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High-resolution chronostratigraphy of the terrestrial Cretaceous-Paleogene transition and recovery interval in the Hell Creek region, Montana

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ABSTRACT

Detailed understanding of ecosystem decline and recovery attending the Cretaceous-Paleogene boundary (KPB) mass extinctions is hindered by limited constraints on the pace and tempo of environmental events near the boundary. To mitigate this shortcoming, high-resolution $^{40}Ar/^{39}Ar$ geochronology was performed on tephras intercalated between fossiliferous terrestrial sediments of the upper Hell Creek and lower Fort Union Formations in the western Williston Basin of northeastern Montana (USA). Tephra samples were collected from 10 stratigraphic sections spanning an area of ~5000 km². Several distinctive tephras can be correlated between sections separated spatially by as much as ~60 km. The tephras are thin distal deposits generally preserved only in lignite beds, which are interbedded with clastic deposits yielding vertebrate faunas of Lancian (late Maastrichtian) to Torrejonian (early Danian) North American Land Mammal Ages. Sanidine from 15 tephra samples was analyzed in 1649 total fusion experiments (1597 on single crystals) and 12 incremental heating analyses of multigrain aliquots. Ages were determined for 13 distinct tephras, ranging from 66.289 ± 0.051 to 64.866 ± 0.023 Ma, including only analytical uncertainties. This level of precision is sufficient to resolve the ages of all of the coal beds that have served as a basis for a regional stratigraphic framework. The data confirm that the Hell Creek–Fort Union formational contact is diachronous, and further support the age of the KPB impact layer at 66.043 ± 0.010 Ma (or ± 0.043 Ma considering systematic uncertainties). Application of the new results to previous magnetostratigraphic data indicates an appreciably compressed time interval between the base of chron C29r and the top of chron C28r, with a maximum duration estimate of 1.421 ± 0.066 Ma. Most notable is the implied brevity of chron C29r, with a maximum estimate of 457 ± 54 ka, and possibly as brief as 345 ± 38 ka, compared to the 710 ka estimate from the *Geologic Time Scale 2012* (GTS2012). Further, application of new results to terrestrial biostratigraphy adds higher precision to the timing and tempo of biotic change before and after the KPB. Our results indicate that the timing of pre-KPB ecological decline is constrained to the last ~200 ka of the Cretaceous, adding further support to the press-pulse extinction hypothesis. Additionally, the duration of the depauperate basal Paleogene Puercan 1 disaster fauna is confined to a 70 ka interval. Faunal recovery in this region, indicated by the appearance of primitive members of the placental mammal radiation and the restoration of taxonomic richness and evenness, occurred within ~900 ka after the KPB. These results show that biotic recovery after the mass extinction in the terrestrial realm was more rapid than in the marine.

INTRODUCTION

The cause(s) of the Cretaceous-Paleogene mass extinction remain contentious despite decades of intense scrutiny (Schulte et al., 2010; Archibald et al., 2010; Courtillot and Fluteau, 2010; Keller et al., 2010). The impact hypothesis (Alvarez et al., 1980) has gained broad support, bolstered by the discoveries of iridium anomalies, shocked quartz, and spherules at Cretaceous-Paleogene boundary (KPB) sites worldwide and of the Chicxulub impact structure (Schulte et al., 2010, and references therein). However, evidence of pre-KPB originations and extinctions as well as paleoenvironmental change (Chenet et al., 2009; Archibald et al., 2010; Wilson, 2005, 2014; Wilson et al., 2014b) involving large climate swings before the KPB (Li and Keller, 1999; Stüben et al., 2003; Wilf et al., 2003; Tobin et al., 2012, 2014) challenge the notion that the impact was the sole cause of the KPB extinctions. The evidence for abrupt extinctions consistent with an impact killing mechanism comes mainly from marine records (D'Hondt, 2005), whereas records of terrestrial vertebrate animals show evidence of more prolonged ecological decline (Wilson, 2005, 2014; Wilson et al., 2014b) starting in the latest Cretaceous. Terrestrial and marine records also yield disparate results for the tempo of ecosystem recovery; e.g., the restoration of atmospheric $\delta^{13}C$ to pre-impact values appears to have occurred orders of magnitude more rapidly than in the oceans (Renne et al., 2013).

In this paper we present a new high-precision $^{40}Ar/^{39}Ar$ geochronology that constrains the ages of faunal and floral assemblages in a key region of North America. These data delimit the rates and nature of terrestrial ecosystem recovery at a local scale, and begin to enable comparisons at larger, more regional scales with high temporal resolution. Such comparisons will ultimately clarify whether or not terrestrial biotic transitions were regionally diachronous, which can illuminate the specific ecological mechanisms for the terrestrial KPB extinctions and subsequent biotic recovery. In addition, applying our results to existing magnetostratigraphy allows us to test currently accepted calibrations of the geomagnetic polarity time scale (GPTS) in relevant parts of the time scale (i.e., chrons C30n through C28n). An improved calibration for the GPTS will allow for a detailed comparison between KPB events in marine and terrestrial realms, which is currently hindered by a lack of high-precision age control, especially in the former. The main source of age control in marine records comes from magnetostratigraphy, whose accuracy depends on both calibration of

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the GPTS and correlation to the GPTS. Orbital tuning offers higher age resolution but also depends on correlation to provide an anchor.

WESTERN WILLISTON BASIN

The Williston Basin, located primarily in the northwestern United States, is among the most thoroughly sampled sources of geological, paleontological, and paleoecological data used to study changes within the terrestrial realm across the KPB (e.g., Hartman et al., 2002; Wilson et al., 2014a, and references therein). Within the Williston Basin, two formations span the KPB: the Hell Creek Formation (mostly Cretaceous); and the Tullock Member of the Fort Union Formation in the western part of the basin and the Ludlow Member of the Fort Union Formation (mostly Paleogene) in the eastern part of the basin. In Canada, the Frenchman Formation is broadly correlative to the Hell Creek Formation, and the Ravenscrag Formation is broadly correlative to the Fort Union Formation (Hartman, 2002). These formations were deposited in predominantly fluvial systems and comprise siltstones, shales, and lignites, representative of floodplain deposits, and sandstones, mainly representative of channel deposits (Gill and Cobban, 1973; Cherven and Jacob, 1985; Fastovsky, 1987).

In the western Williston Basin, south and east of Fort Peck Reservoir (Hell Creek region, Montana), the Tullock Member and (to a lesser extent) the Hell Creek Formation contain numerous sanidine-bearing silicic tephras, which have been radioisotopically analyzed to produce a generalized chronostratigraphy (Swisher et al., 1993, their fig. 4) wherein occurrences of fossils were dated by bracketing tephras. The tephras are almost exclusively found within lignite beds, probably due to preservational bias. Lignites are rare in the Hell Creek Formation and become more numerous in the Fort Union Formation, suggesting increased hydraulic flux and a rise in water table (Fastovsky, 1987). The contact between the Hell Creek and Fort Union Formations (and the historical placement of the KPB) is placed at the first laterally continuous lignite above the stratigraphically highest occurrence of the unreworked remains of non-avian dinosaurs (Calvert, 1912; Brown, 1952; Clemens and Hartman, 2014; Moore et al., 2014; Hartman et al., 2014). In our study area in northeastern Montana, the lignite that defines the contact between the Hell Creek and Fort Union Formations is named the Z coal, with successive lignite units in the Tullock Member receiving successive letter designations in reverse alphabetical order up through U (Collier and Knechtel, 1939). We will use the term "coal" when referring to named lignite deposits for consistency with usage by Collier and Knechtel (1939) and subsequent workers.

Early definitions of the Z coal clearly state that it is probably not a single continuous unit, but rather a sequence of lignite lenses at approximately the same stratigraphic position (Collier and Knechtel, 1939). Subsequent workers have modified the term Z coal to specify occurrences of subunits in particular areas, e.g., IrZ and MCZ. Our field observations indicate that many of the other named lignites are similarly laterally discontinuous, and this is further substantiated by our $^{40}Ar/^{39}Ar$ results.

Currently, the KPB is recognized in this region (Clemens and Hartman, 2014; Moore et al., 2014; Hartman et al., 2014) above the highest stratigraphic appearance of in situ fossils of non-avian dinosaurs, below the lowest occurrence of unreworked Paleocene pollen (Bercovici et al., 2009), locally by the presence of a clay horizon containing an iridium anomaly, shocked quartz, and spherules that is interpreted as an impact debris horizon, and by a –1.5‰ to –2.8‰ carbon isotope anomaly which has allowed the recognition of the KPB in locations where the impact horizon is not preserved (Arens and Jahren, 2000, 2002; Arens et al., 2014). The KPB thus defined is not in all places coincident with the Hell Creek–Fort Union formational contact (Johnson, 1992; Pearson et al., 2001; Nichols and Johnson, 2002; Arens and Jahren, 2002; Clemens and Hartman, 2014) and can be either above or below the contact depending on location.

Over 40 distinct tephra deposits have been identified in our field area, mainly within lignite beds, spanning ~70 m of section from the upper Hell Creek Formation through the Tullock Member of the Fort Union Formation. Every one of these tephras examined to date contains sanidine, many grains of sufficient size to permit high-precision dating of single crystals. Thus, the Hell Creek region provides an opportunity to establish a chronostratigraphic framework of unprecedentedly high resolution for study of the evolution of terrestrial ecosystems from just before the KPB through the recovery from this remarkable event in Earth history. In particular, this work serves to calibrate the ages of mammalian faunas that have been assigned to North American Land Mammal Ages (NALMAs) by previous studies (Archibald, 1982; Lofgren, 1995; Clemens, 2002; Wilson, 2005, 2013, 2014; Clemens and Wilson, 2009).

SAMPLING

Sampling for this work was conducted in 2010–2012, at locations shown in Figure 1. Stratigraphic sections at these locations either (1) coincide with sections characterized in previous studies, or (2) were measured and described in the course of our work. Sampled sections are somewhat bimodally distributed geographically, hence we group them into eastern and western areas.

Western Area

The western portion of our field area is primarily within northern Garfield County. The first radioisotopic age determinations of tephras in the area were made at a site we identify as the Lerbekmo Site (47°30′57.66″N, 106°56′11.64″W; LB in Fig. 1) (Folinsbee et al., 1963). (All locations herein are based on the WGS84 datum.) Outcrops of the Z coal at this location are present in low buttes ~150 m east of the road (Garfield County Route 543) linking the town of Jordan with the Hell Creek State Recreation Area. Here the Z coal is ~160 cm thick, and the impact claystone is present at the base of the coal (Renne et al., 2013, and references therein). Tephras from the Z coal have been sampled by a number of workers at this site, which in the literature has been referred to by several other names (e.g., Divide Knob, Hell Creek Marina Road) (Folinsbee et al. 1963; Shafiqullah et al., 1964; Baadsgaard and Lerbekmo, 1980, 1983; Baadsgaard et al., 1988; Renne et al., 2013; Hartman et al., 2014). The most recent age determinations, using high-precision $^{40}Ar/^{39}Ar$ dating, for two tephras found within the Z coal were presented by Renne et al. (2013) and are referred to in this study (Fig. 2A).

In a map compiled in 1977 and modified in 1980, Archibald (1982) mapped the complex of Z coals from the region between Brownie Butte (bb in Fig. 1) and Hell Hollow (HH), a distance of ~12 km. In this area the Z coal is subdivided by beds of mudstones and siltstones up to a thickness of 13.7 m (Archibald, 1982). This complexity was recognized by distinguishing an upper and a lower Z coal. Brownie Butte is ~6 km west of the Lerbekmo Site (see Appendix C). As a result of ground cover and erosion of the intervening valley of Hart Creek, the exact stratigraphic relationships of the Z coal at the Lerbekmo Site and the upper and lower Z coals in the vicinity of Brownie Butte have yet to be determined.

