Revised geochronology and paleomagnetic interpretations of uppermost Cretaceous and lowermost Paleocene rocks in the southern San Juan Basin

James E. Fassett, 2013, pp. 215-222

in:

Geology of Route 66 Region: Flagstaff to Grants, Zeigler, Kate; Timmons, J. Michael; Timmons, Stacy; Semken, Steve, New Mexico Geological Society 64th Annual Fall Field Conference Guidebook, 237 p.

This page is intentionally left blank to maintain order of facing pages.

REVISED GEOCHRONOLOGY AND PALEOMAGNETIC INTERPRETATIONS OF UPPERMOST CRETACEOUS AND LOWERMOST PALEOCENE ROCKS IN THE SOUTHERN SAN JUAN BASIN, NEW MEXICO

JAMES E. FASSETT

U. S. Geological Survey, Retired, and Independent Research Geologist, 552 Los Nidos Drive, Santa Fe, NM 87501, jimgeology@qwest.net

ABSTRACT—The first radiometric age for the Nacimiento Formation in the San Juan Basin was from an altered volcanic ash bed at Mesa de Cuba, near Cuba, NM. This $^{40}Ar/^{39}Ar$ single-crystal sanidine age of 64.0 ± 0.4 Ma was determined relative to the Fish Canyon Sanidine (FCS) with an age of 28.02 Ma. The age of the FCS has recently been revised to 28.294 Ma which makes the adjusted age for the Nacimiento ash bed 64.63 Ma. Based on this age and a newly reported age for an ash bed in the lower part of the Nacimiento Formation of 65.70 ± 0.03 Ma the base of magnetochron C29n has been moved from within and near the base of the Ojo Alamo Sandstone to about the top of the Ojo Alamo. The base of chron C29n and the Nacimiento Formation-Ojo Alamo Sandstone contact appear to be coeval, with an age of 65.76 Ma. The short normal-polarity interval in the lower part of the Ojo Alamo Sandstone present at multiple localities in the southern San Juan Basin is no longer considered to be part of magnetochron C29n, but rather must be a hitherto unknown short-normal interval within chron C29r. The rate of deposition for the stratigraphic interval between the dated Nacimiento ash bed and the top of the Ojo Alamo Sandstone (base of chron C29n) is 57 m/m.y. Extrapolation over the 201 m interval, between the Nacimiento ash bed and the base of the overlying Eocene San Jose Formation results in an age of 61.1 Ma for the base of the San Jose. The Paleocene-Eocene contact is 56.34 Ma, thus a hiatus of at least 4.8 m.y. must be present at the Paleocene-Eocene contact at Mesa de Cuba (assuming there are no significant, intervening unconformities). Puercan and Torrejonian mammal fossils have been identified in the Nacimiento Formation at numerous localities in the southern San Juan Basin. The boundary between these land-mammal stages is estimated to be at about the top of magnetochron C29n with an age of 65.06 Ma. This makes the duration of the Puercan Stage in the southern San Juan Basin about 1 m.y. In addition, this study shows that a recently reported U-Pb age of 64.8 Ma for a dinosaur bone from the Ojo Alamo Sandstone is too young. However, robust palynologic data still strongly support the Paleocene age of the Ojo Alamo Sandstone and its contained dinosaur fossils throughout the San Juan Basin.

INTRODUCTION

This paper presents revisions of previously published $^{40}Ar/^{39}Ar$ ages for rocks of latest Late Cretaceous and earliest Paleocene age in the southern part of the San Juan Basin, New Mexico. These age refinements are based on a recent publication by Renne et al. (2013) that reports a precise age for the Cretaceous-Paleogene (K-Pg) boundary of 66.043 Ma. This new age is based on the recalibration of the Fish Canyon Sanidine (FCS) to 28.294 Ma (Renne et al., 2011) and new dating of K-Pg sediments in Montana (Renne et al., 2013). The previously accepted age for the K-Pg boundary was 65.5 Ma and the previous age of the FCS was 28.02 Ma (Gradstein et al., 2004). To recalibrate the older published $^{40}Ar/^{39}Ar$ ages discussed herein a multiplier of 1.0098 (28.294/28.02) was used and all ages in this paper have been revised in this way. This simple linear multiplier can be used for rocks of this age especially since the total decay constant for 40K used for FCS at 28.294 and 28.02 Ma are nearly identical (Steiger and Jäger, 1977; Renne et al., 2011). A complicating factor is comparison of data collected by different $^{40}Ar/^{39}Ar$ laboratories (Heizler, 2012). This paper assumes perfect calibration between the Berkeley Geochronology Center results where Renne et al. (2013) dated the K-Pg boundary at 66.043 Ma and the New Mexico Geochronology Research Laboratory that determined the age of the Cuba Mesa ash bed reported by Fassett et al. (2010). Until resolved, this potential complication cannot be evaluated in this study.

STRATIGRAPHIC CROSS SECTION

Figure 1 contains an index map for the San Juan Basin and a larger scale geologic map of the southern edge of the basin. The line of cross section connects six localities where fossil mammals were found in the lower part of the Paleocene Nacimiento Formation. Figure 2 is a stratigraphic cross section showing the lithology of the rocks at these localities. This cross section is a modified version of a section in Williamson (1996, Fig. 9) and similar cross sections in Fassett (2009) and Fassett et al. (2010). At the DNZW, WFKW, and BTW localities (Fig. 2) the paleomagnetic sections shown are from Lindsay et al. (1981). At the MDC locality, the paleomagnetic data for the Cretaceous and lowermost Paleocene strata are from Fassett (2009).

Renne et al. (2011) revised the age of the FCS to 28.294 Ma based on comparison of $^{40}Ar/^{39}Ar$ sanidine dates with U-Pb zircon dates thus making dates from these two systems identical. Renne et al. (2013) studied the Hell Creek area of northeastern Montana and reported extremely precise $^{40}Ar/^{39}Ar$ ages for sanidine crystals from four altered volcanic ash beds just above the K-Pg boundary. The K-Pg boundary in their study area was defined by an iridium-enriched zone and definitive Cretaceous and Paleocene palynomorph collections, less than 10 cm apart, bracketing the iridium-enriched layer. At one of the Renne et al. (2013) study areas an altered ash bed about 18 m above the K-Pg boundary yielded a $^{40}Ar/^{39}Ar$ sanidine-crystal age of 65.990 ± 0.032/0.053 Ma and zircon crystals from this same bed "yielded a weighted mean U-Pb age of 65.988 ± 0.074 Ma," virtually identical ages. Renne et al. (2013) concluded that the K-Pg boundary in northeast Montana has an age of 66.043 ± 0.043 Ma.

