West Bijou Site Cretaceous-Tertiary Boundary, Denver Basin, Colorado

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ABSTRACT

The Cretaceous-Tertiary (K-T) boundary section at the West Bijou Site is remarkable because many of the methods used to constrain the position of a terrestrial K-T boundary have been successfully applied to a local section. These include palynology, magnetostratigraphy, shocked quartz and iridium analysis, vertebrate paleontology, geochronology, and paleobotany. The West Bijou Site K-T boundary records the extinction of the *Wodehouseia spinata* Assemblage Zone palynoflora (21%), followed immediately by the presence of a fern-spore abundance anomaly (74%) and the subsequent appearance of the P1 palynoflora. This palynological extinction is coincident with the presence of shock-metamorphosed quartz grains (5+ planes of parallel lamellae) and an iridium spike of 619 ± 32 parts per trillion within the 3-cm-thick boundary claystone. The boundary lies within a reversely magnetized interval, recognized as subchron C29r, substantiated by a radiometrically dated tuff 4.5 m below the boundary with an age of 65.73 ± 0.13 Ma. Dinosaur remains attributable to the late Maastrichtian *Triceratops* Zone were discovered 4 m below the boundary clay, and a partial jaw of a diagnostic Pu1 mammal was discovered 12 m above. Fossil plants are most abundant in the Paleocene and document a low diversity ecosystem recognizable as the southernmost extension of the FUI disaster recovery flora that radiated in North America following the K-T boundary cataclysm.

Keywords: K-T boundary, extinction, iridium, geochronology, Denver Basin, Colorado.

INTRODUCTION

West Bijou Site Field Trip

The purpose of this field trip is to visit the recently discovered West Bijou Site Cretaceous-Tertiary (K-T) boundary located in the eastern part of the Denver Basin, Colorado (Fig. 1). This K-T boundary section was discovered in August 2000 on the west slope of the West Bijou Creek valley (Barclay, 2002). The K-T boundary at this site has been constrained using multiple lines of evidence, combining the efforts of many scientists working on the Denver Basin Project at the Denver Museum of Nature & Science and the U.S. Geological Survey.

The drive from Denver to the West Bijou Site K-T boundary section takes you east on I-70 across the high plains of eastern Colorado. Layered beneath you are 3700 m of sedimentary rocks that record the erosion of the Ancestral Rocky Mountains, preserve the time when Colorado was covered by a marine seaway, and then document the uplift and erosion of the present Rocky Mountains. Take the Strasburg exit south, the frontage road east for a short distance, and then turn south and continue on this road for 19 km until you reach a "dead end" sign at Arapahoe County

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Road 46. Turn left and drive for 1 mi until the road turns to the left with a red gate on the right. This is the gated entrance to the West Bijou Site K-T boundary, located on private property managed by the Plains Conservation Center. Permission to access the property must be obtained prior to entrance.

The Plains Conservation Center has been in operation for over 50 years. It presently is operating two sites, the original East Hampden Site and the newly acquired West Bijou Site that contains the K-T boundary section. Its principal goals are to educate the public about the valuable short grass prairie ecosystems that are rapidly disappearing along the Front Range of Colorado, as well as to actively participate in the preservation and study of these ecosystems. The Plains Conservation Center is a semi-private organization owned and operated by the West Arapahoe Conservation District. You may contact the Plains Conservation Center for more information about their activities at Plains Conservation Center, 21901 E. Hampden Ave., Aurora, Colorado 80013, USA; 303-693-3621; e-mail: info@plainscenter.org; Web site: http://www.plainsconservationcenter.org/.

K-T Boundary Search

Roland Brown located the first North American Cretaceous-Tertiary boundary section on South Table Mountain in Golden,

