

# A new chronology for middle Eocene–early Miocene South American Land Mammal Ages

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## ABSTRACT

Cenozoic South American Land Mammal Ages (SALMAs) have historically been correlated to the geologic time scale using <sup>40</sup>Ar/<sup>39</sup>Ar dating and magnetostratigraphy. At Gran Barranca (68.7°W, 45.7°S)—one of South America's key areas for constraining SALMAs—existing radioisotopic ages have uncertainties of up to 4 m.y. To better constrain the ages of mammalian assemblages, we employed high-precision ( $\pm < 40$  k.y.) U-Pb dating using single zircon crystals. We dated nine tuffs from the Sarmiento Formation containing middle Eocene–early Miocene faunas (Barrancan, Mustersan, Tinguirirican, Deseadan, Colhuehuapian, and “Pinturan”). The new dates span from  $39.861 \pm 0.037$  Ma to  $19.041 \pm 0.027$  Ma. The La Cancha Tuff, occurring within the Tinguirirican faunal level yielded an age of  $33.581 \pm 0.015$  Ma, confirming that the Vera Member contains the only fossiliferous geologic section encompassing the Eocene–Oligocene transition in the Southern Hemisphere. The pre-Deseadan fauna, La Cantera, is  $\leq 30.77$  Ma, the age of the Colhuehuapian is expanded to 21.1–20.1 Ma, and the Pinturan may be as old as ca. 19 Ma.

The new U-Pb dates confirm that atmospheric temperatures and vegetation remained constant across the Eocene–Oligocene transition in Patagonia and that hypsodonty occurred in South American ungulates much earlier than on any other conti-

ment. Additionally, refinement of the SALMA boundaries will eventually provide the context necessary to compare faunal transitions across continents, although currently too much data are missing to allow such comparisons. Finally, the new ages provide a high-resolution age model from which hypotheses about rates of environmental and evolutionary change at Gran Barranca can be tested.

## INTRODUCTION

South America was an island continent for most of the middle Cenozoic, from ca. 40 Ma, when it lost its former connection to Antarctica, to 9–7 Ma, when the first waif immigrants arrived from North America (Woodburne, 2010; Campbell et al., 2001, 2010; Verzi and Montalvo, 2008), and ca. 3 Ma when the Panamanian Land Bridge formed and wholesale faunal exchange occurred (Marshall et al., 1983). As a result, endemic faunas of South America, including the meridiungulates (e.g., notoungulates, litopterns, astrapotheres, pyrotheres), metatherians (marsupials), and xenarthrans (armadillos and sloths), evolved and radiated largely in geographic isolation. The extinct endemic mammalian faunas from South America, particularly in Patagonia, have been extensively studied for over a century and have pivotally influenced the evolutionary thinking of many paleontologists and biologists (Darwin, 1859; Ameghino, 1906; Patterson and Pascual, 1968; Simpson, 1980).

Although the notoungulates are taxonomically unrelated to ungulates of North America

and Europe, they convergently evolved similar dental and postcranial morphologies, but at different times. A striking pattern in the evolution of the notoungulates is the early and progressive lengthening of tooth crowns, known as hypsodonty, at a time long before ungulates elsewhere (Jacobs et al., 1999). While several North American ungulate lineages (e.g., the equids and camelids) evolved hypsodonty by ca. 18 Ma (Janis et al., 2002), South American ungulates show increases in tooth crown height beginning much earlier, ca. 38 Ma (Madden et al., 2010). Hypsodonty has long been assumed to be an adaptation to the opening of habitats and the spread of grassland biomes and has been used to infer the timing of such habitat change across continents (Jacobs et al., 1999; Strömberg, 2011). Therefore, South America, specifically Patagonia, has been hypothesized as the cradle of grassland evolution (Stebbins, 1981; Jacobs et al., 1999; Zucol et al., 2010), although recent paleobotanical work has challenged this notion (Strömberg and Stidham, 2001; Barreda and Palazzesi, 2007; Strömberg et al., 2010; review in Strömberg, 2011).

Gran Barranca, the “great cliff” in central Patagonia, Chubut, Argentina, preserves the most complete and continuous record of middle Cenozoic terrestrial climatic and biotic evolution in South America and likely the entire Southern Hemisphere. Spanning ca. 42–18.5 Ma, the Sarmiento Formation at Gran Barranca preserves over 80 faunal levels encompassing assemblages from six successive South American Land Mammal Ages (SALMAs; Madden et al.,

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2010). From oldest to youngest, the SALMAs represented at Gran Barranca are: the Barrancan, Mustersan, Tinguirirican, Deseadan, Colhuehuapian, and Pinturan. A faunal assemblage intermediate between Tinguirirican and Deseadan is also preserved. The faunal sequence at Gran Barranca documents the progressive and episodic increase in tooth crown heights among many lineages of notoungulates, and it preserves an extraordinary record of vegetation in the form of phytoliths (Mazzoni, 1979; Zucol et al., 2007, 2010; Sánchez et al., 2010; Strömberg et al., 2010). Additionally, the Sarmiento Formation provides a distal record of volcanism along the Andean Arc beginning in the middle Eocene (Ardolino et al., 1999).

Gran Barranca is the only location in South America that contains six land mammal ages in superposition, and it is the type locality for several of the SALMAs, including the Barrancan, Mustersan, and Colhuehuapian. Therefore, Gran Barranca is widely considered to be the most important sequence for mammalian biostratigraphy in all of South America (Madden et al., 2010).

Much stratigraphic and geochronologic work has recently been compiled for Gran Barranca (Ré et al., 2010a, 2010b; Madden et al., 2010; Bellosi, 2010a, 2010b). The geochronologic framework is based on magnetostratigraphy, calibrated by  $10^{40}\text{Ar}/^{39}\text{Ar}$  radioisotopic dates (Ré et al., 2010b). Due to the fine-grained texture of ashes from Gran Barranca, sanidine separates were not recovered. Therefore, Ré et al. (2010b) used step-heating age spectrum methods on bulk plagioclase and bulk glass separations, laser fusion methods for bulk plagioclase samples, and plateau and integrated ages for basalts. In some cases, their methods yielded large age discrepancies. For example, Ré et al. (2010b) reported 0.33 to 4 m.y. age differences between glass and plagioclase separates from the same samples. The authors attributed the age discrepancies between the bulk samples to argon loss from glass minerals and xenocrystic contamination due to sediment reworking. To address the problem, they calculated arithmetic mean ages using different combinations of preferred results from the glass plateau, plagioclase laser fusion mean ages, and the plagioclase plateau ages (see table 4.1 in Ré et al., 2010b). Error ranges for the arithmetic mean calculations were not reported. For ongoing high-resolution studies of paleoclimate and its effect on vegetation and mammalian evolution at Gran Barranca, a more precise geochronology is needed.

The aim of the current work is to refine the geochronology of Gran Barranca using high-precision U-Pb geochronology of single zircon crystals. Zircon is ideal for this study as the crystals are abundant in the distal tuffs at

Gran Barranca, and they can be dated individually, allowing for better control over reworking. For simple volcanic populations, chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) techniques can produce ages with uncertainties of less than 0.1%, even for relatively young volcanic tuffs (Schmitz and Bowring, 2001). In the current study, we present U-Pb ages obtained from new collections of four tuffs previously dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  (Simpson's Y, Rosado, Kay, and Big Mammal) and six new tuffs, not previously dated (Bed 10, La Cancha, La Cantera, Carbon, and CHW01–24.5).

In combination with existing magnetostratigraphy, our new geochronology provides a highly resolved age model for ongoing paleoecological studies in the Gran Barranca section. Additionally, the new dates (1) provide clarification on the ages of the six members of the Sarmiento Formation at Gran Barranca and the duration of hiatuses in the section, (2) highlight areas of the section spanning the Eocene-Oligocene transition, (3) confirm the age of the important, transitional “pre-Deseadan” La Cantera fauna, and (4) provide age constraints for the middle Cenozoic SALMAs that can be applied more broadly across the continent.

### SALMAs

While regions of Patagonia preserve a rich record of fossil vertebrates, the exposures and fossil localities are often distant from one another, and they lack the geologic context to be placed in a regional stratigraphic framework. Historically, fossil sites were assigned a rough age and stratigraphic position based on the content and evolutionary stage of the fossil mammal assemblages (Ameghino, 1906).

Florentino Ameghino first described the South American faunas of the middle Cenozoic and placed them into an evolutionary sequence (Ameghino, 1897, 1901, 1906), relying heavily on superpositional relationships of fossils found at Gran Barranca. Later, Simpson (1933, 1940) officially distinguished the names of the unique mammalian assemblages based on geographic and geologic criteria. These names form the basis of the middle Cenozoic South American Land Mammal Ages (SALMAs) used broadly today.

While SALMAs are considered merely informal biochronologic units, they have proven useful in temporal correlation in South America (Kraglievich, 1934, 1930; Stirton, 1953; Hoffstetter, 1969; Villarroel, 1974). Consequently, efforts have been made to constrain the ages of the SALMAs by applying chronostratigraphic techniques (magnetostratigraphy and radioisotopic dating) to particular fossil localities (Madden et

al., 1997). Flynn and Swisher (1995) presented a correlated geochronology for the Cenozoic South American Land Mammal Ages using the geomagnetic time scale of Berggren et al. (1995). Their correlation is based on a compilation of the magnetostratigraphy,  $^{40}\text{K}/^{40}\text{Ar}$ ,  $^{40}\text{Ar}/^{39}\text{Ar}$ , and fission-track geochronology available at that time from multiple fossil localities.

Since 1995, refinements in several of the SALMA ages have been made. For instance Flynn et al. (2003) refined age estimates of the Tinguirirican fauna in the Chilean Andes to ca. 31.5 Ma. Deseadan faunas have also been dated at Salla, Bolivia (29.4–25.65 Ma; Kay et al., 1998), and Moquegua, Peru (26.25 ± 0.10 Ma; Shockey et al., 2009). The  $^{40}\text{Ar}/^{39}\text{Ar}$  radioisotope dating and magnetostratigraphic correlation at Gran Barranca, however, provide the most recent and major refinements to the geochronology of these SALMAs (Ré et al., 2010a, 2010b; Madden et al., 2010).

