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A reassessment of the age of the fauna from Cumberland Bone Cave, Maryland, (middle Pleistocene) using coupled U-series and electron spin resonance dating (ESR)

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Abstract

The deposits in Cumberland Bone Cave (Allegany County, Maryland) preserved one of the most taxonomically diverse pre-radiocarbon Pleistocene faunas in the northeastern United States. The site has long been recognized as an important record of Pleistocene life in the region, but numerical age control for the fauna was never developed, and hypotheses for its age have been based upon biochronological assessments of the mammalian fauna. We used fossil teeth and preserved sediment housed in museum collections to obtain the first numerical age assessment of the fauna from Cumberland Bone Cave. Coupled U-series Electron Spin Resonance (US-ESR) was used to date fossil molars of the extinct peccary, *Platygonus* sp. The age estimates of two teeth gave ages of 722 ± 64 and 790 ± 53 ka. Our results are supported by previously unpublished paleomagnetic data generated by the late John Guilday, and by plotting length-width of the first molar (m1) of *Ondatr*a (muskrats) from Cumberland Bone Cave on the chronocline of *Ondatr*a molar evolution in North America. Our age assessments are surprisingly close to the age estimate previously proposed by Charles Repenning, who based his age on a somewhat complicated model of speciation and morphotype evolution among arvicoline rodents.

Keywords: Cumberland Bone Cave; Pleistocene; Irvingtonian; Dating; ESR; U-series; Biochronology; Arvicolines

INTRODUCTION

Cumberland Bone Cave, Allegany County, Maryland, is important for Pleistocene vertebrate paleontology because it preserved a diverse and relatively well-documented biota. The cave and its fauna were originally described by Gidley (1913) and more thoroughly by Gidley and Gazin (1933, 1938). The site was subsequently studied in varying detail by Nicholas (1953, 1955) and Van der Meulen (1978). Although the site still exists, most of it remains under railroad tracks and is inaccessible. Specimens from the cave are curated at the Carnegie Museum of Natural History in Pittsburgh, Pennsylvania, and at the National Museum of Natural History, Smithsonian Institution in Washington, D.C. A collaborative effort to completely re-evaluate the entire fossil biota is currently under way (Eshelman, R., personal communication, 2019) and will make Cumberland Bone Cave the most thoroughly studied biota for the early to middle Pleistocene of the eastern United States.

Biochronological history of eastern North America

The Blancan land mammal age was proposed in the 1940s as a convenient and widely applicable system to organize the faunas of the Pliocene in a broad chronological sequence, and the Irvingtonian and Rancholabrean were established in 1951 to accommodate later Pleistocene biotas (Wood et al., 1941; Savage, 1951; Lundelius et al., 1987; Repenning, 1987; Repenning et al., 1990; Bell et al., 2004a). The classic Blancan and Irvingtonian faunal sequences of the Great Plains that were developed by Claude Hibbard and his students (e.g., Hibbard, 1944, 1949, 1959; Hibbard and Zakrzewski, 1967) were successfully correlated with various

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faunas in the western United States, including those from the Snake River Plain in Idaho (Hibbard, 1969; Zakrzewski, 1969; Repenning et al., 1995; McDonald et al., 1996), southern Arizona (Johnson et al., 1975; Lindsay et al., 1975; Tomida, 1987), and the extensive sedimentary sequence in the Anza Borrego Desert of southern California (e.g., Downs and White, 1968; Zakrzewski, 1972; Downs and Miller, 1994; Cassiliano, 1999).

To the east, many important Irvingtonian faunas from Florida preserve a rich record of vertebrate remains that provide an important perspective on faunal dynamics in the southeastern United States during the early Pleistocene (Morgan and Hulbert, 1995). Several important Irvingtonian faunas also were discovered in cave deposits in Maryland, West Virginia, and Pennsylvania. Those include Cumberland Bone Cave (MD) (Gidley, 1913; Gidley and Gazin, 1933, 1938), Port Kennedy Cave (a fissure-fill deposit in PA) (Cope, 1871; Wheatley, 1871; Daeschler et al., 1993, 2005), Hanover Quarry No. 1 (PA) (Guilday et al., 1984), Hamilton Cave (WV) (Repenning and Grady, 1988; Winkler and Grady, 1990), and Trout Cave (WV) (Pfaff, 1990, 1991). Those sites provide the only perspective we have of Irvingtonian faunas in the northeastern United States, but they have remained a persistent geochronologic challenge (Bell et al., 2004a).

The volcanic ashes that were so crucial for establishing chronological relationships in western and central North American faunas are not present in the east, nor is it likely they would be incorporated as primary deposits in caves. Instead, paleontologists relied upon biochronologic correlations, primarily based upon arvicoline rodents, to place the northeastern cave sites in a rough temporal context that can be compared with the faunal sequence from the rest of North America.

These eastern cave sites were placed in a biochronological context by Repenning (1992). According to Repenning (1992), the fauna from Cumberland Bone Cave had to be somewhat older than that from Hansen Bluff, Colorado, which was estimated to be 820 ka based upon dated tephra, paleomagnetic stratigraphy, and climatic correlations (Rogers et al., 1985, 1992; Repenning, 1992). His justification was based on his conception of *Lasiopodomys deceitensis* as a direct lineal ancestor of *Microtus paroperarius*, and his interpretation of the relative abundances in the fauna from Cumberland Bone Cave of the morphotypes of the voles potentially attributable to those two taxa (Repenning, 1992). His interpretation of the relative abundance of those morphotypes in the faunas from Hanover Quarry No. 1, Hamilton Cave, Cumberland Bone Cave, and Hansen Bluff allowed Repenning to hypothesize an age of 830 ka for the biota from Cumberland Bone Cave (Repenning, 1992). His reasoning was that the fauna from Hansen Bluff, with a numerical age of approximately 820 ka, has no morphotypes referable to *L. deceitensis* but does include morphotypes assignable to *M. paroperarius* (Repenning, 1992). The faunas from the other sites contain both morphotypes in varying relative abundance, so Hansen Bluff had to be the youngest fauna (the morphotype of *L. deceitensis* was extinct by the time of deposition of the Hansen Bluff fauna). The fauna from Hanover Quarry was interpreted to have advanced morphotypes of *L. deceitensis* but no morphotypes of *Microtus* and was, therefore, the oldest fauna of the group. Morphotypes of *Microtus* had not yet evolved; it was interpreted to be approximately 835 ka (Repenning, 1992).