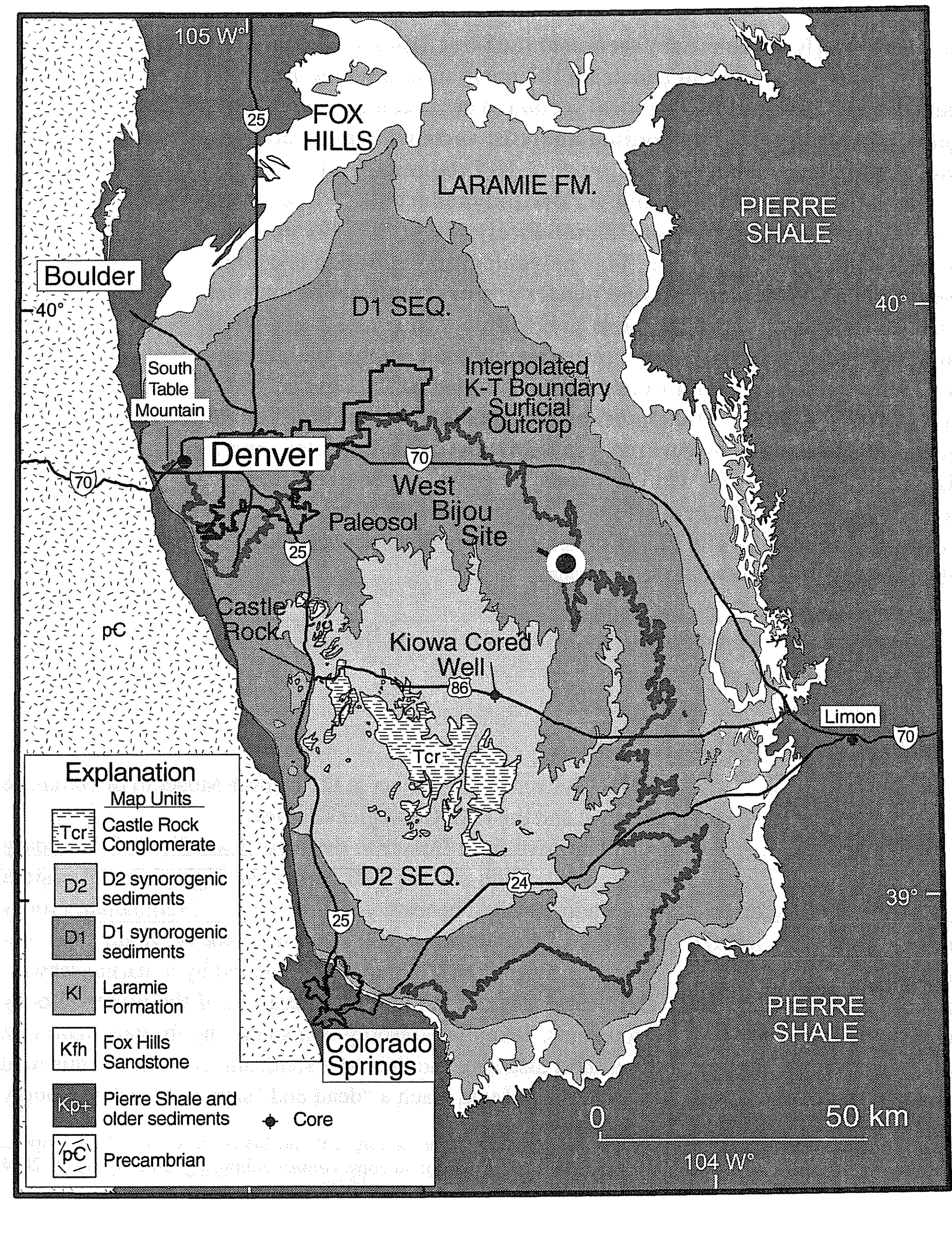

Figure 1. Geological map of Denver Basin synorogenic sedimentary rocks and position of the West Bijou Site. Map created by Robert G. Raynolds and Adrian Kropp using ArcInfo GIS software database of subsurface electric log data interpolated to surface.

Colorado (Brown, 1943). He found Paleocene mammals 24 m above *Triceratops* dinosaur remains and placed the boundary level just below the mammal-bearing horizon. The discovery of iridium at the K-T boundary (Alvarez et al., 1980) and the resulting extraterrestrial impact hypothesis for K-T extinctions demanded greater stratigraphic resolution and presented new tools to achieve that resolution. In the 1980s, precisely located K-T boundary layers were described in the Raton, Powder River, and Williston Basins, but no one was able to locate the precise K-T boundary in the Denver Basin. Roland Brown's K-T boundary at South Table Mountain (Brown, 1943) occurs in the coarse-grained facies typical of the proximal synorogenic deposits. As such, it did not provide appropriate strata necessary for fine-scale palynology, magnetostratigraphy, and geochemistry (Kauffman et al., 1990; Benson, 1998).

The Denver Basin Project began in 1997 with the goals of creating a chronostratigraphic framework for the Denver Basin synorogenic sediments and locating an exposure of the K-T boundary that contained evidence of extraterrestrial impact (Raynolds and Johnson, 2003). The work leading up to this project began in 1991, when scientists at the Denver Museum of Nature & Science started collecting plant and vertebrate fossils in the Denver metro area. Due to the paucity of continuous outcrop in the Denver Basin, the relationship of these localities to each other was not understood. In 1999, Kirk Johnson and Bob Raynolds coordinated a project to drill a 688-m-deep cored well in the town of Kiowa, Colorado (Raynolds and Johnson, 2002). The Kiowa Core served as a continuous subsurface stratigraphic record in the middle portion of the Denver Basin, useful for correlating the poorly constrained surface outcrops and fossil localities. The core was systematically analyzed using palynology and magnetostratigraphy to aid in correlation of surface sites and also to determine the position of the K-T boundary (Nichols and Fleming, 2002; Hicks et al., 2003). Once these samples were analyzed and the K-T boundary level was identified at a depth of 302 m, the Kiowa Core was used to calibrate a three-dimensional model of the basin's stratigraphy based on electric well logs (Raynolds, 2002). The resulting model was used to constrain the age and stratigraphic position of the numerous surface localities. The search for the boundary focused on the eastern portion of the Denver Basin because the distal portions of the synorogenic sequence contained the fine-grained rocks necessary to preserve the detail of events surrounding the K-T boundary extinction.

As a first step in constraining surface localities, the K-T boundary level in the Kiowa Core was projected onto a digital elevation model of the surface using ArcInfo GIS software and mapped relative to existing geological mapping and previously drawn K-T boundary lines. This interpolation used data from the recently drilled Kiowa Core, the Castle Pines Core drilled on the western side of the basin (Robson and Banta, 1993), and known surface exposures of the K-T boundary interval in the towns of Golden and Colorado Springs, Colorado.

Using the interpolated K-T boundary GIS map, potential outcrop areas were scouted by small aircraft and later spot-sampled for pollen analysis. The West Bijou Site was chosen for intensive study because it contained a 50 m exposure of fine-grained fossiliferous strata with a Cretaceous pollen sample at the base and fossil leaves of early Paleocene aspect at the top. Analysis of systematically collected pollen samples through the 50 m of exposure subsequently allowed us to narrow the K-T boundary to the top of a 3 cm claystone in the middle of the hillside.

