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Geochronology of the middle Eocene Purple Bench locality (Devil's Graveyard Formation), Trans-Pecos Texas, USA

Amy L. Atwater, Kelly D. Thomson, E. Christopher Kirk, Meaghan Emery-Wetherell, Logan Wetherell, and Daniel F. Stockli

ABSTRACT

Purple Bench is a middle Eocene fossil locality in the Devil's Graveyard Formation of the Trans-Pecos region of West Texas. In addition to yielding a range of taxa characteristic of the Uintan North American Land Mammal Age, the Purple Bench locality is noteworthy in documenting a number of endemic species that are known only from the site. Despite the Uintan character of the mammalian fauna, the absolute age of Purple Bench is a matter of debate. This uncertainty stems from the wide interval of time encompassed by current radiometric dates bracketing the Purple Bench locality and from conflicting magnetostratigraphic correlations in the Devil's Graveyard Formation. This study constrains the absolute age of the Purple Bench locality through detrital zircon U-Pb geochronological analyses. For these analyses, 147 new detrital zircon U-Pb ages were collected from five tuffaceous sandstones and reworked tuff horizons and analyzed via Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). These new detrital zircon U-Pb geochronological analyses suggest a maximum depositional age of 43.7 +0.8 / -0.2 Ma for the Purple Bench tuff, a significant marker horizon immediately below the Purple Bench locality. These new maximum depositional age dates presented here provide constraints on the true depositional age of the lower and middle members of the Devil's Graveyard Formation, bringing clarity to the previously ambiguous age of the fossil-bearing Purple Bench locality. The age constraints presented here also aid the characterization of the temporally and spatially variable Uintan North American Land Mammal Age.

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INTRODUCTION

The Devil's Graveyard Formation (DGF) includes ~ 500 m of interbedded volcaniclastic sediments and overbank paleosols with discontinuous isolated channels deposited in the Tornillo Basin of southwest Texas (Figure1; Stevens et al., 1984; Lehman, 1991). Paleontological research in the DGF undertaken in the 1970s by J.A. Wilson, J.B. Stevens, and M.S. Stevens led to the discovery of numerous fossil vertebrate localities spanning the middle to late Eocene (Stevens et al., 1984a; Stevens et al., 1984b; Wilson, 1986). Within the DGF, the Purple Bench locality (TMM 41672) has been the subject of intensive collecting efforts since 2005. This locality has yielded an abundant collection of middle Eocene vertebrate fossils (Table 1). The Purple Bench locality occurs at the transition between the lower and middle members of the DGF as defined by Stevens et al. (1984). The fossil assemblage from the Purple Bench locality is noteworthy for including genera that are typical of the Uintan North American Land Mammal Age (NALMA) (e.g., *Amynodon*, *Epihippus*, *Leptoreodon*, and *Protoreodon*; Gunnell et al., 2009; Robinson et al., 2004) as well as a range of taxa that are currently known only from the site (Table 1). These endemic taxa from Purple Bench include the artiodactyl *Texodon* (West, 1982), the primates *Diablomomys* and *Mescalerolemur* (Williams and Kirk, 2008; Kirk and Williams, 2011), and the amphisbaenian *Solastella* (Stocker and Kirk, 2016).

Geology

The Trans-Pecos region of Texas encompasses the southern-most extent of the Rocky

