AN EXCURSION GUIDE TO FOSSIL SOILS OF THE MID-TERTIARY SEQUENCE IN BADLANDS NATIONAL PARK, SOUTH DAKOTA

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Abstract

This excursion guide consists of a series of roadside lectures on fossil soils of the Late Eocene to Oligocene, White River and lower Arikaree Groups in one of their most spectacular areas of outcrop, near Pinnacles Lookout, Badlands National Park, South Dakota. The excursion stops are arranged over a short length (1.9 miles) of South Dakota Highway 240 and should occupy only a few hours.

Abundant fossil soils have been recognized in this sequence from the nature and distribution of fossil root traces, from diffuse discolored and otherwise altered layers (former soil horizons) below minor erosional surfaces, and from the unbedded, massive, jointed nature (former soil structure) of many of these rocks. Decreasingly red hue and clay content and increasingly calcareous composition of the paleosols at progressively higher levels of the sequence reflect increasingly dry climate from the Late Eocene to Oligocene. Several major disconformities within the sequence represent periods of landscape instability and erosion, in part related to climatic deterioration.

Fossil soils of this sequence are helpful for interpreting several aspects of its renowned vertebrate fossil assemblages. Fossil mammals in fossil soils are more likely to be close to where they lived and of about same age as enclosing rocks than fossils found in paleochannels. Changes in the degree of development of fossil soils may be useful for assessing major disconformities in sedimentary successions. Each kind of fossil soil can be regarded as a unique kind of taphonomic situation in which some kinds of fossils were preserved but not others. Each kind of fossil soil also represents a

distinctive ancient ecosystem which may have supported distinctive assemblages of vertebrates. Finally, independent evidence of paleoenvironment from fossil soils can be contrasted with the degree of adaptation of associated vertebrate fossils.

INTRODUCTION

For the pioneers of the last century as much as for motorists now visiting the area by the millions each year, the Badlands of South Dakota and Nebraska are fascinatingly reminiscent of "magnificent ruins of a great silent city painted in delicate shades of cream and pink and buff and green" (O'Harra, 1920). This poetic image encapsulates well three aspects of geological interest in the area. A feeling of antiquity is conveyed by fossil bones littering the Badlands in such abundance and quality of preservation that this region remains a standard for understanding terrestrial Oligocene mammalian life. In its ruined appearance of crumbling towers, razorback ridges, and deep gullies, this area is the original example of badland erosion. The third aspect of O'Harra's image, color banding, has not had such a long history of geological research. When I first visited Badlands National Park, it was explained that color banding was due to staining with iron-bearing minerals of different oxidation states. Such partial answers are a great stimulus to research. My own further studies have shown that this answer is both correct and incomplete. I discovered that the subtle banding of color, texture, and other features of this sequence, is largely a product of ancient soil formation. There are also a few purely sedimentary strata such as channel and levee deposits of ancient streams, but overall the sequence can be considered a thick pile of fossil soils. This new view of the sequence and its consequences for vertebrate paleontology form the main themes of this excursion.

The area around Pinnacles Overlook in Badlands National Park is a small part of the badlands of clayey Late Eocene and Oligocene nonmarine rocks which extend through much of southwestern South Dakota and northwestern Nebraska. The Pinnacles area is one of spectacularly precipitous exposures in which a complete section of the White River and lower Arikaree Groups can be seen along a short length (1.9 miles) of a paved highway (South Dakota Highway 240, formerly known as alternate U.S. Highway 16). For these reasons of accessibility, steepness, and stratigraphic range, it has proven ideal for studies of the Late Eocene to Oligocene stratigraphic succession of paleosols and paleoenvironments (Retallack, 1983a,b).

Because of limitations in scheduling this excursion, I have taken the geologically unusual approach of proceeding from the youngest to the oldest localities, down the hill from the overview provided by Pinnacles Overlook. The trip could equally be done in reverse. Each of the explanations for the stops do not assume knowledge of prior stops. Each of the stops are limited to what can be seen on the surface so the excursion should last only a few hours. Park regulations prohibit unauthorized excavation and collection. Approved scientific investigators are encouraged to confine such activities to areas away from the highway and away from public view. The stratigraphic sections on which this excursion is based (Retallack, 1983a,b) were measured from specially excavated trenches in gullies west of the highway where the sequence differs in detail from that exposed along the highway. Some of the nomenclature used here (particularly of soil horizons) differs slightly from my previous accounts (Retallack, 1983a,b) because of recent advances in soil science (Birkeland, 1984).

ROAD LOG

STOP 1 (see road log).--Pinnacles Overlook allows a good view of the spectacular South Dakota Badlands, a complexly eroded terrain of nonmarine sedimentary rocks separating the prairie of the uplands around Wall from the valley of the White River to the south. This was in days past a difficult barrier to overland travel, thus earning the name badlands from "mauvaises terres á traverser" of the French trappers or "maco sica," in the Lakota Sioux language. This ragged line of cliffs and pinnacles is locally termed "the wall".

The exposed sedimentary rocks are the Late Eocene and Oligocene White River and lower Arikaree Groups (ages after Prothero *et al.*, 1982). The sequence here accumulated just north of a subsiding graben (Clark *et al.*, 1967), trending obliquely southeast from the source terrain of the Black Hills (Figure 1). This graben no longer appears to control streams or sedimentation here, although areas closest to the Black Hills receive less sediment than the distant plains now, as in Oligocene time. Most western North American basins of Tertiary age were similar in this respect. In such a setting, older fossils near uplifted mountain fronts could be continuously eroded out and redeposited in younger rocks; a subject to which we will return in later portions of this road log.

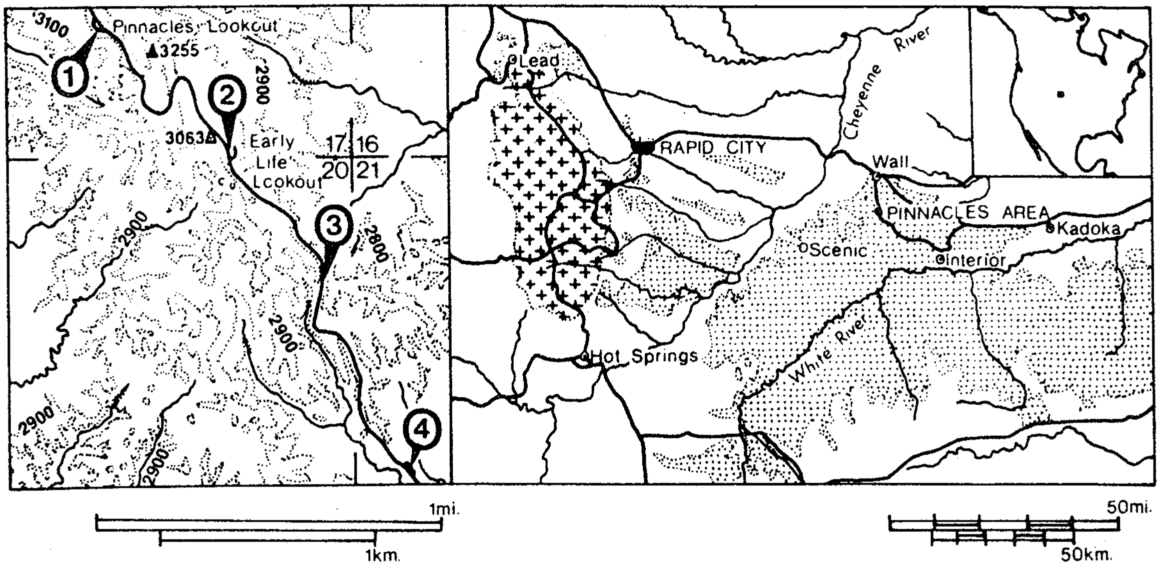

Figure 1. Location of excursion stops in the Pinnacles area (left); Badlands National Park, South Dakota (right). Contour lines (dotted), and spot heights in the map of part of sections 16, 17, 20 and 21, (T2S, R16E, Pennington Co.) in the Pinnacles area are in feet. Shown on the map of southwestern South Dakota are outcrops of the Late Eocene and Oligocene White River Group (stipple), Precambrian crystalline and metamorphic core of the Black Hills (crosses), highways (heavy lines) and major streams (thin lines).