Hamilton Cave preserved a sample that was interpreted to be undergoing an evolutionary transformation, with 75% of the specimens being morphotypes referable to *L. deceitensis* and 25% being morphotypes of a primitive (i.e., early) stage of evolution of *M. paroperarius*. Hamilton Cave was assigned an age of 840 ka (Repenning, 1992). Similarly, the relative abundance of different morphotypes in the fauna from Cumberland Bone Cave was interpreted to place that fauna temporally between Hanover Quarry No. 1 and Hansen Bluff, and the fauna from Cumberland Bone Cave was assigned an age of approximately 830 ka, because of the higher percentage of advanced morphotypes of *Microtus* (Repenning, 1992). The terms "primitive" and "advanced" are used here as they were defined by Repenning (1992).

Other lines of evidence (paleomagnetics and *Ondatra* evolution) point to an older age of Cumberland Bone Cave and provide the foundation for us to test our hypothesis that Cumberland Bone Cave is early to middle Pleistocene in age. We used a combined uranium-series (U-series) and Electron Spin Resonance (ESR) dating methodology to derive the first numerical age assessment for any of these northeastern cave faunas. The age assessment is derived from sediments and fossils from Cumberland Bone Cave. We use the new data, in combination with previously unpublished paleomagnetic data and the well-documented chronocline of the evolution of *Ondatra,* to test previously proposed hypotheses for the age of the Cumberland Bone Cave biota. This gives us four independent lines of evidence—(1) Repenning's stage-of-evolution argument, (2) US-ESR, (3) paleomagnetics, and (4) the chronocline of *Ondatra*—to argue for the age of the deposition of the fossils from Cumberland Bone Cave.

METHODS

Platygonus sp. tooth selection

Five teeth belonging to the Pleistocene peccary, *Platygonus* sp. were selected for dating, because they were relatively large in size, abundant at the site, and were designated as acceptable for limited-destructive procedures by museum staff and researchers. The teeth (USNM PAL 712593–712597) are housed at the National Museum of Natural History, Smithsonian Institution, in Washington D.C. U-series analyses were completed on all five teeth, but enamel for ESR analyses was removed from only two teeth (USNM PAL 712594 and USNM PAL 712595) to satisfy the museum's request for minimal destruction.

Methodology for combined U-series and ESR dating of remains from Cumberland Bone Cave

In the past few decades, advances in U-series analyses combined with ESR (US-ESR) dating protocols allowed for new approaches for direct dating of fossil tooth remains (e.g., Grün, 1989, 1997, 2009; Grün et al., 1988, 2008a, 2008b, 2014; Joannes-Boyau et al., 2010; Joannes-Boyau and Grün, 2011; Joannes-Boyau, 2013). Teeth, and in particular enamel, are composed of highly crystalline material (hydroxyapatite) which when exposed to ionizing radiation resulting from the radioactive decay of naturally occurring radiogenic isotopes (predominately U, Th, and K) and cosmogenic rays, generates specific radicals in the crystal lattice that can be measured with an ESR spectrometer. The number of radicals generated over time is proportional to the dose rate from the environmental surroundings of the sample, to which it has been exposed over its depositional history. By combining the U and Th uptake history within the dental tissues and the ESR measurements, the calculation can be refined to obtain a more accurate age estimation for the amount of time since deposition of a fossil.

Sample preparation

Teeth were first sectioned in half to expose all dental tissues in the sample. All teeth were then scanned with a laser-ablation ESI NWR213 instrument coupled to an Agilent 7700 Inductively Coupled Plasma Mass Spectrometer (ICPMS) quadrupole to evaluate the distribution and concentration of ^{238}U. Each sample was then analyzed by a Multicollector ICPMS (MC-ICPMS) to obtain U-Th isotopic data. A small fragment of enamel was removed from two teeth (using a hand-held diamond saw) in order to be measured by ESR. Any attached dentine (and dirt) was removed from the fragment. The outer surface on each side (lingual and buccal) was stripped of the first ~100 µm with a diamond polishing rotary tool. U-series analyses were performed on enamel and dentine from the remaining tooth in the immediate vicinity of the fragment as well as on the fragment directly to assess variations in U-series isotopic ratios and to calculate an optimum U-uptake model.

Dating protocols

ESR dating

ESR dating was performed on a Freiberg MS5000 ESR X-band spectrometer at a 1 G modulation amplitude, 2 mW power, 100 G sweep, and 100KHz modulation frequency. ESR analyses were performed at Southern Cross University with a Freiberg X-ray irradiation chamber (X-rays as radiation source), which contains a Varian VF50 X-ray gun at a voltage of 40KV and 0.5 mA current. The dose rate was calibrated using one single gamma dose and the output value of the X-ray gun.

Each tooth fragment was mounted onto a Teflon® sample holder, in which the fragment was exposed directly to the X-ray source with minimal shielding by a 200 µm aluminum foil shield for soft X-ray. To estimate the ESR equivalent dose (D_e), each fragment was irradiated eight times, following exponentially increasing irradiation times (i.e., 120, 360, 900, 1800, 3600, 7200, 14,400, and 28,800 s, with an average dose rate of 0.18 Gy/s, which represents an approximate dose step of ~22.6, 67.1, 167, 333.7, 660, 1339.2, 2621.4 and 5135.5 Gy, respectively). During each irradiation step, the output of the X-ray gun was recorded, which allows for the accurate calculation of the dose rate received by the sample at each irradiation step. An additional fragment from the same sample received a single gamma dose and was used to confirm the X-ray irradiation dose response curves (DRCs) and received the same irradiation steps as the associated fragment. DRCs were calculated using the MCDoseE 2.0 (Joannes-Boyau et al., 2018) with a single saturated exponential (SSE) as proposed by Duval and Grün (2016).