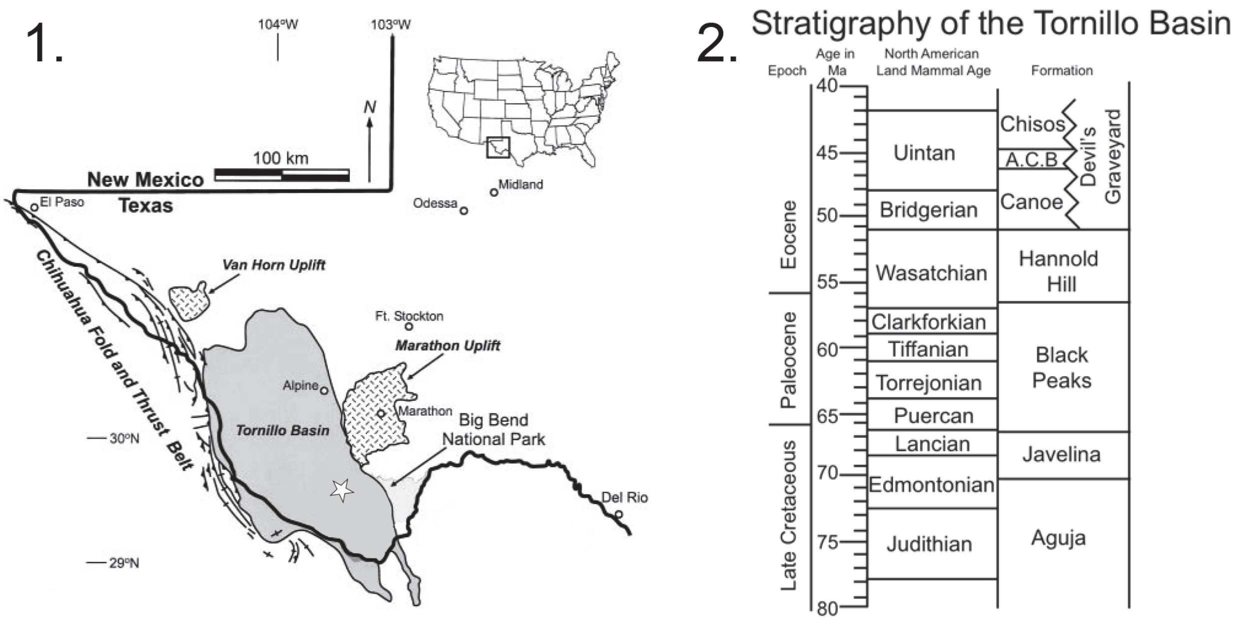

FIGURE 1. 1.1 Map of the Tornillo Basin (modified from Atchley et al., 2004 after Lehman, 1986). Star indicates location of the Devil's Graveyard Formation exposures examined in this study. 1.2. Stratigraphy of the Tornillo Basin and the related North American Land Mammal Ages. A.C.B. = Alamo Creek Basalt (Modified from Lehman, 1991).

TABLE 1. Revised faunal list for the Purple Bench Locality (TMM 41672). Compiled from (West, 1982; Gustafson, 1986; Wilson, 1986b; Walton, 1993; Williams and Kirk, 2008; Kirk and Williams, 2011; Stocker and Kirk, 2016; Kirk, 2018). * = endemic taxon known only from Purple Bench.

HIGHER TAXON	SPECIES	SOURCE
Amphisbaenia	*Solastella cookei**	Stocker and Kirk, 2016
Serpentes	Alethinophidia sp. indet	Stocker and Kirk, 2016
Anguimorpha	Glyptosaurinae sp. indet.	Stocker and Kirk, 2016
Eutheria, incertae sedis	*Simidectes magnus*	Wilson, 1986
Artiodactyla	*Leptoreodon edwardsi*	Wilson, 1986
Artiodactyla	*Leptoreodon major*	Wilson, 1986
Artiodactyla	? *Malaquiferus* sp.	Wilson, 1986
Artiodactyla	*Protoreodon petersoni*	Wilson, 1986
Artiodactyla	*Protoreodon pumilus*	Wilson, 1986
Artiodactyla	?*Protylopus* sp.	Wilson, 1986
Artiodactyla	*Texodon meridianus**	West, 1982
Carnivora	? *Uintacyon scotti*	Gustafson, 1986
Condylarthra	*Hyopsodus uintensis*	West, 1982
Perissodactyla	*Epihippus uintensis*	Wilson, 1986
Perissodactyla	? *Triplopus* sp.	Wilson, 1986
Primates	*Diablomomys dalquesti**	Williams and Kirk, 2008
Primates	*Mescalerolemur horneri**	Kirk and Williams, 2011
Primates	Omomyinae, gen. nov.*	Kirk, 2018
Rodentia	*Leptotomus* sp.	Wilson, 1986
Rodentia	*Microparamys* sp.	Wilson, 1986
Rodentia	*Mysops* sp.	Wilson, 1986
Rodentia	*Paramys* cf. *P. delicatior*	Wilson, 1986
Rodentia	*Pauromys* sp. indet.	Walton, 1993
Rodentia	*Prolapsus* sp.	Wilson, 1986
Rodentia	*Thisbemys* sp.	Wilson, 1986

Mountains in the United States and preserves southern Laramide foreland basin environments from the Eocene (Figure 1; Stevens et al., 1984a; Wilson, 1986a; Runkel, 1990; Lehman et al., 2018). Exposures of the DGF occur entirely within the Tornillo Basin and therefore the southern-most intermontane Laramide basin in the United States (Lehman, 1991). Crustal shortening of the Chihuahua fold-thrust belt and flexural subsidence of the Tornillo Basin occurred from the late Cretaceous to the early Eocene (Lehman, 1991). Middle Eocene deposits of the DGF unconformably overlie Cretaceous deposits (Wilson, 1986b; Runkel, 1990). The source of volcaniclastic sediments of the DGF and time-correlated Canoe and Chisos formations in the Big Bend region potentially originated in two volcanic centers, one from the Sierra Madre Oriental in Mexico, and one from the Christmas Mountains volcanic center (Stevens et al., 1984a; Swanson and McDowell, 1984; Henry and Price, 1989; Runkel, 1990; Nieto-Samaniego et al., 1999; Lawton et al., 2009; Lehman et al., 2018). The preservation of a long continuous stratigraphic record in the Trans-Pecos area makes this region important for understanding the changes in mammalian faunas from the Uintan through the Chadronian NALMAs (Prothero, 1996; Robinson et al., 2004; Williams and Kirk, 2008; Gunnell et al., 2009).