In the lowest visible part of the Badlands, the Early Oligocene part of the Chadron Formation (Figure 2), a pale pink and green claystone breccia, weathers to a distinctive, low, mound-like topography. The overlying mid-Oligocene, Scenic Member of the Brule Formation forms a maze-like system of cliffs with striking red and white bands, like a barber pole. The steep brown unit above is the Poleslide Member of the Brule Formation. Capping these yellowish brown rocks in the foreground is the white Rockyford Ash Member of the basal Sharps Formation of Late Oligocene age. The ashy and sandy basal part of the Sharps Formation is overlain by an upper part of brown claystones which form most of the hill to the east of the lookout except for a thin veneer of Quaternary gravel.

Although the Badlands sequence is largely alluvium, most of the alluvial beds are capped by paleosols. Thus the sequence is, in a sense, a great pile of fossil soils (87 in 143 m of section here), representing as many times of peace and quiet on Late Eocene and Oligocene floodplains between major floods and volcanic ash falls. Several general features of this succession of paleosols reflect changes in soil forming processes during this time interval. The pink-green banding of the upper Chadron Formation was produced in woodland soils under a subhumid climate during the Early

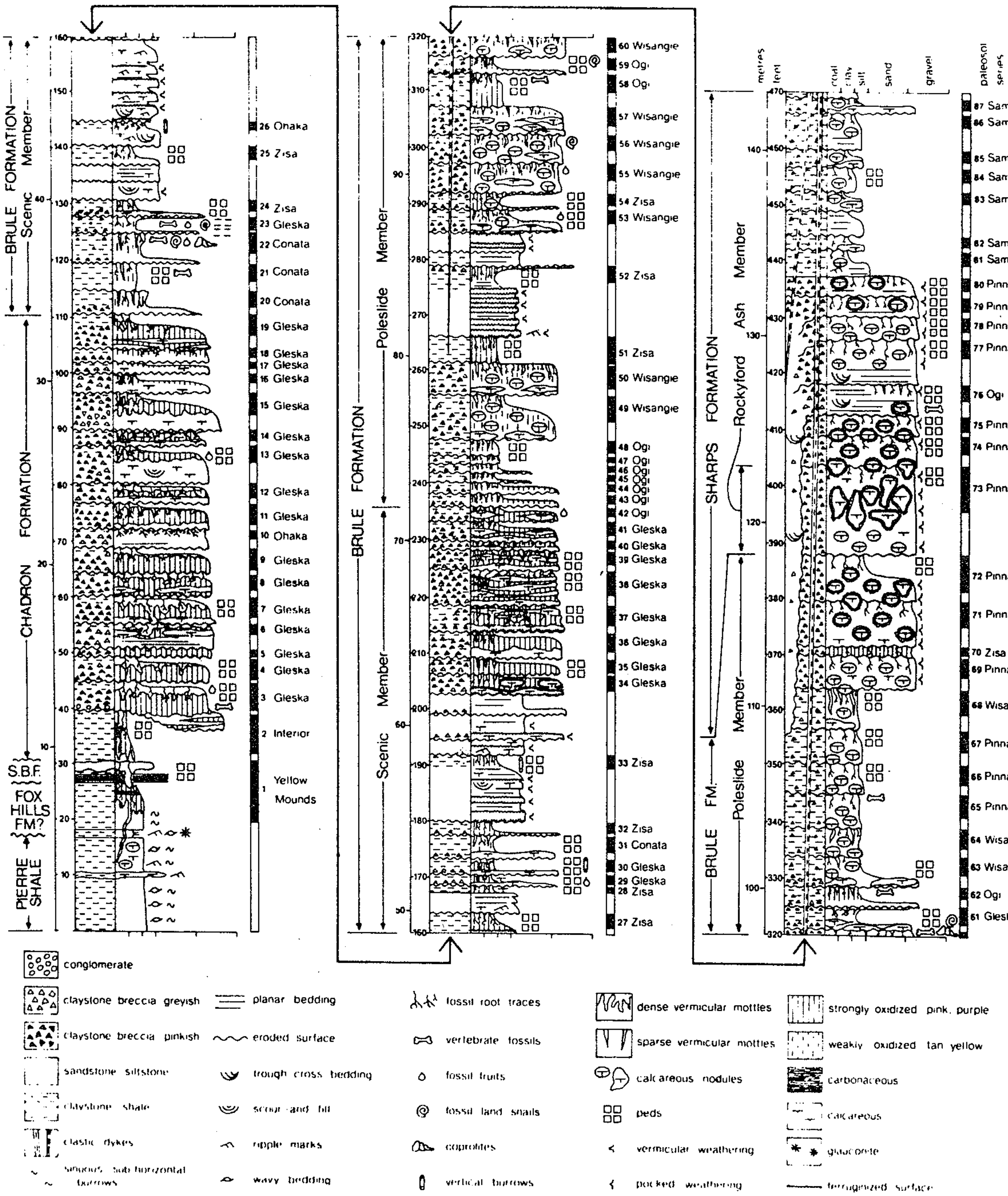

Figure 2. Stratigraphic section of the Late Cretaceous Pierre Shale and Fox Hills Formation, Late Eocene to Early Oligocene Slim Buttes (S.B.F.) and Chadron Formations, mid-Oligocene Scenic Member of the Brule Formation, and Late Oligocene Poleslide Member of Brule Formation and Sharps Formation in the Pinnacles area, Badlands National Park, South Dakota (Reprinted from Retallack, 1983b, with permission from the Bulletin of the Geological Society of America).

Oligocene. As climate became drier later in the Oligocene, the predominantly volcanic ashy parent material was less effectively weathered to clay, more calcium carbonate accumulated in the soils, and vegetation became more open and grassy. Higher in the sequence exposed in the panorama here, the cliffs are silty and sandy rather than clayey. They are also paler because of abundant calcium carbonate stringers and nodules. The pink and green paleosols of woodlands of the mid-Oligocene are associated with striking, red, weakly calcareous, early successional paleosols. There are brown paleosols formed under savanna at this level also. These kinds of paleosols give way in the Late Oligocene to more subtle, lighter colored and thinner paleosols of open grasslands. Fossil bones interred in these fossil soils show comparable changes in mineralization and discoloration within the sequence. The change from reddish, clay-filled bone to light colored, carbonate-encrusted bone is also a feature of North American Tertiary bone in general (Houston *et al.*, 1966). It reflects the development of soils under more open vegetation and drier climate.

The distinctive color of each rock unit is an indication of a consistent pattern of vegetation and other soil-forming factors during its accumulation, which were disrupted at the boundaries of each unit. These boundaries are marked also by closely superimposed, eroded and especially well developed paleosols, and deeply incised paleochannels: all indications of lower rates of sedimentation and increased erosion (Retallack, 1985). A striking example of one of these periods of landscape destabilization is the paleochannel incised 18 m into rocks underlying the Sharps Formation, just across the deep canyon southeast from the lookout. There is evidence from paleosols (such as disappearance of large root traces and declining depth of calcic horizons), that just before this erosional event, the climate was becoming drier, and larger patches of open grassland were appearing in the savanna. As for all the boundaries between rock units in this sequence, this may have exceeded a geomorphic threshold in the ability of the vegetation to stabilize the landscape against erosion. In this particular case the massive influx of the Rockyford Ash Member was a contributing factor in destabilization of the landscape (Retallack, 1985).

Such erosional episodes are important to vertebrate paleontology because they may result in the mixing of bone exhumed from buried soils with bones of animals living on the later eroded landscape. These problems have received little attention in studies of Badlands National Park, although they have sparked considerable controversy in other regions. The vertebrate fauna of Bug Creek Anthills, near Fort Peck, Montana, is a case in point (Archibald and Clemens, 1982; Smit and Vander Kaars, 1984). Are these the remains of a latest Cretaceous mammalian fauna of Paleocene aspect appearing precociously among the last of the dinosaurs? Or are they Paleocene mammals preserved in deeply incised valleys along with Cretaceous fossils exhumed from nearby hills? The former view lends support to the concept that faunal replacement is gradual and effected by piecemeal usurpation of niches within loosely integrated communities. The latter view favors theories of abrupt faunal replacement, either following catastrophic events, or as an artifact of an incomplete record, in which one well integrated community (or chronofauna to use Olsen's, 1952, term) is replaced by another.

