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# Earth and Planetary Science Letters





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# Direct high-precision U–Pb geochronology of the end-Cretaceous extinction and calibration of Paleocene astronomical timescales

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# ARTICLE INFO

Article history: Received 23 March 2016 Received in revised form 16 July 2016 Accepted 23 July 2016 Available online 18 August 2016 Editor: H. Stoll

Keywords: K-Pg boundary geochronology magnetostratigraphy astrochronology Paleocene timescale

#### ABSTRACT

The Cretaceous–Paleogene (K–Pg) boundary is the best known and most widely recognized global time horizon in Earth history and coincides with one of the two largest known mass extinctions. We present a series of new high-precision uranium–lead (U–Pb) age determinations by the chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) method from volcanic ash deposits within a tightly constrained magnetobiostratigraphic framework across the K–Pg boundary in the Denver Basin, Colorado, USA. This new timeline provides a precise interpolated absolute age for the K–Pg boundary of  $66.021 \pm 0.024/0.039/0.081$  Ma, constrains the ages of magnetic polarity Chrons C28 to C30, and offers a direct and independent test of early Paleogene astronomical and  $^{40}$ Ar/ $^{39}$ Ar based timescales. Temporal calibration of paleontological and palynological data from the same deposits shows that the interval between the extinction of the dinosaurs and the appearance of earliest Cenozoic mammals in the Denver Basin lasted ~185 ky (and no more than 570 ky) and the 'fern spike' lasted ~1 ky (and no more than 71 ky) after the K–Pg boundary layer was deposited, indicating rapid rates of biotic extinction and initial recovery in the Denver Basin during this event.

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# 1. Introduction

The geological timescale provides the framework for interpreting Earth history. Major subdivisions of the timescale correspond to mass extinctions such as the K–Pg boundary, one of the two largest extinctions in earth history (e.g. Schulte et al., 2010). Calibration of the timescale in absolute time is critical for examining rates of geological and biological processes. Recent advances in radioisotope geochronology and astrochronology have led to proposed timescale calibrations of unprecedented precision. Astrochronological models are based on the interpretation of sedimentary cyclicity as being driven by astronomical forcing of climate. However, because of uncertainties associated with the chaotic nature of planetary dynamics, astronomical timescales older than  $\sim$ 50 Ma are not considered robust unless tested by independent geochronological methods (Laskar et al., 2011a). Such

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http://dx.doi.org/10.1016/j.epsl.2016.07.041

tests are often difficult because astrochronologies are typically derived from deep sea records where dateable volcanic deposits are rare. Here we use high-precision U–Pb geochronology (CA-ID-TIMS technique) of intercalated ash beds to date the K–Pg boundary and surrounding magnetic polarity reversals in fossiliferous continental rocks from the Denver Basin of Colorado (USA) to calibrate the early Paleogene astronomical timescale and precisely constrain the tempo of extinction and recovery.

The Geomagnetic Polarity Timescale (GPTS) is commonly used to sequence events in geological time yet was traditionally calibrated in absolute time by only a handful of <sup>40</sup>Ar/<sup>39</sup>Ar age determinations from widely separated geographic locations and had relatively large intercalibration uncertainties (e.g. Cande and Kent, 1995, 1992). The most recent GPTS calibrations (GTS2004 – Gradstein et al., 2004 and GTS2012 – Gradstein et al., 2012) have capitalized on advances in geochronology and used a numerical calibration that integrates both radioisotopic and astrochronological constraints. However, stand-alone astronomical timescales prior to the Neogene remain uncertain due to the chaotic nature of planetary interactions (Hinnov and Hilgen, 2012) and varied interpretations of local cyclostratigraphic data (e.g. Dinarès-Turell

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**Fig. 1.** Geological map of the Denver Basin showing trace of K–Pg boundary (dark gray line) and location of Kiowa core drill site and surface outcrop sites discussed in text (adapted from Raynolds, 2002).

et al., 2014). Therefore, these timescales must be tested and refined using independent geochronological methods that can attain higher resolution than the shortest astronomical frequency used. Uranium-lead zircon geochronology by the ID-TIMS method is particularly suitable for high-resolution calibration of geologic time because it takes advantage of two independent radioactive decay schemes with precisely measured decay constants (e.g. Bowring et al., 2006). In addition, the accuracy of U-Pb dates does not rely on the age of mineral standards and the effects of open system behavior in zircon can be readily detected and mitigated. By directly calibrating individual globally correlated stratigraphic events (e.g. K-Pg boundary, Chron boundaries) using multiple high-resolution U-Pb ages in a single integrated stratigraphic framework, we are able to achieve higher precision than most previous studies without reliance on models of sea-floor spreading or long-term sedimentation rates.

