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Geologic implications of an 40AR/39Ar single-crystal sanidine age for an altered volcanic ash bed in the Paleocene Nacimiento Formation in the southern San Juan Basin

James E. Fassett, Matthew T. Heizler, and William C. McIntosh
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New Mexico Geological Society Guidebook, 61st Field Conference, Four Corners Country, 2010, p. 147-156.

GEOLOGIC IMPLICATIONS OF AN $^{40}AR/^{39}AR$ SINGLE-CRYSTAL SANIDINE AGE FOR AN ALTERED VOLCANIC ASH BED IN THE PALEOCENE NACIMIENTO FORMATION IN THE SOUTHERN SAN JUAN BASIN

FASSETT, JAMES E.[1], HEIZLER, MATTHEW T.[2], AND McINTOSH, WILLIAM C.[2]
[1] U. S. Geological Survey, Scientist Emeritus, 552 Los Nidos Drive, Santa Fe, NM 87501, jimgeology@qwest.net
[2] New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, 801 Leroy Place, Socorro, NM 87801

ABSTRACT——The first $^{40}Ar/^{39}Ar$ single-crystal age for Paleogene strata in the southern San Juan Basin was obtained from sanidine crystals recovered from an altered volcanic ash bed in the Paleocene Nacimiento Formation at Mesa de Cuba near Cuba, NM. The age, 64.0 ± 0.4 Ma (2 sigma), is based on single crystal sanidine results relative to Fish Canyon sanidine at 28.02 Ma and a total 40K decay constant of 5.543E-10/a. Due to significant contamination by older K-feldspar crystals, this date is considered a maximum depositional age. Stratigraphically, the dated ash bed is 119 m above the Cretaceous-Tertiary contact and 76 m above the Nacimiento/Ojo Alamo Sandstone contact. This age places the ash bed near the bottom of magnetochron C28n. The lower part of chron C29n was identified within the underlying Ojo Alamo Sandstone at Mesa Portales, about 12 km south of the Mesa de Cuba ash-bed locality; the base of this chron is 98 m below the dated ash bed. This age determination allowed a calculation of the rate of sedimentation for underlying Paleocene strata of 73 m/m.y. (not corrected for compaction). Extrapolating this rate of deposition to overlying Nacimiento Formation strata to the base of the Eocene San Jose Formation places that formation boundary at 61.42 Ma. Because the Paleocene-Eocene contact is 55.8 Ma, a long-lasting hiatus of at least 5.6 m.y. must be present at the Paleocene-Eocene contact at Mesa de Cuba (assuming there are no significant, intervening unconformities present in Nacimiento strata overlying the dated ash bed). Puercan and (or) Torrejonian mammal fossils have been identified at numerous localities in the southern San Juan Basin, including at Mesa de Cuba. The boundary between these two land-mammal zones is estimated to be at about the top of magnetochron C29n with an age of about 64.4 Ma thus making the duration of the Puercan land-mammal age 1.1 m.y. in the San Juan Basin. This newly documented presence of a 5.6 m.y. hiatus between Paleocene and Eocene rocks in the San Juan Basin will require a revised evaluation of the burial history of the San Juan Basin during Tertiary time.

INTRODUCTION

The San Juan Basin of northwestern New Mexico and southwestern Colorado (Fig. 1) is noted for its vertebrate fossils, especially in rocks adjacent to the Cretaceous-Paleogene (K-T) interface. The uppermost Cretaceous rock unit throughout most of the southern part of the basin is the Kirtland Formation of Campanian age. Approximately 7.5 m.y. of latest Cretaceous time (Maastrichtian stage) is not represented by rock strata in the basin (Fassett, 2000, 2009; Fassett, et al., 2002). The lowermost Paleocene formation in the southern part of the basin is the Ojo Alamo Sandstone and paleomagnetic and palynologic evidence indicates that the lowermost 0.3 m.y. of the Paleocene is not represented by sedimentary rock strata (Fassett, 2009). The Paleocene Nacimiento Formation directly and conformably overlies the Ojo Alamo Sandstone in the southern San Juan Basin. In the northern part of the basin, mostly in Colorado, the Animas Formation is the same age as the Ojo Alamo-Nacimiento Formations and unconformably overlies Upper Cretaceous strata, including (from northwest to northeast) the McDermott, Kirtland, and Fruitland Formations.

Vertebrate fossils have historically been the primary biochronologic age indicators for the continental uppermost Cretaceous and Paleogene strata in the San Juan Basin. Beginning in the 1960s, fossil pollen and spores became crucial in determining the stratigraphic position of the K-T interface in the basin (Anderson, 1960, Fassett and Hinds, 1971, Fassett, 2000, 2009; Fassett et al, 2002), but these palynomorphs have not allowed for very precise age determinations within the Cretaceous or within Paleocene strata adjacent to the boundary. Dinosaur fossils in the Kirtland and Fruitland Formations were historically used to help place the

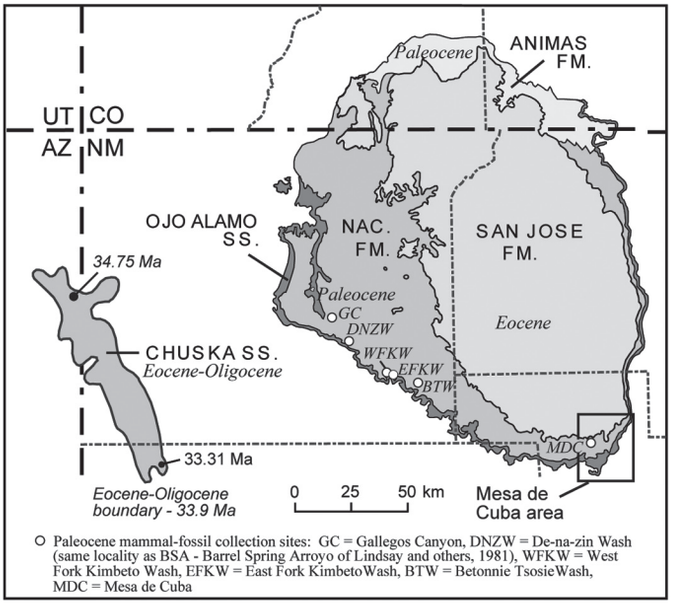


FIGURE 1. Index map of San Juan Basin, northwestern New Mexico and southwestern Colorado, showing geologic formations of Paleogene age. Mesa de Cuba area is shown on Figure 2. Nac. Fm. = Nacimiento Formation. Map is modified from geologic map in Fassett and Hinds (1971).

