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A Case Study of Maximum Depositional Ages from Terrestrial Sandstones near the Cretaceous—Paleogene Transition, Western Williston Basin, USA

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Abstract: We present a new Bayesian method for deriving maximum depositional ages from detrital K-feldspar using total-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ data. Individual analyses weighted by K/Ca ratio, age uncertainty, and percent radiogenic argon prioritize a result to come from accurately measured volcanic sources. Results from this method applied to sandstones from the Hell Creek region of northeastern Montana show that detrital K-feldspar maximum depositional ages align closely with detrital U-Pb zircon ages as well as tephra based chronostratigraphic constraints from both $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb data. An age model informed by maximum depositional ages and available tephra data provides an estimate of 1.74 ± 1.04 Ma for the duration of deposition for the Hell Creek Formation. Combined age model and maximum depositional age data suggest ≤ 1.84 Ma of missing time is represented by the Hell Creek and Fox Hills formational disconformity, coinciding with the final regression of the Western Interior seaway.

Keywords: detrital geochronology; maximum depositional age; Hell Creek Formation; Williston Basin; chronostratigraphy

1. Introduction

Detrital mineral dating is an evolving tool that can provide maximum depositional ages (MDAs) of siliciclastic rocks devoid of fossils or primary tephra horizons. This subset of geochronology has historically been applied to the U-Pb system in detrital zircon, however there is no clear consensus between the numerous approaches to estimate MDAs from populations of detrital U-Pb ages [1–3]. Detrital U-Pb MDAs additionally require the assumption of minimal residency times between volcanic crystallization and the incorporation into sedimentary systems. A promising addition to MDA analysis exists in the application of the $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique to detrital K-feldspar [4–6]. Detrital $^{40}\text{Ar}/^{39}\text{Ar}$ analysis expands the range of materials and lithologies, particularly from horizons which lack tephra, that can be used to inform MDAs while providing independent and complementary age constraints to U-Pb detrital zircon datasets.

Despite differences in the acquisition of U-Pb vs $^{40}\text{Ar}/^{39}\text{Ar}$ detrital data, there are similar analytical complexities and statistical treatments of both types of datasets that affect the determination of MDAs. In the case of detrital $^{40}\text{Ar}/^{39}\text{Ar}$ data, MDAs defined by a grouping of single grain analyses that return a mean square weighted deviates (MSWD) value of ~ 1 inherently assume that said group belongs to a genetically coherent population. This



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assumption can be problematic in detrital settings and weighted mean MDAs calculated in this fashion may be precise but inaccurate. While MDAs determined from weighted means of detrital zircon U-Pb dates suffer from the same problem of combining genetically unrelated grains into a single population, case studies have demonstrated the accuracy of detrital weighted mean MDAs over youngest grain MDAs owing to the unidentifiable degree of post depositional Pb loss in the U-Pb system which may unduly weight the latter [2,7]. Current best practices for U-Pb MDAs are those that mitigate Pb loss and involve a two-step screening by laser-ablation inductively coupled plasma-mass spectrometry (LA ICPMS) followed by chemical abrasion thermal ionization mass spectrometry (CA-TIMS) of the youngest grains identified by LA-ICPMS [8,9].

An opportunity to establish a more objective method of constraining $^{40}\text{Ar}/^{39}\text{Ar}$ detrital MDAs and associated uncertainties exists in the byproduct quantities derived from the $^{40}\text{Ar}/^{39}\text{Ar}$ dating process. When analyzing detrital K-feldspars, relative concentrations of K and Ca (K/Ca) as well as the total radiogenic argon ($^{40}\text{Ar}^*$) of a given analysis provide information that can be used to consider how much an analysis should contribute to an MDA calculation. K/Ca values of K-feldspar have been shown to correlate with the environment of origin such that ~99% of volcanically derived K-feldspar have K/Ca ratios < 200 [10]. MDA accuracy improves if the amount of time between transport and deposition is minimized, thus there is reason to favor K-feldspar analyses with lower K/Ca values as opposed to high K/Ca plutonic K-feldspars which must first be exposed and mobilized before transport and deposition. $^{40}\text{Ar}^*$ is the measured daughter product that has decayed from ^{40}K and is used to directly determine an age for a given analysis. During total fusion experiments, ideal measurements of ^{40}Ar will be dominated by $^{40}\text{Ar}^*$, and analyses with the highest $^{40}\text{Ar}^*$ within a population are often treated as the most reliable. However, the expected $^{40}\text{Ar}^*$ fraction is intrinsically age-dependent: for young samples (e.g., <1 Ma), even pristine grains may have a substantial non-radiogenic component, so “high” $^{40}\text{Ar}^*$ in this case may be slightly below 100%. In contrast, the same K content will have produced more radiogenic $^{40}\text{Ar}^*$ within much older samples (e.g., >10 Ma), such that departures from high $^{40}\text{Ar}^*$ values are more likely to be a result of alteration, excess/deficit trapped Ar, or analytical introduction of atmospheric Ar. Thus, $^{40}\text{Ar}^*$ should be evaluated relative to the age range of the observed data.

While the aforementioned metrics can be subjectively applied to filter a $^{40}\text{Ar}/^{39}\text{Ar}$ dataset, an approach that is informed by additional analytical data allows one to establish the idealized case of a K-feldspar MDA, which is a subset of analyses that represents an accurately measured volcanically derived crystal or distribution of crystals. To test this method, we present a means to more objectively approach total fusion detrital K-feldspar datasets considering each measurement’s K/Ca, $^{40}\text{Ar}^*$, and age uncertainty. We apply it to sandstones of the Hell Creek region, the type area of the Hell Creek Formation (Fm.) in northeastern Montana. We couple these results with single crystal U-Pb zircon data extracted from the same sampled aliquots. The natural laboratory setting of the Hell Creek region allows for tests wherein sampled horizons are quantitatively compared with bracketing tephra constraints. Detrital samples extend to stratigraphic regions that lack reliable tephra ages, allowing for modeled age estimates of the base of the Hell Creek Fm. This study highlights the efficacy of combined detrital chronometers and establishes the validity of utilizing byproduct quantities derived from the $^{40}\text{Ar}/^{39}\text{Ar}$ dating process to inform K-feldspar MDA algorithms.

