A pedotype approach to latest Cretaceous and earliest Tertiary paleosols in eastern Montana

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ABSTRACT

A pedotype approach to the study of paleosols emphasizes individual profiles. It is an alternative approach to the study of geosols, which are laterally extensive suites of paleosols, or pedofacies, which are pedogenically distinctive sedimentary facies. This is the first pedotype study of paleosols across the Cretaceous-Tertiary boundary in eastern Montana.

Pedotypes allow assessment of sedimentation and fossilization. The sequence of paleosols across the Cretaceous-Tertiary boundary at Bug Creek is one of high temporal resolution, because most available geological time can be accounted for by differing degree of development inferred for each pedotype. Paleosols at Bug Creek include pedotypes that preserve plant fossils well, but were unfavorable for preservation of fossil vertebrates.

Pedotypes also allow reassessment of ecosystem change. Despite indications of catastrophe at the Cretaceous-Tertiary boundary, the array of Paleocene and Cretaceous pedotypes are not strikingly different. The Upper Cretaceous Hell Creek Formation includes pedotypes interpreted as gleyed Alfisols, Inceptisols, and Entisols probably formed under seasonally waterlogged forest and mean annual rainfall of the order of 900–1200 mm. Most paleosols of the lower Paleocene Tullock Formation were Histosols, but some can be interpreted as gleyed Inceptisols and Entisols probably formed under bald cypress swamps in a humid climate with >1200 mm mean annual rainfall. Broadly comparable pedotypes were present before and after the Cretaceous-Tertiary boundary, although Paleocene flood-plain forest lived in paleosols chemically a little more oligotrophic than Cretaceous paleosols. This modest difference supports the idea that change to coaly facies in the earliest Paleocene was a local shift in sedimentary environment. Such local changes do not begin to account for profound disruption in specific composition of plant and animal communities at the Cretaceous-Tertiary boundary in eastern Montana.

INTRODUCTION

Pedotype is a new term for an old concept. It is simply a kind of soil or paleosol as recognized in the field. This new term replaces *paleosol series* (Retallack, 1977, 1983, 1990, 1991a). In soil science, the term *soil series* has unfortunate dual usage both as a descriptive local mapping unit (Soil Survey Staff, 1951, 1962) and as the lowest rank in an interpretive system of soil classification (Soil Survey Staff, 1975, 1990). In geology, *series* is something else again: a high-ranking chronostratigraphic unit also named after a locality (North American Commission on Stratigraphic Nomenclature, 1983).

Pedotypes are based on individual profiles of paleosols designated as type profiles. Reference of additional profiles to the same pedotype constitutes a nongenetic field classification of paleosol types. Pedotypes can be named after localities where they occur or from other descriptive features. Inferences of genesis or interpretation are avoided in the naming of pedotypes. The emphasis on profiles, or what in soil science is called a *pedon*, distinguishes the pedotype approach from geosol and pedofacies approaches, which are designed for lateral mapping of paleosols and paleosol features. Geosols are mappable ancient land surfaces, including suites of laterally contiguous pedotypes or soil facies (Morrison, 1978). Pedofacies, on the other hand, are sedimentary facies dominated by features of one or more paleosols, and so include sediments as well as paleosols (Bown and Kraus, 1987).

Pedotypes, geosols, and pedofacies represent alternative nongenetic approaches to the field mapping of paleosols, which are illustrated here with a detailed example of latest Cretaceous and earliest Tertiary paleosols of eastern Montana. The geosol concept has been employed in eastern Montana, though not formally acknowledged as such, in the lateral mapping of coal beds, which are organic horizons of peaty paleosols (Smit and others, 1987; Rigby and Rigby, 1990). The documentation of selected paleosol features of these Cretaceous-Tertiary paleosols to support recognition and interpretation of sedimentary facies (Fastovsky and McSweeney, 1987; McSweeney and Fastovsky, 1987; Fastovsky and others, 1989) constitutes a pedofacies approach, although again not formally acknowledged as such. In this paper I employ a pedotype approach for the first time to characterize numerous complete paleosol profiles at Bug Creek with field, chemical, and petrographic data.

The pedotype approach is especially suited to reconstruction of paleoenvironments. Each pedotype can be considered a trace fossil of a different kind of local ecosystem as well as an indicator of other paleoenvironmental conditions. Such an interpretive approach can be called *ecosystem paleopedology*. This is distinct, yet complementary to other interpretive approaches previously applied to Cretaceous-Tertiary sediments of eastern Montana, including facies sedimentology (Fastovsky, 1987, 1990; Fastovsky and Dott, 1986) and community paleoecology (Estes and Berberian, 1970; Archibald, 1982; Van Valen and Sloan, 1977; Archibald and others, 1982; Archibald and Lofgren, 1990; Sloan and others, 1986; Rigby, 1987; Rigby and others, 1987; Sheehan and others, 1991; Sheehan and Fastovsky, 1992). This paper documents previously unrecognized paleosols interpreted as

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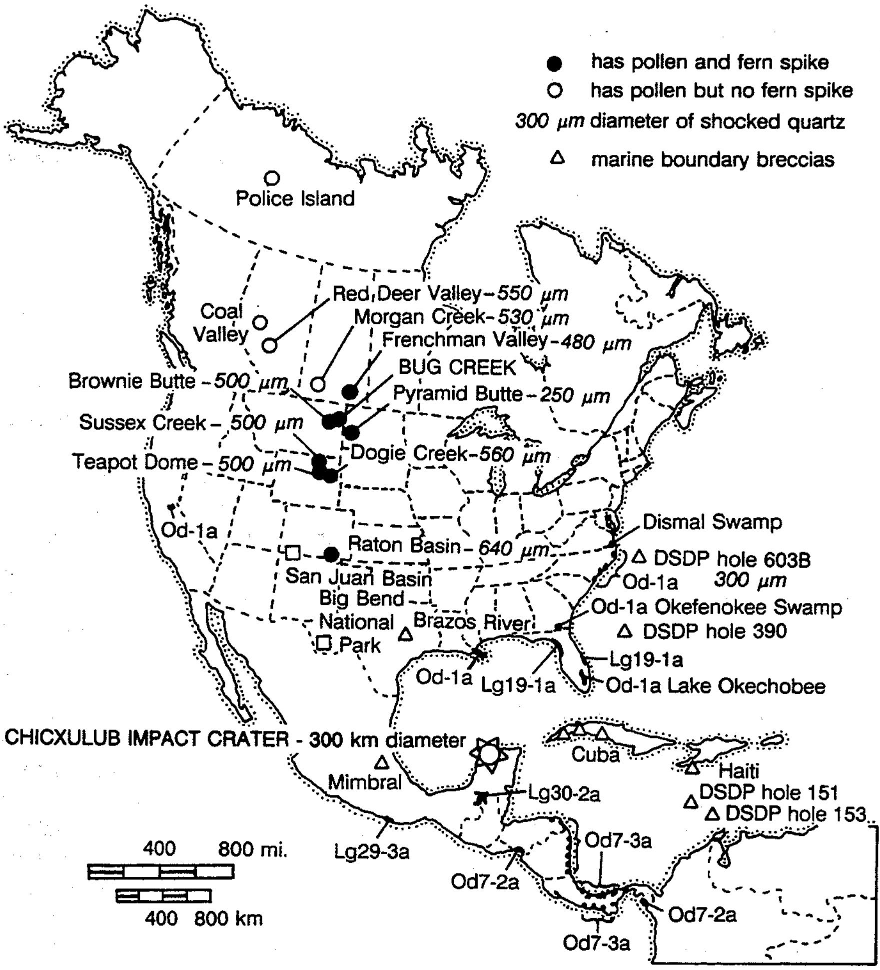

Figure 1. Location of Bug Creek and other mentioned localities and indicators of the Cretaceous-Tertiary boundary in North America (data from Fassett and Rigby, 1987; Lehman, 1987, 1990; Izett, 1990; Sweet and others, 1990; Nichols and Fleming, 1990; Hildebrand and others, 1991; Izett and others, 1993). Black areas with codes such as Od-1a are soil map units of the Food and Agriculture Organization (FAO) of UNESCO (F.A.O., 1975a, 1975b) comparable with Cretaceous and Paleocene paleosols at Bug Creek.

moderately developed and well drained, in addition to the weakly developed and swampy paleosols that have limited past paleoenvironmental interpretation of paleosols here. Interpretations of pedotypes are used to reassess prior reconstructions based on other lines of evidence. Such interpretations, in combination with those based on sedimentary facies and community paleoecology, allow detailed understanding of landscapes and life across the Cretaceous-Tertiary boundary in eastern Montana.

GEOLOGICAL SETTING

There is now general agreement on the basic distribution of rock types and their geological age at Bug Creek, McCone County, Montana (Figs. 1 and 2). My field mapping and fossil collecting in the paleontologically critical area (Fig. 3) have been influenced especially by mapping of local coal seams (Rigby and Rigby, 1990), sedimentary facies (Fastovsky and Dott, 1986), paleochannels (Smit and others, 1987), suites of paleosols (Retallack and others, 1987), and for some poorly exposed units, the soil survey of McCone County (Strom, 1984). Lack of outcrop has been blamed for past disagreements, but there are extensive badlands exposures in the cliffs and gullies of this dry open rangeland (Figs. 2 and 3).

The Cretaceous-Tertiary boundary can be located by palynological changes in the lowest Z coal seam (Norton and Hall, 1969; Hotton, 1988). An insignificant Ir anomaly of 5 ppb was discovered by Carl Orth 10–20 cm below the base of the lowest Z coal (Rigby and others, 1987; Smit and others, 1987). More pronounced concentrations of Ir, shocked quartz, and fern spores at the boundary are known around Brownie Butte, Montana, some 75 km west (Smit and others, 1987; Hotton, 1988; Fastovsky and others, 1989), and elsewhere in North America (Fig. 1). The Ir-bearing coals near Brownie Butte have been radiometrically dated using a variety of techniques at 65.16 ± 0.4 Ma, which is within paleomagnetic Chron 29R (Archibald and others, 1982; Izett and others, 1991; Swisher and others, 1994).

Fossil mammals from the sandstone paleochannel of Bug Creek anthills have been thought to be latest Cretaceous (Sloan and Van Valen, 1965; Van Valen and Sloan, 1977; Rigby, 1987) but are now regarded as earliest Paleocene (Russell, 1977; Smit and others, 1987; Archibald and Lofgren, 1990; Archibald and Bryant, 1990; Lofgren and others, 1990), an interpretation supported by my mapping (Fig. 3). There also have been problems in local definition of the lithostratigraphic boundary between gray claystones of the Hell Creek Formation and lignites of the Tullock Formation of the Fort Union Group (Rigby and others, 1987; Smit and others, 1987; Rigby and Rigby, 1990). Here, the Hell Creek–Tullock contact is taken as the base of the lowest of the Z coals, or the base of any paleochannel, such as the Big Bugger, that has eroded down from the Tullock Formation into the underlying Hell Creek Formation (Retallack and others, 1987; Swisher and others, 1994).

FEATURES OF THE PALEOSOLS

Features used to identify paleosols in the Cretaceous-Tertiary boundary beds of Montana have been reported elsewhere (Fastovsky and McSweeney, 1987; McSweeney and Fastovsky, 1987) and need only be outlined here. Paleosols in these coal-bearing sequences are recognized primarily from root traces, which commonly have carbonaceous material and some cell structure preserved. Surface horizons of paleosols are below the truncated surfaces from which root traces emanate (A horizon of Soil Survey Staff, 1975) or the surface of coal seams (O horizon). Subsurface horizons of paleosols include rocks rich in clay skins and iron staining (Bw or Bt horizons) and levels rich in sideritic or pyritic nodules (Bg horizons). Although many of these paleosols are weakly developed with much relict bedding

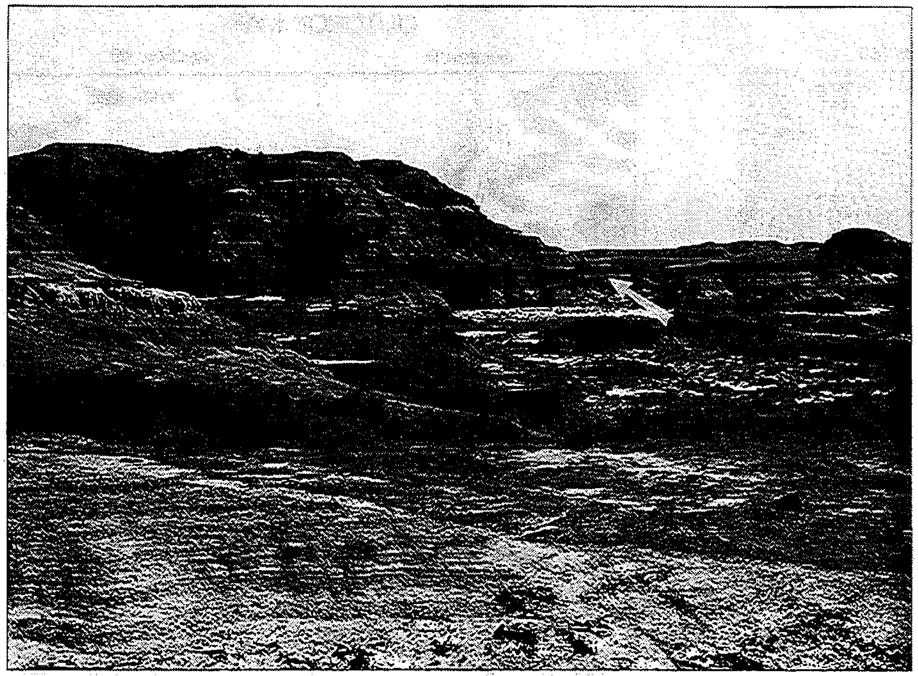

Figure 2. View east toward cliffs and knoll of measured section at Bug Creek, McCone County, Montana. Arrow indicates level of Cretaceous-Tertiary boundary.

preserved, several profiles in the Hell Creek Formation and a few in the Tullock Formation show that original sedimentary features were obliterated by development of complex patterns of clay-coated cracks and iron stain (peds and cutans of Brewer, 1976).

ALTERATION OF THE PALEOSOLS AFTER BURIAL

Modifications of paleosols after burial can compromise their paleoenvironmental interpretation but are becoming increasingly well understood (Retallack, 1991b). Clayey parts of these paleosols contain amounts of organic matter comparable with modern soils (Figs. 5–8; see also Fastovsky, 1987, Table 3), and some of the paleosols include coal seams, so that substantial burial decomposition of organic matter is unlikely. None of the paleosols is red, or affected by burial reddening (Fastovsky and McSweeney, 1987).

Cementation with calcite during burial is likely in sandy paleochannels and paleosols, where the calcite is sparry and fills natural voids (McSweeney and Fastovsky, 1990, Fig. 4), unlike replacive and displacive micritic calcite, which is taken to be pedogenic (McSweeney and Fastovsky, 1990, Fig. 6; see also discussion of Retallack, 1991a, 1991b). Sparry calcite cementation was probably early during burial, because large "log" nodules of locally cemented paleochannels weather to hoodoos or toadstools oriented with paleocurrents (Archibald, 1982; Rigby and Rigby, 1990) and occasionally contain little compacted, articulated skeletons of dinosaurs (Brown, 1907; Fastovsky, 1987).

The Cretaceous-Tertiary boundary at Bug Creek is covered by 70 m of Tullock Formation (Rigby and Rigby, 1990). Basinwide, however, the boundary was covered by as much as 600 m of Paleocene and Eocene sediments before middle Eocene erosion of valleys within which geologically younger sediments accumulated (Cherven and Jacob, 1985). This shallow burial would give peak burial temperatures of ~40 °C using a typical geothermal gradient of 25 °C/km, and this is compatible with the observed coal rank of the lignites. Late Cretaceous and Paleocene coals of this region have calorific values of 6.4–6.9 kcal/g (11 480–12 500 Btu/lb) (Collier, 1924; Bauer, 1924; Hares, 1928; Collier and Knechtel, 1939), which fall within the subbituminous to high volatile bituminous ranks of Teichmüller (1987). A similar rank is likely for the lignites of Bug Creek, for which I determined an average bulk density of 1.66 g/cm^3 (range 1.19–2.11, $2\sigma = 0.54$, $n = 21$). Low rank also explains the pale color of fossil pollen, which had to be stained for study (Hotton, 1988). Under these conditions lithostatic compaction would be minimal: 75% of original thickness for shales and 88% for sandstones, using the standard curves of Baldwin and Butler (1985). Compaction of these coals to 25% of original peat thickness has been proposed by Cherven and Jacob (1985), and this is a maximum compaction considering the observed coal rank (Elliott, 1985).

Illitization of clays would not be expected under such burial depths, and indeed no surficial enrichment in potash was seen in the paleosols. The clays of the paleosols are mainly mixed layer illite/smectite, with minor amounts of kaolinite and illite (Fastovsky, 1987). Pure illite is largely found in silty and sandy rocks associated with paleochannels and so is more likely detrital in origin, rather than altered during burial from pedogenic smectite (Bell, 1965).

The badlands slopes of Bug Creek have a thin (~20 cm) surface of popcorn weathering (Rigby and Rigby, 1990), which can be regarded as a weakly developed Yawdim soil of Strom (1984). Paleosol samples were taken from trenches some 50 cm to 1 m below the surface at the point where coherent samples could be obtained. Nevertheless, scarlet ferruginized nodules and reddish-brown coaly layers were seen in the paleosols. On especially deep excavation these proved to be oxidized at the present outcrop from dark gray siderite nodules and friable coals. Similarly, surface crystals of gypsum associated with a yellow powder of jarosite (Rigby and Rigby, 1990) are due to surface weathering of pyrite and carbonate, as elsewhere in the western United States (Retallack and Dilcher, 1981).