K-T interface in the basin, based on the commonly held belief that dinosaurs were exclusively Cretaceous, having become extinct at the end of the Cretaceous. That assumption has now been shown to be incorrect, as discussed in Fassett and Lucas (2000), Fassett et al. (2000), Fassett et al., (2002), and Fassett, (2009). The use of dinosaurs for age determinations within rock strata adjacent to the K-T interface in the San Juan Basin has been of limited value, primarily because of the fragmentary and endemic nature of those fossils. In addition, wide disagreements among vertebrate paleontologists as to the age significance of dinosaur-fossil assemblages in the San Juan Basin have clouded their value as age indicators. Fassett (2009, p. 23 of the PDF version), discussed this issue and noted that:

> For example, Sullivan, Lucas, and Braman (2005) contended that the Ojo Alamo contains a dinosaur fauna that is latest Campanian or early Maastrichtian whereas Weil and Williamson (2000) and Farke and Williamson (2006) state that the vertebrate fauna of the lower Ojo Alamo is clearly Lancian (latest Maastrichtian) in age.

Thus, an age discrepancy of as much as 5 m.y. exists (using the ages assigned to these different times by Gradstein et al. (2004)) for the fauna of the Ojo Alamo Sandstone as reckoned by the above authors – no small disagreement.

Fossil mammals have also been reported from uppermost Cretaceous strata in the basin, for example: Clemens (1973), Rigby and Wolberg (1987), and summarized in Fassett (2009). However these Cretaceous mammal fossils do not have precise age significance.

The Paleocene Ojo Alamo Sandstone has yielded a rather diverse dinosaur fauna and this fauna (as might be expected) is similar to dinosaur faunas of latest Cretaceous age in other parts of the Western Interior of North America. The Ojo Alamo has also yielded sparse collections of mammal fossils previously assigned to the Cretaceous, but these are now known to be from rocks of Paleocene age (Fassett, 2009). The overlying Paleocene Nacimiento Formation and the Eocene San Jose Formation are well known for their mammal fossils, for example those noted by Simpson (1959) and Williamson (1996). In fact, the Puercan, Torrejonian, and Tiffanian (North American land mammal ages—NALMAs) are named for fossil-mammal localities in the San Juan Basin. Palynological collections from Paleogene strata in the San Juan Basin, however, have only been marginally time diagnostic (Fassett, 2009).

A series of eight $^{40}Ar/^{39}Ar$ ages have been reported for Upper Cretaceous rocks in the southern San Juan Basin (Fassett and Steiner, 1997, Fassett et al., 1997, and Fassett, 2000). These ages range from 75.76 ± 0.34 Ma for the Huerfanito Bentonite Bed of the Lewis Shale to 73.04 ± 0.25 Ma for an altered volcanic ash near the top of the Kirtland Formation. These ages, plus the intervening six ages distributed through the Fruitland and Kirtland Formations, have now allowed the assignment of precise ages to the floral and faunal assemblages previously reported from these Cretaceous formations.

Until now, no radiometric ages had been determined for Paleogene rocks in the central San Juan Basin (Fig. 1), however, we herein present the results of a $^{40}Ar/^{39}Ar$ age determination for sanidine crystals collected from an altered volcanic ash bed in the Paleocene Nacimiento Formation in the southeastern part of the San Juan Basin near Cuba, N.M. at Mesa de Cuba (Fig. 2). This age determination, the first radiometric age to be reported for Paleogene rocks in the central basin, now allows for precise dating of Puercan and Torrejonian faunal zones in this area and it also permits the determination of an approximate age for the contact between the Paleocene Nacimiento Formation and the overlying Eocene San Jose Formation and establishes the presence of a 5.6- m.y. hiatus at that contact.

CHUSKA SANDSTONE

Figure 1 shows the distribution of Paleogene and slightly younger rock strata in the San Juan Basin area. The Chuska Sandstone is present west of the central San Juan Basin and is exposed along a northwest trend that crosses the New Mexico-Arizona State line. The ages for two altered volcanic ash beds from within the Chuska Sandstone were recently published by Cather et al. (2003). An age of 34.75 ± 0.20 Ma was obtained from an ash bed in these author's newly named Deza Member in the lower part of the Chuska and an age of 33.31 ± 0.25 Ma was obtained for an ash bed in the newly named Narbona Pass Member in the upper part of the Chuska Sandstone. Of these two ages, Cather et al. (2003) suggested that the older age is the more precise of the two. These ages place the Chuska Sandstone in the uppermost Eocene-lowermost Oligocene according to Gradstein et al. (2004) who placed the Paleocene-Eocene boundary at 33.9 Ma. Four samples of extrusive trachybasalts that overlie and postdate the Chuska in this area have yielded ages, according to Cather et al. (2003), ranging from 24.83-25.24 Ma with a weighted mean age of 25.05 ± 0.16 Ma.

PALEOGENE OF THE CENTRAL SAN JUAN BASIN

The central part of the San Juan Basin (Fig. 1) contains three Paleogene formations: the Ojo Alamo Sandstone and Nacimiento Formation of Paleocene age and the overlying San Jose Formation of Eocene age. Until now, the ages of the Nacimiento and San Jose Formations have been estimated solely on the basis of their mammal fossils. As mentioned in the Introduction, the three lowest NALMA faunal zones—in ascending order, the Puercan, Torrejonian, and Tiffanian—were named for fossils collected from the San Juan Basin.