GEOLOGICAL SETTING

Denver Basin

The Denver Basin is a Rocky Mountain foreland basin that contains Late Cretaceous and Paleogene synorogenic sediments derived from the erosion of the Front Range mountains during the Laramide Orogeny. This asymmetrical geological structure stretches from Boulder in the north, down to Colorado Springs in the south, and eastward to Limon. The beds dip steeply on the western margin of the basin and become increasingly flat-lying toward the east.

Uplift of the Front Range occurred in two phases. The first commenced during the latest Cretaceous, ca. 68 Ma. Sedimentation continued in the Denver Basin for ~4 m.y., producing an unconformity-bounded package that Raynolds (2002) has termed the D1 sequence. The D1 sequence is predominantly arkosic near Colorado Springs, predominantly andesitic near Denver, and is a mixture of arkosic and andesitic in the center and eastern portions of the basin. A period of ~8 m.y. of nondeposition followed. Sediment accumulation began again in the last million years of the Paleocene, producing the D2 sequence, perhaps in response to renewed uplift along the front. This D2 sequence is an arkosic megafan derived from the Pikes Peak area west of Colorado Springs (Raynolds, 2002).

West Bijou Site

The West Bijou Site K-T boundary occurs in the D1 sequence in rocks previously mapped both as the Dawson Arkose and the Denver Formation (Dane and Pierce, 1936; Reichert, 1956). Raynolds (1997, 2002) places the Denver Formation and Dawson Arkose into his D1 sequence, and we put the exposures at the West Bijou Site in the middle of the 394-m-thick D1 sequence (thickness from the Kiowa Core). The beds at the site are effectively flat-lying, as the regional dip in this area is less than one-half degree to the west. In addition, the West Bijou Creek escarpment where the K-T boundary is located is roughly parallel to strike (Barclay et al., 2003).

Figure 2 is a detailed map of the field area created using differential GPS and contains the location of the three stops discussed in this field guide. The panel diagram in Figure 3 correlates the measured sections and positions of the sampling localities. A field datum was established for the field area surrounding the K-T boundary exposures to constrain the stratigraphic sections measured in the five gullies studied (Figs. 2 and 3). The

