Evidence from paleosols for ecosystem changes across the Cretaceous/Tertiary boundary in eastern Montana

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ABSTRACT

Ancient soils (paleosols) of the latest Cretaceous Hell Creek Formation are mildly calcareous, have clayey subsurface (Bt) horizons, and exhibit abundant large root traces, as is typical of forested soils in subhumid climates. The fact that some of the paleosols are capped by thin, impure coals is evidence for seasonally dry swamps. The paleosol evidence thus supports published reconstructions, based on fossil leaves, pollen, and vertebrates, that this area was subtropical, seasonally dry, subhumid, and forested mainly by angiosperms.

Paleosols within the earliest Tertiary (Paleocene) Tullock Formation have thicker, coaly, surface (O and A) horizons and are more drab colored and less calcareous than paleosols of the Hell Creek Formation. These features are indications of waterlogging and of a humid climate. Large root traces and clayey subsurface (Bt) horizons are evidence of swamp woodland and forest. Inferred base level and paleoclimate are compatible with evidence from fossil leaves and pollen that indicates more abundant deciduous, early successional angiosperms and swamp conifers compared to those of Late Cretaceous time.

Most of the paleosols have drab Munsell hues and can be expected to preserve a reliable fossil record of pollen and other plant remains. The carbonate content of the paleosols declines toward the top of the Hell Creek Formation, and the uppermost 3 m of the formation is noncalcareous. Because of this, the decline in diversity and abundance of bone over this interval is interpreted as a taphonomic artifact. Evidence from paleosols supports paleobotanical evidence for catastrophic change in ecosystems at the Cretaceous/Tertiary boundary.

INTRODUCTION

Catastrophic hypotheses to explain the extinction of dinosaurs at the Cretaceous/Tertiary boundary have been given new impetus by the discovery of anomalous enrichments of iridium, of shocked quartz, or early successional fern spores, and of soot at this stratigraphic level in many parts of the world. This has been taken as evidence of the impact of a large asteroid or comet (Alvarez, 1986), which had dire environmental consequences, including dark global dust clouds, acid rain (Lewis et al., 1982), and wildfires (Wolbach et al., 1985). Biological extinctions especially affected large creatures dependent on fresh plant and animal food rather than small detritus feeders (Sheehan and Hansen, 1986). This scenario of sudden death from the skies has not been universally accepted (Hoffman and Nitecki, 1985). It has been claimed that the fossil record of dinosaurs where best known in the western interior of North America better supports the idea of their gradual decline, either as a result of habitat and biogeographic homogenization following retreat of epeiric seas (Bakker, 1986) or as a result of increasingly effective competition from small mammals (Sloan et al., 1986). By this view, a catastrophic impact may have been incidental to dinosaur extinctions or may merely have hastened a decline already well advanced. These conflicting views based on sedimentological, geochemical, and paleontological studies can now be reassessed by using fossil soils (paleosols).

RECOGNIZING AND CHARACTERIZING PALEOSOLS

Paleosols can be recognized by many of the features of modern soils (Retallack, 1983). Especially useful are fossil root traces. These indicate that plants grew in the host material and that, regardless of its sedimentary mode of origin, it was a soil. Another characteristic is the presence of soil horizons, zones of alteration beneath the upper surface of the profile. The nature of the alteration varies considerably, but it commonly includes subsurface enrichment in clay (Bt horizons), enrichment in combinations of iron and aluminum oxides and organic matter (Bs), or enrichment in calcite or dolomite (Bk). A final feature of paleosols is their distinctive structure, which may appear massive and featureless at first sight but is actually a complex network of altered surfaces (cutans) and clods (peds) that can be recognized on a scale of metres down to microscopic structures (sepic plasmic fabric).