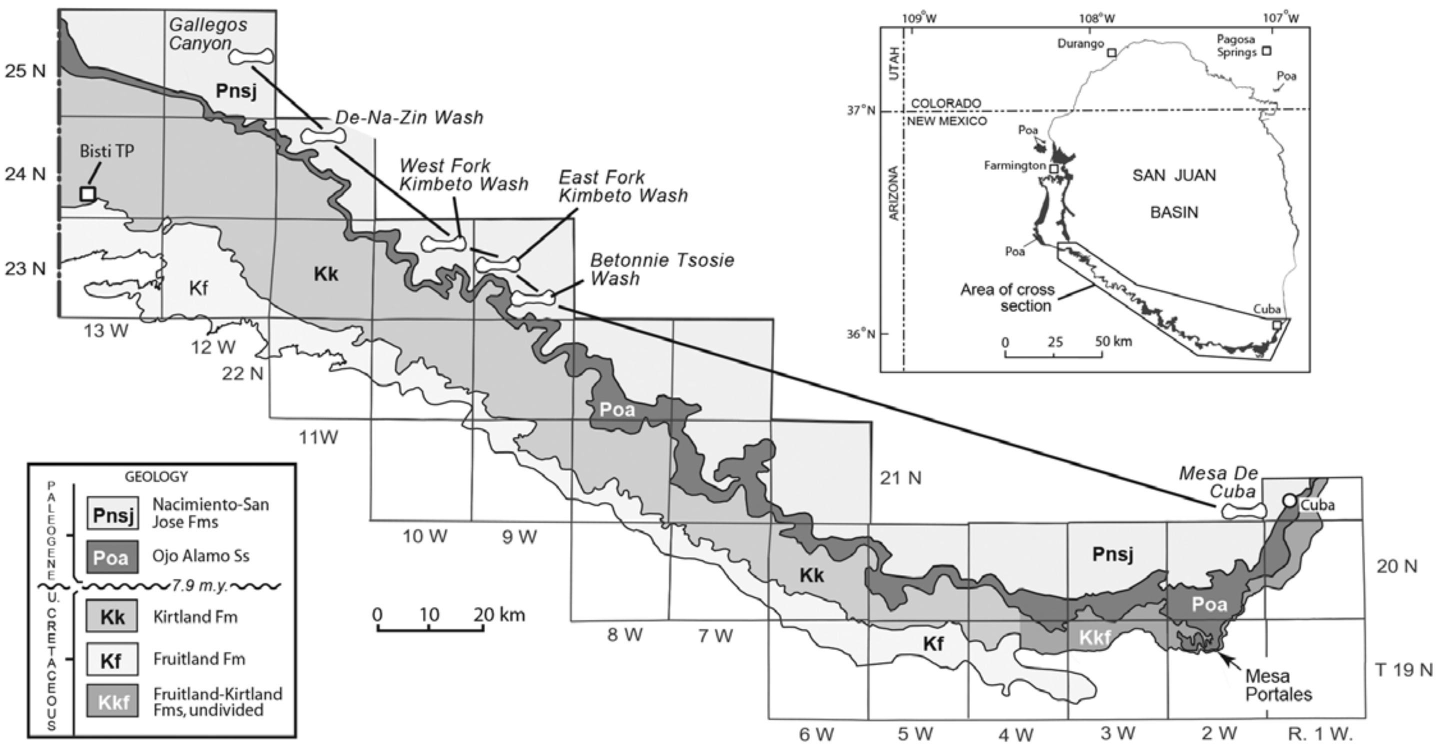


FIGURE 1. Geologic map of southern part of San Juan Basin showing line of section for stratigraphic cross section of Figure 2. Section connects areas of published fossil-mammal localities.

Ignoring inter-laboratory calibration issues (still to be resolved) this level of precision now allows for the recalibration of previously published $^{40}Ar/^{39}Ar$ ages based on the old FCS ages to the new standard with a high degree of confidence.

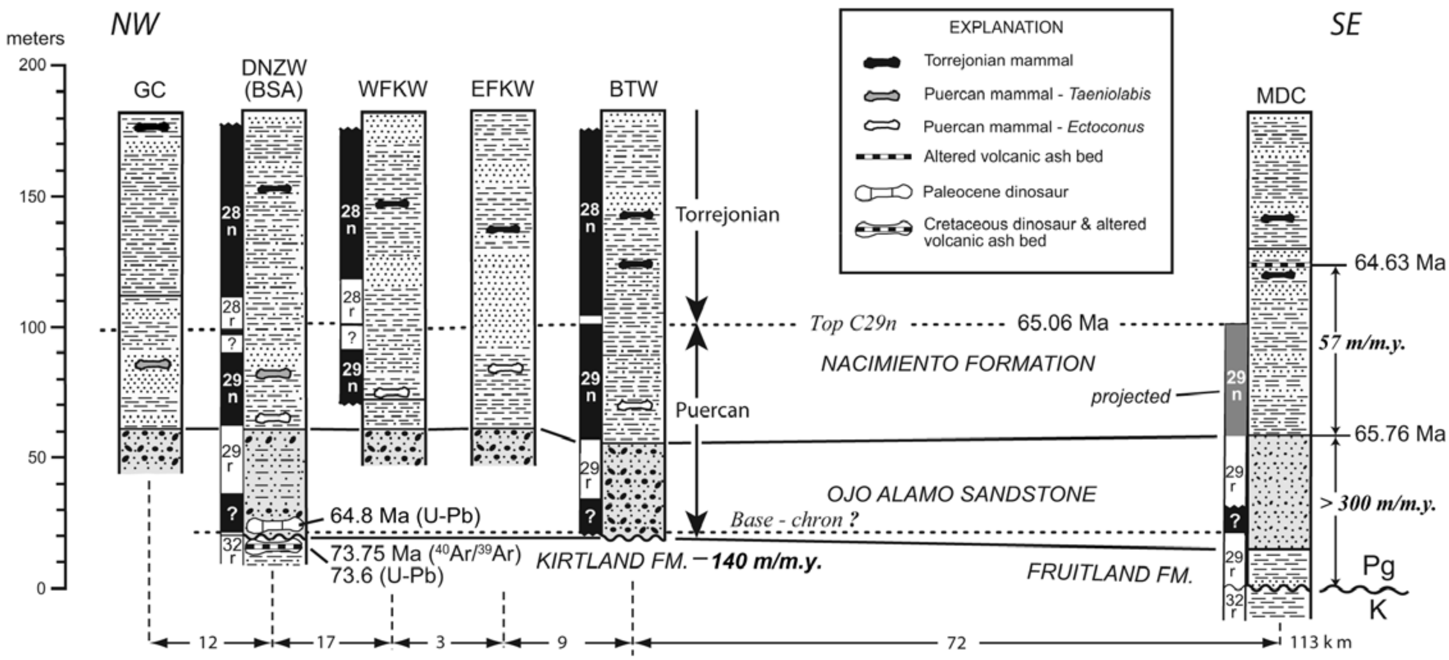
Eight $^{40}Ar/^{39}Ar$ ages have been obtained in the San Juan Basin for sanidine crystals from altered volcanic ash beds in the uppermost Cretaceous Lewis Shale and the Fruitland and Kirtland Formations (Fassett and Steiner, 1997; Fassett et al., 1997; Fassett, 2000). These age determinations were made by U.S. Geological Survey (USGS) geochronologist John Obradovich using the FCS age of 28.02 Ma as a standard. Only one of these ages is relevant to the discussion in this paper and is shown near the top of the Kirtland Formation at location DNZW (Fig. 2). The age shown for this ash bed (ash bed J in earlier publications) is adjusted to 73.75 Ma ± 0.25 Ma. A U-Pb age of 73.6 ± 0.9 Ma was obtained by laser ablation U-Pb methodology for a Cretaceous dinosaur bone (Fassett et al., 2011) near this same locality and at the same stratigraphic level as ash bed J. These two ages are in good agreement and well within the uncertainty range for both age determinations. A U-Pb age of 64.8 ± 0.9 Ma was obtained for a dinosaur-bone sample collected from the lower part of the Ojo Alamo Sandstone near this locality (Fassett et al., 2011); this age is younger than the strata from which it was collected (Fig. 2). The other $^{40}Ar/^{39}Ar$ age shown on Figure 2 is in the Nacimiento Formation at locality MDC and is adjusted to 64.63 ± 0.4 Ma from its originally published age of 64.0 Ma in Fassett et al. (2010).