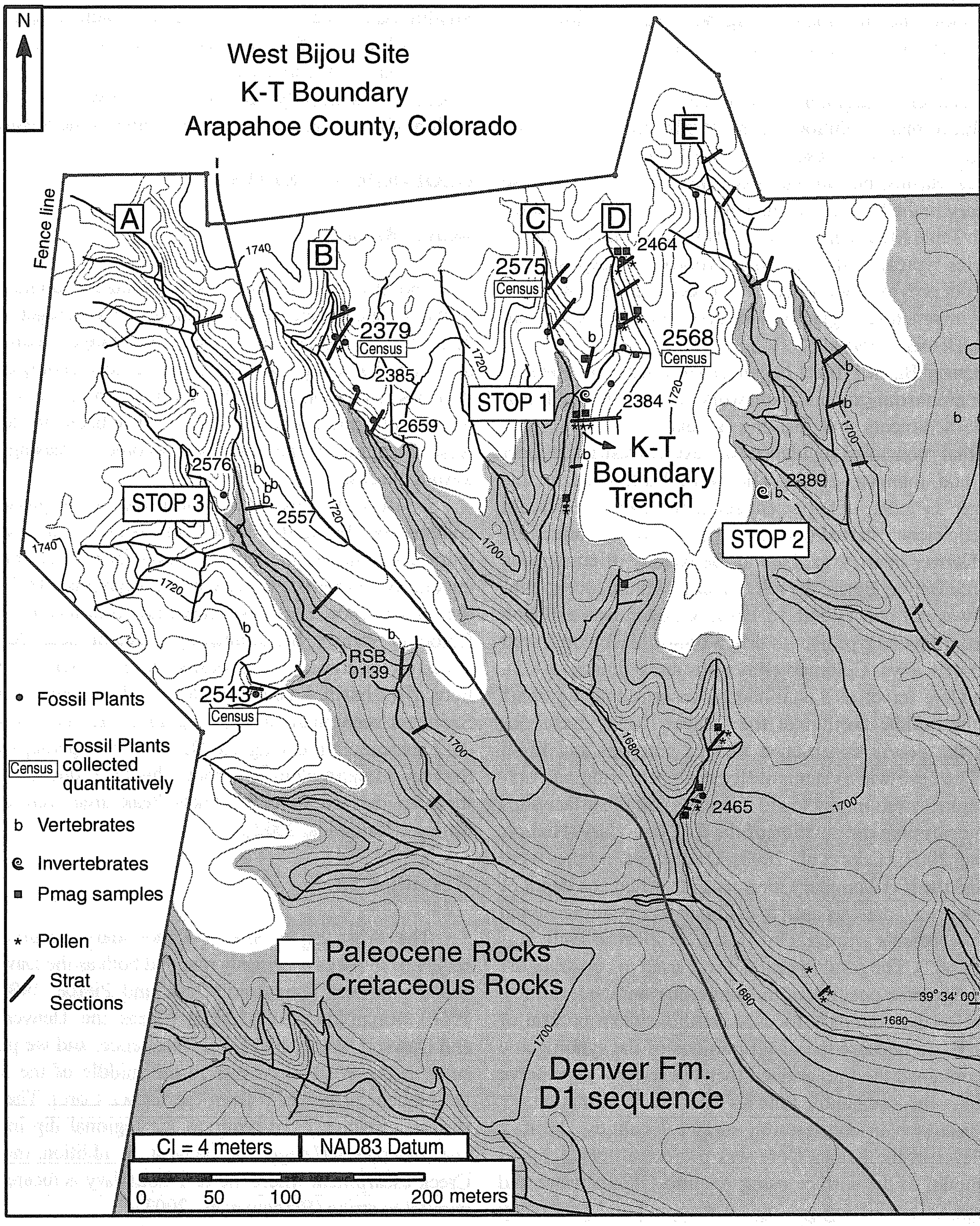

Figure 2. Topographic contour map (scaled in meters) of the field area on the Plains Conservation Center. Map was created using a Trimble® XRS differentially corrected GPS unit. The average horizontal and vertical precision was <1 m, providing the necessary detail to accurately plot the dense set of data. All Trimble® XRS field data was differentially corrected from a base station in Denver. At least 60 readings were taken per position, with less than 6% dilution of precision and a minimum of six satellites in view. Drainages were walked to define the topographic lows. Contour map created by Richard Barclay, Mark Gorman, Nicole Boyle, and Adrian Kropp. Research conducted on private property owned by the West Arapahoe Conservation District, managed by the Plains Conservation Center. See Figure 3 for lithologic descriptions of gullies A–E within the D1 sequence (Denver Formation).

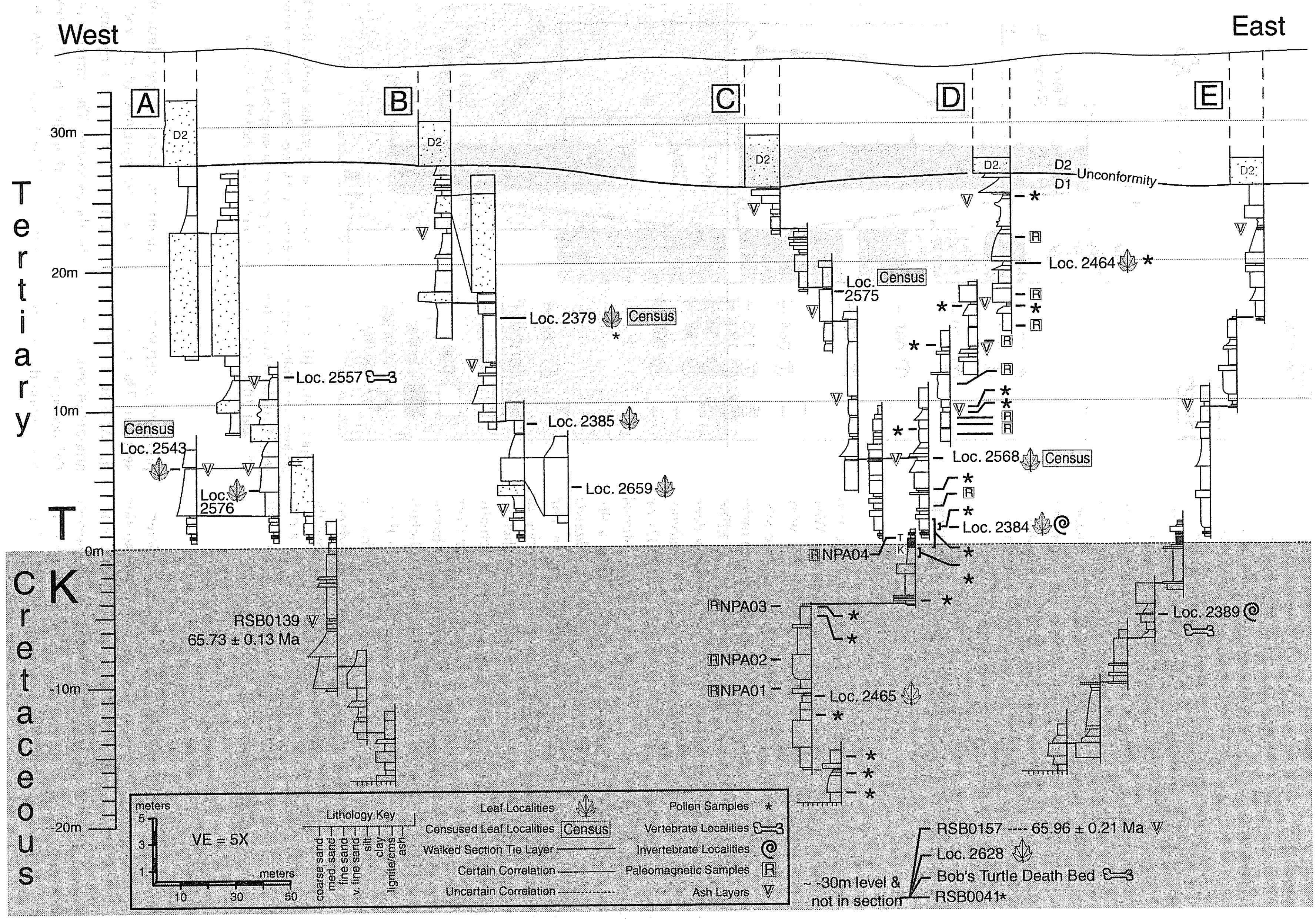

Figure 3. Stratigraphic correlation diagram within D1 sequence (Denver Formation) of the West Bijou Site K-T boundary section on the Plains Conservation Center. Positions of gullies A–E shown in Figure 2.

lowest in a diagnostic series of tuff beds, nicknamed the "Little Dude Ashes," forms the field datum. It has been trenched in each gully and correlated by walking along the characteristic series of tuff beds. It is present in the main research trench (Figs. 2–4).

The Paleocene D1 lithologies at the West Bijou Site are predominantly mudstone, siltstone, very fine-grained sandstone, and lignite. They preserve the depositional environments of floodplains, lakes, stream channels, and floodplain swamps, respectively. The Cretaceous strata contain fewer lignite beds, more sandstone units, and an absence of lacustrine siltstone units that are abundant in the Paleocene section and commonly preserve fossil leaves. The D1 sequence of strata is unconformably overlain by a thin lithified unit of very coarse sandstone of granitic provenance ascribed to the D2 sequence.