2. Geologic Background

Clastic strata in the western Williston Basin of northeastern Montana record one of the few known terrestrial transitions between the Mesozoic and Cenozoic Eras. Within the Hell Creek region (Figure 1), the Fox Hills, Hell Creek, and Fort Union formations (fms.) represent late Maastrichtian to Danian age strata deposited in a dominantly fluvial environment, with sediment sources largely derived from the west. Broadly correlative units outcrop in Colorado, Wyoming, North Dakota, South Dakota, Alberta and Saskatchewan, and several efforts have been made to establish regional facies relationships [11–13]. The Hell Creek and Fort Union fms. have seen considerable interdisciplinary focus in the development and testing of hypotheses leading up to and immediately following the Cretaceous–Paleogene boundary (KPB) mass extinction event [14,15]. Rates of biotic and abiotic change recorded in this basin have been mainly derived from published $^{40}\text{Ar}/^{39}\text{Ar}$ dates of sanidine-bearing tephra preserved in lignite deposits in the Fort Union Fm. and augmented by magnetostratigraphic studies [16–18]. This chronostratigraphy has contextualized post KPB events and identified the diachronous contact between the Hell Creek and Fort Union fms. [19–22].

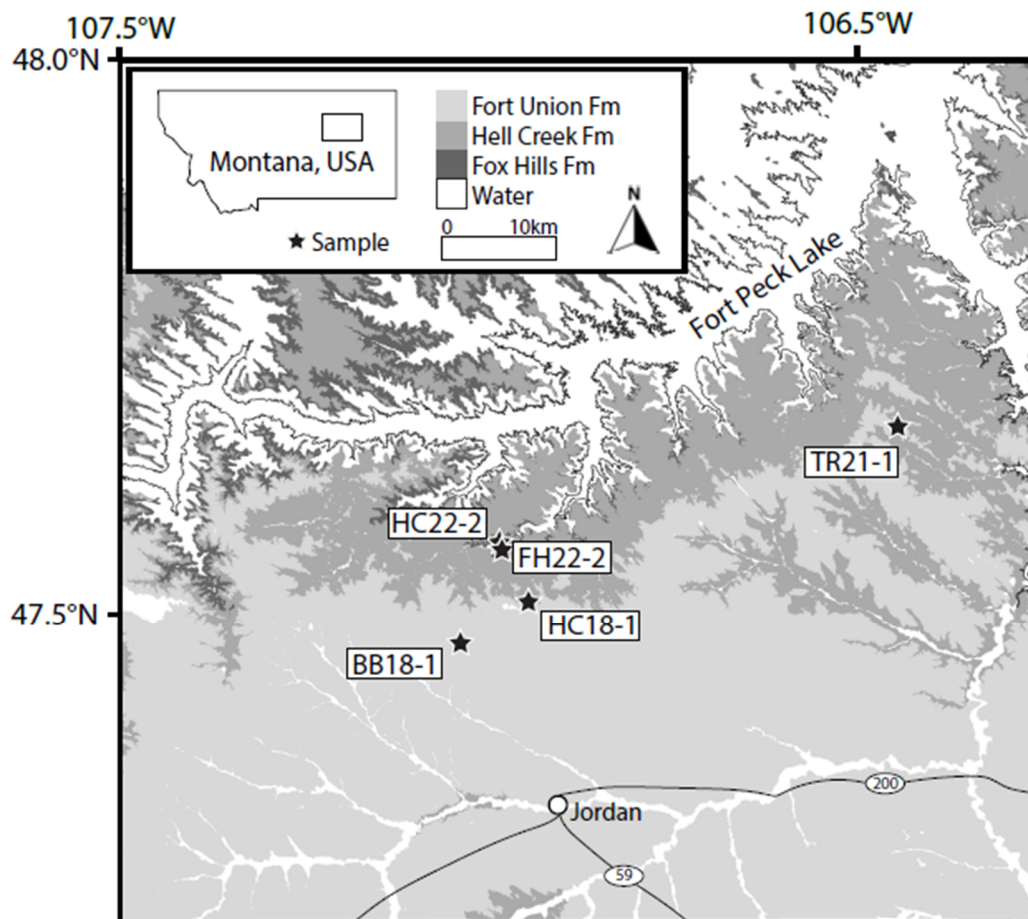


Figure 1. Geologic map of study area showing only the extent of the Fort Union, Hell Creek, and Fox Hills formations in the Hell Creek region of NE Montana near the Fort Peck Reservoir. Bounded white area represents water bodies of the Fort Peck Reservoir and the Missouri River. Stars indicate sample locations. Map data from the National Geologic Map Database.

High energy facies below the KPB are unlikely to preserve discrete tephra beds despite ongoing proximal silicic volcanism tens to hundreds of kilometers to the west [23,24]. While there are sparse depositional estimates, indirect methods have been used to determine time in disparate locations across the basin. Estimates ranging between 1.05 and 2.5 Ma for the depositional duration of the Maastrichtian Hell Creek Fm. were made by extrapolating sedimentation rates based on dated tephra horizons, magnetic polarity durations, and reversal ages [15, 25–27]. Roberts et al. (2025) [28] report two weighted mean U-Pb ages from bentonite beds and a modeled minimum age of $67.102 \pm 0.710 / -0.173$ Ma for the base of a composite section which they assert is equivalent to the base of the Hell Creek Fm. The youngest date from strata below the Hell Creek Fm. is a $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine age of 70.88 ± 0.66 Ma (All $^{40}\text{Ar}/^{39}\text{Ar}$ reported errors are 2σ ; recalculated to Carter et al., 2025 [29]) within the *Baculites grandis* zone in the underlying Pierre Shale Fm. from the Red Bird Section of Wyoming [13,24,30]. This result constitutes a maximum age for the Late Cretaceous Fox Hills Fm., however, true depositional durations are likely diachronous and latitudinally variable across the basin.