Many of these features are abundantly represented in flood-plain sediments of the latest Cretaceous Hell Creek Formation and the earliest Paleocene Tullock Formation in badlands around Bug Creek, south of Fort Peck, Montana (Retallack and Spoon, 1985; Leahy et al., 1985; Fastovsky and McSweeney, 1987; McSweeney and Fastovsky, 1987). Swelling clays of outcrops of these badlands are altered at the surface to a popcorn texture (angular peds of modern weathering), and there is a shallow accumulation of carbonate powder in the cracks (also a modern weathering effect), as is typical for soils of this semiarid region (Ustic Torriorthents of Yawdim Series in Soil Survey of Strom, 1984). In order to characterize Late Cretaceous and early Tertiary paleosols, it is necessary to dig beyond this superficial zone of weathering, often 1 m or more, to fresh bedrock. Four sections were excavated between the high bluffs surrounding the area informally called Russell Basin (by Fastovsky and Dott, 1986) and the fossil locality of Bug Creek anthills (Sloan et al., 1986). Each section was logged (e.g., Figs. 1, 2), and representative paleosols were sampled and described. Of particular interest was the color of the paleosols as a guide to former waterlogging and their calcareousness as a guide to former rainfall. Both were measured from freshly excavated rock, hue with a Munsell color chart and calcareousness by using a five-point scale for the degree of effervescence with hydrochloric acid (Retallack, 1984). Degree of development of the paleosols was also evaluated from the trenches as a guide to the time over which each formed. A five-point scale of development was used on the basis of the degree of destruction of relict bedding and clay enrichment for paleosols with clayey subsurface (Bt) horizons and the thickness of coals for paleosols with organic (O) horizons (Retallack, 1984, 1988).

Detailed sections were made of representative paleosols, and samples of them were examined in thin section to determine their mineralogical content and grain-size variation (quantified by point counting, Fig. 3). Destruction of easily weathered minerals, such as feldspar and mica, and their conversion to clay are important indicators of the degree and kind of soil formation.

Correlation of sedimentary units 3 km from Russell Basin to the Bug Creek anthills locality was also attempted. Opinions differ on relations between these two areas (Smit and van der Kaars, 1984; Fastovsky and Dott, 1986). Direct tracing of paleosols was not useful because none were exposed continuously over this interval; paleosols nearest the boundary have been eroded by ancient stream channels or by modern badland formation (Fig. 4). A useful marker is a zone of several noncalcareous paleosols at the top of the Hell Creek Formation in all localities, including beneath the paleochannel that contains fossils of Bug Creek anthills (Fig. 2). Depletion of carbonate within this zone probably was caused by deep weathering of an earliest Paleocene erosional landscape, due either to a