Enroute. Continue south on South Dakota Highway 240 to Early Life Overlook. In road cuts along the way, the white Rockyford Ash Member of the basal Sharps Formation is rent by numerous clastic dikes, which in places weather out as low walls.

STOP 2 (see road log).--The Early Life Overlook reveals another panorama of badlands from the cliff-forming Rockyford Ash to the Scenic Member below. The main interest of this stop is in the gullies west across the road from the lookout, where a small modern terrace is perched on Late Oligocene rocks of the Poleslide Member of the Brule Formation. A modern soil on the terrace has developed under grassland with scattered small juniper trees. This is a young soil, not yet as fully vegetated by juniper as other similar benches in the Badlands wall. The soil has a dark granular surface (A) horizon, over a little altered calcareous subsurface (Ck) layer. This kind of profile is peculiar to soils of grasslands, because of their fine roots, concentration of biomass near the soil surface and limited ability to leach mobile cations (such as Ca^{++}) from the soil. Soils formed under forest or woodland are more deeply weathered (Birkeland, 1984). Below the modern profile are dark bands within the terrace, representing buried soils also formed under early successional grassy and shrubby vegetation. Some of these dark bands are littered with charcoal, Indian artifacts, and bison bones, indicating that this was an encampment or kill site. From my checking of archaeological literature and South Dakota state records, formal archeological studies of this site do not yet appear to have been undertaken. This part of the terrace is probably Holocene (less than 10,000 years) because no remains of extinct Pleistocene mammals have yet been found. The terrace may have been part of a small alluvial fan built from sediment and colluvial debris washed in from the surrounding slopes.

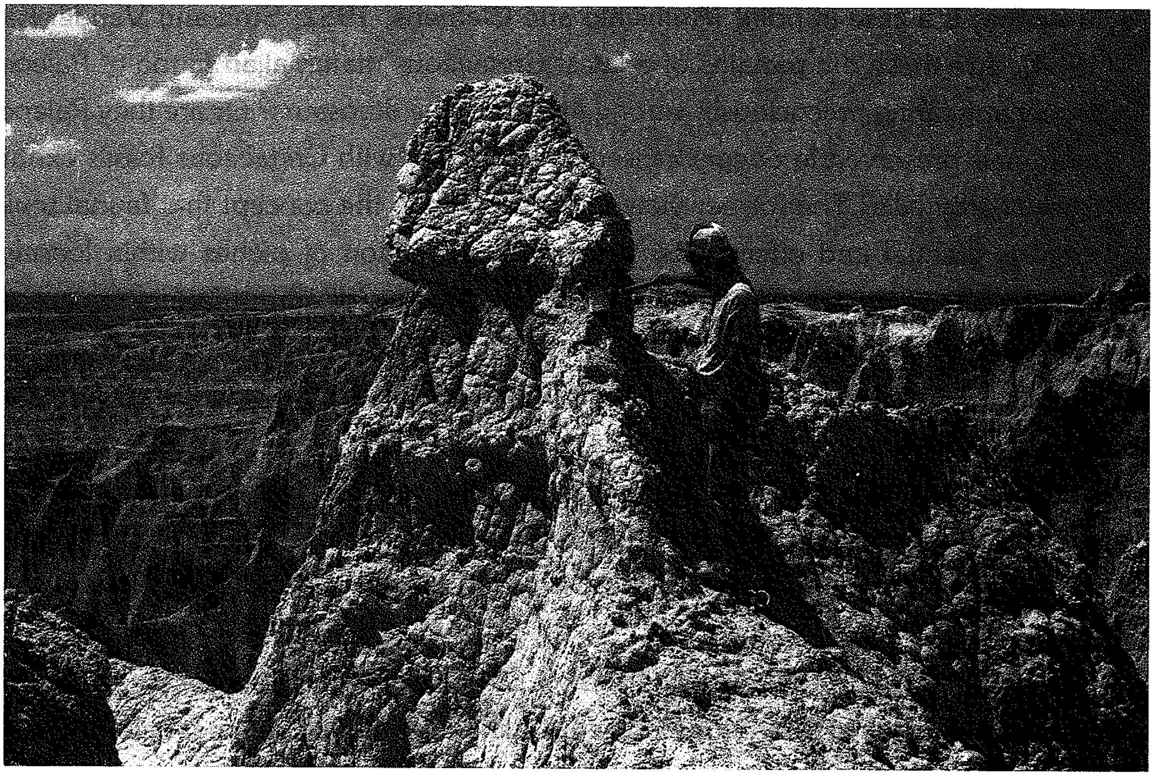

Figure 3. The type Pinnacles silty clay loam paleosol (#75 of Retallack, 1983b; indicated by person), interpreted as a prairie soil of the Late Oligocene (Arikareean) Sharps Formation, in the Pinnacles area of Badlands National Park. Weathered out in this small pinnacle, this paleosol shows more clearly than similar profiles within the sequence, a clayey surface (A) horizon beneath a minor erosional disconformity, and a diffuse, subsurface, nodular calcareous (Ck) horizon.

Paleosols in the upper part of the Tertiary sequence near the terrace are similar in some respects to these Holocene buried soils. They have dark granular A horizons and weakly altered subsurface horizons typical of grassland soils. The dark bands just below the Rockyford Ash are the oldest likely paleosols of prairie currently known in North America. Unlike the recent soil of the terrace, many of these are well developed paleosols with prominent zones of micritic limestone nodules (caliche) in their subsurface (Ck) horizon. These probably took several thousands of years to form to this extent, judging from studies of the formation of calcareous nodules in Quaternary soils (Gile *et al.*, 1966; Birkeland, 1984). Light-colored paleosols bearing similar nodules in this sequence have been called Pinnacles Series paleosols (including the Pinnacles silty clay loam: Figures 3, 4C). Darker grassland paleosols with thinner, better defined calcareous horizons (Samna Series) are found higher in the Sharps Formation. One example of a third kind of paleosol was found interbedded with paleochannel sandstones associated with the Rockyford Ash Member. This paleosol is a reddish brown,