3. Methods

Five sandstone samples were collected from the Hell Creek region, one from the overlying Tullock Member of the Fort Union Fm., three from the Hell Creek Fm., and one from the underlying Fox Hills Fm. (Figure 1). Samples BB18-1 and TR21-1 were selected to test the accuracy of the MDA algorithm against the bounding tephra constraints (Figure 2). Samples from the basal Hell Creek (HC22-2) and upper Fox Hills (FH22-1) were selected based on proximity to the formational contact.

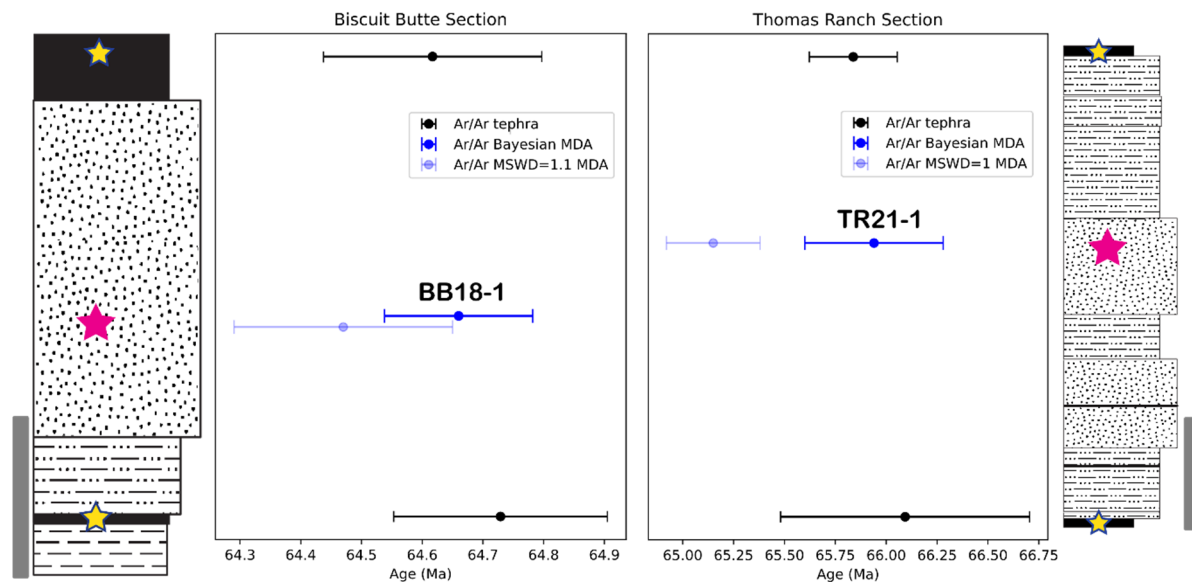


Figure 2. Age depth plots for two detrital samples (BB18-1, TR21-1) from locally named sections that were selected to test against bracketing $^{40}\text{Ar}/^{39}\text{Ar}$ tephra constraints (black symbols) presented in Sprain et al. (2015, 2018) [20,21]. Results from the MDA method presented in this study (dark blue) are plotted next to weighted mean ages (light blue) fit to an MSWD of ~ 1 . Adjacent to each age depth plot is a simplified stratigraphic column showing the relative relationship of a detrital sample (pink star) to the bracketing tephra (yellow star). Dotted fill patterns represent sandstones, dashed and dotted fill patterns represent siltstones, dashed filled patterns represent mudstones, and filled black patterns represent lignite layers. Elevations between the two sections are not to scale, grey vertical bars represent 5 m of stratigraphic height.

Populations of zircons from each sample were dated by U-Pb using LA-ICPMS at the USGS and UC Davis, with the grains analyzed directly on double-sided sticky tape. The youngest zircon grains were removed from the sticky tape and then further analyzed using CA-TIMS at the Berkeley Geochronology Center. U-Pb MDAs presented herein represent either the youngest concordant single grain or a grouping of a concordant population of grains. Details of the LA-ICPMS and CA-TIMS procedures, tracers, calibrations, and data can be found in the Supplement and Data Repository. All single grain K-feldspar analyses underwent total fusion at 7 W by a CO_2 laser and were analyzed with a Mass Analyzer Products 215C mass spectrometer at the Berkeley Geochronology Center. Fish Canyon sanidine was used as a fluence monitor with an age of 28.183 Ma and a total decay constant of $5.5042 \times 10^{-10} \text{ year}^{-1}$ [30]. Full isotopic and relevant meta-data of all analyses are available in the Supplement and Data Repository.

