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AN IMPROVED NEW AGE FOR THE C33N-C32R PALEOMAGNETIC REVERSAL, SAN JUAN BASIN, NW NEW MEXICO AND SW COLORADO

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Abstract—Three new $^{40}Ar/^{39}Ar$ sanidine dates of tephra deposits, along with existing stratigraphic and paleomagnetic data, are used to constrain the magnetochron C33n-C32r reversal to 73.7 Ma. These 3 ages agree well with previously published dates when the later are corrected to equal $^{40}Ar/^{39}Ar$ flux monitor age and ^{40}K decay constant. This age contrasts significantly with the Geologic Time Scale of Gradstein et al. (2012) that places the boundary at 74.6 Ma; 600 ka older. A wide range of error estimates (0.05-0.4 Ma) for the reversal age depend on the statistical approach chosen and demonstrate the difficulty in unambiguously determining the uncertainty of magnetochron boundaries that are based on ages of ash layers that stratigraphically bracket the reversal. Both discrepancies in reported ages of reversal boundaries and their uncertainties plague global time scales and impact the ability to unambiguously determine rates of important evolutionary processes and to make stratigraphic correlations. Here we recommend that our new age of 73.7±0.4 Ma (a conservative error) be adopted for the C33n/C32r paleomagnetic reversal and to be the established age for this reversal in future global time scales.

INTRODUCTION

The paleomagnetic boundary between magnetochrons C33n and C32r has been documented at six localities in the San Juan Basin of northwest New Mexico and southwest Colorado (Fig. 1). At five of these localities in the southern part of the basin (Figs. 1, 2), the reversal is in the continental Fruitland or Kirtland Formation and at the sixth, in the northeast part of the basin (Fig. 3), it is in the marine Lewis Shale. The five paleomagnetic sections in the southwest part of the basin (Figs. 1, 2) are from Butler et al. (1977), Butler and Lindsay (1985), Fassett and Steiner (1997), and Fassett (2009). The sixth paleomagnetic section at the Chimney Rock locality in the northeast part of the basin is from Fassett and Steiner (1997) and Fassett (2009). In addition, eight $^{40}Ar/^{39}Ar$ sanidine ages for volcanic ash beds (Fig. 1) were reported in Fassett and Steiner (1997), Fassett et al., (1997), and Fassett, (2000). Interpolating between the ages of two ash beds above the C33n-C32r reversal and six ages below, an age of 73.50 Ma for the reversal was calculated by Fassett and Steiner (1997) and Fassett (2000). Since these publications, the age of Fish Canyon sanidine, the $^{40}Ar/^{39}Ar$ standard that is commonly used to determine $^{40}Ar/^{39}Ar$ ages, and the ^{40}K decay constant have been modified several times (e.g., Min et al., 2000; Kwon et al., 2003; Kuiper et al., 2008; Renne et al., 2011, 2013). These changes can make it challenging to compare current and past data; however it appears that the one percent level changes to these parameters are likely only to change by small increments (Kuiper et al., 2008), and thus it is now timely to revise earlier estimates of geomagnetic polarity reversals. Also, since the work of Fassett and Steiner (1997), new generation mass spectrometers have been developed thereby allowing much more precise age determinations that prompted recollection and re-dating of three ash layers. Finally, neither of the two most recent geological time scale evaluations (Gradstein et al., 2004, 2012) cited the work of Fassett and Steiner (1997) thereby providing an incomplete and perhaps inaccurate estimate for the C33n-C32r reversal.

PREVIOUS WORK

Paleomagnetism

The locations of the six paleomagnetic sections in the San Juan Basin are shown on Figure 1; a cross section depicting five of these sections across the southern edge of the basin is shown on Figure 2. The first paleomagnetic studies of uppermost Upper Cretaceous-lowermost Paleocene strata in the southern San Juan Basin of New Mexico was by Butler, et al (1977). That study contained a long paleomagnetic section (HW/AW - Hunter Wash-Alamo Wash section of Fig. 1) through the Fruitland and Kirtland Formations and into the basal part of the Ojo Alamo Sandstone. Other sections included a very short one through the uppermost Kirtland Formation and lower Ojo Alamo Sandstone (BBA - Barnum Brown Amphitheater section) and a longer one (BSA - Barrel Spring Arroyo section) through the uppermost Kirtland Formation, all of the Ojo Alamo Sandstone, and well up into the Kirtland Formation (Fig. 1). The Hunter Wash-Alamo Wash section contains a long paleomagnetic normal interval extending from its base in the Fruitland Formation to about the upper third of the Kirtland Formation; this normal interval is overlain by a reversed polarity interval that extends into the lower part of the Ojo Alamo Sandstone (Figs. 1, 2). The nomenclature and age of Ojo Alamo Sandstone/Kirtland Formation rocks have been complicated and disputed by many authors over the years and to this day. For example, Baltz et al. (1966) redefined the lower part of the Ojo Sandstone as the Naashoibito Member of the "Kirtland Shale" (now Kirtland Formation) and many