Ré et al. (2010a, 2010b) correlated the SALMA durations to the geopolarity time scale (GPTS) of Gradstein et al. (2004). Here, we suggest refinements in the ages of the SALMAs at Gran Barranca using the magnetostratigraphic sequence of Ré et al. (2010b), but calibrated using new, more precise and accurate  $^{206}\text{Pb}/^{238}\text{U}$  isotopic dates. We correlate the new age model for Gran Barranca to the astronomically age-calibrated magnetic polarity record of Ocean Drilling Program (ODP) Leg 199, Site 1218 (equatorial Pacific) of Pälike et al. (2006, see their supplementary data), herein referred to as Pälike06. Site 1218 contains a well-constrained record of calcareous nanoplankton and magnetostratigraphy that has resulted in a highly resolved age model for the late Eocene through the early Miocene. For comparison purposes, we show the magnetic time scales of Gradstein et al. (2004) and Cande and Kent (1992) in addition to the Pälike et al. (2006), but age durations for the rock units and corresponding SALMAs presented here are based on correlation to the Pälike06.

### The Sarmiento Formation

Gran Barranca exposes fine-grained, distally deposited volcanoclastic rocks and stretches for 7 km along the southern shore of Lake Colhue-Huapi in Chubut Province, Argentina (45°42'49"S, 68°44'16"W; Fig. 1). Strata are mapped as the superposed Koluel Kaike and Sarmiento Formations. The Sarmiento Formation is an entirely terrestrial unit that was deposited in the San Jorge Basin between 43 and 18.5 Ma (Kay et al., 1999; Ré et al., 2010a, 2010b). It measures 320 m in total thickness (Bellosi, 2010a) and contains mostly pyroclastic material, both primarily and secondarily reworked

through fluvial and pedogenic processes (Spalletti and Mazzoni, 1979). The Sarmiento Formation represents a distal record of Plinian-style volcanic eruptions from the Andean volcanic arc in central Patagonia (Mazzoni, 1985).

The Sarmiento Formation consists of six members: In ascending order, they are the Gran Barranca, Rosado, Lower Puesto Almendra, Vera, Upper Puesto Almendra, and the Colhue-Huapi (Fig. 2). The members are primarily composed of fine-grained tuffaceous siltstones, mudstones, and fine-grained sandstones. Individual horizons likely represent single or sequences of paleosols of various stages of development, as rooting and other forms of bioturbation are evident (Bellosi, 2010a, 2010b, 2010c, 2010d). Within the Upper Puesto Almendra Member, there are lenticular basalt flows occurring in profiles A, H, I, and N (Fig. 2A).

Notable compositional and evolutionary differences between superposed mammalian faunal assemblages along with the presence of distinct and more or less continuous erosional surfaces indicate that several hiatuses occurred during deposition of the Sarmiento Formation (Windhausen, 1924; Simpson, 1940; Feruglio, 1949; Spalletti and Mazzoni, 1979; Legarreta and Uliana, 1994). These hiatuses may have resulted from tectonic uplift and/or local deformation (Simpson, 1940) or changes in base level and accommodation space relating to sea-level fluctuations (Legarreta and Uliana, 1994). Based on field observations at Gran Barranca,

10 discontinuities (numbered 1–10 from bottom to top; see Fig. 2) have been identified (Bellosi, 2010a). The discontinuities are characterized by degree of erosion and include: type A—pronounced erosive unconformities; type B—paraconformities with moderate to slight erosive surfaces; and type C—nonerosive unconformities consisting of stacked paleosols. Type A discontinuities mark distinctive contacts between the members, including discontinuities 5 and 6, which represent deep erosional episodes before the deposition of the Vera and Upper Puesto Almendra Members, respectively. Discontinuity 10 is also a type A erosive episode between the deposition of the Upper Puesto Almendra and the Colhue-Huapi Members. Type B discontinuities occur at the lower contacts of the Simpson's Y tuff, the Rosado Member, and Bed 10 tuff (discontinuities 1, 2, and 4, respectively), the irregular surface at the base of the lenticular basalt flows in the Upper Puesto Almendra (discontinuity 7), the eroded surface at the top of the basalt flows, which includes deposits of coarse-grained conglomerates containing basalt clasts (discontinuity 8), and the slightly irregular base of the Upper Channel Series of the Upper Puesto Almendra Member (discontinuity 9). Type C discontinuities occur at the top of the Gran Barranca Member in profiles A, H, and N and within a calcrete horizon at the top of the Rosado Member within profiles J and M (discontinuity 3). Using the geochronology of Ré et al. (2010b), Bellosi (2010a) estimated temporal gaps at the discontinuities to range between “negligible” to as long as 3.48 m.y. in duration.

dates from glass and plagioclase, calibrated using a Fish Canyon Tuff age standard of 28.27 Ma (according to Kwon et al., 2002). Their dates range in age from 41.27 to 18.5 Ma and include a revised age of the Mazzoni Tuff of 39.08 Ma. They present a chronostratigraphy based on the new dates correlated to a six-profile composite magnetostratigraphy (Ré et al., 2010a) that constrains durations of the deposition of different members and of their corresponding SALMA (Madden et al., 2010).

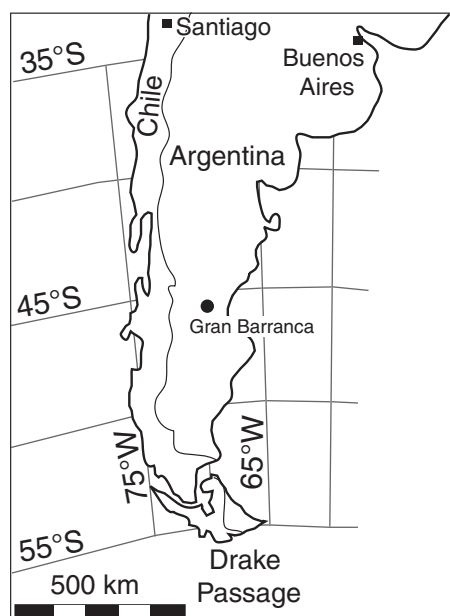
## RESULTS: THE TUFFS AND THEIR U-Pb AGES

Tuff samples (~5 kg each) were collected from all members of the Sarmiento Formation at Gran Barranca (Fig. 1) along well-established measured sections where previous paleomagnetic and  $^{40}\text{Ar}/^{39}\text{Ar}$  dating efforts were concentrated (Bellosi, 2010a; Kay et al., 1999; Ré et al., 2010a, 2010b). Geographic coordinates for the tuff samples are listed in Table S1 in the supplementary data.<sup>1</sup> Concordant U-Pb dates (considering decay constant errors) were obtained from 96 individually analyzed zircon grains from the nine dated samples (Table 1) using CA-ID-TIMS (Mattinson, 2005; Davydov et al., 2010; full analytical methods, data, and images of sample locations and zircon separates may be found in GSA Data Repository [see footnote 1]), and are illustrated as concordia diagrams in Figure 3. Five samples yielded majority clusters of equivalent single zircon  $^{206}\text{Pb}/^{238}\text{U}$  dates, which we interpret as the igneous crystallization age of the zircons and the eruption and deposition age of the tuff. Dates that are older than the majority cluster at 95% confidence are interpreted as basement-derived xenocrysts or antecrysts from an earlier magmatic episode, and are ignored. By contrast five samples (including two samples of the Cantera Tuff) yielded arrays of nonequivalent analyses presumably resulting from mixed populations of volcanic and detrital zircon grains. In these cases, we conservatively interpret the maximum depositional age of each tuff layer from the youngest grain(s) of the sample.

### Gran Barranca Member

The Simpson's Y Tuff is the principal marker horizon in the Gran Barranca Member. It is 4–5 m

<sup>1</sup>GSA Data Repository item 2013071, a full description of analytical methods, all results from zircon analyses, a table describing faunal occurrences per member, images of tuff collection sites and representative zircon separates, is available at <http://www.geosociety.org/pubs/ft2013.htm> or by request to [editing@geosociety.org](mailto:editing@geosociety.org).

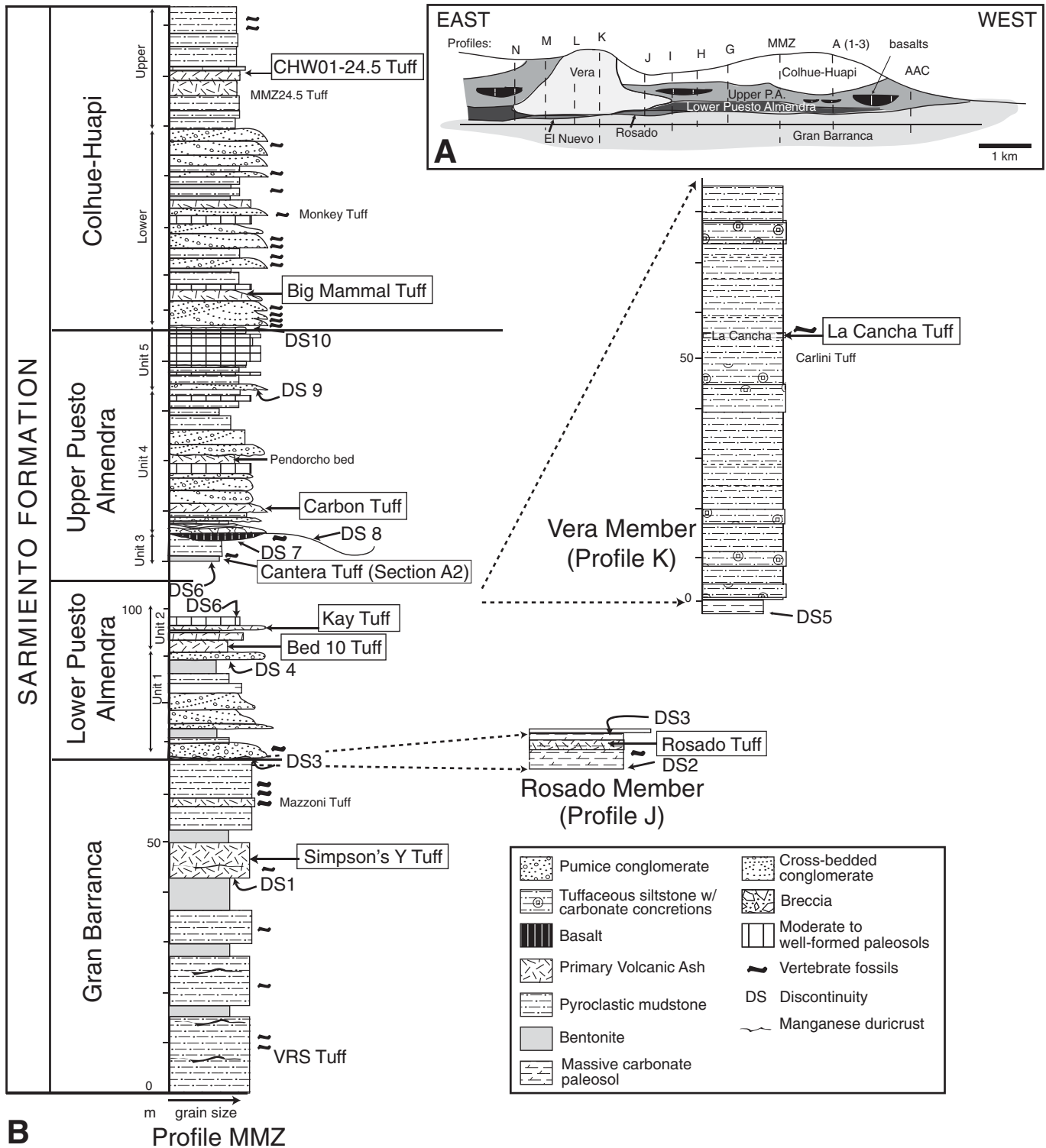


**Figure 1.** Map of southern South America, showing study location: Gran Barranca, Chubut Province, Argentina.

### Previous Geochronologic Studies at Gran Barranca

Four  $^{40}\text{K}/^{40}\text{Ar}$  radioisotopic ages for basalt flows exposed in the Upper Puesto Almendra Member of the Gran Barranca section range from  $28.8 \pm 0.9$  Ma to  $24.3 \pm 0.5$  Ma and broadly correlate with magmatic activity at Scarritt Pocket in the Meseta de Canquel, ~100 km north of Gran Barranca (Marshall et al., 1986). Four  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for the same basalts range from  $28.87 \pm 0.13$  Ma to  $26.34 \pm 0.32$  Ma (Ré et al., 2010b) and were interpreted as separate flows during a hiatus implicated by discontinuity 7 (Fig. 2).