Ojo Alamo Sandstone

The Ojo Alamo Sandstone has been studied intensely in the southern part of the San Juan Basin because its enigmatic dinosaur fossils and its debated age—Cretaceous, or Paleocene, or both—have been disputed almost from the day the formation was first named 100 years ago by Barnum Brown (1910) and rede-

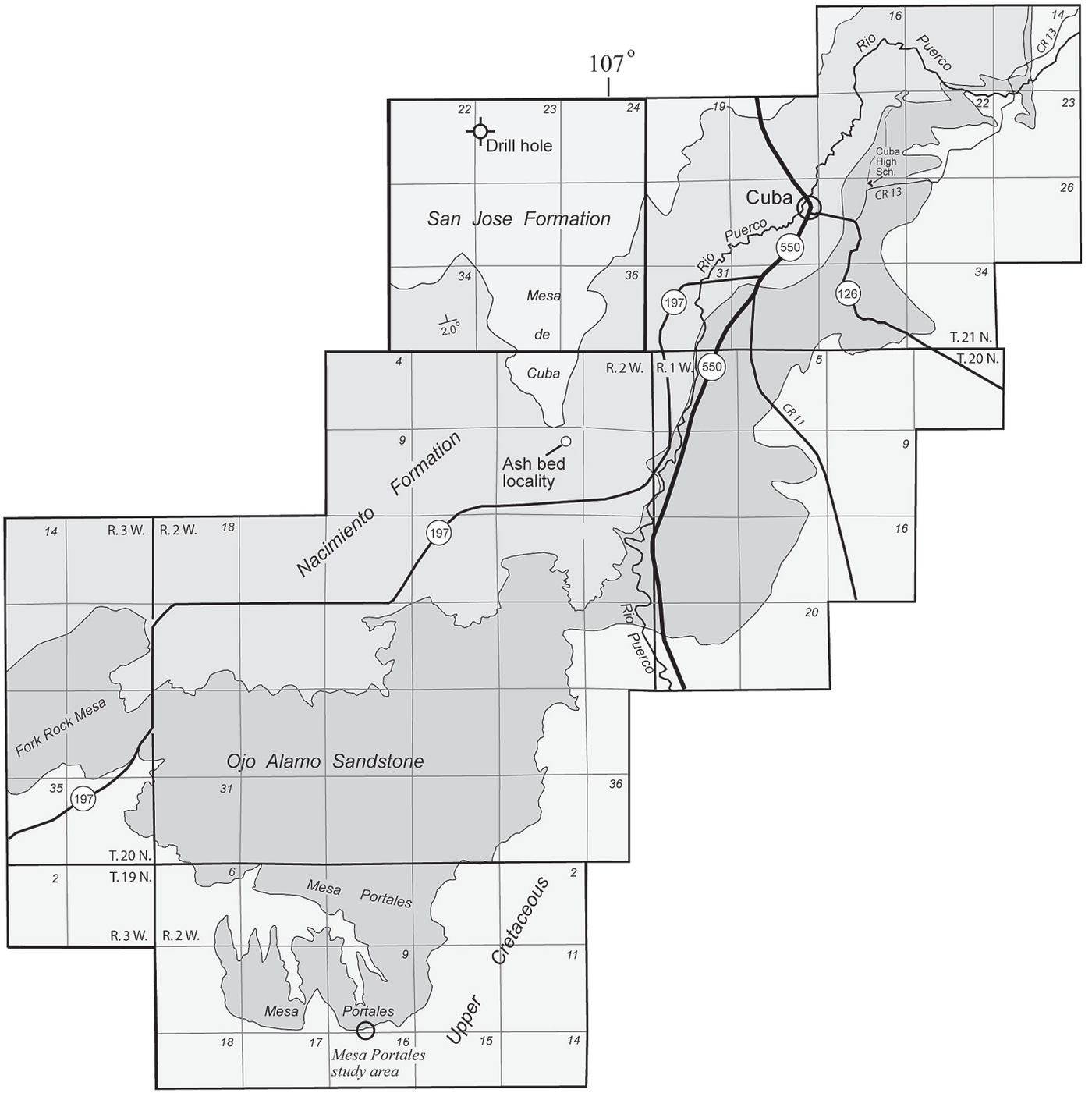


FIGURE 2. Geologic map of the Mesa de Cuba – Mesa Portales area, southeastern San Juan Basin, New Mexico (Fig. 1). Location of dated altered-volcanic-ash-bed locality is shown just south of Mesa de Cuba. Geophysical log of Figure 6 is from the Sun Oil Co. drill hole shown on northern edge of Mesa de Cuba. Sections are 1-mile square, townships are 6-miles square. Map is modified from Fassett (2009, fig. 21).

fined shortly thereafter by Bauer (1916). Moreover, the nature of the contact between the Ojo Alamo and the underlying Kirtland Formation has been in dispute: several publications stated that the contact is conformable whereas others suggested that a multi-million year hiatus separated these formations. Over the last four decades, a palynologic and paleomagnetic data base has slowly been assembled that now clearly demonstrates that the Ojo Alamo Sandstone is entirely Paleocene and that a hiatus of 7.8 m.y. separates the Paleocene Ojo Alamo Sandstone from the Cretaceous Kirtland Formation in the southern San Juan Basin (Fassett, 2009). A detailed discussion of the evolution of the Ojo Alamo controversy, including a complete list of references on this topic is in Fassett (2009).

Nacimiento Formation

The focus of this study is the age determination for an altered volcanic ash bed in the Nacimiento Formation in the southeastern San Juan Basin near Cuba, New Mexico. Figure 2 is a geologic map of this area showing the location of the ash-bed sample site in the NE1/4, Sec. 11, T. 20 N., R. 2 W. The Nacimiento Formation in this area consists of a complex sequence of interbedded mudstone; carbonaceous shale; rare, thin, discontinuous coal beds; siltstone; sandstone; and silcrete beds. Plate 15 is a view of the south-facing end of Mesa de Cuba showing the lithology of the Nacimiento in this excellent exposure and the approximate location of the sampled ash bed.

As discussed above, the age of the Nacimiento was known to be Paleocene because of the Puercan mammal fossils found in its lower part and Torrejonian fossils in its upper part (Williamson, 1996; Fassett, 2009). Based on the presence of lowermost Paleocene (Puercan) fossils in the lower part of the formation, it was thought that it had to be conformable with the underlying Paleocene Ojo Alamo Sandstone, despite the distinctly different lithologies of the two formations. According to Fassett (2009), palynomorph assemblages from the lowermost part of the Nacimiento Formation and from the Ojo Alamo Sandstone show a "high percentage of commonality" which supports an interpretation of continuous deposition across this formation boundary. (See Fassett, 2009, for a detailed discussion of these palynomorph data.) Paleomagnetic traverses in the Nacimiento Formation in the south-central San Juan Basin were published by Butler et al. (1977), Lindsay et al. (1978, 1981, 1982), and Butler and Lindsay (1985). These paleomagnetic data confirmed the mammal-fossil and palynologic age determinations of previous workers. (See Fassett, 2009.)