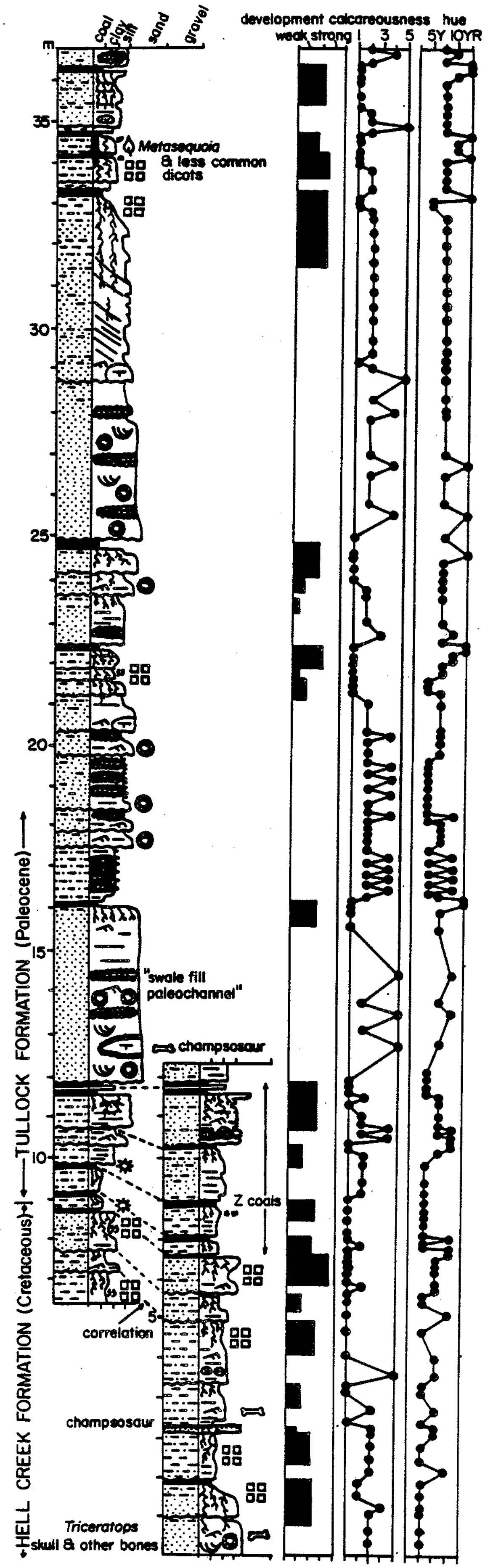

Figure 1. Stratigraphic section of Cretaceous/Tertiary boundary in main cliffs (long section) and low knoll (shorter correlated section) in badlands informally called Russell Basin (Fastovsky and Dott, 1986) in watershed of Bug Creek (NW¼NW¼NE¼ sec. 17, R43E, T22N), McCone County, Montana. Position of paleosols is indicated by black boxes, widths of which correspond to degree of development.

shift to more humid climate at that time (Wolfe and Upchurch, 1986) or to a pulse of acidic rain, as predicted by some impact scenarios (Lewis et al., 1982).

RECONSTRUCTING LATEST CRETACEOUS AND EARLIEST TERTIARY LANDSCAPES

Paleosols of the latest Cretaceous Hell Creek Formation differ from those of the earliest Paleocene Tullock Formation in that they reflect different kinds of ancient landscapes. Large root traces, clayey subsurface (Bt) horizons, and drab hues in many of the latest Cretaceous paleosols (Fig. 3) are evidence of closed canopy, lowland forest, and a shallow and fluctuating water table. Paleosol structures are blocky and platy, as is common in forest soils. No clear granular structure that would indicate open grassland or grassy clearings has been detected. Some paleosols with thin, impure coaly horizons represent seasonally dry swamps. Other little-modified shale and siltstone beds with carbonaceous root traces represent former soils of early successional streamside woodlands. These are most common in paleochannel margins. Most of the paleosols contain dispersed carbonate, an indication of subhumid climate (Birkeland, 1984). Climate may have been seasonally dry. The impure shaly nature of the coaly (O) horizons and the drab

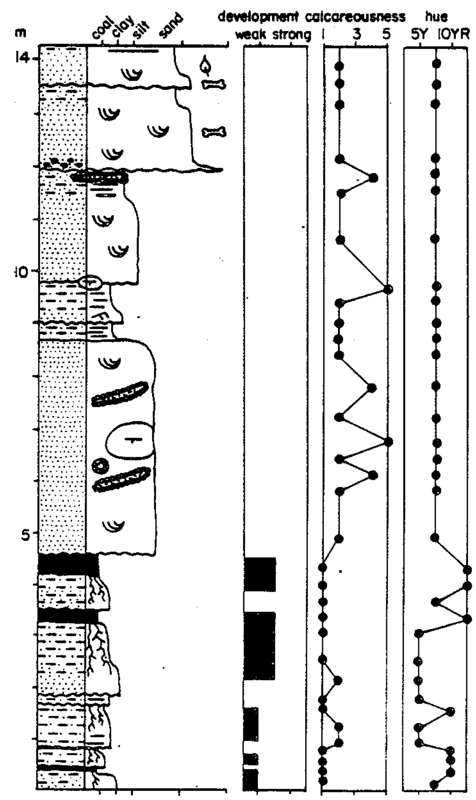

Figure 2. Stratigraphic section, including paleochannel deposits of well-known fossil locality, Bug Creek anthills (SW¼SE¼ sec. 9, R43E, T22N), McCone County, Montana. Symbols and patterns as in Figure 1.

color of paleosols with clayey subsurface (Bt) horizons are indications of waterlogging, but deeply penetrating root traces and clayey subsurface (Bt) horizons are evidence of prolonged periods of good drainage. Paleotemperature is difficult to interpret from paleosols, but microstructures similar to fecal pellets are locally abundant. These indicate a high productivity of soil invertebrates that is more compatible with tropical or subtropical than with temperate conditions.