CHARACTERIZATION OF THE PEDOTYPES

Seven pedotypes were recognized in the upper Hell Creek Formation and lower Tullock Formation in seven trenches excavated to show continuous exposure over the Cretaceous-Tertiary boundary at Bug Creek (Fig. 4; Tables 1 and 2). Selected examples of pedotypes recognized in the field were characterized in detail with petrographic and chemical data (Figs. 5–8). The seven pedotypes at Bug Creek are also recognizable from past descriptions of paleosols elsewhere in Montana and the Dakotas and may be useful throughout the Williston Basin (Fastovsky, 1987; Fastovsky and McSweeney, 1987; McSweeney and Fastovsky, 1987; Rigby and others, 1987; Hotton, 1988; Johnson, 1989). Because of a shortage of place names in the Bug Creek area, pedotype names are descriptive terms from the

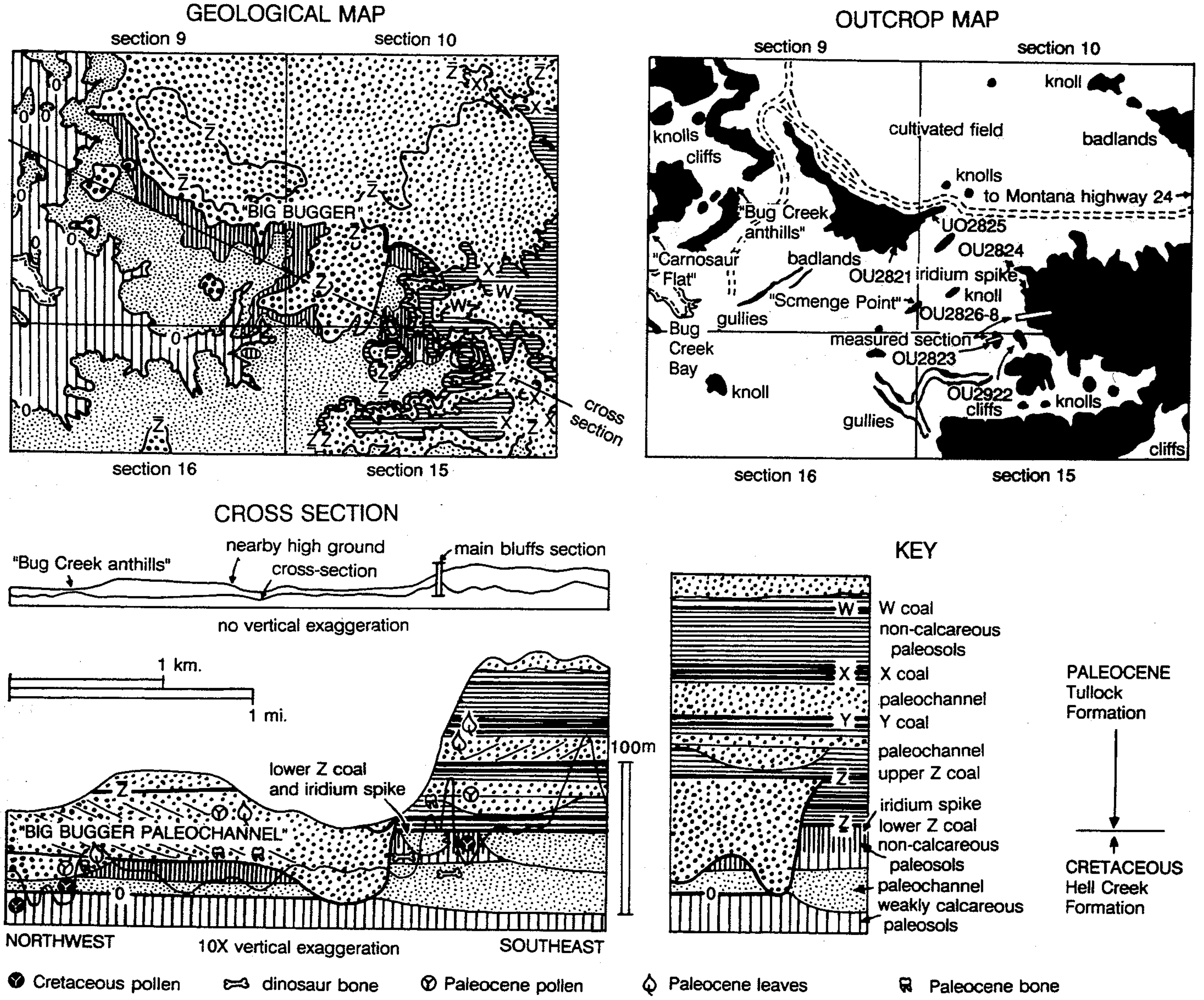

Figure 3. Geological sketch map, outcrop map, lithologic key, and cross section (clockwise from top left) at Bug Creek (T. 22 N., R. 43 E., McCone County), Montana. Black areas in outcrop map represent exposures. Numbers prefixed by OU are assigned to Condon Collection of the University of Oregon fossil localities collected during this study.

local Blackfoot Indian language (Frantz and Russell, 1989).

A standardized graphic and descriptive format has been used for each kind of paleosol (Figs. 5–8). Colors were estimated using charts of the Munsell Color Company (1975) and taken within a few minutes of exposure in the trenches. The lithologic logs include a graphic representation of mean grain size from field work, but a separate plot of percent clay, silt, and sand also was derived from point counting petrographic thin sections using the grain-size scale of soil science (Soil Survey Staff, 1975). This gives an abundance of common minerals (20%–80%) with an error (2σ) of ~4% by volume for the 500 points counted for every specimen (Van der Plas and Tobi, 1965; Murphy, 1983). These data are portrayed in narrow columns so that only differences ≥4% will appear as recognizable trends. Clay has been placed to the left in both textural and mineral plots, and in the latter, progressively more weather-resistant minerals are plotted to the right.

Chemical analyses were obtained using atomic absorption, with error calculated from 10 replicate analyses of standard rock W2. These results were supported by neutron activation analysis. Organic carbon values were determined using the Walkley-Black titration (of Nelson and Sommers, 1982), with error estimated from 50 replicate analyses of a standard soil. Bulk density was calculated from weight difference suspended in water of paraffin-coated clods, with error estimated from 10 replicate analyses of specimen R602. These and other raw data have been placed in the GSA Data Repository.[1] Molecular (also called molar)

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[1] GSA Data Repository item 9425, raw data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

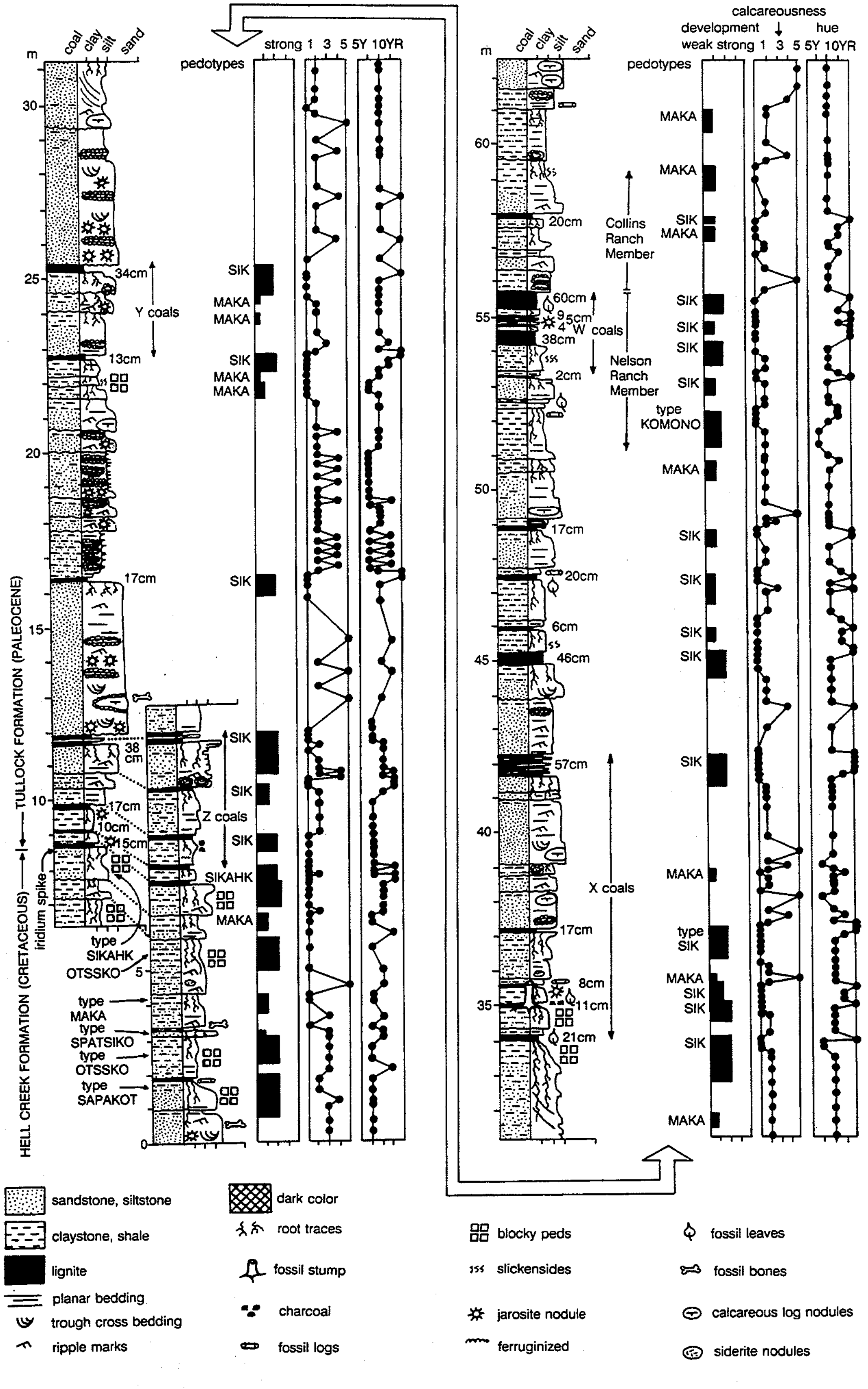

Figure 4. Measured section of paleosols across the Cretaceous-Tertiary boundary in the cliffs and a low knoll north of Bug Creek (NW¼ NW¼NE¼ sec. 15, T. 22 N., R. 43 E., McCone County), Montana. Scales of development estimated from subsurface enrichment in clay and surface accumulation of peat, and of calcareousness from reaction with dilute acid are from Retallack (1990) and hue from charts of Munsell Color Company (1975).

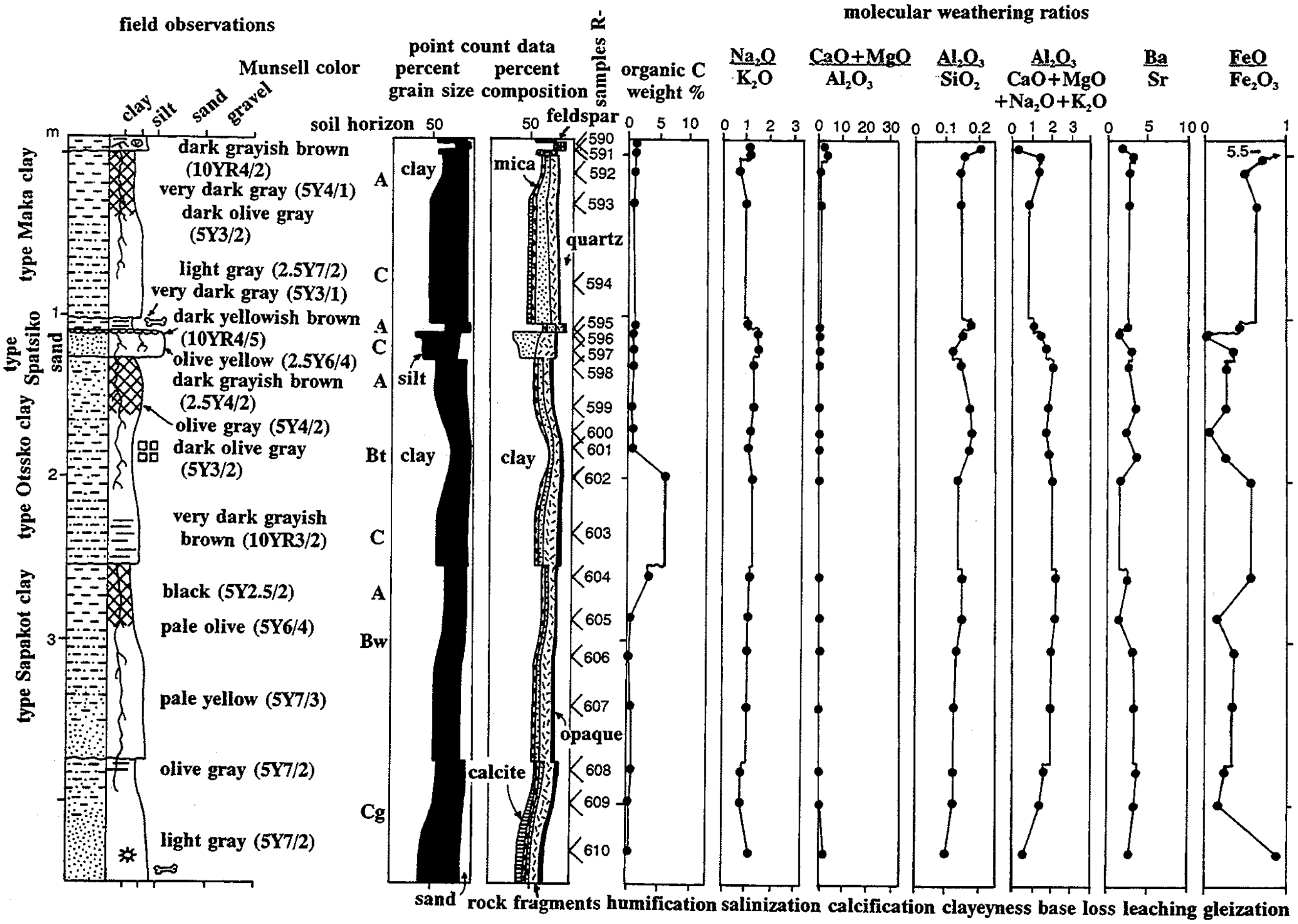

Figure 5. Measured section, Munsell colors, soil horizons, grain size, mineral composition, organic carbon, and selected molecular weathering ratios of the type Sapakot clay, type Otssko clay, type Spatsiko sand, and type Maka clay paleosols in the upper Hell Creek Formation, within a knoll west of the main bluffs north of Bug Creek, Montana. This is at 0–4.5 m in Figure 4. Lithologic key is after Figure 4.

weathering ratios were calculated by normalizing weight percent to atomic weights, an approach that avoids assumptions about parent material or stable constituents (Retallack, 1990, 1991a).

The paleosols studied contain a variety of fossils ranging from dinosaur bones to pollen grains. Fossils collected during the present work are in the Condon Collection of the University of Oregon. These and previously published collections of fossils from the various pedotypes are summarized in Table 3.

INTERPRETED PALEOENVIRONMENTS OF THE PALEOSOLS

Each pedotype recognized represents a local paleoenvironment, which can be interpreted using two distinct approaches. One way to try to understand the formation of these ancient soils is to identify them in a classification of modern soils (Table 2) and make direct comparisons with similarly identified modern soils or suites of soils. Four separate soil classifications have been used (Soil Survey Staff, 1975; F.A.O., 1974; Stace and others, 1968; Northcote, 1974). Unlike the classification of paleosols by Mack and others (1993), these classifications allow specific comparisons within the vast descriptive literature on soils and embrace a variety of perspectives on soils (Retallack, 1990, 1993).

Another approach for interpretation of paleosols is the factor-function approach popularized by Hans Jenny (1941), whereby specific soil-forming factors such as climate, vegetation, paleotopography, parent material, and time for formation can be inferred from specific features of paleosols thought to be controlled by these factors in soils (Retallack, 1990, 1994). Table 3 is a summary of such paleoenvironmental interpretations of each pedotype, and a general interpretation for each stratigraphic level is given in the following paragraphs.

Late Cretaceous

Paleoclimate. The Bug Creek area during Late Cretaceous time was probably humid, because all the paleosols that were moderately well drained (with clay skins and deeply penetrating root traces) are also deeply weathered (low alkaline earth:alumina and high alumina:bases ratios). Nevertheless, a very humid climate is unlikely, because carbonate clasts persist in paleochannels and deep within some paleosols, and none of the paleosols appear podzolized (with quartz-rich eluvial horizons, or Ba:Sr ratios approaching 10). In the

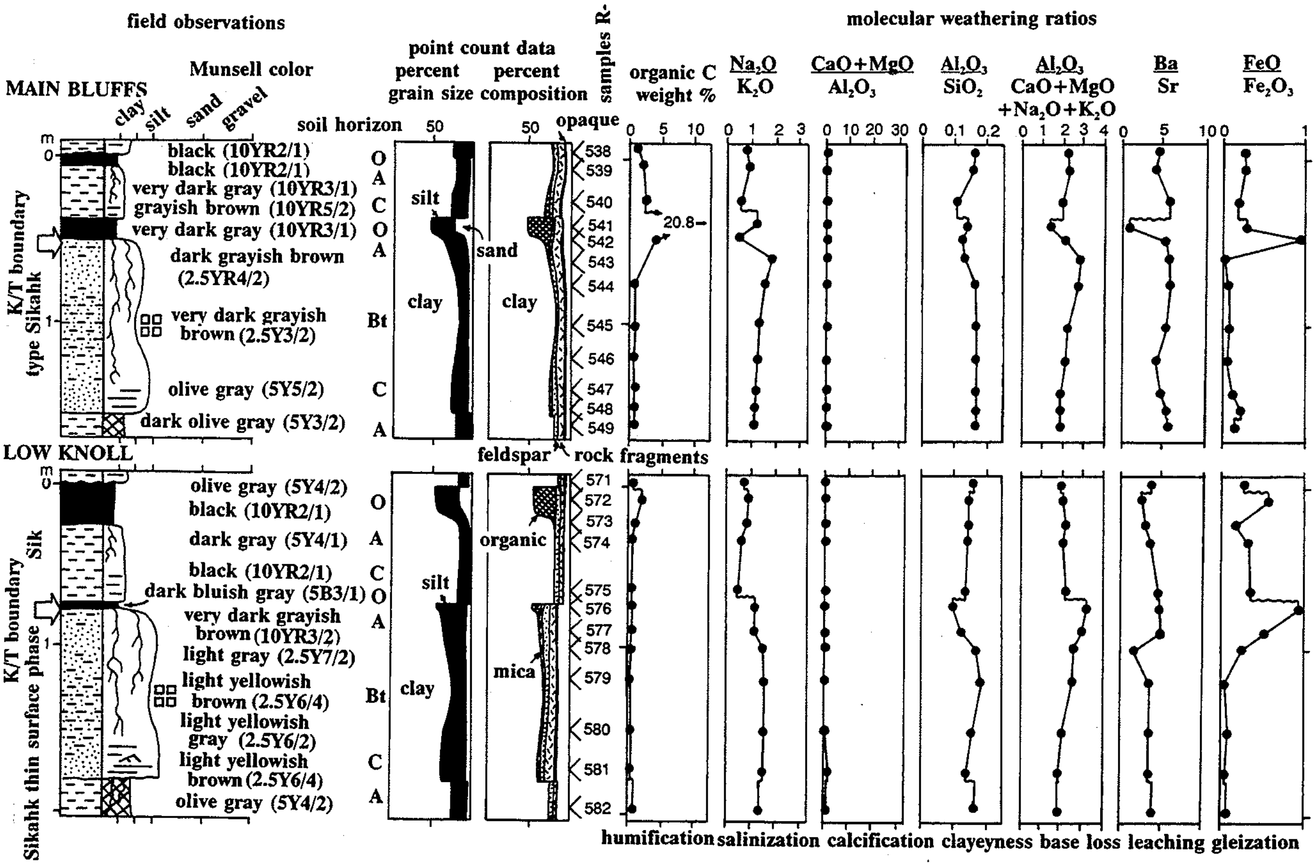

Figure 6. Measured section, Munsell colors, soil horizons, grain size, mineral composition, organic carbon, and selected molecular weathering ratios of the type Sikahk clay (above) in the main bluffs, and of the Sikahk clay thin surface phase paleosols (below), within a knoll west of the main bluffs north of Bug Creek, Montana. These both include the Cretaceous-Tertiary boundary within the uppermost 10–20 cm below the coal, and the Hell Creek–Tullock Formation boundary at the base of the coal, at 8.7 m in Figure 4. Lithologic key is after Figure 4.

middle Hell Creek Formation, stratigraphically below the interval sampled, there are some paleosols with carbonate nodules (McSweeney and Fastovsky, 1990) suggestive of a subhumid paleoclimate. A likely range of mean annual precipitation for the uppermost Hell Creek Formation is some 900–1200 mm, by comparing carbonate distribution in soils (outlined by Yaalon, 1983; Retallack, 1994). An increasingly wet climate from the middle to the upper part of the Hell Creek Formation also is in evidence from the increased size of fossil leaves (Johnson and Hickey, 1990) and diversity of moss, liverwort, and fern spores (Hotton, 1988).

