happened in the past, but how these events affected their preservation in the rock record.

A variety of features of sequences of paleosols may provide quantifiable evidence of the causes and effects of paleoenvironmental change. Paleosols are abundant in some sequences and may provide a surprisingly detailed record of the past. The richness of this record reveals complexities fundamental to understanding the long-term accumulation of such sequences. These complexities, such as the robustness of landscapes in the face of external environmental change, are especially promising future topics for research on sequences of fossil soils.

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