It is difficult to assess precise X-ray irradiation doses for DRCs, because of sample symmetry and complex backscattering effects (Grün et al., 2012). This can sometimes give wrong dose equivalency results and therefore each tooth needs to be evaluated against gamma irradiation (Grün et al., 2012). A second fragment of each sample was measured before and after receiving a known gamma dose of 80 ± 2 Gy, and then irradiated with the same X-ray protocol. A simple subtraction of the measured natural signal was performed on the merged spectra at each irradiation step making the gamma irradiated signal the new natural signal for the DRC. For every irradiation step the fragment was measured over 180° on the X, Y, and Z configurations (see Joannes-Boyau and Grün, 2011). Isotropic and baseline corrections were applied uniformly across the measured spectra. The amount of unstable non-orientated radicals (NOCORs) was estimated to be around 23 ± 3% using angular measurements as outlined by Joannes-Boyau (2013) and used to correct for the DRC. The environmental gamma-ray dose rate was estimated using the U, Th, and K concentration obtained from sediment geochemical analyses of the backdirt of the Gidley excavation of 1913. Sediment samples were provided by the Carnegie Museum of Natural History. The cosmogenic dose rate was estimated to be negligible according to the burial context of the cave (i.e., depth of deposition, latitude, geography).

U-series analysis

Each tooth was measured for U and Th concentrations by laser ablation, using an ESI NW193 ArF Excimer laser coupled to a MC-ICPMS Neptune Plus. Sections of enamel and dentine were mapped using small rasters to document compositional variability in the teeth and constrain diffusion processes (see Fig. 1). U-series measurements were taken across the dentine and enamel surface for all teeth. Each individual measurement consists of an average value obtained across a raster or ablation track measuring 150 µm x 310 µm in size (this was done twice on each sample);

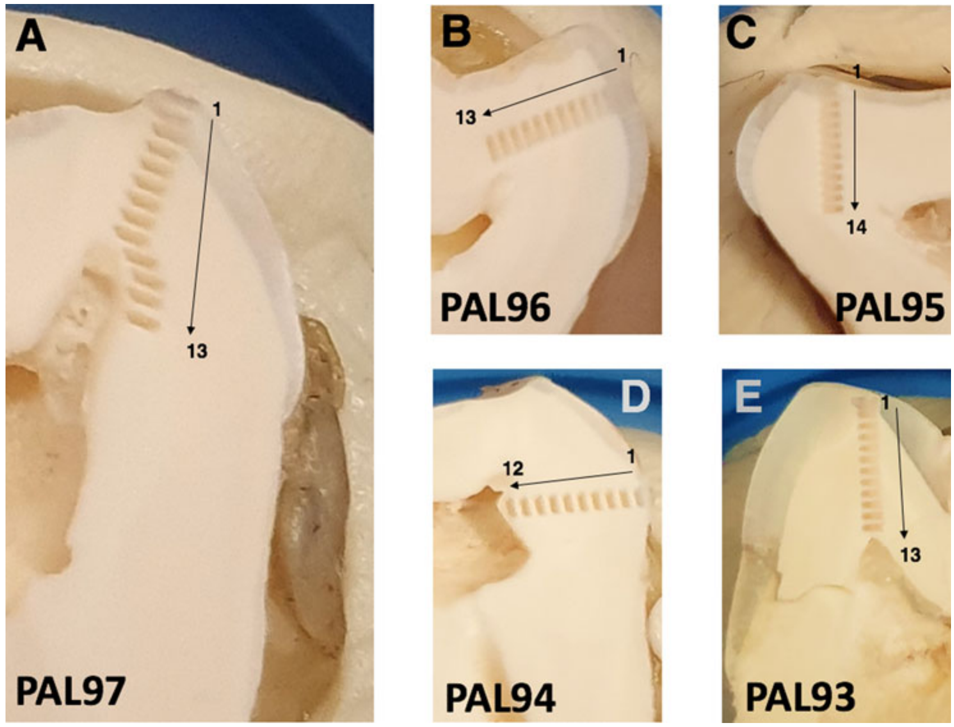

Figure 1. (color online) Location of laser-ablation rasters for each tooth analyzed using a LA-MC-ICPMS. For (A) 13 rasters USNM PAL 712597, (B) 13 rasters USNM PAL 712596, (C) 14 rasters USNM PAL 712595, (D) 12 rasters USNM PAL 712594 and (E) 13 rasters USNM PAL 712593 of fossil teeth of *Platygonus* sp. In the figure, specimen numbers were abbreviated to PAL and the last two numbers of the specimen listed above. All raster sequences were analyzed from enamel to dentine following approximately the growth direction of the tooth and usual diffusion pathway (pulp to enamel-dentin-junction) and reported in Table 1.

i.e., a succession of short measurements was taken along a raster and then averaged into one value. Measurements were performed at an ablation rate of 20 Hz and a scan speed of 5 µm/s. The rasters were positioned in a series of transects following the growth axis of the dental tissue. The ESR internal dosimetry was calculated by averaging the values of the rasters. Additional measurements were taken across each tooth in areas away from the ESR fragment to assess U variability and diffusion gradients. Baseline and drift were corrected using a NIST 612 glass standard, while two coral standards (the MIS7 Faviid and MIS5 Porites corals from the Southern Cook Islands, South Pacific) (Woodroffe et al., 1991) were used to calculate U^{234}/U^{238} and U^{230}/U^{238} ratios and assess the accuracy of measurements. Each coral standard value was obtained by solution MC-ICPMS and used for reference. To account for potential matrix effects, a bovid tooth fragment from South Africa, with known isotope concentrations (U-series at equilibrium) was used to verify measurements. To account for tailing effects, measurements were carried out at half-masses of 229.5 and 230.5 for Th^{230} and 233.5 and 234.5 for U^{234}. The isotopic data were converted into ages using the Isoplot 3.75 Microsoft® Excel Add-In (Ludwig, 2012). The combined US-ESR ages were calculated using the Monte Carlo approach described by Shao et al. (2014), with the values updated from those given by Guérin et al. (2011). Water content of enamel, dentine, and sediment was estimated at 3 ± 1, 8 ± 2, and 17 ± 10%, respectively.