There also are indications in the paleosols of a marked, though not severe, dry season. None of the paleosols in the uppermost Hell Creek Formation is highly oxidized or red and yet many are deeply penetrated by root traces (Fastovsky and McSweeney, 1987, Fig. 3) and burrows (McSweeney and Fastovsky, 1987, Fig. 7). Water table may have retreated as much as a meter or two during a dry season (to depth of elevated ferrous/ferric iron ratios of Fig. 5). This dry season may also have been a time of wildfires, which left abundant charcoal within paleosols and paleochannels (Rigby and Rigby, 1990). Charcoal can be distinguished from coalified wood by a variety of features (Cope and Chaloner, 1985), including uncompacted cell walls with fused middle lamella (illustrated for these paleosols by Fastovsky and McSweeney, 1987, Fig. 9). On the other hand, the dry season could not have been severe, because no evidence was seen of deep cracking and deformation (mukkara) or hummocky surfaces (gilgai) in these clayey paleosols. Given the paleogeographic setting of these paleosols on the margin of a meridionally oriented continental seaway downwind from the actively uplifted North American Cordillera, the dry season was probably short and during the winter as part of a subtropical dry belt exaggerated by a local rain shadow, rather than a prolonged monsoonal or Mediterranean-style dry season (Horrell, 1991). Drab color, deeply penetrating roots, and common charcoal are features of soils now found in northern Florida (Mitsch, 1984; Izlar, 1984; Coultas and Duever, 1984; Lugo and others, 1984).

Moderate climatic seasonality is also compatible with fossil evidence: tuber-bearing fossil equisetaleans (Watson and Batten, 1990), growth rings in fossil wood of taxodiaceous conifers (Wolfe and Upchurch, 1987a), the deciduous taxodioid shoots as well as evergreen cupressoid shoots of fossil *Glyptostrobus* (Henry and McIntyre, 1926; Chaney and Axelrod, 1959), and co-occurrence of evergreen magnoliid and lauralean with deciduous hamamelid fossil angiosperms (Johnson and Hickey, 1990).

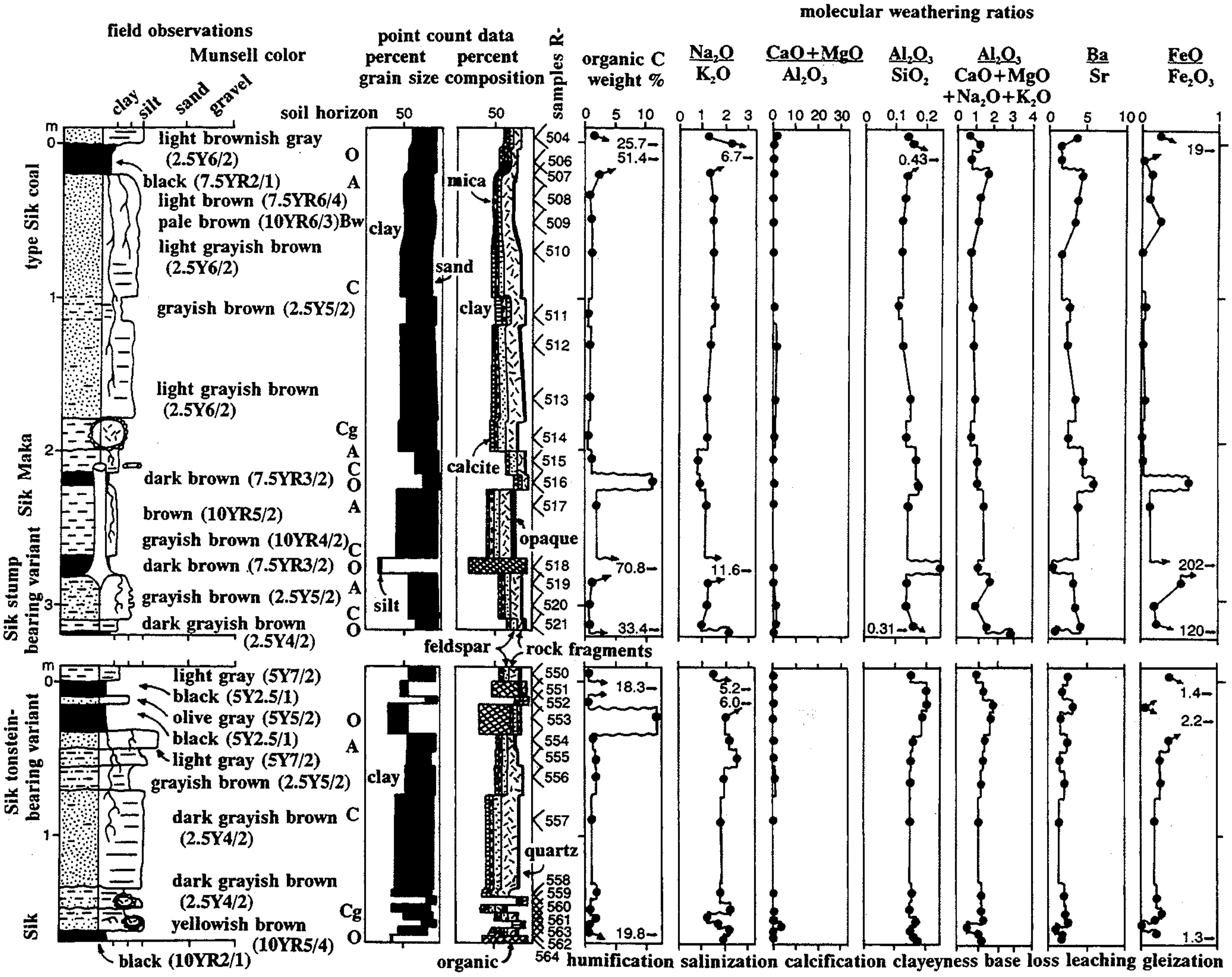

Figure 7. Measured section, Munsell colors, soil horizons, grain size, mineral composition, organic carbon, and selected molecular weathering ratios of the Sik paleosols in Paleocene Tullock Formation in the main bluffs north of Bug Creek, Montana. These are at 10.5–12 m (lower section) and 34–37.2 m (upper section) in Figure 4. Lithologic key is after Figure 4.

Paleotemperature is difficult to estimate from paleosols, but an overall tropical-to-subtropical temperature regime would be compatible with evidence for a highly productive ecosystem. The degree of surficial humification and obliteration of original bedding by root traces and burrows in the type Otssko clay is impressive when compared with the moderate chemical differentiation of this profile, particularly in alumina:silica and alumina:bases ratios compared with parent material (Fig. 5). The Spatsiko pedotype shows extensive weathering of rock fragments in thin section despite its very weak profile development.

More precise paleotemperature estimates come from paleobotanical evidence. A frost-free climate is indicated by the presence of fossil palms (*Palmacites* leaves of Johnson, 1989) and screw pines (*Pandaniidites* pollen of Hotton, 1988). Cycadlike leaves in the uppermost Hell Creek Formation do not necessarily indicate warm climates, because some Mesozoic cycadlike plants were deciduous, had short shoots, and lacked the large, frost-sensitive terminal meristems of modern cycads and palms (Spicer and Chapman, 1990). A nontropical climate is indicated by the dominance in swamps (Sik pedotype) of taxodiaceous conifers, unlike angiosperm-dominated coals and underclays of the Raton Basin of Colorado and New Mexico in the Late Cretaceous (Wolfe and Upchurch, 1987b) and modern swamps of Central America south of Mexico today (Breedlove, 1973; Porter, 1973; Hartshorn, 1983; Best and others, 1984). The proportion of fossil angiosperm leaves with entire margins is like that of Asian forests under a mean annual temperature of 16 °C, which is warm temperate (Hotton, 1988; Johnson and Hickey, 1990).

Ancient Vegetation. Only remains of thickets of stout herbaceous equisetaleans were found in sandy paleosols with prominent relict bedding (Spatsiko pedotype at "Fig Patch" locality of Shoemaker, 1977). Stout woody root traces are present in clayey paleosols with prominent relict bedding (Maka pedotype), which may have supported small pole trees scattered among herbaceous and shrubby plants, like colonizing forests of Africa and India (Retallack, 1991a). Sapakot paleosols show greater de-

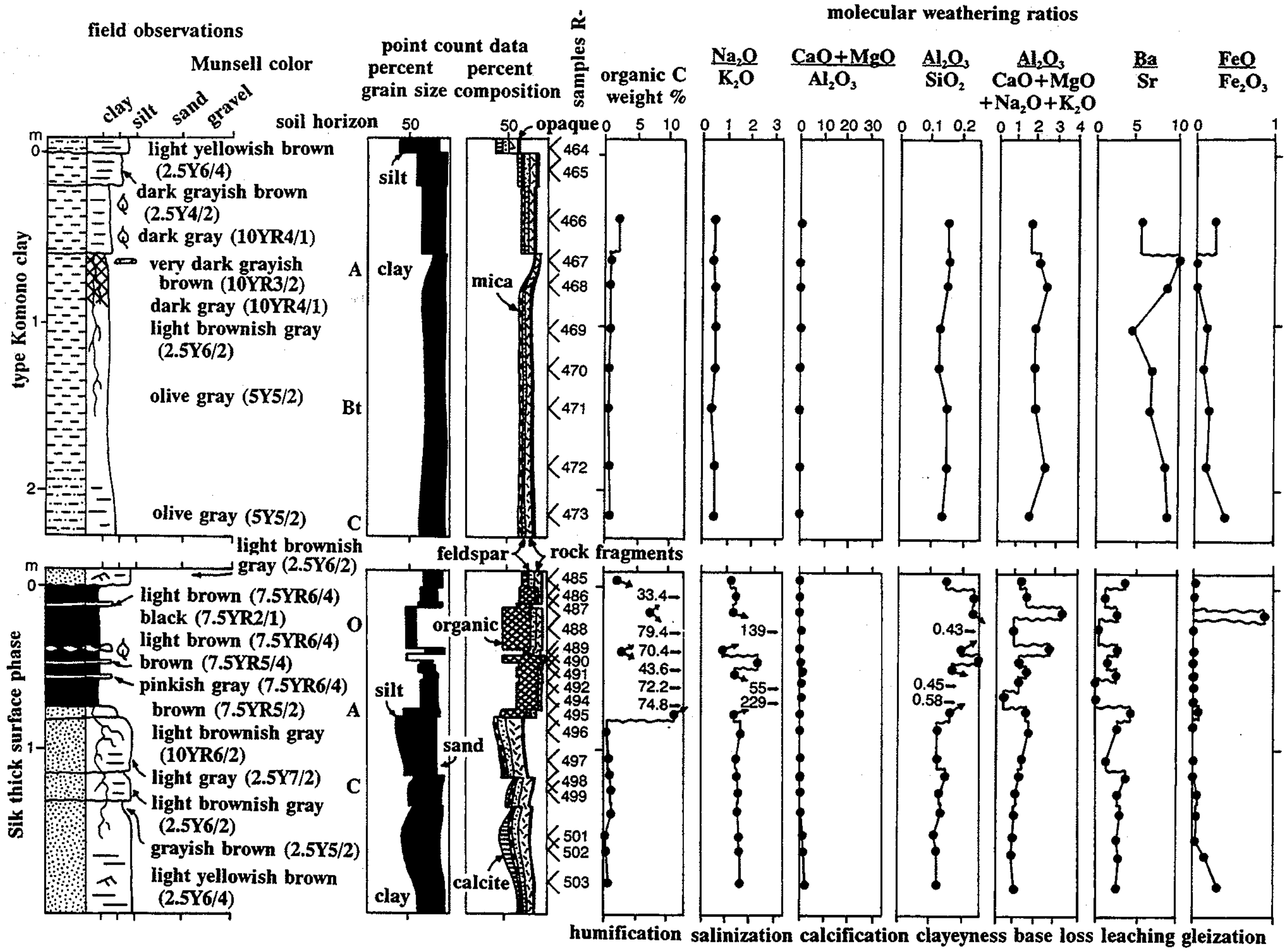

Figure 8. Measured section, Munsell colors, soil horizons, grain size, mineral composition, organic carbon, and selected molecular weathering ratios of the Sik coal thick surface phase and type Komono clay paleosols in the Paleocene Tullock Formation in the main bluffs north of Bug Creek, Montana. These are at 42.3–40.5 m and 53.0–51.0 m, respectively, in Figure 4. Lithologic key is after Figure 4.

velopment of soil features as found under forests more advanced in ecological succession. Otssko profiles are like those of old growth forests, to judge from the depth and degree of development of the paleosols and woody root traces. Although these various pedotypes occur one on top of another, they probably represent a former mosaic of local ecosystems (Fig. 9), considering the different sedimentary facies in which they are found (following Fastovsky, 1987, 1990; Fastovsky and Dott, 1986).

Many paleosols in the uppermost Hell Creek Formation contain well-preserved fossil plants, so that the taxonomic composition of vegetation supported by each pedotype may be determined in addition to the ecosystem type indicated by features of the profiles and root traces. From collections available (Table 3), the vegetation of early successional paleosols was relatively low in diversity compared with the regional fossil flora (Shoemaker, 1966, 1977; Hotton, 1988; Johnson, 1989) and is dominated by archaic hamamelid dicots, particularly early relatives of katsura and sycamore. Swamps supported vegetation dominated by the taxodiaceous conifers, but with a varied component of pteridophytes and dicots, broadly similar to vegetation of the modern Okefenokee Swamp of Georgia outlined by Best and others (1984). Some fossil plants have been found in a paleosol similar to Otssko Series a little lower stratigraphically within the Hell Creek Formation near Marmarth, North Dakota (Table 3). This is suggestive of a diverse semievergreen forest for Otssko paleosols. A broadly similar living floristic analog is relict subtropical laurel-oak forests of the Canary Islands and parts of Asia described by Axelrod (1975).

Former Animal Life. Pedotypes most fossiliferous with vertebrate remains are Maka and Sapakot paleosols (Table 3), which include a dinosaur fauna dominated by *Triceratops horridus* (species name used in broad sense of Ostrom and Wellnhofer, 1990). Spatsiko pedotypes yielded aquatic champsosaur remains. Two quarries for partial skeletons of *Tyrannosaurus rex* excavated by P. and N. Larson (Black Hills Institute, Hill City, South Dakota) 8 km northwest of Buffalo, South Dakota, proved to be in Spatsiko (Stan quarry) and Maka pedotypes (Duffy quarry). Neither Sik nor Otssko pedotypes of Cretaceous age have yet yielded bone, but this is not surprising considering that they are noncalcareous and so probably were too acidic to preserve bone (Retallack and oth-