STOP 1. WEST BIJOU SITE K-T BOUNDARY TRENCH

Palynology

In the summer of 2000, a Cretaceous pollen sample was collected at the bottom of the 50 m of exposure at the West Bijou Site. Since fossil plants of probable Paleocene age were previously known from near the top of the exposures, we systematically collected pollen samples through the section in order to narrow the position of the K-T boundary. This initial effort constrained the boundary to a 3 m interval where we dug a deep section to expose fresh rock for detailed sampling. The palynological analysis conducted by Nichols and Fleming (2002) on these samples narrowed the K-T boundary to a 1 cm interval directly above a 3-cm-thick claystone bed found within a 90-cm-thick lignite. Palynomorphs attributable to the *Wodehousia spinata* Assemblage Zone are found in all samples below and within the 3 cm claystone. A 50% decrease of the species of palynomorphs is observed directly above this claystone. Nichols and Fleming (2002) note that this 50% local extirpation actually represents a 21% extinction because some of the taxa absent from the Paleocene of the West Bijou Site are present in other basins in the Western Interior above the K-T boundary layer (Nichols and Fleming, 2002). The boundary is overlain by a 4-cm-thick anomaly where fern spore abundance spikes to 74% from a Cretaceous background level of less than 5%. The abundance of fern spores then diminishes to 8% at the 7 cm level above the boundary claystone. The fern spore interval is replaced by a pollen assemblage attributable to palynofloral Zone P1 of the early Paleocene, as described by Nichols and Ott (1978).

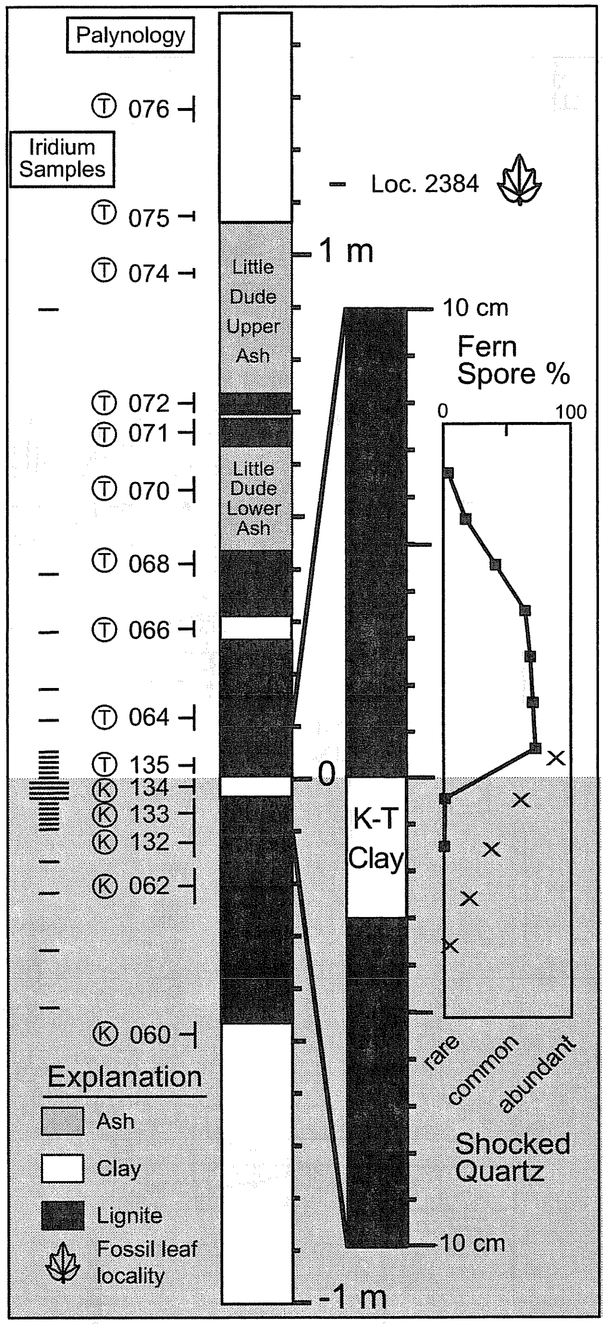

Figure 4. West Bijou Site K-T boundary stratigraphic section RSB0075. Iridium and pollen sample numbers are Denver Basin Project numbers (e.g., DBP-00-076). Iridium anomaly present in samples DBP-00-107, 108, 109, and 110 identified by double width bars on the left of the diagram.

Magnetostratigraphy

Jason Hicks of the Denver Museum of Nature & Science collected samples from twelve sites throughout the 50 m section at the West Bijou Site for paleomagnetic analysis (Hicks et al., 2003; Figs. 2 and 3 herein). All samples are of reversed magnetic polarity, placing the exposure in subchron C29r, based upon the association with the K-T palynological transition. This interpretation is supported by radiometric dates (see geochronology section). The reversed paleomagnetic signature of the rocks at the West Bijou Site provides the best means for determining the amount of time represented by the exposure. The duration of the Paleocene portion of subchron C29r is thought to be ~270,000 yr based upon the cyclostratigraphy of D'Hondt et al. (1996). In the