Most paleosols of the early Paleocene Tullock Formation, in contrast, have thick coaly horizons, and some also have large (up to 51 cm diameter) fossil trunks. These were soils of permanently waterlogged swamps. The Tullock Formation also contains paleosols of early successional vegetation and rare paleosols of lowland forest, similar in some ways but distinct from those of the Hell Creek Formation. All these paleosols are noncalcareous, but the alluvium on which they formed has remained moderately calcareous in places beyond the zone of ancient weathering. This is an indication that climate had become more humid. There is no evidence of changed paleotemperature in that evidence of soil invertebrates is locally abundant in paleosols that were not permanently waterlogged.

The transition between the lowland, forest ecosystems of the Late Cretaceous and the early Paleocene swamps involved a complex series of events, including sea-level change, extraterrestrial impact, climate change, erosion, and an accelerated rate of deposition. Paleosols provide evidence that these events occurred at separate times and probably in the order listed above. Evidence of impact is provided by spore anomalies followed by a transitional Cretaceous-Tertiary palynoflora (Hotton, 1984; 1985, personal commun.) just above the base of the lowest of the boundary (Z) coals. Enrichment in iridium (2 to 3 times background) has been detected from this bed, although it is very slight compared to other anomalies (10 to 15 times background) at the Cretaceous/Tertiary boundary (Fastovsky and Dott, 1986). This lowest Z coal forms an organic horizon to a strongly developed paleosol with a brown clayey subsurface (Bt) horizon. This boundary paleosol supported lowland forest better drained than one would expect, considering its coaly surface horizon. Thus, a rise of water table, possibly related to transgression of the early Paleocene Cannonball Sea (Cherven and Jacob, 1985), predated the impact. The boundary paleosol and several others below it are noncalcareous. This can be explained in several ways: a gradual change to more humid climate, deep weathering during an abrupt change to more humid climate, or an abrupt pulse of acid rain at the boundary. An abrupt change seems more likely than a gradual one because there is a noncalcareous zone in the uppermost Hell Creek Formation at deeper stratigraphic levels along strike (Fig. 3). Whether this abrupt change was caused by normal or acid rain cannot yet be resolved from these paleosols. An acid-rain surge could have decalcified the upper Hell Creek Formation and developed the boundary paleosol in a much shorter time than rainfall of ordinary pH, but its final effects would have been similar. Thus, the duration of the hiatus for development of the boundary paleosol is difficult to determine. If one assumes a humid climate with normal rainfall (as in chronosequences in Pennsylvania and Ohio summarized by Birkeland, 1984), the hiatus could have been as long as 40000 yr; much shorter times are likely in the case of unusually acidic weathering. After these events near the Cretaceous/Tertiary boundary, several more swampland soils formed, each representing several thousand years before a dramatic change in alluvial architecture. At the stratigraphic level of the highest of the boundary (Z) coals, paleochannels cut deeply (at least 30 m for the paleochannel labeled the Big Bugger by Fastovsky and Dott, 1986) into underlying strata. These represent much larger and more powerful streams than existed in this area during latest Cretaceous time. This early Paleocene channel-cutting episode probably was due to tectonic uplift and deformation (Cherven and Jacob, 1985). At the end of this period of downcutting, sedimentation resumed at much greater rates, and so moderately developed paleosols are widely separated by thick accumulations of alluvial sediments (Fig. 1).