# 2. Geological background and sampling sites

The Denver Basin is an ideal place for developing a highresolution timescale for the latest Cretaceous and early Paleogene because it has a thick sequence of fossiliferous synorogenic sediments that are well suited for paleomagnetic analysis and include abundant interbedded volcanic ash deposits, all of which are accessible via correlative core and outcrop records (Fig. 1). All sampling for this study was carried out in the upper Cretaceous–Paleocene D1 sequence. The D1 sequence is an unconformity bounded package of fluvial/paludal sandstone, mudstone, and lignite beds, underlain by the Laramie Formation and overlain by the lower Eocene D2 sequence (Raynolds, 2002). The K–Pg boundary itself is exceptionally well preserved in the D1 sequence, with evidence of bolide impact and biotic change that includes an iridium and osmium anomaly (Barclay, 2003; Zaiss et al., 2014), shocked quartz (Barclay, 2003), extinctions of dinosaurs and plants (Nichols and Fleming, 2002; Carpenter and Young, 2002; Barclay, 2003), and subsequent biotic recovery (e.g. fern "spike" and mammal diversification; Nichols and Fleming, 2002; Dahlberg et al., 2016). However, testing of extinction and recovery models in the basin has been hindered by a lack of detailed high-resolution chronologies across the boundary interval. The multiple interbedded volcanic ash beds across the K–Pg boundary in the D1 sequence studied here allow calibration of this interval with unprecedented levels of precision and accuracy.

One core (Kiowa core) and four surface stratigraphic sections (Haas Ranch, Easy-to-Reach, My Lucky Number, and West Bijou Creek) were sampled for this study (Fig. 1). The 688 m (2256 ft) Kiowa core (39.35242°N, 104.46642°W) was drilled in 1999 and resulted in 93% core recovery through the Pierre, Fox Hills, Laramie, D1 and D2 lithological units (Raynolds et al., 2001). The surface sections lie along the western slope of the adjacent West Bijou Creek Escarpment, which cuts progressively down section toward the north (Figs. 1 and 2). Many fossil localities have been tied to these surface sections and provide an important biostratigraphic framework that cannot otherwise be achieved in the core (Johnson et al., 2003).

# 3. Methods

#### 3.1. Paleomagnetic methods

Twenty-three oriented paleomagnetic samples were collected from the Kiowa core at the USGS Core Repository and subsequently cut into 8 cm<sup>3</sup> cubes at the University of New Hampshire (UNH). Two of the samples were large enough to create separate subsamples which allowed us to perform duplicate analyses at these two levels. Sampling levels in the core were selectively chosen to increase the magnetostratigraphic resolution achieved by Hicks et al. (2003) and thus were concentrated near previously identified polarity reversal boundaries. Sampling was limited to horizons with mudstone and fine sandstone lithologies appropriate for paleomagnetic analysis. Detailed lithological logs of the Kiowa core can be found in Raynolds et al. (2001).

In addition to resampling the Kiowa core, three of the surface sections were sampled to develop a parallel polarity record from outcrops that can be correlated to the core. Three or more oriented hand samples were collected from (1) 10 sites within the My Lucky Number section, (2) 8 sites within the Easy-to-Reach section, and (3) 12 sites within the Haas Ranch section (Fig. 1). The West Bijou Creek section was previously analyzed by Hicks et al. (2003). Like in the Kiowa core, samples were taken from appropriate lithologies (mudstone to fine sandstone) and cut into 8 cm<sup>3</sup> cubes for further analysis. In some cases, poor exposure or the existence of large channel sandstones limited the sampling resolution that could be achieved in the surface exposures. Lithological information for samples from these surface sections can be found in Table S2.

All paleomagnetic analyses were conducted in the paleomagnetics laboratory at UNH with an HSM2 SQUID cryogenic magnetometer, a Molspin tumbling alternating-field demagnetizer, and an ASC Model TD48 SC thermal demagnetizer. Sample demagnetization protocol was based on the prior results of Hicks et al. (2003) and involved step-wise alternating field demagnetization in 2 mT steps up to 25 mT and then 5 mT steps thereafter until the natural remanent magnetization (NRM) intensity dipped below the sensitivity of the magnetometer or until the NRM no longer decreased in intensity. Several samples that were not completely demagnetized by this AF protocol were further demagnetized using stepwise thermal demagnetization to eliminate any remaining NRM



**Fig. 2.** Fence diagram showing the stratigraphic framework for this study. Kiowa core information is on left showing chronostratigraphy, lithostratigraphy ("lith"), pollen biostratigraphy (Nichols and Fleming, 2002), magnetostratigraphic data ("inclination" of characteristic remanent magnetization), and proposed correlation to the Geomagnetic Polarity Timescale (GPTS; Gradstein et al., 2012). Outcrop sections are on the right showing magnetostratigraphic information (VGP lat = latitude of virtual geomagnetic pole) and proposed correlation to the GPTS and Kiowa core. Map at upper right shows the location of the Kiowa core and outcrop sections. Vertical axis for Kiowa core graph is depth below surface. Vertical axis for Haas Ranch, Easy to Reach, and My Lucky Number sections is elevation as determined by differential GPS. Vertical axis for West Bijou Creek is stratigraphic level above/below the K–Pg boundary layer. New paleomagnetic data from this study are shown as black points and previously published data (Hicks et al., 2003) are shown as gray points (each representing a mean of 3–4 samples). Asterisks show stratigraphic positions of volcanic ashes that were dated in this study using U–Pb geochronology (see Table 1 and Fig. 4). Stratigraphic scales are shown in feet (as well as meters) because that is the original drilling depth unit for the Kiowa core.

and isolate any high coercivity components. After these demagnetization procedures, samples with NRM directions exhibiting a relatively linear decay to the origin were characterized by least squares analysis (Kirschvink, 1980). Those samples that exhibit initial decay followed by strong clustering of vector end points, but no linear decay to the origin, were calculated using a Fisher mean. In some samples, the overlapping unblocking spectra of the magnetic components obscured any linear demagnetization trends, and we used the progression of remanence directions along a great circle path from the overprinting direction to a characteristic direction to describe the Characteristic Remanent Magnetization (ChRM). In a few cases, samples exhibited unstable demagnetization behavior and could not be used for purposes of polarity determination. For sites that included samples characterized by a great circle, the methods of McFadden and McElhinney (1988) were used to calculate a mean. Because the Kiowa core was unoriented with respect to azimuth, only the inclination of the ChRM is used for determining polarity in those samples, however both declination and inclination are used for samples from surface sites.