We introduce a Bayesian method that leverages multiple data attributes to estimate the K-feldspar MDAs presented in this study. In this framework, the posterior probability ($P(\theta|y)$) is proportional to the product of a prior distribution, ($P(\theta)$), and the likelihood function, ($P(y|\theta)$) (Figure 3). For each sample, the prior is constructed using a weighted kernel density estimate (KDE) that integrates analysis specific attributes of each grain. These attributes include: K/Ca ratios, relative age uncertainties scaled to the range expressed in the sample, and $\%^{40}\text{Ar}^*$ scaled to the range expressed in the sample. K/Ca ratios for each sample are evaluated against the KDE derived from volcanic feldspar data compiled from the GEOROC database (<https://georoc.eu/>; downloaded 24 May 24 2024), and follow concepts and corrections outlined by Renne (2025) [10]. The combined weightings are designed to preferentially emphasize K-feldspars that are both analytically precise and volcanically derived. The bandwidth for the weighted prior is determined by leave-one-out cross-validation to account for differences in uncertainty among individual grains. The likelihood function is assumed to be normally distributed, with its uncertainty defined by each grains analytical age uncertainty. Posterior sampling is performed using a Markov Chain Monte Carlo (MCMC) approach wherein candidate samples are accepted or rejected following the Metropolis-Hastings algorithm. Adaptive tuning is applied every 1000 iterations, with the first 20,000 discarded as burn-in to minimize the sensitivity to initial conditions. The MDA is drawn from the post burn-in posterior distribution and is reported with a symmetric 95% credible level uncertainty. Within this framework, the MDA is defined as the youngest age supported by the posterior probability inferred through the combination of a volcanically informed prior and the observed age distribution.

Posterior $\propto$ Prior $\cdot$ Likelihood

$$P(\theta|y) \propto P(\theta)P(y|\theta)$$

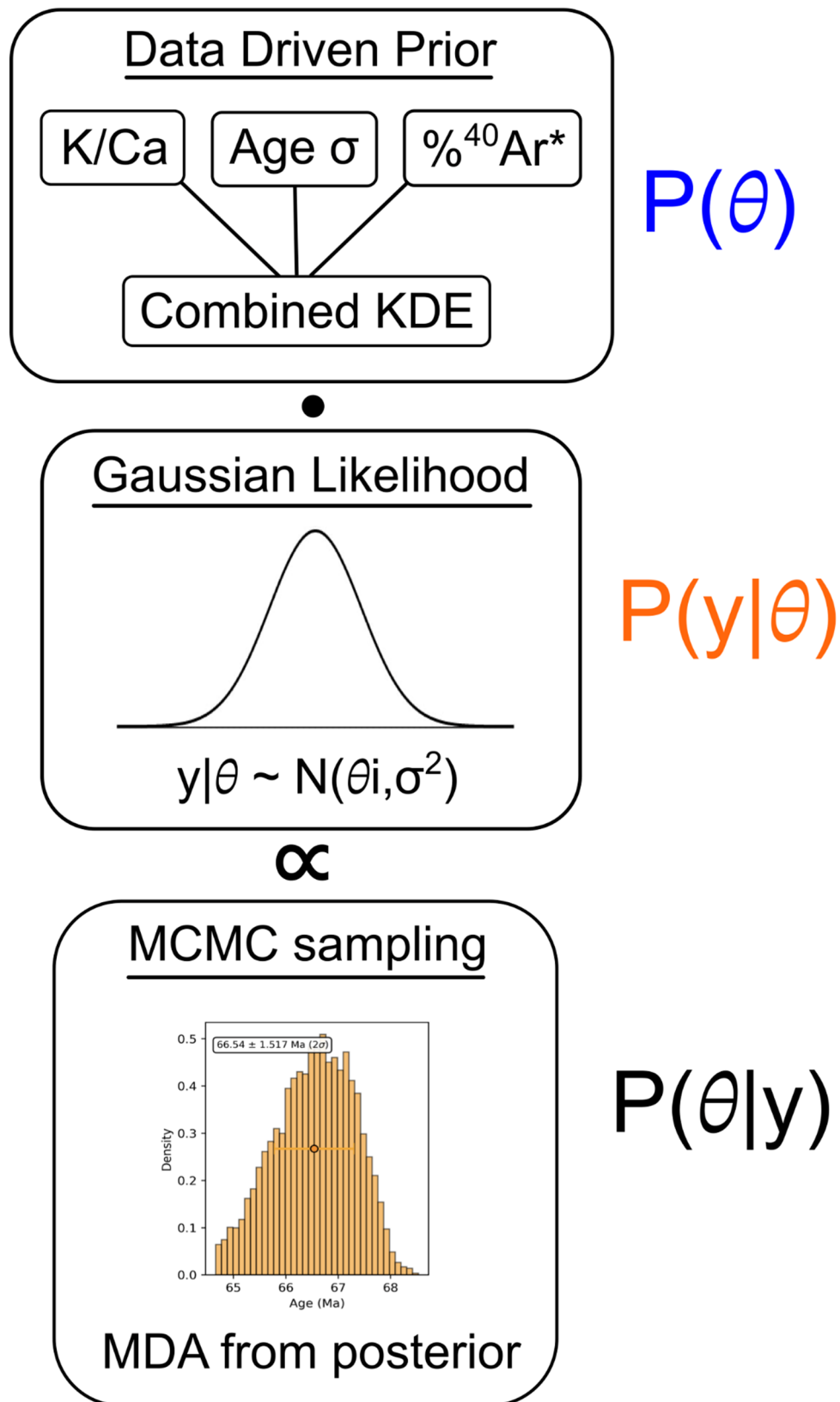


Figure 3. Conceptual diagram of the Bayesian method for K-feldspar maximum depositional age estimates presented in this study.

K-feldspar and U-Pb MDAs were plotted along with $^{40}\text{Ar}/^{39}\text{Ar}$ tephra data reported in Sprain et al. (2015, 2018) [20,21] with all sampled locations corrected relative to the KPB plane using Equation (1) from Tobin et al. (2014) [16]. All tephra ages, K-feldspar MDAs, and U-Pb MDAs, including systematic uncertainties, were used as inputs to an age model constructed using the Chron.jl software package and extrapolated to the elevation of the base of the Hell Creek Fm. (Figure 4) [31].