In 2006, an informal collaborative study was initiated by the authors of this report to locate dateable volcanic ash beds in the Paleogene rocks of the central San Juan Basin and to recollect and redate the previously sampled and dated Cretaceous ash beds whose ages had been reported in Fassett and Steiner (1997) and Fassett (2000). In September 2006, a thin altered volcanic ash bed was discovered by Fassett in the Nacimiento Formation on Mesa de Cuba (Fig. 2 and Plate 15); the precise location of this first sample locality is lat 35.98344 N, long 107.00987 W. This same ash bed was later sampled at a second locality about 65 m to the west at lat 35.98273 N, long 107.01002 W. Figure 3 is a view of the first locality where this formation consists of mostly mudstones and carbonaceous mudstones. The ash layer is at the base of a thin but conspicuous, dirty (high-ash) coal bed that appears to be relatively continuous throughout this general area. Samples of this coal bed and underlying carbonaceous mudstones were collected and analyzed for their pollen and spore content; the resulting palynomorph assemblages were identified as "lower Paleocene" by U. S. Geological Survey (USGS) palynologist D.J. Nichols (written commun., 2007). These palynologic data are reported in full in Fassett (2009).

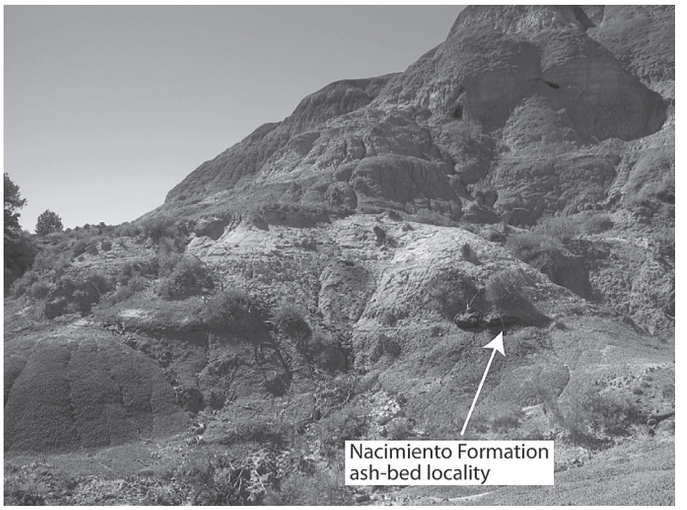


FIGURE 3. View of the Nacimiento Formation ash-bed locality in saddle on south flank of Mesa de Cuba, New Mexico. Note geologic pick at tip of white arrow for scale (see Fig. 4 for close-up view of this locality). Location is lat 35.98344 N, long 107.00987 W.

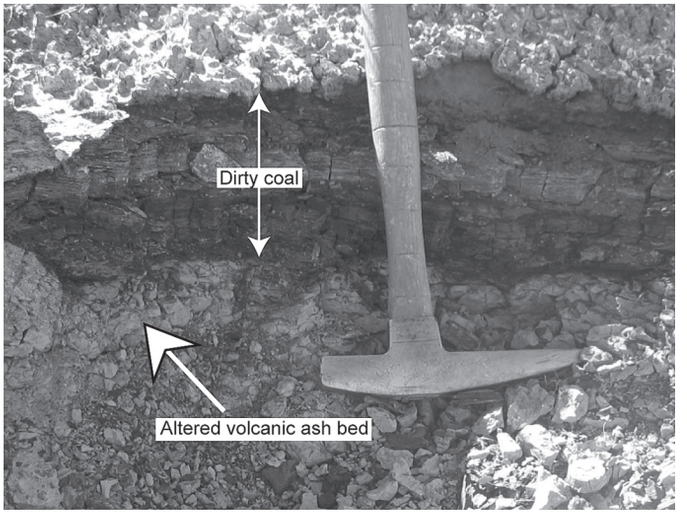


FIGURE 4. Close-up view of Nacimiento Formation ash bed. Hammer handle is scaled in tenths of a foot.

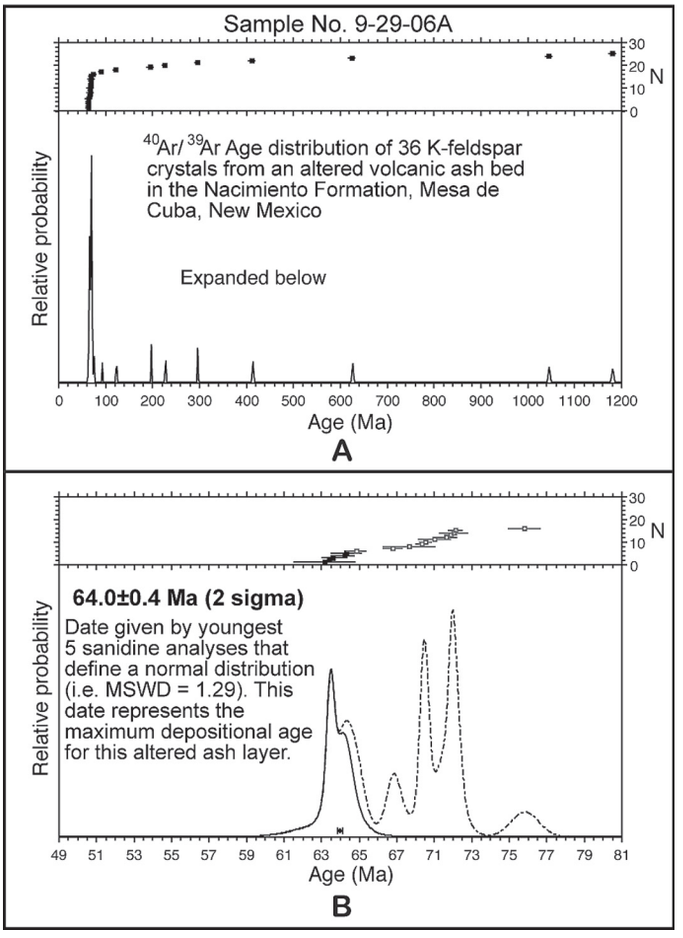


FIGURE 5. Relative probability plots A and B showing age distribution of of K-feldspar crystals from Nacimiento Formation ash bed. The youngest population of ages is taken as the preferred age of the ash. Several data-reduction methods generated different age minima and the combination of these age minima provided the preferred age of 64.0 ± 0.4 Ma for the Nacimiento Formation ash bed. Ages that are older than the minima are inherited grains related to contamination during eruption and/or during post deposition reworking.