Kay et al. (1999) presented a geochronology for the Gran Barranca section based on an early paleomagnetic section that was calibrated by a laser fusion  $^{40}\text{Ar}/^{39}\text{Ar}$  date for plagioclase from the Mazzoni Tuff (MZ-7) of  $36.01 \pm 0.67$  Ma. This key study confirmed that the Casamayoran SALMA was at least 18–20 m.y. younger than previously assumed. More recently, Ré et al. (2010b) presented 10  $^{40}\text{Ar}/^{39}\text{Ar}$  radioisotopic



**Figure 2.** (A) Schematic diagram looking south at the Gran Barranca showing lateral extent of the members of the Sarmiento Formation. Approximate locations of established stratigraphic profiles are indicated by letter. Single letters are G.G. Simpson section designations. Sections MMZ (Mario Martín Mazzoni) and AAC (Alfredo Armando Carlini) are more recent (see Bellosi, 2010a). (B) Composite geologic section of Sarmiento Formation at Gran Barranca, indicating member, lithostratigraphy, grain size, vertebrate fossil-bearing levels, marker beds, and volcanic tuff layers dated in this study. VRS Tuff—Vilas and Ré Silicified Tuff (modified from Bellosi, 2010b).

TABLE 1. SUMMARY OF VOLCANIC TUFF SAMPLES AND AGES

Tuff name	Sample number	Profile	Member	$^{206}\text{Pb}/^{238}\text{U}$ age (Ma)*	MSWD	Probability of fit	<i>n</i>
CHW01-24.5	SGB09-282	C-H West	Colhue-Huapi	19.041 ± 0.027 (0.035)	1.2	0.32	5 of 7
Big Mammal	SGB09-275	C-H West	Colhue-Huapi	20.890 ± 0.033 (0.040)	2.8	0.02	5 of 10
Carbon	RGB09-007	MMZ	U. Puesto Almendra	≤23.13			1 of 8
La Cantera	SGB09-093/099	A2	U. Puesto Almendra	≤30.77			2 of 16
La Cancha	SGB09-007	K	Vera	33.581 ± 0.015 (0.043)	2.1	0.03	10 of 11
Kay	RGB09-05	A	L. Puesto Almendra	≤36.73			2 of 14
Bed 10	SGB09-179	A	L. Puesto Almendra	37.000 ± 0.014 (0.046)	1.6	0.14	8 of 10
Rosado	SGB09-118	J	Rosado	≤38.03			2 of 11
Simpson's Y	SGB09-037	MMZ	Gran Barranca	39.861 ± 0.037 (0.060)	2.7	0.01	7 of 9

\*All weighted mean ages with a probability of fit >0.05 are reported with internal  $2\sigma$  errors; those with a probability of fit <0.05 are reported with the internal  $2\sigma$  errors expanded by the square root of the mean square of weighted deviates (MSWD) and the Student's *t* multiplier for *n* - 1 degrees of freedom (Ludwig, 2003). The second error in parentheses includes systematic uncertainties in tracer calibration (0.05%) and  $^{238}\text{U}$  decay constant (0.106%). Maximum ages in italics are based upon the youngest grain(s) in tuff samples with abundant reworked zircon.

thick, very light gray, and massive. The basal contact is sharp, slightly undulating, and erosive, forming the discontinuity 1 surface (Bellosi, 2010a). It entombs Barrancan faunas and occurs ~40 m above the lowest Barrancan faunal level, 37 m above the Vilas and Ré Silicified (VRS) tuff (dated via  $^{40}\text{Ar}/^{39}\text{Ar}$  on plagioclase at  $41.7 \pm 0.4$  Ma; Ré et al., 2010b), and 7 m below the highest Barrancan level (see supplemental data for a list of fossil occurrences by member [see footnote 1]). From a sample collected at the base of the Simpson's Y tuff at profile MMZ (Fig. S1 [see footnote 1]), a large population of elongate prismatic zircon crystals was recovered (Fig. S2 [see footnote 1]). Excluding two older grains, seven zircons indicate a depositional age of  $39.861 \pm 0.037$  Ma (Fig. 3).

### Rosado Member

The Rosado Tuff occurs ~4 m above the base of the Rosado Member, within a zone of Mustersan faunas distributed throughout the member. The tuff is light gray and massive, measuring 1–2 m in thickness. Our sample was collected just west of the profile J axis, along an old road cut (Fig. S1). The tuff sample yielded an array of nonequivalent zircon grains, including three Mesozoic xenocrysts and eight grains ranging from 38.59 Ma to 38.00 Ma (Fig. 3). A robust magmatic age for the Rosado Tuff cannot be calculated; however, the maximum age of tuff deposition is estimated at  $\leq 38.03$  Ma from the weighted mean of the youngest two crystals. Ré et al. (2010b) calculated a tuff age of 38.66 Ma for the Rosado Tuff based on the mean of two glass plateau ages and one plagioclase laser fusion age.

### Lower Puesto Almendra Member

The Bed 10 Tuff occurs ~25 m above the base of the Lower Puesto Almendra Member, the basal conglomerate of which hosts Mustersan fossils. Bed 10 forms a prominent marker horizon along profiles A–H with a uniform thick-

ness of around 4 m. It consists of a poorly sorted basal conglomerate (0.5 m thick) and a massive unit (2 m thick), capped by 1.5 m of bioturbated tuff (Fig. S1). The base is slightly erosive and represents discontinuity 4. Our sample was collected 1 m from the base of the tuff in the massive zone. Excluding two clearly older xenocrysts, eight grains define a weighted mean date and interpreted eruptive age of  $37.000 \pm 0.014$  Ma (Fig. 3).

The Kay Tuff occurs 0–3 m above the Bed 10 Tuff and is similar in thickness and appearance; however, it is less continuously exposed (profiles A–J). Our sample was collected from the massive zone of the tuff, 1 m from the base (Fig. S1). The analysis of 14 zircons resulted in an array of nonequivalent dates ranging from 40.56 Ma to 36.72 Ma (Fig. 3). A maximum age of tuff deposition is estimated at  $\leq 36.73$  Ma based on the weighted mean of the youngest two crystals. The U-Pb age for the Kay Tuff is slightly younger but consistent with the previously published mean  $^{40}\text{Ar}/^{39}\text{Ar}$  age of 37.045 Ma (Ré et al., 2010b).

### Vera Member

The La Cancha Tuff is a thin, light-gray tuff (0.3 m thick) occurring within a 3-m-thick zone containing Tinguirirican fossils, ~55 m above the base of the Vera Member (Fig. S1 [see footnote 1]). The La Cancha Tuff occurs 1–3 m above the Carlini Tuff, which was dated by Ré et al. (2010b) at ca. 34 Ma. Ten zircons from the La Cancha Tuff indicate a depositional age of  $33.581 \pm 0.015$  Ma, excluding one older grain (Fig. 3).

### Upper Puesto Almendra Member

The La Cantera Tuff forms the basal stratum (Unit 3) of the Upper Puesto Almendra Member and entombs taxa intermediate between Tinguirirican and Deseadan type faunas. It is a massive unit, 8 m thick, consisting of pale-gray tuffaceous mudstone (Fig. S1). The base of

the tuff was deposited on an erosional surface (discontinuity 6), cutting into the Bed 10 Tuff in profile A-2 (Fig. 2A). Two separate samples, SGB09-093 (base of tuff) and SGB09-099 (5 m above the base), yielded similar arrays of nonequivalent dates ranging from 61.8 Ma to 30.7 Ma. We interpret the weighted mean of the two youngest grains as the maximum age of tuff deposition near 30.77 Ma.

The Carbon Tuff occurs ~4 m above the base of the Upper Puesto Almendra Member in profile MMZ, and 1.5 m above major unconformities associated with basalt pebbles and Deseadan faunas (discontinuity 8). The tuff is pale gray, massive, and ranges from 2 to 4 m in thickness (Fig. S1). A maximum age of 23.13 Ma is inferred from the youngest zircon in an array of eight nonequivalent ages (Fig. 3).

### Colhue-Huapi Member

The Big Mammal Tuff occurs ~6 m above the base of the Colhue-Huapi Member, within a zone of Colhuehuapian faunas that extends from 2 to 30 m above the member base. The tuff is pale gray, massive, and has a poorly sorted basal conglomerate that forms an erosive contact (Fig. S1). Five zircon crystals indicate a depositional age of  $20.890 \pm 0.033$  Ma, excluding five older grains (Fig. 3). This age is over 1 m.y. older than the  $^{40}\text{Ar}/^{39}\text{Ar}$  mean age of 19.75 Ma presented by Ré et al. (2010b).

The CHW01-24.5 Tuff occurs ~51 m above the base of the member and 8 m below a 3-m-thick zone of "Pinturan" faunas. The tuff is 8 m above the MMZ24.5 Tuff dated as 19.295 Ma by Ré et al. (2010b). It is a pale-gray, massive unit, around 4 m thick. Five zircons indicate a depositional age of  $19.041 \pm 0.027$  Ma, excluding two slightly older grains (Fig. 3). The U-Pb age is younger than the Ar/Ar age of the MMZ 24.5 Tuff, which occurs 8 m below our sample, consistent with stratigraphic positioning.