Paleomagnetics

In the 1970s, John Guilday of the Carnegie Museum of Pittsburgh collected oriented samples of a speleothem from Cumberland Bone Cave and measured their natural remnant magnetization (NRM) on a Superconducting Technology (SCT) cryogenic magnetometer in the paleomagnetic laboratory of Victor Schmidt at the University of Pittsburgh. The limited data and the original correspondence pertaining to these analyses are archived in the John Guilday Archive (Box 13 on Cumberland Bone Cave) at the Carnegie Museum.

Ondatra teeth

We compared the morphology of the occlusal surface of the m1s (CM 20274, CM 84588, and USNM 12044) (CM = Carnegie Museum of Natural History; USNM = United States National Museum of Natural History) to type specimens of different recognized species of *Ondatra* from the literature (Brown, 1908; Martin, 1996). We then plotted the teeth on the well-known chronocline of *Ondatra* evolution established by Nelson and Semken (1970) in order to interpret an age of the fossils.

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Table 1. U-series age data for the transects made across the teeth. Note: PAL 94 = USNM PAL 712594, etc. Measurements with U/Th ratio <500 or uranium concentration <1 ppm were excluded from age calculations.

Sample	U/TH	U (ppm)	$^{234}U/^{238}U$	1s-error	$^{230}Th/^{238}U$	1s-error	Age (ka)	1s-error
PAL94_1	2.3	0.3	1.5530	0.0480	1.6400	0.1100	-	-
PAL94_2	7.4	0.1	1.7000	0.0610	1.7700	0.1600	-	-
PAL94_3	27809.1	3.1	2.0306	0.0054	2.1440	0.0170	273.1	7.5
PAL94_4	349200.0	3.5	2.0281	0.0050	2.1371	0.0076	271.5	4.0
PAL94_5	137166.7	3.3	2.0195	0.0057	2.1370	0.0093	275.7	4.9
PAL94_6	360750.0	4.3	2.0351	0.0057	2.0840	0.0190	248.5	6.9
PAL94_7	109810.8	4.1	2.0259	0.0040	2.1030	0.0140	259.1	5.5
PAL94_8	87822.2	4.0	2.0211	0.0056	2.1090	0.0160	263.6	6.7
PAL94_9	434111.1	3.9	2.0123	0.0048	2.1030	0.0140	265.3	6.0
PAL94_10	67821.4	3.8	2.0088	0.0044	2.1211	0.0091	274.4	4.5
PAL94_11	33278.7	4.1	2.0029	0.0059	2.0870	0.0110	263.3	5.1
PAL94_12	3213.7	3.8	1.9976	0.0070	2.1080	0.0110	274.5	5.9
Average age for USNM PAL 712594							**266.2**	**5.7**
PAL95_1	1.0	0.0	1.5910	0.0550	1.8220	0.0660	-	-
PAL95_2	116.0	0.1	1.8110	0.0700	2.0100	0.1800	-	-
PAL95_3	4581.8	0.2	1.8020	0.0190	1.9230	0.0270	-	-
PAL95_4	36191.9	3.6	2.0005	0.0057	2.1100	0.0120	273.8	5.9
PAL95_5	1223333.3	3.7	1.9922	0.0059	2.0990	0.0190	273.4	8.6
PAL95_6	260200.0	3.9	1.9905	0.0062	2.1060	0.0190	277.3	8.9
PAL95_7	635166.7	3.8	1.9840	0.0067	2.0940	0.0140	275.4	7.0
PAL95_8	510857.1	3.6	1.9762	0.0059	2.0970	0.0120	280.9	6.3
PAL95_9	183500.0	3.7	1.9785	0.0052	2.1105	0.0080	285.8	4.8
PAL95_10	68290.9	3.8	1.9818	0.0065	2.1120	0.0140	284.7	7.5
PAL95_11	240312.5	3.8	1.9848	0.0050	2.1180	0.0120	285.8	6.3
PAL95_12	42114.9	3.7	1.9819	0.0050	2.1150	0.0110	286.0	5.9
PAL95_13	565857.1	4.0	1.9838	0.0051	2.1240	0.0130	289.2	6.9
PAL95_14	9130.4	4.2	1.9895	0.0055	2.0590	0.0200	258.5	8.0
Average age for USNM PAL 712597							**279.2**	**6.9**
PAL97_1	132.7	0.2	1.6350	0.0220	1.7410	0.0390	-	-
PAL97_2	3531.9	0.2	1.8150	0.0260	1.8730	0.0480	-	-
PAL97_3	967500.0	3.9	2.0022	0.0051	2.1380	0.0190	285.3	9.2
PAL97_4	224705.9	3.8	2.0004	0.0066	2.0540	0.0340	252.0	12.6
PAL97_5	152592.6	4.1	2.0102	0.0042	2.1307	0.0094	277.7	4.6
PAL97_6	47882.4	4.1	2.0016	0.0059	2.1125	0.0094	274.3	5.0
PAL97_7	6350.0	3.8	1.9995	0.0069	2.1000	0.0150	270.1	7.1
PAL97_8	79313.7	4.0	1.9972	0.0046	2.1190	0.0140	279.4	6.7
PAL97_9	152692.3	4.0	1.9950	0.0045	2.0740	0.0270	261.8	10.7
PAL97_10	101111.1	4.6	1.9961	0.0041	1.9900	0.0390	232.0	12.3
PAL97_11	1123250.0	4.5	2.0006	0.0051	2.0200	0.0190	240.1	6.6
PAL97_12	6921.9	4.4	2.0129	0.0037	2.0540	0.0140	246.9	5.1
PAL97_13	4848.4	4.4	2.0165	0.0051	2.0730	0.0095	252.1	4.0
Average age for USNM PAL 712595							**261.1**	**7.6**
PAL96_1	3.8	0.1	2.0210	0.0410	2.2240	0.0880	317.5	58.4
PAL96_2	2793.7	0.4	2.0720	0.0220	2.1240	0.0400	247.7	15.8
PAL96_3	63087.7	3.6	2.1181	0.0060	2.0790	0.0210	219.1	5.8
PAL96_4	41385.5	3.4	2.1046	0.0051	2.1050	0.0150	230.4	4.6
PAL96_5	404888.9	3.6	2.1108	0.0069	2.1150	0.0150	231.3	4.9
PAL96_6	172238.1	3.6	2.0982	0.0051	2.1160	0.0120	235.7	4.0
PAL96_7	70826.1	3.3	2.0889	0.0055	2.1260	0.0100	242.1	3.8
PAL96_8	45214.3	3.2	2.0742	0.0071	2.1120	0.0150	242.9	5.5
PAL96_9	37666.7	3.4	2.0710	0.0066	2.1220	0.0140	247.4	5.3
PAL96_10	136000.0	3.4	2.0630	0.0062	2.0960	0.0200	241.9	6.8
PAL96_11	37232.6	3.2	2.0519	0.0066	2.1320	0.0120	258.6	5.2
PAL96_12	43514.3	3.0	2.0422	0.0070	2.1280	0.0170	261.4	7.1
PAL96_13	167647.1	2.9	2.0389	0.0058	2.1320	0.0110	264.4	5.0