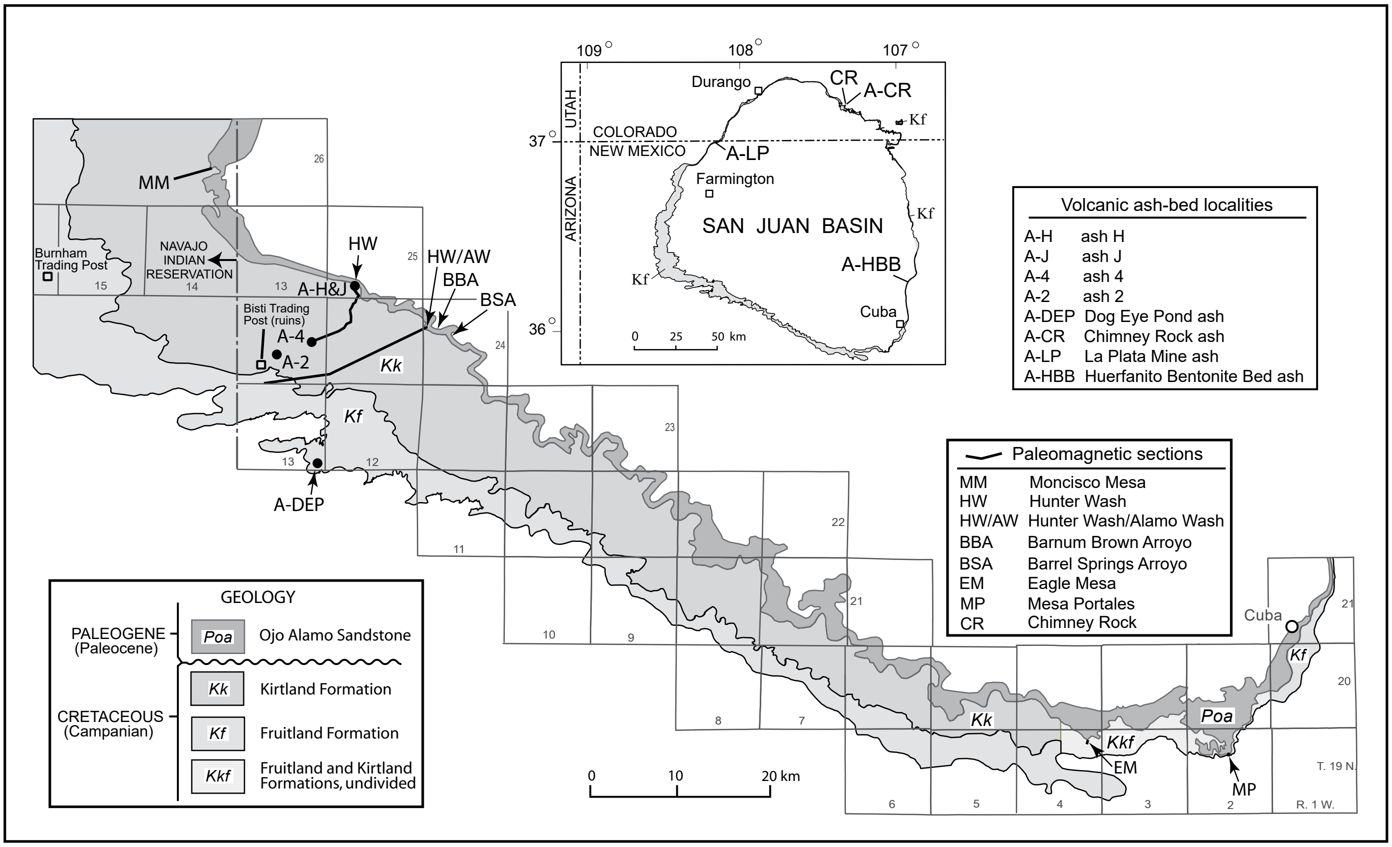
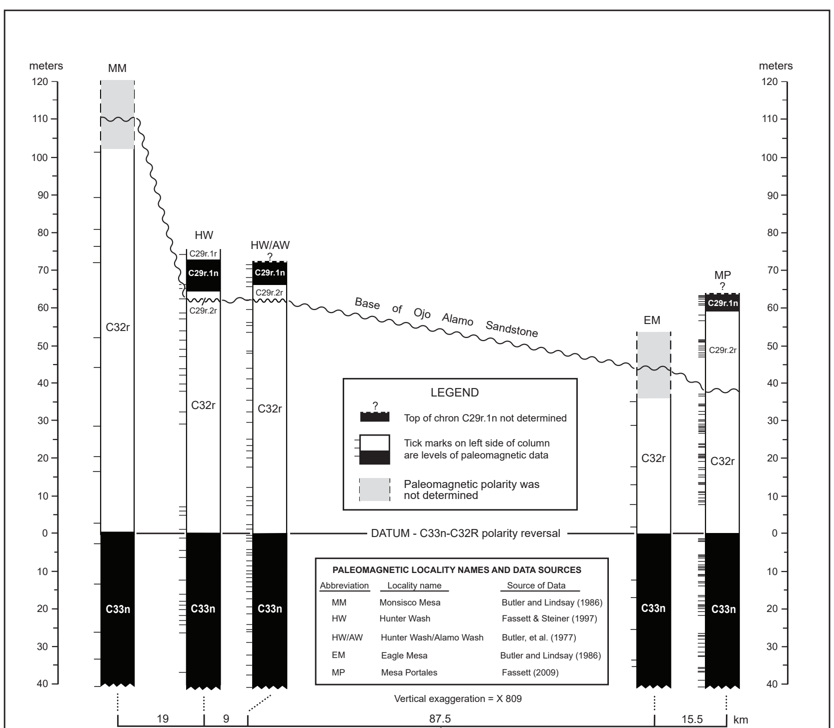