The Monkey Tuff, 22 m from the base of the Colhue-Huapi section, was dated by Ré et al. (2010b) as 19.81 Ma (Fig. 2). We made no

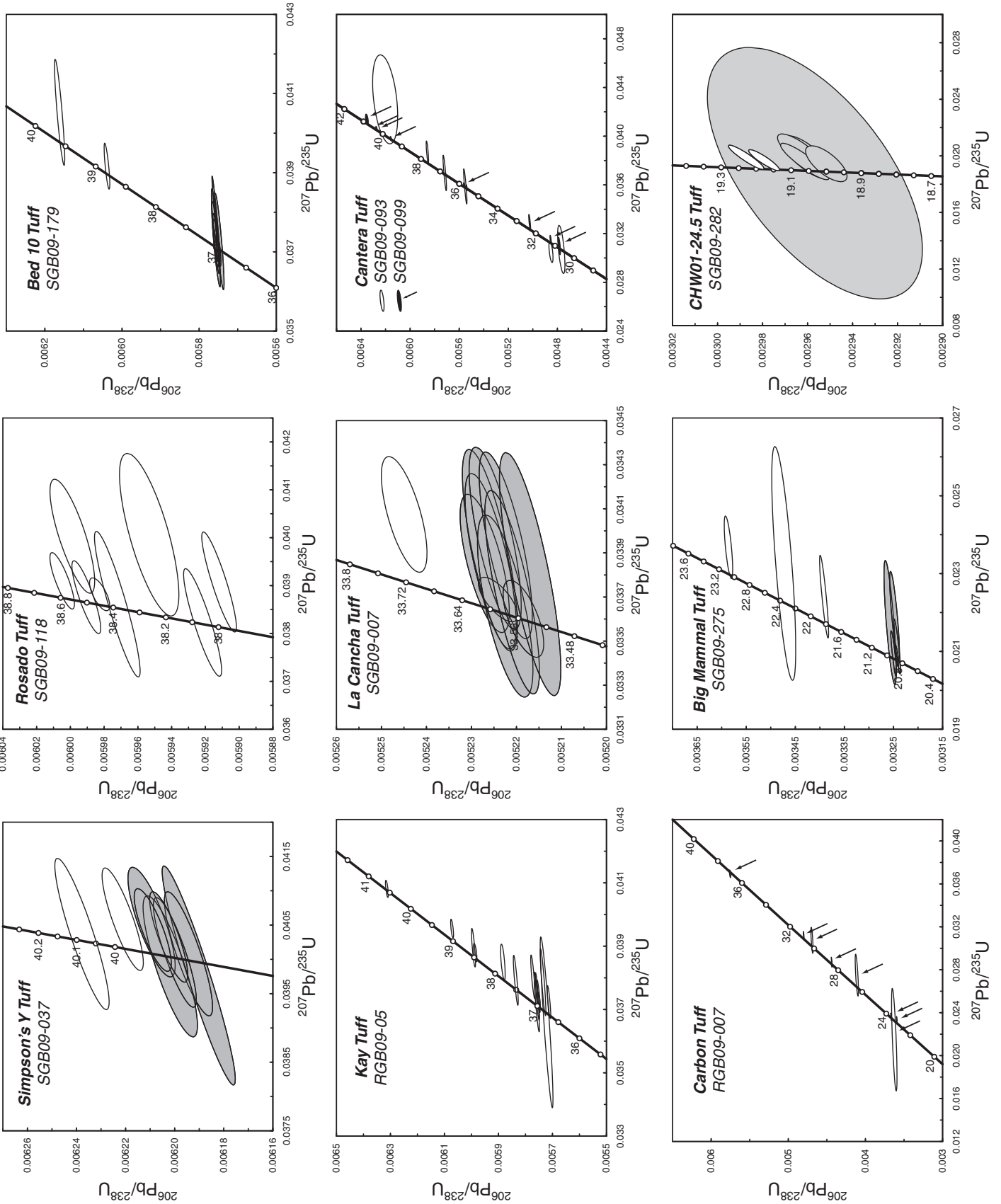


TABLE 2. SUMMARY OF MEMBER AND DISCONTINUITY MAXIMUM AND MINIMUM INTERVALS AND DURATIONS

Formation	Minimum interval (Ma)	Maximum interval (Ma)
Gran Barranca	41.70–38.45	42.11–38.16
Rosado	38.03–38.03	38.16–37.96
LPA	37.52–36.73	38.03–36.67
Vera	34.15–33.58	35.25–33.23
UPA3	30.77–26.34	30.77–26.34
UPA4	23.13–22.30	23.13–22.06
UPA5	22.06–22.06	22.30–21.11
Colhue-Huapi	20.89–19.04	21.11–18.62
Discontinuity	Minimum duration (m.y.)	Maximum duration (m.y.)
1 (Gran Barranca)	1.2	1.2
2 (Gran Barranca–Rosado)	0.00	0.20
3 (Rosado–LPA)	0.44	1.03
5 (LPA–Vera)	1.42	2.58
6 (Vera–UPA3)	2.46	2.96
7 (UPA3–basalt)	1.44	4.28
8 (basalt–UPA4)	3.21	6.05
9 (UPA4–UPA5)	0.00	0.24
10 (UPA5–C-H)	0.00	1.17

*Notes:* LPA—Lower Puesto Almendra Member; UPA3, 4, 5—units 3, 4, and 5 of the Upper Puesto Almendra Member; C-H—Colhue-Huapi Member. Discontinuity 4 is viewed as representing negligible time (Bellosi, 2010a). The maximum age for the Barranca Member is based on the relative durations of C19n vs. C19r and the absolute duration of C19n (Pälike et al., 2006). Ages from oldest to youngest are: 42.11 Ma = age of base of C19r; 41.7 Ma = age of VRS Tuff; 38.45 Ma = top of C18n.1n; 38.16 Ma = base of C17n.3n; 37.96 Ma = top of C17n.3n; 38.03 Ma = maximum age of Rosado Tuff; 37.52 Ma = base of C17n.1n; 37.00 Ma = age of Bed 10 Tuff; 36.73 Ma = maximum age of Kay Tuff; 36.67 Ma = top of C17n.1n; 35.25 Ma = base of C15n; 34.15 Ma = top of C13r.1n; 33.58 Ma = age of La Cancha Tuff; 33.23 Ma = top of C13n; 30.77 Ma = age of La Cantera Tuff; 30.62 Ma = top of C12n; 26.34 Ma = age of youngest basalt; 23.13 Ma = maximum age of Carbon Tuff; 22.30 Ma = base of C6Bn.2n; 22.06 Ma = top of C6Bn.2n; 21.11 Ma = top of C6AA n; 20.89 Ma = age of Big Mammal Tuff; 19.04 Ma = age of CHW01–24.5 tuff; 18.62 Ma = top of C6n; all chron ages are from Pälike et al. (2006). Age of oldest basalt (needed for estimating durations of discontinuity 7 and 8) = 29.18 Ma (Ré et al., 2010b).

attempt to date this level, but considering sedimentation rates of ~16 m/m.y. calculated using the U-Pb ages for Big Mammal Tuff and the CHW01–24.5 Tuff, the Ar/Ar date for the Monkey Tuff is consistent with what would be expected at this stratigraphic level.

## DISCUSSION

### Gran Barranca Section—Comparison of $^{206}\text{Pb}/^{238}\text{U}$ to $^{40}\text{Ar}/^{39}\text{Ar}$ Dates

Our new accurate, high-precision (<0.1%) dates from the Gran Barranca section generally agree with published arithmetic mean ages of the combined bulk plagioclase and bulk glass  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of Ré et al. (2010b). Of the re-dated tuffs (Simpson's Y, Rosado, Kay, and Big Mammal Tuff), our results differed from the  $^{40}\text{Ar}/^{39}\text{Ar}$  calculated means by 0.011 m.y. for the Simpson's Y Tuff, 0.63 m.y. for the Rosado Tuff, 0.315 m.y. for the Kay Tuff, and 1.14 m.y. for the Big Mammal Tuff. However, the greater precision of the U-Pb ages dramatically increases our confidence in magnetostratigraphic correlation.

←  
**Figure 3. U-Pb concordia diagrams for zircon analyses from dated tuffs. All sample error ellipses are plotted at  $2\sigma$ . Small ellipses are highlighted with arrows. Gray filled ellipses are included in weighted mean calculations. For the Cantera Tuff, two samples are plotted together as open versus filled ellipses.**

### Paleomagnetic Correlation: Ages of the Members and Durations of Hiatuses

Through correlation of the magnetostratigraphic section to Pälike et al. (2006), we propose the following maximum and minimum durations of deposition for the six members and durations of the major discontinuities (see also Table 2). Except for the Big Mammal Tuff, our dated tuffs and magnetic signals correlate with Pälike06. The rarity of reversed magnetic intervals in the upper Gran Barranca, Rosado, and Lower Puesto Almendra Members causes ambiguities in the durations of deposition and hiatuses, as discussed for each member in the following sections.

#### Gran Barranca Member

Based on our dates and the new magnetic correlation, we estimate that the Gran Barranca Member spans minimally from 41.7 (age of VRS Tuff) to >38.45 Ma (top of C18n.1n), or maximally from 42.11 (base of C19r) to ca. 38.16 Ma (bottom of C17n.3n). These ranges more or less agree with the previous estimate of Ré et al. (2010b) of 41.6–38.7 Ma. The minimum base age is constrained by the  $^{40}\text{Ar}/^{39}\text{Ar}$  mean age of  $41.7 \pm 0.38$  Ma for the VRS Tuff (Ré et al., 2010b). If the VRS Tuff is in C19r, then, assuming there are no discontinuities below DS1, the normal polarity zone just under DS1 would correlate to C19n (Fig. 4). The age of Simpson's Y Tuff indicates that the normal polarity zone above DS1 is C18n.2n, so DS1 could represent removal of reversed polarity rocks corresponding to C18r, which is