Existing Relative and Absolute Age Constraints

Fossils from the Purple Bench locality were included in the Serendipity local fauna described by Wilson (1986). Comparisons to other North American faunas of this time period place the Serendipity local fauna in the late Uintan (Ui3) NALMA, as revealed by the presence of the perissodactyl *Epihippus uintensis* and the artiodactyls *Protoreodon petersoni* and *P. pumilus* (Table. 1; Robinson et al., 2004; Wilson and Stevens, 1986b;

Murphey et al., 2018). According to Robinson et al. (2004), the Uintan NALMA spans a time interval between approximately 46.3 – 41.3 Ma. Published radiometric dates bracketing the Purple Bench locality were derived from K/Ar analysis of biotite-rich tuffs dated to 43.9 ± 0.9 Ma (2s standard error) from the lower portion of the lower member, and to 42.7 ± 1.6 Ma (2s standard error) from the upper portion of the middle member of the DGF (Stevens et al., 1984b; Walton, 1992). The imprecision of these dates places the fossil assemblage from the Purple Bench locality within a 3.6 Ma time interval (i.e., 41.1 – 44.7 Ma). Additionally, the Purple Bench locality occurs stratigraphically above a series of localities in the lower member of the DGF (Figure 2) that have yielded a mammalian fauna distinctive of the early Uintan (Ui1b) NALMA (Campisano et al., 2014; Stocker and Kirk, 2016). Recent biotite and sanidine $^{40}Ar/^{39}Ar$ radiometric dating of volcanic tuffs constrain the Ui1b Whistler Squat Quarry of the DGF to be between 45.04 ± 0.05 and 44.88 ± 0.04 Ma (2s standard error; biotite and sanidine respectively; Campisano et al., 2014). Mammalian taxa characteristic of the Duchesnean NALMA occur stratigraphically higher than the Purple Bench locality in the DGF (Wilson and Stevens, 1986; Robinson et al., 2004). The beginning of the Duchesnean NALMA can be no later than 39.75 ± 0.04 Ma (2s standard error), based on biotite $^{40}Ar/^{39}Ar$ dates from the type section of the Duchesnean in eastern Utah (Prothero and Berggren, 2014; Murphey et al., 2018). These factors constrain the absolute age of fossils from the Purple Bench locality to be between 41 – 45 Ma.

Two different research groups have previously attempted to further clarify the absolute ages of fossil localities in the DGF through magnetostratigraphic measurements and correlations, but these analyses produced conflicting interpretations. Walton (1992) correlated the middle member of the DGF to the C20R-C20N Chron transition, suggested an absolute age of 43.43 Ma for the Purple Bench locality (recalibrated to GST2012; Gradstein et al., 2012). Prothero (1996) indicated that the Purple Bench locality is actually within the C18r Chron and is therefore younger (~41 Ma; recalibrated to GST2012; Gradstein et al., 2012) than that estimated by Walton (~43.43 Ma; Walton, 1992).

These differing interpretations of DGF magnetostratigraphic section, combined with the broad time interval encompassed by bracketing radiometric dates, have led to uncertainty regarding the absolute date of the faunal samples from the Purple Bench locality. While absolute dating of tuff horizons would be ideal, detrital zircon U-Pb dating is a powerful method that may be used to constrain the maximum depositional age of stratigraphic horizons in areas like the DGF that are characterized by active volcanism (Dickinson and Gehrels, 2009; Johnstone et al., 2019; Coutts et al., 2019). Although post-eruption reworking of sediment and interbedded tuffs leads to mixed zircon age components in sediments collected from a single stratigraphic horizon, the youngest age mode recovered by detrital zircon U-Pb dating should represent the syn-depositional volcanic age mode and hence can be used to constrain an upper bound estimate of the true depositional age of the sediment (Dickinson and Gehrels, 2009). The aim of this study is to constrain the true depositional age of the Purple Bench locality via detrital zircon U-Pb dating of samples that stratigraphically bracket the fossil-bearing horizon.

Abbreviations

Argon-Argon ($^{40}Ar/^{39}Ar$); Devil's Graveyard Formation (DGF); Kilograms (kg); Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS); Maximum Depositional Age (MDA); North American Land Mammal Age (NALMA); Potassium-Argon (K/Ar); True Depositional Age (TDA); Two sigma (2s); University of Texas at Austin (UT); Uranium-lead (U-Pb).

MATERIALS AND METHODS

Five tuffaceous sandstone horizons were sampled from exposures of the DGF at Midwestern State University's Dalquest Desert Research Station in Brewster County, Texas. The five samples (2-3 kg) were collected from fine- to medium-grained tuffaceous sandstones that are stratigraphically adjacent to fine-grained fossil horizons associated with the following localities (Figure 2): Rhino's Loaf (TMM 45914), Krister Step (TMM 44174), Purple Bench (TMM 41672), and Peaches (TMM 46513). Two separate sublocalities (TMM 41672, sublocalities 8 and 19) were sampled for Purple Bench locality because this site encompasses multiple discontinuous exposures along the south fork of the Alamo de Cesario Arroyo for a distance of about 1.3 km. These distinct fossiliferous exposures are designated as separate sublocalities of TMM 41672, but occur at approximately the same stratigraphic horizon. The sample used for detrital zircon U-Pb dating at Purple Bench sublocality 8 was collected from the Purple Bench tuff marker horizon itself, which occurs stratigraphically