FIGURE 1. Geologic map of Upper Cretaceous-lower Paleocene strata in the southern San Juan Basin. Localities of paleomagnetic sections and dated altered volcanic ash beds are shown. An index map showing the full extent of the inner San Juan Basin and its location in the Four Corners Area is included.



subsequent authors adopted that terminology. Subsequently, Lucas and Sullivan (2000), Sullivan and Lucas (2003), and Sullivan et al. (2005) redefined the Naashoibito as a lower member of the Ojo Alamo Sandstone. Other authors, however (for example, Farke and Williamson, 2006 and Lehman et al., 2006), continue to refer to the "Naashoibito" as a member of the Kirtland Formation. The authors cited above claimed that the Naashoibito Member was Cretaceous, whereas Fassett, in multiple papers (for example 2000, 2009, 2010), maintains that there is no rock-stratigraphic "Naashoibito Member" and that the Kirtland Formation is late, but not latest Cretaceous and that the entire conglomeratic Ojo Alamo Sandstone is Paleocene. The stratigraphic nomenclature and age of the Ojo Alamo Sandstone/Kirtland Formation is much too complex a topic to be discussed in more de-

FIGURE 2. Paleomagnetic cross section trending southeast across the southern San Juan Basin. Localities of individual paleomagnetic sections are shown on Figure 1.

tail in this brief report, however, Fassett (2010) discusses these nomenclature and age complexities in detail and the interested reader is referred to that publication for a full discussion of this issue. The Ojo Alamo Sandstone of this report is the undivided interbedded conglomeratic sandstone/mudstone complex lying above the Kirtland Formation as defined in Fassett (2010), and is so labeled in the various figures herein.

Butler et al. (1977) labeled the upper part of the lower normal interval magnetochron C30n and the overlying reversed interval C29r. The other two sections mentioned above – the Barnum Brown Amphitheater and the Barrel Spring Arroyo sections – started well above the reversal boundary of the Hunter Wash-Alamo Wash section and are thus not relevant to this discussion. Two additional Kirtland Formation paleomagnetic reversals were reported by Butler and Lindsay (1985) at the northwest and southeast ends of the outcrop map of Figure 1. Those sections are labeled MM (Moncisco Mesa) and EM (Eagle Mesa) on Figures 1 and 2. (Other paleomagnetic sections in the southern San Juan Basin that did not include the C33n-C32r reversal boundary were obtained and discussed in subsequent papers by the Butler-Lindsay team and so are not relevant to this discussion (those sections are discussed in detail in Fassett, 2009).

