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Ecosystem changes across the Cretaceous-Tertiary boundary in eastern Montana.

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INTRODUCTION

Catastrophic hypotheses to explain the extinction of dinosaurs and many other creatures at the Cretaceous-Tertiary boundary have been entertained for some time, but were not taken seriously until recently. Evidence of anomalous enrichments of iridium, of shocked quartz, of microtektites, of early successional fern spores and of soot at this stratigraphic level in many parts of the world, has given new respectability to the idea that the Cretaceous period was terminated by impact of a large asteroid or comet. Its dire environmental consequences, including dark global dust clouds, acid rain and wildfires may have caused widespread extinctions (Alvarez 1986), especially of large creatures dependent on fresh plant or animal food, rather than small detritus feeders (Sheehan and Hansen 1986). This unsettling scenario of sudden death from the skies has not been universally accepted. The fossil record of dinosaurs where best known in the western interior of North America has been claimed better to support the idea of their gradual decline as a result of habitat and biogeographic homogenization following retreat of epeiric seas (Bakker 1986) or due to increasingly effective competition from small mammals (Sloan et al. 1986). By this view, a large impact may have been incidental to dinosaur extinctions or merely have hastened a decline already well advanced.

These conflicting views based on sedimentological, geochemical and paleontological studies, can now be reassessed using fossil soils (paleosols). Unlike fossils and sediments, paleosols are in place. As trace fossils of former ecosystems and as preservational environments for many kinds of fossils, paleosols also provide independent evidence for completeness of the fossil record (Retallack 1984). Here we outline the role of paleopedology in assessing paleontological evidence for events at the Cretaceous-Tertiary boundary, but only after a consideration of interpretations based solely on evidence from paleosols.

METHODS

Paleosols are abundant in flood plain sediments of the latest Cretaceous, Hell Creek Formation and earliest Paleocene, Tullock Formation in the dinosaur collecting fields of the badlands around Bug Creek, south of Fort Peck, Montana (Retallack and Spoon 1985; Leahy et al. 1985). Swelling clays of these badlands outcrops are altered at the surface to a popcorn texture, and there is a shallow accumulation of carbonate powder in the cracks, as is typical for soils of this semiarid region (Strom 1984). In order to characterize late Cretaceous and early Tertiary paleosols it is necessary to dig beyond this superficial zone of weathering, often a meter 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 (Fig. 1) and representative kinds of 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 using a five point scale for the degree of effervescence with hydrochloric acid. Degree of development was assessed from degree of destruction of relict bedding and clay enrichment for paleosols with clayey subsurface (Bt) horizons, and based on thickness of coals for paleosols with organic (O) horizons (Retallack 1984).

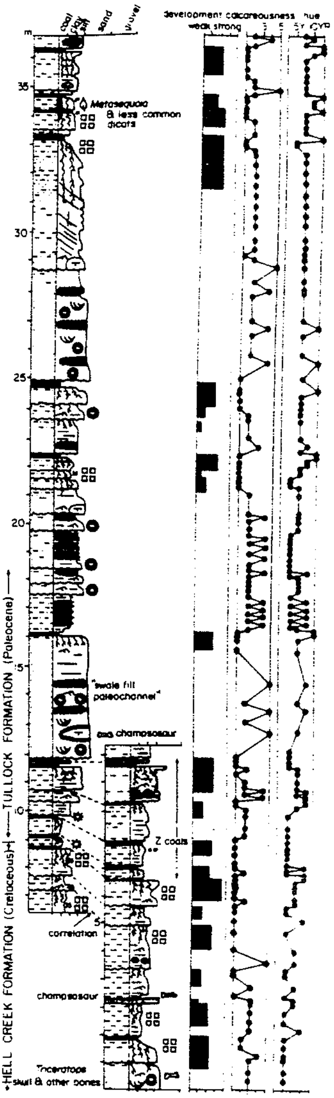
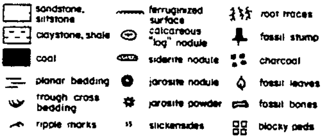


Fig. 1. A stratigraphic section of the Cretaceous-Tertiary boundary in the main cliffs (long section) and a low knoll (shorter correlated section) in badlands informally called "Russell Basin" (by Fastovsky and Dott 1986) in the watershed of Bug Creek (NW 1/4 NW 1/4 NE 1/4 sect. 17, R43E T22N), McCone Co., Montana. Position of paleosols is indicated by black boxes whose width corresponds to degree of development.