REVISION OF PALEOMAGNETIC INTERPRETATIONS

Paleocene Strata

One of the changes made to the Figure 2 cross section from its earlier version in Fassett et al. (2010) was to align the top of magnetochron C29n at the top of the short normal-polarity intervals at localities DNZW and WFKW and the longer normal-polarity interval at BTW thus making this essentially a horizontal line on the cross section. This was a judgment call that made this isochron virtually parallel to the base of the very short normal-polarity interval (labeled with a query) within and near the base of the Ojo Alamo Sandstone. As Figure 2 shows, the top of chron C29n with an age of 65.06 Ma (adjusted from Gradstein et al., 2004) is projected into the MDC section.

Mason et al. (2013) reported an age for an altered volcanic ash bed in the lower part of the Nacimiento Formation of 65.7 Ma. An exact stratigraphic level for this ash bed in the Nacimiento Formation was not provided. The adjusted age of the base of magnetochron C29n from that given in Gradstein et al. (2004) is 65.76 Ma. At the DNZW and the BTW localities (Fig. 2) the base of a long, normal paleomagnetic interval is present very near the top of the Ojo Alamo Sandstone. Because the age of the base of this normal interval is slightly below the Mason et al. (2013) age of 65.70 Ma, the base of this normal interval at the two localities must represent the actual base of magnetochron C29n. It must therefore be concluded that the base of chron C29n in the southern San Juan Basin is at the top of the Ojo Alamo Sandstone, and



NOTES: 1. GC = Gallegos Canyon, DNZW = De-na-zin Wash (same locality as BSA - Barrel Spring Arroyo of Lindsay and others, 1981), WFKW = West Fork Kimbeto Wash, EFKW = East Fork Kimbeto Wash, BTW = Betonnie Tsosie Wash, MDC = Mesa de Cuba

FIGURE 2. Stratigraphic cross section trending southeast across south edge of San Juan Basin. Section localities (Fig. 1) are sites where Paleocene mammal fossils have been identified in the Nacimiento Formation (modified from Fassett, 2009, Fig. 42, and Fassett et al., 2010, Fig. 7); those cross sections are modifications of Figure 9 of Williamson (1996).

not near its base as was stated in Fassett (2009) and Fassett et al. (2010). The very short normal interval near the base of the Ojo Alamo that was stated to be the base of C29n in earlier publications must now be considered to be a hitherto unknown normal interval in the upper part of magnetochron C29r.

These data make it possible to calculate the rate of deposition for the lowermost Nacimiento Formation; that is the interval between the 64.63 Ma Nacimiento Formation ash bed at Mesa de Cuba and the top of the Ojo Alamo Sandstone (base of C29n) at 65.76 Ma (see MDC column on Fig. 2). This 64 m interval represents 1.13 m.y., thus the rate of deposition for the lower part of the Nacimiento Formation in the southern San Juan Basin is 57 m/m.y. With the top of the Ojo Alamo Sandstone at 65.76 Ma and the K-Pg boundary at 66.04 Ma (Renne et al., 2011) the maximum time available for deposition of the Ojo Alamo Sandstone would have been 0.28 m.y. Because previous studies (for example Fassett, 2009) have indicated that the base of the Ojo Alamo probably does not represent the base of the Paleocene, for purposes of calculating a rate of deposition for the Ojo Alamo Sandstone, it is here assumed that the base of the Paleocene at the Mesa de Cuba locality may be about 65.95 Ma. Because this interval measures about 60 m and occupies an estimated time span of about 0.2 m.y., the resulting sedimentation rate for this interval would be about 300 m/m.y. (Fig. 2). This high rate of deposition comes as no surprise given the nature of the Ojo Alamo as a high-energy, conglomeratic, braided-stream deposit with abundant occurrences of soft-sediment deformation within it as discussed in numerous publications, such as Fassett (2000, 2009).

Deposition rates for uppermost Upper Cretaceous strata in the San Juan Basin averaged 144 m/m.y. from 76.39 Ma to 73.65 Ma – the time during which the final regression of the Pictured Cliffs Sandstone shoreline (the western margin of the Western Interior Seaway) across the San Juan Basin area took place (Fassett, 2000). These data suggest the following geologic history: the San Juan Basin area was subsiding during latest Cretaceous time providing accommodation space averaging about 144 m/m.y. Later, this episode of subsidence ceased and was followed by an episode of erosion and possibly non-deposition lasting 7.9 m.y. Next, the basin again began to subside in early Paleocene time, first allowing for the rapid pulse of Ojo Alamo Sandstone deposition to occur, followed by a period of much slower subsidence and deposition during Nacimiento Formation time.