The westernmost extent of Archibald's mapping is Hell Hollow. From 1977 into the early 1980s, prospecting and mapping were extended southwestward into an area the field parties dubbed Hauso Flats (HF). At an isolated butte in the flats, now called Iridium Hill, both the upper and lower Z coals are exposed and separated by ~18 m of mudstones and siltstones (Swisher et al., 1993; Renne et al., 2013). In

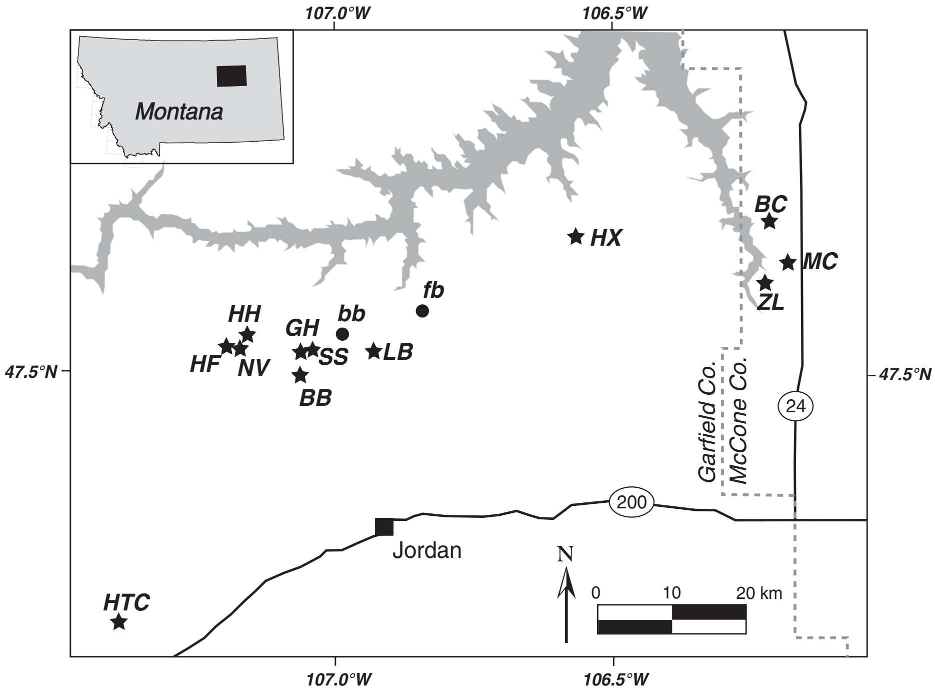


Figure 1. Location map showing the study area in the Hell Creek region of northeastern Montana (USA). Fort Peck Reservoir is shown in gray. Labeled stars show locations of measured stratigraphic sections where tephras for geochronologic dating were collected. Note the bimodal distribution between western and eastern sections. HTC—Horsethief Canyon; HF—Hauso Flats; HH—Hell Hollow; NV—Nirvana; SS—Saddle Section; BB—Biscuit Butte; GH—Garbani Hill; LB—Lerbekmo; HX—Haxby Road; BC—Bug Creek; MC—McGuire Creek; ZL—Z-Line. Also shown are Brownie Butte (bb) and Flag Butte (fb) locations referred to in text, indicated by filled circles.

the summer of 1980 the impact claystone was discovered within what had been mapped as the lower Z coal (Alvarez, 1983; Clemens and Hartman, 2014) and has subsequently been shown to temporally correlate with the Chicxulub bolide impact and the KPB (Renne et al., 2013). Swisher et al. (1993) renamed the lower Z coal of Archibald the Iridium Z (IrZ) coal and the upper Z coal the Hauso Flats Z (HFZ) coal. We follow the usage of Swisher et al. (1993). As noted in Figure 2A (Hauso Flats section), tephras in both the IrZ and HFZ coals have previously yielded radioisotopic age determinations (Renne et al., 2013). In the western research area, we collected additional samples from tephras of IrZ and HFZ coal sites as well from the Y, W, V, and U coals. Western stratigraphic sections are summarized in Figure 2A.

Hell Hollow

The Hell Hollow (HH) locality is ~3 km northeast of Hauso Flats. At this location both the IrZ and HFZ coals recognized at Hauso Flats have been mapped (Archibald, 1982). The IrZ coal at Hell Hollow is in places incised by the Hell Hollow Channel sandstone, which contains vertebrate fossils assigned to the early Puercan (Pu1) NALMA (Swisher et al., 1993) (University of California Museum of Paleontology locality [UCMP loc.] V74111). The Hell Hollow Channel sandstone is capped by the HFZ coal. Tephras from both coals, correlated in the field with those dated by Renne et al. (2013) at Hauso Flats, were sampled for dating.

The IrZ coal at this locality (47°32′3.60″N, 107°10′22.14″W) is ~10 cm thick and contains a ~1- to 4-mm-thick, pink (Munsell color, 5 R 8/2), sanidine-bearing tephra. The thickness of the tephra is highly variable, and it is absent from some outcrops, possibly as a result of erosion by the Hell Hollow Channel, which locally cuts down into or through the IrZ coal.

The HFZ coal in this location (47°32′23.16″N, 107°10′16.62″W) is 2–3 m thick and contains at least two tephras. One tephra is ~0.5–1.0 cm thick and occurs roughly 1 m above the base of the coal. This tephra is red (10 R 5/4) in color and contains sanidine. Coarse pseudomorphs of cuspate glass shards are apparent. A second ~5-cm-thick tephra occurs roughly in the middle of the coal, ~12 cm above the first deposit. This tephra is red (10 R 5/4) in color and contains very fresh, coarsely crystalline, euhedral sanidine crystals and biotite. The upper tephra was sampled for dating.

Nirvana

An additional IrZ coal tephra was sampled at a locality (47°31′37.14″N, 107°11′10.98″W) informally known as "Nirvana" (NV) ~1 km southwest from our Hell Hollow locality. In this location the IrZ coal is ~15 cm thick, and a 1- to 3-mm-thick, pink (5 R 8/2) tephra appears roughly 1 cm from the top of the coal. The tephra contains abundant sanidine crystals that were used for $^{40}Ar/^{39}Ar$ dating. A channel filling 1.6–6.3 m below the base of the IrZ coal has yielded a Lancian vertebrate fauna (UCMP loc. V77130).

Garbani Hill

The Garbani Hill (GH) locality (47°30′57.60″N, 107°4′6.06″W) is ~8 km southeast from the Hell Hollow area. The Garbani Quarry is in an exposure of the Garbani Channel filling on the southwest slope of Garbani Hill. It is not included in the Garbani Hill section (Fig. 2A). The fossiliferous strata in the quarry have been divided into a series of sub-localities. Of these, the most productive is UCMP loc. V73080. The quarry has yielded a local fauna probably of Pu3 age (Clemens, 2013).

In this area, the Y coal occurs as a doublet. Locally the Garbani Channel can be shown to have cut down through the X coal to the level of the Y coal. To the south in the Biscuit Butte (BB) area, the W coal caps the channel filling.

At Garbani Hill, we collected tephras from the Y coal doublet. The lower Y coal in the doublet at Garbani Hill is ~50 cm thick, with roughly 1 m of shale separating the lower coal from the 1-m-thick upper Y coal. In the lower coal, a 1- to 3-cm-thick pink-gray (5 YR 8/1) tephra occurs ~2 cm below the top of the coal. This tephra contains abundant sanidine and was sampled for dating.

Within the upper Y coal, two tephras were identified. Approximately 50 cm from the base of the coal, a massive gray (10 R 8/2) tephra is located. This tephra is 20–30 cm thick and contains abundant sanidine crystals. Ten centimeters above this deposit, the second tephra is located. This tephra is roughly 2 cm below the top of the upper coal and is ~1–2 cm thick with a distinctive pink (5 R 8/2) color. In this location, the tephra is unconsolidated and laterally discontinuous. The lower massive tephra was selected for dating due to the coarser grain size of sanidine crystals.

The X coal as mapped by Archibald (1982) also crops out at this locality, but no tephra deposits could be identified within the coal here.

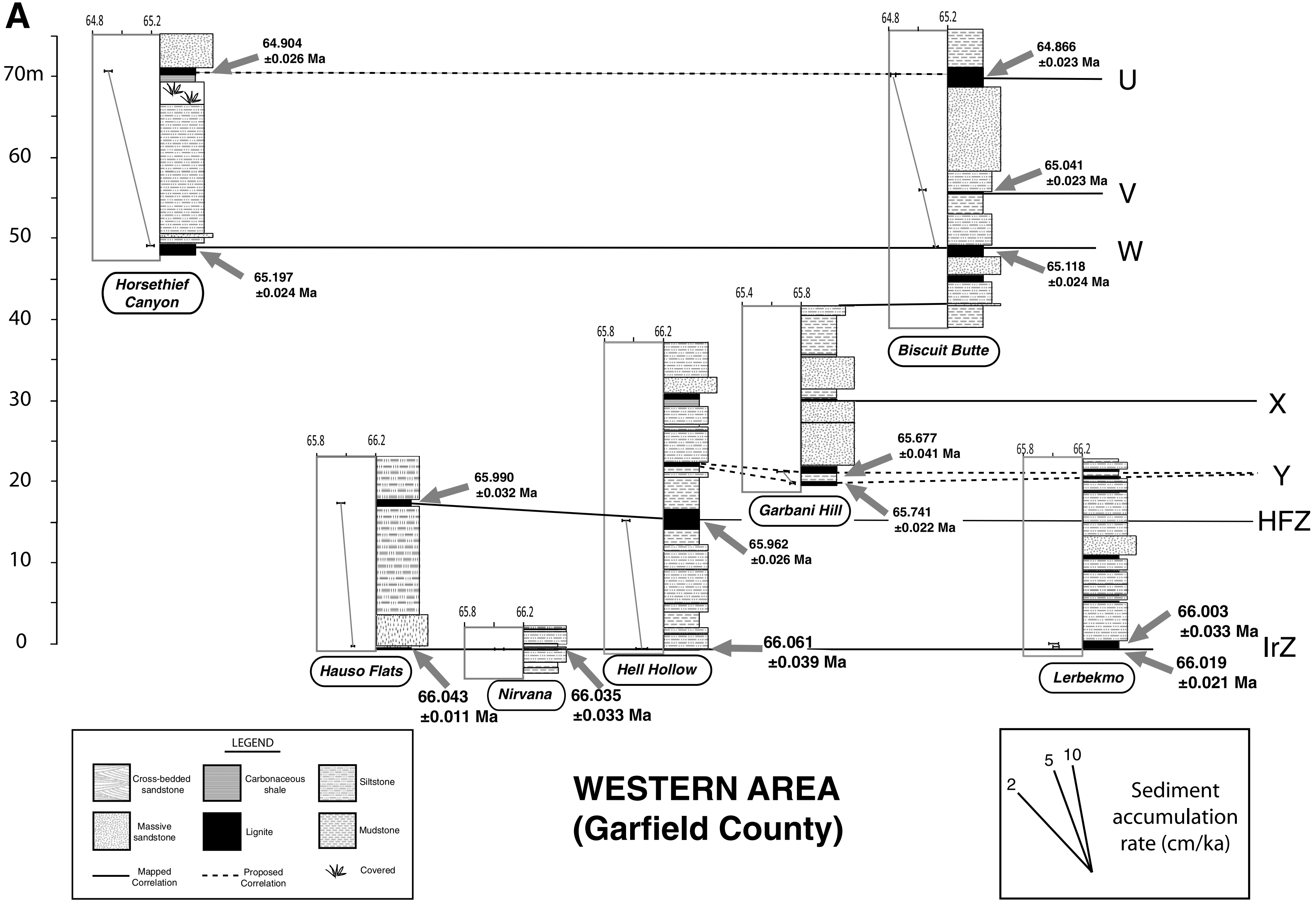


Figure 2 (*on this and following page*). **Stratigraphy and correlations for sections within Garfield (western) and McCone (eastern) Counties, Montana. Black lines indicate mapped correlations, and dotted black lines indicate proposed correlation. Boxes next to each section plot age versus stratigraphic height. In sections where more than one age has been determined, sediment accumulation rates are calculated (gray line). (A) Garfield County sections from west to east. Geochronologic data from both the Hauso Flats and Lerbekmo (Hell Creek Marina Road) localities were presented by Renne et al. (2013). Stratigraphic sections were adapted from Archibald (1982: Horsethief Canyon and Hell Hollow IrZ–HFZ), Swisher et al., (1993: Hauso Flats), Turner (2010: Nirvana), LeCain et al. (2014: Garbani Hill and Biscuit Butte), and this study (Lerbekmo and Hell Hollow HFZ–top). Note that the stratigraphy of the Saddle Section locality is consistent with the basal Biscuit Butte and as such is not included in the figure.**