#### 3.2. U-Pb geochronology methods

Zircons were separated from interbedded tuffs from 5 samples from the Kiowa core and 9 samples from the outcrops, spanning the Maastrichtian (Chron C29r) to the Early Paleocene (Chron C28n). Heavy mineral separation from bentonitic tuffs was achieved by an ultrasonic device (Hoke et al., 2014), followed by magnetic and high-density liquid separation; individual zircons were hand selected for analysis under a binocular microscope based on grain morphology and clarity. A total of 159 zircons were analyzed by the U-Pb isotope dilution thermalionization mass spectrometry (ID-TIMS) technique following the detailed procedures described in Ramezani et al. (2011). All zircons were pre-treated by a chemical abrasion (CA-TIMS) method modified after Mattinson (2005) to mitigate the effects of radiationinduced Pb loss, and spiked with the EARTHTIME ET535 mixed <sup>205</sup>Pb-<sup>233</sup>U-<sup>235</sup>U tracer (Condon et al., 2015; McLean et al., 2015) prior to dissolution and analysis. Complete U-Pb data appear in Table S3.

Table 1							
Summary	of calculated	U-Pb	ages	and	their	uncertaintie	s.

Sample	Location	Latitude	Longitude	Elev/Level/Depth	lev/Level/Depth Elev/Level/Depth $^{206}$ Pb/ $^{238}$ U age Uncertainty (2 $\sigma$ )		)	MSWD	п	#		
				(ft.)	(m)		X	Y	Ζ			
KJ04-56	Haas Ranch	39.41198	-104.34049	6079.28	1852.97	64.380	0.065	0.074	0.100	0.49	5	8
KJ07-55B	My Lucky No.	39.52267	-104.32809	5741.98	1750.15	65.747	0.043	0.054	0.088	0.25	5	8
KJ07-54E	My Lucky No.	39.52366	-104.32127	5685.77	1733.02	65.917	0.054	0.064	0.095	0.17	5	11
KJ04-70	Bowring Pit	39.57059	-104.30306	3.29	1.00	65.889	0.027	0.044	0.083	1.10	11	14
KJ04-72	Bowring Pit	"	"	2.83	0.86	65.966	0.020	0.039	0.080	0.82	13	13
KJ09-66	Bowring Pit	"	"	1.77	0.54	65.969	0.023	0.039	0.081	0.67	8	11
KJ04-75	Bowring Pit	"	"	1.69	0.52	65.993	0.019	0.037	0.079	1.30	14	21
KJ12-01	Bowring Pit	"	"	0.38	0.12	66.084	0.045	0.064	0.095	1.60	9	11
KJ08-157	Bowring Pit	"	"	-1.51	-0.46	66.082	0.022	0.037	0.080	0.78	12	14
KJ08-17	Kiowa core	39.35242	-104.46642	572.58	174.52	64.520	0.029	0.043	0.081	0.76	8	12
KJ07-63	Kiowa core	"	"	588.13	179.26	64.633	0.049	0.063	0.094	0.57	6	8
KJ08-53	Kiowa core	"	"	878.40	267.74	65.801	0.038	0.054	0.088	0.93	8	11
KJ10-04	Kiowa core	"	"	992.66	302.56	66.019	0.024	0.038	0.080	0.94	5	9
KJ10-09	Kiowa core	"	"	1130.25	344.50	66.304	0.029	0.044	0.083	0.58	6	8

Notes: Latitude/Longitude: Relative to WGS 84 datum; Elev/Level/Depth (ft.): Elevation above sea level for outcrop sections (Haas Ranch and My Lucky No.), stratigraphic level relative to the top of the K–Pg boundary clay layer for Bowring Pit, and depth below surface for Kiowa Core; X: internal (analytical) uncertainty in the absence of all external or systematic errors; Y: incorporates the U–Pb tracer calibration error; Z: includes X and Y, as well as the uranium decay constant errors; MSWD: mean square of weighted deviates; n: number of analyses from the total # included in the calculated weighted mean date.

#### Table 2

Revised depth and ages of boundaries between Chrons C28r through C30n in the Kiowa Core.

Chron boundary	Depth (ft)	+/- (ft)	Depth (m)	+/- (m)	Age (Ma)	+/- (my)
C28r/C28n	574.67	1.13	175.16	0.34	64.535	0.040
C29n/C28r	652.78	2.23	198.97	0.68	64.893	0.056
C29r/C29n	880.82	5.19	268.47	1.58	65.806	0.048
K/Pg boundary	993.85	0.00	302.93	0.00	66.021	0.024
C30n/C29r	1193.85	1.35	363.89	0.41	66.436	0.039

Notes: Ma - Million years ago; +/- uncertainty in age represents the fully propagated 95% confidence interval including stratigraphic error.