The very short normal paleomagnetic interval near the base of the Ojo Alamo Sandstone (labeled with a query on Figure 2) is present at the DNZW, BTW, and MDC localities (Fig. 2). This normal interval was also found at three other localities in the southern San Juan Basin at about the same level in the Ojo Alamo Sandstone (Fassett, 2009); in that paper (p. 40 of the PDF version), the following conclusions were drawn:

> *At six localities (Figures 26, 27), a normal polarity interval was found to be present in the lower part of the Ojo Alamo Sandstone. In the four sections where this normal interval was bracketed by reversed-polarity sites (Figures 26, 27), it is about 11 m thick. Biochronologic*

[primarily palynologic] *evidence (discussed below) unequivocally shows that the Ojo Alamo Sandstone is Paleocene, thus the normal polarity interval in the lower Ojo Alamo is the lowermost part of chron C29n (herein labeled C29n.2n).*

The evidence presented above, however, clearly shows that the base of magnetochron C29n is at or near **the top** of the Ojo Alamo Sandstone and thus the normal polarity interval within and near the base of the Ojo Alamo cannot be chron C29n.2n as indicated by Fassett (2009). In that paper, Fassett stated that because chron C29n was present in the Ojo Alamo Sandstone, that finding supported its Paleocene age. With the new placement of the base of C29n near the top of the Ojo Alamo Sandstone, Fassett's 2009 argument that paleomagnetism supports the Paleocene age of the Ojo Alamo is no longer valid. The normal paleomagnetic interval in the lower part of the Ojo Alamo Sandstone (Fig. 2) would probably not have been preserved and detected had it not been for the very rapid rate of deposition of the Ojo Alamo Sandstone. Even though these findings eliminate what was thought to be an independent paleomagnetic confirmation of the Paleocene age of the Ojo Alamo Sandstone, the powerful and robust palynologic data base for the Ojo Alamo Sandstone and underlying strata (Fassett and Lucas, 2000; Fassett, et al., 2000; Fassett et al., 2002; Fassett, 2009) still supports the Paleocene age of this formation. In the Renne et al. (2013) paper discussed above, palynologic data helped to precisely define the K-Pg boundary within a few centimeters, therefore those results reinforce the fact that palynology is a powerful and very sharp tool with which to define the K-Pg boundary throughout the Western Interior of North America (including in the San Juan Basin).

Cretaceous Strata

Figure 3, a geologic map of the MDC-Mesa Portales area, shows the location of a drill hole in the northern part of the map area (the geophysical log of this drill hole is shown on Figure 4).

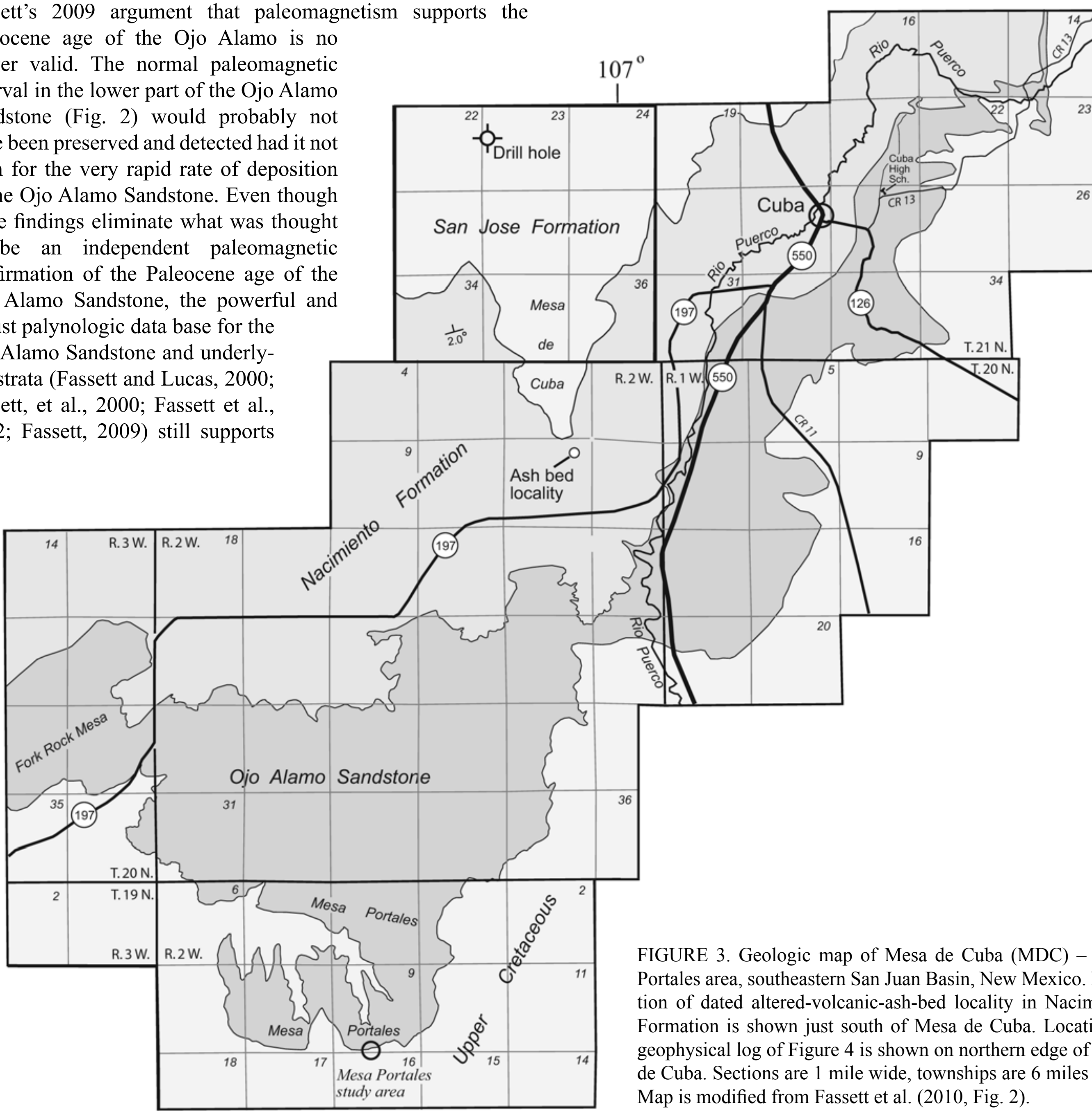


FIGURE 3. Geologic map of Mesa de Cuba (MDC) – Mesa Portales area, southeastern San Juan Basin, New Mexico. Location of dated altered-volcanic-ash-bed locality in Nacimiento Formation is shown just south of Mesa de Cuba. Location of geophysical log of Figure 4 is shown on northern edge of Mesa de Cuba. Sections are 1 mile wide, townships are 6 miles wide. Map is modified from Fassett et al. (2010, Fig. 2).