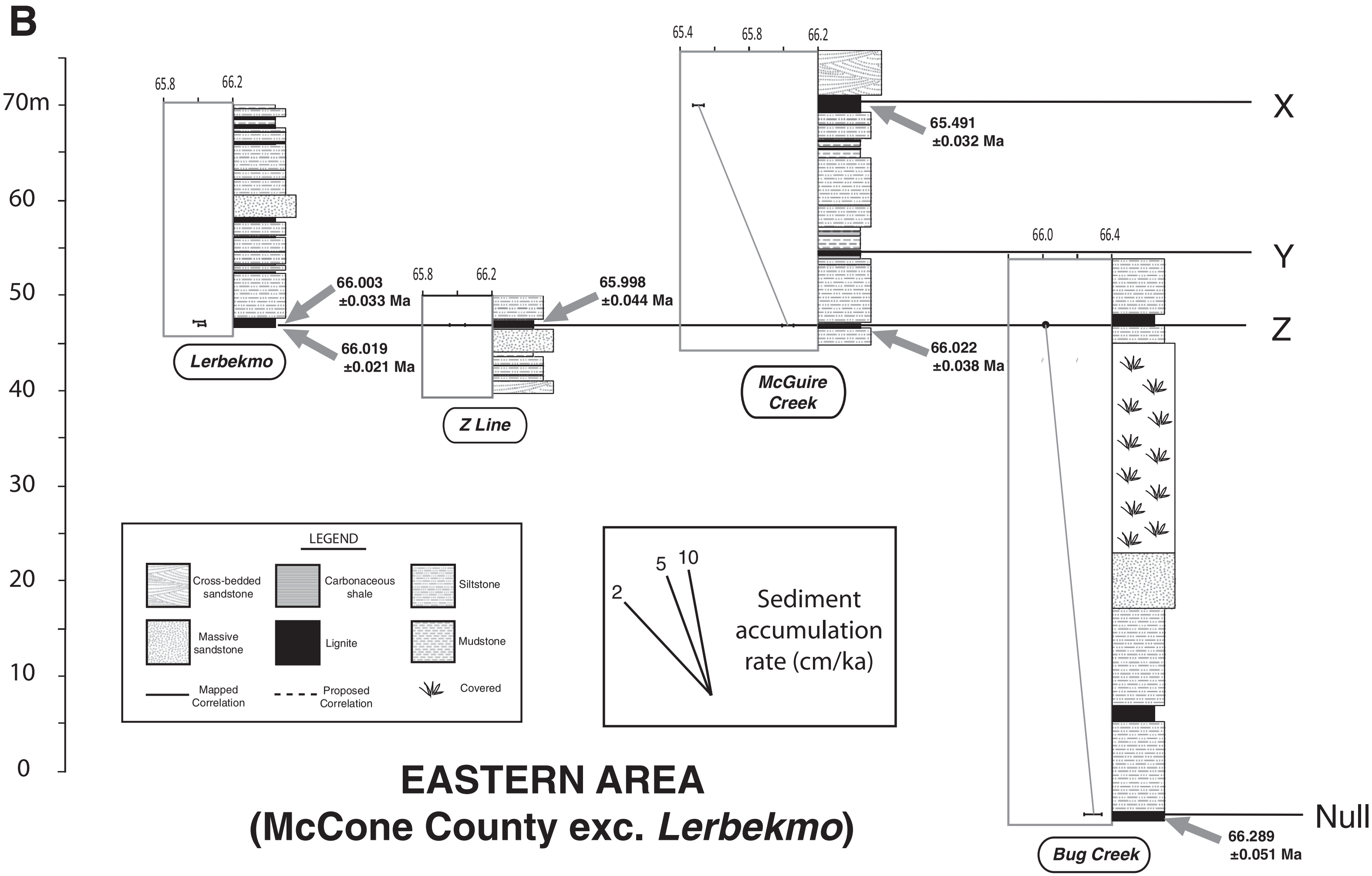


Figure 2 (*continued*). (B) McCone County localities, which include Z-Line, McGuire Creek, and Bug Creek. Lerbekmo locality is included for comparison. Stratigraphic sections for Z-Line and McGuire Creek are adapted from Lofgren (1995), and Bug Creek was adapted from Archibald et al. (1982). Stratigraphy was not collected from the Haxby Road section. Stratigraphy was plotted using Matstrat (Lewis et al., 2011).

Saddle Section

Approximately 1 km southwest from Garbani Hill, the W coal occurs as a doublet at the informally named "Saddle Section" (SS) locality (47°30′34.80″N, 107°4′54.90″W). Each coal of the doublet is ~1 m thick with ~2 m of sediment between the two. The lower coal contains at least six tephra layers varying in thickness from 1 to 40 mm. All tephras have apparent sanidine crystals and are either pink or gray.

The upper coal of the doublet contains at least eight distinct tephra layers that vary in thickness from a few millimeters to 4 cm and again are pink or gray. A ~4-cm-thick gray (N 7) tephra with conspicuously coarse sanidine crystals occurs ~6 cm below the top of the coal. This is the second tephra counting down from the top of the coal, and was used for dating.

Biscuit Butte

Approximately 2.5 km to the south of the Saddle Section, the W, V, and U coals crop out on the side of the basin just to the north of Biscuit Butte (BB). At this location, we collected tephra samples from the U (47°29′13.08″N, 107°4′7.64″W) and V (47°29′21.84″N, 107°4′23.82″W) coals. The W coal at Biscuit Butte, as at the Saddle Section and elsewhere in the region, is also a doublet with abundant tephra deposits (six or more in each coal). Due to stratigraphic position and distinctive grain size, we were able to identify the tephra we collected and dated from the top of the upper unit at the Saddle Section and are confident, based on the distinctive number of tephras in each coal and stratigraphic position, that this W coal outcrop at Biscuit Butte is time-stratigraphically correlative.

The V coal is located ~6 m above the top of the upper W coal, as shown (but not named) by LeCain et al. (2014). It is ~30 cm thick and contains one tephra, a ~0.5- to 1.0-cm-thick pink (5 YR 8/1) tephra found 7–10 cm below the top of the coal. This tephra was used for dating.

Thirteen meters above the V coal is the U coal, the base of which marks the contact between the Tullock Member and the overlying Lebo Member of the Fort Union Formation. At this location, the U coal is ~2.5 m thick and contains multiple sanidine-bearing tephras. Approximately 85 cm above the base of the coal, an 18-cm-thick gray-pink (5 YR 8/1) tephra occurs that we sampled for dating. This tephra is almost certainly the same one analyzed by Swisher et al. (1993) based on the tephra's diagnostic thickness.

Horsethief Canyon

The Horsethief Canyon (HTC) locality is roughly 35 km south from Hell Hollow on the Bliss Ranch. Two coals were identified at this location: one crops out at the base of a channel sandstone deposit, and the other crops out at the top of that channel deposit. The channel deposit contains the Horsethief Canyon vertebrate fossil localities (UCMP locs. V73094 and V73095), which are earliest Torrejonian (To1) in age (Archibald et al., 1982; Clemens and Wilson, 2009). The coal at the base of the sandstone was tentatively identified as a coal termed UW coal by W. Rohrer of the U.S. Geological Survey (Archibald, 1982). This coal (47°11′55.68″N, 107°23′7.26″W) was sampled. The coal here is 1.45 m thick and contains over 18 distinct tephra deposits. Tephra deposits range in thickness from a few millimeters to a few centimeters. Most deposits are pink in color, and all appear to contain sanidine. Approximately 10 cm below the top of the coal we sampled a coarsely crystalline 2- to 4-cm-thick tephra for dating. The tephra is gray (N7) in color and contains abundant sanidine crystals. Based on coal descriptions, particularly the great number of tephras, we believe this deposit correlates to the upper unit of the W coal, cropping out at our Saddle Section and Biscuit Butte localities.

Capping the channel sandstone deposit is a coal tentatively designated by Archibald (1982) as the U coal. The coal deposit sampled (47°11′37.74″N, 107°24′6.06″W) is ~1 m thick and contains at least four tephra layers. A reddish-brown (10R 5/4) tephra roughly 4 cm thick located in the middle of the coal was sampled for dating. This tephra contains coarse crystals of euhedral sanidine.

Eastern Area

In the eastern part of our field area, primarily in McCone County, the base of the Tullock Member is exposed in the area between the valley of Bug Creek and, to the south, the valley of McGuire Creek. For over a century, the valley of Bug Creek has been a focus of paleontological, and later, beginning in the 1960s, geological research (Clemens and Hartman, 2014). Recognizing differences in their geology, exposures of the Hell Creek Formation and Tullock Member in the valley of Bug Creek have been separated into two areas (see, e.g., Fastovsky and Dott, 1986; Smit et al., 1987). To the east is the complex stratigraphic section exposed in Russell Basin. The western area includes the Bug Creek Anthills fossil locality (UCMP loc. V65127 and sub-localities). With the exception of the palynological study by Arens et al. (2014), the research reported here is based on outcrops in the western area.

In the valley of Bug Creek, we followed a section measured by Archibald et al. (1982) from the Null coal in the Hell Creek Formation through the basal lignite of the Tullock Member exposed on the southern slope of the ridge overlooking the Bug Creek Anthills locality. Samples of tephra were taken from the basal lignite of the Tullock Member, which has been identified by a variety of names: Z coal of Sloan and Van Valen (1965); the unnamed coal of Smit and van der Kaars (1984, their fig. 4); Coal with Marker, Facies D, of Fastovsky and Dott (1986); upper Z coal of Smit et al. (1987); and formational or upper Z coal of Rigby and Rigby (1990). Primarily based on palynological data, this lignite and the sandstone on which it rests have been shown to be of earliest Paleocene age (Rigby et al., 1987).

To the south, the geology of the strata exposed in the valley of McGuire Creek and Black Spring Coulee was studied in detail by Lofgren (1995) who dubbed the basal lignite of the Tullock Member the McGuire Creek Z (MCZ) coal. Two sections in this area were studied, and tephras were collected from the included lignites. In both sections, the MCZ coal was deposited on strata of earliest Paleocene age.

The MCZ coal in this area varies in thickness between ~0.5 m and 2 m, and has been found to contain between zero and four distinct tephras. The most distinctive tephra contains abundant biotite, is ~8 cm thick, and is typically gray-green (5GY 5/2) in color. This tephra has been used as a criterion for identification of the basal coal of the Tullock Member (Z coal) across McCone County and into eastern portions of Garfield County (Swisher et al., 1993). As noted below, on the basis of color, texture, thickness, stratigraphic position, and mineralogy, the two tephras sampled in the MCZ coal are correlative with the basal two tephras sampled in the valley of Bug Creek and tephras in the Z coals in our Haxby Road (HX) and Lerbekmo (LB) localities in Garfield County. To the best of our knowledge, concentrations of iridium large enough to indicate the presence of an impact claystone have yet to be discovered in the eastern area. Eastern stratigraphic sections are summarized in Figure 2B.

Bug Creek

Five kilometers north of McGuire Creek (47°40′52.50″N, 106°11′44.04″W), we sampled the basal lignite of the Tullock Member above the Bug Creek Anthills vertebrate fossil locality (Sloan and Van Valen, 1965; UCMP loc. V65127 and sub-localities). The lignite in this section (BC) is ~1 m thick and contains three tephras. The lowermost of these, 31 cm above the base of the lignite, is 2 cm thick, pink (10 R 8/2), and contains abundant sanidine. The second tephra is 23 cm above the lowermost tephra, is ~6 cm thick, is gray-green (5 GY 5/2), contains abundant biotite, and underlies a ~1-cm-thick, pink (10 R 8/2) sanidine- and altered biotite–bearing tephra 37 cm above. These tephras were sampled for chemical analysis, but were not dated.

Below the Hell Creek–Fort Union formational contact (47°40′48.60″N, 106°12′49.56″W), we collected a tephra in the Null coal mapped by Rigby and Rigby (1990), which is correlative with the Tonstein Lignite mapped several kilometers to the south by Lofgren (1995), based on stratigraphic position and presence of tephra. Possible correlatives of this coal, with one or two superficially similar tephras, are also present on the western side of the Big Dry Arm (Lofgren, 1995). The Null coal is the only known coal in the Cretaceous strata of the Hell Creek Formation within this region that includes a tephra deposit. This coal lies ~50 m below the basal lignite of the Tullock Member at Bug Creek and is ~20 m below the Bug Creek Channel deposit at the Bug Creek Anthills locality. The coal is 17 cm thick, with a pink (5 R 8/2) 2-cm-thick tephra ~10 cm from the bottom of the coal. The tephra is fine grained, and small sanidine crystals were used for dating.