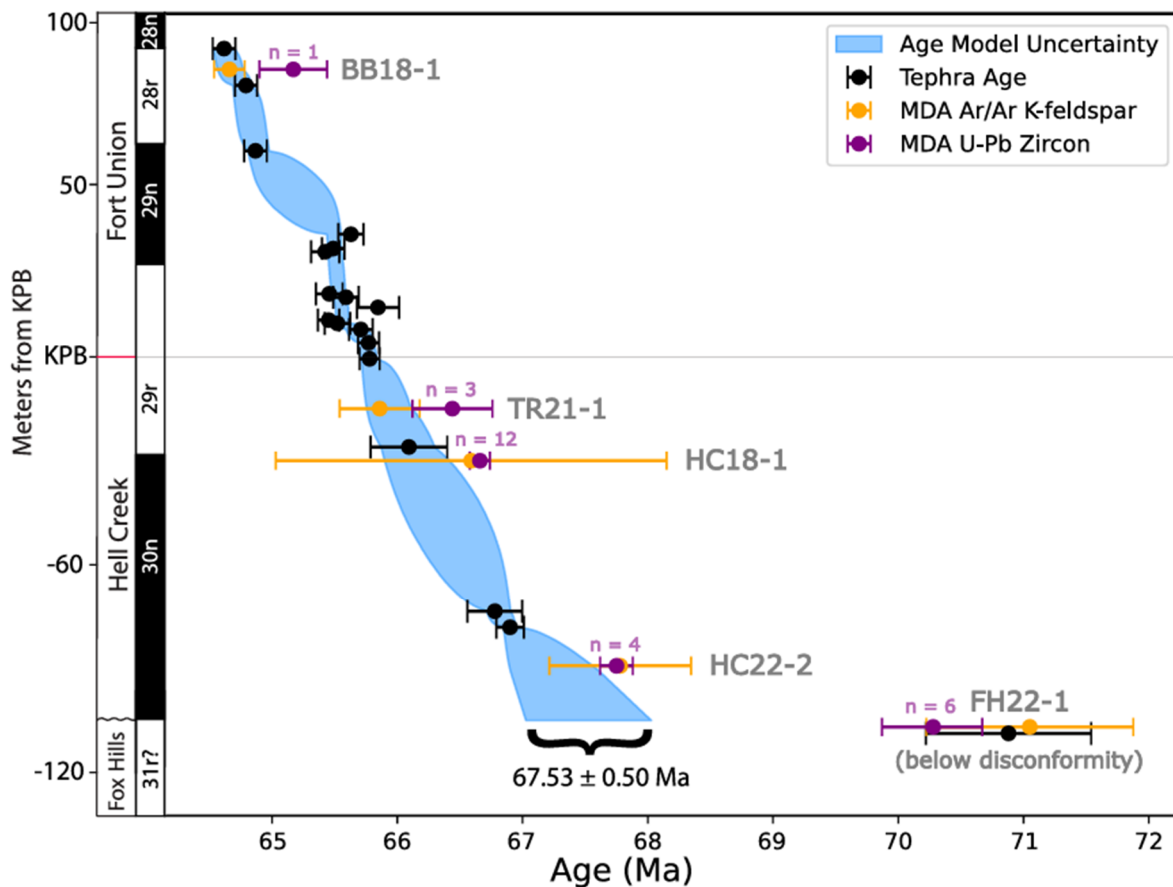


Figure 4. Summary chronostratigraphic figure depicting ages as a function of stratigraphic height with 2σ systematic uncertainties for tephtras (black symbols) presented in Sprain et al. (2015, 2018) [20,21], K-feldspar maximum depositional ages (orange symbols), and zircon maximum depositional ages (purple symbols). Elevations are plotted relative to the KPB boundary, formational relationships depicted in the left column are with polarity chrons following Sprain et al. (2018) [20]. Blue region represents the 95% confidence interval for an age model using the Chron.jl software package [31].

4. Results

In the following section, we report MDAs based on U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ data from the stratigraphically lowest to the highest samples. Sample FH22-1 comes from a fine-grained unit in the uppermost Fox Hills Fm. The K-feldspar MDA of 71.04 ± 0.84 Ma overlaps with a concordant weighted mean U-Pb zircon CA-TIMS age of 70.27 ± 0.40 Ma from six crystals, representing the first depositional age estimates from the Fox Hills Fm. in the Hell Creek region. Sample HC22-2 comes from a basal sandstone of the Hell Creek Fm. within ~15 m of the contact with the underlying Fox Hills Fm. The K-feldspar MDA of 67.78 ± 0.57 Ma overlaps the zircon weighted mean of 67.75 ± 0.13 Ma from four crystals and together represent the oldest plausible depositional ages for the Hell Creek Fm. Sample HC18-1 yields a K-feldspar MDA of 66.54 ± 1.52 Ma which overlaps though is significantly less precise than the weighted mean zircon MDA of 66.66 ± 0.08 Ma defined by 12 grains. Sample TR21-1 is from the upper Hell Creek Fm. and lies between two tephra constraints reported by Sprain et al. (2018) [20]. The K-feldspar MDA of 65.86 ± 0.32 Ma overlaps with the weighted mean of the youngest three zircons of 66.44 ± 0.32 Ma and together agree with bracketing age constraints (Figure 2). Sample BB18-1 comes from the Tullock Member of the Fort Union Fm., and its K-feldspar MDA of 64.66 ± 0.12 Ma overlaps with bracketing tephra bed constraints (Figure 2). Only one zircon, dated to 65.17 ± 0.26 Ma, yields an age that is older than the $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar MDA.