Figure 4 shows that the uppermost Cretaceous is represented at the Mesa Portales locality (Fig. 3) by the Fruitland Formation. The results of a paleomagnetic traverse up the front of Mesa Portales through the Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, and lower part of the Ojo Alamo Sandstone were published in Fassett (2009) and as Figure 4 shows, that traverse crossed the C33n-C32r paleomagnetic reversal. This same reversal was also found northwest of Mesa Portales at two localities in the De-na-zin area of Figure 1. In that area five precise $^{40}Ar/^{39}Ar$ ages bracketed (three below, two above) this reversal allowing for the determination of a precise age for the C33n-C32r reversal there. That age, published in Fassett and Steiner (1997) and Fassett (2000), was found to be 73.50 ± 0.19 Ma. Adjusting this age relative to the Renne et al. (2011) age for the FCS yields an age of 74.22 Ma for this reversal (Fig. 4). The Gradstein et al. (2012) time-scale publication did not reference this precise age determination for the C33n-C32r paleomagnetic reversal in the San Juan Basin thus they show a far less precise age for this reversal of 74.309 Ma based on extrapolations and projections. The failure of Gradstein et al. (2012) to include the Fassett and Steiner (1997) and Fassett (2000) very precise age for the C33n-C32r reversal is a serious flaw in their work for determining the age of not only the C33n-C32r reversal, but also may affect their ages for the paleomagnetic reversals in the overlying Cretaceous-strata up to the K-Pg boundary. A recalibration of those reversal ages, however, is beyond the scope of this short report.

OTHER RADIOMETRIC AGES

At locality DMZW on the Figure 2 cross section, a dinosaur bone is shown in the lower part of the Ojo Alamo Sandstone with an age of 64.8 ± 0.9 Ma. This age was obtained on a sample labeled BB-1 from a fragment of a very large hadrosaur femur using laser ablation U-Pb methodology (Fassett et al., 2011). The recalibration of the base of chron C29n at or near the top of the Ojo Alamo Sandstone with an age of 65.76 Ma makes the mean age of 64.8 ± 0.9 Ma for BB-1 too young even considering the relatively high uncertainty for the 64.8 Ma date. Because the sampled bone was only 1.8 m above the base of the Ojo Alamo Sandstone, its true age must be about 65.9 Ma, i.e., the estimated age of this stratigraphic level. The oldest end of the uncertainty range for the 64.8 age of the BB-1 bone sample places it at 65.7 Ma or not quite within the revised age for the top of the Ojo Alamo. Work is

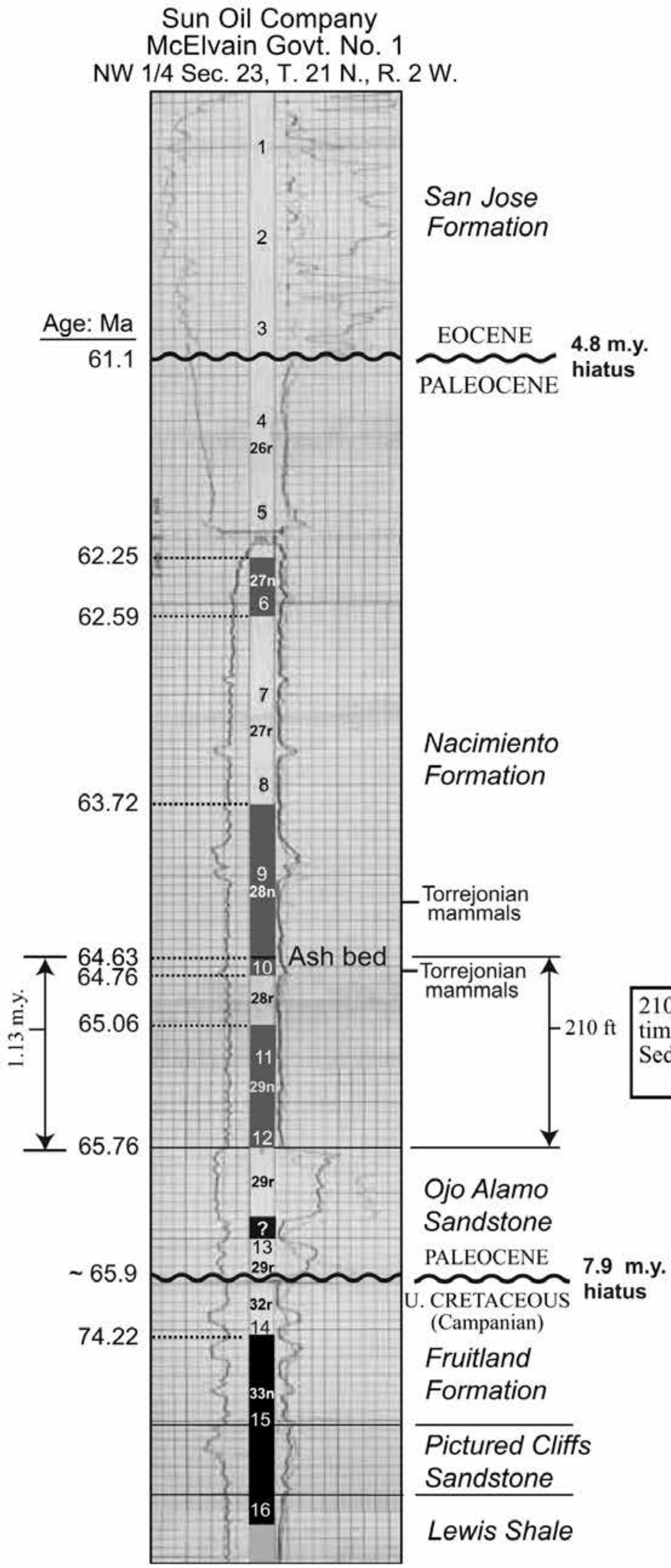


FIGURE 4. Electric log showing geologic strata penetrated in the Sun Oil Co. McElvain Govt. No. 1 drill hole in the Mesa de Cuba area (Fig. 3); section shown is from Upper Cretaceous Lewis Shale through Eocene San Jose Formation. Nacimiento Formation ash bed at Mesa de Cuba is projected into log. Log depths shown are in hundreds of feet. Paleomagnetic chrons within Nacimiento Formation are projected into log based on reversal dates adjusted from Gradstein et al. (2004). Paleomagnetic data shown in uppermost Upper Cretaceous rocks and Ojo Alamo Sandstone from Fassett (2009). Figure is modified from Fassett et al. (2010).