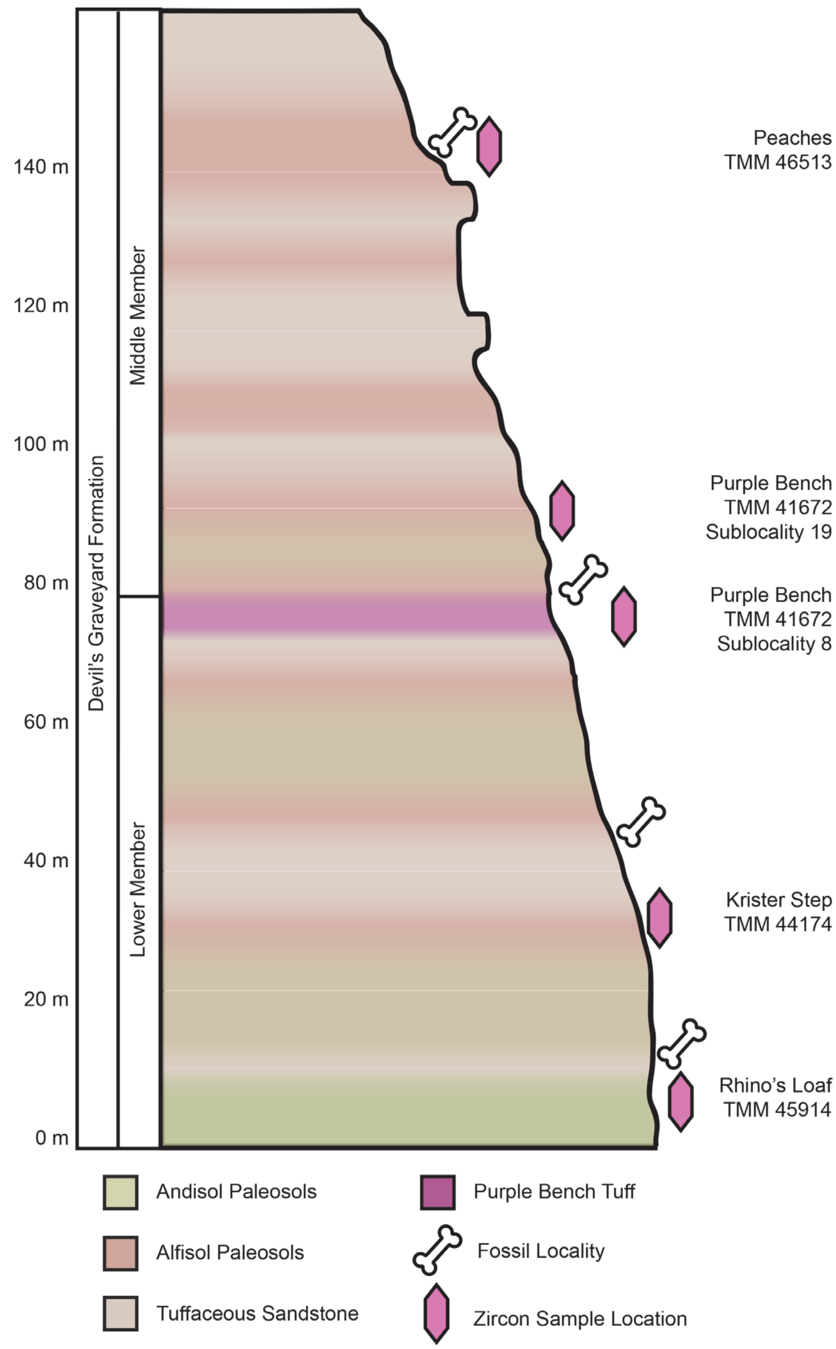

FIGURE 2. Generalized stratigraphic column of the lower and middle members of the Devil's Graveyard Formation. Symbols denote detrital zircon sample locations and known fossil localities. X-axis represents erosional profile. Colors represent visual expression of outcrop correlating to paleosol type (Emery-Wetherell et al., 2016). Note that the detrital zircon U-Pb sample identifications listed at the far right do not stratigraphically coincide with the associated fossil localities, which are identified by the bone symbols.

below the fossiliferous horizon. In contrast, the Purple Bench sublocality 19 sample was collected from a tuffaceous sandstone that is located stratigraphically above both the fossiliferous horizon and the Purple Bench tuff. The Rhino's Loaf locality is stratigraphically lower in the DGF section than the other fossil localities sampled for this analysis, but the precise stratigraphic relationships are obscured by local faulting. The Krister Step locality lies within the lower member of the DGF and is stratigraphically below the Purple Bench tuff (Stevens et al., 1984; Wilson, 1986). The Purple Bench locality is located 0.3-0.9 m stratigraphically above the Purple Bench tuff and is one of three key fossil localities occurring near the base of the middle member of the DGF (Stevens et al., 1984). The Peaches locality lies stratigraphically above the Purple Bench locality within the middle member of the DGF, immediately above the "upper red to white repeat" described by Stevens and others (1984).