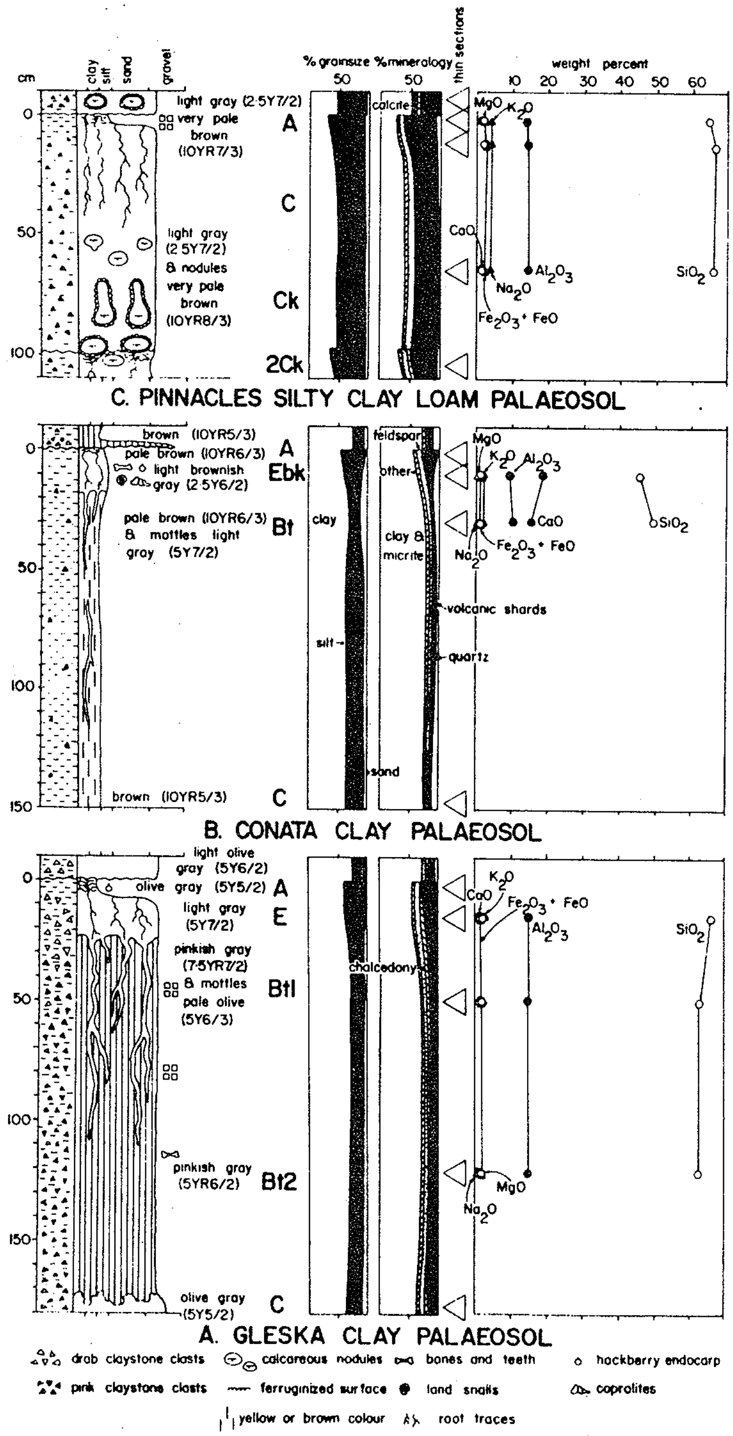

Figure 4. Columnar sections, grain size and mineralogical variation and chemical composition of selected paleosols: A, type Gleska clay paleosol (#3 of Retallack, 1983a), interpreted as a woodland soil of the Early Oligocene (Chadronian) Chadron Formation; B, type Conata clay paleosol (#22 of Retallack 1983a), interpreted as a savanna soil of the mid-Oligocene (Orellan) Scenic Member of the Brule Formation; C, type Pinnacles silty clay loam paleosol (#75 of Retallack, 1983b), interpreted as a prairie soil of the Late Oligocene (Arikareean) Sharps Formation.

granular structured rock with large manganese and drab haloed root traces (Ogi Series paleosol #76 of Retallack, 1983b). The manganese-rich part of the halo is probably due to poor drainage, as are manganese accumulations in soils generally (Birkeland, 1984). The drab part of the halo could have been created within the zone of chemical influence of the formerly living root or by local reduction associated with decay of the root after burial (Retallack, 1983b). I currently favor the latter interpretation, but by both hypotheses, these drab haloed root traces represent the last crop of trees on the paleosol. Older root traces would already have decayed in such well drained soils, and their influence on the surrounding soil would have waned at the time of burial. Considering these large drab-haloed root traces, the Ogi Series paleosol probably supported a few streamside trees. Other paleosols in the upper Poleslide Member and Sharps Formation are evidence of widespread open grassland and semi-arid climate.

Lower within the Tertiary sequence here, paleosols of the Late Oligocene Poleslide Member are mostly profiles with abundant fine root traces, scattered large drab-haloed root traces, and numerous large, potato-like, calcareous nodules (Figure 5). Unlike the paleosols higher in the sequence, these have slightly more clayey subsurface (Bt) horizons. These Wisangie Series paleosols (Retallack, 1983b) probably formed under savanna: trees scattered in grassland. There are a few Pinnacles Series paleosols in the uppermost Poleslide Member, an indication that trees were becoming more scarce with time. There are also some reddish bands: clayey layers which are slightly calcareous and still have some bedding despite the disruptive effect of fine root traces. These are Zisa Series paleosols and probably formed under streamside, early successional, herbaceous vegetation.

The climatic drying trend evident in this upper part of the mid-Tertiary sequence proceeded from semi-arid to arid during the Late Oligocene. Dunes and other desert deposits of latest Oligocene age are found in other parts of the Great Plains (Stanley, 1976). No sediment accumulated in this part of the Badlands at this time, but the large clastic dikes extending through the Sharps Formation and Poleslide Member here may be a legacy of this arid period. These deep (up to 60 m) clastic dikes are filled with silty ash, and show vertical bedding and striations, often stained by manganese in a way indicative of successive opening and closing. These are very similar to giant desiccation cracks, which can be seen in air photos of many modern desert playas (Retallack, 1983b). These are so large that their direction is often partly controlled by local structural features. The orientation of these dikes in the Badlands (Smith, 1952) is to some

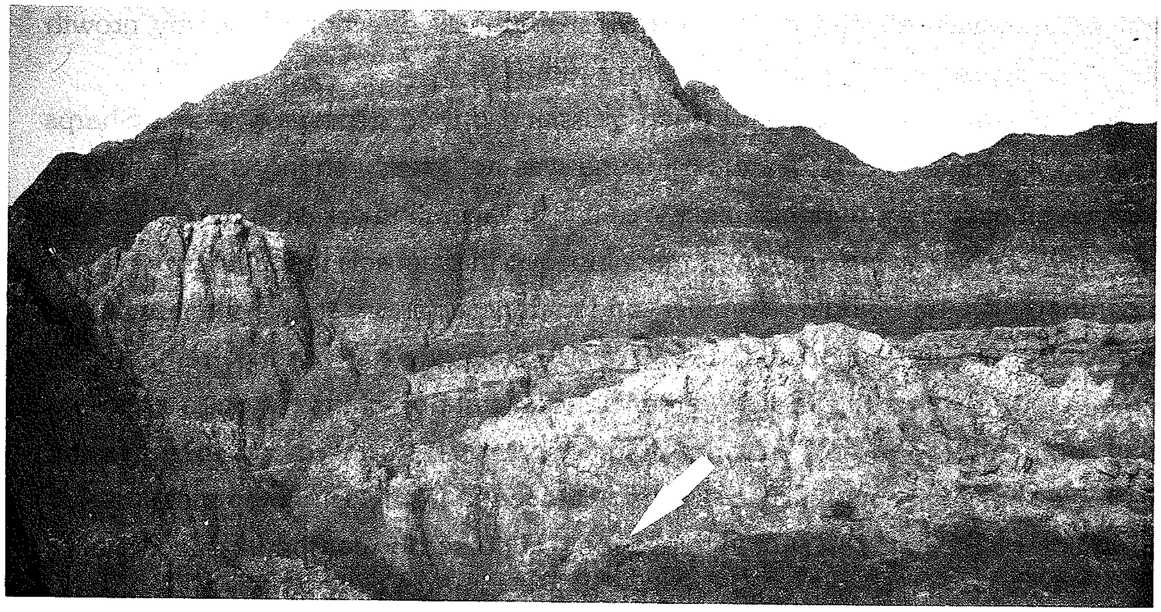

Figure 5. A Wisangie Series paleosol (in foreground, #49 of Retallack, 1983b) interpreted as a savanna soil of the Late Oligocene (Whitneyan) Poleslide Member of the Brule Formation, showing potato-like calcareous nodules, here prominent because wet by rain a few hours before the photograph was taken. The steep slope behind, including several similar paleosols, extends up to the stratigraphic level of the Rockyford Ash Member of the Sharps Formation. This small gully is 200 m south along the paved road from Early Life Overlook. The iron pipe of the exhumed bench mark in the foreground (at arrow) is about 4 cm diameter.

Figure 6. An enlarged view of rounded, equant (granular) units of soil structure (peds) outlined by iron-stained clayskins (sesquiargillans; at arrow) in places preferentially cracked, from the B horizon of the type Conata clay paleosol (#22 of Retallack, 1983b), interpeted as a savanna soil from the mid-Oligocene (Orellan) Scenic Member of the Brule Formation. Scale is in millimeters.

extent preferentially aligned in the northwest-southeast direction of nearby growth faults of the synsedimentary graben to the south.