Fassett and Steiner (1997) sampled the HW (Hunter Wash) paleomagnetic section in Hunter Wash (Fig. 1) about nine km west of the Hunter Wash-Alamo Wash section of Butler et al. (1977). This section extended from the uppermost part of the Fruitland Formation, through the Kirtland Formation, and into the lower part of the Ojo Alamo Sandstone and contained a reversal from normal to reversed polarity in the Kirtland Formation at about the same level as was found in the Hunter Wash-Alamo Wash section of Butler et al. (1977; Fig. 2).

Fassett and Steiner (1997) also sampled a paleomagnetic section at the CR (Chimney Rock) locality (Figs. 1, 3) in the northeast part of the San Juan Basin in the marine Lewis Shale; this section contained a reversal from normal to reversed polarity that was found to be the same reversal found at the five localities in the southern San Juan Basin. Fassett (2009) reported the presence of this same polarity reversal in the Fruitland Formation in a paleomagnetic section at the Mesa Portales locality in the southeastern San Juan Basin (Figs. 1, 2). The history of the changing interpretations of all existing pmaleomagnetic sections by Butler/Lindsay and by Fassett/Steiner are discussed in detail in Fassett (2009).

Dating of tephra deposits

In the late 1970s through the mid-1990s, a focused effort was made by Fassett to locate and sample altered volcanic ash beds in rocks adjacent to the polarity reversal discussed above. This effort was focused on establishing a precise age for the paleomagnetic reversal based on $^{40}Ar/^{39}Ar$ sanidine dates of ashes above and below the reversal (Figs. 1, 3). These ash beds were in 384 m of uppermost Upper Cretaceous rock strata including the Lewis Shale, Pictured Cliffs Sandstone, and the Fruitland, and Kirtland Formations (Figs. 1, 3). The original age determinations from the oldest to youngest ash-bed ages spanned 2.72 my – from 75.76-73.04 Ma (Table 1). Because all the rocks containing the dated tephra are time-transgressive (Fig. 3), both ash beds and the paleomagnetic boundary are placed stratigraphically relative to the Huerfanito Bentonite Bed as shown on Figure 3. Six of the dated ash beds are below the C33n/C32r reversal and two are above it. Based on interpolation between these ages, it was determined that the paleomagnetic reversal had an age of 73.50±0.19 Ma.

Butler et al. (1977) and Butler and Lindsay (1985) labeled the Kirtland Formation paleomagnetic reversal in the southern San Juan Basin C30n-C29r and based on that interpretation stated that there must have been relatively continuous deposition across the "Cretaceous-Tertiary" boundary in the San Juan Basin. Identification of the Ojo Alamo Arroyo reversal as C30n-C29r in the Butler et al. (1977) paper was based in part on a comparison of the San Juan Basin's magnetostratigraphic pattern to the sea-floor spreading magnetic polarity pattern and the magnetostratigraphic sequence at Gubbio, Italy. Alvarez and Vann (1979, p. 68-69) and Fassett (1979, p. 69-70) challenged the work of Butler et al. (1977). Fassett (1979) stated that "Marine invertebrate paleontologic evidence indicates that uppermost Upper Cretaceous rocks are not present in the San Juan Basin" and concluded that the significant hiatus at the "K-T" boundary in the basin precluded the labeling of this boundary as the C30n-C29r reversal. Fassett and Steiner (1997) di-