(*Continued*)

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Table 1. Continued.

Sample	U/TH	U (ppm)	$^{234}U/^{238}U$	1s-error	$^{230}Th/^{238}U$	1s-error	Age (ka)	1s-error
Average age for USNM PAL 712596							**243.2**	**5.3**
PAL93_1	36.8	0.1	1.8610	0.0280	2.0210	0.0530	-	-
PAL93_2	2629.6	0.1	1.9420	0.0270	2.0370	0.0390	-	-
PAL93_3	177761.9	3.7	2.0495	0.0054	2.1270	0.0140	257.8	5.6
PAL93_4	198947.4	3.8	2.0528	0.0063	2.1270	0.0150	256.4	6.0
PAL93_5	186333.3	3.9	2.0569	0.0061	2.1380	0.0270	258.7	10.2
PAL93_6	180150.0	3.6	2.0648	0.0041	2.1400	0.0140	256.1	5.3
PAL93_7	35781.8	3.9	2.0684	0.0062	2.1350	0.0150	252.9	5.8
PAL93_8	228894.7	4.3	2.0584	0.0057	2.1020	0.0110	245.5	4.3
PAL93_9	222300.0	4.4	2.0590	0.0040	2.1133	0.0087	249.1	3.4
PAL93_10	199523.8	4.2	2.0683	0.0053	2.1186	0.0086	247.3	3.5
PAL93_11	119677.4	3.7	2.0719	0.0047	2.1010	0.0120	240.2	4.2
PAL93_12	195600.0	3.9	2.0655	0.0059	2.1230	0.0110	249.9	4.4
PAL93_13	178181.8	3.9	2.0689	0.0065	2.1120	0.0140	244.9	5.2
Average age for USNM PAL 712593							**250.8**	**5.3**

RESULTS

Numerical age determination

U-series

We obtained direct, minimum U-series ages of five *Platygonus* sp. teeth that show consistent diffusion of uranium in the dental tissues (Table 1, Fig. 1). These five U-series results show consistent ratio and concentration across the different dental tissues with a minimum age of ∼250 ka for the fossils.

ESR results

The DRC for both samples was calculated using MCDoseE 2.0, giving an equivalent dose for USNM PAL 95 and USNM PAL 94 of 504 ± 18 and 477 ± 22 Gy (1-σ error), respectively. The dose recovered was 86 ± 6 Gy for USNM PAL 95 and 92 ± 8 Gy for USNM PAL 94.

Coupled US-ESR dating

US-ESR age estimates were calculated on two teeth (USNM PAL 712594 and USNM PAL 712595) yielding ages of 722 ± 64 ka and 790 ± 53 ka (1-σ) respectively (Table 2). Both ages are statistically indistinguishable from one another and we advocate for a potential age for the deposition of Cumberland Bone Cave at 756 $^{+87}/_{-98}$ ka.

Paleomagnetics

Previously unpublished paleomagnetic data from the Guilday archives at the Carnegie Museum are presented in Figure 2. Moments were 10^{-6} to 10^{-7} emu/cc. The samples were not demagnetized, but the natural remanent magnetizations (NRMs) of the set displayed a range of directions consistent with varying degrees of a recent, normal overprint on a reversed primary magnetization. If this interpretation is correct, then the speleothem was formed prior to the Brunhes-Matuyama reversal (780 ka) (Bassinot et al., 1994).

Ondatra chronocline

The lower m1s used in this study have five to six closed alternating triangles, two roots, and an enamel closure pattern that is consistent with *O. annectens.* The dimensions of the three m1s from Cumberland Bone Cave are provided in Table 3. *O. annectens* and *O. idahoensis* overlap in time and morphology, but the dimensions (length/width) of the three m1s from Cumberland Bone Cave (Table 3) place them within the size range of *O. annectens*. However, if only size was taken into account, Cumberland Bone Cave specimens 2 (CM 94588) and 3 (USNM 12044) on Figure 3 would fall in *O. idahoensis*. *O. idahoensis*, however has only five closed alternating triangles on the m1, and the two specimens 2 and 3 have six, which is a characteristic of *O. annectens.* We therefore elected to call them *O. annectens*. All three teeth measured smaller (length/width) than Cudahy specimens, indicating an age older than 670 ka, the age of the Lava Creek-B ash associated with the Cudahy fauna. Results are presented in Table 3 and Figure 3.