PALEOBOTANICAL RECORD

Considering the generally drab Munsell hue of all the paleosols (Fig. 2), the excellent preservation of fossil roots, leaves, pollen, and spores in them is not surprising. Furthermore, such remains in paleosols can be expected to be close to their place of growth and representative of the associations in which they grew, unlike plant remains in lacustrine sediments (Retallack, 1984). For these reasons, the paleobotanical record of Cretaceous/Tertiary events in this area

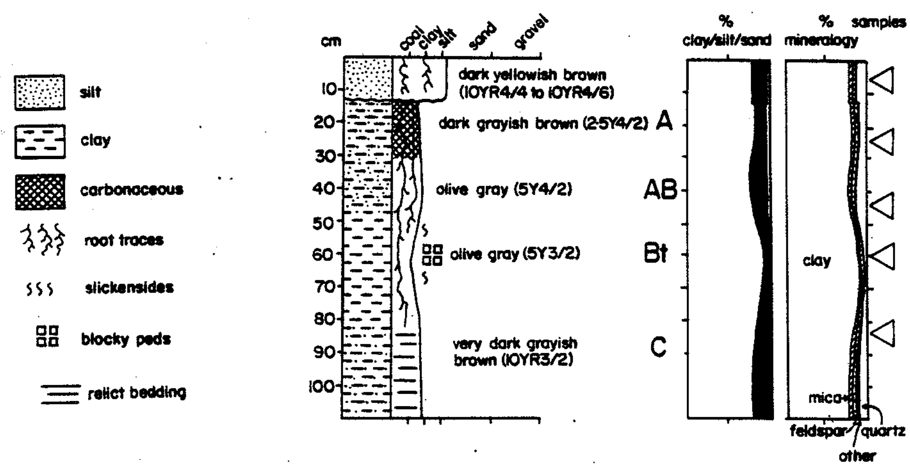

Figure 3. Stratigraphic section measured in field and corresponding grain size and mineralogical composition determined by point-counting petrographic thin sections of paleosol in Late Cretaceous upper Hell Creek Formation (at 2 m in Fig. 1) in badlands of Bug Creek, Montana.

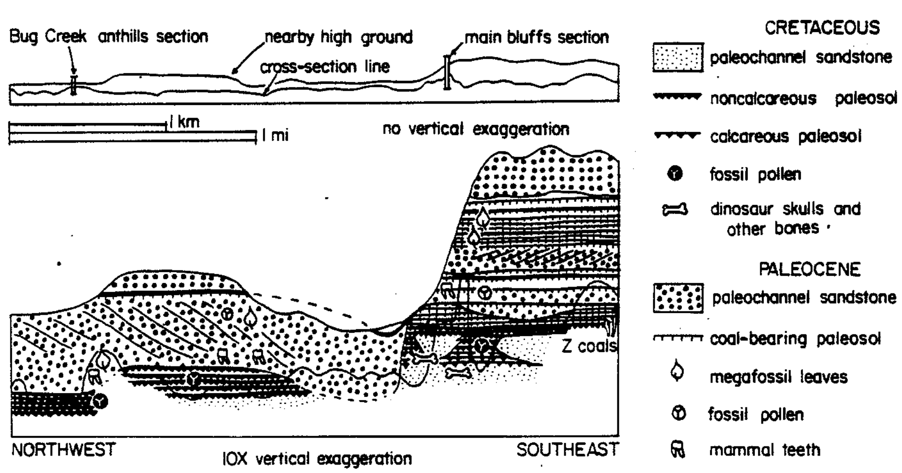

Figure 4. Lateral correlation of sediments and paleosols between main bluffs of Russell Basin (of Fig. 1) in straight line, through paleochannel informally known as Big Bugger (in Fastovsky and Dott, 1986) to fossil locality of Bug Creek anthills.