Nacimiento Formation ash bed

Figure 4 is a close-up photograph of the Nacimiento Formation ash bed, which at this locality is 6-cm thick and directly underlies the coal bed that is about 12 cm thick. The ash bed itself is not visible on the outcrop but was only discovered in the process of digging out the overlying thin coal bed. The coal bed was excavated at this locality (Fig. 4) because coal swamps are commonly the best places for volcanic ash falls to be preserved because of their low-lying nature. Ash layers that fall into these depressions are less susceptible to dispersal or washing away and dilution of the ash material. Many of the Late Cretaceous ash beds discussed above were found well preserved within coal beds. The only problem with ash beds preserved in depressions is that their thicknesses might be greater than the original ash fall because additional ash may wash into the depression increasing the apparent total thickness of the ash layer. For this reason, the most pristine part of the ash bed for sampling is always the lowermost part where larger, sanidine crystals tend to be concentrated.

A plot of the individual age determinations of the 36 K-feldspar crystals from the Nacimiento ash bed is shown on Figure 5 and tabulated on Table 1. Figure 5A is a small-scale plot of all of the crystals showing that the ages of these crystals are scattered, ranging from nearly 1.2 Ga to a cluster of ages at about 65 Ma. Figure 5B is a larger scale plot for the cluster of 16 ages at around 65 Ma from Figure 5A. These crystal ages range from 75 Ma to about 64 Ma, with a mean age for the five youngest crystals of 64.0 ± 0.4 Ma.

STRATIGRAPHIC AND BIOCHRONOLOGIC IMPLICATIONS OF ASH-BED AGE

Rates of deposition and the Paleocene-Eocene boundary

Figure 6 is a geophysical log from a drill hole located about 6 km north of the Nacimiento ash bed sample-collection locality (Fig. 2). Such logs are useful because the formation thicknesses shown thereon are extremely accurate compared to hand-leveled thicknesses measured on surface outcrops. As can be seen, the formation boundaries of the rocks adjacent to the K-T interface visible on this well log are easily distinguished; these formations include the Upper Cretaceous Pictured Cliffs Sandstone and Fruitland Formation and the Paleogene Ojo Alamo Sandstone, Nacimiento Formation, and San Jose Formation. The log expressions of the massive sandstones of the Ojo Alamo Sandstone and San Jose Formation are especially conspicuous on this log.

The dated Nacimiento ash bed is not visible on this log because it is too thin to be detected, however, it was possible to estimate the stratigraphic level of this bed on the log based on its position below the base of the San Jose Formation at the front of Mesa de Cuba. The level of the prominent coal/silcrete bed shown on Plate 15 is also projected into the well log.

Rates of deposition

The Paleocene Ojo Alamo Sandstone and underlying uppermost Cretaceous rocks, including the Lewis Shale, Pictured Cliffs Sandstone, and Fruitland Formation, crop out on the south side of Mesa Portales, about 12 km south of the Nacimiento ash bed locality (Fig. 2). Detailed studies of the Ojo Alamo and underlying Cretaceous strata at Mesa Portales have included large-scale geologic mapping (Fassett, 1966), palynologic collections and analysis (Fassett and Hinds, 1971, Fassett, 2000, 2009, and Fassett et al., 2002), and a paleomagnetic traverse across the K-T interface (Fassett, 2009). The Ojo Alamo was deposited by high-energy streams flowing from the north and (or) northwest in early Paleocene time and commonly is characterized by massive coarse-grained to conglomeratic sandstone beds that typically form prominent cliffs (Figs. 3.2 and 3.3 of Day 3 road log and Plate 13 in the color-plates section of this guidebook). The massive sandstone beds of the Ojo Alamo are also quite prominent on geophysical logs (Fig. 6). The overlying Nacimiento Formation (Plate 15) consists of fine-grained mudstones, carbonaceous mud-