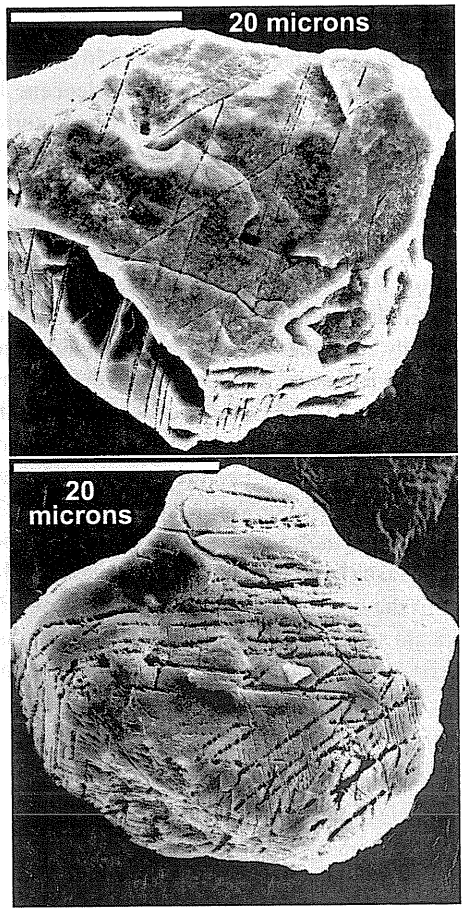

Figure 5. Electron-microscopic images of HF-etched shocked quartz grains from West Bijou Site K-T boundary claystone, section RSB0075. Lower grain shows 5+ sets of parallel shock lamellae.

Kiowa Core, the complete Paleocene section of subchron C29r is 35 m thick, but only 28 m (80%) of this section is preserved at the West Bijou Site. Based on this, we estimate that the Paleocene exposure at the West Bijou Site was deposited over ~216,000 yr. The majority of the fossil plant specimens are contained within the Paleocene section, so the recovery interval has been the focus of much of the paleobotanical work conducted at this boundary section.

Shocked Quartz and Iridium

The palynological extinction above the 3 cm boundary claystone directly coincides with both shocked quartz and iridium anomalies (Fig. 4). Five samples taken from a 5 cm interval across the K-T boundary claystone were analyzed by Bill Betterton of the U.S. Geological Survey for presence of shocked quartz grains. He found an increasing abundance of shocked quartz grains, with the highest concentration of grains occurring at the same stratigraphic position as the palynological K-T boundary (Barclay et al., 2003). Electron microscopic images show that these quartz grains record high levels of shock metamorphism, containing 5+ sets of parallel shock lamellae (Fig. 5). The HF-etching technique used by Betterton is described in Appendix F of Barclay (2002).

Frank Asaro at the Lawrence Berkeley National Laboratory analyzed samples from the West Bijou Site K-T boundary for presence of iridium with the Luis W. Alvarez Iridium Coincidence Spectrometer after neutron activation at the University of Missouri Columbia Research Reactor Center (Barclay et al., 2003). These samples were collected through a 3-m-thick section that included the palynological extinction and the shocked quartz grains (Fig. 4). He determined that there was an anomalously high Ir abundance of 619 ± 32 parts per trillion (ppt) within the 3 cm boundary claystone against a background level of <10 ppt. Iridium levels above 200 ppt in the interval 20 cm below the level of the maximum anomaly complicate the interpretation of this section.

Geochronology

The West Bijou Site contains multiple horizons of volcanic tuffs, both above and below the K-T boundary claystone. The majority of these tuffs have not been radiometrically dated but do contain sanidine and zircon crystals useful for analysis. Two tuffs were dated (4.5 m and ~30 m below the claystone) using the $^{40}Ar/^{39}Ar$ method on sanidine crystals (Hicks et al., 2003). The tuff 4.5 m below the K-T boundary was dated at 65.73 ± 0.13 Ma and is located within gully A, shown in Figures 2 and 3. This date supports the interpretation that the reversed polarity of the West Bijou paleomagnetic samples represents subchron C29r (Hicks et al., 2003).

The tuff ~30 m below the K-T boundary was dated at 65.96 ± 0.21 Ma, but it was not possible to directly measure its position in the stratigraphic section because it lies outside of the area mapped in Figure 2 and is ~4.5 km to the south of the main field area. Its stratigraphic position was determined solely upon its relative elevation compared to the boundary claystone. This tuff (RSB0041) is located in a small cutbank outcrop of West Bijou Creek at the coordinates 39°31′53″N, 104°17′38″W, NAD27. Both age determinations for these volcanic tuffs are consistent with all other West Bijou Site data and the recently recalibrated age of the K-T boundary as 65.51 ± 0.10 Ma (Hicks et al., 2002).

STOP 2. CRETACEOUS VERTEBRATE AND INVERTEBRATE FOSSIL SITE

Hadrosaurian dinosaur teeth and a ceratopsian dorsal vertebra were discovered in a thin, iron-rich sandstone located 4 m below the K-T boundary (DMNH loc. 2389; determinations made by Ken Carpenter of the Denver Museum of Nature & Science). The presence of these specimens provides evidence that the late Maastrichtian *Triceratops* Zone is present in the section below the palynological extinction horizon (Barclay et al., 2003).

This is the only locality at the West Bijou Site that has produced dinosaurian fossil material. The fauna from this site also includes turtles, crocodiles, champsosaurs, gar fish, lizards, gastropods, and bivalves.

Jaelyn Eberle of the University of Colorado at Boulder collected a partial jaw of the early Paleocene mammal *Protungulatum donnae* (DMNH loc. 2557, DMNH specimen 44371) 12 m above the K-T boundary (Eberle, 2003). This taxon is diagnostic of the basal portion of the Puercan North American Land Mammal "Age" (NALMA), dating the Paleocene strata at the West Bijou Site as Pu1.