Zircon fractions were isolated following standard mineral separation techniques (crushing, grinding, water table separation, heavy liquid separation, and magnetic separation). Zircon separates were grain mounted on double-sided adhesive and analyzed using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) depth-profiling U-Pb analysis at the UTChron Geo-Thermochronology Laboratory. Sixty individual zircon crystals were targeted from each sample for U-Pb analyses in order to obtain a robust statistical coverage of detrital age components present within each sample and to accurately capture the youngest syn-depositional volcanic age component (Vermeesch, 2004; Andersen, 2005; Coutts et al., 2019). The sixty grains analyzed per sample ensures a 95% confidence of capturing all U-Pb age components that comprise at least 8.5% of the population distribution (Vermeesch, 2004). LA-ICP-MS U-Pb data were processed using the Iolite-based VizualAge data reduction scheme with GJ1 zircon as a primary standard for depth-dependent element fractionation correction (Jackson et al., 2004; Paton et al., 2011; Petrus and Kamber, 2012). Detailed methodology and instrument settings for LA-ICP-MS analyses can be found in Thomson and others (2017). Results were excluded from single grain analysis with greater than 15% discordance between $^{235}U/^{207}Pb$ age and $^{238}U/^{206}Pb$ age and greater than 10% $^{238}U/^{206}Pb$ analytical uncertainty at 2s level. Weighted mean ages for the youngest coherent age population were calculated for each sample using the tuff age extractor (TuffZirc) Excel plugin from the ISOPLOT package (Ludwig and Mundil, 2002; Ludwig, 2003). The TuffZirc algorithm was designed for the extraction of a reliable age from primarily deposited tuffs and reworked tuffaceous units. The algorithm automatically excludes ages with high analytical uncertainty, ranks ages in order, and identifies the largest cluster of five or more grains that yield a probability of fit > 0.05. The calculated TuffZirc age is a median age of the identified largest cluster, the asymmetric error bars represent a 95% confidence interval of the calculated median age (Ludwig and Mundil, 2002). TuffZirc requires the assumptions that >40% of the ages in the sample are cogenetic and that the majority of ages have not suffered from significant post crystallization lead loss (Ludwig, 2003).

RESULTS

Detrital zircon U-Pb results are displayed in Figure 3 and summarized in Table 2. Full detrital zircon U-Pb results are available in the Supplementary data table, including the highly discordant ages that were excluded from weighted mean calculations labeled "DISC" in the "Best Age (Ma)" column. Individual detrital zircon ^{238}U-^{206}Pb ages with < 10% analytical uncertainty (2s) and <15% discordance between ^{238}U-^{206}Pb and ^{235}U-^{207}Pb age were used to calculate weighted means for each sample using the TuffZirc plugin for Excel (Ludwig and Mundil, 2002; Ludwig, 2003). A weighted mean of 45.4 +0.6 / -1.1 Ma was calculated from a coherent group of 19 zircons from the 50 analyzed zircons from the Rhino's Loaf locality. The Krister Step locality yielded the fewest zircons during separation (n= 20), providing a weighted mean age of 45.5 +0.2 / -1.4 Ma from a coherent group of six zircon ages (96.9% confidence). Fifty-four detrital zircons were analyzed from Purple Bench tuff at sublocality 8. Individual zircon ^{238}U-^{206}Pb ages range from 41.1 ± 0.7 Ma to 49.4 ± 1.8 Ma. The TuffZirc weighted mean calculated was found to be 43.7 +0.8 / -0.2 Ma (95% confidence interval calculated from coherent group of 17). By comparison, a weighted mean of 44.2 +0.3 / -0.7 Ma (95.1% confidence) was calculated for Purple Bench sublocality 19 from a coherent group of 17 zircons out of the 57 total zircons dated. The Peaches locality yielded a weighted mean age of 42.8 +1.0 / -0.4 Ma (95.9% confidence) calculated from a coherent group of 20 zircon ages out of the total 57 zircons dated.

Eighty percent of the 145 dated grains with < 15% discordance yield ages ranging from 40 - 47 Ma. Three samples contain individual detrital zircon U-Pb ages older than 47 Ma in addition to the dominant young syn-depositional zircon U-Pb age component. The Rhino's Loaf sample contains: two grains with ages > 47 Ma, one yielding an age of 50.5 ± 1.3 Ma and the other age of 388.7 ± 5.0 Ma. The Purple Bench sublocality 19 sample contains: 12 grains with ages > 47 Ma, two grains with ages from 70-72 Ma, five grains with ages from 81-101 Ma, two grains with ages from 230-260 Ma, two grains with ages from 360-380 Ma, and one grain with an age of 1362.7 ± 8.3 Ma. The Peaches sam-