Many of the Denver Basin tuff samples contain xenocrystic zircon from older sources (see below). Sample dates representing the best estimate for the depositional age are thus derived from weighted mean <sup>206</sup>Pb/<sup>238</sup>U date of a statistically coherent cluster of the voungest zircon analyses from each sample, provided that there are more than 3 precise analyses to form a cluster. All calculated date uncertainties are reported at the 95% confidence level  $(2\sigma)$  and follow the notation  $\pm X/Y/Z$  Ma (Table 1), where X is the internal (analytical) uncertainty in the absence of all external errors, Y incorporates the U-Pb tracer calibration error and Z includes the latter as well as the U decay constant errors. Complete uncertainties (Z) are necessary for comparison between U–Pb and <sup>40</sup>Ar/<sup>39</sup>Ar age data. Uncertainties referred to in text are analytical uncertainties only unless otherwise noted. Linear interpolation is used to calculate estimated ages and their associated uncertainties for events between dated horizons (e.g. K-Pg boundary).

# 4. Results

# 4.1. Paleomagnetism

All but one (KJ08-59) of the 25 samples from the Kiowa core exhibited clear demagnetization behavior and could be characterized by least squares analysis (Table S1, Fig. S1). Initial AF demagnetization up to 100 mT successfully isolated the ChRM for 19 of the 25 samples. Samples KJ08-31B, KJ08-50A, KJ08-59A, KJ08-61A, KJ08-62A, and KJ08-63A were subjected to additional thermal demagnetization as well. ChRM inclinations separate into two distinct groups with means of  $50.0^{\circ}$  (normal polarity) and  $-35.4^{\circ}$  (reverse polarity; Fig. S2A). This asymmetry between normal and reversed mean inclinations is likely due to a present-day overprint (or drilling overprint) leaving reverse polarity samples (upward oriented inclinations) with shallower than expected ChRMs. The

resulting revised magnetostratigraphy for the Kiowa core significantly improves the stratigraphic resolution of polarity reversals first identified by Hicks et al. (2003) (Fig. 2). Table 2 shows the new stratigraphic constraints for the Chron C30n-C28n reversals (the very short Chron C30r is not recorded in the Kiowa core; Hicks et al., 2003). These geomagnetic reversals in the Kiowa core now have an average stratigraphic uncertainty of  $\pm 0.76$  m (=  $\pm 2.5$  feet; < ~ 8 ky; stratigraphic levels here are reported in English as well as metrics units for direct comparison to original drilling units of feet) which significantly minimizes one important source of error in assigning ages and durations to geomagnetic chrons.

Magnetostratigraphic results from outcrop sections exhibit a polarity record that can be easily correlated to the adjacent Kiowa core record (Figs. S1 and S2B). Site statistics for those sites that pass the Watson Test of randomness are listed in Table S2 (Watson, 1956). These sites pass the reversal test at the 95% confidence interval (Tauxe et al., 2014; Fig. S2C). The majority of these sites (64%) were based on sample directions that were all calculated by least squares analysis whereas the others included sample directions calculated using a fisher mean or great circle (see Table S2 for details). The stratigraphically lowest section (My Lucky Number) exhibits reverse polarity at the base, interpreted here to represent part of Chron C29r, and normal polarity towards the top, interpreted to be part of Chron C29n. The stratigraphically higher Easy to Reach section exhibits normal polarity throughout which is interpreted to represent part of Chron C29n. The uppermost Haas Ranch section exhibits a short zone of reverse polarity near the base, interpreted to be Chron C28r, and normal polarity above, interpreted to be Chron C28n. The top of the section is truncated disconformably by the D2 sequence of conglomerates likely deposited during the early Eocene. By integrating these new magnetostratigraphic data with differentially corrected GPS (dGPS) locations for the sample sites, we constructed a composite outcrop record of polarity changes that is referenced to absolute elevation and can be easily correlated to the record from the Kiowa core (Fig. 2). Only C28r shows significant differences in thickness between the core (22.78–24.83 m = 74.75-81.47 ft) and the outcrop (< 15.4 m = < 50.5 ft) which could be related to (1) the dynamic depositional processes associated with this active foreland basin, (2) a poor dGPS reading for site DB0701 which was in a steep gully, or (3) a thick coarse channel sandstone that lies just above site DB0701 (see Table S2), the base of which may represent a local disconformity.



**Fig. 3.** (A) Magnetostratigraphy of Kiowa core (new data in black, data from Hicks et al., 2003 in gray, see Fig. 2) with comparison of Denver Basin U–Pb age model (red circles) to previously published age models (black squares). Size of data point encompasses the error bars for stratigraphic uncertainty (*y* axis) and 95% confidence interval on age (*x* axis). New Denver Basin U–Pb age model (red circles) plots age and stratigraphic positions for Kiowa core volcanic ash beds analyzed in this study whereas previously published age models (black squares) show estimated ages for relevant GPTS tie points (K–Pg and Chron boundaries). (B) Average difference in age (ky) of tie points (K–Pg and Chron boundaries) between Denver Basin age model and previously published age models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

#### 4.2. U–Pb geochronology

Volcanic ash horizons of the Denver Basin are volcanoclastic deposits that almost invariably contain xenocrystic zircon from sources as old as ca. 1.4 Ga. Analytical precision of 0.1% ( $2\sigma$ ) or better on individual  $^{206}$ Pb/ $^{238}$ U dates allow isolation of the youngest population of zircons from each ash in order to calculate statistically valid weighted mean dates. The latter can serve as close estimates for the depositional age, once it can be demonstrated that dates from successive, closely spaced, ash beds are mutually resolvable (outside analytical uncertainty) and obey their stratigraphic order. The U–Pb age results and their detailed uncertainties are listed in Tables 1 and S3 and illustrated in Fig. S3.