TABLE 1. Argon isotopic data

	ID	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar(x\ 10^{-3})$	$^{39}Ar_K$ (x 10^{-15} mol)	K/Ca	$^{40}Ar^*(\%)$	Age (Ma)	±1σ (Ma)
	9-29-06A, Sanidine, J=0.0014043±0.05%, D=1.002±0.001, NM-197M, Lab#=56472								
	48	26.03	0.0185	2.691	0.477	27.5	97.0	62.82	0.56
	22	25.86	0.0086	0.6742	0.922	59.1	99.2	63.87	0.25
	24	25.94	-0.0144	-0.3685	0.433	-	100.4	64.82	0.49
	33	26.09	-0.0250	0.0693	0.185	-	99.9	64.9	1.4
x	44	26.58	-0.0062	1.342	0.499	-	98.5	65.15	0.51
x	35	26.42	-0.0075	0.6535	0.408	-	99.3	65.25	0.63
x	16	27.11	0.0030	0.7934	0.457	168.7	99.1	66.84	0.48
x	23	27.14	0.0102	0.5822	0.111	50.3	99.4	67.1	1.8
x	12	27.25	0.0089	-0.7364	0.606	57.2	100.8	68.27	0.82
x	20	27.80	0.0068	0.1365	0.940	74.8	99.9	68.98	0.25
x	25	27.80	0.0019	-0.0073	0.837	261.8	100.0	69.11	0.27
x	26	28.36	-0.0096	1.338	0.231	-	98.6	69.48	0.91
x	11	28.47	0.0053	1.085	1.541	95.6	98.9	69.93	0.36
x	38	27.96	-0.0079	-0.6429	0.398	-	100.7	69.95	0.65
x	03	28.55	0.0052	0.6547	1.932	98.9	99.3	70.44	0.29
x	29	30.28	-0.0077	3.062	0.264	-	97.0	72.94	0.96
x	32	37.19	0.0200	2.163	0.226	25.5	98.3	90.3	1.1
x	04	37.33	0.0055	0.1407	1.072	93.6	99.9	92.09	0.51
x	08	50.15	0.0051	3.362	0.674	100.1	98.0	120.43	0.83
x	37	58.98	-0.0072	1.186	0.567	-	99.4	142.74	0.91
x	31	72.94	-0.0074	6.018	0.193	-	97.6	171.8	2.0
x	10	81.38	0.0002	1.278	1.017	3309	99.5	194.36	0.68
x	28	92.19	-0.0067	2.499	1.419	-	99.2	217.98	0.60
x	09	94.97	0.0026	3.244	1.198	196.3	99.0	223.72	0.75
x	30	105.5	-0.0074	1.416	0.545	-	99.6	248.4	1.2
x	07	125.9	0.0018	1.905	1.879	284.8	99.6	292.45	0.63
x	27	125.4	-0.0215	-0.2013	0.859	-	100.0	292.7	1.1
x	06	180.1	-0.0008	1.214	0.960	-	99.8	406.1	1.4
x	34	190.5	-0.0237	3.923	0.221	-	99.4	425.3	3.1
x	18	249.2	0.0057	2.031	0.561	90.0	99.8	540.3	2.4
x	45	269.5	0.0752	17.93	0.075	6.8	98.0	569.4	8.6
x	14	294.0	-0.0019	1.377	1.114	-	99.9	622.8	1.7
x	43	342.8	0.1043	10.23	0.104	4.9	99.1	703.9	6.2
x	05	555.0	0.0011	1.338	2.710	473.4	99.9	1039.0	1.9
x	17	636.7	0.0077	1.590	0.602	66.5	99.9	1151.8	5.0
x	02	653.4	0.0013	1.444	1.457	406.7	99.9	1174.0	2.3
x	21	687.6	0.0360	2.158	0.283	14.2	99.9	1218.4	6.0
	Mean age ± 2s		n=4	MSWD=2.57				63.9	0.7

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.

Errors quoted for individual analyses include analytical error only, without interfering reaction or J uncertainties.

Mean age is weighted mean age of Taylor (1982). Mean age error is weighted error of the mean (Taylor, 1982), multiplied by the root of the MSWD where MSWD>1, and also incorporates uncertainty in J factors and irradiation correction uncertainties.

Decay constants and isotopic abundances after Steiger and Jäger (1977).

x symbol preceding sample ID denotes analyses excluded from mean age calculations.

Ages calculated relative to FC-2 Fish Canyon Tuff sanidine interlaboratory standard at 28.02 Ma

Decay Constant (LambdaK (total)) = 5.543e-10/a

Correction factors:

$(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00068 ± 2e-05

$(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00028 ± 1e-05

$(^{38}Ar/^{39}Ar)_K$ = 0.0125

$(^{40}Ar/^{39}Ar)_K$ = 0 ± 0.0004

Four data reduction methods provide dates between 64.2 and 63.8

63.8±0.3 Ma

63.9±0.3 Ma

64.1±0.3 Ma

64.2±0.2 Ma

Ma and yield a combined and preferred age for the ash of 64.0±0.4 Ma. Error at 2 sigma.

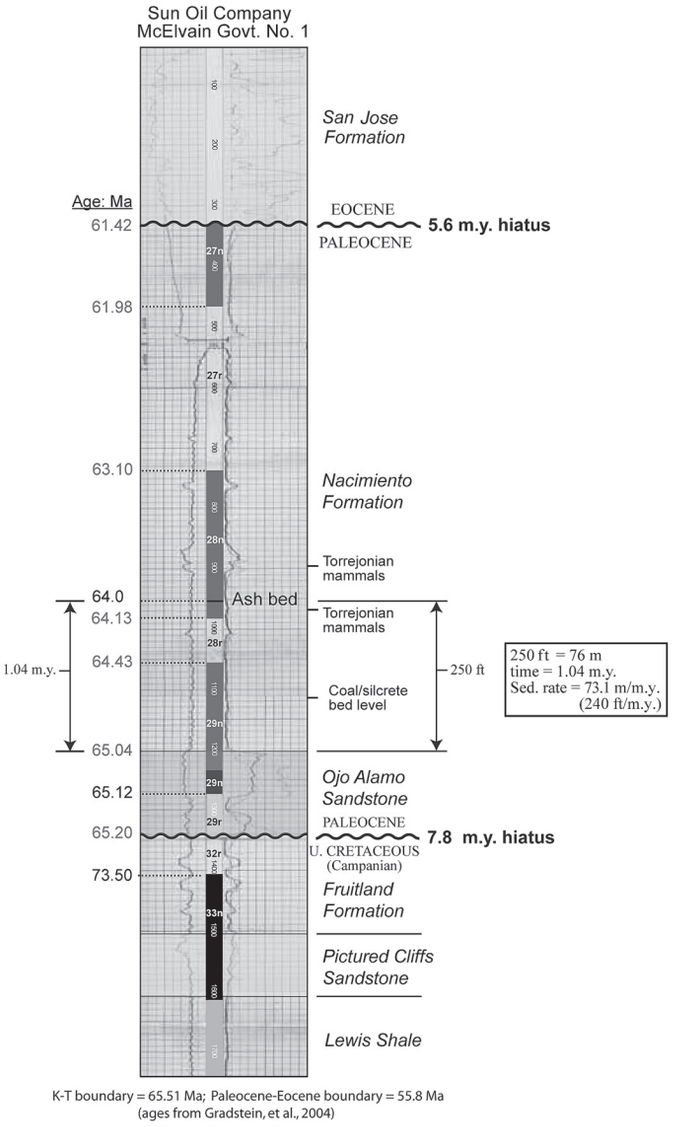


FIGURE 6. Electric log showing geologic strata penetrated in the Sun Oil Co. McElvain Govt. No. 1 well in the Mesa de Cuba area; section shown is from the Upper Cretaceous Lewis Shale through the Eocene San Jose Formation. The Nacimiento Formation ash bed at Mesa de Cuba is projected into this log. Drill-hole location is shown in Figure 2.