TABLE 1. DESCRIPTIONS OF CRETACEOUS-TERTIARY PEDOTYPES AT BUG CREEK, MONTANA

Top (cm)	Horizon	Rock type	Prominent colors	Other	Microfabric	Bottom
Type Sapakot clay paleosol						
0	A	Carbonaceous claystone	Black (5Y2.5/2), weathers brown–dark brown (7.5YR4/2).	Weakly calcareous; locally coaly at the surface, with medium platy peds and numerous carbonaceous root traces.	Porphyroskelic mosepic; illuviation sesquiargillans and diffusion ferrans after root traces.	Wavy gradual
−21	Bw	Sandy claystone	Pale olive (5Y6/4), weathers light gray to gray (5Y6/1).	Weakly calcareous; numerous carbonaceous root traces up to 1 cm in diameter of dark grayish brown (10YR4/2).	Agglomeroplasmic clinobimasepic; illuviation sesquiargillans after root traces.	Smooth diffuse
−63	Bw	Clayey fine sandstone	Pale yellow (5Y7/3), weathers light olive (5Y6/2).	Strongly calcareous; numerous carbonaceous root traces and some relict bedding.	Agglomeroplasmic mosepic; illuviation sesquiargillans after root traces.	Abrupt wavy, broken
−142	C	Silty shale	Olive gray (5Y5/2), weathers light gray to gray (5Y6/1).	Moderately calcareous, with carbonaceous root traces and relict bedding.	Agglomeroplasmic mosepic, thin (2 mm) clastic dikes (silans) that are granular silasepic.	Gradual smooth
−155	Cg	Fine-grained sandstone	Light gray (5Y7/2), weathers light gray (5Y7/1).	Moderately calcareous; pyrite nodules, to 22 cm diam., brownish yellow (10YR6/6), with interior olive yellow (2.5Y6/6); ripple marks and cross bedding; dinosaur rib (7 cm wide, 3 cm thick) and champsosaur vertebra.	Agglomeroplasmic mosepic grading down to granular silasepic; illuviation sesquiargillans after root traces.	Abrupt wavy
Type Otskko clay paleosol						
0	A	Carbonaceous claystone	Dark grayish brown (2.5Y4/2), weathers light gray (5Y7/2).	Root traces, reddish brown (5YR5/3); joint faces, yellowish brown (10YR5/4); thick platy peds; gypsum crystals, light gray (2.5Y7/4), on fossil twigs (1 cm wide), stained yellow (10YR7/6); moderately calcareous.	Porphyroskelic clinobimasepic; abundant opaque root traces and leaf cuticles.	Diffuse smooth
−21	AB	Silty claystone	Olive gray (5Y4/2), weathers light gray (5Y7/2).	Common root traces and blocky angular peds defined by slickensided clay skins (argillans); moderately calcareous.	Porphyroskelic clinobimasepic; illuviation sesquiargillans after root traces.	Diffuse smooth
−35	Bt	Carbonaceous claystone	Dark olive gray (5Y3/2), weathers light olive gray (5Y6/2).	Common large root traces and blocky angular peds defined by slickensided surfaces stained with iron-manganese (mangans) of dark bluish gray (5B4/1); moderately calcareous.	Porphyroskelic clinobimasepic; root traces surrounded by diffusion ferrans, filled with agglomeroplasmic insepic clayey silt.	Diffuse smooth
−57	C	Carbonaceous silty shale	Very dark grayish brown (10YR3/2), weathers light olive gray (5Y6/2).	Moderately calcareous; clear relict bedding; few iron stains (sesquans) of yellowish brown (10YR5/4).	Porphyroskelic clinobimasepic; root traces with diffusion ferrans.	Gradual smooth
Type Spatsiko silty clay loam paleosol						
0	A	Fine-grained sandstone	Dark yellowish brown (10YR4/4–4/6), weathers light olive gray (5Y6/2).	Abundant fine root traces and a fossil vertebra of a champsosaur; moderately calcareous.	Porphyroskelic clinobimasepic; agglomeroplasmic paragranotubules after burrows; root traces and leaf cuticles.	Clear smooth
−1	A	Fine-grained sandstone	Olive yellow (2.5Y6/4), weathers light olive gray (5Y6/2).	Abundant root traces up to 6 mm wide, dark brown (10YR3/3); common iron-stained joints (sesquans) of yellowish red (10YR5/6); moderately calcareous.	Agglomeroplasmic skelmosepic, diffusion ferrans along joint planes.	Abrupt wavy
Type Maka clay paleosol						
0	A	Carbonaceous shale	Very dark gray (5Y4/1), weathers light gray (2.5Y7/2).	Scattered fine root traces and relict bedding; noncalcareous.	Porphyroskelic mosepic; diffusion ferrans around organic root traces.	Diffuse smooth
−26	C	Silty shale	Dark olive gray (5Y3/2), weathers light olive gray (5Y6/2).	Prominent relict bedding of dark gray (5Y3/1) clayey laminae and very dark gray (5Y3/2) silty laminae; noncalcareous.	Agglomeroplasmic insepic; some laminae granular silasepic.	Diffuse smooth
−54	—	Siltstone	Light gray (2.5Y7/2), weathers light gray (5Y7/2).	Relict bedding of light gray (5Y7/2) laminae and dark grayish brown (2.5Y4/2) laminae rich in fossil plant chaff; ripple marks; moderately calcareous.	Agglomeroplasmic insepic, poorly preserved fecal pellets.	Abrupt wavy
Type Sikahk coal paleosol						
0	O	Lignite	Very dark gray-black (10YR3/1-2/1), weathers dark gray (5Y4/1).	Finely laminated and stained with jarosite powder of yellow (5Y8/6); noncalcareous.	Porphyroskelic clinobimasepic; abundant organic root traces.	Clear smooth
−7	O	Clayey lignite	Very dark gray–black (10YR3/1-2/1), weathers dark gray (5Y4/1).	Noncalcareous.	Porphyroskelic argillasepic; common fecal pellets.	Abrupt wavy
−15	A	Clayey siltstone	Dark grayish brown (2.5YR4/2), weathers dark gray (5Y4/1).	Common carbonaceous root traces of very dark brown (10YR2/2); noncalcareous.	Porphyroskelic mosepic; illuviation sesquiargillans after root traces.	Gradual smooth
−46	Bt	Silty claystone	Very dark grayish brown (2.5Y3/2), weathers gray (5Y5/1).	Root traces as above; coarse angular blocky peds; slickensided clay skins; iron-stained joints, yellowish brown–brownish yellow (10YR5/6-6/6); noncalcareous.	Porphyroskelic clinobimasepic; root traces as above; pellet-filled metaisotubule after a burrow.	Gradual smooth
−89	C	Clayey siltstone	Olive gray (5Y5/2), weathers gray (5Y5/1).	Sparse root traces and prominent relict bedding; noncalcareous.	Porphyroskelic clinobimasepic grading down to mosepic.	Abrupt wavy
Type Sik coal paleosol						
0	O	Lignite	Dark brown–black (7.5YR3/2-2/1).	Laminated; noncalcareous.	Agglomeroplasmic insepic.	Abrupt smooth
−2	O	Lignite	Dark brown–black (7.5YR3/2-2/1), weathers very dark gray (5Y3/1).	Noncalcareous.	Agglomeroplasmic insepic.	Abrupt wavy

TABLE 1. (*Continued*)

Top (cm)	Horizon	Rock type	Prominent colors	Other	Microfabric	Bottom
Type Sik coal paleosol (continued)						
−21	A	Silty claystone	Light brown (7.5YR6/4), weathers very pale brown (10YR6/3).	Common carbonaceous root traces of strong brown (7.5YR5/8) and ferruginized mottles of pink (7.5YR7/4); noncalcareous.	Agglomeroplasmic insepic; diffusion ferrans around organic root traces.	Clear wavy
−24	A	Siltstone	Pale brown (10YR6/3), weathers light gray (2.5Y7/2).	Carbonaceous root traces, brown (7.5YR5/4) and pink (7.5YR7/4); interbedded siltstone, in 2-cm-thick beds, and silty claystone, 1 cm thick; noncalcareous.	Agglomeroplasmic mosepic, with much organic matter.	Gradual smooth
−45	Bw	Clayey siltstone	Grayish brown (2.5Y6/2), weathers light olive gray (5Y6/2).	Root traces to 1.5 cm wide, strong brown (7.5YR5/8); relict bedding disrupted by slickensided clay skins and coarse blocky structure; noncalcareous.	Agglomeroplasmic insepic, with much organic matter.	Gradual smooth
−62	C	Siltstone	Light brownish gray (2.5Y6/2), weathers light olive gray (5Y6/2).	Common root traces; relict bedding, ripple marks and scour-and-fill structures, accentuated by finely comminuted charcoal, strong brown (7.5YR5/6) and brown (7.5YR5/4); noncalcareous.	Agglomeroplasmic insepic.	Gradual smooth
−100	C	Silty claystone	Grayish brown (2.5Y5/2), weathers light yellowish brown (2.5Y6/2).	Some root traces up to 6 mm wide, yellowish brown (10YR5/6); ferruginized joints in modern outcrop are dark yellowish brown (10YR4/6) and yellowish brown (10YR5/6); noncalcareous.	Agglomeroplasmic insepic.	Abrupt smooth
−118	C	Siltstone	Light brownish gray (2.5Y6/2), weathers light yellowish brown (10YR5/6).	Ferruginized joints in modern outcrop are light yellowish brown (2.5Y6/4) and brownish yellow (10YR6/8); fine (3–4 mm wide) root traces, dark grayish brown (10YR4/2); weakly calcareous.	Agglomeroplasmic insepic in clayey laminae to granular argillasepic in silty laminae.	Abrupt smooth
−177	Cg	Silty claystone	Light brownish gray (7.5Y6/2), weathers light yellowish brown (2.5YR6/4).	Common relict bedding; root traces, strong brown (7.5YR5/8); large (to 60 cm wide by 30 cm thick) siderite nodules, light brownish gray (2.5Y6/2) with a 1 cm weathering rind, strong brown (7.5YR5/6); nodules strongly calcareous but matrix weakly calcareous.	Agglomeroplasmic argillasepic grading downward to granular silasepic, with siderite nodules porphyroskelic calciasepic.	Abrupt smooth
Type Komono clay paleosol						
0	A	Carbonaceous shale	Very dark grayish brown–black (10YR3/2-2/1), weathers light brownish gray (10YR6/2).	Common carbonaceous root traces to 3 cm wide; noncalcareous.	Porphyroskelic clinobimasepic; illuviation sesquiargillans and diffusion ferrans after root traces.	Clear irregular to broken
−7	A	Carbonaceous claystone	Dark gray (10YR4/1), weathers light brownish gray (2.5Y6/2).	Carbonaceous root traces, dark brown (7.5YR3/2) and yellow (10YR8/8); slickensided clay skins (argillans); coarse subangular blocky peds; noncalcareous.	Porphyroskelic clinobimasepic; illuviation sesquiargillans and diffusion ferrans after root traces.	Gradual smooth
−22	AB	Claystone	Light brownish gray (2.5Y6/2), weathers light brownish gray (2.5Y6/2).	Carbonaceous root traces up to 2 cm wide, dark brown (7.5YR6/2); common slickensided clay skins (argillans) defining a coarse subangular blocky structure; noncalcareous.	Porphyroskelic mosepic; illuviation sesquiargillans after root traces and agglomeroplasmic insepic metagranotubules after burrows.	Diffuse smooth
−64	Bt	Claystone	Olive gray (5Y5/2), weathers light brownish gray (2.5Y6/2).	Carbonaceous root traces, dark grayish brown (10YR3/2); ferruginized joint planes of modern outcrop, brownish yellow (10YR6/8); slickensided clay skins (argillans); persistent relict beds; weakly calcareous.	Porphyroskelic mosepic; illuviation sesquiargillans after root traces and para-aggrotubules after burrows.	Diffuse smooth
−110	C	Silty claystone	Olive gray (5Y5/2), weathers light brownish gray (2.5Y6/2).	Sparse root traces and relict bedding; some ferruginized joint planes, olive yellow (2.5Y6/6 and 2.5Y6/8); weakly calcareous.	Porphyroskelic mosepic; illuviation sesquiargillans after organic root traces.	Diffuse smooth

Note: Only type profiles located and labeled in Figures 5–8 are detailed here as reference profiles for the various pedotypes. Terminology is from Munsell Color Company (1975), Soil Survey Staff (1975), and Brewer (1976).

ers, 1987). Because of this taphonomic bias, the uppermost Hell Creek Formation is not a good place to establish ancient vertebrate communities of various paleosol types. This would be feasible, however, in the middle Hell Creek Formation with its more calcareous paleosols containing a marginally greater diversity of vertebrates (Sheehan and others, 1991).

Paleotopography. The paleotopographic setting of the uppermost Hell Creek Formation has been established from both regional and local sedimentological studies (Cherven and Jacob, 1985; Fastovsky and Dott, 1986; Fastovsky, 1987) as a broad lowland alluvial plain east of the Cordillera uplifted by Laramide mountain building and northeast of a retreating epicontinental seaway (Fig. 9). It was a swampy lowland in which none of the paleosols were free from seasonal flooding, considering their relatively high content of organic matter (Fig. 5). Nevertheless, minor variations in drainage corresponded to different parts of the depositional system. Sik paleosols with their peaty surface horizons would have been permanently waterlogged. The only example found is widespread ("Null Coal" of Rigby and Rigby, 1990) and formed an extensive swamp isolated from clastic input of paleochannels. Sandstones including Spatsiko paleosols have geometry and sedimentary structures similar to those of crevasse splays and point bars (Fastovsky and Dott, 1986). Maka paleosols developed in more clayey parts of levee deposits. Sapakot paleosols also are found in point bar

TABLE 2. DIAGNOSES AND IDENTIFICATIONS OF CRETACEOUS-TERTIARY PEDOTYPES AT BUG CREEK, MONTANA

Pedotype	Indian meaning	Age	Type profile	Diagnosis	United States	F.A.O. map	Australian	Northcote
Komono	Violet, green	Paleocene	52.3 m in bluffs section (includes OU2826-8 in Fig. 3).	Gray claystone surface (A) with carbonaceous root traces over deeply decalcified clayey subsurface (Bg).	Aquept	Dystric Gleysol	Humic Gley	Gn3.91
Maka	Short, stunted	Cretaceous and Paleocene	4.3 m in knoll section (includes OU2823 in Fig. 3).	Gray claystone surface (A) with carbonaceous root traces and relict bedding.	Fluvent	Dystric Fluvisol	Alluvial Soil	Uf1.21
Otssko	Green, blue	Cretaceous	3.1 m in knoll section.	Dark gray claystone surface (A) over blue-green clay-rich subsurface (Bt) horizon.	Aqualf	Gleyic Luvisol	Gleyed Podzolic	Gn3.94
Sapakot	Layer, stack	Cretaceous	1.8 m in knoll section.	Gray claystone surface (A) with carbonaceous root traces over calcareous sandstone.	Aquept	Humic Gleysol	Humic Gley	Gn2.81
Sik	Black, dark	Cretaceous and Paleocene	11.8 m in bluffs section.	Coal surface (O) over gray underclay or sand.	Fibrist	Dystric Histosol	Acid Peat	O
Sikahk	Set aside, exclude	Cretaceous-Tertiary boundary	8.8 m in bluffs section.	Coal surface (O) on gray claystone with carbonaceous root traces (A) over yellow-gray silty clay, noncalcareous subsurface (Bt) horizon.	Aquult	Gleyic Acrisol	Gleyed Podzolic	O
Spatsiko	Sand	Cretaceous and Paleocene	3.2 m in knoll section.	Bedded sandstone with root traces (A).	Psamment	Dystric Regosol	Siliceous Sand	Um1.21

and levee deposits, but their greater and deeper profile differentiation than that of Maka profiles is evidence that they formed in more elevated and less floodprone parts of the levee system. Otssko paleosols are entirely within clayey flood-plain deposits and were away from levees of streams and from swamps. Their abundant clay skins and deeply penetrating root traces would have formed above water table, which was thus below ~1 m for most of the time during their formation.

Parent Material. Laramide source terrains provided sediment of illitic clays, quartz, feldspar, and fragments of carbonate, volcanic, and metamorphic rocks (Bell, 1965) as parent materials to the paleosols. Redeposited nodules and claystone clasts in the paleosols were probably cannibalized from older soils of the drainage basin (McSweeney and Fastovsky, 1987; Fastovsky and McSweeney, 1987). Some local soils of clayey river banks collapsed to claystone breccias in paleochannels (Rigby and Rigby, 1990).

Time for Formation. Otssko paleosols, with their subsurface horizons enriched in clay to the extent that they qualify as argillic (in the sense of Soil Survey Staff, 1975), are the best-developed paleosols found in the upper Hell Creek Formation. In well-drained Quaternary flood-plain soils reviewed by Birkeland (1990) and Walker and Butler (1983), this degree of clay accumulation takes 10 000 to 60 000 yr. Gleyed soils (Ochraqualfs), with subsurface horizons enriched in clay (6.1%–9.6% more than C horizon), have formed in lake deposits with 38.9% ± 2.7% clay and 23.7% ± 3.9% carbonate only 12 000 yr old in northwestern Ohio, an area with mean annual temperature of 10 °C and mean annual precipitation of 850 mm (Smith and Wilding, 1972). This is a less clayey parent material and less humid and warm climate than envisaged during the Late Cretaceous in the present area of Bug Creek, but this example is an indication of the time for argillic horizons to form in seasonally waterlogged soils. Similar comparisons with Commerce, Sharkey, and Mhoon soils of the Mississippi Delta, known to have formed Bw horizons in 2000 yr and A horizons in hundreds of years (Matthews, 1983, 1984), help fix the time for formation of comparably developed Sapakot, Maka, and Spatsiko paleosols. Clastic dikes of clay and silt (gleyans) were seen in weakly to very weakly developed paleosols, like those thought to induce subsurface enrichment of clay in similar soils archaeologically dated as <2000 yr old in seasonally flooded alluvial plains in Bangladesh, Malaysia, and Spain (Brammer, 1971). Such comparisons with Quaternary soils of known age are the basis for estimates of time for formation of each pedotype (Table 3).

Estimates on the high end of the ranges given are plausible considering that there are two Otssko paleosols, one comparably developed Sikahk paleosol, two Maka, one Sapakot, and one Spatsiko paleosol in the sequence between the Cretaceous-Tertiary boundary and the base of paleomagnetic Chron 29R (in paleochannel at base of Fig. 4, and at 9.5 m in Fig. 2 of Retallack and others, 1987, following Archibald and others, 1982), which has been estimated to represent ~300 000 yr (Courtillot and others, 1990; d'Hondt and Herbert, 1992). Although several pessimistic estimates of stratigraphic completeness of fluvial sequences across the Cretaceous-Tertiary boundary have been made using other means (Dingus, 1984; Fastovsky, 1987, 1990), the figures presented here account for much of the time available in relatively rapid events of sedimentation punctuated by long periods of soil formation. Unlike stochastic models of incompleteness used previously, paleosols are evidence of both position and relative magnitude of breaks in sedimentation (indicated by the width of black boxes in Fig. 4).