5. Discussion

New K-feldspar detrital MDA methods presented in this study establish a basis for utilizing grain specific metrics gathered from the $^{40}\text{Ar}/^{39}\text{Ar}$ dating process to evaluate a sample. In the case of sample BB18-1, several weighted mean ages can be constructed from the near continuous set of younger ages, however when the age distribution is weighted by K/Ca, relative $\%^{40}\text{Ar}^*$, and σ , discrete age populations are revealed, which likely yields a more accurate MDA (Figures 2 and S3). Direct tests against established chronostratigraphic constraints provide examples where traditional MSWD calculations may be problematic or inaccurate. In the case of sample TR21-1, the MSWD weighted mean age is distinctly younger than both tephra constraints and violates superposition (Figure 2). In general, our MDA method does not often result in significantly different mean ages from traditional weighted means when applied to results from other studies, though differences in uncertainties are notable (Figures S11 and S12).

A direct quantitative estimate for the duration of the Hell Creek Fm. is of critical importance for future evaluations of biotic turnover in the lead up to the end-Cretaceous mass extinction and evaluations of broader Western Interior tectonics. In showing that MDAs for detrital K-feldspar and zircons agree with the established chronostratigraphic framework, we infer these MDAs to be close to depositional ages (Figure 4). Modeled age-depth results imply that sedimentation rates were relatively constant over the duration of deposition of the Hell Creek Fm. and extrapolate to an age of 67.53 ± 0.50 Ma for the base of the Hell Creek Fm. A Monte Carlo resampling using this result and the KPB age of 65.80 ± 0.04 Ma returns a duration of 1.74 ± 1.04 Ma for the Hell Creek Fm. Though this estimate for the duration of the Hell Creek Fm. agrees with previous estimates, its precision is on the order of previous estimates and does not dramatically constrain the duration of Hell Creek Fm. deposition. A comparison of the modeled mean age for the base of the Hell Creek Fm. with the youngest ages from the 71.04 ± 0.84 Ma and 70.27 ± 0.40 Ma detrital MDA distributions from the uppermost Fox Hills Fm. implies ≤ 1.84 Ma of missing time. Notably, this break in sedimentation coincides with a marine regression, and its timing provides the best age constraint available for the final withdrawal of the Western Interior sea in this area [32]. The proposed duration of the disconformity established by our dataset indicates that the reversed magnetic polarity results from the upper Fox Hills sediments may not represent Chron 30r [33]. Expanded analysis of detrital sediments at this formational contact across the basin could further clarify the degree of diachroneity represented by this transition as this disconformity is likely variable from east to west across the Williston Basin [32,34].

Opportunities to inform post-KPB faunal recovery rates abound within the Fort Union Fm., particularly within the sandy upper members that lack lignite or tephra beds therein but have been shown to contain populations of euhedral, unabraded zircons [35]. All other factors held constant, the K-feldspar MDA method presented here is most precise when K-feldspar grain size is maximized, thus further detrital K-feldspar sampling of the coarsest sandstone is advised. Volcanic activity from the Bitterroot lobe of the Idaho Batholith, the likely source region of these sediments, is documented to last until ~ 54 Ma [23,36], suggesting that ample opportunities exist to build an integrated chronologic framework to address regional mechanisms for basin transgressive/regressive cycles if these techniques are applied broadly to other regions of the Williston Basin [12,35,37].

6. Conclusions

In this work, we demonstrate the capability to improve and expand terrestrial chronostratigraphic constraints of strata through paired detrital $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb geochronology. We show that viable MDAs can be extracted accurately from detrital K-feldspar datasets using a Bayesian framework utilizing unique metrics from each analysis to construct priors from a given dataset. We show that these estimates fall close to expected depositional ages based on dated tephra constraints and assert that this approach is especially fruitful when there is a reasonable expectation *a priori* that contemporaneous and more or less continuous silicic volcanism was feeding the depocenter's watershed. Results from an age model constrained by a basal Hell Creek Fm. sample indicate that the total duration of the Hell Creek Fm. is 1.74 ± 1.04 Ma. MDAs from the uppermost Fox Hills Fm. suggest that the disconformity between the Hell Creek and Fox Hills Fms. represents ≤ 1.84 Ma of missing time. Extension of this work to other depocenters around the Williston Basin would likely clarify the nature of catchment source changes and the spatial-temporal pattern of regression of the Western Interior seaway.

Supplementary Materials

The additional data and information can be downloaded at: <https://media.scilit.com/articles/others/2608241059186066/GTTSR-26010163-SI.zip>. Refs. [4,38,39] are cited in the supplementary materials.

Author Contributions

A.J.T.: conceptualization, investigation, formal analysis, methodology, validation, visualization, writing—original draft, review & editing; J.N.C.: software, methodology, formal analysis, validation, visualization, writing—reviewing & editing; N.P.G.: investigation, formal analysis, writing—reviewing & editing; R.M.: investigation, formal analysis, writing—reviewing & editing; G.P.W.M.: project administration, writing—reviewing & editing; L.P.: investigation, writing—reviewing & editing; A.J.F.: investigation, visualization, writing—reviewing & editing; P.R.R.: supervision, conceptualization, investigation, validation, resources, project administration, funding acquisition, writing—reviewing & editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data and code used in this study are hosted by figshare.com at <https://doi.org/10.6084/m9.figshare.33261036>.

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Conflicts of Interest

The authors declare no conflict of interest. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Use of AI and AI-Assisted Technologies

No AI tools were utilized in this study.