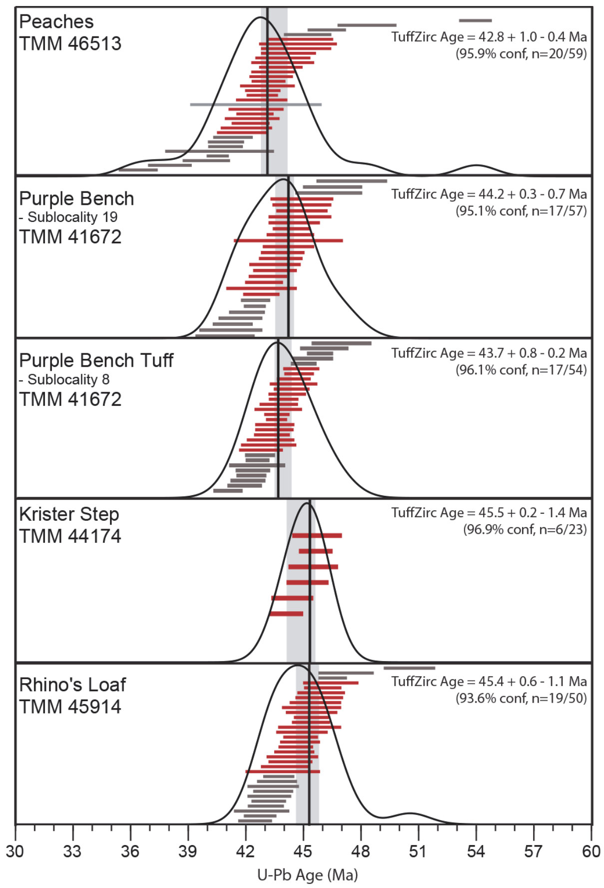

FIGURE 3. Zircon U-Pb results from tuffaceous sandstones of the Devil's Graveyard Fm. analyzed via LA-ICP-MS. Results were filtered to exclude single grain ages with >15% discordance between $^{235}U/^{207}Pb$ age and $^{238}U/^{206}Pb$ age, or >10% propagated analytical error in $^{238}U/^{206}Pb$ age. Weighted means were calculated for each sample using Tuff extractor plugin from the ISOPLOT package (Ludwig and Mundil, 2002; Ludwig, 2003). Number of grains used in TuffZirc algorithm displayed as n= # of ages used by TuffZirc / # of ages total for sample. Data are displayed as kernel density estimators (KDEs) with a bandwidth of 1 Myr (Vermeesch, 2018). Individual zircon ages and 2s standard errors are displayed as vertically stacked boxes. Individual ages in red were used in the calculation of the weighted mean. Weighted means and errors are displayed as a grey box with a bar representing the mean.

ple contains: eight grains with ages > 47 Ma, two grains with ages from 54-65 Ma, one grain with an age of 76.0 ± 2.1 Ma, two grains with ages from 97-105 Ma, two grains with ages from 395-450 Ma, and one grain with an age of 597.0 ± 11 Ma.

DISCUSSION

The maximum depositional ages (MDAs) presented herein represent an upper bound estimate of the true depositional ages (TDAs) of these sedimentary horizons and thus the fossils contained within (Dickinson and Gehrels, 2009; Coutts et al., 2019). Following the principle of inclusions (Lyell, 1832), any zircon contained within a sandstone or tuffaceous sandstone must be older than the sandstone or tuffaceous sandstone itself. The time difference between the zircon derived MDA estimate and the TDA incorporates the time required for the zircon to crystalize, erupt from its volcanic center, erode and be transported into the basin before it is deposited. This time lag can be assumed to be negligible (or within analytical uncertainty) in depositional environments located in close proximity to volcanic centers that were active at the time of deposition (Dickinson and Gehrels, 2009).

Given the close proximity of syn-depositionally active volcanic centers, the MDAs presented here are interpreted as the TDAs of the sedimentary strata (Dickinson and Gehrels, 2009; Coutts et al., 2019). A negligible time lag between zircon crystallization and deposition of these sandstones and tuffaceous sandstones is assumed (Dickinson and Gehrels, 2009; Coutts et al., 2019). These zircon grains were most likely derived from volcanic centers in the vicinity of the Tornillo Basin, as evidenced by the high proportion of euhedral zircons composing the youngest coherent age mode and regional geologic studies (Stevens et al., 1984; Runkel, 1990). Further evidence supporting a negligible time lag between zircon crystallization and deposition include the dominance of young ages within the samples, the overlap of the young ages with existing depositional age constrains for the basin, the clustering of young ages indicating a single point source, and the gradual decrease in individual ages and MDAs up-section. While young “syn-depositional” zircon ages dominate all of the samples, several units also yielded subordinate age components older than the syn-depositional ages. These older ages indicate either inheritance within the magma chamber or the reworking of previously deposited tuffs and sandstones during sediment transport and deposition.

The MDA of Purple Bench tuff (TMM 41672) was found to be 43.7 +0.8 / -0.2 Ma at sublocality 8. The MDA of the tuffaceous sandstone collected stratigraphically higher than the Purple Bench tuff at sublocality 19 (TMM 41672) is 44.2 +0.3 / -0.7 Ma (Figure 2). Error ranges for the two samples overlap, suggesting that both the Purple Bench tuff

TABLE 2. Detrital zircon geochronometric results from TuffZirc algorithm (Isoplot; Ludwig, 2003). Full tabulated results of individual zircon U-Pb ages are provided in supplementary data files.