DISCUSSION

We are fortunate that the history of collections at Cumberland Bone Cave spans many decades and encompasses the changing attitudes and practices of vertebrate paleontologists. We were able to obtain a numerical age assessment for the Cumberland Bone Cave biota because the collections at the Carnegie Museum and the Natural History Museum at the Smithsonian Institution included a large sample of bones from large-bodied mammals that could be used for this study, and cave matrix collected during one of the earlier excavations was retained and preserved by museum staff. The temptation to discard such materials is always present

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Table 2. Combined U-series–ESR results and parameters for the two fossil teeth from Cumberland Bone Cave.

SAMPLE	USNM PAL 712595		USNM PAL 712594
ENAMEL			
Dose (Gy)[a]	504 ± 18		477 ± 22
U (ppm)[b]	0.15 ± 0.12		0.25 ± 0.08
U^{234}/U^{238}[b]	1.8020 ± 0.0100		1.6265 ± 0.0169
Th^{230}/U^{234}[b]	1.0671 ± 0.0166		1.0412 ± 0.0117
Thickness (m)	1289 ± 193		1411 ± 212
Water (%)	3 ± 1		3 ± 1
DENTINE			
U (ppm)[b]	3.8 ± 0.1		3.85 ± 0.55
U^{234}/U^{238}[b]	1.9843 ± 0.0132		2.0168 ± 0.0106
Th^{230}/U^{234}[b]	1.0671 ± 0.0101		1.0451 ± 0.0178
Water (%)	8 ± 2		8 ± 2
SEDIMENT			
U (ppm)[c]		1.44 ± 0.21	
Th (ppm)[c]		1.78 ± 0.33	
K (%)[c]		0.81 ± 0.1	
Water (%)		17 ± 10	
EXTERNAL DOSE RATE SEDIMENT			
Beta dose (mGy a^{-1})	65 ± 10		59 ± 9
γ Dose + Cosmic (mGy a^{-1})[d]		374 ± 47	
COMBINED US-ESR AGE			
Internal dose rate (mGy a^{-1})[c]	126 ± 31		166 ± 57
Beta dose dentine (mGy a^{-1})[c]	73 ± 18		62 ± 21
P enamel[e]	−0.82 ± 0.01		−0.75 ± 0.06
P dentine[e]	−0.79 ± 0.02		−0.70 ± 0.08
Total dose rate (mGy a^{-1})[c]	638 ± 40		661 ± 63
AGE (ka)[c]	**790 ± 40**		**722 ± 64**

[a]Dose equivalent D_e obtained using McDoseE 2.0 (Joannes-Boyau et al., 2018).
[b]Uranium concentration values were obtained by LA-MC-ICPMS (dentine values are averaged over the entire tooth).
[c]Values were obtained on the sediment by LA-ICPMS analyses.
[d]Value was extrapolated from the sediment concentration obtained by LA-ICPMS analyses.
[e]Parameters and ages were calculated using Shao et al., 2014 and updated values from Guerin et al., 2011.

in museums that must, of necessity, place a premium on space. Many paleontologists are trained to understand that saved matrix and non-diagnostic materials may be useful for future applications under technologies that have not yet been developed. This is an excellent example of the old adage proving its worth!

Our age model allows us to test the claim made by Charles Repenning (1992) that the chronological age of Cumberland Bone Cave is approximately 830 ka. Repenning's estimate of the age of the fauna from Cumberland Bone Cave was based entirely upon biochronology, and his conceptual model of how evolution happened and how it would be reflected in the fossil record (see Bell and Jass, 2011). Repenning viewed evolution as being gradational and anagenetic within lineages. A key component of his biochronological age estimates was an assessment of the morphotype(s) and stage of evolution of a sample of fossil specimens. He conceptualized such samples as the fossilized remains of organisms from an interbreeding population. This was especially important for evaluation of faunas that lacked age control, but that could, via stage of evolution, be correlated to sites for which there were one or more direct age controls.

This all seems somewhat convoluted, but it is interesting that Repenning's methodology—including his conceptualization of how speciation took place, the pattern it would yield in the fossil record, and his explicit embrace of paraphyletic taxonomy—yielded an age estimate that is roughly consistent with our independent age model for the fauna from Cumberland Bone Cave. Although the centroid ages of the two samples subjected to ESR analysis are younger than Repenning's estimate by 40,000 to 110,000 years, respectively, the error bar for one sample yields a maximum age of 843 ka, and for the second a maximum age of 786 ka. Therefore, our data, to a large extent, confirm Repenning's hypothesis of the age of the fauna, although we would argue that this assemblage is likely several tens of thousands of years younger.

The remnant reversal in the paleomagnetic sample indicates that fossil deposition was likely before the Brunhes-Matuyama reversal, because that is the most recent time of a reversal in the Earth's magnetic field (Ogg, 2012). Sometimes evolution itself can give us indicators for the age of a fossil. *Ondatra* have long been recognized for their biochronological utility, and many would argue that they are one of