Despite semi-arid climate and open grassland during deposition of the Sharps Formation, its earliest Arikareean fossil fauna was not greatly changed compared to that which enjoyed a more humid climate and lush vegetation earlier in the Oligocene. There are more burrowing forms and more burrows in paleosols in the Sharps Formation compared to the Poleslide Member, and many species are smaller than ancestral species in this region (Macdonald, 1963, 1970). Nevertheless, diversity remained as high as before (Prothero, 1985), a rather unusual state of affairs for open grassland faunas compared to those of savanna (Gregory, 1971). Furthermore, there was no discernable change in cursoriality of the ungulate fauna (as measured by metatarsal to femur ratios by Bakker, 1983) or in hypsodonty of horses (by comparing Macdonald's 1963, 1970, specimens with data on paracone height of M^3 of Badlands and other Great Plains fossil horses of Simpson, 1944). The "White River Chronofauna" (of Emry, 1981, including the Chadronian, Orellan, Whitneyan, and early Arikareean Land Mammal "Ages") appears to have persisted in the face of considerable environmental adversity. It was not to last. The especially arid climate of the latest Oligocene ushered in an essentially new fauna (late Arikareean), which was much more clearly adapted to open, grassy vegetation (Webb, 1977).

STOP 3 (see road log).--Near the pullout on the eastern (northbound) side of South Dakota Highway 240, the badland slopes come close to both sides of the road. These variegated red, pink, gray, and white sedimentary rocks are the Scenic Member of the Brule Formation.

Red paleosols (Zisa Series) are interbedded with white sandstones deposited in loosely sinuous, partly braided streams. These soils formed in the swales of levees and point bars, as can be seen in cross-sections of swales, across the gully a few hundred meters farther south down the road. As in examples from the overlying rocks already described, these red paleosols have fine root traces and considerable relict bedding. This latter feature is indicative of a short time of formation, too short for appreciable accumulation of calcium carbonate which would have made them pale in color like other paleosols of the Scenic Member. Zisa Series paleosols probably formed under early successional, herbaceous, streamside vegetation.

There are also some brown paleosols at this stratigraphic level thought to have formed under savanna. Some of these, at the base of the Scenic Member, lack the calcareous nodules of Wisangie Series paleosols. They are similar in other respects and have been called Conata Series paleosols (Retallack, 1983b; Figure 4B). Also thought to have formed under savanna were Ogi Series paleosols, which form a conspicuous orange band at the base of the Poleslide Member. Like other paleosols thought to have supported savanna, these have granular soil structure (Figure 6), abundant fine root traces, and scattered, large, drab-haloed, root traces. They are distinguished by their orange hue and conspicuous, thin zones of black, manganese stain within the rim of the drab root halos. Both their hue and manganese could be the results of formation in low lying parts of the floodplain, where floodwaters were slow to drain (Retallack, 1983b).

The most conspicuous paleosols here are Gleska Series (Figure 4A), within the green and pink claystones with thin, white limestone bands. The relationships of these various lithologies and colors, as revealed in excavations, are a succession of thick paleosols with gray-green eluvial (E) over reddish-brown illuvial (Bt) horizons and white stringers of limestone (petrocalcic horizons) within the lower horizons (Bk and Ck). These paleosols are so riddled with drab-haloed root traces that the upper part of the B horizon is mottled almost equally pink and green. This and their laterally continuous illuvial (Bt) horizons are indications that they supported woodland vegetation. It was an open, old growth woodland in most cases, because petrocalcic horizons of the kind preserved, form over many thousands of years in climates with annual rainfall in the subhumid range or drier (Gile *et al.*, 1966; Birkeland, 1984). Gleska Series paleosols separate brown savanna (Conata Series) paleosols from paleochannels in vertical sections, so probably formed streamside gallery woodlands within more widespread savanna. This local application of Walther's (properly Gressly's) Facies Law can be confirmed in places where Gleska paleosols can be traced laterally into Conata Series paleosols, as at Conata Picnic Ground south of here.

There are a variety of nonmarine trace fossils known from Badlands National Park. Some of the best preserved and understood are in the petrocalcic horizon of a Gleska Series paleosol (#30 of Retallack, 1983b) in the upper Scenic Member on the western side of the road (Figure 7). This paleosol and its trace fossils are along strike from those described in a gully 400 m southwest of here (Retallack, 1984a). The round balls of micritic limestone which are dislodged so easily upon hammering have been called *Pallichnus dakotensis* Retallack 1984a. They are interpreted as internal

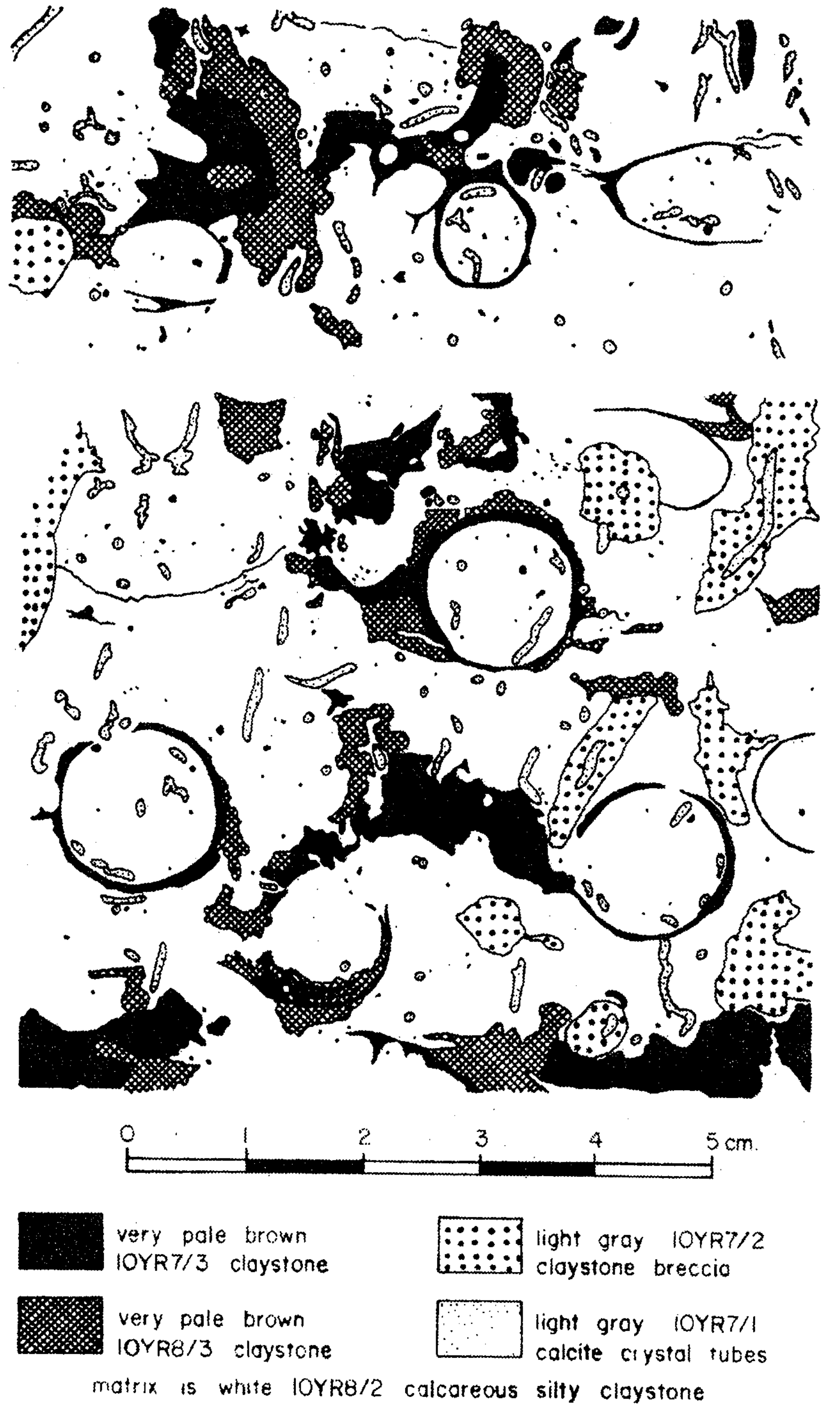

Figure 7. Sketches of vertically oriented, sawn slabs from the petrocalcic horizon of unnamed Gleska paleosol (#30 of Retallack, 1983b) in the mid-Oligocene (Orellan) upper Scenic Member of the Brule Formation, showing root traces (claystone breccia and calcite crystal tubes), and trace fossil larval cells and burrows (*Celliforma ficoides*) of sweat bees (above) and fossil pupal cells and burrows (*Pallichnus dakotensis*) of dung beetles (below), in each case outlined by brown claystone, presumably washed in from the overlying B horizon of the paleosol (modified from Retallack, 1984a).

