Reports

Single-Crystal ^{40}Ar/^{39}Ar Dating of the Eocene-Oligocene Transition in North America

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Explanations for the causes of climatic changes and associated faunal and floral extinctions at the close of the Eocene Epoch have long been controversial because of, in part, uncertainties in correlation and dating of global events. New single-crystal laser fusion (SCLF) ^{40}Ar/^{39}Ar dates on tephra from key magnetostratigraphic and fossil-bearing sections necessitate significant revision in North American late Paleogene chronology. The Chadronian-Orellan North American Land Mammal "Age" boundary, as a result, is shifted from 32.4 to 34.0 Ma (million years ago), the Orellan-Whitneyan boundary is shifted from 30.8 to 32.0 Ma, and the Whitneyan-Arikareean boundary is now approximately 29.0 Ma. The new dates shift the correlation of Chron C12R from the Chadronian to within the Orellan-Whitneyan interval, the Chadronian becomes late Eocene in age, and the North American Oligocene is restricted to the Orellan, Whitneyan, and early Arikareean. The Eocene-Oligocene boundary, and its associated climate change and extinction events, as a result, correlates with the Chadronian-Orellan boundary, not the Duchesnean-Chadronian boundary.

THE TRANSITION FROM THE EOCENE to the Oligocene was a period of profound change in Earth's climate and biota. The earth changed from the warm, equable, mostly subtropical world that persisted from the Mesozoic to the beginning of the glaciated world we have today (*1, 2*). As a consequence, there were major changes in the world's biota, including the most significant extinctions since the demise of the dinosaurs (*2, 3*). These Eocene-Oligocene extinctions, which are recorded worldwide, have been postulated to have extraterrestrial causes (*4*) and to be part of a suggested 26-million-year extinction cycle (*3*). However, the lack of high resolution dates on extinctions from geographically distant areas has prevented precise global correlation and as a result an accurate age estimate of the Eocene-Oligocene transition (*5–7*). An understanding of the timing and correlation of the various extinctions is crucial to determine their pattern and cause.

The correlation of the North American terrestrial record to standard European stages (ages) has been particularly difficult. Traditionally, the Chadronian NALMA (North American Land Mammal Age), has been considered to be early Oligocene, the Orellan to be middle Oligocene, and the Whitneyan to be late Oligocene (*8, 9*). Because there was little faunal exchange with other parts of the world during this time, these correlations were based primarily on stage of evolution, and since the mid-1960s, ^{40}K-^{40}Ar dates (*10*). The ^{40}K-^{40}Ar dates suggested that the Chadronian ranged from at least 36 Ma to approximately 32 Ma. Berggren *et al.* (*6*) incorporated these dates and the magnetostratigraphy developed on the North American terrestrial sections (*11, 12*) into a proposed Cenozoic time scale that placed the Eocene-Oligocene boundary at approximately 36.5 Ma. The ^{40}K-^{40}Ar dates from North America were made in the early years of radioisotopic dating, however, and were published without error estimates (*10*). Younger age estimates for the Eocene-Oligocene boundary have since been proposed, based on detailed geochronology developed at Massignano (Ancona, Italy) (*13*). Interpolation of ^{40}K-^{40}Ar, ^{40}Ar/^{39}Ar, and Rb-Sr dates below and above the Eocene-Oligocene boundary at Gubbio and Massignano, Italy, indicated an age of 33.7 ± 0.5 Ma (*14, 15*).

Recent advances in mass spectroscopy and the development of laser-fusion ^{40}Ar/^{39}Ar dating techniques (*16*) have resulted in the ability to date individual volcanic crystals. Multiple analyses and the ability to date single crystals allow the identification of multiple age components due to detrital contamination and thus permit improved precision and accuracy (*17*). To refine the calibration of the North American chronology, we redated a number of ashes previously dated by ^{40}K-^{40}Ar methods and also dated previously undated Oligocene ashes (Table 1 and Fig. 1). All of our ^{40}Ar/^{39}Ar dates are based on laser fusions of single crystals of volcanic minerals.