STOP 3. PALEOCENE FOSSIL PLANT LOCALITY

West Bijou Site Paleobotanical Record

The Paleocene rocks at the West Bijou Site contain abundant fossil leaves, while the Cretaceous section yielded only two poor localities. This discrepancy is not well understood; however, the Cretaceous portion does not seem to contain the siltstone facies where the fossil leaves are abundantly preserved in the overlying Paleocene. The only age-diagnostic plant species found at the site is *Paranymphaea crassifolia* (Newberry) Berry, 4 m above the K-T boundary claystone (DMNH loc. 2567). *Paranymphaea crassifolia* is only known from the early Paleocene FUI megafloral zone of the northern Great Plains, which corresponds to the Puercan NALMA and an undetermined portion of the Torrejonian NALMA.

We collected over 2300 specimens from nine Paleocene localities, with 1548 of those specimens collected from four localities using a quantitative census method (Barclay et al., 2003). The sampled megaflora consists of 49 morphotypes and is taxonomically dominated by dicotyledonous angiosperms (74%), monocotyledonous angiosperms (10%), ferns and fern allies (11%), and conifers (5%). Diversity is low in the 28 m of Paleocene strata. The localities average 11.5 morphotypes at a rarefied richness level of 300 specimens per locality, with a range of 7.5–14.5 morphotypes per locality (Barclay et al., 2003). The localities are strongly dominated by a few morphotypes. The six most dominant taxa (Fig. 6) constitute 88% of the total specimens collected from the quantitatively collected localities. No statistically significant trend toward increasing diversity is observed during the first 28 m of the Paleocene at the West Bijou Site.

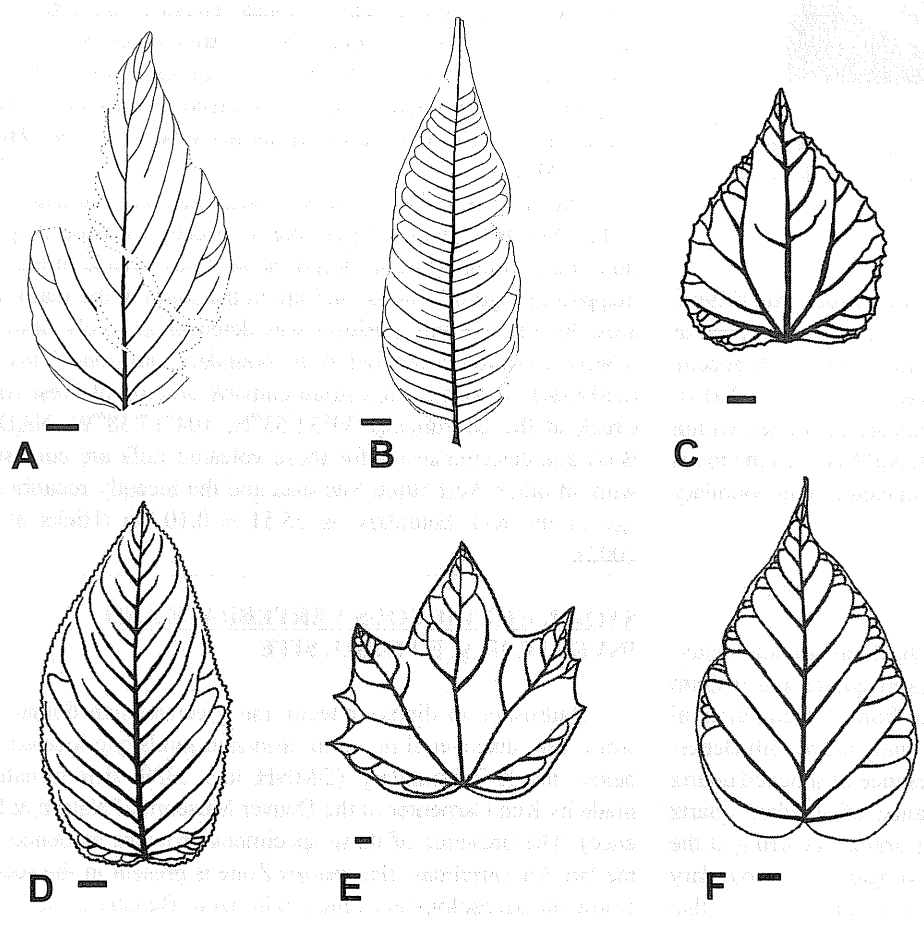

Figure 6. Line drawings of dominant Paleocene species at West Bijou Site. These six taxa dominate the flora, representing 88% of total specimens collected. (A) *Cornophyllum newberryi* (Hollick) McIver and Basinger (BC10 = 23.3%). (B) cf. *Averrhoites affinis* Hickey (BC09 = 21.6%). (C) "*Populus*" *nebrascensis* Newberry (BC37 = 15.6%). (D) *Dicotylophyllum anomalum* (Ward) Hickey (BC36 = 10.4%). (E) "*Cissites*" *panduratus* Knowlton (BC35 = 9.2%). (F) *Penosphyllum cordatum* (Ward) Hickey (BC27 = 7.9%). BC numbers refer to the Bijou Creek morphotype number and percentage of specimens from combined collections at all Paleocene sites on the West Bijou Site. Scale bar lengths: 1 cm.