K-Pg boundary = 66.04 Ma; Paleocene-Eocene boundary = 56.34 Ma. Paleocene paleomagnetic reversal ages shown on left side of log column recalibrated from Gradstein, et al. (2004); age of C33n-C32r magnetochron reversal recalibrated from age reported in Fassett (2000). Magnetochrons in Nacimiento Formation are all projected into this log section based on recalibrated ages from Gradstein et al. (2004).

in progress to try and increase the precision and accuracy of the laser-ablation U-Pb age of BB-1.

The adjusted $^{40}Ar/^{39}Ar$ age of 73.75 Ma for the ash bed at the top of the Kirtland Formation (shown at locality DNZW on Figure 2) is in the upper part of the Campanian; Gradstein et al. (2012) give an age of 72.1 Ma for the Campanian-Maastrichtian boundary. This means that about 1.5 m.y. of the uppermost Campanian and all of the Maastrichtian are missing in the San Juan Basin due to the 7.9 m.y. hiatus at the K-Pg boundary. Most of the missing section is from the uppermost Cretaceous with only about an estimated 0.05 m.y. of section missing from the lowermost Paleocene. This conclusion is supported by a detrital-sanidine age of 66.5 ± 0.2 Ma (Mason et al., 2013) for the lower part of the Ojo Alamo Sandstone near the DNZ locality of Figure 1. A detrital sanidine age, of course, can only provide a maximum age for a rock unit because there is no way of knowing if the youngest detrital sanidine grains representing the true age of the rock unit were present in the sample. Thus, this age in no way contravenes the robust palynologic database (Fassett, 2009) confirming the Paleocene age of the Ojo Alamo Sandstone.

MAMMAL-ZONE AGES

Figure 2 also shows the levels of published, Paleocene mammal-fossil localities in the southern San Juan Basin as provided by Williamson (1996). The Figure 2 cross section shows that the North American Land Mammal Ages (NALMA) represented thereon are based on the identification of Puercan and Torrejonian fossils within the Nacimiento Formation. The Puercan Stage was further subdivided into the *Taeniolabus* and *Ectoconus* zones in Williamson (1996) as shown. All of the Puercan-age mammals are in magnetochron C29n and the Torrejonian age mammals are in chron C28n. The boundary between these two Stages is about at the top of chron C29n with an age of 65.06 Ma. This would make the duration of the Puercan Stage in the southern San Juan Basin about 1 m.y.

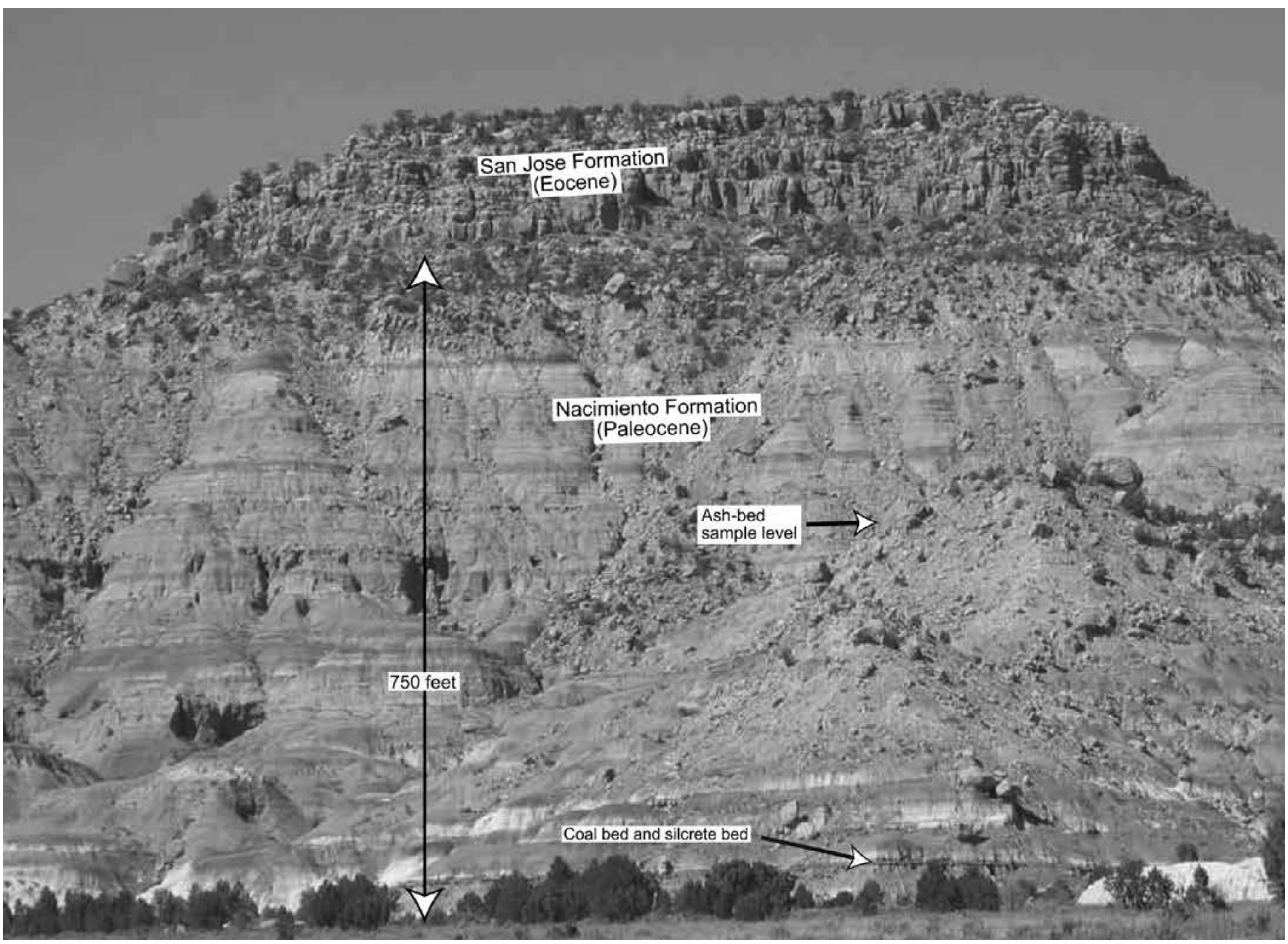


FIGURE 5. View looking north at the south end of Mesa de Cuba, southwest of Cuba, New Mexico (see paper by Fassettt, this guidebook). The Nacimiento Formation ash-bed sample locality is in a small saddle in the cliff face behind the prominent ridge in the foreground mantled and armored by San Jose Formation landslide blocks. Tip of the uppermost white arrow is at base of San Jose Formation where an unconformity of about 4.8 m.y. is present. (See also Color Plate 10)