Z-Line

The Z-Line locality (ZL) is located ~1 km south of the McGuire Creek Bay, off of the eastern side of the Big Dry Arm of the Fort Peck Reservoir in McCone County (47°36′37.26″N, 106°12′37.74″W). Here the MCZ coal is ~85 cm thick and contains two distinct tephras. A 2.0- to 2.5-cm-thick pink (10 R 8/2) tephra was located ~22 cm above the base of the coal and roughly 30 cm below a ~7-cm-thick, biotite-bearing gray (5 GY 5/2) tephra. The lower tephra does not contain biotite but does contain abundant euhedral sanidine crystals that were used for $^{40}Ar/^{39}Ar$ dating. The MCZ coal here caps the Z-Line Channel of Lofgren (1995) that contains a Pu1 vertebrate fauna (UCMP loc. V84194). The two tephras correlate to the lower two tephras present in the basal lignite of the Tullock Member at our Bug Creek locality based on color, thickness, texture, stratigraphic order, and mineralogy, particularly the appearance of biotite found in the upper tephra.

McGuire Creek

A second locality (MC) ~2 km northeast of McGuire Creek was also sampled. The section here (47°37′47.50″N, 106°10′12.40″W) corresponds to section sB of Lofgren (1995) which is the northeasternmost section included in his cross section Y–Y′. At this locality, the MCZ coal is ~60 cm thick and contains three tephra deposits. The lowest tephra is ~3 cm above the base of the deposit. It is pink (10 R 8/2), is 0.5 to 1.0 cm thick, and contains abundant sanidine crystals. Approximately 11 cm above this tephra a 6- to 7-cm-thick, biotite-bearing gray (5 GY 5/2) tephra is present, ~26 cm below the third tephra deposit. The third tephra is ~7 cm below the top of the deposit. It is 3–5 cm thick, contains abundant sanidine crystals and altered biotite, and is pink (5 R 8/2) in color. The bottom two tephras best correlate with the two tephras identified in the Z-Line and Bug Creek localities based on appearance (thickness, color, etc.), mineralogy, and stratigraphic order. Sanidine from the lowermost tephra was used for $^{40}Ar/^{39}Ar$ dating. At this locality, the MCZ coal overlies strata yielding the “Swamp Local Fauna” of Lofgren (1995; UCMP locs. V85085, V85086, V86093). The absence of dinosaurian remains suggests that this local fauna is of Paleocene age.

In addition to the MCZ coal, tephra in a second coal was identified in Lofgren’s (1995) sB section for radioisotopic dating. This coal, which was mapped as the X coal by Rigby and Rigby (1990), is ~18 m above the MCZ coal. The lignite deposit here is ~1.8 m thick, and the unit contains three distinct tephras. The first tephra is ~20 cm thick and located 25 cm from the bottom of the coal deposit. Roughly 46 cm above this tephra deposit, a second tephra is located that is ~0.5 cm thick and contains abundant sanidine crystals. A third overlying tephra is located ~45 cm above the second tephra. It is 0.5 cm thick and is sanidine bearing. All tephra deposits are pink (10 R 8/2) in color. Sanidine from the second tephra was used for radioisotopic dating.

Haxby Road

In addition to locations in McCone County, our study has also identified numerous occurrences of the basal lignite of the Tullock Member in eastern Garfield County. One locality (HX) is just off the Haxby Road (47°38′49.80″N, 106°33′37.14″W), ~26 km west of the McGuire Creek locality. At least two tephras have been identified in this 112-cm-thick coal deposit. The lower of these is ~67 cm from the base of the coal, and is 2 cm thick, pink (10 R 8/2), and sanidine rich. Approximately 20 cm above this tephra, there is a second, 6- to 10-cm-thick, gray (5 GY 5/2), biotite-bearing tephra. These tephras correlate, based on color, thickness, texture, mineralogy, and stratigraphic positions, with the two present at Z-Line and the bottom two present at the McGuire Creek, Bug Creek, and Lerbekmo localities. We collected sanidine from the lower tephra for $^{40}Ar/^{39}Ar$ dating.

$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

The first geochronologic work conducted in the Hell Creek region used K-Ar, U-Pb, and Rb-Sr methods to date the diagnostic thick tephra found within the Z coal at the Lerbekmo locality in Garfield County (Folinsbee et al., 1963; Shafiqullah et al., 1964; Baadsgaard and Lerbekmo 1980, 1983; Baadsgaard et al., 1988). Ages (uncorrected for modern constants) reported for this tephra range from 63.5 to 66.5 Ma with uncertainty estimated at ~500 ka. The first study to use a high-precision dating technique was conducted by Swisher et al. (1993) using the $^{40}Ar/^{39}Ar$ method on single crystals of sanidine and plagioclase to date tephras from the IrZ, Z, HFZ, W, and U coals. Our study presents 15 high-precision $^{40}Ar/^{39}Ar$ sanidine ages from the Null, IrZ, MCZ, Z, HFZ, Y, X, W, V, U, and “unknown” coals, two refining previous work and 13 from previously undated units, many in previously undescribed stratigraphic sections (Table 1). New ages are constrained with a relative precision of ~0.2%, more than an order of magnitude better than early determinations and roughly half that of Swisher et al. (1993). The dates reported here represent a small fraction of the more than 40 tephras we have identified in the upper Hell Creek and Fort Union Formations. A detailed account of methods utilized is given in Appendix A.

Detailed discussion of the results for each sample is given in the Appendix B. A summary of these results is given in Figures 3 and 4 and Table 1. Pooled ages are given in Table 2. These are computed from two or more locations where appropriate, including data from Renne et al. (2013), as described in Appendix B.

DISCUSSION

Sediment Accumulation Rates

Dated tephras in their stratigraphic contexts, and proposed correlations, are shown in Figures 2A–2B. A noteworthy feature of our results is the consistency of average implied sediment accumulation rates (SARs), which vary between 5 and 10 cm/ka, within uncertainties, above the level of the HFZ. Below this level, SARs are 19 ± 4 cm/ka between the Null coal and basal lignite of the Tullock Member at Bug Creek, and 21 ± 7 cm/ka at Hell Hollow and 26 ± 8 cm/ka at Hauso Flats, both between the IrZ and HFZ coals. The significance of these higher rates is obscured by the fact that nearly half of the intervening Bug Creek section is poorly exposed. Slope wash in this interval suggests that the underlying strata are dominated by sandstones, which might be expected to record higher accumulation rates than the finer-grained deposits that constitute much of the other sections. This hypothesis is supported by previous studies that have shown that the basal lignite of the Tullock Member rests upon a silty sandstone, referred

TABLE 1. SUMMARY OF $^{40}Ar^{*}/^{39}Ar$ AGES

Coal	Sample	Section	Age (Ma)	±σ (Ma)*	±σ (Ma)†	Method§	N/N_0#
U	BB11-1	BB	64.865	0.024	0.047	SCTF	119/119
U	BB11-1	BB	64.867	0.031	0.052	SHP	54/57
U	**BB11-1**	**BB**	**64.866**	**0.023**	**0.047**	**Comb**	
U?	**HTC12-3**	**HTC**	**64.904**	**0.026**	**0.049**	**SCTF**	**71/73**
V	**BB12-1**	**BB**	**65.041**	**0.023**	**0.048**	**SCTF**	**175/179**
W	**HTC12-1**	**HTC**	**65.197**	**0.024**	**0.048**	**SCTF**	**85/93**
W	**SS11-3**	**SS**	**65.118**	**0.024**	**0.048**	**SCTF**	**68/68**
X	MC11-3	MC	65.494	0.038	0.056	SCTF	52/52
X	MC11-3	MC	65.488	0.039	0.057	SHP	35/47
X	**MC11-3**	**MC**	**65.491**	**0.032**	**0.053**	**Comb**	
Y	**GC12-2**	**GH**	**65.677**	**0.041**	**0.059**	**SCTF**	**118/243**
Y	**GC12-3**	**GH**	**65.741**	**0.022**	**0.048**	**SCTF**	**104/106**
HFZ	**HH12-2**	**HH**	**65.962**	**0.026**	**0.050**	**SCTF**	**77/79**
MCZ	LG11-1	MC	66.015	0.052	0.066	SCTF	72/150
MCZ	LG11-1	MC	66.028	0.050	0.065	SHP	18/42
MCZ	**LG11-1**	**MC**	**66.022**	**0.038**	**0.057**	**Comb**	
Z	**HX12-1**	**HX**	**66.002**	**0.033**	**0.054**	**SCTF**	**93/94**
MCZ	**ZL12-2**	**ZL**	**65.998**	**0.044**	**0.061**	**SCTF**	**89/90**
IrZ	**HH12-1**	**HH**	**66.061**	**0.039**	**0.059**	**SCTF**	**70/74**
IrZ	**NV12-1**	**NV**	**66.035**	**0.033**	**0.052**	**SCTF**	**55/56**
Null	**BC11-1, BC-1PR**	**BC**	**66.289**	**0.051**	**0.065**	**SCTF**	**54/174**

Note: Coal designations are based on references cited in text. Section abbreviations are described in Figure 1. Ages are based on the calibration of Renne et al. (2011).
*,†Age uncertainties excluding (*) and including (†) systematic sources are shown.
§Method refers to single-crystal total fusion (SCTF) or step-heating plateau (SHP) ages; where appropriate, these are combined (Comb) as the weighted mean.
#N/N_0 refers to the number of analyses (single-crystal fusions or incremental heating steps) used for age calculation relative to the number of ages obtained.

to as the Big Bugger, at other outcrops of the basal lignite within the western part of the valley of Bug Creek (Fastovsky and Dott, 1986; Smit et al., 1987). Similarly, large channel deposits exist between the IrZ and HFZ coals at Hell Hollow and Hauso Flats.

The intervals between dated tephra in the W to U coals in the Biscuit Butte section exemplify the consistency of SARs. The W–V and V–U intervals indicate similar SARs of 8 ± 4 and 7 ± 1 cm/ka, respectively. This is also seen between different locations for the same stratigraphic interval. The lowest SAR recorded in any section is that for the lower part of the Z coal at the Lerbekmo section. There, we ascribe the pooled age (66.043 ± 0.010 Ma) of the IrZ coal tephra to the iridium anomaly at the base of the Z coal, and the pooled age of 66.013 ± 0.015 Ma for the Z coal tephra as discussed in Appendix B. This 80 cm interval predominantly comprising lignite thus apparently represents 30 ± 18 ka, corresponding to a mean SAR of 3 ± 2 cm/ka This rate is indistinguishable from SARs of 3–12 cm/ka estimated for similar-aged lignite in North Dakota (Chin et al., 2013).

Magnetostratigraphy and the Geomagnetic Polarity Time Scale

The relatively uniform SARs for each stratigraphic interval, regardless of location, support the validity of interpolating between dated tephras to constrain the ages of various features in these sections, including geomagnetic polarity reversals. Using polarity sequences from previous magnetostratigraphic studies in the study area (LeCain et al., 2014; Swisher et al., 1993; Archibald et al., 1982), we calculated reversal ages using linear interpolation between dated tephras and reversal boundaries. For this procedure, we placed reversals halfway between the bounding sample sites defining the reversal, and used half the distance between these bounding sites as the uncertainty. This estimate of uncertainty in placement of reversals amounts to the 100% confidence interval, provided that no systematic uncertainties exist in the paleomagnetic data. Uncertainty in the resulting chron boundary ages is dominated by the coarse spacing of samples defining the chron boundaries. With improved chron boundary placement in existing sections, and additional sections to test the applicability of linear SARs, it may be possible to improve calibration of the geomagnetic polarity time scale.

Base of Chron C29r

To calculate an age for the chron 30n/29r reversal, we utilized a magnetostratigraphic section reported by Archibald et al. (1982) from the Bug Creek locality. At this locality the reversal is bounded by two coals, the basal lignite of the Tullock Member ~30 m above the reversal and the Null coal ~21 m below. A distance of ±1 m was used as a proxy for uncertainty in reversal placement. Using our $^{40}Ar/^{39}Ar$ age for the Null coal and our pooled age for tephras in the Z coal (see Appendix B for the basis for calculation of pooled ages), we calculated a reversal age of 66.177 ± 0.032/0.044 Ma (errors given as non-systematic/systematic). However, we note that the two sites bracketing the reversal have within-site directional clustering that is reportedly (Archibald et al., 1982) indistinguishable from random. Thus, we use the uppermost of six successive normal polarity sites having statistically non-random directional clustering as a maximum age for the base of C29r to calculate a maximum age of 66.195 ± 0.042/0.052 Ma. The most conservative possible constraint our data yield is that the base of C29r is younger than the age of the Null coal tephra dated at 66.289 ± 0.051/0.065 Ma.