General Comparisons. Another method for reconstructing paleoenvironments is to identify paleosols within a classification of soils using proxy characteristics outlined elsewhere (Retallack, 1990, 1993). Otssko paleosols are gray and weakly oxidized and yet show considerable subsurface accumulation of clay in shiny clay skins, as in Gleyic Luvisols of the Food and Agriculture Organization of UNESCO (F.A.O., 1974) or Aqualfs of the U.S. soil taxonomy (Soil Survey Staff, 1975). Sapakot paleosols have less marked subsurface clay accumulation and conspicuous relict bedding, as in Humic Gleysols or Aquepts. Spatsiko and Maka paleosols have root traces in bedded alluvium as in poorly developed soils such as F.A.O. Fluvisols and U.S. Entisols. The coals of Sik paleosols are more than thick enough, considering lithostatic compaction already discussed, to qualify as Histosols in both F.A.O. and U.S. classifications. Considered as a genetically related suite, these paleosols indicate a landscape of Gleyic Luvisols, with lesser areas of streamside Humic Gleysols, Dystric Fluvisols, and few swampy areas of Dystric Histosols. Landscapes with this as-

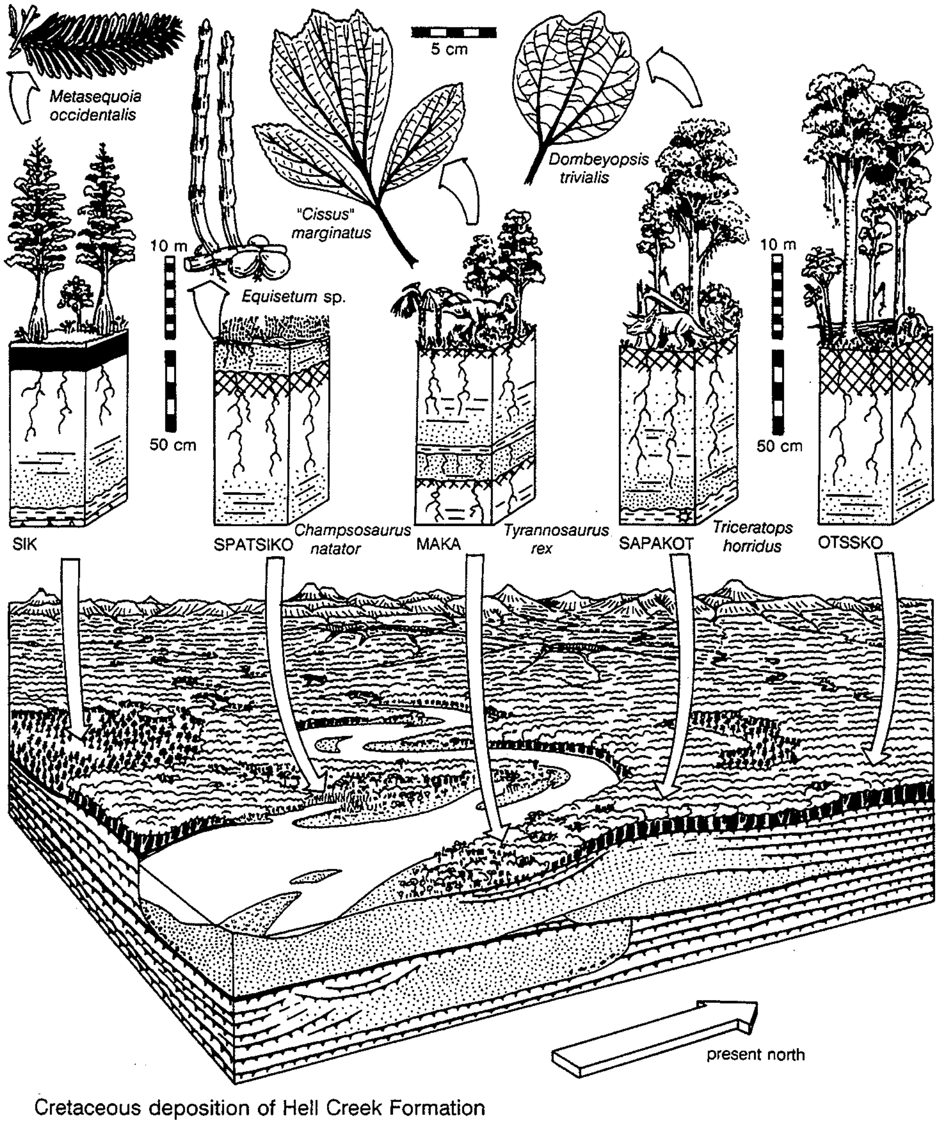

Figure 9. Interpreted pedotypes and representative fossil plants and animals within a sedimentary framework (established by facies analysis) in eastern Montana during latest Cretaceous time. Breaks in scales between vegetation and soil and between landscape and sediments have been used to emphasize details of pedotype profiles and sedimentology. Ticked lines represent paleosols, and stipple pattern is for paleochannels. Other lithologic symbols are as for Figure 4.

semblage of soils are in alluvial plains extending from the states of Campeche and Tabasco in Mexico into Guatemala (map unit Lg 30-2a of F.A.O., 1975a), in coastal plains of the Rio Verde delta in Oaxaca, Mexico (Lg 29-3a), and in coastal northwestern and central eastern Florida (Lg 19-1a of F.A.O., 1975b). In addition, Sharkey to Mhoon, Commerce, Baldwin, and Barbary soils of the Mississippi River in Louisiana form a catena from levees to backswamps (Lytle and others, 1956; Dance and others, 1968; Murphy and others, 1977; Matthews, 1983, 1984; Trahan and others, 1989) and are very similar to Maka, Spatsiko, Sapakot, Otssko, and Sik paleosols, respectively.

Paleosols of the Hell Creek Formation can be considered evidence against several prior concepts of latest Cretaceous paleoenvironments. There is no evidence among paleosols in the uppermost Hell Creek Formation of Bug Creek for "fern savannas" (of Coe and others, 1987) or for angiosperm shrublands (of Crane, 1987). Both kinds of vegetation would produce calcareous, red Inceptisols or Vertisols, with shallow and small root traces, such as were widespread during Silurian and Devonian time (Retallack, 1985, 1992). In contrast, root traces of the Hell Creek Formation are thick and deeply penetrating, and the paleosols are decalcified and drab. Nor is there any evidence among paleosols for an environment like that of the Kimberley region of Western Australia, regarded as similar by Rigby (1987). In alluvial areas of this monsoonal semiarid region of northwestern Australia, the soils are red and yellow Inceptisols and calcareous Vertisols (Isbell, 1983), very different from paleosols in the Hell Creek Formation. Among the most influential images of the habitat of *Tyrannosaurus* and *Triceratops* are murals by Charles Knight in the Field Museum in Chicago (Czerkas and Glut, 1982) and by Rudolph Zallinger in the Peabody Museum at Yale University (Czerkas and Olson, 1987). Both murals depict dinosaurs in a wooded grassland (savanna) habitat. If this were the case, Mollisols would be expected (Retallack, 1991a), and none have yet been found in the Hell Creek Formation. Closer to the mark is Eleanor Kish's reconstruction (for Russell, 1977) of *Triceratops* within a cypress swamp. Histosols with taxodiaceous conifers are found in the uppermost Hell Creek Formation, although rare and not yielding *Triceratops*, which is found in less organic and presumably better drained associated paleosols. Her reconstruction of forest sheltering *Stygimoloch* (for Russell, 1989) is better, as is the reconstruction offered by Van Valen and Sloan (1977). However, rain-forest trees with buttressed trunks depicted in both these reconstructions are found in vegetation of markedly wetter climates than the semievergreen subtropical forest envisaged here. Because they employ much artistic license, such reconstructions could be considered immune from scientific criticism, but with new evidence from paleosols they are increasingly testable hypotheses.

Cretaceous-Tertiary Transition

Paleoclimate. A transition to more humid paleoclimate is evident by comparison of latest Cretaceous with earliest Tertiary paleosols at Bug Creek, as well as other sequences of paleosols across the Cretaceous-Tertiary boundary in Big Bend National Park, Texas (Lehman, 1989, 1990), and in the Rocky Mountain foothills of Alberta (Jerzykiewicz and Sweet, 1988). An important question for these paleosols (Retallack

TABLE 3. INTERPRETED CRETACEOUS-TERTIARY PALEOENVIRONMENTS OF PEDOTYPES AT BUG CREEK, MONTANA

Pedotype	Paleoclimate	Ancient vegetation	Former animals	Topography	Parent material	Time for formation
Komono	Humid (>1200 mm mean annual precipitation), subtropical, mildly seasonal.	Lowland seasonally wet forest, with following fossils. **Paleocene:** at 52.3 m in section (UO2826, F35015-22), 25 specimens in 6 species, mainly katsura (*Cercidiphyllum genetrix*, 24%, and *Nyssidium arcticum*, 12%) and water pine (*Glyptostrobus europaeus*, 28% foliar spurs, 4% cones), with cypress (*Cupressinocladus interruptus*, 12%) and dogwood (aff. *Cornus* spp., 8%) and platanoid (*Platanus raynoldsii*, 4%)	No fossils found in area.	Seasonally wet, lowland, clayey, floodplain.	Quartzofeldspathic, mildly calcareous, smectitic clayey siltstone.	1000–10 000 yr, estimated from degree of destruction of relict bedding compared with surface soils of known age.
Maka	Not sufficiently developed to be a paleoclimatic indicator.	Lowland colonizing forest, some fossils found in area, as well as elsewhere. **Paleocene:** Marmarth locality 88103g (Johnson, 1989, has 106 specimens in 8 species, mainly archaic dicots (*Dicotylophyllum anomalum*, 56.6%), dogwood (aff. *Cornus* sp., 11.3%) and palm (*Palmacites*, 11.3%). **Earliest Paleocene:** "Big Bugger" point bar in gully NW¼NW¼SW¼ sec. 10 (UO2825, F34331-4), 8 specimens, 4 species, katsura (*Cercidiphyllum genetrix*, 38%), platanoid (cf. *Wardiaphyllum daturaefolium*, 25%), trochodendralean (*"Populus" nebrascensis*, 12%) and dawn redwood (*Metasequoia occidentalis*, 25%). **Latest Cretaceous:** 56 species of palynomorphs (BG82-C22 of Hotton, 1988) mainly *Gunnera*-like pollen (*Tricolpites microreticulatus*, 37.5%), and apialean? dicot (*Kurzipites circularis*, 15%); also Marmarth locality 88128 (Johnson, 1989), 146 specimens in 11 species, mainly laurels (*Dombeyopsis trivialis*, 56.8%; morphotyes HC162, 8.2%, and HC163, 2.5%), platanoid (*"Cissus" marginatus*, 10.3%), magnoliid (*"Liriodendron" laramiense*, 4.8%), and nymphaealean (*Paranymphaea hastata*, 3.4%).	**Earliest Paleocene:** in "Big Bugger" point bar, NW¼NE¼SE¼ sec. 9 (UO2821, F34317-25), crocodylian (*Leidyosuchus sternbergi*), champsosaur (*Champsosaurus natator*), and turtle (*Compsemys victa*). **Latest Cretaceous:** in footslopes of badlands 200 m northeast of measured section, NE¼NW¼ sec. 15 (not collected), frill and limb bones of *Triceratops horridus*; Duffy Quarry north of Buffalo, South Dakota (SW¼SW¼ sec. 34, T. 20 N., R. 4 E., 500 m south of Stan Quarry, collected by P. Larson and N. Larson of Black Hills Institute), partial skeleton of *Tyrranosaurus rex*.	Clayey swales of levee area of large meandering streams.	Quartzofeldspathic, mildly calcareous, smectitic silty shale.	100–500 yr, estimated from relict bedding compared with surface soils.
Otssko	Humid (900–1200 mm mean annual precipitation), subtropical, mildly seasonal.	Lowland forest, fossils not found in area, but known elsewhere. **Late Cretaceous:** Marmarth locality 88111 (Johnson, 1989), a little older (zone HCIIa), has 197 specimens in 15 species, mainly ginkgo (*Ginkgo adiantoides*, 24.9%), ?Sabiaceae (*"Dryophyllum" subfalcatum*, 16.8%), and platanoid (*Platanophyllum montanum*, 12.7%).	No fossils found.	Seasonally wet, lowland, clayey floodplain.	Quartzofeldspathic, mildly calcareous, clayey siltstone.	10 000–60 000 yr, estimated from development of subsurface clayey (Bt) horizon compared with surface soils.
Sapakot	Not a good indicator.	Lowland riparian forest, no fossils in area, but known elsewhere. **Latest Cretaceous:** Marmarth locality 88015 of Johnson (1989), with one specimen each of trochodendralean (*Trochodendroides nebrascensis*), laurel (*Dombeyopsis trivialis*), platanoid (*"Cissus" marginatus*), and indeterminate dicot (morphotype HC176).	**Latest Cretaceous:** 1 m in measured section, frill and rib of *Triceratops horridus*; Maramrth locality 88105 of Johnson (1989) has frill of *Triceratops horridus*.	Levee tops of sandy meandering streams.	Quartz sandstone and siltstone in fining-upwards bed.	1000–10 000 yr, estimated from relict bedding compared with surface soils.
Sik	Not a good indicator.	Swamp woodland, some fossils known from area as well as elsewhere. **Paleocene:** at 35 m in section (UO2827, F35023-4), water pine (*Glyptostrobus europaeus*) and dicot (*Dicotylophyllum anomalum*); Marmarth localities 87150, 88100, and 87130 of Johnson (1989). **Earliest Paleocene:** 23 species (DR-A1 of Hotton, 1988), mainly ferns (*Laevigatosporites haardtii*, 41.5%) and swamp cypress (*Taxodiaceaepollenites-Sequoiapollenites*, 24.5%), some hamamelid dicots (*Tricolpites parvus*, 11.5%); also locality 86107 of Johnson (1989), with 490 specimens in 30 species, mainly trochodendraleans (*"Populus" nebrascensis*, 50.6%), floating dicot (*"Lemna" scutata*, 23.5%), dicot (*Dicotylophyllum anomalum*, 12.2%), and nymphaealean (*Paranymphaea crassifolia*, 10.4%). **Latest Cretaceous:** 87 species of (BG-82-A9 of Hotton, 1988) mainly swamp cypress (*Taxodiaceae-pollenites-Sequoiapollenites*, 14%) and ferns (*Laevigatosporites haardtii*, 11%), with some archaic santalalean? dicots (*Sindorapollis granulatus*, 9%).	**Earliest Paleocene:** in coal swale 300 m northwest of measured section, SW¼NE¼SW¼ sec. 10 (UO2824, F34330), vertebra of *Champososaurus natator*.	Permanently water-logged swampy lowland.	Quartzofeldspathic, mildly calcareous, smectitic clayey siltstone.	740–9780 yr, estimated from peat accumulation and relict bedding compared with surface soils.
Sikahk	Humid or acid rain, subtropical, mildly seasonal.	Lowland forest succeeded by swamp woodland, fossils not found in area, but at Herpijunk Promontory, Hell Creek area; Smit and others (1987) found mainly dicots in underclay (*Ulmipollenites* spp. and *Aquilapollenites* spp.) followed by a "fern spike" (*Laevigatosporites*).	No fossils found.	Clayey, seasonally wet floodplain, changing to permanently wet swamp.	Quartzofeldspathic, mildly calcareous, smectitic clayey siltstone.	15 000–30 000 yr, estimated from peat accumulation and relict bedding.
Spatsiko	Not a good indicator.	Lowland colonizing vegetation, with following fossils. **Latest Cretaceous:** "Fig Patch" locality of Shoemaker (1966), horsetails (*Equisetum* sp.).	**Latest Cretaceous:** at 3.2 m (UO2823, F34328-9), vertebra of *Champsosaurus natator*; Stan Quarry, Buffalo, South Dakota, *Tyrranosaurus rex*.	Young sandy point bars, levees, crevasse splays.	Quartz sandstone.	100–500 yr, estimated from relict bedding.

and others, 1987), is whether rainfall changed from subhumid to humid across the Cretaceous-Tertiary boundary gradually during accumulation of the last 3 m of sediment below the boundary coal (one Sikahk, Maka, and Otssko paleosol estimated here to represent some 150 000 yr) or abruptly at the boundary followed by leaching of the underlying 3 m of section. The degree of base depletion (alumina:bases of Fig. 6) of the boundary paleosol (Sikahk clay) is intermediate but more like that of comparably developed Cretaceous (Otssko) than of Paleocene (Komono) paleosols. In addition, there are base-rich paleosols (Maka and Spatsiko) between more deeply weathered paleosols (Sapakot and Otssko) and the boundary (Sikahk). Thus leaching from the boundary is unlikely to have reached down 3 m. The change to more humid climate was probably gradual over the last 150 000 yr of the Cretaceous. It may have been related to locally rising base level, as indicated by regionally diachronous onset of thick coal accumulation (Fastovsky, 1987; Izett, 1990; Nichols and Brown, 1992).

The change to more deeply weathered soils may have been due to strong acids such as nitric acid generated during atmospheric shock by an extraterrestrial bolide (Zahnle, 1990), sulfuric acid generated by massive volcanic eruptions (Sigurdsson, 1990), vaporization of evaporites during impact (Sigurdsson and others, 1992), or weak acids such as the organic acids of swamp waters or carbonic acid of normal rainfall (Retallack, 1990). These alternatives cannot be teased apart at Bug Creek, because Sikahk paleosols at the boundary are too well developed to record a short-term pulse of acid rain, and the whole landscape was buffered by calcareous alluvium. Such time scales of only a few years are represented by a thin (1.5 cm) kaolinitic boundary claystone at Brownie Butte, Montana, which contains sparse root traces, clay skins, and other features of a very weakly developed paleosol (Fastovsky and others, 1989). The kaolinitic boundary bed at Brownie Butte and elsewhere in North America (Izett, 1990) could be evidence of a massive pulse of acid rain over too short a period to be reflected in coeval moderately developed paleosols at Bug Creek.

There is no evidence from paleosols for pronounced changes in seasonality or temperature; drab profiles with clay skins and deeply penetrating root traces, fossil charcoal, and strongly bioturbated paleosols persist into the Paleocene. Fossil plants are well preserved in these paleosols and more informative on these issues. Slightly declining leaf size and a dramatic decline in the percentage of entire-margined fossil leaves across the Cretaceous-Tertiary boundary in North Dakota and eastern Montana have been taken as evidence of slightly drier and markedly cooler climate (Johnson and Hickey, 1990). However, this could be an artifact of preferential survival of early successional archaic hamamelid angiosperms with dentate to crenate margins in a post-traumatic recovery flora, as argued for fossil floras of the Raton Basin of Colorado and New Mexico by Wolfe and Upchurch (1987b). A similar transition flora, including a fern spike immediately above the boundary, has long been known from palynological studies of the Cretaceous-Tertiary boundary in eastern Montana (Norton and Hall, 1969; Smit and others, 1987; Hotton, 1988). The idea of long-term cooling across the boundary is undermined by the persistence into Paleocene rocks of palm leaves (Johnson, 1989) and screw pine pollen (Hotton, 1988). A controversial claim for local freezing for a few years, based on supposed frost-deformed fossil leaf cuticles from Cretaceous-Tertiary boundary beds at Teapot Dome, Wyoming (Wolfe, 1991; Nichols and others, 1992), is not supported by any apparent frost heave structures in paleosols at Bug Creek.