Lone Tree ashes B, F, G, I, and J, from the Flagstaff Rim section, in Natrona County, Wyoming (*9*), are associated with vertebrate fossils of middle Chadronian age. Early Chadronian fossils occur below Ash B, but no datable volcanic rocks were found in

Table 1. ^{40}K-^{40}Ar and SCLF ^{40}Ar/^{39}Ar dates. The ^{40}K-^{40}Ar dates by Evernden *et al.* (*10*) except RRA by Obradovich *et al.* (*21*) and summary of single-crystal laser fusion ^{40}Ar/^{39}Ar dates, L#, Berkeley Geochronology Laboratory number; age, mean age of multiple dates; cv, coefficient of variation; Anor, anorthoclase; Plag, plagioclase. Data on file at the Berkeley Geochronology Center; available upon request.

Unit	^{40}K-^{40}Ar Age (Ma)	^{40}Ar/^{39}Ar L#	Mineral Dated	*N*	Age (Ma)	SD (Ma)	cv (%)	SEM (Ma)
Nebraska								
RRA	28.7 ± 0.7	1745	Biotite	9	28.59	0.96	3.34	0.32
NPAZ		2566	Biotite	5	30.05	0.19	0.64	0.09
UWA		1584	Biotite	11	30.58	0.61	1.99	0.18
LWA		1582	Biotite	10	31.85	0.02	0.07	0.01
		1583	Anor	4	31.81	0.05	0.16	0.03
		1621	Plag	2	31.67	0.22	0.69	0.16
Wyoming								
PWL		1746	Biotite	5	33.91	0.13	0.39	0.06
LTJ	32.4	1152	Biotite	8	34.48	0.23	0.67	0.08
		1155	Anor	12	34.72	0.13	0.36	0.04
LTI		1148	Biotite	8	35.38	0.29	0.83	0.10
LTG	33.5	1147	Biotite	9	35.57	0.17	0.46	0.06
		1157	Anor	7	35.72	0.07	0.20	0.03
LTF	34.6	1156	Biotite	11	35.72	0.38	1.06	0.11
	36.6	1153	Anor	5	35.81	0.09	0.24	0.04
LTB	34.2	1146	Biotite	12	35.92	0.34	0.96	0.10
	36.1	1151	Anor	4	35.97	0.45	1.24	0.22

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the lower part of the Flagstaff Rim section. These ashes were dated previously with conventional ^{40}K-^{40}Ar dating methods (*10*). From four SCLF anorthoclase analyses, the lowest dated ash (ash B) yielded a mean of 35.97 ± 0.22 Ma; 12 SCLF biotite analyses resulted in a mean of 35.92 ± 0.10 Ma. The ^{40}Ar/^{39}Ar dates for the uppermost dated ash, the last Chadronian ash J (^{40}K-^{40}Ar dated at 32.6 Ma, corrected for new constants), are 34.72 ± 0.04 Ma based on 12 anorthoclase dates and 34.48 ± 0.08 Ma from 8 biotite dates. These dates, and those from ashes F, G, and I (Table 1), indicate that the middle part of the Flagstaff Rim section was deposited in only 1.2 million years, not 2 to 3 million years as previously thought.

The Glory Hole ash, or the Persistent White layer (PWL), also known as the Purplish White layer (*9, 12, 18*), marks the boundary between the Chadron Formation and overlying Orella Member of the Brule Formation. The PWL is commonly associated with the Chadronian-Orellan transition, although the last appearance of titanotheres (a group used to define the end of the Chadronian) occurs 8 m above the PWL in eastern Wyoming (*9, 12*). Five SCLF ^{40}Ar/^{39}Ar dates on biotite extracted from this ash yield a mean of 33.91 ± 0.06 Ma (Table 1 and Fig. 1).