(Shoemaker, 1966; Norton and Hall, 1969; Wolfe and Upchurch, 1986) can be regarded as reliable. These fossil floras provide evidence of seasonally dry, subtropical lowland forests, largely of dicotyledonous angiosperms, during latest Cretaceous time. Throughout the western United States, at the stratigraphic level just above the base of the lowest boundary (Z) coals and iridium anomalies, an early successional flora of ferns and then one of deciduous dicotyledonous angiosperms appear abruptly. This transition flora is later (stratigraphically near the top of the Z coals in Bug Creek) replaced by swamp woodland vegetation dominated by dawn redwood (*Metasequoia*). Large dicotyledonous leaves with drip tips are evidence of a change to a more humid climate. The affinities of Paleocene plants with those of temperate climates have been interpreted as evidence for climatic cooling. However, frost-intolerant screw pines and palms persisted, and the other Paleocene angiosperms are early successional and disturbance-tolerant plants. Wolfe and Upchurch (1986) considered that these plants were selected by catastrophic events rather than by climatic cooling.

The sequence of events reconstructed from paleobotanical data is in close agreement with that from paleosols. Especially useful is information on specific kinds of plants present, complementing data from paleosols on the general structure of vegetation or "plant formations," as that phrase is used by plant geographers. Also useful is evidence of an abrupt change toward humid climate, an event difficult to distinguish from gradual change in paleosols because its effects overlap older paleosols.

VERTEBRATE RECORD

The fossil record of dinosaurs and mammals across the Cretaceous/Tertiary boundary is much less complete than that of plants, primarily because bones are not preserved in noncalcareous paleosols of the critical boundary interval (Retallack and Leahy, 1986). Acidic dissolution of bones and teeth in soils is suggested by the disappearance of small mammal bones and teeth (they have higher surface-to-volume ratio compared to dinosaur remains) at stratigraphic levels below the last dinosaur bone (Fastovsky and Dott, 1986). Dinosaurs may have been present in abundance and diversity to the end of the Cretaceous. Some mammals persisted, because their ancestors are preserved in Paleocene deposits, but neither dinosaurs nor mammals are found in the uppermost 2 to 3 m of the Hell Creek Formation. The apparent dwindling in abundance and diversity of dinosaur remains in paleosols is thus a taphonomic artifact rather than evidence for gradual decline (contrary to Sloan et al., 1986).

These preservational biases did not extend to paleochannels. Streams were buffered from acidic ground water by moderately calcareous sediment load (Figs. 1, 2), and they preserved locally rich assemblages of bones and teeth. Unfortunately, some paleochannels near the boundary contain assemblages of Cretaceous and Paleocene mammals and of dinosaurs that are so thoroughly mixed that they are difficult to interpret. Tectonic events just above the boundary initiated incision of Paleocene streams into an erosional landscape of Cretaceous sediments (Fig. 4). Depending on the level of this weathered surface into which streams incised, they included Paleocene mammal remains mixed with Cretaceous mammal and dinosaur remains or with only Cretaceous dinosaur remains. The persistence and apparent decreasing abundance of dinosaur remains in these earliest Paleocene paleochannels (Sloan et al., 1986) probably reflect resorting by bank erosion that was curtailed as the erosional disconformity was blanketed by later Paleocene deposits.

CONCLUSIONS

Acidic dissolution of bones and teeth from noncalcareous paleosols near the Cretaceous/Tertiary boundary and the mixing of remains of various ages during a period of deep erosion shortly after the beginning of the Tertiary critically compromise the fossil record of vertebrates across the Cretaceous/Tertiary boundary in eastern Montana. In contrast, fossil plant remains are well preserved in place within a sequence of paleosols for which times of formation were no longer than a few tens of thousands of years, perhaps less if the best developed paleosol (below the boundary) was created by a surge of especially acidic rain. Fossil plants and paleosols show changes that are compatible with a catastrophic impact. If these and other indications can be considered evidence of global disaster, dinosaurs are likely to have been affected as well.

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ACKNOWLEDGMENTS

Funded by a Baldwin Fellowship of the Department of Geology to Spoon; publication aided by National Science Foundation Grant EAR 8503232 to Retallack. We thank D. Retallack and K. Johnson for help with field work and W. A. Clemmons, D. E. Fastovsky, C. Hotton, and D. A. Russell for useful discussion.

Manuscript received June 1, 1987
Revised manuscript received September 15, 1987
Manuscript accepted September 23, 1987