Ancient Vegetation. The type Sikahk clay at the Cretaceous-Tertiary boundary is evidence of a forest ecosystem like that envisaged for Otssko paleosols sharply overlain and overprinted by swamp vegetation like that envisaged for Sik paleosols. Pedogenic features of this paleosol lack the resolution now needed to unravel vegetation changes across the Cretaceous-Tertiary boundary, but its carbonaceous composition encourages confidence that its palynological record of vegetation change is representative (Retallack and others, 1987). From pollen preserved in the Sikahk paleosol in the Bug Creek area, diverse Cretaceous forests were temporarily replaced by vegetation dominated by ferns, and then a low-diversity assemblage of angiosperms (Rigby and others, 1987; Smit and others, 1987; Hotton, 1988). The transition flora is also represented in the Bug Creek area by some palynological preparations from a Sik paleosol above the "Bug Creek anthills" locality (sample DR-A1 of Hotton, 1988) and by a small collection of leaves from a Maka Series paleosol within the "Big Bugger" paleochannel (Table 3). Lost at the boundary were many dicots, including archaic lauraleans, magnoliids, the little-known producers of *Aquilapollenites* and *Wodehousia* pollen, as well as cycadlike leaves. Wolfe and Upchurch (1987b) argue that these plants of stable soils were casualties of traumatic destabilization by bolide impact, with initial colonization by ferns and then early successional deciduous angiosperms.

Former Animal Life. Bug Creek has featured prominently in arguments for gradual extinction of dinosaurs (Sloan and others, 1986), but recent surveys of nearby fossil fields have shown an abrupt extinction (Sheehan and others, 1991). Supposed evidence of gradual extinction has been undermined by a variety of recent discoveries. Dinosaur remains now appear to have been reworked from Cretaceous rocks into at least a few Paleocene channels (Lofgren and others, 1990). The 2 m gap between the last dinosaur bone in paleosols and the Ir anomaly, shocked quartz, fern spike, and other evidence of extraterrestrial impact at the Cretaceous-Tertiary boundary, seen at Bug Creek (Fig. 4) as at many other boundary sections, could be a statistical artifact of the reduced likelihood of finding generally rare fossils near the end of their stratigraphic range (Signor and Lipps, 1982) or a taphonomic artifact of poor preservation in noncalcareous paleosols near the boundary (Retallack and others, 1987). Both now seem likely. Lockley (1991) has discovered large hadrosaur tracks on sandstone separated by only 37 cm of coal from the Ir layer in Colorado. Sheehan and others (1991) found bone within 60 cm of the boundary near Glendive, Montana. Jan Smit found a marrow "ghost" of a large vertebra encapsulated in fossil root traces within the Maka paleosol only 1 m below the lower Z coal in the Bug Creek area (Rigby and Rigby, 1990). Dinosaur bone also has been found within 1 m of the boundary at Dogie Creek, Wyoming (Bohor and others, 1987), and a skeleton of *Thescelosaurus* was found 1.5 m below the boundary at Sand Arroyo, Montana (Galton, 1974). Such rare finds are the result of increasingly intense scrutiny of the boundary interval. Poor preservation of the bone is to be expected considering the noncalcareous nature of the paleosols (Retallack, 1984) and their degree of weathering revealed here (particularly alumina:bases ratios of Fig. 5). Acidic dissolution of bone may also be the reason why, with the possible exception of the "Bug Creek anthills" fauna, accumulations of dinosaur bone are not found at the Cretaceous-Tertiary boundary.

In eastern Montana, the Cretaceous-Tertiary boundary was a time of abrupt extinction of almost all land herbivores and carnivores, primarily dinosaurs, but survival of a variety of presumably insectivorous and scavenging mammals and birds, and of almost all aquatic and amphibious creatures (Sheehan and Fastovsky, 1992). This pattern, together with a decline in angiosperms in favor of conifer dominance, and the decline of insect pollination in favor of wind pollination (Hotton, 1988; Johnson and Hickey, 1990) are explicable as a result of acid rain and more humid climate at the Cretaceous-Tertiary boundary. Acid-induced oligotrophy of such well-buffered soils can be predicted to shift dominance from protists to fungi, from earthworms to microarthropods, from snails to slugs, and from herbivorous to saprophytic insects, considering what is known about the soil biology of eutrophic versus oligotrophic ecosystems (Wallwork, 1976; Pelczar and others, 1986). In such an acid rain crisis, limestone caves could have been important refugia for birds, mammals, amphibians, and small reptiles.

Paleotopography. The close juxtaposition of the moderately drained lower part and poorly drained upper part of the type Sikahk clay could be interpreted as a paleotopographic change but was not an especially profound one, because even the Otsskolike lower part of the Sikahk paleosol probably had a water table within a meter of the surface, as indicated by high FeO/Fe_2O_3 ratios (Fig. 5). Similar modern profiles are common in fluviodeltaic settings such as the upper delta plain of the Mississippi River and are a natural product of subsidence of levees below swamps and lagoons after channel abandonment (Coleman, 1988). There were two or three additional moderately developed coaly paleosols above the lower Z coal (Fig. 4), indicating that swampy lowland landscapes and rates of subsidence comparable to those in the Hell Creek Formation persisted for several thousand years into the Tertiary (as estimated from time for formation of Sik paleosols; Table 3). At some time before the accumulation of the uppermost Z coal, however, there was unusually deep channel downcutting by 20 m or more (Fig. 10; by the "Big Bugger" of Smit and others, 1987). From then on paleosols are not so well developed and are well spaced in the sequence. These are indications of a dramatic increase in the rate of sediment accumulation, probably due to regional uplift of the ancestral Bighorn Mountains and Black Hills (Cherven and Jacob, 1985). A time of gully erosion represented by the "Big Bugger" paleochannel represents a time of geomorphic adjustment between the relatively stable lowland alluvial plain of Cretaceous to earliest Paleocene time, and the rapidly aggrading, yet even more swampy, alluvial outwash of Paleocene time.

Parent Material. Sediment composition across the Cretaceous-Tertiary boundary reflects a mix of materials derived from a volcanic arc developed on metamorphic rocks of the Cordillera and sedimentary rocks from the rising Rocky Mountains, including forerunners of the Bighorn Mountains and Black Hills. Starting with filling of the "Big Bugger" paleochannel at a time significantly into the Paleocene, carbonate and other sedimentary clasts begin to dominate the volcanic component (Cherven and Jacob, 1985).

Time for Formation. The type Sikahk clay paleosol includes the palynological Cretaceous-Tertiary boundary and a weak Ir anomaly some 10 to 20 cm below the contact between claystone and coal. It probably formed for some 10 000–60 000 yr before the boundary, as for comparable Otssko paleosols, and is overlain by 15 cm of coal. Woody peats typically accumulate at rates of 0.5–1 mm/yr (Moore and Bellamy, 1973; Retallack, 1990), so assuming a compaction of the coal to 25% of peat thickness (Cherven and Jacob, 1985), this coal represents some 600 to 1200 yr. As a record of events before and at the boundary, this paleosol has a resolution of only tens of thousands of years, but the coaly surface (O) horizon has a high-resolution palynological record (Smit and others, 1987; Hotton, 1988).

The total thickness of Z coals, beneath and excluding the uppermost Z coal, is 42 cm (Fig. 4). Using the same method of estimating from coal thickness, the time elapsed between the Cretaceous-Tertiary boundary and the erosional downcutting of the "Big Bugger" that truncates these coals would have been ~3000 yr (1680–3360 calculated) for peat accumulation and 4000 yr for development of Makalike underclays. Several thousand years also is represented by the upper Z coal, some 38 cm thick.

Early Paleocene

Paleoclimate. The type Komono clay is one of the few moderately developed Paleocene paleosols lacking coal and so potentially the most useful indicator of paleoclimate, as opposed to a swamp soil microclimate. The Komono clay is impressively leached of alkalies and alkaline earths (high alumina:bases ratio of Fig. 8) compared with its calcareous parent materials, and yet the degree of clay enrichment (Fig. 8) and persistence of some relict bedding are indications of weak to moderate development. This is evidence of a humid climate, probably well in excess of 1200 mm mean annual precipitation by comparison with the calcic/noncalcic boundary in Quaternary soils (discussed by Yaalon, 1983; Retallack, 1994).

There is no clear evidence from paleosols for change in mean annual temperature or in seasonality in Paleocene compared with Cretaceous time. Charcoal is as common in Paleocene as Cretaceous swamp paleosols (Rigby and Rigby, 1990), and as abundant as in modern, seasonally dry swamps such as the Okefenokee Swamp of Georgia (Izlar, 1984).

Ancient Vegetation. Taxodiaceous conifers such as water pine (*Glyptostrobus*) became very abundant in widespread swamps during Paleocene time, as indicated by fossil foliar spurs and pollen associated with Sik paleosols (Fig. 11, Table 3). Both short-leafed evergreen (cupressoid) and long-leafed deciduous (taxodioid) foliage of *Glyptostrobus* have been found, presumably a reflection of seasonal variation in water or nutrient availability (Chaney and Axelrod, 1959; Hickey, 1977). Fossil stumps in one of the Sik paleosols (at 35 m in Fig. 4), and fossil logs in many of them, are evidence that these were swamp woodlands. They also included ferns and a variety of deciduous angiosperms, in vegetation generally similar to that of Okefenokee Swamp, Georgia (Best and others, 1984). Some Paleocene wetlands may have been fern dominated (Hotton, 1988), but such marshes were not as common here in the Williston Basin as in coeval wetlands of the Powder River Basin to the southwest in Wyoming (Nichols and Brown, 1992).

Plants probably lost their leaves during a short dry season, when the water table was low, as indicated by deeply penetrating root traces, slickensided clay skins, chemical weathering beneath the coals (Figs. 7 and 8), and abundant charcoal (Rigby and Rigby, 1990). Extinct deciduous relatives of sycamore and katsura remained prominent in colonizing forests of clayey levees (Maka Series) and in midsuccessional forests of seasonally wet flood plains (Komono Series). Also common in midsuccessional forests was a cypress (*Cupressinocladus interruptus* leaves of Johnson, 1989; better

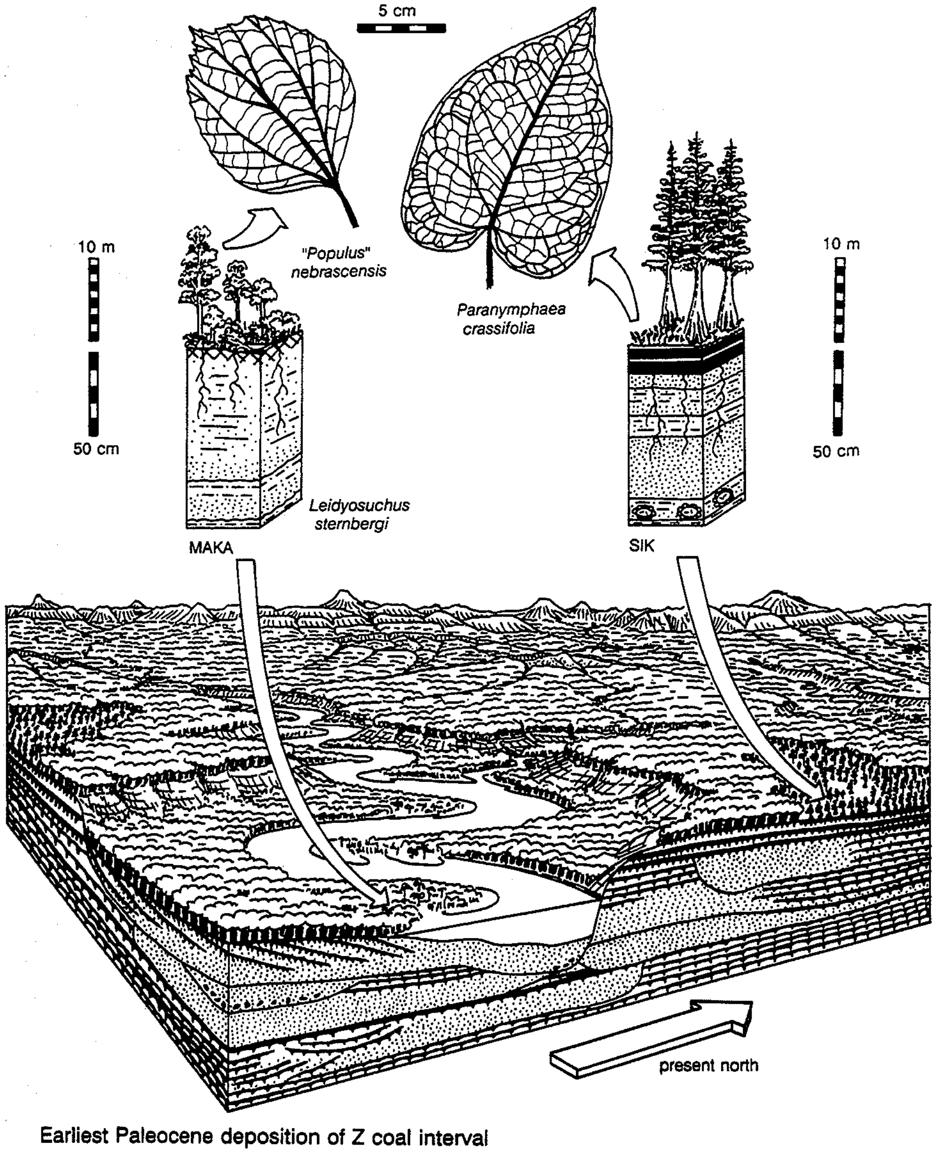

Figure 10. Interpreted pedotypes and representative fossil plants and animals within a sedimentary framework (established by facies analysis) in eastern Montana during earliest Paleocene time. Breaks in scales between vegetation and soil and between landscape and sediments have been used to emphasize details of pedotype profiles and sedimentology. Ticked lines represent paleosols, and stipple pattern is for paleochannels. Other lithologic symbols are as for Figure 4.

understood as the cones *Mesocyparis borealis* of McIver and Basinger, 1987). All the paleosols were either waterlogged or strongly depleted of nutrients, so these were oligotrophic woodland ecosystems.

Former Animal Life. Paleocene Komono paleosols were noncalcareous and so not suitable for preservation of bone (Retallack, 1984). Fossil vertebrates found in Maka and Sik paleosols included crocodiles, champsosaurs, and turtles (Table 3), which are all interpreted as aquatic creatures. Calcareous paleochannel sandstones in the Bug Creek area have preserved a record of the dramatic early Paleocene adaptive radiation of a variety of small arboreal mammals (Archibald, 1982; Archibald and Bryant, 1990; Sloan and others, 1986). Among abundant fish, amphibians, reptiles, and birds from these Paleocene paleochannels were large boas, birds, champsosaurs, and crocodiles (Estes and Berberian, 1970). With the disappearance of dinosaurs, these communities with so few large terrestrial animals would have been unusual by comparison with modern North American swamps, such as the Okefenokee swamp of Georgia, with its deer, black bear, and cougar (Laerm and others, 1984).

Paleotopography. The abundant coals of the Paleocene Tullock Formation are evidence of a coastal plain west of the Cannonball Sea of North Dakota (Fig. 11; Cherven and Jacob, 1985). Swamp woodlands were dissected by sinuous streams (Diemer and Belt, 1991) whose levees were less permanently saturated and so probably more elevated than the adjacent channel or backswamp, thus allowing subsurface clay accumulation in some paleosols (type Komono clay).

Parent Material. Paleochannels and other sedimentary parent materials of Paleocene paleosols are moderately to strongly calcareous, with slightly more common clasts of carbonate and shale than lower in the sequence studied. Overall, sedimentary parent material remained quartzofeldspathic in composition, and neither heavy minerals nor clay composition changed appreciably across the Cretaceous-Tertiary boundary at Bug Creek (Bell, 1965). Increased carbonate clasts may be related to ongoing uplift of the Bighorn Mountains and Black Hills and their Paleozoic limestones (Cherven and Jacob, 1985).

Time for Formation. Maka paleosols are very weakly developed and represent only hundreds of years of soil formation, but weakly to moderately developed Komono paleosols may represent several thousands of years (Table 3). These are radiocarbon age estimates for Commerce, Sharkey, and Mhoon soils of the modern Mississippi Delta (Matthews, 1983, 1984), which show profile differentiation and destruction of bedding comparable with the paleosols.

Most of the Paleocene paleosols in the studied section were Sik pedotypes, which are lignites formed from logs and, in some cases, stumps of swamp woodland trees. Because tree roots require oxygen to live, the accumulation of peat in swamp woodlands is scaled close to the rate of growth of trees. At high rates of subsidence trees are flooded by lakes, and at low rates peat decays as fast as it accumulates. Bald cypress in the Okefenokee Swamp of Georgia has accumulated 5.9 m of peat in 7000 yr (Cohen, 1985), for a long-term accumulation rate of 0.84 mm/yr. Marsh peats of the Mississippi Delta (Frazier and Ozanik, 1969) and *Sphagnum* peats of alpine bogs (Moore and Bellamy, 1973) accumulate at faster rates, but woody peats

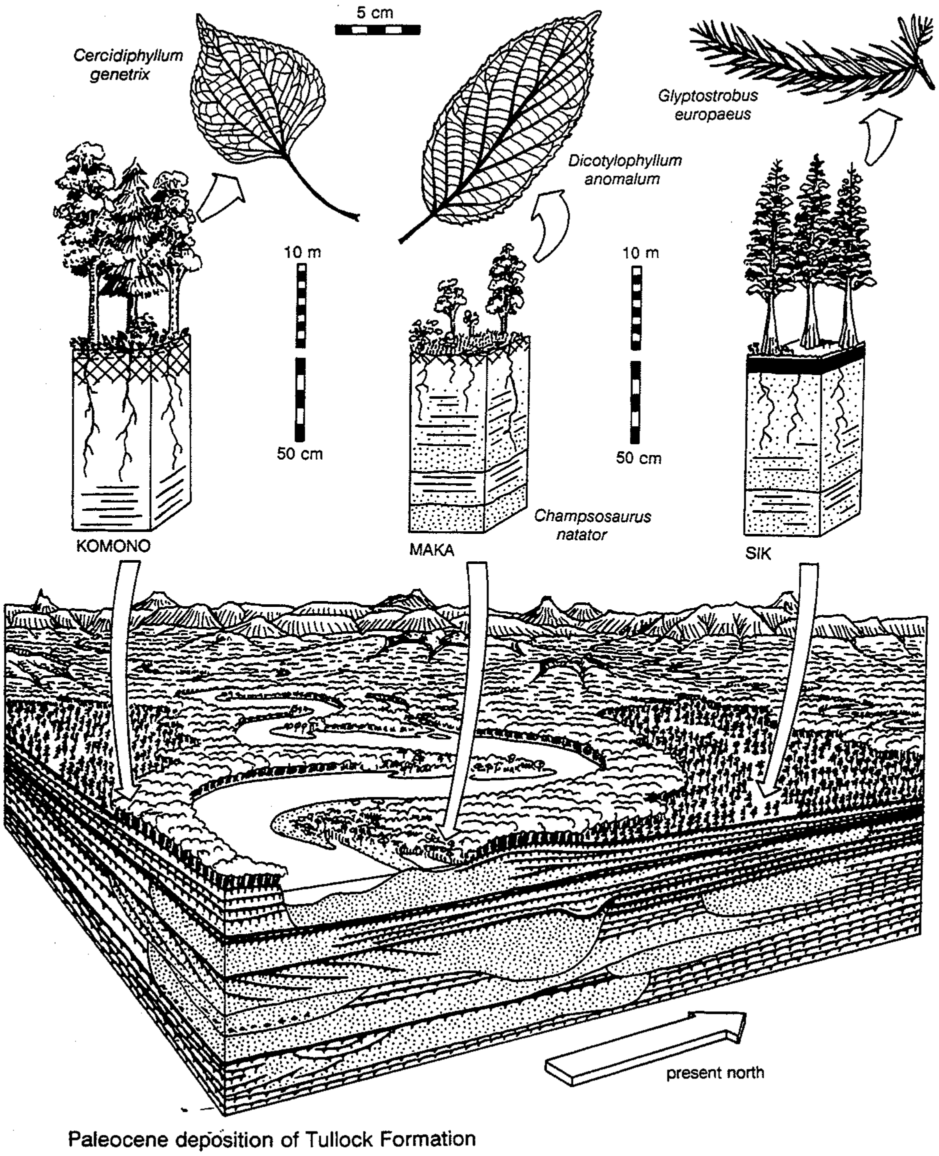

Figure 11. Interpreted pedotypes and representative fossil plants and animals within a sedimentary framework (established by facies analysis) in eastern Montana during early Paleocene time. Breaks in scales between vegetation and soil and between landscape and sediments have been used to emphasize details of pedotype profiles and sedimentology. Ticked lines represent paleosols, and stipple pattern is for paleochannels. Other lithologic symbols are as for Figure 4.