#### 4.2.1. Kiowa core

Five interstratified volcanic ash horizons from the Kiowa core were analyzed spanning Chrons C29r to the C28r-C28n reversal boundary and including the K-Pg boundary (Table 1; Fig. S3). The weighted mean dates range from 66.304  $\pm$  0.029 Ma to 64.520  $\pm$ 0.029 Ma (analytical  $2\sigma$  uncertainties only), are in the expected stratigraphic order, and all have 95% confidence intervals of less than 50 ky. By combining these new isotopic dates with the updated Kiowa core magnetostratigraphy, it is possible to develop a high-resolution age model for the Core and assess the existing absolute age calibrations for the GPTS (Fig. 3). Close proximity of the dated ash beds to the polarity reversal boundaries and the K-Pg boundary in the Core allow their ages to be constrained with minimal interpolation (e.g., sample K]10-04 is only 36 cm = 14.17 in above the K-Pg boundary layer, Figs. 2, 4). Interpolated ages for the Chron C30n/C29r, C29r/C29n, C29n/C28r, and C28r/C28n polarity reversals as well as the K-Pg boundary are given in Table 2. The age progression of the five dated ashes in the Kiowa core indicates somewhat higher than average sediment accumulation rates

in the Maastrichtian and near the K–Pg boundary compared to that in the overlying Paleocene (Fig. 3).

#### 4.2.2. Denver Basin outcrops

U-Pb zircon age determinations were also carried out on three ash samples collected from exposed outcrops adjacent to the Kiowa core site in order to further test the Kiowa age model. The analyzed samples were collected from the Haas Ranch and My Lucky Number stratigraphic sections where the Chron C28n-C28r and C29n-C29r (respectively) polarity reversals are also recorded (Tables 1 and S3; Fig. S3). At My Lucky Number, the stratigraphically lower sample (KI07-54E) was collected from 17 m (=56 ft) below the reversal and the upper one (KJ07-55B) from between the reversed and normal polarity sites that define the reversal boundary in the section. As in the core, the ages are in the expected stratigraphic order and have 95% confidence intervals of less than 65 ky. The age for the Chron C29r-C29n boundary in the Kiowa core and in the My Lucky Number outcrop section overlap within uncertainty showing excellent reproducibility despite  $\sim$ 22 km distance between them (Fig. 4). The single sample (KJ04-56) from the Haas Ranch section also closely corroborates the age of the C28n-C28r reversal in the Kiowa core (Fig. 4).

#### 4.2.3. Bowring Pit

The stratigraphic position of the K–Pg boundary in the Denver Basin sequence has been identified precisely in outcrop records in the West Bijou Creek area based on palynology, as well as impact-derived proxies such as iridium and osmium concentrations, and shocked quartz (Barclay, 2003; Nichols and Fleming, 2002; Zaiss et al., 2014). Several parallel trenches have been excavated here to expose the K–Pg boundary stratigraphy for detailed study. The K–Pg boundary is preserved in a sequence of interbedded gray mudstone and lignite with numerous interspersed thin



**Fig. 4.** Comparison of the integrated geochronology for the (A) Chron C28r–28n reversal, (B) Chron C29r–C29n reversal and (C) K–Pg boundary in the outcrop record (right) and Kiowa core record (left) of the Denver Basin. Black paleomagnetic data points are from this study and grey ones are from Hicks et al. (2003). Red lines indicate position of volcanic ash beds that have been dated using high precision U–Pb geochronology (dates in million years). The polarity reversals and K–Pg boundary are calibrated to be the same age (within error) in both outcrop and Core records. Stratigraphic scales are shown in feet because that is the original drilling depth unit for the Kiowa core. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

volcanic ash beds (Fig. S4 and Table S4). A series of 6 successive and closely spaced volcanic ash samples from one of these trenches called the Bowring Pit (Zaiss et al., 2014) were analyzed for U-Pb zircon geochronology in order to determine a precise age of the K-Pg boundary and better constrain the timing of associated biotic extinction and recovery (Fig. S4; Table 1). The samples range in stratigraphy from 0.46 m (1.51 ft) below to 1.00 m (3.29 ft) above the K-Pg boundary layer and in calculated U-Pb dates from  $66.082 \pm 0.022$  Ma to  $65.889 \pm 0.027$  Ma, respectively. With only one exception, all ash samples yielded mutually resolvable dates consistent with the expected stratigraphic age progression (Table 1; Fig. S4). Sample KJ12-01 (0.12 m = 0.38 ft above the boundary) produced a weighted mean date of  $66.084 \pm 0.045$  Ma, essentially identical to that of the underlying sample KJ08-157 (0.46 m = 1.51 ft below the boundary) and inconsistent with the observed upward age progression. The former is suspected of containing a predominantly detrital (reworked) zircon population that is demonstrably older than its true depositional age and thus excluded from the age model.