PALEOCENE-EOCENE (NACIMIENTO-SAN JOSE FORMATION) CONTACT

Figure 3 shows the geology of the MDC (Mesa de Cuba) area and shows the location of a drill hole in the northwest part of the area in Sec. 23, T. 21 N., R. 2 W. Also shown on this figure is the location of the 64.63 Ma Nacimiento Formation ash bed in Sec. 11, T. 20 N., R. 2 W. Figure 5 shows annotated photographs of Mesa de Cuba. The annotated geophysical log of the MDC drill hole is shown on Figure 4. This log includes the geologic section from the lower part of the Eocene San Jose Formation at the top to the Cretaceous Lewis Shale at the base. The contacts of the San Jose Formation, Nacimiento Formation, Ojo Alamo Sandstone, Fruitland Formation, Pictured Cliffs Sandstone, and Lewis Shale are clear on this log. The level of the dated Nacimiento ash bed is projected into this log along with the projected position of the top and base of magnetochron C29n. The short magnetochron in the Ojo Alamo Sandstone plus the underlying polarity zones shown were determined based on field work in the Mesa Portales area in Sec. 9, T. 19 N., R. 2 W. in the southern part of Figure 3 as discussed in detail in Fassett (2009).

On the Figure 4 geophysical log, the stratigraphic interval between the dated Nacimiento ash bed and the base of the San Jose Formation at Mesa de Cuba is 660 ft (201 m). The time elapsed for deposition of this interval as determined, by extrapolation of a deposition rate of 57 m/m.y. is 3.5 Ma. The contact between the top of the Nacimiento Formation and the base of the San Jose Formation is thus estimated to be about 61.1 Ma. The recalibrated age of the Paleocene-Eocene boundary (from that reported in Gradstein et al., 2004) is 56.34 Ma., thus there is an apparent 4.8 m.y. hiatus at this contact on Mesa de Cuba (assuming there are no significant undetected unconformities in the uppermost part of the Nacimiento Formation and the rate of deposition remained constant throughout this time interval). Further examination of the rock strata in this interval may reveal additional dateable ash beds; also, a paleomagnetic survey at Mesa de Cuba could help to refine these interpretations. Because the exact age of the lowermost part of the San Jose Formation is not known, it is possible that there is an additional hiatus in the lower part of the Eocene in this area, thus the estimated 4.8-m.y. hiatus could be longer by an unknown amount.

ACKNOWLEDGMENTS

This paper continues studies initiated and supported by a U.S.G.S. Gilbert Fellowship awarded to the author in 1987. Further work has been supported by U.S.G.S. Bradley-Scholar grants awarded to the author as a U.S.G.S Scientist Emeritus since his retirement in 2000. This paper was improved by careful peer reviews by Gil Mull, Santa Fe, NM, and Matt Heizler, New Mexico Tech, Socorro, NM. Matt Heizler and Bill McIntosh at NM Tech have been incredibly helpful both in spending time in the field with the author, but also in dating most of the rock samples discussed in this report and I thank them and the entire staff of the New Mexico Geochronology Research Laboratory for their superb work in pursuit of the Truth about the K-Pg boundary rocks of the San Juan Basin. Geologic interpretations are not always totally agreed to by all colleagues, thus I hasten to add that even though this report represents my best interpretations of the available data, these interpretations may not be totally endorsed by all of those acknowledged above.

REFERENCES

Fassett, J.E., Cobban, W.A., and Obradovich, J.D., 1997, Biostratigraphic and isotopic age of the Huerfanito Bentonite Bed of the Upper Cretaceous Lewis Shale at an outcrop near Regina, New Mexico, in Anderson, O.J., Kues, B.S., and Lucas, S.G., eds., Mesozoic geology and paleontology of the Four Corners Region, New Mexico: New Mexico Geological Society 48th Annual Field-Conference Guidebook, p. 229-232.

Fassett, J.E., and Steiner, M.B., 1997, Precise age of C33n-C32r magnetic-polarity reversal; San Juan Basin, New Mexico and Colorado, in Anderson, O. J., Kues, B.S., and Lucas, S.G., eds., Mesozoic geology and paleontology of the Four Corners Region: New Mexico Geological Society 48th Annual Field-Conference Guidebook, p. 239-247.

Fassett, J.E., 2000, Geology and coal resources of the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado, Chapter Q, in Kirschbaum, M. A., Roberts, L.N.R., and Biewick, L.R.H., eds., Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah, compiled by Colorado Plateau Coal Assessment Group: U.S. Geological Survey Professional Paper 1625-B, p. Q1-Q131. [CD-ROM]. http://pubs.usgs.gov/pp/p1625b/Reports/Chapters/Chapter_Q.pdf

Fassett, J.E., and Lucas, S.G., 2000, Evidence for Paleocene dinosaurs in the Ojo Alamo Sandstone, San Juan Basin, New Mexico, in Lucas, S. G., and Heckert, A.B., eds., Dinosaurs of New Mexico: New Mexico Museum of Natural History and Science Bulletin 17, Albuquerque, NM, p. 221-230.

Fassett, J.E., Lucas, S.G., Zielinski, R.A., and Budahn, J.R., 2000, Compelling new evidence for Paleocene Dinosaurs in the Ojo Alamo Sandstone, San Juan Basin, New Mexico and Colorado, USA, in Koeberl, C., chairperson, Catastrophic events and mass extinctions: Impacts and beyond: Vienna, Austria, July 9-12, 2000: Lunar and Planetary Institute, Houston, Texas, p. 45-46.