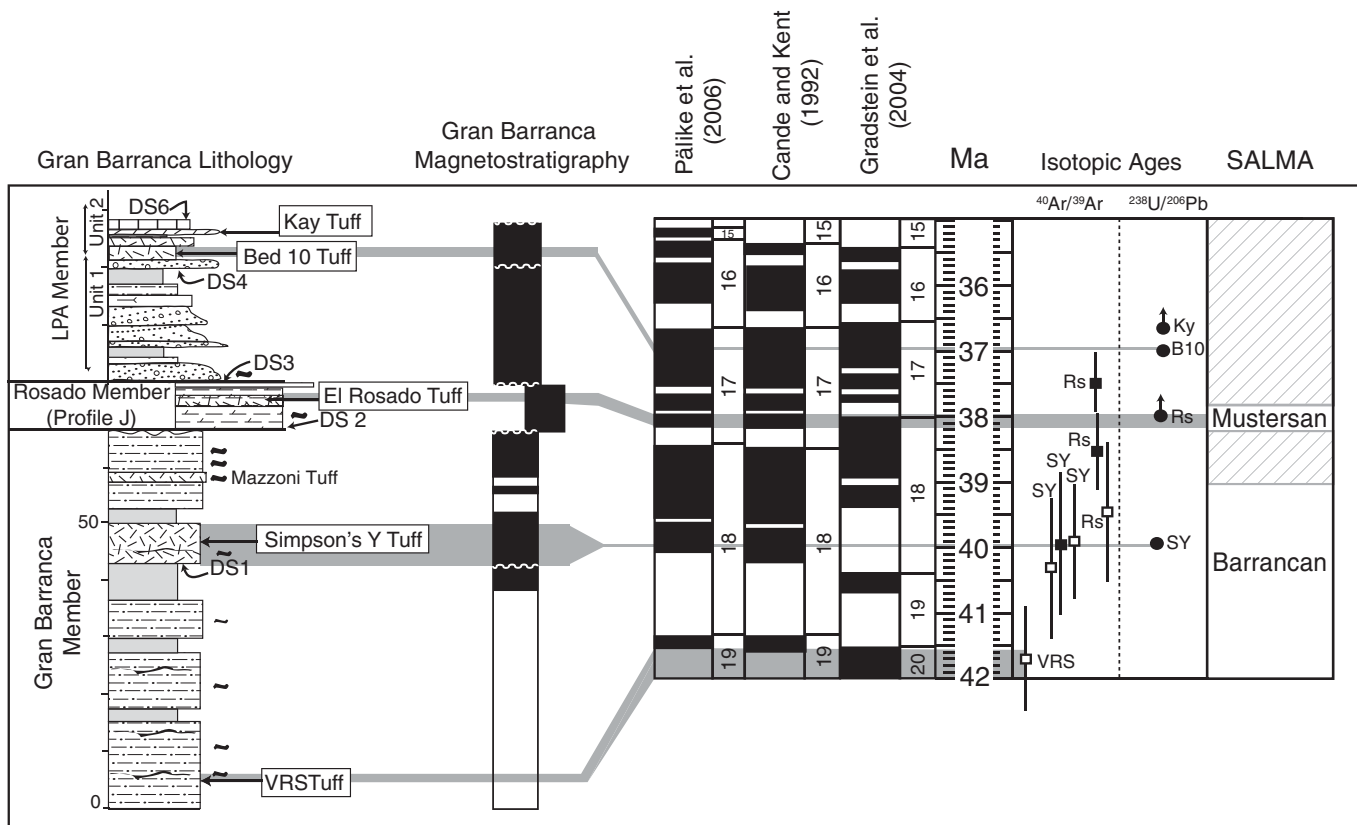
~1.2 m.y. long. The normal polarity zone at the top of the Gran Barranca Member would probably correlate to C18n.1n, which is supported by the (somewhat unreliable) mean age of 39.08 Ma determined by Ré et al. (2010b) for the Mazzoni Tuff, which occurs in a reversed polarity zone that could correlate to C18n.1r. Ages for the top of the Gran Barranca Member are maximally constrained by the age of the Rosado Tuff in the overlying Rosado Member at  $\leq 38.03$  Ma, which occurs in a normal polarity zone correlated to C17n.3n (38.16 Ma).

#### Rosado Member

There is a single normal polarity site for the Rosado Member at profile M (site MI12 in Ré et al., 2010a). The Rosado Tuff age correlates to chron C17n.3n (38.159–37.956 Ma; Fig. 4). However, given the coarse resolution of the Ré et al. (2010a) magnetostratigraphic record for the Rosado Member, which could have potentially missed some of the short reversed intervals within C17, and the presence of discontinuities above and below the member, it is difficult to reliably estimate its duration.

#### Lower Puesto Almendra Member

Because the Lower Puesto Almendra is entirely normal in polarity, a lower bounding age is ambiguous. However, Bed 10 and the overlying Kay Tuff ages both correspond to chron C17n.1n (37.520–36.668 Ma; Fig. 4). Therefore, we estimate a maximum age duration of the Lower Puesto Almendra Member from the top of the Rosado Tuff to the top of chron C17n.1n (ca. 38.03–36.67 Ma). The minimum



**Figure 4.** Geochronology for lower part of the Sarmiento Formation. Member lithostratigraphy is plotted along with magnetostratigraphy of Ré et al. (2010a). Gray bars demonstrate correlation of lithostratigraphy and magnetostratigraphy from Gran Barranca to global polarity time scales of Pälke et al. (2006, and their supplementary data). Cande and Kent (1992) and Gradstein et al. (2004) are shown for comparison. Isotopic age determinations are those from the  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of Ré et al. (2010b; open squares—best plagioclase dates; closed squares—best glass ages). Closed circles indicate U-Pb ages (this study). Abbreviations: VRS Tuff—Vilas and Ré Silicified Tuff; SY—Simpson's Y tuff; Rs—El Rosado Tuff; B10—Bed 10 Tuff; Ky—Kay Tuff; LPA—Lower Puesto Almendra. For U-Pb dates,  $2\sigma$  error range is smaller than the symbol, and thus error ranges are the widths of the gray horizontal lines. Black arrows on U-Pb dates indicate maximum ages for those samples. South American Land Mammal Ages (SALMAs) are also indicated. See Figure 2 legend for explanation of stratigraphic symbols.

duration is defined by the base of chron C17n.1n (37.52 Ma) and the youngest zircon from the Kay Tuff (36.73 Ma).

#### Vera Member

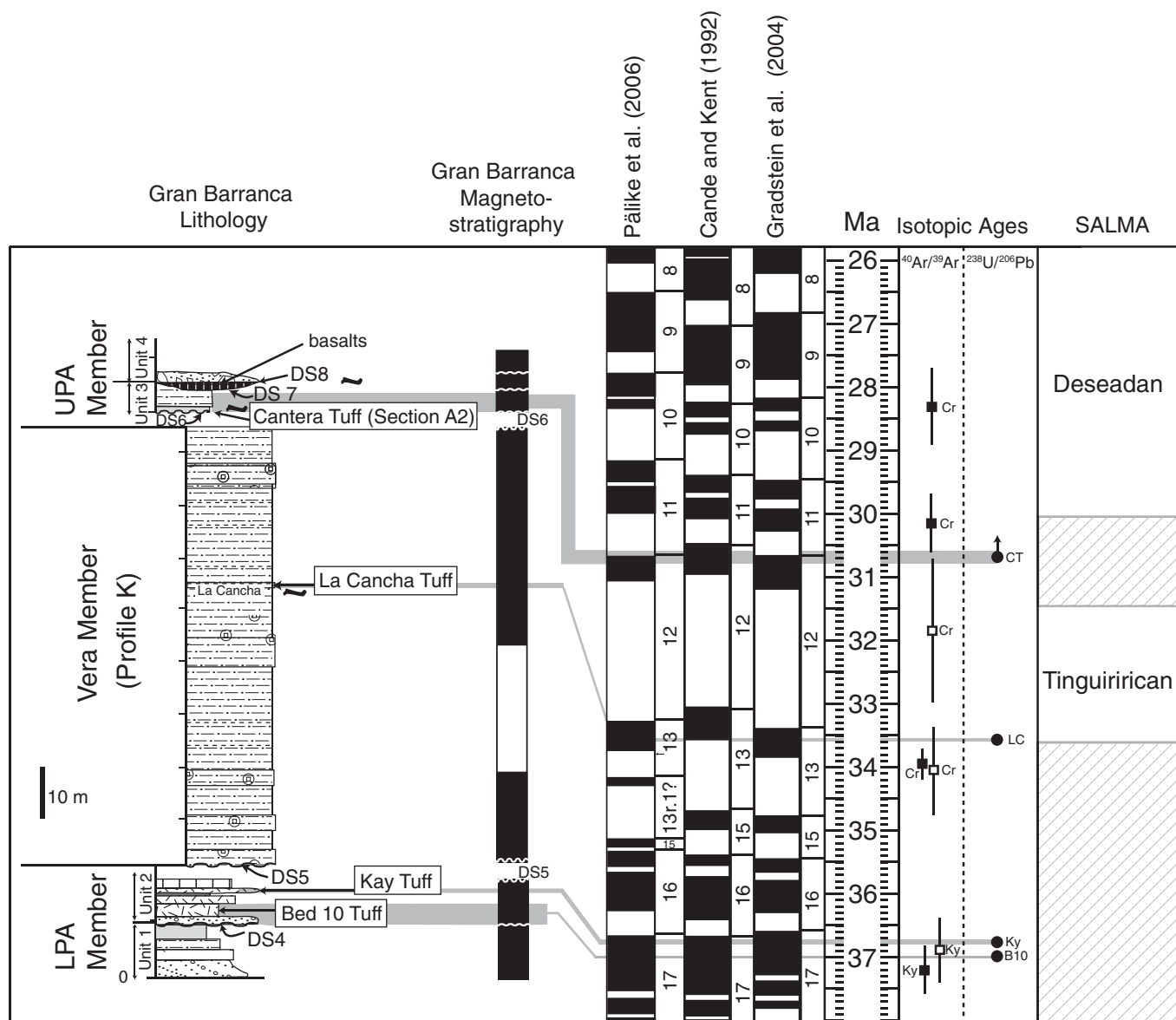
The Vera Member, measuring ~90 m in thickness, represents the thickest unit at Gran Barranca, but it was deposited in a relatively short interval. The section is uniform in composition, and no major unconformities have been identified within the member. The La Cancha Tuff age (33.58 Ma) correlates to chron C13n (33.705–33.232 Ma). There are two possible interpretations of the age of the Vera Member when correlating to the Pälke06. Because the lowest part of the Vera Member is also of normal polarity, it could correlate to C15n (35.254–35.126 Ma) or to C13r.1n (34.285–34.151 Ma; Fig. 5). The existence of chron C13r.1 is controversial, as

it has not been recorded in high-resolution records elsewhere, including the Eocene-Oligocene boundary sections in Italy (Lowrie and Lanci, 1994), or ODP Site 1220 in the equatorial Pacific (Parés and Lanci, 2004). However, Channell et al. (2003) found chron C13r.1n in cores from ODP Site 1090 in the South Atlantic Ocean. Due to the presence of C13r.1n in both the equatorial Pacific and the South Atlantic records, this chron may also occur in the paleomagnetic record for Gran Barranca. This has important implications for the duration of the Vera Member. Excluding chron C13r.1n from the correlation, the Vera Member could span from 35.254 Ma to 33.232 Ma (C15n–C13n). With inclusion of C13r.1n, the Vera could span from 34.285 Ma to 33.232 Ma (C13n–C13n.1n), a difference of 1 m.y.