Top of Chron C29r

The chron 29r/29n reversal age was calculated from the Pearl Lake magnetostratigraphic section reported in LeCain et al. (2014). This section is ~1 km northeast from our Garbani Hill locality. Within the Pearl Lake locality, LeCain et al. (2014) identified the IrZ coal, the HFZ coal, and a Y coal stringer, traced to the Y coal at Garbani Hill. The reversal is bounded ~6 m above by the Y coal and ~10 m below by the HFZ coal. A distance of ±1 m was used as a conservative proxy for uncertainty in reversal placement. Using our age for sample GC12-3 (the lower coal in the Y coal doublet from Garbani Hill) and our pooled age for the HFZ coal,

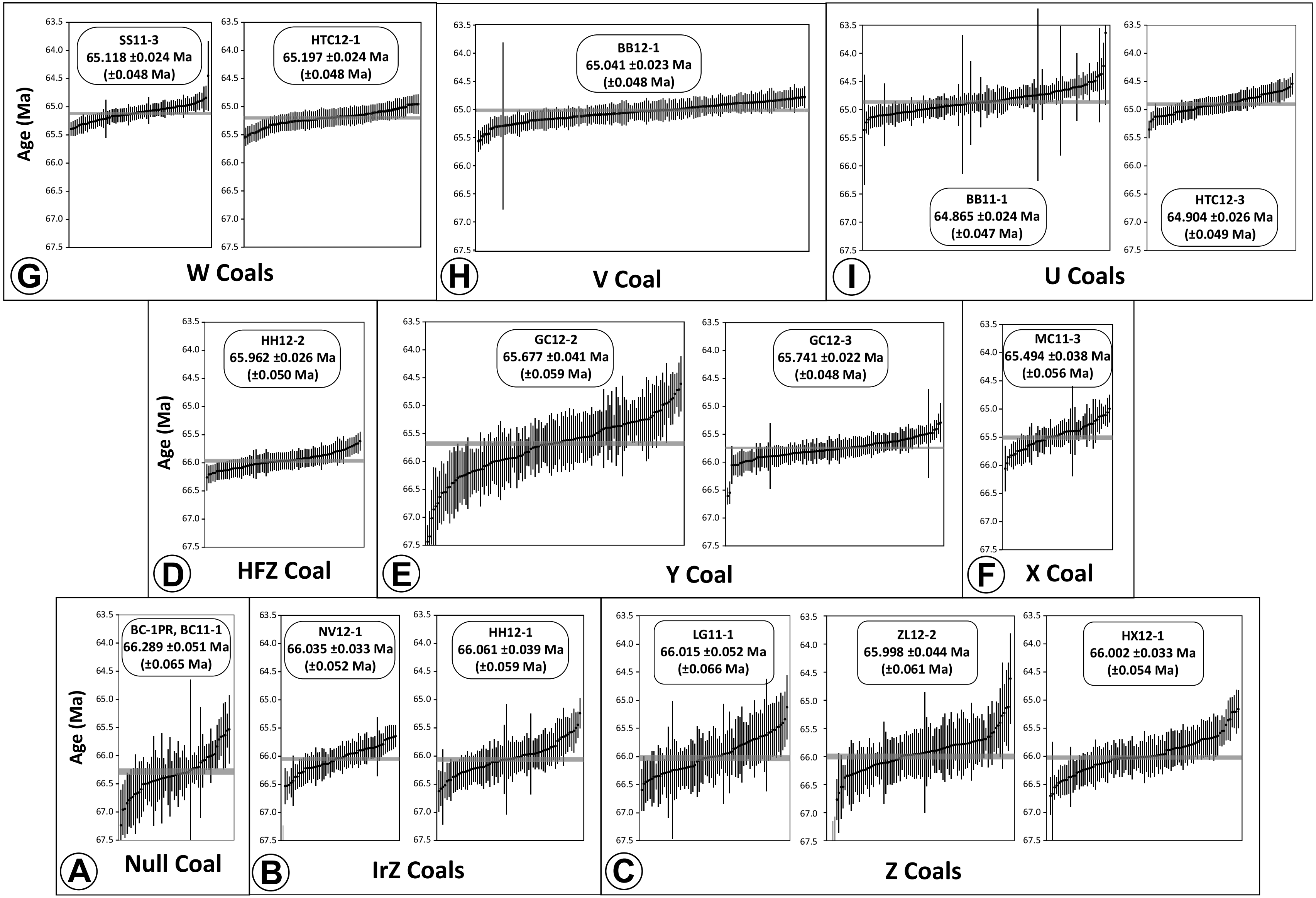
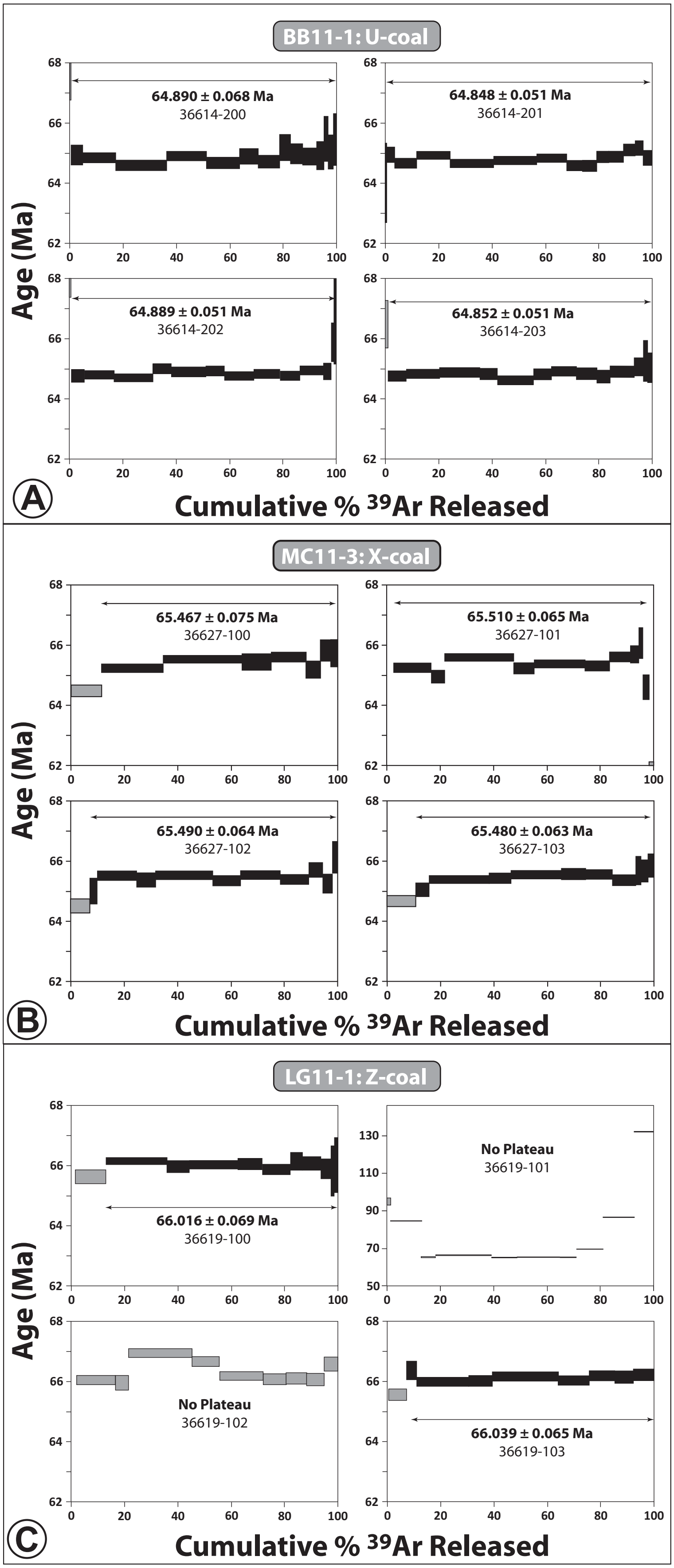


Figure 3. Summary of single-crystal $^{40}Ar/^{39}Ar$ results for tephras. Stratigraphic relationships are described in Figure 2. Individual ages are shown in rank order with analytical uncertainty limits of 1σ. Errors reported as non-systematic/systematic. Gray boxes show uncertainty limits for the weighted mean age for each sample. (A) Null Coal at the Bug Creek (BC) section. (B) IrZ coal at two locations, Hell Hollow (HH) and Nirvana (NV), yielding indistinguishable ages. (C) Z coal at three locations—Z-Line (ZL), Haxby Road (HX), and McGuire Creek (LG, MC in Fig. 1)—yielding indistinguishable ages. (D) HFZ coal at Hell Hollow (HH). (E) Two tephras collected from the upper and lower beds of the Y coal doublet at Garbani Hill (GC, GH in Fig. 1). Ages are consistent with stratigraphic order and are distinguishable at 1σ. (F) X Coal at the McGuire Creek section (MC). (G) Tephras collected at two locations of the W coal, the Saddle Section (SS) and Horsethief Canyon (HTC). Ages are similar but distinguishable at 95% confidence, favoring credence that different tephras were collected from each site. (H) V Coal at Biscuit Butte (BB). (I) U Coal at Biscuit Butte (BB) and at Horsethief Canyon (HTC). Although ages are not distinguishable at 95% confidence, based on field evidence and tephra characteristics we do not believe the same tephra was collected at each site.

Figure 4. $^{40}Ar/^{39}Ar$ age spectra for multi-grained aliquots of feldspar samples from the U coal (A), X coal (B), and Z (MCZ) coal (C).



a reversal age of 65.832 ± 0.019/0.036 Ma was estimated. We note that the Y coal as recognized by Archibald et al. (1982) at Purgatory Hill and by Swisher et al. (1993) at Hauso Flats occurs less than 2 m above the top of C29r. The discrepancy between these relationships and that reported by LeCain et al. (2014) may reflect variable SARs, diachrony of the Y coal, or ambiguity in identification of the Y coal. In any case, our $^{40}Ar/^{39}Ar$ age is most straightforwardly attributed to the section of LeCain et al. (2014), thus we use this for the present purposes.

Top of Chron C29n

An age for the chron 29n/28r boundary was constrained using the Biscuit Butte magnetostratigraphic section reported by LeCain et al. (2014). The reversal at this locality is bounded by the V coal ~3.5 m above and by the W coal ~4.5 m below. A distance of ±0.5 m was used as a conservative proxy for uncertainty in reversal placement. Using our ages for the V coal at Biscuit Butte and W coal at the Saddle Section, which is unambiguously traceable to the Biscuit Butte section, we calculate a reversal age of 65.075 ± 0.017/0.035 Ma. The placement of this boundary in the same stratigraphic section is more uncertain using the magnetostratigraphy of Swisher et al. (1993), from which we calculate an age of 65.071 ± 0.055/0.065 Ma for the boundary. The two results are indistinguishable, hence we prefer the more precise age of 65.075 ± 0.017/0.035 Ma derived from the data of LeCain et al. (2014).

Top of Chron C28r

To calculate an age for the chron 28r/28n boundary, we again used the Biscuit Butte magnetostratigraphic section from LeCain et al. (2014). Bounding the reversal are the U coal (~5.5 m above) and the V coal (~9 m below). A conservative reversal placement uncertainty of ±6 m was used. A reversal age of 64.931 ± 0.072/0.078 Ma was calculated using our ages for the U and V coals from Biscuit Butte. At the same stratigraphic section, Swisher et al. (1993) constrained the placement of this reversal much more precisely, and from their data we calculate an age of 64.868 ± 0.025/0.048 Ma. The difference between the two ages is insignificant, hence we prefer the more precise age of 64.868 ± 0.025/0.048 Ma derived from the data of Swisher et al. (1993).