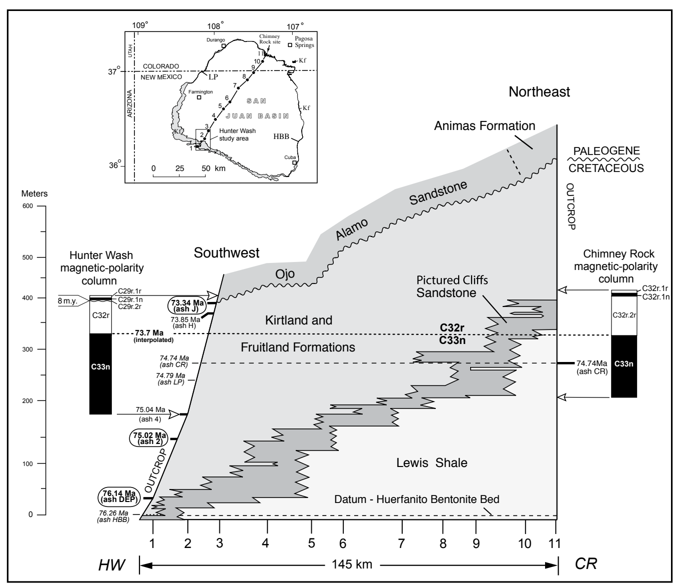


FIGURE 3. Geophysical-log stratigraphic cross section showing the subsurface relations of Upper Cretaceous-lower Paleocene formations. Index map shows the trace of northeast-trending cross section (well names and locations for drill holes in section are in Fassett and Steiner (1997, p. 245). Stratigraphic levels for the eight dated volcanic ash beds are shown along with their best current ages. The three recently dated ash beds that are the focus of this report are circled on the southwest end of the cross section. The level of the C33n-C32r paleomagnetic reversal is from paleomagnetic sections in the southwest and one section in the northeast part of the basin. Because of the time-transgressive nature of these strata, the Pictured Cliffs Sandstone rises about 400 m stratigraphically across the basin and is 2.92 my younger in the northeast than in the southwest part. Figure is after Fassett and Steiner (1997).

rectly addressed the labeling of this reversal and stated that based on invertebrate paleontologic and palynologic evidence plus radiometric dating of the relevant strata the reversal must be the C33n-C32r reversal and not the C30n-C29r as claimed by Butler et al. (1977).

THIS STUDY

$^{40}Ar/^{39}Ar$ dating results

For this study, some of the eight ash beds discussed above were recollected and three (ash beds DEP, 2, and J) were dated at the New Mexico Geochronology Research Laboratory. All new ages are reported relative to a Fish Canyon age of 28.201 Ma (Kuiper et al., 2008) and a total ^{40}K decay constant of 5.463×10^{-10}/a (Min et al., 2000) whereas the data from Fassett and Steiner (1997) used 28.02 Ma for Fish Canyon (Renne et al., 1998) and 5.543×10^{-10}/a (Steiger and Jager, 1977). The two data sets are normalized in Table 1 and all errors for the preferred dates are presented at 2 sigma. Sanidines were dated by either the single crystal laser fusion (SCLF) method or by the age spectrum method that utilized 3 or 4 incremental heating steps (Supplemental data Tables 1, 2). Ash bed DEP (Fig. 1) is named for Dog Eye Pond, a stock tank near the collection site shown on the Tanner Lake 1:24,000-scale USGS topographic quadrangle map. Ash DEP is yellow-brown, 18 cm thick, and is in the upper part of a high-ash coal bed in the lowermost part of the Fruitland Formation; this bed is very near the top of the underlying Pictured Cliffs Sandstone (Fig. 3 and photo 1, Supplemental data). Eight SCLF ages for DEP yielded a normal distribution (MSWD = 1.71) and a weighted mean age of 76.14±0.12 Ma (Fig. 4, Table 1). This age is approximately 3 times more precise than the adjusted age of 76.06±0.41 Ma reported by Fassett and Steiner (1997) however the two ages are nearly identical and well within analytical uncertainty.

Ash bed 2 is also in the Tanner Lake quadrangle; it is white, 18 cm thick, and is at the top of a middle Fruitland coal bed in Hunter Wash (Photo 2, Supplemental data). This locality is about 3.2 km up Hunter Wash from the ruins of the Bisti Trading Post (Fig. 1). Two discrete layers were collected (H08-Ash-6, 7) that were separated by about 1 m and a total of 29 single sanidines were step-heated (Supplemental data Table 2). Many of the spectra are flat while some show very minor age gradients that could be related to mass fractionation of ^{40}Ar and ^{39}Ar during the step-heating process (Supplemental data Fig. 1). The total gas ages of these 29 spectra analyses are plotted on Figure 4 with 27 yielding a weighed mean age of 75.02±0.04 Ma with a somewhat elevated MSWD of 19.4. The scatter is suspected to be dominated by variation in neutron flux across the irradiation tray pits, however since there may also be some geological scatter the analytical uncertainty is increased by the square root of the MSWD as a more conservative error estimate for the age of the sample. This new and more precise age is essentially identical to the adjusted value of 75.05±0.13 Ma reported in Fassett and Steiner (1997).