Linear interpolation between the samples immediately above and below the K-Pg boundary layer results in an age of  $66.040 \pm$ 0.021 Ma which is indistinguishable from the interpolated K-Pg boundary age from the Kiowa core results (66.021  $\pm$  0.024 Ma). The estimated age of the K-Pg boundary from the Bowring pit does not change significantly depending on which dates from the pit are included in the interpolation. We prefer the 66.021  $\pm$ 0.024/0.039/0.081 Ma age for the K-Pg boundary because (1) sample KJ10-04 in the Kiowa core is closest to the boundary thus requiring minimal interpolation and (2) the Bowring Pit interpolated K-Pg boundary age (66.021  $\pm$  0.024 Ma) is identical to the Kiowa age when the stratigraphically highest (KJ04-70) and lowest (KJ08-157) ashes in the Bowring Pit are used as the bracketing points. The sediment accumulation rate within the Bowring pit appears to be relatively linear despite the short time interval covered. However, sediment accumulation rates in the pit are slower by an order of magnitude than the long-term accumulation rate calculated for the same part of the Kiowa core. This could be due to calculating the accumulation rates over different thicknesses, however normally sediment accumulation rates are faster when calculated over shorter stratigraphic intervals because they average fewer hiatuses and paraconformities (Sadler, 1981). The discrepancy could also indicate a period of especially slow sedimentation during the K-Pg boundary interval itself followed by a rapid rise in accumulation immediately after the boundary. This would be consistent with the landscape instability hypothesis proposed by Fastovsky et al. (2008) and is further corroborated here by the presence of what we interpret to be an entirely reworked ash bed above the K-Pg boundary (sample KJ12-01).

### 5. Discussion

#### 5.1. Time scale implications

The Geomagnetic Polarity Timescale (GPTS) plays a primary role in interpreting stratigraphic records of Earth history because polarity reversals are geologically rapid and globally distributed making them ideal timelines for correlating between different depositional environments and geographic locations. Accurate and precise calibration of the GPTS in absolute time is critical for resolving rates of geological and biological processes which in turn help constrain the underlying causes of those processes. Numerical calibration of the GPTS was traditionally carried out by interpolation between a limited number of <sup>40</sup>Ar/<sup>39</sup>Ar dates for volcanic ash deposits from superpositional sequences with well-defined magnetostratigraphic records. More recently, the Neogene Period of the GPTS has been calibrated using high-resolution astrochronological methods, however the application of these approaches to pre-Neogene parts of the timescale is controversial given the uncertainties in relevant astronomical parameters this far back in time (Laskar et al., 2004, 2011a, 2011b) and differing interpretations of local cyclostratigraphic records (e.g. Dinarès-Turell et al., 2007; Hilgen et al., 2010; Westerhold et al., 2008). Dinarès-Turell et al. (2007) reported a provisional astrochronology for the Paleocene based on an integrated magneto-, bio- and cyclo-stratigraphic records of the Zumaia section in the Basque Basin of Spain (see also Dinarès-Turell et al., 2003). Westerhold et al. (2008) presented a floating astrochronological calibration of the Paleocene GPTS by matching cyclic patterns in geochemical proxies of climate change recovered from several Ocean Drilling Program (ODP) cores to the stable 405 ky eccentricity cycle (Laskar et al., 2004). This calibration was floating because of uncertainties associated with the absolute age of the tie points (the Cretaceous-Tertiary boundary and the Paleocene-Eocene Thermal Maximum) and a cyclostratigraphic gap in the overlying Eocene record. Hilgen et al. (2010) suggested that the Paleocene had twenty five 405-ky cycles, rather than the

24 cycles that Westerhold et al. (2008) had identified, and retuned the record accordingly, GTS2012 integrated the Hilgen et al. (2010) astrochronological solution (see Table 28.2 of Gradstein et al., 2012) with an independent radio-isotopically calibrated age model to derive their final "combined" age model for the Paleocene. Westerhold et al. (2012) re-tuned the cyclostratigraphic records from several sections to the updated LA2010 and LA2011 astronomical models (Laskar et al., 2011a, 2011b) and derived new age estimates for the PETM and K-Pg boundary that are entirely independent of radioisotopic dates (see also Husson et al., 2011). Most recently, Dinarès-Turell et al. (2014) re-examined several Danian records and developed a new early Paleocene astrochronology that reportedly resolved previously disputed discrepancies for this time interval. Although the discrepancies between these various calibrations of the Paleocene timescale have reduced over time, there is still significant uncertainty about the best approach for calibrating Paleogene time given the inherent uncertainties of astronomical solutions past ~50 Ma (Laskar et al., 2011a). Recent <sup>40</sup>Ar/<sup>39</sup>Ar geochronology from the classic Hell Creek sections in Montana provided an independent test of the late Cretaceous-early Paleocene GPTS calibrations. However ongoing debate concerning the age of the Fish Canyon Tuff (FCT) sanidine standard that is used in <sup>40</sup>Ar/<sup>39</sup>Ar date calibration complicates their interpretation (Kuiper et al., 2008; Channell et al., 2010; Renne et al., 2010; Rivera et al., 2011; Westerhold et al., 2012). Our new results from the Denver Basin provide a new test of the various calibration methods for the pre-Neogene timescale by independently dating several Paleocene polarity chrons using high-precision U-Pb geochronology within a tightly constrained magnetostratigraphy.