The Paleocene West Bijou Site flora represents the southernmost example known of the FUI disaster-recovery flora, a flora that rose to dominance following the K-T boundary cataclysm in North America (Johnson, 2002; Barclay et al., 2003). This FUI flora spread across more than 400,000 km^2, stretching from Denver to southern Saskatchewan. The West Bijou Site contains the seven most abundant taxa present in the early Paleocene Fort Union Formation of the Williston Basin of North Dakota (700 km) and shares nine taxa in common with the early Paleocene Ravenscrag flora of southern Saskatchewan (1100 km). While the West Bijou Site shares many taxa in common with early Paleocene floras of the northern Great Plains, there is almost no overlap between coeval floras on the western margin of the Denver Basin, where high diversity floras exhibit rainforest characteristics in the early Paleocene (Johnson and Ellis, 2002; Johnson et al., 2003).

Paleoecology and Paleoclimate

The West Bijou Site is located in the distal portion of the Denver Basin. It was once a low relief floodplain dominated by broad-leafed angiosperms, with small, ephemeral lakes and occasional conifer-dominated swamps. A mean annual temperature estimate of 18.6 ± 2.6 °C (Fig. 7; estimate calculated using 34 dicot leaf morphotypes using the leaf margin analysis method of Wilf, 1997) is consistent with the interpretation of a warm climate for the Denver Basin in the early Paleocene (Johnson et al., 2003; Barclay et al., 2003). The presence of palm fronds in the localities suggests that the ecosystem did not experience sustained freezing (Sakai and Larcher, 1987). Mean annual precipitation was also elevated, with an average of 155 cm/yr (Fig. 8; using the leaf area analysis method of Wilf et al., 1998), consistent with the presence of many small, ephemeral lakes, and aquatic vertebrate taxa (Barclay et al., 2003). Versions of Figures 7 and 8 published in Barclay et al. (2003) contain significant typographical errors, which are corrected here.

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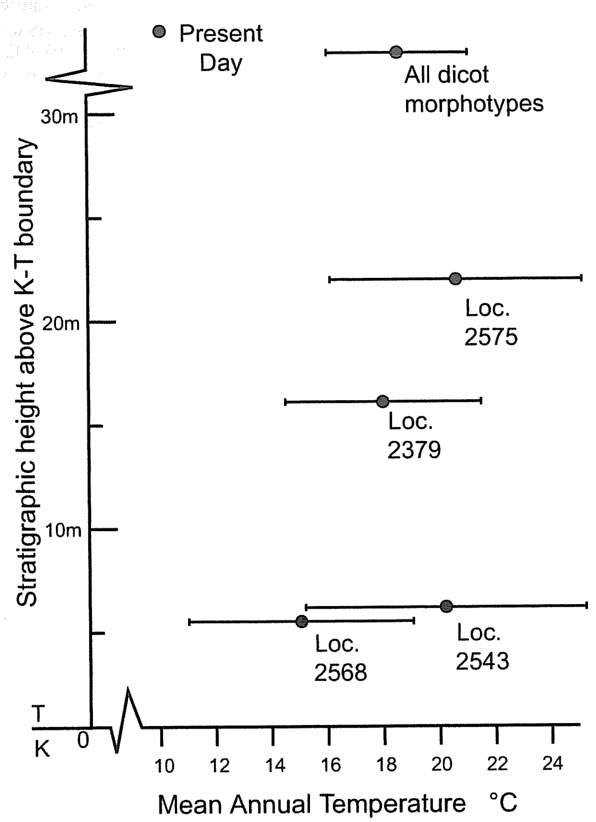

Figure 7. Estimates of mean annual temperature derived using leaf margin analysis on quantitatively collected Paleocene floras. The West Bijou Site value was calculated using 34 dicots from nine Paleocene localities. Present-day Denver mean annual temperature is from 51 mean values (modern data from High Plains Regional Climate Center, University of Nebraska).

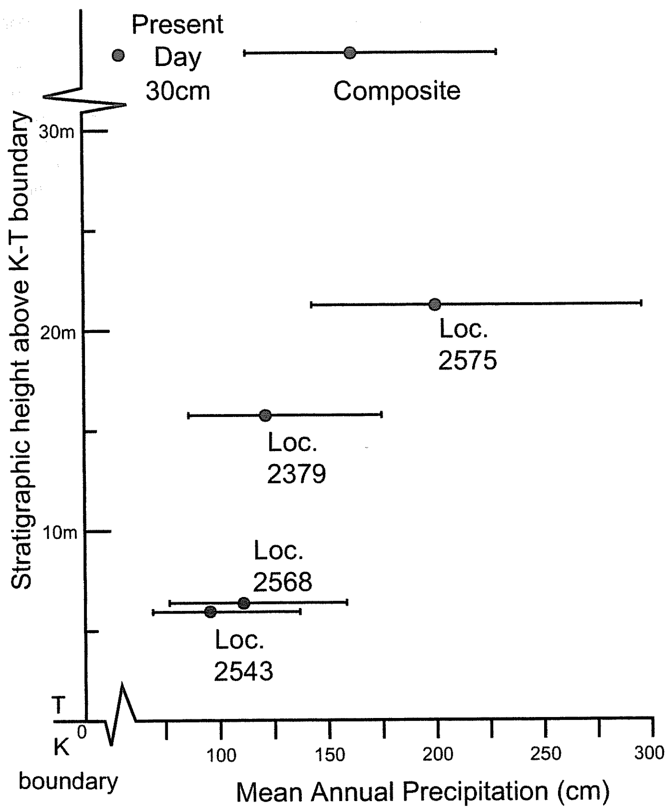

Figure 8. Estimates of mean annual precipitation derived using leaf margin analysis on quantitatively collected Paleocene floras. The West Bijou Site composite value was calculated using data from all four censused localities. Present-day mean annual precipitation for Denver is from 51 mean values (modern data from High Plains Regional Climate Center, University of Nebraska).

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