Ash bed J is in the uppermost part of the Kirtland Formation, 4.9 m below the base of the overlying Ojo Alamo Sandstone, and is slightly east of the north end of the Hunter Wash (HW) paleomagnetic section (Fig. 1). This ash bed is white, 21 cm thick, and is underlain by green-gray mudstone and overlain by a 1.4-m chocolate-brown mudstone bed (Photo 3, Supplemental data). The collection site is in a small Rincon that provides a narrow window into a bedrock exposure of the uppermost Kirtland Formation that is mostly covered by slope-wash material in most of this area. This ash bed is in the Alamo Mesa West 1:24,000-scale USGS topographic quadrangle map. Thirteen single sanidine crystals were step-heated and their age spectra mostly reveal climbing ages with about 0.3-0.5 Ma separating the youngest age from the oldest age of the individual spectra (Supplemental data Fig. 2). The weighted mean of the integrated ages is 73.34±0.06 Ma with a range of about 0.5 Ma (Fig. 4). This relatively large range results in a high MSWD of ~64 and

TABLE 1. Compilation of eight late Cretaceous sanidine ages of altered volcanic ash beds sampled in the San Juan Basin, their stratigraphic positions, and geographic locations.

Ash	Age (Ma): Fassett (2000)	Age (Ma): Adjusted[1]	New Ages (Ma): This study	Meters[2]	Location: Latitude N-Longitude W
J	73.04±0.25	73.52±0.25	73.34±0.12	384	36.36446 - 108.13205
H	73.37±0.18	73.85±0.18		359	36.36066 - 108.13822
CR	74.25±0.13	74.74±0.13		277	37.19032 - 107.30849
LP	74.30±0.38	74.79±0.38		238	~36.98620 - 108.17851[3]
4	74.55±0.29	75.04±0.29		180	36.30969 - 108.18536
2	74.56±0.13	75.05±0.13	75.02±0.04	136	36.29403 - 108.23017
DEP	75.56±0.41	76.06±0.41	76.14±0.12	29	36.18938 - 108.1721
HBB	75.76±0.34	76.26±0.34		0	36.23855 - 106.91627

[1]Ages reported in Fassett (2000) adjusted to Fish Canyon sanidine age of 28.201 Ma and ^{40}K decay constant of 5.463×10^{-10}/a.
[2]Distance in m above the Huerfanito Bentonite Bed reference datum
[3]The LP ash was sampled in the La Plata coal mine when the coal bed it was found in was actively mined. The mine is now abandoned and reclaimed thus destroying the original sample site.

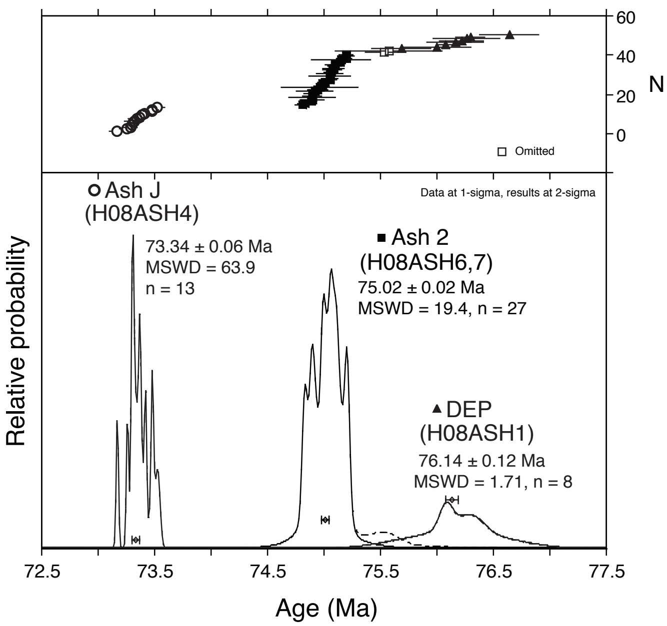


FIGURE 4. Relative probability plot of sanidine geochronology data. Ash J and 2 are total gas ages from single crystal step-heating data whereas DEP is single crystal fusion data. All samples reveal similar scatter based on age range, however the higher MSWD values for Ash J and 2 are due to increased precision relative to DEP.