Fig. 3B shows the various proposed calibrations, ordered by publication date, for the early- to mid-Paleocene compared to the chronostratigraphic framework developed here from the Denver Basin. The first and most important pattern in these comparisons is the obvious convergence in age calibration solutions through time. Whereas earlier numerical calibrations of the GPTS widely diverged from each other, the more recent ones are very similar to each other and converge with our new U-Pb based model from the Denver Basin. The differences between various calibrations for the Paleocene GPTS are now typically less than 100,000 yrs (e.g., one short eccentricity cycle) which is a tribute to the progress made by the geochronological and astrochronological communities over the last 20 yrs. In order to measure the overall fit of our new age model to the previous calibrations, we calculated the average difference between the calibrated ages of all comparable polarity reversals (Fig. 3B). The closest fits to our new age model are GTS2012 and the astrochronological calibration of Dinarès-Turell et al. (2014), with Hilgen et al. (2010) and Westerhold et al. (2008) Option 3 falling closely behind. The Sprain et al. (2015) <sup>40</sup>Ar/<sup>39</sup>Ar model fits well also except for the C29r/C30n and C28n/C28r reversals where it diverges significantly from the Kiowa age model (as it does from GTS2012). In particular, our data support a longer duration for Chron C29r ( $630 \pm 62$  ky) compared to Sprain et al. (2015;  $345 \pm 38$  ky), more consistent with GTS2012 (710 ky). Recent U-Pb age calibration of the Deccan flood basalts yielded a somewhat longer duration of  $736 \pm 37$  ky for Chron C29r (Schoene et al., 2015), however that outcrop sequence is relatively discontinuous compared to the core records from the deep sea and Denver Basin.

The new U–Pb derived age for the K–Pg boundary reported here for the Denver basin sequence ( $66.021 \pm 0.024/0.039/0.081$  Ma) is very close to the  ${}^{40}$ Ar/ ${}^{39}$ Ar derived age for the K–Pg boundary from the Hell Creek sequence in Montana ( $66.043 \pm 0.086$  Ma; fully propagated  $2\sigma$  uncertainty, Renne et al., 2013; Sprain et al., 2015) suggesting these two independent isotopic chronometers are converging despite ongoing debate regarding the true age of the Fish Canyon Tuff  ${}^{40}$ Ar/ ${}^{39}$ Ar standard (Kuiper et al., 2008; Westerhold et al., 2012) and the possible magma residence time for zircons (see review in Costa, 2008). Furthermore, the K-Pg boundary age from Denver Basin is almost identical to that from the astrochronological models (Dinarès-Turell et al., 2014) entirely independent of radioisotopic geochronology. As direct isotopic dating and astronomical calibration of Chron boundaries becomes more commonly applied, it will soon be possible to calibrate the entire late Cretaceous-Cenozoic GPTS without reference to marine magnetic anomaly profiles and the underlying assumption concerning rates of sea-floor spreading. As direct scaling of superpositional sequences increasingly relies on high-resolution isotope geochronology and calibrated astrochronology, the reduction of age and stratigraphic uncertainties associated with datable samples will become even more important for attaining the highest possible temporal precision for the GPTS. Isotopic age uncertainties comparable to - or smaller than - the shortest recorded cyclostratigraphic periodicity are needed to fully assess the synchronicity of radioisotopic and astrochronological time scales (e.g., Machlus et al., 2015).

# 5.2. Biotic implications

The high-resolution chronostratigraphic framework presented here has important implications for understanding rates of biotic extinction and recovery across the K-Pg boundary. For instance, a fern spore abundance anomaly ("fern spike") at the K-Pg boundary has been documented in the Kiowa core (where fern spores reached 97.5% abundance; Nichols and Johnson, 2008) and at the West Bijou Creek locality (where fern spores reached 74% abundance; Barclay, 2003; Nichols and Fleming, 2002). Such an increase in the relative abundance of fern spores directly superimposed on sedimentary evidence for a bolide impact at the K-Pg boundary has been observed in many terrestrial sites across the globe and has long been cited as strong evidence for widespread ecological turnover caused by events associated with the impact (see Vajda and Bercovici, 2014 for review). The new age model presented here allows for a precise temporal calibration of the fern spike. Using the median sediment accumulation rate of 142 yrs/cm (=361 yrs/inch) calculated from all possible pair-wise comparisons between the new U–Pb dates reported here (including their  $2\sigma$ uncertainties) indicates that the  $\sim$ 0.6 cm (=0.24 inch) in stratigraphic thickness between the top of the K-Pg boundary layer and the peak in fern spore abundance (Barclay, 2003; Nichols and Fleming, 2002) represents  $\sim$ 85 yrs and the  $\sim$ 6 cm (= 2.36 in) thick recovery interval after the initial peak in fern abundance lasted  $\sim$ 850 yrs, suggesting the entire fern spike occurred over  $\sim$ 1000 yrs. However, sediment accumulation rates were probably highly variable during the K-Pg boundary interval due to associated changes in landscape stability and the above estimate does not account for that. Conservatively, the entire 6.6 cm (2.60 in) fern spike interval represents between 0 and 71,000 yrs given that it is bracketed between the K-Pg boundary layer ( $66.021 \pm 0.024$  Ma) and sample KJ04-75 (65.993  $\pm$  0.019 Ma), which lies 51.5 cm (20.27 in) above the K-Pg boundary layer in the Bowring Pit.