typically accumulate at long-term rates of 0.5–1 mm/yr (Retallack, 1990). At these rates and a likely compaction of Tullock lignites to 25% of former peat thickness (Cherven and Jacob, 1985), a range of estimates of the time in years for accumulation of each coal can be calculated by multiplying thickness of the coal (in centimeters from Fig. 4) by 40–80. The thinnest coal seen was 6 cm thick (240–480 yr), and the thickest was 60 cm (2400–4800 yr), although one seam had 116 cm of coal (5760–9280 yr) divided by four thin claystone beds. To this can be added ~500 yr for each Makalike underclay, representing disruption of bedding by deeply rooted vegetation prior to peat accumulation. These estimates seem low considering that there is an aggregate thickness of coal of 144 cm representing ~10 000 yr (5760–11 520) of peat accumulation and 3500 yr of underclay development between the basal Z coal and the top of the Y coals, an interval that represents ~200 000 yr of magnetic Chron 29R (Archibald and others, 1982; Courtillot and others, 1990; d'Hondt and Herbert, 1992). These estimates do not include time missing in the erosional scour of paleochannels such as the "Big Bugger," which could amount to tens of thousands of years.

General Comparisons. Considered from the perspective of the F.A.O. world map of soils, the suite of common Dystric Histosols, with less abundant Dystric Fluvisols and Dystric Gleysols in the Tullock Formation is most like soil assemblages of coastal swamps in El Salvador, Honduras, Panama, Costa Rica, Nicaragua, and Belize (map units Od7-2a and Od7-3a of F.A.O., 1975a); the Mississippi Delta in Louisiana; the Dismal Swamp in Virginia and North Carolina; the Sacramento Delta in California; the Okefenokee Swamp in Georgia; and the eastern Everglades in Florida (Fig. 1; map unit Od1-a of F.A.O., 1975b). Sik paleosols were peaty and had gleyed underclays like Pamlico soils of Okefenokee and Okechobee Swamps in Florida and Georgia (McCollum and Pendleton, 1971; Howell, 1984; Coultas and Duever, 1984) and Barbary muck soils of the Mississippi Delta in Louisiana (Matthews, 1983, 1984). Mississippi Delta-plain soils similar to Maka and Komono paleosols in their limited destruction of silty laminae are Mhoon and Sharkey soils, respectively (Lytle and others, 1956; Matthews, 1983, 1984; Trahan and others, 1989). Mississippi Delta swamps dominated by deciduous taxodiaceous conifers (*Taxodium distichum*), levees colonized by live oak (*Quercus virginiana*), and frost-intolerant palmetto (*Sabal minor*; Frazier and Ozanik, 1969) also are floristically similar to the fossil flora of the Tullock Formation.

DISCUSSION

Cretaceous-Tertiary sediments of eastern Montana are well suited for comparison of different approaches to the study of paleosols because they are varied in sedimentary facies, richly fossiliferous, and recently studied in detail by many investigators. Individual lignite seams can be regarded as geosols, but other kinds of paleosols are too numerous and poorly exposed for a geosol approach to be useful for them (Fig. 3). Lateral correlation of many paleosols is hampered by imperfect exposures and abundant paleochannels, and these limitations have also made facies and pedofacies mapping difficult and controversial (Fastovsky and Dott, 1986; Rigby and others, 1987). Pedotypes, in contrast, carry no implication of lateral mappability. The pedotype approach emphasizes profiles, many of which can be recognized in trenches excavated to improve the slumped badlands exposures of claystones at Bug Creek (Fig. 4). Each paleosol does not need a separate name, because the pedotype approach merely groups similar profiles together. In emphasizing whole profiles, pedotypes present unique combinations of features and allow identification of profiles within classifications of soils, unlike the more generalized consideration of features of paleosols used in sedimentary facies and pedofacies studies. On the other hand, pedofacies and geosol approaches to paleosols can more rapidly establish the distributions of paleosol features stratigraphically and within sedimentary facies, because they do not require trenching and supporting laboratory analysis of the pedotype approach. Pedotypes, pedofacies, and geosols are alternative nongenetic approaches to the study of paleosols.

Pedotypes can serve as a basis for interpretation of paleoenvironments complementary to community paleoecology and sedimentary facies analysis. Pedotypes provide a basis for grouping fossil assemblages into paleoecosystem types and are especially useful for collating sparse fossil data, as in the Sapakot and Spatsiko pedotypes at Bug Creek. Pedotypes can be recognized within sedimentary facies, which provide a framework for reconstructing their paleotopographic position (Figs. 9–11). Pedotype interpretations also provide new perspectives on paleoenvironments not attainable by other means.

Pedotypes allow reassessment of the fossil record. At Bug Creek, interpretation of pedotypes as preservational environments for fossils lends support to inferences of catastrophic disruption of plant communities (Hotton, 1988; Johnson and Hickey, 1989) rather than gradual change in vertebrate fossils (Sloan and others, 1986). Most of the paleosols are drab colored and rich in organic matter (Figs. 5–8) and so are favorable to the preservation of fossil plants. In contrast, only a few of the paleosols are calcareous enough to preserve fossil bone, most of which is found in mixed and transported assemblages of paleochannels (Retallack and others, 1987).

Pedotypes also allow reassessment of sedimentation rates and processes, largely because they indicate the lengths of time between sedimentary events. Paleosol spacing and development (Fig. 4) are evidence of a profound discontinuity some distance above the Cretaceous-Tertiary boundary when sedimentation rates accelerated. Across the Cretaceous-Tertiary boundary itself, however, which is marked by a change to more coaly facies, sedimentation remained relatively steady and slow, with accumulation of a succession of moderately developed paleosols. The time for formation for each paleosol estimated by comparison with soils (Table 3) allows assessment of rate of sediment accumulation, and these estimates tally well with paleomagnetic estimates for the duration of this section. This is a relatively high-resolution record of the Cretaceous-Tertiary boundary for a sequence of paleosols that by definition includes numerous small breaks in sedimentation. The individual breaks in sedimentation also can be identified and their relative magnitude estimated.

Finally, pedotypes are records of past ecosystems. It is remarkable how little local soils changed following the disruption of plant and animal communities at the Cretaceous-Tertiary boundary. There are indications of crisis at the boundary, but they are slight and of shorter duration than the moderately developed paleosols at the boundary at Bug Creek. Peaty soils were much more widespread after the boundary than before, but this was local facies shift of a kind seen many times in the Western Interior during Late Cretaceous time (Jerzykiewicz and Sweet, 1988). Peaty soils, clayey moderately drained soils, and nearstream sandy and clayey soils were present both during the latest Cretaceous and earliest Paleocene. Comparable modern soils can be found in lowland southwestern United States and parts of Central America. The striking extinctions of plant (Hotton, 1988; Johnson and Hickey, 1990) and vertebrate species (Sheehan and others, 1991; Sheehan and Fastovsky, 1992) seem out of all proportion to the slight paleoenvironmental changes indicated by paleosols. In terms of species, Late Cretaceous communities were different from those of the earliest Paleocene, but in terms of ecosystem properties reflected in paleosols, early Paleocene flood-plain forests were only a little more oligotrophic than comparable Cretaceous ecosystems. The theater and much of its fundamental organization survived, though many of the players and subplots did not.

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REFERENCES CITED

Archibald, J. D., 1982, A study of Mammalia and geology across the Cretaceous-Tertiary boundary in Garfield County, Montana: University of California Publications in Geological Sciences, v. 122, 286 p.

Archibald, J. D., and Bryant, L. J., 1990, Differential Cretaceous/Tertiary extinctions of nonmarine vertebrates: Evidence from northeastern Montana, *in* Sharpton, V. L., and Ward, P. E., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 549–562.

Archibald, J. D., and Lofgren, D. L., 1990, Mammalian zonation near the Cretaceous-Tertiary boundary in the Western Interior of North America, *in* Rose, K. D., and Bown, T., eds., Dawn of the Age of Mammals in the northern part of the Rocky Mountain interior: Geological Society of America Special Paper 243, p. 31–50.

Archibald, J. D., Butler, R. F., Lindsay, E. H., Clemens, W. A., and Dingus, L., 1982, Upper Cretaceous-Paleocene biostratigraphy and magnetostratigraphy, Hell Creek and Tullock Formations, northeastern Montana: Geology, v. 10, p. 153–159.

Axelrod, D. I., 1975, Evolution and biogeography of Madrean-Tethyan sclerophyll vegetation: Missouri Botanical Garden Annals, v. 62, p. 280–284.

Baldwin, B., and Butler, C. O., 1985, Compaction curves: American Association of Petroleum Geologists Bulletin, v. 69, p. 622–626.

Bauer, C. M., 1924, The Ekalaka lignite field: U.S. Geological Survey Bulletin 751-F, p. 231–267.

Bell, R. E., 1965, Geology and stratigraphy of the Fort Peck fossil field, northwest McCone County, Montana [Master's thesis]: Minneapolis, University of Minnesota, 166 p.

Best, G. R., Hamilton, D. B., and Auble, G. J., 1984, An old growth cypress stand in Okefenokee Swamp, *in* Cohen, A. D., Casagrande, D. J., Andrejko, M. J., and Best, G. R., eds., The Okefenokee Swamp: Los Alamos, New Mexico, Wetland Surveys, p. 132–143.

Birkeland, P. W., 1990, Soil geomorphic research—A selective overview, *in* Kneupfer, P. L. K., and McFadden, L. D., eds., Soils and landscape evolution: Geomorphology, v. 3, p. 207–224.

Bohor, B. F., Triplehorn, D. M., Nichols, D. J., and Millard, H. T., 1987, Dinosaurs, spherules and the "magic" layer: A new K-T boundary clay site in Wyoming: Geology, v. 15, p. 896–899.

Bown, T. M., and Kraus, M. J., 1987, Integration of channel and floodplain suites in aggrading fluvial systems. I, Developmental sequence and lateral relations of lower Eocene alluvial paleosols, Willwood Formation, Bighorn basin, Wyoming: Journal of Sedimentary Petrology, v. 57, p. 587–601.

Brammer, H., 1971, Coatings in seasonally flooded soils: Geoderma, v. 6, p. 5–16.

Breedlove, D. E., 1973, The phytogeography and vegetation of Chiapas (Mexico), *in* Graham, A., ed., Vegetation and vegetational history of northern Latin America: Amsterdam, Elsevier, p. 149–165.

Brewer, R., 1976, Fabric and mineral analysis of soils (second edition): New York, Krieger, 482 p.

Brown, B., 1907, The Hell Creek beds of the Upper Cretaceous of Montana: American Museum of Natural History Bulletin, v. 23, p. 823–845.

Chaney, R. W., and Axelrod, D. I., 1959, Miocene floras of the Columbia Plateau: Carnegie Institution of Washington Publication 617, 237 p.

Cherven, V. B., and Jacob, A. F., 1985, Evolution of Paleogene depositional systems, Williston basin, in response to global sea level change, *in* Flores, R. M., and Kaplan, S. S., eds., Cenozoic paleogeography of west-central United States: Denver, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 127–167.

Cohen, A. S., 1985, The Okefenokee Swamp: A low-sulfur end-member of a depositional model for coastal plain coals, *in* Cross, A. T., ed., Economic geology: Coal, oil and gas: Neuvième Congrès International de Stratigraphie et de Géologie du Carbonifère, Comptes Rendus, v. 4, p. 189–298.

Coleman, J. M., 1988, Dynamic changes and processes in the Mississippi River Delta: Geological Society of America Bulletin, v. 100, p. 999–1015.

Collier, A. J., 1924, The Scobey lignite field, Valley, Daniels and

Sheridan Counties, Montana: U.S. Geological Survey Bulletin 751-E, p. 157–230.

Collier, A. J., and Knechtel, M., 1939, The coal resources of McCone County, Montana: U.S. Geological Survey Bulletin 1055B, p. 11–57.

Coe, M. J., Dilcher, D. L., Farlow, J. O., Jarzen, D. M., and Russell, D. A., 1987, Dinosaurs and land plants, *in* Friis, E. M., Chaloner, W. G., and Crane, P. R., eds., The origins of angiosperms and their biological consequences: New York, Cambridge University Press, p. 225–258.

Cope, M. J., and Chaloner, W. G., 1985, Wildfire: An interaction of ecological and physical processes, *in* Tiffney, B. H., ed., Geological factors in the evolution of plants: New Haven, Connecticut, Yale University Press, p. 257–277.

Coultas, C. L., and Duever, M. J., 1984, Soils of cypress swamps, *in* Ewel, K. C., and Odum, H. T., eds., Cypress swamps: Gainesville, University of Florida Press, p. 51–59.

Courtillot, V., Vandamme, D., Besse, J., Jaeger, J. J., and Javoy, M., 1990, Deccan volcanism at the Cretaceous Tertiary boundary; Data and inferences, *in* Sharpton, V. L., and Ward, P. E., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 401–409.

Crane, P. R., 1987, Vegetational consequences of the angiosperm diversification, *in* Friis, E. M., Chaloner, W. G., and Crane, P. R., eds., The origins of angiosperms and their biological consequences: New York, Cambridge University Press, p. 107–144.

Czerkas, S. J., and Glut, D. F., 1982, Dinosaurs, mammoths and cavemen: The art of Charles R. Knight: New York, E. P. Dutton, 119 p.

Czerkas, S. J., and Olson, E. C., eds., 1987, Dinosaurs past and present, Volume II: Los Angeles, Natural History Museum of Los Angeles County, 150 p.

Dance, R. E., Griffis, B. J., Nutt, B. B., White, A. G., Lytle, S. A., and Seaholm, J. E., 1968, Soil survey of east Baton Rouge Parish, Louisiana: U.S. Soil Conservation Service Soil Survey, v. 7, 80 p.

d'Hondt, S., and Herbert, D., 1992, Precessional chronostratigraphy of the Cretaceous-Tertiary boundary: International Geological Congress, 29th, Kyoto, Japan, Abstracts, v. 2, p. 244.

Diemer, J. A., and Belt, E. S., 1991, Sedimentology and paleohydraulics of the meandering river systems of the Fort Union Formation, southeastern Montana: Sedimentary Geology, v. 75, p. 85–108.

Dingus, L. W., 1984, Effects of stratigraphic completeness on interpretation of extinction rates across the Cretaceous-Tertiary boundary: Paleobiology, v. 10, p. 420–438.

Elliott, R. E., 1985, Quantification of peat to coal compaction stages, based especially on phenomena in the East Pennine coalfield, England: Yorkshire Geological Society Proceedings, v. 45, p. 163–172.

Estes, R., and Berberian, P., 1970, Paleoecology of a Late Cretaceous vertebrate community from Montana: Breviora 343, 35 p.

F.A.O., 1974, Soil map of the world, Volume I, Legend: Paris, U.N.E.S.C.O., 59 p.

F.A.O., 1975a, Soil map of the world, Volume III, Central America: Paris, U.N.E.S.C.O., 96 p.

F.A.O., 1975b, Soil map of the world, Volume II, North America: Paris, U.N.E.S.C.O., 210 p.

Fassett, J. E., and Rigby, J. K., eds., 1987, The Cretaceous-Tertiary boundary in the San Juan and Raton basins, New Mexico and Colorado: Geological Society of America Special Paper 209, 200 p.

Fastovsky, D. E., 1987, Paleoenvironments of vertebrate-bearing strata during the Cretaceous-Paleogene transition, eastern Montana and western North Dakota: Palaios, v. 2, p. 281–295.

Fastovsky, D. E., 1990, Rocks, resolution and the record: A review of depositional constraints on fossil assemblages at the terrestrial Cretaceous/Paleogene boundary, eastern Montana and western North Dakota, *in* Sharpton, V. L., and Ward, P. E., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 541–548.

Fastovsky, D. E., and Dott, R. H., 1986, Sedimentology, stratigraphy and extinctions during the Cretaceous-Paleogene transition at Bug Creek, Montana: Geology, v. 14, p. 279–282.

Fastovsky, D. E., and McSweeney, K., 1987, Paleosols spanning the Cretaceous-Paleogene transition, eastern Montana and western North Dakota: Geological Society of America Bulletin, v. 99, p. 66–77.

Fastovsky, D. E., McSweeney, K., and Norton, L. D., 1989, Pedogenic development at the Cretaceous-Tertiary boundary, Garfield County, Montana: Journal of Sedimentary Petrology, v. 59, p. 758–767.

Frantz, D. G., and Russell, N. J., 1989, Blackfoot dictionary of stems, roots and affixes: Toronto, University of Toronto Press, 470 p.

Frazier, D. E., and Ozanik, A., 1969, Recent peat deposits—Louisiana coastal plain, *in* Dapples, E. C., and Hopkins, M. E., eds., Environments of coal deposition: Geological Society of America Special Paper 114, p. 63–85.

Galton, P. M., 1974, Notes on *Thescelosaurus*, a conservative ornithopod dinosaur from the Upper Cretaceous of North America, with comments on ornithopod classification: Journal of Paleontology, v. 48, p. 1048–1067.