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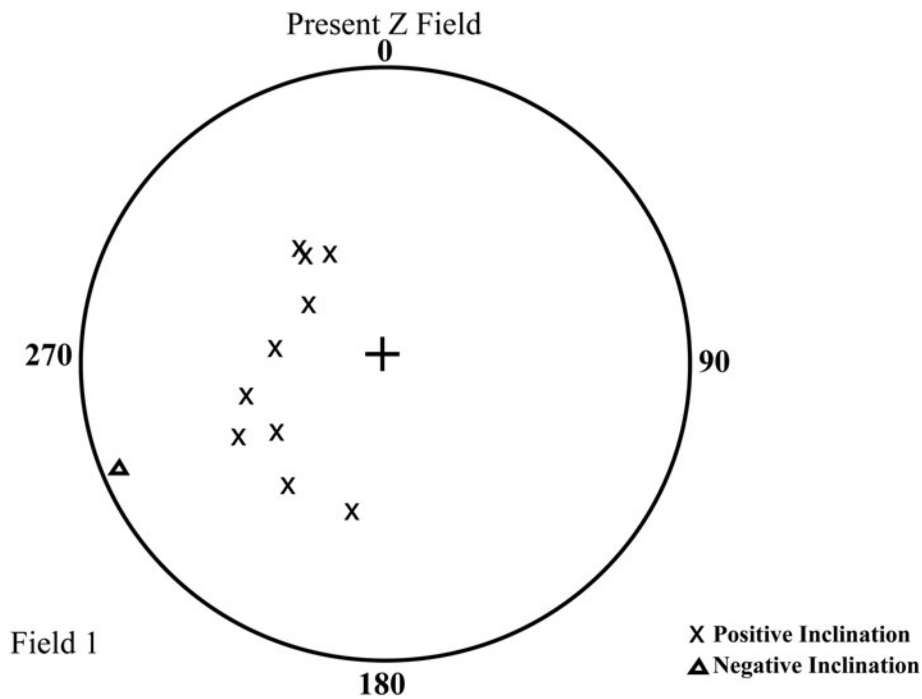

Figure 2. Cumberland Bone Cave paleomagnetics. Results presented to John Guilday by Victor Schmidt, University of Pittsburgh (Guilday Archives, Box 13, Carnegie Museum of Natural History).

the best mammalian examples of anagenetic evolution via phyletic gradualism. This is because the measurements of length-versus-width of the m1 documents a linear increase in the size of the tooth from the Pliocene to the modern, across North America (Nelson and Semken, 1970). When the data for the specimens from Cumberland Bone Cave are plotted on the chronocline of Nelson and Semken (1970) and updated with specimens from Cathedral Cave, NV (Jass and Bell, 2011; Fig. 4), the data show that the specimens from Cumberland Bone Cave are smaller than those from the Cudahy fauna of Kansas, which is radioisotopically dated by the Lava Creek B Ash with an upper boundary of 670 ka (Izett et al., 1992; Izett and Honey, 1995; Bell et al., 2004b). If the fauna from Cumberland Bone Cave was younger than the fauna from Cudahy then we would expect the m1s of *Ondatra* to be larger than those from the Cudahy fauna. The paleomagnetic and *Ondatra* chronocline evidence point to an age for Cumberland Bone Cave that is older than 670 ka.

Table 3. Measurements of *Ondatra* (muskrat) lower first molars recovered from Cumberland Bone Cave, MD. CM = Carnegie Museum of Natural History, Pittsburgh, PA. USNM = United States National Museum of Natural History, Smithsonian Institution, Washington, D.C. R = right; L = Left.

Museum Number	Side	Length (mm)	Width (mm)
CM 20274	R	6.1	2.4
CM 84588	L	5.1	1.9
USNM 12044	L	4.6	1.8

We finally have the ability to test hypotheses of early to middle Pleistocene faunal dynamics in northeastern North America, because we can place one of those faunal assemblages in a reliable chronological context. The spatial context to understand the paleobiota from Cumberland Bone Cave has long been understood, and the taxonomic assemblage itself is now undergoing a major revision. If faunas with established age control (e.g., Cudahy at 670 ka) are at least roughly contemporaneous with those from northeastern caves, then recognition of a northeastern faunal region may be justified because of the distinct differences in the makeup of the faunal communities between the Great Plains and the northeastern cave sites (Fejfar and Repenning, 1992). Numerical age control for the fauna from Cumberland Bone Cave opens this possibility for the first time, and has the potential to greatly expand our understanding of the early to middle Pleistocene in the eastern United States.

CONCLUSION

Much of our knowledge about mammalian faunal dynamics in the Pleistocene is derived from deposits dating to the latest part of the Pleistocene, and specifically to the interval that falls within the range of radiocarbon chronology from approximately 50,000 to approximately 10,000 yr BP (Bell et al., 2004a). Sole reliance on the late Pleistocene record for data pertaining to faunal dynamics, particularly those related to climatic perturbations, is problematic and potentially misleading (Barnosky, 2004). Age control of fossil assemblages allows the development of a more refined understanding of evolutionary change, faunal dynamics,

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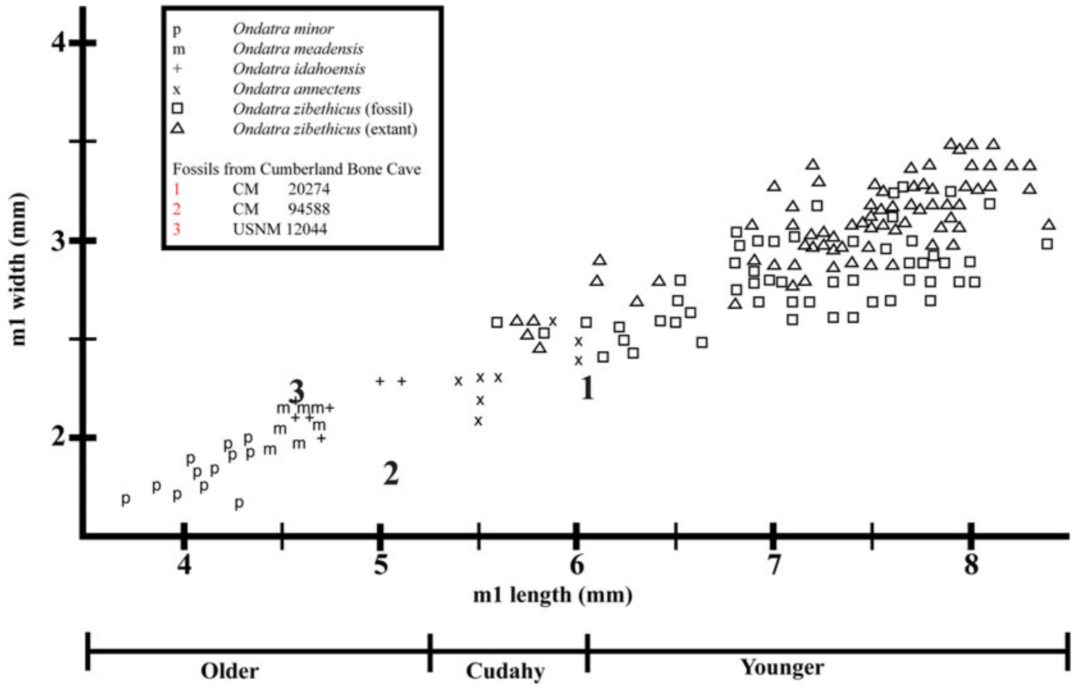