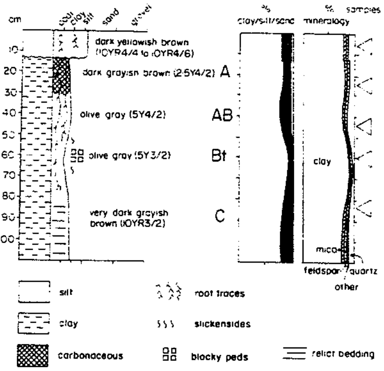


Fig. 2. Stratigraphic section measured in field, and composition determined by point counting petrographic thin sections of a paleosol in the Late Cretaceous, upper Hell Creek Formation (at 2 m in Fig. 1) in the badlands of Bug Creek, Montana.

More detailed sections were made of representative kinds of paleosols, and samples of them examined in petrographic thin sections for their mineralogical content and grainsize variation, which was quantified by point counting (Fig. 2). 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.

An attempt also was made to correlate sedimentary units 3 km from Russell Basin to the Bug Creek anthills locality. There have been considerable differences of opinion on the relationships between these two areas (Smit and van der Kaars 1984; Fastovsky and Dott 1986). Direct tracing of paleosols was not useful since none were exposed continuously over this interval (Fig. 3). A more useful marker was a zone of two or three non-calcareous paleosols at the top of the Hell Creek Formation in all localities, including beneath the paleochannel containing the fossils of Bug Creek anthills. Depletion of carbonate within this zone is thought to have been caused by deep weathering of an earliest Paleocene erosional landscape, due either to a 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.

RECONSTRUCTING LATEST CRETACEOUS AND EARLIEST TERTIARY LANDSCAPES

Paleosols of the latest Cretaceous, Hell Creek Formation differ from those of the earliest Paleocene, Tullock Formation, and reflect different kinds of ancient landscapes. Large root traces, clayey subsurface (Bt) horizons and drab hues in many of the latest Cretaceous paleosols (Fig. 2) are evidence of closed canopy, lowland forest, with 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 yet been detected. Some paleosols with thin impure coaly horizons have been found, representing seasonally dry swamps. Other little modified, bedded shale and siltstone, with carbonaceous root traces, represent early successional streamside woodlands. Most of the paleosols contain dispersed carbonate, an indication of subhumid climate (Birkeland 1984). It may have been seasonally dry, considering the impure shaly nature of the coaly (O) horizons and the drab color of paleosols with clayey subsurface (Bt) horizons. 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 temperate conditions.

Most paleosols of the early Paleocene Tullock Formation, in contrast, have thick coaly horizons and in some cases also 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, distinct from those of the Hell Creek Formation. All these paleosols are non-calcareous, but the alluvium on which they formed has remained moderately

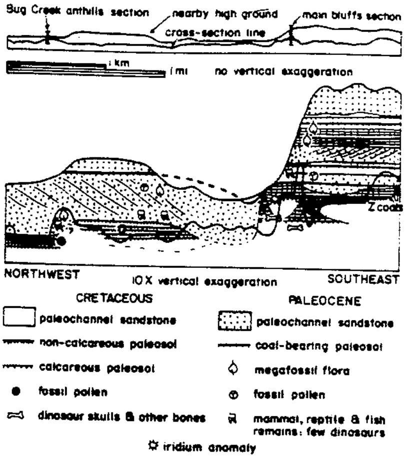


Fig. 3. A lateral correlation over 3 km of sediments and paleosols between the main bluffs of "Russell Basin" (of Fig. 1) in a straight line through a paleochannel informally known as the "Big Bugger" (in Fastovsky and Dott 1986) to the fossil locality, Bug Creek anthills (SW 1/4 SE 1/4 NW 1/4 sect. 9 R43E T22N), McCone Co., Montana.