The Whitneyan NALMA is based on fauna from the Whitney Member of the Brule Formation and its correlatives (*9*). Two widespread marker ashes occur in the Whitney Member, the Lower and Upper Whitney ashes (LWA and UWA) (*9, 12, 18*). These ashes, especially the LWA, have been traced in the subsurface and from surface exposures throughout parts of Wyoming, Nebraska, and South Dakota (*19*). The LWA yielded concordant mean SCLF ^{40}Ar/^{39}Ar dates on anorthoclase (four dates), biotite (ten dates), and plagioclase (two dates) of 31.85 ± 0.01, 31.81 ± 0.03, and 31.67 ± 0.16 Ma, respectively (Table 1 and Fig. 1). The UWA yielded a mean SCLF ^{40}Ar/^{39}Ar date of 30.58 ± 0.18 Ma based on 11 biotite dates. As Whitneyan faunas first occur about 18 m below the LWA, the Orellan-Whitneyan boundary must be slightly older than 31.85 Ma.

Approximately 150 m of brownish siltstone that occur above the Whitney Member but below rocks attributed to the Gering Formation (base of the Arikaree Group) have been informally described as the brown siltstone member of the Brule Formation (*19, 20*). The brown siltstone represents the uppermost phase of White River deposition, which in most places is unconformably overlain by coarser-grained fluvial deposits of the Gering Formation. An ashy zone in the brown siltstone, termed the Nonpareil ash, is widespread in Nebraska and may be a correlative of the Rockyford Ash at the base of the Sharps Formation in South Dakota. Five SCLF ^{40}Ar/^{39}Ar dates on biotite separated from the Nonpareil ash collected from the Roundtop section (*18–20*) of northwestern Nebraska yielded a mean of 30.05 ± 0.09 (SEM). These ashes lie just below faunas that typically mark the beginning of the Arikareean NALMA (*20*) yet above faunas typical of the Whitneyan NALMA. The Whitneyan-Arikareean boundary is slightly younger than 29.0 Ma, unless the intermediate faunas from the brown siltstone member of the Brule Formation are included within the Arikareean NALMA, which would extend the age of the Arikareean to approximately 30.0 Ma. The tenth sample is from the lower white ash (RRA) exposed in the basal part of the Gering Foundation at Roundhouse Rock, Morrill County, Nebraska, where it underlies typical early Arikareean faunas. Nine SCLF ^{40}Ar/^{39}Ar dates on biotite separated from this ash yielded a mean of 28.59 ± 0.32 Ma, consistent with an earlier ^{40}K-^{40}Ar date on biotite of 28.7 ± 0.7 Ma from the same unit (*21*).

These new dates force a reinterpretation of Prothero's (*11, 12*) correlation of the magnetic stratigraphy of White River sections with the magnetic polarity time scale. The reversed interval between ashes B and J at Flagstaff Rim was previously interpreted as Chron C12R, because it appeared to span 2 to 3 million years based on the ^{40}K-^{40}Ar dates (*10*), and in most versions of the magnetic polarity timescale, the estimated length of C12R was 2.4 million years (*6, 22*). In that C12R was the only reversed event of such great length in the entire Paleogene, Prothero used it to tie the magnetostratigraphy of the terrestrial sections to the magnetic polarity time scale. Berggren *et al.* (*6*) followed Prothero's identification of C12R and used the ^{40}K-^{40}Ar dates at Flag-