Figure 3. *Ondatr*a (muskrat) chronocline as proposed by Nelson and Semken (1970) updated with Cumberland Bone Cave muskrats. Modified from Jass and Bell (2011).

paleobiogeographic patterns, and the impacts of environmental change on past communities. Compared to the latest intervals of the Pleistocene, early, middle, and early-late Pleistocene faunas of North America have been particularly challenging to place in a reliable chronological context. Faunas from open-air sites that are associated with volcanic ashes derived from eruptions around the Yellowstone hot-spot and elsewhere have been successfully dated across the Great Plains, and provide important anchor-points for temporalizing biostratigraphic correlations. Resultant

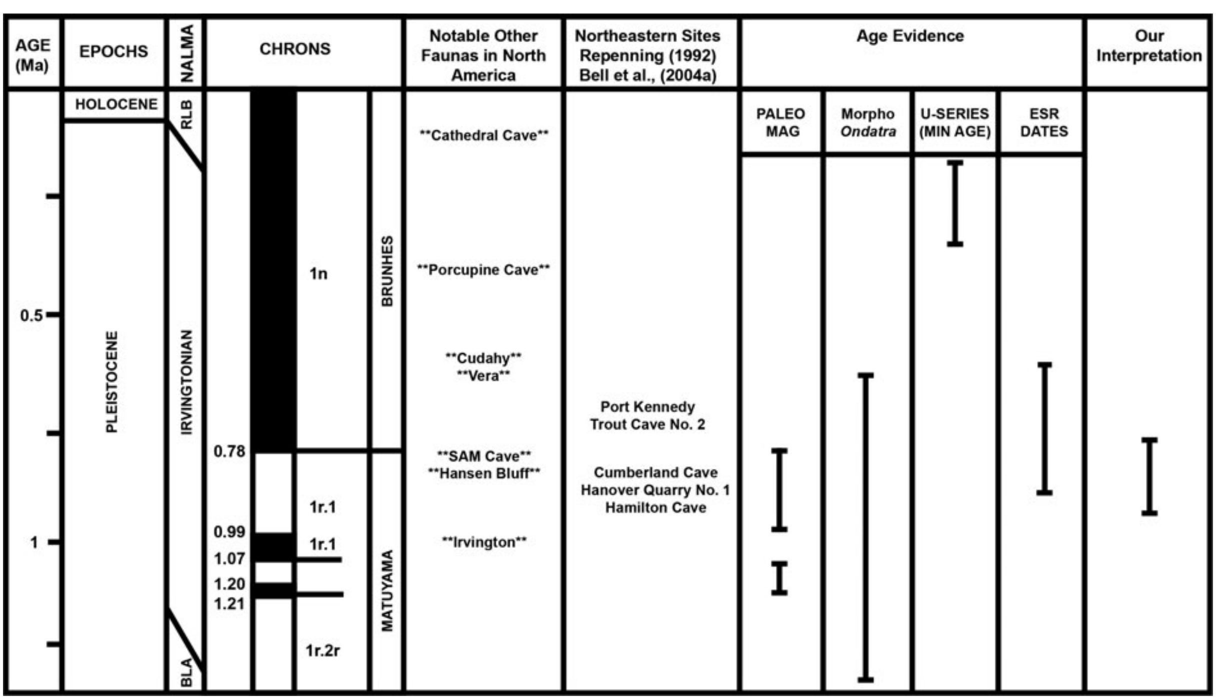

Figure 4. Stratigraphic column showing the hypothesized age of the northeastern Irvingtonian sites by Repenning (1992) and Bell et al., (2004a), the independent evidence for the age of the fauna from Cumberland Bone Cave, and our interpretation of the most likely time span of deposition of Cumberland Bone Cave, Maryland.

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biochronologies have been tested and refined over the last several decades in the western and central United States, but the important faunas from cave deposits in the northeastern part of the country have remained undated, and biochronological age assessments have not been independently tested until now.

Our combined US-ESR dates, paleomagnetics, and data from the *Ondatra* chronocline provide independent evidence that the fauna from Cumberland Bone Cave is between 660–830 ka with a most likely age of 756 $^{+87}/_{-98}$ ka (Fig. 4). These results support prior biochronological age assessments based on arvicoline rodents, and Charles Repenning's estimation of the age of Cumberland Bone Cave is remarkably close to the results we obtained. That he obtained his result from somewhat eccentric lines of argumentation makes the congruence all the more remarkable.

Our success in dating the Cumberland Bone Cave biota cannot be replicated for Pennsylvania's Port Kennedy Cave deposit and Hanover Quarry No. 1, both which are now inaccessible. But if fossil-bearing matrix is still preserved within Hamilton Cave and Trout Cave in West Virginia, our methods could be applied at those sites as well. This will be an important area for further investigation. The subtle differences in the faunas from those sites suggests an approximate, but not exact, contemporaneity with the fauna from Cumberland Bone Cave. The slightly younger, but well-dated faunas from the southern Great Plains in Kansas and north Texas show important faunal similarities with those from Cumberland Bone Cave, but they lack some of the endemic species reportedly found only in the northeastern caves (e.g., *Microtus cumberlandensis*, *Microtus guildayi*, *Platygonus cumberlandensis*, etc.), and contain species that are not reported from the northeastern caves. Therefore, the dating of Cumberland Bone Cave opens the door to a plethora of possible questions that can be addressed surrounding the biota of eastern North America during the early to middle Pleistocene.

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