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, since evidence of soil invertebrates is 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. Evidence of impact is provided by iridium and spore anomalies (Fastovsky and Dott 1986) just above the base of the lowest of the boundary (Z) coals. This 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 non-calcareous. 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 since there is a non-calcareous zone in the uppermost Hell Creek Formation at deeper stratigraphic levels along strike (Fig. 3). Whether this abrupt change was due to 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. Assuming a humid climate with normal rainfall (as in chronosequences in Pennsylvania and Ohio summarized by Birkeland, 1984), it could have been as long as 40,000 years; much shorter times are likely in the case of unusually acidic weathering. Following 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 boundary (Z) coals there are paleochannels that 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 of this region (Cherven and Jacob 1985). At the end of this period of downcutting, sedimentation resumed at much greater rates than before, so that moderately developed paleosols are widely separated by thick accumulations of alluvial sediments (Fig. 1).

THE 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, the record of 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 (Wolfe and Upchurch 1986) can be regarded as reliable. Fossil floras provide evidence of seasonally dry, subtropical lowland forests, largely of dicotyledonous angiosperms, during latest Cretaceous time. At the stratigraphic level just above the base of the lowest boundary (Z) coal and iridium anomaly, an early successional flora of ferns and deciduous dicotyledonous angiosperms appears abruptly. This "transition flora" is later (stratigraphically near the top of the Z coals) replaced by swamp woodland vegetation dominated by dawn redwood (Metasequoia). Large dicotyledonous leaves with drip tips persist and 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. But frost-intolerant screw pines and palms persisted, and the other Paleocene angiosperms are early successional and disturbance tolerant plants. It is more likely that catastrophic events selected for them, rather than climatic cooling (Wolfe and Upchurch 1986).

THE VERTEBRATE RECORD

Unlike the fossil record of plants, that of dinosaurs and mammals across the Cretaceous-Tertiary boundary is incomplete, primarily because their bones are not preserved in non-calcareous paleosols of the critical boundary interval (Retallack and Leahy 1986). Acidic dissolution of bones and teeth in soils is especially suggested by the disappearance of small mammal bones and teeth, with their higher surface to volume ratio compared to dinosaur remains, at stratigraphic levels below the last dinosaur bone. Dinosaurs may have been present in abundance and diversity right to the end of the Cretaceous. Some mammals certainly persisted, since their ancestors are found 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 thus is seen as a taphonomic artifact, rather than as evidence for gradual decline (contrary to Sloan et al. 1986).

These preservational biases do not appear to have extended also to paleochannels. Streams were buffered from acidic groundwater by moderately calcareous sediment load (Fig. 1) and preserved locally rich assemblages of bones and teeth. Unfortunately some of these paleochannels near the boundary contain assemblages of Cretaceous and Paleocene mammals, and also dinosaurs, 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. 3). 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 Cretaceous dinosaur remains only. The persistence and apparent decreasing abundance of dinosaur remains in these earliest Paleocene paleochannels (Sloan et al. 1986), probably reflects 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 non-calcareous paleosols near the boundary and the mixing of remains of various age during a period of deep erosion shortly after the boundary, critically compromise the fossil record of vertebrates across the Cretaceous-Tertiary boundary in eastern Montana. On the other hand, fossil plant remains of various kinds 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 soils both show changes above the layer enriched in iridium that are compatible with a catastrophic impact. If these and other indications can be considered evidence of global disaster, then this is likely to have affected dinosaurs as well.

Acknowledgments

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