References

1. Copeland, P. On the use of geochronology of detrital grains in determining the time of deposition of clastic sedimentary strata. *Basin Res.* **2020**, *32*, 1532–1546. <https://doi.org/10.1111/bre.12441>.
2. Coutts, D.S.; Matthews, W.A.; Hubbard, S.M. Assessment of widely used methods to derive depositional ages from detrital zircon populations. *Geosci. Front.* **2019**, *10*, 1421–1435. <https://doi.org/10.1016/j.gsf.2018.11.002>.
3. Vermeesch, P. Maximum depositional age estimation revisited. *Geosci. Front.* **2021**, *12*, 843–850. <https://doi.org/10.1016/j.gsf.2020.08.008>.
4. Heizler, M.T.; Karlstrom, K.E.; Albonico, M.; et al. Detrital sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ dating confirms < 2 Ma age of Crooked Ridge paleoriver and subsequent deep denudation of the southwestern Colorado Plateau. *Geosphere* **2021**, *17*, 438–454. <https://doi.org/10.1130/GES02319.1>.
5. Hollingworth, R.S.; Leary, R.J.; Heizler, M.T. Detrital U-Pb zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite geochronology from Middle Pennsylvanian strata in the Anadarko Basin, Texas Panhandle, USA. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2021**, *579*, 110573. <https://doi.org/10.1016/j.palaeo.2021.110573>.
6. Leslie, C.E.; Peppe, D.J.; Williamson, T.E.; et al. Revised age constraints for Late Cretaceous to early Paleocene terrestrial strata from the Dawson Creek section, Big Bend National Park, west Texas. *GSA Bull.* **2018**, *130*, 1143–1163. <https://doi.org/10.1130/B31785.1>.
7. Rasmussen, C.; Mundil, R.; Irmis, R.B.; et al. U-Pb zircon geochronology and depositional age models for the Upper Triassic Chinle Formation (Petrified Forest National Park, Arizona, USA): Implications for Late Triassic paleoecological and paleoenvironmental change. *GSA Bull.* **2021**, *133*, 539–558. <https://doi.org/10.1130/B35485.1>.
8. Herriott, T.M.; Crowley, J.L.; Wartes, M.A.; et al. Accuracy and validity of maximum depositional ages in light of tandem (laser ablation and isotope dilution) U-Pb detrital zircon geochronology, including results from northern Alaska. *Geochronology* **2025**, *7*, 513–543. <https://doi.org/10.5194/gchron-7-513-2025>.
9. Mundil, R.; Gehrels, G.; Deino, A.L.; et al. Zircon U-Pb analyses by TIMS and LA-ICPMS on the same material. In Proceedings of the AGU Fall Meeting Abstracts, San Francisco, CA, USA, 15–19 December 2008.

10. Renne, P.R. Implications of sanidine K/Ca compositions for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *Geochim. Cosmochim. Acta* **2025**, *407*, 91–104. <https://doi.org/10.1016/j.gca.2025.08.018>.
11. Cherven, V.B.; Jacob, A.F. *Evolution of Paleogene Depositional Systems, Williston Basin, in Response to Global Sea Level Changes*; Rocky Mountain Section (SEPM): Denver, CO, USA, 1985.
12. Gill, J.R.; Cobban, W.A. *Stratigraphy and Geologic History of the Montana Group and Equivalent Rocks, Montana, Wyoming, and North and South Dakota*; US Government Printing Office: Washington, DC, USA, 1973; Volume 776.
13. Hicks, J.F.; Obradovich, J.D.; Tauxe, L. Magnetostratigraphy, isotopic age calibration and intercontinental correlation of the Red Bird section of the Pierre Shale, Niobrara County, Wyoming, USA. *Cretac. Res.* **1999**, *20*, 1–27. <https://doi.org/10.1006/cres.1998.0133>.
14. Archibald, J.D.; Butler, R.F.; Lindsay, E.H.; et al. Upper Cretaceous–Paleocene biostratigraphy and magnetostratigraphy, Hell Creek and Tullock Formations, northeastern Montana. *Geology* **1982**, *10*, 153–159. [https://doi.org/10.1130/0091-7613\(1982\)10<153:UCBAMH>2.0.CO;2](https://doi.org/10.1130/0091-7613(1982)10<153:UCBAMH>2.0.CO;2).
15. Wilson, G.P.; Clemens, W.A.; Horner, J.R.; et al. (Eds.) *Through the End of the Cretaceous in the Type Locality of the Hell Creek Formation in Montana and Adjacent Areas*; Geological Society of America: Boulder, CO, USA, 2014. <https://doi.org/10.1130/9780813725031>.
16. Tobin, T.S.; Wilson, G.P.; Eiler, J.M.; et al. Environmental change across a terrestrial Cretaceous–Paleogene boundary section in eastern Montana, USA, constrained by carbonate clumped isotope paleothermometry. *Geology* **2014**, *42*, 351–354. <https://doi.org/10.1130/G35262.1>.
17. Weaver, L.N.; Tobin, T.S.; Claytor, J.R.; et al. Revised stratigraphic relationships within the lower Fort Union Formation (Tullock member, Garfield County, Montana, USA) provide a new framework for examining post K–Pg mammalian recovery dynamics. *Palaios* **2022**, *37*, 104–127. <https://doi.org/10.2110/palo.2021.011>.
18. Hovatter, B.T.; Chester, S.G.; Wilson Mantilla, G.P. New records of early Paleocene (earliest Torrejonian) plesiadapiforms from northeastern Montana, USA, provide a window into the diversification of stem primates. *J. Hum. Evol.* **2024**, *192*, 103500. <https://doi.org/10.1016/j.jhevol.2024.103500>.
19. Renne, P.R.; Deino, A.L.; Hilgen, F.J.; et al. Time scales of critical events around the Cretaceous–Paleogene boundary. *Science* **2013**, *339*, 684–687. <https://doi.org/10.1126/science.1230492>.
20. Sprain, C.J.; Renne, P.R.; Clemens, W.A.; et al. Calibration of chron C29r: New high-precision geochronologic and paleomagnetic constraints from the Hell Creek region, Montana. *GSA Bull.* **2018**, *130*, 1615–1644. <https://doi.org/10.1130/B31890.1>.
21. Sprain, C.J.; Renne, P.R.; Wilson, G.P.; et al. High-resolution chronostratigraphy of the terrestrial Cretaceous–Paleogene transition and recovery interval in the Hell Creek region, Montana. *GSA Bull.* **2015**, *127*, 393–409. <https://doi.org/10.1130/B31076.1>.
22. Swisher, C.C., III; Dingus, L.; Butler, R.F. $^{40}\text{Ar}/^{39}\text{Ar}$ dating and magnetostratigraphic correlation of the terrestrial Cretaceous–Paleogene boundary and Puercan Mammal Age, Hell Creek–Tullock formations, eastern Montana. *Can. J. Earth Sci.* **1993**, *30*, 1981–1996. <https://doi.org/10.1139/e93-174>.
23. Gaschnig, R.M.; Vervoort, J.D.; Lewis, R.S.; et al. Migrating magmatism in the northern US Cordillera: In situ U–Pb geochronology of the Idaho batholith. *Contrib. Mineral. Petrol.* **2010**, *159*, 863–883. <https://doi.org/10.1007/s00410-009-0459-5>.
24. Gill, J.R.; Cobban, W.A. *The Red Bird Section of the Upper Cretaceous Pierre Shale in Wyoming*; US Government Printing Office: Washington, DC, USA, 1966. Volume 393.
25. Hicks, J.F.; Johnson, K.R.; Obradovich, J.D.; et al. Magnetostratigraphy and geochronology of the Hell Creek and basal Fort Union Formations of southwestern North Dakota and a recalibration of the age of the Cretaceous–Tertiary boundary. In *The Hell Creek Formation and the Cretaceous–Tertiary Boundary in the Northern Great Plains: An Integrated Continental Record of the End of the Cretaceous*; Geological Society of America: Boulder, CO, USA, 2002; Volume 361, pp. 35–55.
26. Lund, S.P.; Hartman, J.H.; Banerjee, S.K. *The Hell Creek Formation and the Cretaceous–Tertiary Boundary in the Northern Great Plains: An Integrated Continental Record of the End of the Cretaceous*; Geological Society of America: Boulder, CO, USA, 2002; Volume 361, p. 57.
27. Wilson, G.P. Mammalian faunal dynamics during the last 1.8 million years of the Cretaceous in Garfield County, Montana. *J. Mamm. Evol.* **2005**, *12*, 53–76.
28. Roberts, E.M.; Hendrix, M.S.; Ramezani, J.; et al. High precision CA-ID-TIMS U–Pb zircon age for the Dueling Dinosaur locality, with implications for regional correlation, basal age and duration of the Hell Creek Formation, Montana. *bioRxiv* **2025**, <https://doi.org/10.1101/2025.07.10.664044>.
29. Carter, J.N.; Hasler, C.E.J.; Fuentes, A.J.; et al. Bayesian calibration of the 40K decay scheme with implications for 40K-based geochronology. *Geochim. Cosmochim. Acta* **2025**, *397*, 149–163. <https://doi.org/10.1016/j.gca.2025.03.024>.