In terms of vertebrates, the stratigraphically highest dinosaur specimens recovered in the Denver Basin come from 4 m (13.1 ft) below the K–Pg boundary at the West Bijou Site (Barclay, 2003) and a specimen of the Puercan 1 fossil mammal *Protungulatum donnae* was found 9 m (29.5 ft) above the K–Pg boundary in the same area (Dahlberg et al., 2016). Using the same median sediment accumulation rate described above, our data suggest that dinosaur extinction occurred within ~57 ky of the boundary layer and initial Paleocene mammalian radiation started no more than ~128 ky after the boundary (=185 ky for the interval between the uppermost dinosaur occurrence and the lowermost Cenozoic mammal occurrence). This 13 m (42.6 ft) stratigraphic interval is

bracketed by samples KJ08-53 (65.801  $\pm$  0.038 Ma) and KJ10-09 (66.304  $\pm$  0.029 Ma) in the Kiowa core, which suggests a conservative estimate of less than 570 ky for the interval between the extinction of the latest non-avian dinosaurs and the establishment of the earliest Cenozoic mammal assemblages. Since dinosaur and mammal fossils are relatively uncommon at the West Bijou Creek Site, these estimates represent maximum durations and these durations may decrease with additional sampling. These represent some of the tightest temporal constraints on biotic turnover across the K–Pg boundary for a continental system and suggest that both extinction and initial recovery were geologically rapid in this setting.

The K-Pg boundary extinction is generally thought to be due to the catastrophic effects of the Chicxulub bolide impact, the more prolonged environmental effects of the Deccan Traps volcanic eruptions, or some combination of the two (Alvarez et al., 1980; Courtillot et al., 1986; Schulte et al., 2010; Schoene et al., 2015). The age reported here for the K-Pg boundary layer in the Denver Basin (66.021  $\pm$  0.024/0.039/0.081 Ma) overlaps within  $2\sigma$  errors with the age of the K-Pg boundary layer in the Hell Creek Formation of Montana based on  ${}^{40}\text{Ar}/{}^{39}\text{Ar}$  geochronology (66.043  $\pm$ 0.086 Ma; Renne et al., 2013; Sprain et al., 2015) and both of them are indistinguishable from the <sup>40</sup>Ar/<sup>39</sup>Ar age of Chixculub tektites (66.038  $\pm$  0.098 Ma; Renne et al., 2013) providing strong support for the contemporaneous emplacement of ejecta across western North America directly after the Chicxulub impact. Our data also indicate that the fern spike occurred within  $\sim$ 1000 yrs of the ejecta layer, consistent with the timescale for the carbon isotope anomaly in the Hell Creek sections (Renne et al., 2013), and supportive of the existence of landscape scale terrestrial ecosystem disruption due to effects of the impact. The observed highest stratigraphic occurrence of dinosaurs and lowest Pu-1 mammals in the Denver basin are also consistent with the impact playing an important role in ecosystem reorganization, but coincident influences from the main phase of Deccan Trap volcanism cannot be ruled out given the sampling resolution for these fossil groups.

# 6. Conclusions

A new U-Pb age model from a series of volcanic ash beds within a well-constrained latest Cretaceous-Paleocene magnetobiostratigraphic framework in the Denver Basin provides an age of  $66.021 \pm 0.024/0.039/0.081$  Ma for the K-Pg boundary and allows precise temporal calibration for this part of the Geomagnetic Polarity Timescale. These new results closely corroborate the most recently proposed marine-based astronomical timescale for the same time interval and agree well with a recent <sup>40</sup>Ar/<sup>39</sup>Ar age model for the Hell Creek sequence in Montana but differ from that model in indicating a longer Chron C29r, consistent with the astronomical solution. Analytical methods for temporal calibration of the geological timescale (U-Pb, 40Ar/39Ar, astrochronology) seem to be converging to within uncertainties of each other, making the reduction of geological and stratigraphic uncertainties associated with datable samples ever more important for improving future timescales. The new geochronological information also provides key new constraints on the rates of biotic extinction and recovery across the K-Pg boundary. The interval between the highest documented dinosaurs and the lowest sampled early Paleocene ("Puercan-1") mammals in the Denver Basin spans  $\sim$ 185 ky (and bracketed to be no longer than 570 ky) in duration and initial recovery of plant ecosystems (as inferred by the end of the fern spike) occurred  $\sim 1$  ky (and no more than 71 ky) after the K–Pg boundary layer.

# Acknowledgements

Property access to the West Bijou and My Lucky Number sites was provided by the Plains Conservation Center; to the Easy to Reach section by Toby Pippin; to the Hass Ranch section by Robert and Dale Haas. The project was supported by NSF grants EAR 9805474 to KRJ and R. Raynolds, EAR 0643158 to SAB, EAR 0642291 to WCC and EAR 0642838 to KRJ. We thank R. Barclay, T. Barnum, R. Dodds, B. Ellis, I. Miller, R. Raynolds and K. Tsukui, for help with field work, lab work and helpful discussions. Thanks to J. Crowley for preliminary U–Pb analyses from the Bowring Pit at MIT. An anonymous reviewer and J. Dinarès-Turell provided valuable reviews of the manuscript.

# Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.07.041.

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