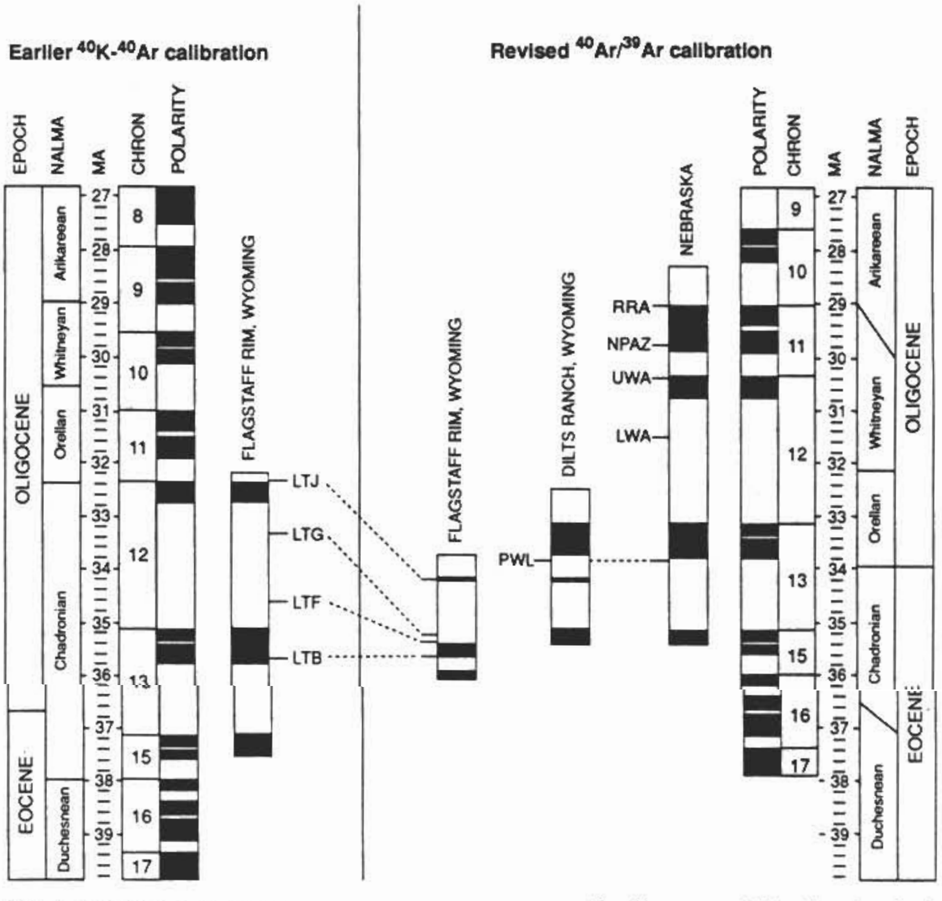

Fig. 1. Berggren *et al.* (*6*) time scale based on Flagstaff Rim ^{40}K-^{40}Ar dates (Table 1) and revised correlation based on new SCLF ^{40}Ar/^{39}Ar dates (Table 1). Changes in the dates shorten the duration of the Flagstaff Rim magnetic reversal (left and center) and force a revised correlation with Chron C13R, not the long Chron C12R as previously reported. The Dilts Ranch section produces a similar pattern, with middle Chadronian faunas at the base, and early Orellan faunas at the top. New SCLF ^{40}Ar/^{39}Ar dates of 33.91 ± 0.06 Ma on the PWL and 30.58 ± 0.18 Ma on the UWA indicate that the best candidate for C12R is the long reversal in the late Orellan and early Whitneyan. The revised duration and correlation of Paleogene NALMA (from bottom to top: Duchesnean, Chadronian, Orellan, Whitneyan, Arikareean) are shown on the right. Abbreviations: LTB, LTF, LTG, LTI, LTJ, Flagstaff Rim ashes; PWL, Persistent White layer; LWA, Lower Whitney Ash; UWA, Upper Whitney Ash; NPAZ, Nonpareil ash zone; RRA, Roundhouse Rock Ash.

staff Rim (*10*) as calibration points in their version of the timescale. These dates heavily influenced their estimate of 36.5 Ma for the Eocene-Oligocene boundary.

The new ^{40}Ar/^{39}Ar Flagstaff Rim dates show that this reversed interval actually spans only 34.7 to 35.9 Ma, an interval much shorter than that estimated for Chron C12R. Because the same pattern is apparent in the Dilts Ranch section, we reinterpret this reversed interval as Chron C13R (Fig. 1). This interpretation is corroborated by the new dates from the overlying Brule Formation. Dozens of magnetostratigraphic sections through Orellan and Whitneyan rocks of the Brule Formation from localities all over the High Plains (*11, 12*) have produced a consistent magnetic pattern. There is an early Orellan normal polarity interval, a long reversed interval spanning the late Orellan and early Whitneyan, and a short mid-Whitneyan normal interval, and a latest Whitneyan–early Arikareean normal interval (Fig. 1). The date of 33.91 ± 0.06 Ma on the PWL (just below the early Orellan normal event) and 30.58 ± 0.18 Ma on the UWA (in the midst of the late Whitneyan normal event) brackets the long Orellan-Whitneyan reversed interval and suggests that it spans about 2.5 million years. Clearly, this must be the characteristically long Chron C12R event. These revisions suggest that the Chadronian-Orellan boundary is about 34.0 Ma, not 32.4 Ma, and that the Orellan-Whitneyan boundary is 32.0 Ma, not 30.8 Ma. As shown in Fig. 1, this makes the duration of the Chadronian much shorter, and the Orellan and Whitneyan longer and older.