The La Cancha Tuff (33.58 Ma) is ~10 m above the base of C13n (33.71 Ma), which

would indicate accumulation rates on the order of 80 m/m.y. This is more or less consistent with the deposition of an additional 30 m of normal polarity rock above the La Cancha Tuff, and it would place the top of the Vera Member around 33.2 Ma, but still within C13n. Correlation of the lower normal polarity zone within the Vera Member to C13r.1n is also consistent with this sedimentation rate. In contrast, correlation to C15 would require a tenfold decrease in accumulation rates during the deposition of the reversed polarity zone of the Vera Member. Potentially, there was a hiatus in deposition during the reversal; however, no such unconformity has as yet been identified in the section. A radioisotopic date is needed at the base of the Vera to select between the two alternatives. Given our estimate for the minimum upper age of the Lower Puesto Almendra Member (36.7 Ma) and the two interpretations for the base of the Vera





**Figure 5.** Geochronology for middle part of Sarmiento Formation. Symbols are the same as in Figure 4. Abbreviations: LPA—Lower Puesto Almendra; UPA—Upper Puesto Almendra; B10—Bed 10 Tuff; Ky—Kay Tuff; Cr—Carlini Tuff; LC—La Cancha Tuff; CT—Cantera Tuff. South American Land Mammal Ages (SALMAs) are also indicated. See Figure 2 legend for explanation of stratigraphic symbols.

Member, we estimate that either 1.4 or 2.4 m.y. elapsed at discontinuity 5.

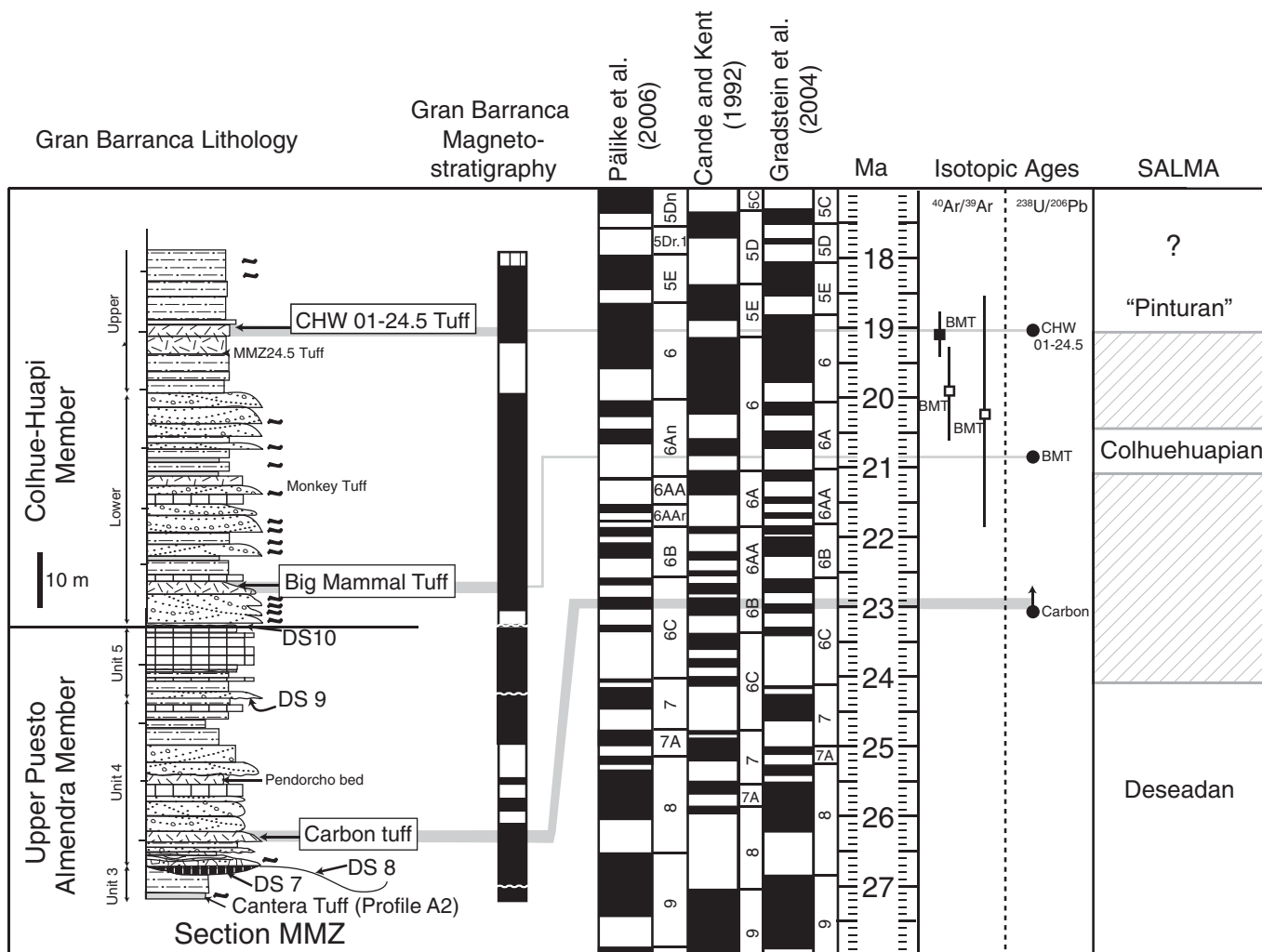
#### Upper Puesto Almendra Member

We estimate a total duration of the Upper Puesto Almendra Member from  $\leq 30.77$  Ma to at least 22.06 Ma and perhaps as young as 21.11 Ma. This extends the upper age estimate of Ré et al. (2010b) by 2–3 m.y. (30.6–24.2 Ma). The lower bound is based on the Cantera Tuff age ( $\leq 30.77$  Ma; Fig. 5) at the base of the Upper Puesto Almendra Member where it occurs in profile A-2. An upper age for the Upper Puesto

Almendra Member was estimated by calibrating the magnetic section using the maximum U-Pb age for the Carbon Tuff ( $\leq 23.13$  Ma). The Carbon Tuff has normal polarity, whereas its maximum numerical age falls within a magnetically reversed interval (chron C6C.2r). Since the numerical age is a maximum, the oldest likely age corresponds with the next youngest normal chron, C6Cn.2n (23.026–22.854 Ma; Fig. 6). Using this as a calibration point, assuming there are no hiatuses in deposition (at least below discontinuity 9), the top of Unit 4 would fall within chron C6Bn.2n (22.299–22.062 Ma).

Since Unit 5 is of normal polarity, and must be older than the Big Mammal Tuff (20.89 Ma), it may correlate to any of the normal intervals occurring between chron C6Bn.2n and the top of chron C6AAn (22.299–21.114 Ma).

The Cantera Tuff at the base of this unit is of normal polarity, and it correlates to chron C12n (Figs. 5 and 6). The top of chron C12n is 30.617 Ma, limiting deposition of tuffaceous strata between 30.77 and 30.617 Ma. Therefore, sedimentation below the basalts must have been of short duration, probably no more than 160 k.y. (Cantera Tuff age to top of chron C12n). Under



**Figure 6.** Geochronology for upper part of Sarmiento Formation. Symbols are the same as Figure 4. Abbreviations: Carbon—Carbon Tuff; BMT—Big Mammal Tuff; 01–24.5—CHW01–24.5. South American Land Mammal Ages (SALMA) are also indicated. See Figure 2 legend for explanation of stratigraphic symbols.

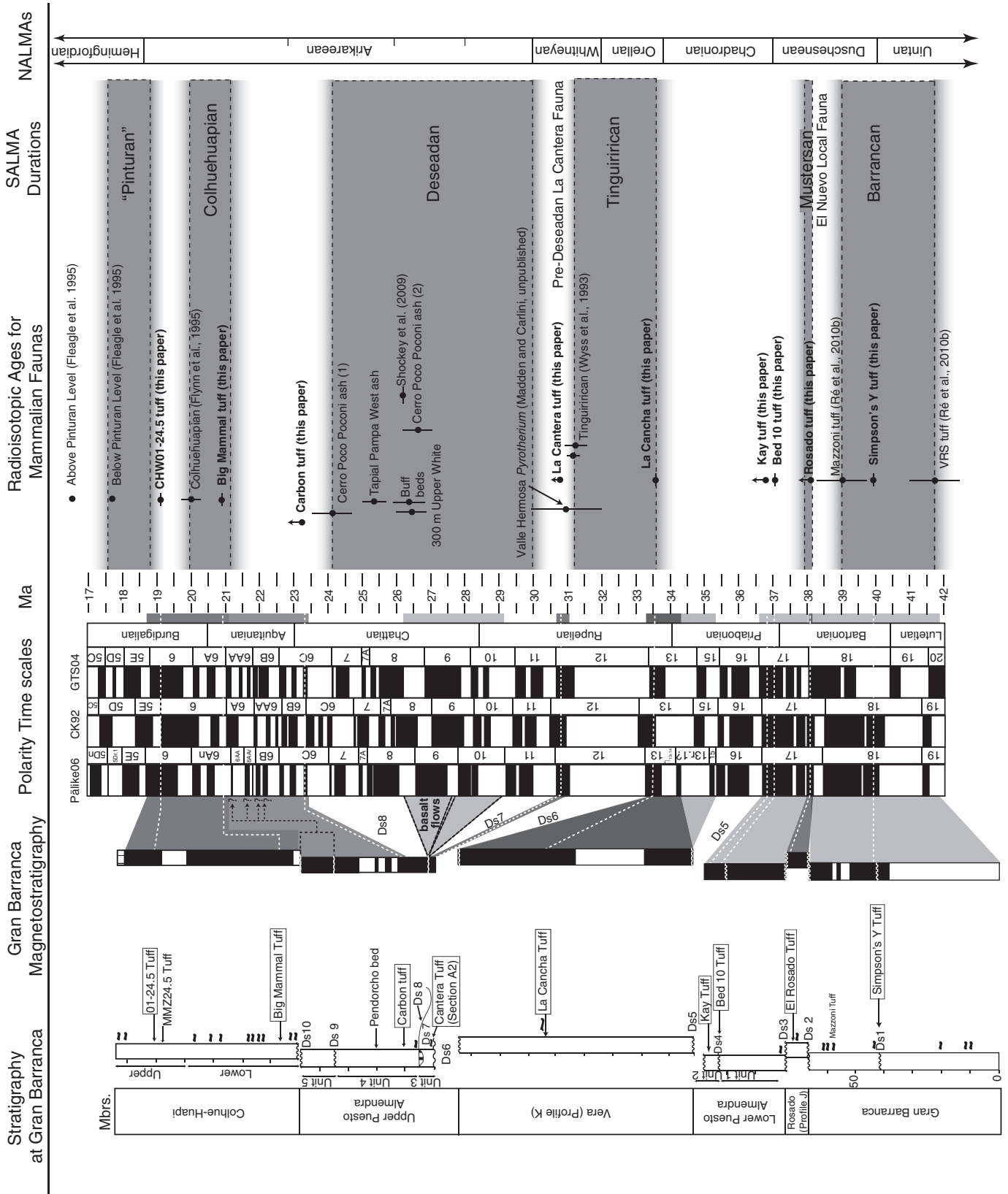
this scenario, the duration of discontinuity 7 could span from 1.44 m.y. (30.617–29.18 Ma, the age of the oldest basalt flow) to 4.28 m.y. (30.617 Ma to 26.34 Ma, age of the youngest basalt; see Fig. 7). Unit 4 of the Upper Puesto Almendra Member was deposited between 23.13 and 22.062 Ma. Therefore, discontinuity 8, above the basalts, spans anywhere from 3.21 m.y. (26.34–23.13 Ma) to 6.05 m.y. (29.18 Ma to 23.13 Ma).