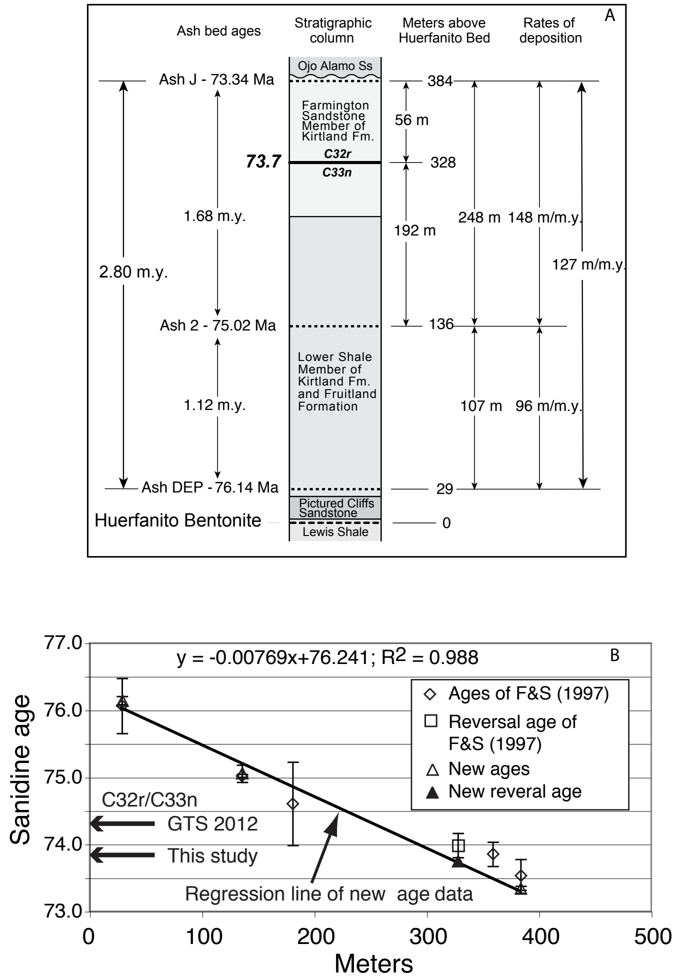


FIGURE 5. **A.** Stratigraphic column showing the rock strata in the Hunter Wash area (location of this area is shown on the index map on Fig. 3). Stratigraphic levels and ages of the three newly dated ash beds discussed in this report are shown. The age of the C33n-C32r paleomagnetic reversal is based on stratigraphic position and linear regression of the 3 new ages. Calculated rates of deposition for Upper Cretaceous strata are also shown – these rates supersede those shown in Fassett (2000, Fig. 11). **B.** Summary diagram of dates (adjusted to Fish Canyon age of 28.201 Ma) from Fassett and Steiner (1997) and the 3 new age determinations. Previous and new data agree within analytical uncertainty. Linear regression of new age versus stratigraphic position indicates that the C33n-C32r reversal occurs at 73.7 Ma. This value is ~0.6 Ma younger than the reported value in the Geological Time Scale of Gradstein et al. (2012).

as described above is primarily caused by variation in neutron flux between individual grains. Fassett and Steiner (1997) reported an adjusted age of 73.52±0.25 Ma that is somewhat older than the new age, but still within analytical error (Table 1).

REVISED AGE FOR C33N-C32R PALEOMAGNETIC REVERSAL

Figure 5a is a stratigraphic section showing the relative positions of the three newly dated ash beds in the Fruitland and Kirtland Formations and the distances these beds are above the Huerfanito Bentonite Bed datum. This figure shows that the C33n-C32r reversal is 328 m above the Huerfanito Bentonite Bed and that ash J is 56 m above and ash 2 is 192 m below the reversal. Figure 5b is a plot comparing the original 8 ages reported by Fassett and Steiner (1997) recalculated to the Fish Canyon standard age of 28.201 Ma to the 3 new age determinations. As discussed above the new ages are in agreement with the previous work and despite the scatter of individual grain ages they yield significantly more precise ash deposition ages. Linear regression of these 3 ages coupled with a reversal location at 328 m above the Huerfanito Bentonite Bed datum yields a calculated age of 73.7 Ma for C33n-C32r reversal. This compares to the adjusted age (i.e., calculated to the standard age of 28.201 Ma) of 74.0 reported by Fassett and Steiner (1997) for this boundary. There are many sources of uncertainty for the age of the reversal that include 1) analytical error of the tephra dates; 2) exact stratigraphic position of the reversal; 3) uncertainty of the age of the standard; 4) uncertainty of the ^{40}K decay constant; 5) calibration between laboratories; and 6) assumption of linear deposition rate and likely others.