TABLE 2. SUMMARY OF POOLED $^{40}Ar^{*}/^{39}Ar$ AGES

Coal	Samples	Sections	Age (Ma)	±σ (Ma)†	±σ (Ma)§
HFZ	HH12-2	HH	65.962	0.026	0.050
HFZ	HF-3PR	HF*	65.990	0.032	0.053
HFZ	**Pooled**		**65.973**	**0.020**	**0.047**
Z (MCZ)	LG11-1	MC	66.022	0.038	0.057
Z	HX12-1	HX	66.002	0.033	0.054
Z (MCZ)	ZL12-2	ZL	65.998	0.044	0.061
Z	HC-2PR	LB*	66.019	0.021	0.046
Z	**Pooled**		**66.013**	**0.015**	**0.044**
IrZ	HH12-1	HH	66.061	0.039	0.059
IrZ	NV12-1	NV	66.035	0.033	0.052
IrZ	HF-1PR	HF*	66.043	0.011	0.043
IrZ	**Pooled**		**66.043**	**0.010**	**0.043**

Note: Ages are pooled from multiple localities. Section abbreviations are described in Figure 1.
*Denotes data from Renne et al. (2013).
†,§Age uncertainties excluding (†) and including (§) systematic sources are shown.

Discussion of Chron Durations

Our results indicate a significantly compressed time interval between the base of C29r and the top of C28r (Fig. 5) compared with *Geologic Time Scale 2012* (GTS2012; Ogg, 2012). The latter indicates a duration of 1.731 Ma for this interval, with no uncertainties stated. The most conservative limit provided by our data uses the abovementioned age of 64.868 ± 0.025/0.048 Ma for the top of C28r and our age (66.289 ± 0.051/0.065 Ma) for the Null coal as a maximum limit on the base of C29r, which yields a maximum interval duration of 1.421 ± 0.066 Ma. If we accept the placement of the base of C29r as located by Archibald et al. (1982), this interval decreases to 1.309 ± 0.053 Ma. The biggest difference between our results and GTS2012 is the duration of C29r. Our results indicate a maximum duration of 0.457 ± 0.054 Ma and a possible duration as brief as 0.345 ± 0.038 Ma for this interval, corresponding to the two possible placements of the base of C29r used above. The GTS2012 duration estimate for chron 29r is 710 ka (Ogg, 2012), twice the duration (345 ± 38 ka) calculated here using the Archibald et al. (1982) placement, and 1.6 times longer than our inferred maximum duration. Discrepancies involving C29r are not unexpected because GTS2012 draws heavily on the results of Swisher et al. (1993) for the IrZ coal, which has been shown to be ~200 ka too old relative to other dated coals in the Tullock Member (Renne et al., 2013).

Estimations for the duration of C29r using precession cycle counting on astronomically tuned sections from Ocean Drilling Program Holes 1267B (Husson et al., 2011) and 762C (Thibault et al., 2012) and from Zumaia in Spain (Kuiper et al., 2008) suggest a total duration for C29r between 540 and 677 ka. Results of Westerhold et al. (2008) on sections from Walvis Ridge (ODP Expedition, Leg 208), Shatsky Rise (ODP Expedition, Leg 198), and Zumaia sections suggest a longer duration of 713–725 ka. While these values exceed our minimum estimate for the duration of C29r, they overlap with our maximum estimate. Specifically, the duration of 540 ka calculated using Husson et al.'s (2011) estimate for the Cretaceous portion of C29r, which is better constrained in most marine sections than the Paleogene portion, is within uncertainty of our maximum estimation. We note that none of the orbital tuning results take into account the possible effects of climate signals other than those due to orbital forcing, whereas climate perturbations attending the KPB extinctions might have introduced extra signal that could bias ages based on cycle counting.

The timing and duration of C29r bears special importance to the study of the KPB for several reasons. Accurate and precise calibration of the chron boundaries will facilitate correlation between marine and terrestrial records with improved resolution, because the former have few opportunities for direct, high-resolution dating. Moreover, the duration of C29r is relevant to assessment of the potential contribution of other events to the KPB extinctions, such as the Deccan Traps volcanism (Chenet et al., 2007; Keller, 2008; Chenet et al., 2009; Tobin et al., 2012). According to many workers, more than 80% of Deccan volcanism is constrained to fall within C29r (e.g., Chenet et al., 2007, and references therein). If the majority of the volcanism was confined to C29r, our new estimate suggests a significantly shorter period over which it was most active, implying that the output of climate-modifying magmatic volatiles would have been more concentrated in time than previously believed. Such a short time interval for the majority of Deccan volcanism would favor hypotheses that volcanism may have played a major role in applying stress to ecosystems prior to the Chicxulub impact (Arens et al., 2014), although a foreshortened time scale of Deccan volcanism also implies a shorter time interval for pre-Chicxulub volcanogenic effects on climate. In addition, the temporal proximity of the main surge of volcanism to the impact make it difficult to tease apart the poorly understood biotic effects of the impact from those of the volcanism. That is, an apparently abrupt pattern of extinction in the fossil record may reflect effects of the impact or volcanism or both, depending on the sampling density of the rock record. Accordingly, due to the importance of the age and duration of C29r, we suggest that further work is required to validate the results given here. Improved constraints on the age and tempo of Deccan volcanism are also critically needed to test their possible role in KPB phenomena.

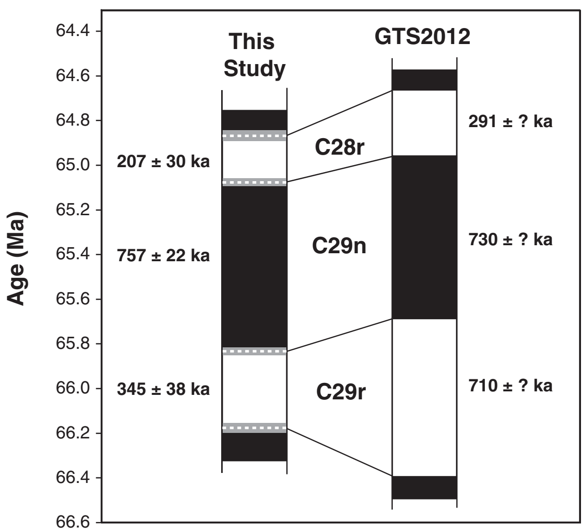


Figure 5. Paleomagnetic-reversal age comparison between this study and the *Geologic Time Scale 2012* (GTS2012; Ogg, 2012). Dashed white lines denote weighted mean age estimates, and gray boxes indicate systematic uncertainty estimates at 1σ. Values next to chron intervals denote chron duration. GTS2012 did not report uncertainties for these chron boundary ages.

Diachronous Hell Creek–Fort Union Contact

The contact between the Hell Creek and Fort Union Formations is defined by the first lignite (Z, IrZ, MCZ) above the stratigraphically highest non-avian dinosaur remains (Calvert, 1912; Brown, 1952; Collier and Knechtel, 1939). This definition is based on the fact that lignite deposits are much more abundant in the Tullock Member of the Fort Union Formation than in the Hell Creek Formation. The Tullock Member also contains more variegated beds than the Hell Creek Formation (Fastovsky, 1987). The paleoenvironmental implications of the lithostratigraphic contact include increased hydraulic flux and a rise in the water table around KPB time (Fastovsky, 1987).

Studies of these formations across the Williston Basin (between sections in Montana and North Dakota) show that the lithostratigraphically defined formational contact is not synchronous everywhere. In North Dakota, previous studies showed that the KPB is not coincident with the Hell Creek–Fort Union contact and occurs as much as 2.6 m above the formational contact (Johnson, 1992). In Montana, early studies found an opposite trend, with the KPB corresponding to the base of the Tullock Member of the Fort Union Formation in locations in north-central Garfield County, whereas in eastern Garfield and western McCone counties the KPB appeared to be located below the formational contact (Lofgren, 1995; Clemens, 2002), as early Puercan (Pu1) faunas and floras are found in the uppermost 2–3 m of the Hell Creek Formation.

In the region of the present study (Fig. 1), the KPB and the formational contact are coincident in the part of the western area studied so far, and both are coincident with the IrZ coal, i.e., with the impact claystone preserved at the base of the coal or immediately below it, where that coal is present. In the eastern area of Figure 1, the formational contact lies above the KPB and is coincident with the base of the MCZ coal (*sensu* Lofgren, 1995, or the formational Z *sensu* Rigby and Rigby, 1990). Unfortunately, the stratigraphic relationship between the IrZ and so-called Z coals in our eastern study area is obscure because no section has yet been found that contains both of these coals as identified by their distinctive tephras. However, at the Lerbekmo (LB) section of Figure 1, the impact layer and the palynologically defined KPB occur at the base of the Z coal, whereas the diagnostically distinct thick tephra deposit identified in outcrops of the Z (MCZ) coal in the eastern area occurs higher in the coal. The thin tephra identified in IrZ coal deposits in the western area is absent from the LB section and has never been reported east of it. In the eastern area of Figure 1, impact signals are absent from the defining basal lignite (Z or MCZ coal) at the Hell Creek–Fort Union formational contact. Furthermore, vertebrate localities in the uppermost Hell Creek Formation in eastern Garfield County and western McCone County yield earliest Puercan (Paleocene, Pu1) local faunas (Clemens, 2002). The evidence that the formational boundary is diachronous is quantitatively substantiated by our pooled $^{40}Ar/^{39}Ar$ age determinations for tephras in the Z and IrZ coals, which indicate an age difference of 30 ± 18 ka.

The diachronous nature of the lithostratigraphically defined Hell Creek–Fort Union formational contact in the study area, and more broadly in the greater Williston Basin, may have important implications for the nature of the KPB environmental transition. There was clearly not a regionally synchronous lithofacies change at the KPB. It is possible to infer an eastward migration of coal-forming environments through our study area on the time scale of 30 ± 18 ka, possibly consistent with the effects of a regression in a coastal plain environment, but this trend is reversed farther east in North Dakota where the KPB lies above the lithostratigraphic formational contact (Johnson, 1992). Further mapping and stratigraphic analysis may clarify the paleoenvironmental significance of the diachronous contact, but for now we conclude that the record of lithofacies transition represented by the contact is not obviously consistent with an instantaneous forcing mechanism. Our data and observations support the conclusions of Fastovsky (1987) and Retallack (1994) that paleoenvironmental change across the KPB in the Hell Creek region of northeastern Montana occurred over tens of thousands of years.

Faunal and Floral Turnover

The new radioisotopic dates presented here provide both greater resolution of the tempo of the evolution of the biota in northeastern Montana and more precise correlation of fossil localities distantly separated from our research area. Fossil assemblages from the middle to upper third of the Hell Creek Formation to the KPB document a pattern of declining evenness in both mammalian and amphibian local faunas. This pattern has been interpreted as a sign of increasing ecological instability of local communities (Wilson, 2005, 2014; Wilson et al., 2014b). The new date for the Null coal and the refined estimate for the base of chron C29r, both presented in this paper, help to constrain the timing of this pre-KPB ecological decline to the last ~200 ka of the Cretaceous, compared to previous estimates indicating the last ~400–700 ka of the Cretaceous. The more rapid rate of change further supports the press-pulse hypothesis (Arens and West, 2008), suggesting that local biotic communities would have been particularly vulnerable to collapse from the poorly understood environmental effects of the KPB impact.

Mammalian and amphibian fossil assemblages from the lowermost Tullock Member in our western study area and the uppermost Hell Creek Formation and lowermost Tullock Member in our eastern study area (Fig. 1) represent earliest Paleogene (Pu1) “disaster” faunas: low taxonomic diversity, low evenness, and an influx of immigrant taxa (Clemens, 2010; Wilson, 2013, 2014; Wilson et al., 2014b). Bracketed by the KPB and the HFZ coal in the western study area, or the KPB and the MCZ coal in the eastern study area, these Pu1 faunas are constrained to the first ~70 ka of the Paleogene, compared to previous estimates of roughly 390 ka (Swisher et al., 1993), providing insight into the immediate aftermath of the Cretaceous-Paleogene impact and the rate of colonization by the immigrant taxa.

A >20 m stratigraphic gap in the fossil record separates the Pu1 faunas found below the HFZ from the superjacent Garbani Channel deposits bracketed by the Y and W coals. The new dates indicate that this gap in our sampling represents ~232 ka. Sites in our research area yielding local faunas clearly of Pu2 age have yet to be discovered and described. These would hold clues to the nature and tempo of the initial transition from “disaster” to “recovery” faunas. Fossil assemblages from the thick Garbani Channel deposits in the middle of the Tullock Member show a recovering mammalian fauna and an early phase of placental mammal radiation: high taxonomic diversity and local first appearance of some higher-level taxa, such as triisodontids, pantodonts, taeniodonts, and plesiadapiforms (Clemens, 2002, 2011, 2013; Wilson, 2014). Bracketed by the Y and W coals, the new dates imply that this mammalian recovery occurred relatively rapidly, less than ~925 ka after the KPB, compared to the 2–3 Ma estimates for marine ecosystems (D’Hondt, 2005).