30. Obradovich, J.D. A Cretaceous time scale. In *Evolution of the Western Interior Basin*; Geological Association of Canada: St. John's, NL, Canada, 1993; Volume 39, pp. 379–396.
31. Keller, C.B. *Chron.jl: A Bayesian Framework for Integrating Eruption Age and Age-Depth Modelling*; OSF: Charlottesville, VA, USA, 2018. <https://doi.org/10.17605/osf.io/TQX3F>.
32. Belt, E.S.; Hicks, J.F.; Murphy, D.A. A pre-Lancian regional unconformity and its relationship to Hell Creek paleogeography in south-eastern Montana. *Rocky Mt. Geol.* **1997**, *31*, 1–26.
33. LeCain, R.; Clyde, W.C.; Wilson, G.P.; et al. Magnetostratigraphy of the Hell Creek and lower Fort Union formations in northeastern Montana. In *Through the End of the Cretaceous in the Type Locality of the Hell Creek Formation in Montana and Adjacent Areas*; Geological Society of America: Boulder, CO, USA, 2014; Volume 503, pp. 137–147.
34. Rigby, J.K.; Rigby, J.K., Jr. Geology of the Sand Arroyo and Bug Creek Quadrangles, McCone County, Montana. *Brigh. Young Univ. Geol. Stud.* **1990**, *36*, 69–134.
35. Finzel, E.S. Detrital zircon microtextures and U-PB geochronology of Upper Jurassic to Paleocene strata in the distal North American Cordillera foreland basin. *Tectonics* **2017**, *36*, 1295–1316.
36. Ickert, R.B.; Mulcahy, S.R.; Sprain, C.J.; et al. Chemical and Pb isotope composition of phenocrysts from bentonites constrains the chronostratigraphy around the Cretaceous Paleogene boundary in the Hell Creek region, Montana. *Geochem. Geophys. Geosyst.* **2015**, *16*, 2743–2761. <https://doi.org/10.1002/2015GC005898>.
37. Lillegraven, J.A.; Ostresh, L.M., Jr. Late Cretaceous (earliest Campanian Maastrichtian) evolution of western shorelines of the North American western interior seaway in relation to known mammalian faunas. In *Dawn of the Age of Mammals in the northern part of the Rocky Mountain Interior, North America*; Bown, T.M., Rose, K.D., Eds.; Geological Society of America: Boulder, CO, USA, 1990; Volume 243, pp. 1–30.
38. Black, L.P.; Kamo, S.L.; Allen, C.M.; et al. Improved ²⁰⁶Pb/²³⁸U microprobe geochronology by the monitoring of a trace-element related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. *Chem. Geol.* **2004**, *205*, 115–140. <https://doi.org/10.1016/j.chemgeo.2004.01.003>.
39. Slama, J.; Kosler, J.; Condon, D.J.; et al. Plesovice zircon—A new natural reference material for U-Pb and Hf isotopic microanalysis. *Chem. Geol.* **2008**, *249*, 1–35. <https://doi.org/10.1016/j.chemgeo.2007.11.005>.