Sample Locality	Total number zircons dated	Number of ages used in weighted mean	TuffZirc weighted mean age (Ma)	Error (Ma)	
				+	-
Peaches TMM 46513	59	20	42.8	1.0	0.4
Purple Bench TMM 41672 Sublocality 19	57	17	44.2	0.3	0.7
Purple Bench tuff TMM 41672 Sublocality 8	54	17	43.7	0.8	0.2
Krister Step TMM 44174	23	6	45.5	0.2	1.4
Rhino's Loaf TMM 45914	50	19	45.4	0.6	1.1

and the fossils from the Purple Bench locality to have a TDA range of 43.5 – 44.5 Ma. These dates represent the first MDA estimates for the Purple Bench locality and Purple Bench tuff based on detrital zircon U-Pb, and significantly improve upon the chronostratigraphic precision from prior K/Ar radiometric analyses (41.1 – 44.7 Ma; Stevens et al., 1984; Walton, 1992). An estimated absolute age for the Purple Bench locality between 43.5 – 44.5 Ma (Figure 4) is consistent with Walton's (1992) interpretations that the fossil assemblage correlated to the C20R-C20N Chron transition (43.43 Ma, recalibrated to GST2012; Gradstein et al., 2012).

The spread in ages between the lower (Rhino's Loaf, 45.4 +0.6 / -1.1 Ma; Krister Step, 45.5 +0.2 / -1.4 Ma) and upper units (Peaches, 42.8 +1.0 / -0.4 Ma) sampled indicates the intervening sediments accumulated over a period of between 0.2 – 3.1 Myr. The absolute ages calculated here for Rhino's Loaf (44.3 – 46.0 Ma) and Krister Step (44.1 – 45.7 Ma) are in good agreement with the sanidine $^{40}Ar/^{39}Ar$ age estimate (44.88 ± 0.04 Ma) reported for the Whistler Squat Quarry fossil locality (TMM 41372; Campisano et al., 2014). Like Rhino's Loaf and Krister Step, the Whistler Squat Quarry occurs in the lower member of the DGF (Wilson, 1986), but the relative stratigraphic positions of the three localities are currently unclear. Nevertheless, the detrital zircon dates for Rhino's Loaf and Krister Step indicate that both localities may be broadly contemporaneous with the Whistler Squat Quarry and other early Uintan (Ui1b) localities comprising the Whistler Squat local fauna (Campisano et al., 2014). Furthermore, the range of absolute dates for the DGF reported here (lower date limit for Rhino's Loaf: 46.0 Ma, upper date limit for Peaches: 42.4 Ma) are consistent with the Uintan character of the fauna collected at fossil localities in the lower and middle members of the DGF (Wilson et al., 1986; Williams and Kirk, 2008; Gunnell et al., 2009; Campisano et al., 2014) and with the absolute dates of 46.3 – 41.3 Ma reported by Robinson (2004) for the entire Uintan NALMA.

The magnetostratigraphic studies of the DGF have historically been complicated by multiple interpretations for Chron assignments in the middle member of the DGF (Walton, 1992; Prothero 1996; Murphey et al. 2018). This study brings clarity to the debate of the absolute age of the Purple Bench locality, which has positive implications for defining the Uintan NALMA on a broader, continental level. The absolute ages provided here for the lower and middle members of the DGF allow for better characterization of the late Uintan (Ui3) NALMA and the potential for better correlation between late Uintan localities in Utah, California, Texas, Montana, and Saskatchewan (Robinson et al. 2004). Indeed, with an absolute age range of 43.5 – 44.5 Ma calculated here for the Purple Bench locality (Ui3) and 44.88 ± 0.04 Ma calculated by Campisano et al. (2014) for the Whistler Squat Quarry (Ui1b), the Ui1/Ui2 transition (marked by the first appearance of a range of taxa, including artiodactyls *Achaenodon, Bunomeryx, Diplobunops, Leptotragulus,* and *Mesomeryx*; Gunnell et al., 2009) is increasingly constrained to a relatively narrow time interval. The best estimate for the TDA for the Purple Bench locality based on the calculated MDA ages presented herein, and the Ui3 fauna collected at the Purple Bench locality is 43.5 – 44.5 Ma. If so, then classic Ui2 assemblages known from other regions