Fossil assemblages from the Farrand Channel (in the BB section) and the Horsethief Canyon localities (HTC section) occur in the upper third of the Tullock Member and represent the earliest Torrejonian (To1) faunas in North America (Clemens and Wilson, 2009). The Farrand Channel localities are bracketed by the W and V coals, and thus constrain the beginning of the Torrejonian to no later than 1 Ma after the KPB. The Horsethief Canyon localities, ~35 km to the southwest, are bracketed by the coals tentatively identified as correlative with the W and U coals

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in the valleys of Hell Creek and Snow Creek. A V coal has not been identified in this section.

Further application of our new ages to palynological records established by Arens et al. (2014) from this region suggests a shortened interval over which reported angiosperm species richness declined leading up to the KPB. Using our new SAR estimate for the Hell Creek Formation from our Bug Creek locality, we calculated an interval of ~18 ka, with a maximum of between 33 and 48 ka, over which angiosperm species richness declined in the last 3.5 m of the Hell Creek Formation in Russell Basin. This result is significantly shorter than the 78 ka to 110 ka period estimated by Arens et al. (2014), but may be spurious due to aforementioned uncertainty about the anomalously high SAR determined from the Bug Creek section. Using an SAR of 7 cm/ka, typical of the Tullock Member in this area, this interval expands to a maximum of 65–80 ka, still marginally shorter than estimated by Arens et al. (2014). However, angiosperm species richness may have begun to decline earlier, as the data of Arens et al. (2014) only extend to 3.5 m below the KPB.

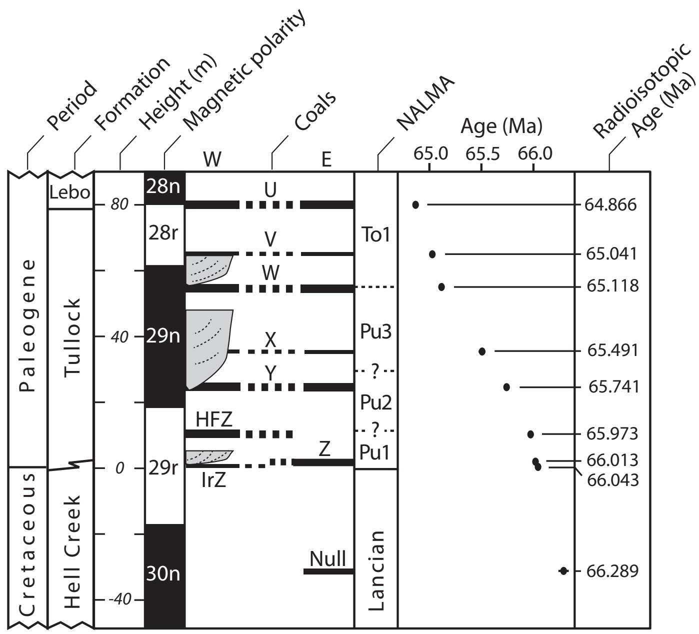

Figure 6. Composite chronostratigraphic summary. Dashed lines indicate uncertain chronostratigraphic relationships between the western (W) and eastern (E) portions of the study area. Major channels (Hell Hollow, Garbani, and Farrand, in ascending order) are shown schematically, and their placement in the diagram is not meant to indicate that they are confined to the western versus eastern areas. Placement of paleomagnetic polarity chrons follows LeCain et al. (2014) except the C28r/C28n boundary, which follows Swisher et al. (1993). Error bars (σ) in the age versus stratigraphic height panel are smaller than the symbols for all units except the Null coal tephra. NALMA—North American Land Mammal Age; Pu1, Pu2, Pu3—Puercan 1, 2, and 3; To1—Torrejonian 1.

CONCLUSIONS

Our dates for 15 samples representing 13 distinct tephras include at least one tephra from each coal bed in the sequence Null, IrZ, Z, MCZ, HFZ, Y, X, W, V and U, identified by previous workers in the Hell Creek and Fort Union (Tullock Member) Formations within the study region. A generalized, composite chronostratigraphic section is shown in Figure 6. Distinctive tuffs in the Z and MCZ coals establish that the main portions of these coals were deposited isochronously over a region of at least 250 km^2, but it is unclear whether the coal is (or was, prior to erosion) continuous over this area. Similarly, our results indicate that W coal outcrops separated by ~60 km are essentially contemporaneous. It remains to be seen, however, whether other coals assigned the same name in different locations, and by different workers, are time-stratigraphically equivalent. In particular, there are significant uncertainties remaining as to how coals with the same letter designation in the eastern and western areas are correlated. Further work, including tephrochemical studies, will address this issue and is in progress.

Our results confirm conclusions from previous studies that the Hell Creek–Fort Union formational boundary is diachronous, not just between sites within the Williston Basin but also within the Hell Creek region. This point is quantitatively substantiated by our pooled age determinations for tephras in the IrZ and Z (MCZ) coals (both representing the lithostratigraphically defined formational contact), which show an age difference of 30 ± 18 ka. Our pooled age for the IrZ of 66.043 ± 0.010/0.043 Ma we consider to be the best age available for the KPB due to the occurrence of this tephra within ~1 cm of the impact claystone. As such, the diachronous nature of the Hell Creek–Fort Union formational contact suggests there was not a synchronous lithofacies change at the KPB, which further supports conclusions that the paleoenvironmental change across the KPB in the Hell Creek region was gradual (Fastovsky, 1987; Retallack, 1994).

An additional finding from our study is the consistent average SARs calculated for sections with more than one dated horizon, varying between 5 and 10 cm/ka above the level of the HFZ, and ~20 cm/ka below the HFZ. The relatively uniform SARs for each stratigraphic interval, regardless of location, support the validity of using linear interpolation between dated tephras to constrain ages for geomagnetic polarity reversals within these sections. As a preliminary test, our study used previously collected polarity sequences from magnetostratigraphic studies conducted in our region, to calculate reversal ages and ultimately durations for polarity chrons C29r–C28r. Our results show a significantly compressed time interval from the base of C29r to the top of C28r, with a maximum estimate of 1.421 ± 0.066 Ma and minimum estimate of 1.309 ± 0.053 Ma, compared to the estimate of 1.731 Ma presented in GTS2012 (Ogg, 2012). The most notable result is the drastically reduced estimate (roughly half of GTS2012) for the duration of C29r at 345 ± 38 ka. If correct, this estimate significantly shortens the time interval over which the main phase of Deccan volcanism was active, as it has been constrained to have occurred mainly within C29r (Chenet et al., 2007). Such a short interval may favor hypotheses that volcanism played a significant role in the mass extinction. Similarly, marine biostratigraphic and chemostratigraphic records whose time scales are based on the ages of C29r boundaries would tend to be foreshortened. Improved constraints on these reversal ages will likely be obtained by additional mag-

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netostratigraphic studies that are in progress. The dominant contributor to uncertainty in our reversal age estimates was the coarse sampling of previous studies. By improving sampling intervals, the stratigraphic placement of chron boundaries, in addition to providing further tests of the consistency of SARs, our ages can ultimately be used as a calibration for the GPTS and can be exported to marine records.

Our new radioisotopic dates applied to paleontological records from the Hell Creek region add precision to the record of terrestrial ecosystem evolution from just before the KPB mass extinction through biotic recovery. Our results show that the timing of ecological decline prior to the mass extinction is estimated to begin 200 ka before the KPB compared to previous estimates of 400–700 ka. This new estimate favors the hypothesis that these local biotic communities would have been vulnerable to collapse due to the additional stresses caused by the KPB impact. Additionally, our work further constrains rates of earliest Paleogene (Pu1) disaster faunas to within the first 70 ka of the Paleogene, with mammalian recovery occurring no less than ~925 ka after the mass extinction. We have further been able to constrain the beginning of the Torrejonian NALMA to no later than 1 Ma after the KPB.

APPENDIX A. METHODS FOR ^{40}Ar/^{39}Ar GEOCHRONOLOGY

Feldspars for dating were separated from 1 to 5 kg samples of tephra that were collected from thin interbeds within lignite deposits. Samples were disaggregated using crushing and/or water suspension techniques, followed by washing and sieving. The feldspars were concentrated using a combination of magnetic and density separations, followed by ultrasonic cleaning in 7% hydrofluoric acid for ~5 min. Some samples required an additional treatment of hydrogen peroxide to remove excess coal prior to density separation. Feldspars were then handpicked from size fractions ranging from 177 to 595 microns. Large, clear grains were picked preferentially.

^{40}Ar/^{39}Ar analyses were conducted at the Berkeley Geochronology Center (BGC; California). Samples were irradiated in the Cadmium-Lined In-Core Irradiation Tube (CLICIT) facility of the Oregon State University TRIGA reactor, in three separate 50 h irradiations. Samples were loaded into 1–3 Al disks as figured by Renne et al. (2013) for each irradiation. Fast neutron fluence represented by the parameter J was determined for each of six positions spanning each disk using analysis of single crystals of the Fish Canyon sanidine standard. The value of J for each unknown sample was determined by interpolation within a planar fit to the J values determined by the standards. The relative precision of these interpolated J values was better than 0.1% in all cases.

For mass spectrometry, we used the methods and facilities described in Renne et al. (2013). In brief, samples were analyzed mainly by total fusion, augmented in some cases by incremental heating, with CO_2 lasers on two different extraction systems coupled to MAP 215 mass spectrometers (MAP1 and Nexus). MAP1 is a 215C and Nexus is a MAP 215-50. Both have Nier-type ion sources and analog electron multiplier detectors. The mass spectrometry applied peak-hopping by magnetic field switching on a single detector in 15 cycles. Blanks were measured between every 1–3 unknowns.

Ages were computed from blank-, discrimination-, and decay-corrected Ar isotope data after correcting data for interfering isotopes based on production ratios determined from fluorite and Fe-doped $KAlSiO_4$ glass as reported by Renne et al. (2013). Ages are based on the calibration of Renne et al. (2011). Ar isotope data are shown in Table DR1 of the GSA Data Repository[1]. Results of single-crystal laser fusion analyses are shown in Figure 3. Age spectra (Fig. 4) were obtained from incremental heating experiments on multigrain aliquots of a few samples in which no xenocrysts were evident from the single-crystal analyses. Age uncertainties are given at one standard deviation and are stated as ± X/Y, where X is the analytical uncertainty and Y includes systematic uncertainties arising from the calibration. In cases where only one uncertainty value is given, as in calculating interval durations, it refers to analytical sources alone.

Plateau ages (i.e., for samples depicted in Fig. 4) are defined here by having more than three contiguous steps releasing more than 50% of the ^{39}Ar, with all steps having mutually indistinguishable ages at the 95% confidence level considering only experimental uncertainties.

APPENDIX B. DETAILS OF ^{40}AR/^{39}AR RESULTS FOR INDIVIDUAL SAMPLES

From samples BC-1PR and BC11-1 in the Null coal at Bug Creek, 174 feldspar crystals (149–177 microns) were analyzed. The two samples were collected at precisely the same locality in successive years, but were prepared and irradiated separately. Both samples yielded a broad spectrum of single-crystal ages ranging from 218.590 ± 0.630 to 65.532 ± 0.483 Ma, with a well-defined younger mode. Despite the preponderance of xenocrysts, the identification of this unit as a tephra is supported by the presence of beta-quartz pseudomorphs, which indicate a volcanic origin. Seventy crystals from BC-1PR were run on MAP 1 and 29 on Nexus (Appendix A). Of these 99 crystals, 21 yielded ages defining the younger mode, with the remainder interpreted as xenocrysts. In an effort to concentrate the younger mode, sample BC11-1 was subjected to a more restricted density separation based on the observation that the xenocrysts tended to have higher K/Ca values. Crystals from BC11-1 were also selected with higher standards of optical clarity than those of BC-1PR. Accordingly, 33 of 75 (44%) grains of sample BC11-1 (all run on MAP 1) yielded ages defining a younger mode. The 54 grains from both samples defining the younger mode yielded a weighted mean age of 66.289 ± 0.051/0.065 Ma.

From sample HH12-1 of the IrZ coal at Hell Hollow, 74 feldspar crystals (210–297 microns) were analyzed individually by total fusion followed by argon isotope analysis with the MAP 1 mass spectrometer. Of the 74 grains, three were identified as plagioclase on the basis of K/Ca ratios. Of the remaining 71 grains, one grain showed a parabolic evolution of ^{40}Ar and was excluded from age analysis. The resulting 70 grains yielded a weighted mean age of 66.061 ± 0.039/0.059 Ma.