molds of pupal cells of dung beetles, similar to those of living *Onthophagus* and *Geotrupes*. These beetles excavate branching burrows beneath dung pads, lay eggs at the ends of the branches, and then stuff the branches with dung. After sealing of the brood burrows, the eggs hatch into larvae which consume the provided dung. When fully grown, each larva constructs a cell for pupation from the surrounding soil, remaining dung, and larval faeces. This is abandoned by the young beetle which digs its way out to the surface. An irregular exit hole mars the otherwise spherical molds of these fossil larval pupal cells. There are also some tear-shaped structures with smoothly polished walls which have been called *Celliforma ficoides* Retallack 1984a. These are internal molds of larval cells very similar to those of sweat bees, such as living *Lasioglossum*. They are called sweat bees because of their annoying habit of gathering moisture from mammals. They do not depend on animals, however, and can gather water from any available source. Their larval cells are supplied with pollen and nectar for the developing larva. Both kinds of burrowing bees and beetles are most common and widespread in well drained, firm soils of subhumid climates. Both kinds of burrows found as fossils are neither the simplest or most complex kinds found in modern dung beetles and bees. They are indications of the initiation of some aspects of the coevolution of plants, insects, and mammals of open grassy woodlands that had not yet attained the degree of sophistication and interdependence seen in modern creatures of these habitats.

The vertebrate fauna (Orellan) of the Scenic Member has conventionally been regarded as savanna-adapted (Clark *et al.*, 1967; Webb, 1977). This is reasonable compared to preexisting Eocene forest faunas, which contained markedly less cursorial ungulates (Bakker, 1983) and slightly less hypsodont horses (Simpson, 1944). By comparison with the spectrum of feeding, locomotion, and body weight found in modern faunas, on the other hand, the mid-Oligocene carnivores (Van Valkenburg, 1982) and ungulates (Janis, pers. comm., 1984) are more like those of forest than of savanna. In the past, former vegetation of the Badlands has been interpreted from such data, on the implicit assumption that the organisms were more or less optimally adapted to their environment. Using information from fossil soils, it is no longer necessary to rely on such an assumption, which Gould and Lewontin (1979) have lampooned as the "Panglossian paradigm". Mid-Oligocene fossil soils of the Badlands are evidence of early successional meadows, streamside gallery woodlands, and widespread savanna. The mid-Oligocene fossil fauna of the Badlands is now seen as much less adapted to such vegetation than, for example, the big game of East Africa today.

Similar conclusions emerge from re-analysis of vertebrate fossils found in different kinds of paleosols. The idea that fossils found in these paleosols are close to where the animals died is supported by various lines of evidence (summarized by Retallack, 1983b): such as the already weathered appearance of excavated bone, rodent gnawing on excavated bone, and coprolites found around concentrations of bone reminiscent of "marking" by modern carnivores. From my re-evaluation of those paleosols yielding collections of fossil vertebrates made to assess former communities (by Clark *et al.*, 1967), savanna paleosols (Conata Series) contain largely rabbits (*Palaeolagus* 26%), squirrel-like rodents (*Ischyromys* 23%), and chevrotain-like deer (*Leptomeryx* 21% and *Hypertragulus* 17%). Woodland paleosols (Gleska Series), on the other hand, contain largely oreodons (*Merycoidodon* 31%) and horses (*Mesohippus* 24%). No fossils have been found in early successional paleosols (Zisa Series). Aquatic rhinoceroses (*Metamynodon*) are found in paleochannel sandstones and may have lived like the modern hippopotamus. The absence of bone in noncalcareous Zisa Series paleosols is probably related to its more acidic original pH. Gleska Series paleosols were probably only slightly less alkaline than Conata Series paleosols. Small bones are less likely to have been preserved in Gleska Series soils because of this less favorable preservational environment and the higher surface to volume ratio of smaller bones (Retallack, 1984b). This taphonomic bias also explains in part why the Gleska faunal assemblage deviates more markedly than the Conata faunal assemblage from the ideal relationship between abundance and size found in modern faunas (Damuth, 1982). This is one possible reason why the preserved savanna (Conata) fauna has more fossil mammals of smaller original body size than the preserved woodland (Gleska) fauna. It does not explain, however, why the savanna fauna was not appreciably better adapted to open country than the woodland fauna, as they are in East Africa today. Thus overall, as well as within its constituent communities, this Oligocene fauna appears to have been a very tentative early stage in the evolution of mammalian faunas of savanna environments.

STOP 4 (see road log).--Near the pullout along South Dakota Highway 240 where a short paved track leads east to a lookout, the lower portion of the White River Group is especially well exposed in gullies west of the road.

The drab, clayey mounds of the Chadron Formation, of Late Eocene to Early Oligocene age, contrast with the underlying, runneled, silty, yellow slopes of Pierre Shale, a Late Cretaceous marine deposit (Figure 8). The transition between marine Cretaceous and nonmarine Late Eocene deposits is represented by a thick, very strongly developed paleosol, which has obscured remnants of two intervening formations. The glauconitic and sandy beds in the uppermost Late Cretaceous rocks within the paleosol are interpreted as a thin remnant of Fox Hills Formation (Retallack, 1983b), which crops out extensively north of Wall, South Dakota (Waage, 1968). The uppermost part of the paleosol consists of interbedded sandstone and red, kaolinitic clay referred to the Slim Buttes Formation, better known from fossiliferous conglomerates in the Badlands and elsewhere in South Dakota (Clark *et al.*, 1967). More recent work on fossils from this unit in the Badlands (P.R. Bjork, pers. comm., 1985) casts some doubt on whether they were coeval with the fauna of the Slim Buttes Formation at Slim Buttes in northwestern South Dakota, which is Late Eocene ("Duchesnean" or earliest Chadronian of Emry, 1981) in age. Similar rocks in the Badlands are more likely younger (Chadronian) in age. The rocks themselves are distinct from the Chadron Formation, however, and so could be regarded as part of the Slim Buttes Formation or as a new formation. Large root traces penetrate the thin remnant of kaolinitic claystone and quartz sandstone here referred to the Slim Buttes Formation. Before final stabilization by these roots, this complex fossil soil was probably prone to sheet erosion, as is common in comparatively strongly developed soils today (Cady and Daniels, 1968). This fossil soil has been called the Yellow Mounds silty clay loam paleosol (Retallack, 1983b). It has a sandy, quartz-rich, near-surface horizon, with some relict bedding. Its subsurface (Bt) horizon is clayey, and its kaolinitic, base-poor composition contrasts with the smectitic parent material of the underlying Pierre Shale. Also, unlike Pierre Shale, the upper portion of the paleosol is noncalcareous. Some calcareous nodules, very highly weathered, have remained from the Pierre Shale 4 m below the surface, and there is also a thick weathered and ferruginized relict calcareous layer 5.3 m below the surface. The yellow weathered zone of the upper Pierre Shale extends for up to 27 m below the top of the paleosol, beyond which the unweathered shale is gray.

From these observations of this complex paleosol, the following geological sequence of events can be reconstructed (Retallack, 1983b). After withdrawal of the Late Cretaceous seaway from South Dakota, marine shale (Pierre Shale) was overlain by marine and deltaic deposits (Fox Hills Formation). With uplift and intrusion of the