stone, and siltstones, with some discontinuous lensing sandstone beds. Because the Ojo Alamo Sandstone is so radically different lithologically from the lower part of the Nacimiento Formation, it was thought prudent to attempt to determine the rates of deposition for these two formations separately. The base of the Ojo Alamo in the San Juan Basin is approximately 65.2 Ma (Fig. 6), based on paleomagnetic data obtained at numerous localities in the basin (Fassett, 2009). The contact of the C29r-C29n paleomagnetic reversal is 65.118 Ma (65.12 in Fig. 6) as reported in Gradstein et al. (2004). The base of chron C29n was located at Mesa Portales (Fig. 1) within the Ojo Alamo Sandstone at about the level shown on Figure 6. The base of the Ojo Alamo on the electric log (Fig. 6) is at 1346 ft and the base of chron C29n is at 1273 ft, thus this interval is 73 ft thick. (Note: Because the electric log of Figure 6 is calibrated in feet, this discussion will refer to thicknesses thereon in feet (3.28 ft = 1 m)). Because the time difference between these two levels is 0.08 m.y. (80 k.y.), the rate of deposition for this part of the Ojo Alamo Sandstone is about 900 ft/m.y. (275 m/m.y.). (Rates of deposition are not corrected for compaction.) Extrapolating to the top of the Ojo Alamo (at 1204 ft on the log) based on this rate, the top of the Ojo Alamo should be about 78 k.y. younger than the base of magnetochron C29n, or 65.04 Ma.

The distance from the top of the Ojo Alamo Sandstone to the Nacimiento ash bed is 250 ft (1204 ft – 954 ft on the log, Fig. 6) and the mean time difference between these two levels is 1.04 m.y. (65.04-64.0). Thus, the sedimentation rate for this interval is 240 ft/m.y. (73 m/m.y.). On the basis of the eight dated ash beds reported in Fassett and Steiner (1997) and Fassett (2000), the average rate of basin subsidence at the time the latest Cretaceous Pictured Cliffs Sandstone and Fruitland and Kirtland Formations were being deposited was calculated to be about 375 ft/m.y. (114 m/m.y.) (Fassett, 2000, p. Q34). Thus, the sedimentation rate of 73 m/m.y. for the lower Nacimiento Formation is somewhat less than that calculated for uppermost Cretaceous rocks.

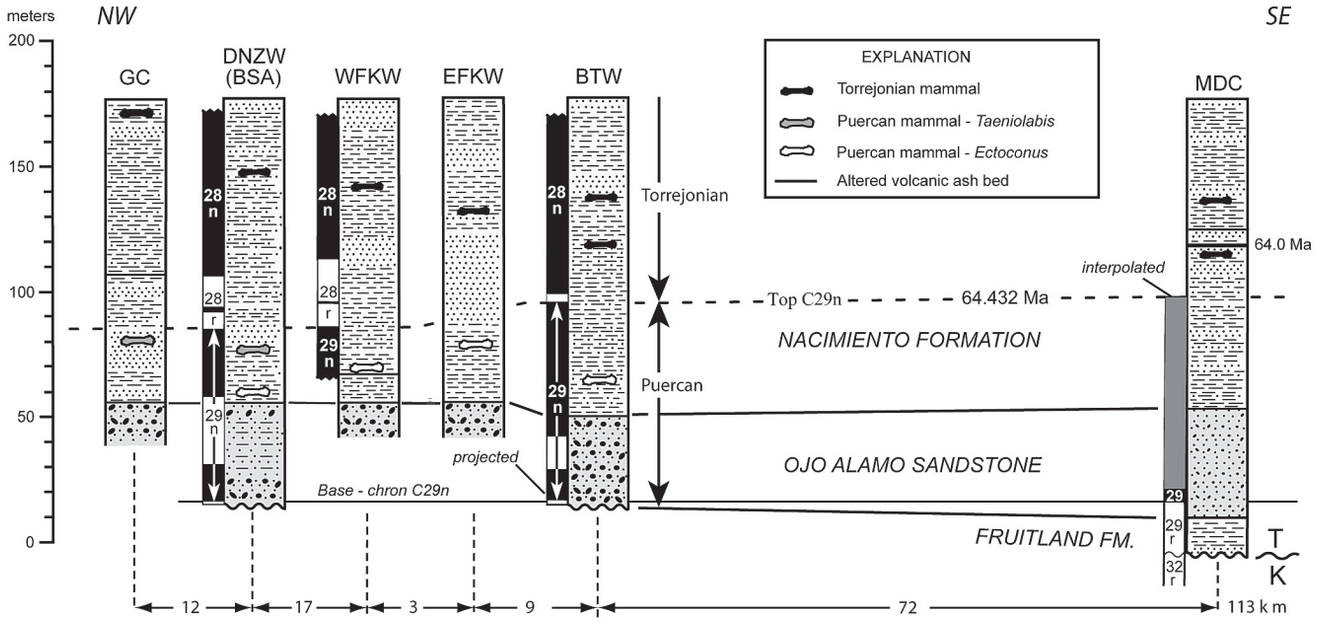
Paleocene-Eocene (Nacimiento-San Jose Formations) boundary

The stratigraphic interval between the dated Nacimiento ash bed and the base of the San Jose Formation at Mesa de Cuba is 621 ft (189 m) thick (954 ft – 333 ft, Fig. 6). The time elapsed for deposition of this interval, as determined by extrapolation, is 1.59 m.y. The contact between the top of the Nacimiento Formation and the base of the San Jose Formation is thus estimated to be about 61.42 Ma. According to Gradstein et al. (2004) the Paleocene-Eocene boundary is 55.8 Ma., thus there is at least a 5.6 m.y. hiatus at this contact on Mesa de Cuba, assuming there are no significant undetected unconformities in the uppermost 621 ft of the Nacimiento Formation. (Further examination of the rock strata in this interval may reveal additional dateable ash beds; also, a paleomagnetic survey could help to resolve this question.) Because there are no radiometric dates for the lowermost part of the San Jose Formation, it is possible that there is an additional time gap within the lower part of the San Jose, and that our reported hiatus of 5.6 m.y. is greater by an unknown amount.