Fassett, J.E., Zielinski, R.A., and Budahn, J.R., 2002, Dinosaurs that did not die; evidence for Paleocene dinosaurs in the Ojo Alamo Sandstone, San Juan Basin, New Mexico, in Koeberl, C., and MacLeod, K.G., eds., Catastrophic Events and Mass Extinctions: Impacts and Beyond: Geological Society of America Special Paper 356, p. 307-336.

Fassett, J.E., 2009, New geochronologic and stratigraphic evidence confirms the Paleocene age of the dinosaur-bearing Ojo Alamo Sandstone and Animas Formation in the San Juan Basin, New Mexico and Colorado: Palaeontologia Electronica, v. 12, no. 1, 146 p. (on-line pub. at: http://palaeo-electronica.org/splash/index12_1.html).

Fassett, J.E., Heizler, M.T., and McIntosh, W.C., 2010, Geologic implications of a $^{40}Ar/^{39}Ar$ single-crystal sanidine age for an altered volcanic ash bed from the Paleocene Nacimiento Formation in the southern San Juan Basin, in Fassett, J.E., and Zeigler, K.E., eds., Geology of the Four Corners Country: New Mexico Geological Society 61st Annual Field Conference Guidebook, p. 147-156.

Fassett, J.E., Heaman, L.M., and Simonetti, A., 2011, Direct U-Pb dating of Cretaceous and Paleocene dinosaur bones, San Juan Basin, New Mexico: Geology, v. 39, p. 159-162, doi:10.1130/G31466.1.

Gradstein, F.M., Ogg, J.G., and Smith, A.G., 2004, A geologic time scale 2004: Cambridge University Press, Cambridge, UK., 589 p.

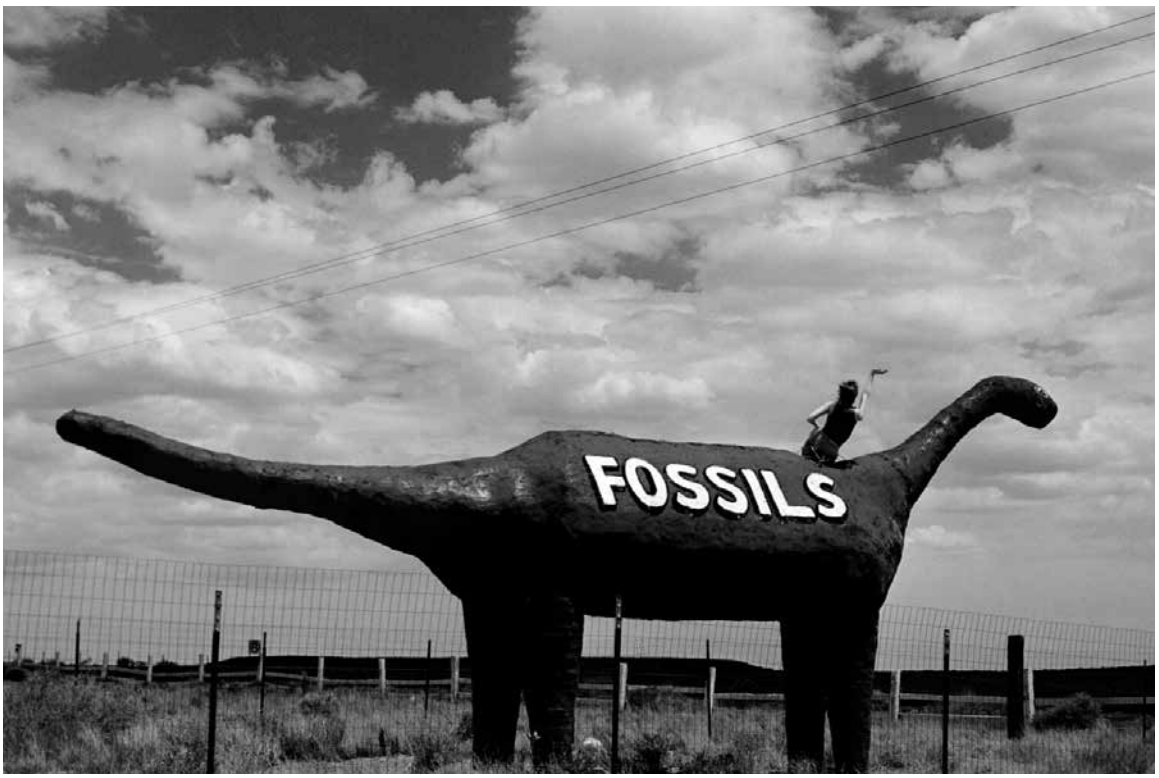
Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., 2012, The geologic time scale 2012: Elsevier, 2 volumes, 1144 p.

Heizler, M.T., 2012, Higher Precision: Opening a new $^{40}Ar/^{39}Ar$ can of worms, abs. V21E-02, presented at 2012 Fall Meeting, AGU, San Francisco, California, December 3-7.

Lindsay, E.H., Butler, R.F., and Johnson, N.M., 1981, Magnetic polarity zonation and biostratigraphy of Late Cretaceous and Paleocene continental deposits, San Juan Basin, New Mexico: American Journal of Science, v. 281, p. 390-435.

Mason, I.P., Heizler, M.T., and Williamson, T.E., 2013, $^{40}Ar/^{39}Ar$ sanidine chronostratigraphy of K-Pg boundary sediments of the San Juan Basin, NM, (abs.): New Mexico Geological Society 2013 Spring Meeting Proceedings

Volume, Socorro, NM, April 12, 2013.
Renne, P.R., Balco, G, Ludwig, K.R., Mundil, R., and Min, K., 2011, Response to the comment by W.H. Schwarz et al. on Joint determination of 40K decay constants and $^{40}Ar^{*}/^{40}K$ for the Fish Canyon sanidine standard, and improved accuracy for $^{40}Ar/^{39}Ar$ geochronology by Renne et al. (2010): Geochimica et Cosmochimica Acta v. 75, p. 5097.
Renne, P.R., Deino, A.L., Hilgen, F.J., Kuiper, K.F., Mark, D.F., Mitchell, W.S, III, Morgan, L.E., Mundil, R., and Smit, J., 2013, Time scales of critical events around the Cretaceous-Paleogene boundary: Science, v. 339, p. 684-687.
Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planet Science Letters, v. 36, p. 359-362.
Williamson, T. E., 1996, The beginning of the age of mammals in the San Juan Basin: Biostratigraphy and evolution of Paleocene mammals of the Nacimiento Formation, New Mexico Museum of Natural History and Science Bulletin 8, 141 p.



Green “fossils” dinosaur. *Photo courtesy of Steve Semken.*