These correlations, if correct, have many implications not only for the North American land mammal chronology, but also for the magnetic polarity time scale. The dates from LTB of Flagstaff Rim provide age calibration for the middle of Chron C15N, LTF for the base of Chron C13R. The PWL provides an age for the top of Chron C13R and the UWA for Chron C12N. The other reported dates lie in the middle of polarity intervals but show consistency with this overall pattern. It is clear from these correlations that the late Eocene-Oligocene part of the polarity time scale must be shifted considerably younger than in earlier estimates. The correlation shown in Fig. 1 places the Eocene-Oligocene boundary (upper third of Chron C13R) around 34.0 Ma. This age is in good agreement with recent dates from Gubbio and Massignano in the Italian Apennines (*13–15*) that push the Eocene-Oligocene boundary much younger than 36.5 Ma. It is also in good agreement with a number of dates from North America including dates from late Eocene microtektites (*23*), volcanic ignimbrites from New Mexico and Colorado (*24*), the Castle Hayne Limestone from the Gulf Coast of North Carolina (*25*), and recent SCLF ^{40}Ar/^{39}Ar dates of 34.3 ± 0.07 Ma (SEM) on sanidine and 34.3 ± 0.05 Ma (SEM) on biotite from a bentonite in the upper Eocene Jackson Group of the Gulf Coast in Mississippi (*26*). All of these are high-temperature dates on ashes, bentonites, or microtektites; none are based on glauconites, which have given unreliable ages in the past (*6, 7, 27*).

If the Eocene-Oligocene boundary is shifted to about 34.0 Ma, then it corresponds to the Chadronian-Orellan faunal transition, which is also located in upper Chron C13R and lies just above the PWL date of 33.9 ± 0.06 Ma. This correlation implies that the Chadronian-Orellan faunal transition corresponds closely in time to the terminal Eocene event, not the mid-Oligocene event, as traditionally thought (*2, 28*). As recently demonstrated by many workers (*2*), the terminal Eocene event is represented by relatively minor extinctions in the marine record, as are the Chadronian-Orellan extinctions (*2, 9, 28*). The largest marine extinctions took place during the Bartonian-Priabonian (middle-late Eocene) transition at about 40 Ma. This age would correlate on land with the major faunal turnover recorded from the late Uintan to Chadronian, a period represented by the Duchesnean NALMA (*2*). The occurrence of other extinction events during the 10-million-year interval from 40 to 30 Ma, contradicts the notion of a single extinction peak predicted from periodicity models (*3*). The occurrence of microtektites in the mid-Priabonian (*4*) appears to be the only association of an extraterrestrial event and an extinction event, and this is one of the least significant of the late Eocene extinctions (*2*). The recognition of a series of extinction events at the close of the Eocene appear to be more consistent with models in which global climate change is invoked (*2*). The actual causes of the deterioration of the climate at the close of the Eocene remain controversial.

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30. We thank M. F. Skinner and R. J. Emry for developing a stratigraphy of the White River deposits of western Nebraska, South Dakota, and Wyoming; G. H. Curtis for his encouragement and discussions on this project; and A. Deino for his endless help on ^{40}Ar/^{39}Ar computer software. C.C.S. was funded by NSF grant EAR89-16431; D.R.P. was funded by NSF grant EAR87-08221. Funding for the dates and collection of the Nonpareil Ash was provided by J. Swinehart and the Nebraska Conservation and Survey Division.

2 February 1990; accepted 6 June 1990