#### *Colhue-Huapi Member*

Deposition of the Colhue-Huapi Member spanned at least 1.9 m.y. ( $\geq 20.89$  Ma to  $\leq 19.04$  Ma) and no more than 2.5 m.y. ( $\leq 21.11$  Ma to  $\geq 18.62$  Ma). The lowermost dated tuff in the Colhue-Huapi Member, the Big Mammal Tuff ( $20.890 \pm 0.033$  Ma), was reported by Ré et al. (2010b) as normal in polarity. All recent

paleomagnetic time-scale compilations (Pälke et al., 2006; Gradstein et al., 2004; Cande and Kent, 1992, 1995), however, indicate reversed polarity (C6An.2r) for this time. The paleomagnetic signal from the tuff collection site is considered an oblique virtual magnetic pole—a result intermediate between normal and reversed polarity. Because other paleomagnetic samples at the base of the Colhue-Huapi are reversed, we infer that the bottom of the section, including the Big Mammal Tuff, occurs in chron C6An.2r (21.114–20.652 Ma). Thus, initiation of sediment emplacement must have occurred by 21.11 Ma, but no later than 20.89 Ma. The CHW01–24.5 Tuff occurs in an upper normal interval. Its age ( $19.041 \pm 0.027$  Ma) correlates with chron 6n, which terminated at 18.616 Ma, suggesting that deposition of the Colhue-Huapi Member ceased sometime between 19.0 and 18.6 Ma.

**Figure 7.** Summary geochronology for the Gran Barranca section showing timing of hiatuses and durations of the Sarmiento Formation members and South American Land Mammal Age (SALMA) occurrences. Radioisotopic ages from other vertebrate localities in South America are plotted and provide continent-wide age constraints for the SALMAS. Refer to Table 3 for references of radioisotopic dates. White dashed lines correlate U-Pb ages from this paper with the magnetostratigraphic section, bold black dashed lines show correlation of basalt ages, and thin dashed black lines show possible chron correlation of rock units. North American Land Mammal Age (NALMA) durations and age boundaries are from Woodburne (2004) and Albright et al. (2008).



Our dates extend the age of the Colhue-Huapi Member estimated by Ré et al. (2010b) slightly (0.1–0.7 m.y.). Given our revised age for the top of the Upper Puesto Almendra Member (between 22.06 and 21.11 Ma), the hiatus indicated by discontinuity 10, between deposition of the Upper Puesto Almendra Member and Colhue-Huapi Member, may have been negligible or as long as 1.17 m.y.

### Calibration and Correlation of the Eocene–Miocene Paleontologic Record—South American Land Mammal Ages

Because Gran Barranca is the only section in South America that contains six successive SALMA associations, the ages of their occurrences at Gran Barranca in combination with known ages of other localities help to constrain the age durations of these SALMAs. The following discussion considers all recent radiometric constraints for the SALMA durations (see also Table 3; Fig. 7). Details about the lowest and highest mammal fossil occurrences and a list of pertinent index taxa per SALMA at Gran Barranca are described in the supplementary material in the GSA Data Repository (see footnote 1).

#### Barrancan SALMA

The original Casamayoran SALMA proposed by Simpson (1933, 1940) was split into an older Vacan and younger Barrancan subages by Cifelli (1985), and, because their faunas are so distinct, we refer to them each as separate SALMAs. Therefore, the age of the Barrancan SALMA cor-

responds to the age of the Gran Barranca Member, which we estimate to begin ca. 41.7 Ma. The highest occurrence of Barrancan faunas at Gran Barranca is 8 m above the base of Simpson's Y Tuff, and 7 m above a reversed polarity zone (site MI06 in Ré et al., 2010a) that may correspond to chron C18n.2r. Therefore, the highest Barrancan fossil occurrences likely fall within C18n.1n (39.554–38.449 Ma), and above the Mazzoni Tuff, dated as 39.08 Ma (Ré et al., 2010b). Therefore, we estimate the Barrancan to span from 41.7 to 39.0 Ma. Barrancan fossils are known from at least three other locations in Patagonia that have not been dated (see Cifelli, 1985). Dating tuffs from these other areas may help to refine the lower and upper age limits of the Barrancan SALMA.

#### Mustersan SALMA

The Mustersan SALMA occurs at Gran Barranca throughout the Rosado Member and in the Lower Puesto Almendra Member, below the Bed 10 Tuff (Bond and Deschamps, 2010). Therefore, the duration of the Mustersan mammal age is equivalent to the age of the Rosado and part of the Lower Puesto Almendra Member. Because the Rosado stratigraphic level is all of normal polarity, the Mustersan at Gran Barranca cannot be older than the base of chron C17n.3n (38.159 Ma), but Mustersan assemblages from the Lower Puesto Almendra Member (Coley's Quarry, Simpson's #64) have not been relocated. Therefore, the highest occurrences of Mustersan faunas at Gran Barranca are uncertain, but they can be no younger than 37 Ma based on the age of Bed 10. Other Mustersan localities in Patago-

nia have not been dated (Bond and Deschamps, 2010). In northwestern Argentina, a putative Mustersan faunal assemblage in the Geste Formation (López, 1997; Goin et al., 1998; Pascual, 1983; Reguero et al., 2008) is associated with detrital zircon ages between 37 and 35 Ma (DeCelles et al., 2007). Based on the oldest dated assemblages from Gran Barranca, and the youngest faunas in northwestern Argentina, the Mustersan may range from ca. 38.2 Ma to 35 Ma, but we suggest a conservative estimate of 38.2–38.0 Ma based on the well-defined Mustersan levels at Gran Barranca.

#### Tinguirirican SALMA

The Tinguirirican SALMA is defined by faunas from the Chilean Andes (Wyss et al., 1990) and helps fill a long interval in the South American fossil record between late Eocene (Mustersan) and late Oligocene (Deseadan) faunas. Other Tinguirirican assemblages have also been described from northern Patagonia (e.g., Rocas Bayas; Vucetich et al., 2010a) and at Gran Barranca (Madden et al., 2010). The only assuredly Tinguirirican fauna at Gran Barranca is found within the La Cancha Tuff, here dated at 33.58 Ma. In the type area in the Chilean Andes, Tinguirirican faunas are associated with tuffs with  $^{40}\text{Ar}/^{39}\text{Ar}$  dates of  $31.65 \pm 0.32$  Ma and  $31.34 \pm 0.17$  Ma (Wyss et al., 1993; Flynn et al., 2003; Fig. 7). These ages imply that the Tinguirirican spans at least 33.6–31.3 Ma.

#### La Cantera Faunas

The La Cantera Tuff in Unit 3 of the Upper Puesto Almendra Member contains a unique

TABLE 3. PUBLISHED ISOTOPIC DATES FOR VERTEBRATE LOCALITIES

SALMA	Formation	Relation to fossils	Reference	Method (standard)	Age (Ma)
Mustersan	Geste	Unclear	1	$^{238}\text{U}/^{206}\text{Pb}$ detrital zircons	$37.3 \pm 1.5$
	Geste	Unclear	1	$^{238}\text{U}/^{206}\text{Pb}$ detrital zircons	$35.4 \pm 0.55$
Tinguirirican	Abanico	Within fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$31.65 \pm 0.32$
	Abanico	Within fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$31.34 \pm 0.17$
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$31.5 \pm 1.0$
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$31.4 \pm 1.0$
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$34 \pm 1.3$
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$34.5 \pm 1.3$
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$35.6 \pm 0.9$
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$37.67 \pm 0.31$
	Abanico	Below fossil zone	2, 3	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$37.22 \pm 0.85$
Deseadan	Salla beds	Buff rubbly beds	4	$^{40}\text{Ar}/^{39}\text{Ar}$ (LP-6 & MAC-83)	$26.4 \pm 0.4$
	Salla beds	Nowhere ash (unit 2)	4	$^{40}\text{Ar}/^{39}\text{Ar}$ (LP-6 & MAC-83)	$31.5 \pm 0.5$
	Salla beds	Cerro Poco Poconi ash (1)	4	$^{40}\text{Ar}/^{39}\text{Ar}$ (LP-6 & MAC-83)	$24.2 \pm 0.6$
	Salla beds	Cerro Poco Poconi ash (2)	4	$^{40}\text{Ar}/^{39}\text{Ar}$ (LP-6 & MAC-83)	$26.6 \pm 0.4$
	Salla beds	Tapial Pampa West ash	4	$^{40}\text{Ar}/^{39}\text{Ar}$ (LP-6 & MAC-83)	$25.4 \pm 0.3$
	Salla beds	300 m Upper White	4	$^{40}\text{Ar}/^{39}\text{Ar}$ (LP-6 & MAC-83)	$26.5 \pm 0.4$
	Moquegua	Within fossil zone	5	No analytical details provided	$26.25 \pm 0.1$
Colhuehuapian	Abanico	Within fossil zone	6	$^{40}\text{Ar}/^{39}\text{Ar}$ (FCT 27.84 Ma)	$20.09 \pm 0.27$
Pinturan	Pinturas	Within fossil zone	7	Unknown	17.7
	Pinturas	Above fossil zone	7	Unknown	16.5

Note: SALMA—South American Land Mammal Age; FCT—Fish Canyon Tuff. References: 1—DeCelles et al. (2007); 2—Wyss et al. (1993); 3—Flynn et al. (2003); 4—Kay et al. (1998); 5—Shockey et al. (2009); 6—Flynn et al. (1995); 7—Fleagle et al. (1995).

assemblage of taxa transitional between Tinguirirican and Deseadan faunas referred to as “pre-Deseadan” (Madden et al., 2010). The unique faunal assemblage includes one of the oldest occurrences of rodents in Argentina (Vucetich et al., 2010a), the first appearance of large carnivorous borhyaenid marsupials, and the oldest record of Toxodontidae in South America (Madden et al., 2010). Ré et al. (2010a) could not correlate the normal polarity signal of the La Cantera tuff to a specific chron, they but did constrain it to chrons C12n, C11n.2n, or C11n.1n, spanning from 31.1 to 29.5 Ma. Despite evidence of sediment reworking, our U-Pb dates suggest a maximum age of 30.77 Ma. This date correlates to chron C12n, suggesting that the La Cantera fauna is older than the top of this magnetic zone, 30.617 Ma. Therefore, the pre-Deseadan assemblage of La Cantera is likely between 30.77 and 30.617 Ma.