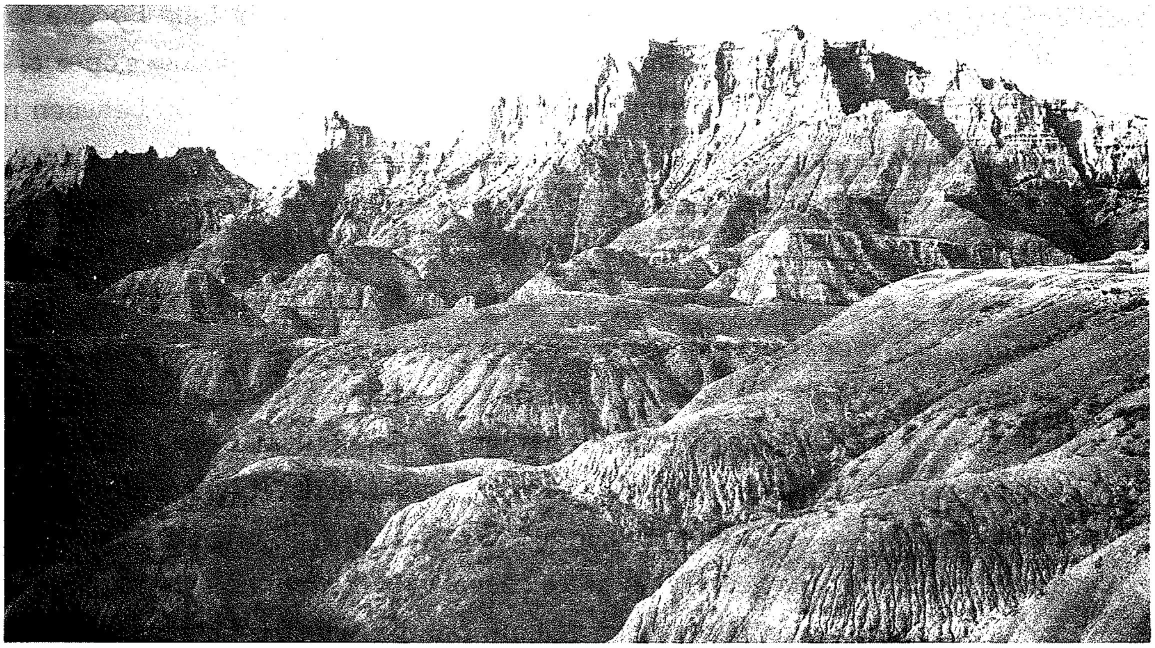

Figure 8. View of Badlands west of Stop 4, showing weathered uppermost Pierre Shale and remnant of Fox Hills Formation (runneled slope in foreground), sandy surface horizon of Yellow Mounds paleosol (light colored band in foreground), red clayey subsurface (B) horizon of Interior paleosol (dark band in foreground), clayey Chadron Formation (mound-like outcrops of foreground), Scenic Member of Brule Formation (dark and light banded cliffs in distance), Poleslide Member of Brule Formation (dark slopes in distance), and Sharps Formation (light colored sediments of distant hilltop).

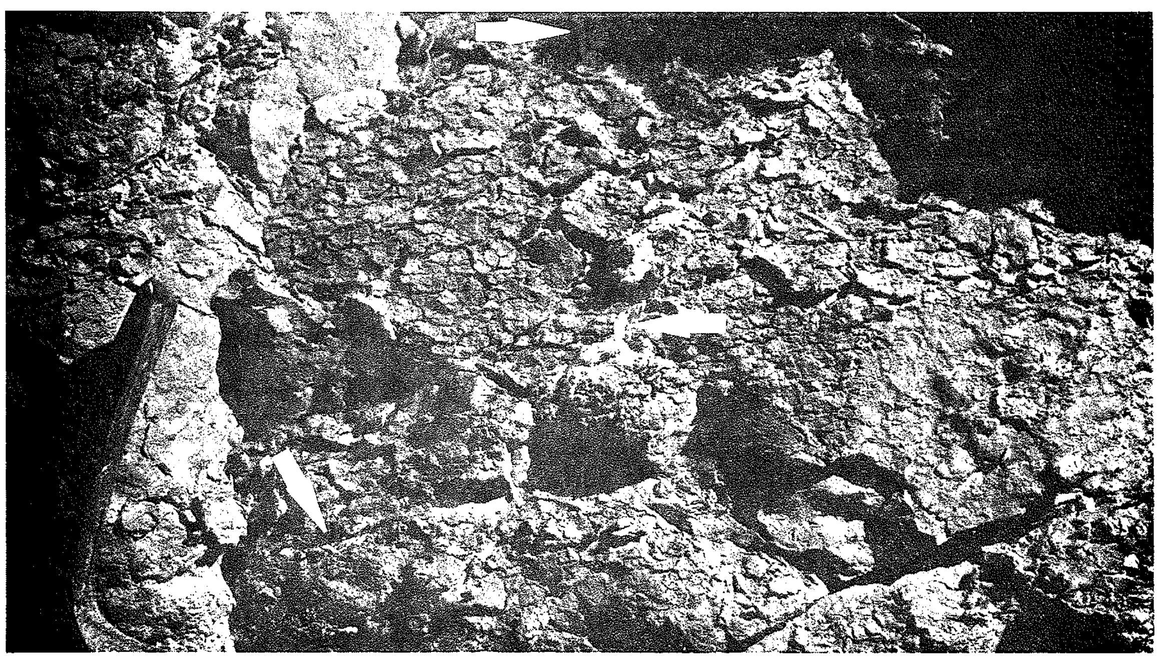

Figure 9. Large fossil root trace (at arrows) replaced by calcite, and with a gray-green reduction halo, in the purple subsurface (Bt) horizon of the type Gleska clay paleosol (#3 of Retallack, 1983b) in the gully beside the highway 200 m northwest of Stop 4.

nearby Black Hills during Paleocene and Eocene time, this became a hilly region from which much of the Cretaceous section was eroded. In this area only a thin (3 m) remnant of deltaic deposits remained overlying the marine shale. Deep forested soils developed on this well-drained hilly landscape. Prolonged weathering under forest in a humid climate resulted in the removal of soluble cations such as Ca^{++}, Mg^{++}, Na^{+} and K^{+} from the profile. The strongly differentiated subsurface clayey (Bt) and surface sandy (E) horizons sometimes proved unstable on the hilly slopes. By latest Eocene time, floodplain sediments began to accumulate on this eroded landscape, perhaps because of the initiation of subsidence within a broad graben extending southeast from the Black Hills. At this time, some of the partly eroded soils of the unconformity were again stabilized by forest, and the filling of the old hilly landscape with alluvial deposits (Slim Buttes Formation) began.

Immediately overlying the Yellow Mounds paleosol is another very strongly developed, red paleosol, the Interior clay (Retallack, 1983b). It forms the most prominent red band in the cliffs here. It is not certain whether it or the Yellow Mounds paleosol represents the "Late Eocene paleosol" mapped widely in South Dakota (Pettyjohn, 1966). Paleosols of this ancient erosional landscape are more complex than hitherto believed. The Interior clay is a similarly red, thick, and kaolinitic paleosol and also formed on a well drained, hilly landscape, under closed canopy woodland, in a humid climate. Remains of volcanic shards within this paleosol are an indication of initiation of eruptions of rhyolitic volcanic ash which forms most of the parent material for paleosols in the overlying sequence. The Interior clay formed on high land to the north of a deep (at least 18 m) valley, now filled with sediments of the lower Chadron Formation west of the town of Scenic in Indian Creek. The downcutting of this valley below the level of the Yellow Mounds paleosol into fresh Pierre Shales in Indian Creek is an indication that it was incised after formation of that paleosol. This was one of the major erosional episodes that punctuated the unsteady accumulation of sediments in this area. Most of these erosional episodes are suspected to have unearthed older fossils which were redeposited within the subsequent filling sequence. In the case of this early filling cycle this suspicion is proven by the occurrence of Cretaceous marine bivalves and ammonites within the nonmarine Interior clay and lowermost Chadron Formation at several localities in this region (Loomis, 1904; Ward, 1922). Erosional episodes entail not only resorting of fossils to confound paleontologists, but also produce ragged erosional unconformities within which it is difficult to assess the stratigraphic position of fossil finds. An unfortunate mistake made by early workers in this area was to record the stratigraphic position of titanothere skulls in feet stratigraphically above the Interior paleosol. When this was discovered to be a hilly erosional surface, a monumental prior study of the taxonomy and phylogeny of titanotheres lost much credibility (Clark, 1937).