Figure 6 also shows the projected positions of paleomagnetic reversals within the Nacimiento Formation on Mesa de Cuba, based on the rate of deposition for these rocks of 73 m/m.y. As discussed above, the base of chron C29n was discovered at Mesa Portales (Fig. 2) and the top of this magnetochron at 64.43 Ma (Gradstein et al., 2004) is estimated to be about 31 m below the 64.0 Ma dated ash bed(Fig. 6). The magnetochron boundaries for C29n-C28r, C28r-C28n, C28n-C27r, and C27r-C27n are also projected into the well log of Figure 6.

Puercan-Torrejonian NALMA boundary

Figure 6 also shows the known levels of Torrejonian mammal-fossil localities in the Mesa de Cuba area shown in Simpson (1959)



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 7. Line of section trending southeast across south edge of San Juan Basin. Section localities (shown on Fig. 1) are sites where Paleocene mammal fossils have been found. Magnetochrons in black: C29n and C28n, are normal polarity; chrons in white: 28r and unlabeled, are reversed polarity. K/T is Cretaceous-Tertiary boundary. Modified from Fassett (2009, fig. 42).

and Fassett (2009, fig. 43). No Puercan fossils have been discovered in the area between Mesa de Cuba and Mesa Portales, thus the lower boundary of the Torrejonian in this area is not known. Fassett (2009, fig. 42), however, presented a stratigraphic line of section across the southern part of the San Juan Basin showing the stratigraphic levels of six known Puercan and Torrejonian fossil localities, including the Mesa de Cuba locality – the six localities are shown in Figure 1. This cross section is reproduced herein as Figure 7. This figure also shows the paleomagnetic patterns at three sites northwest of Mesa de Cuba through the lower part of the Nacimiento Formation; thus, in these areas, the Nacimiento mammal-fossil levels can be placed in their stratigraphic position relative to the magnetochrons shown. All of the Puercan fossils discovered thus far at these localities are in the middle-to-upper part of chron C29n and the Torrejonian fossils are all in chron C28n. A detailed discussion of this line of section is presented by Fassett, 2009. The dashed line between the columns in Figure 7 connects the top of chron C29n (64.432 Ma) across the length of the section; at Mesa de Cuba, the top of C29n is estimated to be 31 m below the dated Nacimiento ash bed (64.0 Ma). The variation in thickness of C29n between the BTW locality and the WFKW and DNZW localities may reflect different rates of subsidence/deposition in these areas, or alternatively, the top of C29n may actually be at the top of the thin normal-polarity intervals in C28r at the WFKW and DNZW localities which would place the top of C29n at exactly the same level across the entire line of section. The interval between the highest Puercan fossil at the Gallegos Canyon (GC) locality and the lowest Torrejonian fossil at the Mesa de Cuba (MDC) locality is about 33 m. Fassett (2009, p. 65 of the PDF version) stated that:

> The Puercan-Torrejonian boundary can thus be placed fairly precisely in the lower part of the Nacimiento Formation (Figure 42)[Fig. 7 of this report] between the lowest Torrejonian mammal level at the MDC locality and the highest Puercan mammal level at the GC locality. The age of this boundary is estimated to be about 64.4 Ma because it is at the top of chron C29n which has an age of 64.432 Ma (Gradstein et al., 2004). Thus, the Puercan in the San Juan Basin has a duration of about 1.1 m.y., ranging from the base of the Paleocene at 65.5 Ma to the Puercan-Torrejonian boundary at 64.4 Ma (Figure 42) [Fig. 7]. The Torrejonian mammals identified in the lower part of the Nacimiento Formation in the five sections all appear to fall within magnetochron C28n. *The two Torrejonian fossil localities at the MDC site, however, appear to be in chron C28r (Figure 42) [Fig. 7].* [Note: The revised Nacimiento ash-bed age from 64.4 in Fassett (2009) to 64.0 in this paper results in putting the two Torrejonian fossil localities at the MDC locality in chron C28n (Fig. 6); virtually the same placement as in the other sections shown on Fig. 7.] A paleomagnetic survey of the Nacimiento Formation at Mesa de Cuba would supply a valuable data set to help clarify these interpretations.

CONCLUSIONS

The Nacimiento Formation ash bed about 76 m above the top of the Ojo Alamo Sandstone at Mesa de Cuba has an age of 64.0 ± 0.40 Ma. The calculated rate of deposition of strata from the base of the Nacimiento Formation to the ash bed is 73 m/m.y.; extrapolating this rate for strata up to the contact between the top of the Nacimiento Formation and the base of the overlying Eocene San Jose Formation; the age of this contact is 61.42 Ma. Because the age of the Paleocene-Eocene boundary is 55.8 Ma (Gradstein et al., 2004), there must be a hiatus at this contact on Mesa de Cuba of about 5.6 m.y. If the base of the San Jose Formation is not equivalent to the Paleocene-Eocene boundary and some amount of the lowermost Eocene is not represented by rock strata here, then this hiatus could be of longer duration at this location. Torrejonian mammals have been found in the Mesa de Cuba area above and below the level of the Nacimiento ash bed indicating that the Torrejonian-Puercan boundary is below this ash-bed level and probably close to the top of C29n, 31 m below.

In a tectonic sense, it is interesting to note that subsidence of the San Juan Basin throughout the latest Cretaceous continued until near the end of the Cretaceous, at which time subsidence must have ceased for as much as 8 m.y. Beginning in early, but not earliest Paleocene time, basin subsidence resumed at a slower rate than during Late Cretaceous time and continued until around 61 Ma. At this time, subsidence again ceased for at least 5.6 m.y. and then resumed at an unknown rate resulting in deposition of the San Jose Formation throughout the San Juan Basin. There had to have been a final time of non-subsidence of the basin that occurred in the middle to late Eocene, because the Chuska Sandstone of late Eocene to early Oligocene age is flat-lying on top of upturned Cretaceous strata on the west edge of the San Juan Basin. The dating of San Jose strata in the San Juan Basin will help fill in the gaps of our knowledge regarding the geologic history of that formation.

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