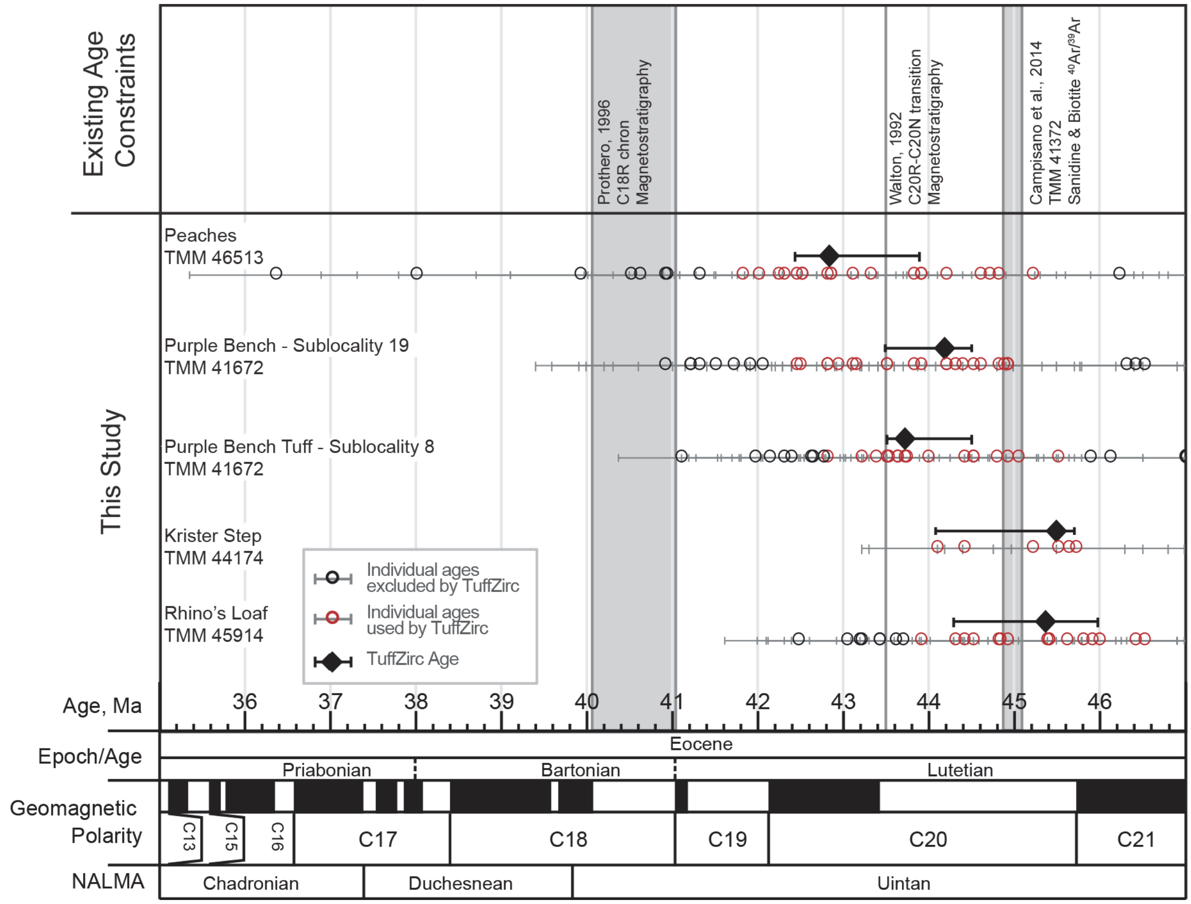

FIGURE 4. Comparison of new and published age estimates for the Devil's Graveyard Fm. and the Purple Bench tuff. Walton (1992) placed the Purple Bench tuff at the C20R-C20N chron transition (43.43 Ma; recalibrated to GST2012; Gradstein et al., 2012), while Prothero (1996) placed the Purple Bench tuff within the C18R chron (41.15- 40.14 Ma; recalibrated to GST2012; Gradstein et al., 2012).

of North America (e.g., the White River Pocket sample from the Uinta Basin of Utah; Gunnell et al., 2009) probably date to between 43.5 and 44.9 Ma.

CONCLUSIONS

Here we report the first absolute dates for the lower and middle members of the DGF based on detrital zircon U-Pb geochronology. The maximum depositional age calculated for the Purple Bench locality (43.5 – 44.5 Ma) constrains the absolute age of the late Uintan NALMA (Ui3) within the Tornillo Basin. The stratigraphically lower Krister Step and Rhino's Loaf fossil localities in the lower member of the DGF have an absolute age range of 44.1 – 45.7 Ma and 44.3 – 46.0 Ma, respectively. The stratigraphically higher Peaches locality in the middle member of the DGF has an absolute age range of 42.4 – 43.9 Ma. These new U-Pb data are consistent with prior radiometric dates for the DGF and the Uintan character of the fauna recovered from these fossil localities. These new dates provide further evidence supporting magnetostratigraphic age models placing the lower and middle members of the DGF at the C20R and C20N Chron transition. These chronostratigraphic constraints aid the characterization of the temporally and spatially variable Uintan land mammal age.

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SUPPLEMENTARY DATA

Full zircon U-Pb geochronometric results of all grains analyzed from the Devil's Graveyard Formation. Individual zircon 238U-206Pb ages with > 10% analytical uncertainty (2s) or >15% discordance between 238U-206Pb and 235U-207Pb age were excluded from TuffZirc weighted mean calculations. All analyses were conducted at the UTchron laboratory at the University of Texas at Austin.

A zipped spreadsheet file available at https://palaeo-electronica.org/content/2020/2898-devil-s-graveyard-u-pb-dating