Overlying the Interior clay paleosol are greenish-gray and purple claystones and white limestones of an Early Oligocene part of the Chadron Formation. This unit crops out poorly because the clays are smectitic, and thus swell after rain and crack while drying. Excavations through the surface weathered part of this sequence have shown that these rocks are largely claystone breccia, rather than claystone. The breccia clasts contain remains of root traces and mottles, and represent chunks of earlier paleosols redeposited by floods. Some of these breccia-laden floodwaters may have been almost as viscous as mudflows (Clark *et al.*, 1967), but they appear to have been too widespread, thin, and in an area of too low relief to actually have been mudflows in the strict sedimentological sense. At least 17 superimposed paleosols were found in the Chadron Formation in this area. One of these has a dark surface (A) horizon full of fine root traces over a little altered subsurface (C) horizon. This Ohaka Series paleosol (Retallack, 1983b) probably supported early successional vegetation. The others all have greenish gray surface (E) horizons extending down into purple subsurface (Bt) horizons. Many of these Gleska Series paleosols, especially those higher within the Chadron Formation, have a white calcareous (calcic) horizon at depth. The green is thought to be due to post-depositional bacterial reduction of organic matter within the profile. The purple color may be redder than originally because of dehydration of iron oxyhydrate minerals. The original soils can thus be envisaged as clayey, especially below the surface, with gray, slightly organic surface (A and E) horizons and brown iron-stained subsurface (Bt) horizons. This kind of profile, together with the abundance of large root traces (Figure 9) and comparisons with modern soils, are evidence of woodland vegetation. The smectitic composition of the clay and presence of calcium carbonate horizons are evidence of a much drier climate than that previously. It was still wet enough to weather most volcanic ash to clay. Presumably climate was subhumid and perhaps also cooler (more like warm temperate) than before.

Few fossils are found in paleosols at this low level of the Badlands sequence, presumably because soils were not yet alkaline enough for the preservation of abundant bone (Retallack, 1984b), among other reasons. Most of the fossil bone found in the local Slim Buttes (Duchesnean of Clark *et al.*, 1967; more likely early Chadronian according to P.R. Bjork) and Chadron (Chadronian) Formations has been found in paleochannels and closely associated sediments little altered by soil formation. The demise of subtropical wet forests at the transition between these formations is coincident with a major faunal overturn from archaic to discernably more modern faunas (the "White River Chronofauna" of Emry, 1981). There are few likely ancestors for most of this new fauna among older North American mammals. It appears to have immigrated from more open country elsewhere rather than evolving locally. Among the new mammals, many are similar to Asiatic Eocene forms (Emry, 1981; Bakker, 1983). The three lowest paleosols in the sequence have been interpreted to represent changes from humid, well drained forest to less humid, well drained closed canopy woodland to subhumid lowland closed canopy woodland. The change in vegetation was not initially profound and may have been gradual or a graded series of changes. This may be contrasted with the profound overturn of vertebrate faunas, thus supporting the traditional idea that this new fauna immigrated, rather than having evolved locally.

CONCLUSIONS

The view espoused here that the mid-Tertiary sequence in Badlands National Park and other similar variegated and red bed sequences are piles of fossil soils has a number of consequences for stratigraphic, taphonomic, paleoecological, and evolutionary studies of vertebrates. Such studies of the future will depend on wider recognition of paleosols. Familiarity with modern soils and their characteristics does help, but in addition there are three general criteria useful for differentiating fossil soils from enclosing sedimentary deposits: root traces, soil horizons, and soil structure.

Fossil root traces are best preserved in formerly waterlogged paleosols. In oxidized paleosols, like those of Badlands National Park, organic matter is not preserved and root traces are filled with clay, calcite, or other materials (Figure 9). In such cases, root traces must be recognized from their general features of irregular, tubular shape, tapering and branching downward. Often, they are crushed like a concertina because of compaction of the surrounding paleosol during burial. The top of a paleosol may be recognized where root traces and other trace fossils are truncated by an erosional surface.

Soil horizons usually have more gradational boundaries than seen in sedimentary layering (Figure 3). These gradational changes show a fixed relationship to the truncated upper surface of the paleosol. Diffuse subsurface horizons of red claystone (illuvial, argillic, or Bt horizons) or of calcareous nodules (calcic or Ck horizons) are good examples in Badlands National Park.

Soil structure appears massive and jointed compared to sedimentary layering, metamorphic foliation, and igneous crystalline textures. The basic units of soil structure (peds) are defined by a variety of modified (for example, iron-stained or clayey) surfaces (cutans). Peds of woodland paleosols in the Badlands are commonly subangular, irregularly shaped (blocky), moderately sized (more than 5 cm) and defined by slickensides. Within grassland (savanna and prairie) paleosols the peds are smaller (5 to 10 mm) and more equant and rounded in shape (granular; Figure 6). Calcareous nodules and nodular layers are also original structures of many Badlands paleosols.

Complications to be considered during field recognition of paleosols include the erosion of parts of profiles before burial, overlap of horizons of different paleosols, development of paleosols on materials eroded from preexisting paleosols, and the development of paleosols under two successive and different regimes of weathering. In the Badlands, these complications were found to be most severe near major disconformities which generally coincide with boundaries of recognized rock units. For the rest of the sequence paleosols are more easily recognizable, especially when the slopes are trenched beyond the zone of modern weathering.

Recognition is only the first step in a study of paleosols. Later phases in the interpretive study of paleosols cannot be described in so few words. The following outline of four particularly promising lines of research involving vertebrate fossils and paleosols discussed during this excursion may indicate why such detailed interpretive studies are worth the effort.

Paleosols may be used to assess the resolution of vertebrate biostratigraphy. In the Badlands there is considerable evidence that bones littered ancient land surfaces and were little transported from where the animals died. Since the time for formation for most of the paleosols was less than a few thousand years, such assemblages provide a better basis for biostratigraphy than bones within paleochannels. Major erosional disconformities are also evident from paleosols, because paleosols become better developed, overlap underlying paleosols, and are more severely eroded beneath major disconformities. Calculations of the temporal resolution of the Badlands sequence, using time for formation of analogous modern soils, have shown that only at time spans of a million years or so can the sequence be regarded as acceptably complete. Major temporal disconformities were recognized between each major rock unit. These represent cutting and filling cycles with a duration of about 2 million years. Each episode of erosional downcutting provided opportunity for recycling of previously fossilized vertebrate remains into younger rocks. Such recycled vertebrates should be largely confined to paleochannels and to the basal portion of flood deposits on which the paleosols formed.

Paleosols are especially useful as indicators of paleoenvironment because they are independent of other indicators such as vertebrate fossils. They provide evidence of ecosystems where vertebrate fossils are not preserved, as well as where they are. Each kind of paleosol represents a taphonomic or burial environment, as well as a living or surficial one. In the Badlands bone is largely found in calcareous paleosols of the middle and upper portion of the sequence. These soils presumably formed in a dry climate and had an alkaline reaction suitable for the preservation of bone.

The variety of paleosols at each stratigraphic level reflects the diversity of subenvironments within ancient landscapes. Variations in assemblages of fossil vertebrates within different paleosols may thus provide clues to the habitat specificity of particular species and to the nature of former communities. Complications such as seasonal migration, catastrophic death assemblages, or the scattering of bone by sheetwash, may confound attempts to reconstruct communities exactly. Nevertheless, assemblages of fossils in paleosols provide more promising materials for paleoecological reconstructions than bones transported within paleochannels. In the Badlands, for example, reappraisal of prior paleoecological studies in the middle part of the sequence have revealed differences in vertebrate faunas from paleosols of contemporaneous woodland and savanna.

Many features of paleoenvironments have been interpreted from the degree of adaptation of animal fossils. For example, high-crowned teeth and elongate forelimbs with a reduced number of digits, as in modern horses, have been taken to infer open grassy vegetation. Such inferences assume unrealistically that the animals were optimally adapted to their environment. Using independent evidence of paleoenvironments from fossil soils, it is now possible to assess the degree to which animals were maladapted to their environment. Although long regarded as a savanna-adapted fauna, mammals of the Badlands ("White River Chronofauna") show a range of adaptations more like modern forest faunas. From fossil soil studies, it is now known that this fauna thrived in savanna environments during mid-Oligocene time and persisted with little modification in Late Oligocene open grassland. Although many of the coevolutionary linkages between plants, insects, and mammals found in modern grassland ecosystems can be documented in these early grassland fossils, these interactions were much less sophisticated than in modern grasslands. In this sense the "White River Chronofauna" can be seen as a tentative early attempt in the evolution of grassland ecosystems.

These four kinds of studies involving vertebrate fossils and paleosols have been attempted only in a preliminary way. Although the Badlands of South Dakota and Nebraska have been a focus for Oligocene vertebrate paleontology for more than a century, the scientific potential of this spectacular rock and fossil record is far from exhausted.

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