Hares, C. J., 1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: U.S. Geological Survey Bulletin 775, 110 p.

Hartshorn, G. S., 1983, Plants, *in* Janzen, D. H., ed., Costa Rican natural history: Chicago, University of Chicago Press, p. 118–158.

Henry, A., and McIntyre, M., 1926, The swamp cypresses *Glyptostrobus* of China and *Taxodium* of America, with notes on allied genera: Royal Irish Academy Proceedings, v. 37, p. 90–116.

Hickey, L. J., 1977, Stratigraphy and paleobotany of the Golden Valley Formation (Early Tertiary) of western North Dakota: Geological Society of America Memoir 150, 183 p.

Hildebrand, A. R., Penfield, G. T., Kring, D. A., Pilkington, M., Camargo, Z. A., Jacobsen, S. B., and Boynton, W. V., 1991, Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico: Geology, v. 19, p. 867–871.

Horrell, M. A., 1991, Phytogeography and palaeoclimate interpretation of the Maastrichtian: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 86, p. 87–138.

Hotton, C. L., 1988, Palynology of the Cretaceous-Tertiary boundary in central Montana, U.S.A., and its implications for extraterrestrial impact [Ph.D. thesis]: Davis, University of California, 732 p.

Howell, D. A., 1984, Soil survey of Columbia County, Florida: U.S. Soil Conservation Service Soil Survey, v. 38, 187 p.

Isbell, R. F., 1983, Kimberley-Arnhem-Cape York (III), *in* CSIRO, ed., Soils: An Australian viewpoint: Melbourne, Australia, Academic Press, p. 190–199.

Izett, G. A., 1990, The Cretaceous/Tertiary boundary interval, Raton Basin, Colorado and New Mexico, and its content of shock-metamorphosed minerals: Evidence relevant to the K/T boundary impact theory: Geological Society of America Special Paper 247, 100 p.

Izett, G. A., Cobban, W. A., Obradovich, J. D., and Kunk, M. J., 1993, The Manson impact structure: ^{40}Ar/^{39}Ar age and its distal impact ejecta in the Pierre Shale in southeastern South Dakota: Science, v. 242, p. 729–732.

Izett, G. A., Dalrymple, G. B., and Snee, L. W., 1991, ^{40}Ar/^{39}Ar age of Cretaceous-Tertiary boundary tektites from Haiti: Science, v. 252, p. 1539–1542.

Izlar, R. L., 1984, Some comments on fire and climate in the Okefenokee swamp-marsh complex, *in* Cohen, A. D., Casagrande, D. J., Andrejko, M. T., and Best, G. R., eds., Okefenokee Swamp: Los Alamos, New Mexico, Wetland Surveys, p. 70–85.

Jenny, H., 1941, Factors in soil formation: New York, McGraw-Hill, 281 p.

Jerzykiewicz, T., and Sweet, A. R., 1988, Sedimentological and palynological evidence of regional climatic changes in the Campanian to Paleocene sediments of the Rocky Mountains, Canada: Sedimentary Geology, v. 59, p. 29–76.

Johnson, K. R., 1989, A high-resolution megafloral biostratigraphy spanning the Cretaceous/Tertiary boundary in the northern Great Plains [Ph.D. thesis]: New Haven, Connecticut, Yale University, 556 p.

Johnson, K. R., and Hickey, L. J., 1990, Megafloral change across the Cretaceous/Tertiary boundary in the northern Great Plains and Rocky Mountains, U.S.A., *in* Sharpton, V. L., and Ward, P. E., eds., Global catastrophes in Earth history: Geological Society of America Special Publication 247, p. 433–444.

Laerm, J., Freeman, B. J., Vitt, L. J., and Logan, L. E., 1984, Appendix A, checklist of vertebrates of Okefenokee Swamp, *in* Cohen, A. D., Casagrande, D. J., Andrejko, M. J., and Best, M. R., eds., Okefenokee Swamp: Los Alamos, New Mexico, Wetland Surveys, p. 682–701.

Lehman, T. H., 1989, Upper Cretaceous (Maastrichtian) paleosols in Trans-Pecos Texas: Geological Society of America Bulletin, v. 101, p. 188–203.

Lehman, T. H., 1990, Paleosols and the Cretaceous/Tertiary transition in the Big Bend region of Texas: Geology, v. 18, p. 362–364.

Lockley, M., 1991, Tracking dinosaurs: Cambridge, United Kingdom, Cambridge University Press, 238 p.

Lofgren, D. L., Hotton, C. L., and Runkel, A. C., 1990, Reworking of Cretaceous dinosaurs into Paleocene channel deposits, upper Hell Creek Formation, Montana: Geology, v. 18, p. 874–877.

Lugo, A. E., Nessel, J. K., and Hanlon, T. M., 1984, Root distribution in a north-central Florida cypress stand, *in* Ewel, K. C., and Odum, H. T., eds., Cypress swamps: Gainesville, University of Florida Press, p. 279–285.

Lytle, S. A., McMichael, C. W., and Francis, E. L., 1956, Soil survey of Terrebonne Parish, Louisiana: U.S. Soil Conservation Service Soil Survey, v. 1, 43 p.

Matthews, S. D., 1983, Soil survey of Jefferson Parish, Louisiana: U.S. Soil Conservation Service Soil Survey, v. 24, 15 p.

Matthews, S. D., 1984, Soil survey of Lafourche Parish, Louisiana: U.S. Soil Conservation Service Soil Survey, v. 25, 106 p.

McCollum, S. H., and Pendleton, R. F., 1971, Soil survey of Okechobee County, Florida: U.S. Soil Conservation Service Soil Survey, v. 14, 62 p.

McIver, E. E., and Basinger, J. F., 1987, *Mesocyparis borealis* gen. et sp. nov., a fossil Cupressaceae from the early Tertiary of Saskatchewan, Canada: Canadian Journal of Botany, v. 65, p. 2338–2351.

McSweeney, K., and Fastovsky, D. E., 1987, Micromorphological and SEM analysis of Cretaceous-Paleogene petrosols from eastern Montana and western North Dakota: Geoderma, v. 40, p. 49–63.

McSweeney, K., and Fastovsky, D. E., 1990, Recognition and interpretation of cemented subsurface horizons in sandy paleosols of Cretaceous-Paleogene age, eastern Montana, *in* Douglas, L. A., ed., Soil micromorphology: A basic and applied science: Amsterdam, Elsevier, p. 683–688.

Mitsch, W. J., 1984, Seasonal patterns of a cypress dome in Florida, *in* Ewel, K. C., and Odum, H. T., eds., Cypress swamps: Gainesville, University of Florida Press, p. 25–33.

Moore, P. D., and Bellamy, D. J., 1973, Peatlands: New York, Springer, 221 p.

Morrison, R. B., 1978, Quaternary soil stratigraphy—Concepts, methods and problems, *in* Mahaney, W. C., ed., Quaternary soils: Norwich, England, Geoabstracts, p. 77–108.

Munsell Color Company, 1975, Munsell color chart: Baltimore, Munsell Color, 24 p.

Murphy, C. P., 1983, Point-counting pores and illuvial clay in thin section: Geoderma, v. 31, p. 133–150.

Murphy, K. E., Daigle, J. T., and Roetker, L. J., 1977, Soil survey of Lafayette Parish, Louisiana: U.S. Soil Conservation Service Soil Survey, v. 14, 80 p.

Nelson, D. W., and Sommer, E., 1982, Total carbon, organic carbon and organic matter, *in* Page, A. L., ed., Methods of soil analysis, part 2 (second edition): Madison, Wisconsin, Soil Science Society of America, p. 539–579.

Nichols, D. J., and Brown, J. L., 1992, Palynostratigraphy of the Tullock Member (lower Paleocene) of the Fort Union Formation in the Powder River Basin, Montana: U.S. Geological Survey Bulletin 1917F, 35 p.

Nichols, D. J., and Fleming, R. F., 1990, Plant microfossil record of the terminal Cretaceous event in the western United States and Canada, *in* Sharpton, V. L., and Ward, P. D., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 445–455.

Nichols, D. J., Hickey, L. J., McSweeney, L. J., and Wolfe, J. A., 1992, Plants at the K/T boundary: Discussion and reply: Nature, v. 356, p. 295–296.

North American Commission on Stratigraphic Nomenclature, 1983, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841–875.

Northcote, K. H., 1974, A factual key for the recognition of Australian soils: Adelaide, Australia, Rellim, 123 p.

Norton, N. J., and Hall, J. W., 1969, Palynology of the Upper Cretaceous and lower Tertiary of the type locality of the Hell Creek Formation: Palaeontographica, v. B125, p. 1–64.

Ostrom, J. H., and Wellnhofer, P., 1990, *Triceratops*: An example of flawed systematics, *in* Carpenter, K., and Currie, P. J., eds., Dinosaur systematics: New York, Cambridge University Press, p. 247–254.

Pelczar, M. J., Chan, E. C. S., Krieg, N. R., and Pelczar, M. F., 1986, Microbiology: New York, McGraw-Hill, 918 p.

Porter, D. M., 1973, The vegetation of Panama: A review, *in* Graham, A., ed., Vegetation and vegetational history of northern Latin America: Amsterdam, Elsevier, p. 167–201.

Retallack, G. J., 1977, Triassic palaeosols in the Narrabeen Group of New South Wales. Part II. Classification and reconstruction: Geological Society of Australia Journal, v. 34, p. 19–35.

Retallack, G. J., 1983, Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota: Geological Society of America Special Paper 193, 82 p.

Retallack, G. J., 1984, Completeness of the rock and fossil record: Some estimates using fossil soils: Paleobiology, v. 10, p. 59–78.

Retallack, G. J., 1985, Fossil soils as grounds for interpreting the advent of large plants and animals on land: Royal Society of London Philosophical Transactions, v. B309, p. 105–142.

Retallack, G. J., 1990, Soils of the past: London, Unwin-Hyman, 520 p.

Retallack, G. J., 1991a, Miocene paleosols and ape habitats in Pakistan and Kenya: New York, Oxford University Press, 520 p.

Retallack, G. J., 1991b, Untangling the effects of burial alteration and ancient soil formation: Annual Review of Earth and Planetary Sciences, v. 19, p. 183–206.

Retallack, G. J., 1992, What to call early vegetation on land: Palaios, v. 7, p. 508–520.

Retallack, G. J., 1993, Classification of paleosols: Discussion: Geological Society of America Bulletin, v. 105, p. 1635–1637.

Retallack, G. J., 1994, The environmental factor approach to the interpretation of paleosols, *in* Amundson, R., Harden, J., and Singer, M., eds., Factors of soil formation, a fiftieth anniversary retrospective: Soil Science Society of America Special Publication, v. 33, p. 31–64.

Retallack, G. J., and Dilcher, D. L., 1981, Early angiosperm reproduction: *Prisca reynoldsii* gen. et sp. nov. from mid-Cretaceous coastal deposits in Kansas, U.S.A.: Palaeontographica, v. B179, p. 103–137.

Retallack, G. J., Leahy, G. D., and Spoon, M. D., 1987, Evidence from paleosols for ecosystem changes across the Cretaceous/Tertiary boundary in eastern Montana: Geology, v. 15, p. 1090–1093.

Rigby, J. K., Jr., 1987, The last of the North American dinosaurs, *in* Czerkas, S. J., and Olson, E. C., eds., Dinosaurs past and present, Volume II: Los Angeles, Natural History Museum of Los Angeles County, p. 119–135.

Rigby, J. K., Jr., Newman, K. R., Smit, J., van der Kaars, S., Sloan, R. E., and Rigby, J. K., Sr., 1987, Dinosaurs from the Paleocene part of the Hell Creek Formation, McCone County, Montana: Palaios, v. 2, p. 296–302.

Rigby, J. K., Sr., and Rigby, J. K., Jr., 1990, Geology of the Sand Arroyo and Bug Creek quadrangles, McCone County, Montana: Brigham Young University Geology Studies, v. 36, p. 69–134.

Russell, D. A., 1977, A vanished world: The dinosaurs of western Canada: Ottawa, Ontario, National Museums of Canada, 142 p.

Russell, D. A., 1989, An odyssey in time: Dinosaurs of North America: Toronto, Ontario, Toronto University Press, 239 p.

Sheehan, P. M., and Fastovsky, D. E., 1992, Major extinctions of land dwelling vertebrates at the Cretaceous-Tertiary boundary, eastern Montana: Geology, v. 20, p. 556–560.

Sheehan, P. M., Fastovsky, D. E., Hoffmann, R. G., Berghaus, C. B., and Gabriel, D. L., 1991, Sudden extinction of the dinosaurs: Latest Cretaceous, upper Great Plains, U.S.A.: Science, v. 254, p. 835–839.

Shoemaker, R. E., 1966, Fossil leaves of the Hell Creek and Tullock Formations of eastern Montana: Palaeontographica, v. B119, p. 54–75.

Shoemaker, R. E., 1977, Fossil fig-like objects from the Upper Cretaceous sediments of the Western Interior of North America: Palaeontographica, v. B161, p. 165–175.

Signor, P. W., and Lipps, J. P., 1982, Sampling bias, gradual extinction and catastrophes in the fossil record, *in* Silver, L. T., and Schultz, P. H., eds., Geological implications of impacts of large asteroids and comets on the Earth: Geological Society of America Special Paper 190, p. 291–296.

Sigurdsson, H., 1990, Assessment of the atmospheric impact of volcanic eruptions, *in* Sharpton, V. L., and Ward, P. E., eds., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 99–110.

Sigurdsson, H., d'Hondt, S., and Carey, S., 1992, The impact of the Cretaceous/Tertiary bolide on evaporite terrane and generation of major sulfuric acid aerosol: Earth and Planetary Science Letters, v. 109, p. 543–559.

Sloan, R. E., Rigby, J. K., Jr., Van Valen, L., and Gabriel, D., 1986, Gradual dinosaur extinction and simultaneous ungulate radiation in the Hell Creek Formation: Science, v. 234, p. 1173–1175.

Sloan, R. E., and Van Valen, L., 1965, Cretaceous mammals from Montana: Science, v. 223, p. 1177–1179.

Smit, J., van der Kaars, W. A., and Rigby, J. K., Jr., 1987, Stratigraphic aspects of the Cretaceous-Tertiary boundary in the Bug Creek area of eastern Montana, U.S.A.: Société Géologique de France Mémoire 150, p. 53–73.

Smith, M., and Wilding, L. P., 1972, Genesis of argillic horizons in Ochraqualfs derived from fine textured till deposits of northwestern Ohio and southeastern Michigan: Soil Science Society of America Proceedings, v. 36, p. 808–815.

Soil Survey Staff, 1951, Soil survey manual: U.S. Department of Agriculture Handbook 18, 503 p.

Soil Survey Staff, 1962, Supplement to U.S.D.A. Handbook 18, Soil survey manual (replacing p. 173–188): Washington, D.C., U.S. Government Printing Office.

Soil Survey Staff, 1975, Soil taxonomy: U.S. Department of Agriculture Handbook 436, 754 p.

Soil Survey Staff, 1990, Keys to soil taxonomy: Soil Management Support Services Technical Monograph, v. 19, 422 p.

Spicer, R. A., and Chapman, J. L., 1990, Climate change and the evolution of high latitude terrestrial vegetation and floras: Trends in Ecology and Evolution, v. 5, p. 279–284.

Stace, H. C. T., Hubble, G. D., Brewer, R., Northcote, K. H., Sleeman, J. R., Mulcahy, M. J., and Hallsworth, E. G., 1968, A handbook of Australian soils: Adelaide, Australia, Rellim, 435 p.

Strom, D. E., 1984, Soil survey of McCone County, Montana: Bozeman, Montana, U.S. Soil Conservation Service, 361 p.

Sweet, A. R., Braman, D. R., and Lerbekmo, J. F., 1990, Palynological response to K/T boundary events: A transitory interruption within a dynamic system, *in* Sharpton, V. R., and Ward, P. D., eds., Catastrophes in Earth history: Geological Society of America Special Paper 247, p. 457–469.

Swisher, C. C., Dingus, L., and Butler, R. F., 1993, ^{40}Ar/^{39}Ar dating and magnetostratigraphic correlation of terrestrial Cretaceous-Paleogene boundary and Puercan mammal age, Hell Creek–Tullock Formation, eastern Montana: Canadian Journal of Earth Sciences, v. 30, p. 1981–1996.

Teichmüller, M., 1987, Organic material and very low grade metamorphism, *in* Frey, M., ed., Low temperature metamorphism: Glasgow, Blackie, p. 114–161.

Trahan, L. J., McDaniel, D. R., and Nolde, R., 1989, Soil survey of St Bernard Parish, Louisiana: U.S. Soil Conservation Service Soil Survey, v. 35, 96 p.

Van der Plas, L., and Tobi, A. C., 1965, A chart for judging the reliability of point counting results: American Journal of Science, v. 263, p. 87–90.

Van Valen, L., and Sloan, R. E., 1977, Ecology and extinction of the dinosaurs: Evolutionary Theory, v. 2, p. 37–64.

Walker, P. H., and Butler, B. E., 1983, Fluvial processes, *in* CSIRO, ed., Soils: An Australian perspective: London, Academic Press, p. 83–90.

Wallwork, J. A., 1976, The distribution and diversity of soil fauna: London, Academic Press, 355 p.

Watson, J., and Batten, D. J., 1990, A revision of the English Wealden flora II. Equisetales: British Museum of Natural History, Geological Series, Bulletin 46, p. 37–60.

Wolfe, J. A., 1991, Palaeobotanical evidence for a June "impact winter" at the Cretaceous/Tertiary boundary: Nature, v. 352, p. 420–422.

Wolfe, J. A., and Upchurch, G. R., 1987a, North American nonmarine climates and vegetation during the Late Cretaceous: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 61, p. 33–77.

Wolfe, J. A., and Upchurch, G. R., 1987b, Leaf assemblages across the Cretaceous-Tertiary boundary in the Raton Basin, New Mexico and Colorado: U.S. National Academy of Sciences Proceedings, v. 84, p. 5096–5100.

Yaalon, D. H., 1983, Climate, time and soil development, *in* Wilding, L. P., Smeck, N. E., and Hall, G. F., eds., Pedogenesis and soil taxonomy. I. Concepts and interactions: Amsterdam, Elsevier, p. 233–251.

Zahnle, K., 1990, Atmospheric chemistry by large impacts, *in* Sharpton, V. L., and Ward, P. E., Global catastrophes in Earth history: Geological Society of America Special Paper 247, p. 271–288.

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