[1]GSA Data Repository item 2014325, ^{40}Ar/^{39}Ar analytical data, is available at http://www.geosociety.org/pubs/ft2014.htm or by request to editing@geosociety.org.

From sample NV12-1 in the IrZ coal at the Nirvana site, 56 feldspar crystals (250–297 microns) were analyzed as single crystals: 31 on MAP 1 and 25 on Nexus. All were sanidine based on K/Ca. Excluding one obvious xenocryst at 67.55 ± 0.32 Ma, the remainder yielded a unimodal distribution with a well-defined weighted mean age of 66.035 ± 0.033/0.052 Ma, indistinguishable from the age reported by Renne et al. (2013) for the tephra in the IrZ coal at nearby Hauso Flats or from that (sample HH12-1) at Hell Hollow reported herein.

From sample ZL12-2, from the MCZ coal at the Z-Line quarry, 90 feldspar crystals (177–210 microns) were analyzed individually by total fusion: 61 on MAP 1 and 29 on Nexus. All but one were alkali feldspars based on K/Ca. Excluding one obvious xenocryst at 87.74 ± 2.34 Ma, the remaining samples yielded a unimodal age distribution with a weighted mean age of 65.998 ± 0.044/0.061 Ma.

From sample LG11-1, from the MCZ coal at McGuire Creek, 150 feldspar crystals (177–210 microns) were analyzed by total fusion: 109 on MAP 1 and 41 on Nexus. Seventy-two (72) of these were alkali feldspar based on K/Ca. The alkali feldspars yielded a unimodal and symmetric age distribution with a weighted mean age of 66.015 ± 0.052/0.066 Ma. The remaining 78 feldspar grains also yielded a unimodal age distribution, but with a distinct skew toward younger ages suspected to be due to subtle alteration. Although the weighted mean of plagioclase ages (65.69 ± 0.15 Ma) is indistinguishable at 95% confidence from the sanidine results, we exclude them as being likely biased. This sample is noteworthy in yielding a much larger proportion of plagioclase than any other sample. This may have resulted from unusual preservation, as plagioclase is typically altered in the samples of this study, or it may reflect a relatively poor mineral separation. In addition to the single-crystal analyses, four aliquots comprising 10–15 grains each were analyzed by incremental heating on Nexus. Two of these yielded well-defined plateau ages of 66.016 ± 0.069 and 66.039 ± 0.065 Ma. The two aliquots failing to define plateaux are clearly suspect of containing xenocrysts, particularly apparent in aliquot 36619-101 (Fig. 4C). The weighted mean of the two well-defined plateau ages is 66.028 ± 0.050/0.065 Ma. Data pooled from the two experiments yielding plateaux and the single-crystal sanidine analyses yield a weighted mean age of 66.022 ± 0.038/0.057 Ma.

From sample HX12-1 of the Z coal at a site near the Haxby Road, 94 feldspar crystals (177–210 microns) were analyzed individually by total fusion on MAP 1. All proved to be alkali feldspars based on K/Ca ratios. One distinctly older (68.38 ± 0.33 Ma) grain interpreted as a xenocryst was excluded. The remaining grains yielded a unimodal age distribution with a weighted mean age of 66.002 ± 0.033/0.054 Ma.

From HH12-2 of the HFZ coal at Hell Hollow, 79 feldspar crystals (297–420 microns) were analyzed individually by total fusion followed by argon isotope analysis with the MAP 1 mass spectrometer. Of the 79 crystals, one was identified as plagioclase based on K/Ca ratios with an anomalous value of 39.55 ± 35.84 Ma. An additional outlier was excluded on the basis of low percent radiogenic argon. From the remaining 77 grains, a weighted mean age of 65.962 ± 0.026/0.050 Ma was computed.

From sample GC12-3, from the lower Y coal at Garbani Hill, 106 feldspar crystals (250–297 microns) were analyzed by total fusion: 81 on MAP 1 and 25 on Nexus. All were alkali feldspars based on K/Ca. Excluding two apparent xenocrysts at 66.55 ± 0.20 and 66.61 ± 0.15 Ma, the remaining crystals defined a

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unimodal age distribution with a weighted mean age of 65.741 ± 0.022/0.048 Ma.

From sample GC12-2 of the upper Y coal at Garbani Hill, 243 feldspar crystals (177–210 microns) were analyzed individually by total fusion followed by argon isotope analysis with the MAP 1 mass spectrometer. Of the 243 crystals, 125 crystals proved to be either plagioclase (on the basis of K/Ca ratios) or were distinctly xenocrystic, yielding ages ranging from 67 Ma to 3.0 Ga. The remaining 118 grains yielded a weighted mean age of 65.677 ± 0.041/0.059 Ma.

From sample MC11-3, from the X coal at McGuire Creek, 52 aliquots of 5 grains (177–210 microns) each were analyzed by total fusion on MAP 1. K/Ca ratios were consistent with all grains being alkali feldspar. All analyses defined a unimodal age distribution with a weighted mean age of 65.494 ± 0.038/0.056 Ma. In addition, four aliquots comprising 10–15 grains each were analyzed by incremental heating on Nexus, yielding plateau ages of 65.467 ± 0.075 to 65.510 ± 0.065 Ma (Fig. 4B). The weighted mean plateau age is 65.488 ± 0.039/0.057 Ma. Data pooled from all experiments yield a weighted mean age of 65.491 ± 0.032/0.053 Ma.

From sample SS11-3 of the upper W coal near Garbani Hill, 68 feldspar crystals (595–841 microns) were analyzed individually by total fusion on MAP 1. All proved to be alkali feldspars based on K/Ca ratios, but these ratios are distinctly higher than in most other samples, and they may properly be termed anorthoclase. A unimodal age distribution yielded a weighted mean age of 65.118 ± 0.024/0.048 Ma.

From sample HTC12-1 of the W coal at Horsethief Canyon, 93 feldspar crystals (420–595 microns) were analyzed individually by total fusion of 73 grains on the MAP 1 mass spectrometer and 20 grains on the Nexus mass spectrometer. Of these crystals, all but six grains were identified as alkali feldspars on the basis of K/Ca ratios. Plagioclase ages were all distinguishably younger than alkali feldspar ages, presumably due to subtle alteration, and were excluded from age calculations. In addition to plagioclase, one sanidine crystal was excluded due to incorrigible mass spectrometry data, and one was a clear xenocryst. From the remaining 85 crystals, a weighted mean age of 65.197 ± 0.024/0.048 Ma was calculated.

From sample BB12-1 of the Biscuit Butte V coal tephra, 179 feldspar crystals (297–420 microns) were analyzed individually using total fusion and argon isotope analysis. Of these grains, 159 were analyzed on the MAP 1 mass spectrometer and 20 were analyzed on the Nexus mass spectrometer. All crystals yielding measurable Ar were identified to be alkali feldspars on the basis of K/Ca ratios. Two compositionally distinct populations are present: one with K/Ca = 60 ± 24 (N = 112) and one with K/Ca = 357 ± 127 (N = 63). Both phases appear cognate, as there is no statistically significant age difference between them. Excluding one anomalously young outlier at 64.11 ± 0.26 Ma and three due to incorrigible mass spectrometry data, the remaining 175 grains yielded a weighted mean age of 65.041 ± 0.023/0.048 Ma.

From sample HTC12-3 of the U coal at Horsethief Canyon, 73 feldspar crystals (297–420 microns) were analyzed individually by total fusion followed by argon isotope analysis with the MAP 1 mass spectrometer. All crystals analyzed proved to be alkali feldspar on the basis of K/Ca ratios. Excluding one outlier at 66.91 ± 0.19 Ma, interpreted to be a xenocryst, and one due to incorrigible mass spectrometry data, the remaining 71 grains yielded a unimodal age distribution with a weighted mean age of 64.904 ± 0.026/0.049 Ma.

From sample BB11-1 of the U coal at Biscuit Butte, 119 feldspar crystals (250–297 microns) were analyzed as single crystals, all on MAP 1. All were sanidine based on K/Ca, and all defined a unimodal age distribution with a weighted mean age of 64.865 ± 0.024/0.047 Ma. Four aliquots, each of 10–20 grains, were analyzed by incremental heating on Nexus. Each aliquot yielded a plateau comprising >99% of the ^{39}Ar released, with plateau ages ranging from 64.848 ± 0.051 to 64.890 ± 0.068 Ma (Fig. 4), indistinguishable from the single-crystal fusion results. The weighted mean plateau age is 64.867 ± 0.031/0.052 Ma. A pooled weighted mean of results from both types of experiment yields 64.866 ± 0.023/0.047 Ma.

Pooled Results

In several cases, we have dated the same tephra at multiple locations, as indicated by correlations based on physical continuity, stratigraphic position, mineralogy, and mineral chemistry. These are referred to here by the coals in which they occur. The pooled age is calculated from the weighted (by inverse variance) mean of the individual sample mean ages. Because each sample has a specific *J* value (Appendix A), associated uncertainties are treated as random. Uncertainties associated with decay constants and the $^{40}Ar^*/^{40}K$ of the standard are treated as systematic, as in all other computations. Pooled ages are shown in Table 2.

IrZ Coal

Samples NV12-1 and HH12-1 may be combined with results of Renne et al. (2013; HF-1PR) from Hauso Flats to yield a weighted mean age of 66.043 ± 0.010/0.043 Ma (Appendix A). Given the occurrence of this tephra within ~1 cm of an impact claystone containing an iridium anomaly and shocked quartz (Alvarez, 1983), we consider this to be the most reliable age available for the KPB.

MCZ Coal, Z Coal on Haxby Road, and Z Coal in the Lerbekmo Section

Three of the samples reported here (LG11-1, ZL12-2, HX12-1) are correlative with the lower tephra (sample HC-2PR) at the Hell Creek Marina Road section (same as our Lerbekmo section) shown in Renne et al. (2013, their figure 1). In all four of these occurrences, the dated tephra lies 10–30 cm below a distinctively thick (5–10 cm) biotite-bearing tephra that serves as a unique marker. The weighted mean age for the dated unit is 66.013 ± 0.015/0.044 Ma. We note that correlation of this distinctive tephra over a relatively large area does not necessarily imply that the hosting coals are laterally continuous throughout the intervening area. The pooled age for this tephra is indistinguishable from that (66.024 ± 0.040/0.059 Ma) reported by Moore et al. (2014) for a tephra ~3 m above an impact clay layer identified as the KPB at Flag Butte, ~7 km northeast of our LB locality (Fig. 1).

HFZ Coal

Our sample HH12-2 is a tephra ~12 cm above one correlated with sample HF-3PR of Renne et al. (2013) from Hauso Flats. The correlated tephra is unique in the region in that it is a deep red-brown color and contains remarkably well-preserved pseudomorphs of cuspate glass shards easily visible with a hand lens. Because the 12 cm stratigraphic separation between the two tephras at Hell Hollow represents a time difference that is below age resolution, it is valid to attribute the combined results to the age of the HFZ coal. The weighted mean age for these two samples is 65.973 ± 0.020/0.047 Ma.

APPENDIX C. GAZETTEER

Sample location coordinates based on GPS measurements (WGS84) are listed in the text. The locations of several other places mentioned in the text are given below. Where a specific point location is designated, GPS coordinates are given; where a broader area is intended, the cadastral survey coordinates (section [sec.], Township [T], and Range [R]) are given.

Brownie Butte summit: 47°31′49.78″N, 107°01′01.25″W.

Hauso Flats: sec. 1, T20N, R35E. This area includes the informally named Iridium Hill.

Haxby Road: Montana State Highway 341. Prior to the flooding of the Fort Peck Reservoir, which began in 1937, this road extended from Jordan, Montana, to the settlement at Lismas. A ferry across the Missouri River connected Lismas with Fort Peck (Clemens and Hartman, 2014).

Hell Hollow: secs. 25 and 36, T21N, R35E.

Iridium Hill summit: 47°31′36.69″N, 107°12′38.6″W.

Pearl Lake: Bureau of Land Management reservoir, dam at 47°31′30.94″N, 107°03′42.52″W.

Russell Basin: SE¼ sec. 10 and NE¼ sec. 15, T 22 N, R 43 E. The basin is delimited on maps in Fastovsky and Dott (1986) and Smit et al. (1987).

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