Complete analysis of these uncertainties towards assessment of the boundary error remains for future work, however we briefly discuss uncertainty estimates based on various statistical approaches and also consider potential error based on determining the stratigraphic position of the reversal. Fassett and Steiner (1997) reported an uncertainty of the C33n/C32r reversal at 0.18 Ma. This was based on the approach of Renne et al. (1993) that used two bracketing age layers to interpolate the boundary age with an error based mainly in proportion to the error estimates of the tephra ages. Using this method with the new age data that is more than an order of magnitude more precise yields an uncertainty for the reversal of ~0.04 Ma. Considering the many sources of error listed above, an error of 0.04 Ma appears to be an optimistic uncertainty for the reversal.

Perhaps a more meaningful error estimate comes from the entire data set that not only factors in data point uncertainty, but also includes scatter about the linear regression of the multiple data points. Utilizing all 5 ash ages from Hunter Wash section presented in Fassett and Steiner (1997) into a single linear regression yields a 2σ standard error of the mean (SEM) at 0.25 Ma. This error is similar to the new data that constrains the regression with 3 very precise data points but leads to an uncertainty and 0.36 Ma. Thus, in both cases the error is magnified by the scatter about the linear regression rather than a simple function of the precision of the age estimate of the ash layers. Additionally, it is important to consider the uncertainty on the stratigraphic position of the reversal. Fassett and Steiner (1997) place this boundary at 328 m, however there are several relatively short normal and reversed intervals below this datum (see Fassett and Steiner, 1997, Figure 2). The choice for the C33n/C32r boundary of Ogg (2012) came from Husson et al. (2011) who preformed astronomical tuning of marine core records and "hung" their tuning on a K-Pg boundary age at 66.0 Ma. Husson et al. (2011) report several short normal and reversed intervals in C32r that span several hundred thousand years which may make it somewhat difficult to precisely estimate the top of C33n. Therefore, it is possible that Fassett and Steiner (1997) captured at least pieces of these short normal and reversed subchrons within C32r and following the definition of Husson et al. (2011) the top of C33n could be lower in the Fassett and Steiner (1997) section, perhaps somewhere between about 305 to 315 m. Because the depositional rate is on the order of 100 m/my, moving the reversal boundary to 315 Ma from 328 m yields an age of 73.8 Ma versus 73.7 Ma. Thus the positioning choice for the reveal is overall a small contribution to the final uncertainty when considering the degree of scatter in the age vs. stratigraphic position regressions. Combining the linear regression error with the stratigraphic positioning uncertainty leads to an overall uncertainty of ~0.4 Ma (2σ). This may be a conservative error estimate as other sources of potential error listed above are not incorporated into the final error calculation.

Given this conservative error estimate, our new age is still significantly younger than the value reported by Gradstein et al. (2012), which again is mostly based on the work of Husson et al. (2011). It is difficult to pinpoint areas for this discrepancy, but in detail, the estimate of Husson et al. (2011) has several potential pitfalls due to the need to combine multiple data sets towards choosing a K-Pg boundary age. That said, the New Mexico Geochronology Laboratory has a variety of unpublished data sets (Heizler, unpubl. data) that support a K-Pg boundary age at 65.9±0.1 Ma, thus Husson's et al. (2011) placement of the K-Pg doesn't significantly close the ca. 600 ka gap between our reversal estimate and that of Ogg (2012). Perhaps Husson et al. (2011) included an extra eccentricity cycle in their tuning such that they over estimate the boundary age by 405 ka. More work is certainly warranted to solidify the geomagnetic polarity time scale. Towards this end there can be little doubt that improvement in dating precision that is afforded by new mass spectrometry will reduce the uncertainty for the age of the reversal. Also, the improved knowledge of the age of Fish Canyon sanidine and the ^{40}K decay constant has resulted in a significant shift of the reversal age that was reported by Fassett and Steiner (1997) and our new data reported here should be strongly considered in any future efforts to construct a geological time scale for the Cretaceous.

The current age and error discrepancies for chron boundaries are very meaningful differences in light of the potential of high precision geochronology to estimate rates of biological radiation following mass extinction events. For instance, Renne et al. (2013) suggest that less then 100 ka was required for development of Puercan mammals following the K-Pg impact event. If the important time-scale tool of paleomagnetism houses inaccuracies of 100's of thousands of years there will be significant errors in correlating stratigraphic sections and biotic events.

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Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2017005