#### Deseadan SALMA

Past ages estimates for the Deseadan SALMA have ranged from 37.5 Ma to 21 Ma (see Flynn and Swisher, 1995). The oldest dated fossil of Deseadan age is a *Pyrotherium* mandible from Valle Hermoso between 29.9 and 32.1 Ma (Madden and Carlini, unpublished data). The age of *Pyrotherium* at Salla ranges from 29.4 to 25.8 Ma (Kay et al., 1998). A recent  $^{40}\text{Ar}/^{39}\text{Ar}$  date of a Deseadan site in Moquegua, Peru, of  $26.25 \pm 0.10$  Ma falls within this range (Shockey et al., 2009). The pre-Deseadan fossil mammal assemblage at La Cantera is now known to be  $\leq 30.77$  Ma. On this basis, a basal age for the Deseadan SALMA can be established at ca. 30 Ma.

At Gran Barranca, Deseadan mammals occur along the erosional surfaces atop the basalts. If the tops of all the basalts were weathered at the same time (i.e., a single discontinuity 8), then the Deseadan assemblages at Gran Barranca must be younger than 26.34 Ma, the age of the youngest basalt (Ré et al., 2010b). If instead there were multiple erosional discontinuities associated with the tops of several basalt flows of different ages, then some of the Deseadan mammals at Gran Barranca could be as old as 28.9 Ma. Both scenarios are consistent with chronologic constraints from Bolivia and Peru. Another possibility is that these fossils from the base of Unit 4 are likely ca. 23.0 Ma, but possibly as young as ca. 22.6 Ma (Fig. 7), which would extend the Deseadan age range considerably. The beds are not sufficiently well exposed nor are the faunas of Deseadan aspect well enough preserved to select among these alternatives.

The age of the Cerro Poco Poconi Ash at Salla ( $24.2 \pm 0.6$  Ma; Kay et al., 1998) provides the youngest securely dated fossil mammal assemblage of Deseadan age with *Pyrotherium*.

However,  $^{40}\text{K}/^{40}\text{Ar}$  ages as young as 23.4 and 21.6 Ma have been reported from Scarritt Pocket (Marshall et al., 1986). Confirming these young occurrences of Deseadan mammals will require more accurate  $^{40}\text{Ar}/^{39}\text{Ar}$  or  $^{206}\text{Pb}/^{238}\text{U}$  methods. Taking all of the current information into account, we estimate a minimum age range of 29.4–24.2 Ma for the Deseadan SALMA, possibly extending from 30 to 23 Ma.

#### Colhuehuapian SALMA

Colhuehuapian mammal-bearing strata at Gran Barranca span a reversed polarity zone correlated to chron C6An.2r (21.114–20.652 Ma) and below the Big Mammal Tuff (20.89 Ma) nearly to the top of a normal polarity zone correlated to chron C6An.2n (20.652–20.425 Ma). Given this correlation, we estimate that the Colhuehuapian fauna occurs between ca. 21.0 and 20.5 Ma at Gran Barranca.

Other Colhuehuapian faunas from Argentina have not been dated (see Vucetich et al., 2010b), but a Colhuehuapian assemblage from the Abanico Formation in the Chilean Andes was dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  at  $20.09 \pm 0.27$  Ma (Flynn et al., 1995). Altogether, we estimate the duration of the Colhuehuapian SALMA to be  $\sim 1$  m.y., 21.0–20.1 Ma, slightly expanding the proposed duration of Madden et al. (2010) of 20.2–20.0 Ma.

#### Pinturan SALMA

The Pinturan is recognized as a distinct assemblage between Colhuehuapian and Santacrucian faunas (see Kramarz et al., 2010), and we refer to it here as a SALMA. At Gran Barranca, vertebrate faunas characteristic of Pinturan assemblages occur  $\sim 8$  m above the CHW01–24.5 Tuff (19.04 Ma) within the same magnetically normal interval, C6n. Because C6n terminates at 18.616 Ma, Pinturan faunas at Gran Barranca are bracketed between 19.04 and 18.62 Ma.

In the type area of the Pinturan, in NW Santa Cruz Province, a  $^{40}\text{Ar}/^{39}\text{Ar}$  age from the base of the vertebrate levels is 17.5 Ma, whereas a  $^{40}\text{Ar}/^{39}\text{Ar}$  date from above the faunal levels is 16.5 Ma (Kramarz et al., 2010). Thus, the maximum duration for the “Pinturan” is 19.04–16.5 Ma. This interval overlaps recently published bracketing  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $18.79 \pm 0.11$  Ma and  $17.5 \pm 0.4$  Ma (Croft et al., 2007) for a Santacrucian fauna from Chucal, Chile (Croft et al., 2004, 2007). These data imply a smaller maximum span for the Pinturan, from 19.04 to 17.5 Ma.

#### EOCENE-OLIGOCENE TRANSITION AND HYPSONDONTY EVOLUTION

Previous  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations for the La Cancha Tuff, a massive tuff embedded

within the La Cancha faunal horizon, have been problematic. Despite an arithmetic mean age of 33.995 Ma for the bulk glass and plagioclase samples (Ré et al., 2010b), high uncertainties in the age determination of this tuff limited interpretation of the significance of the Vera Member with respect to the Eocene-Oligocene climatic transition. Pälke et al. (2006) presented an interpolated age for the Eocene-Oligocene boundary of 33.79 Ma based on magnetostratigraphy of C13r(0.14), which predates the oxygen isotope Oi-1 excursion. The new precise La Cancha Tuff age of  $33.581 \pm 0.015$  Ma clearly postdates the Eocene-Oligocene transition. The magnetostratigraphy of lower strata, however, implies initial deposition no later than ca. 34.1 Ma, well before the Eocene-Oligocene transition. These data confirm that the Vera Member preserves the only documented terrestrial fossil-bearing Eocene-Oligocene transition section in the Southern Hemisphere.

The new date for the La Cancha fauna of Gran Barranca verifies its occurrences as the oldest Tinguirirican fauna. Additionally, the new date adds temporal certainty to work showing that no major atmospheric temperature change occurred across the Eocene-Oligocene transition at Gran Barranca, based on oxygen isotopes in tooth enamel (Kohn et al., 2004). In agreement with the apparently stable atmospheric temperatures at Gran Barranca surrounding the Eocene-Oligocene transition, a record of phytoliths shows that vegetation apparently did not change significantly during this episode of major global climatic change (Strömberg et al., 2010). These patterns suggest that the terrestrial, local climatic, and biological consequences of the global climate changes at the Eocene-Oligocene transition were complex and that substantially more work is needed to fully understand this climatic event.

The improved age correlation also provides firm dates for the successive changes in faunal hypsodonty in Patagonia, corroborating the long-standing notion that hypsodonty evolved at least 20 m.y. earlier in Southern South America than elsewhere (Stebbins, 1981; Jacobs et al., 1999; Madden et al., 2010). The earliest faunas with several hypsodont members occurred at 38 Ma at Gran Barranca, whereas faunas with equivalent prevalence of hypsodonty did not appear in North America, Western Eurasia, and Africa until after 18 Ma (Damuth and Janis, 2011; Jacobs et al., 1999; Janis et al., 2002; Jernvall and Fortelius, 2002; Strömberg, 2011). Hypsodonty evolution in mammalian herbivores was therefore not a uniform, direct response to global, climatic events; rather, the factors influencing it have to be sought on a continent-by-continent basis (Strömberg, 2011).

South America remains a strikingly unique case, but one that is vital for fully understanding the controls of adaptation and convergent evolution.

#### DID FAUNAL EVOLUTION TRACK CLIMATE CHANGE?

The new ages may help advance research on climate change as a catalyst for mammalian evolution. This concept "...has pervaded the paleontological literature for nearly two centuries..." (Alroy et al., 2000, p. 285) but remains hotly debated (e.g., Vrba, 1995; Webb and Opdyke, 1995; Prothero, 1999; Alroy et al., 2000; Barnosky, 2001; Woodburne et al., 2009; Figueirido et al., 2011), and different studies have reached nearly diametrically opposed conclusions. Most studies emphasize North American faunal change, because the faunal record and chronologies there are generally more complete. Many of the major faunal turnover events in North America, however, were influenced strongly by immigration from other continents, and were not necessarily the direct result of climate change (but see Woodburne et al., 2009). Consequently, isolating the effects of climate change remains problematic. Because South America was largely (albeit not completely) isolated from other continents through much of the Cenozoic, it may provide a clearer perspective on this subject. Since land mammal ages by their construction are based on evolutionary trends in indigenous taxa, there is no reason that a biochron from one continent should correlate to another. However, if global climate change drives patterns of evolutionary faunal change, then we might expect some correspondence between SALMA boundaries and either climate trends or mammal-based biostratigraphies on other continents, such as the North American Land Mammal Ages (NALMA) or the European Land Mammal Ages (ELMA). That is, direct intra- or intercontinental correlation could provide an important test of the climate-faunal evolution hypothesis. Here, we discuss the potential of such comparisons, but also remaining problems.

It is important to remember that the mammalian groups that made up the mid-Cenozoic faunas of South America, most of which are completely extinct, were only distantly related to the clades (e.g., Perissodactyla, Artiodactyla) that inhabited other parts of the world. Two notable exceptions include caviomorph rodents, which arrived by the middle Eocene (Antoine et al., 2011), and platyrrhine primates, present by the late Oligocene (Hoffstetter, 1969; MacFadden et al., 1985). This major phylogenetic disjunction limits direct, taxonomic comparisons among continents. Nevertheless, evaluation

of the timing of turnover events across continents, signaled by respective land mammal age boundaries, may be just as useful. Specifically, it provides a means by which to explore whether extinction, origination, or immigration events in mammalian faunas were globally synchronized during certain periods of the Cenozoic.

The largest obstacle to comparing in detail the SALMAs to other land mammal ages relates to the persisting uncertainty in the exact dates for SALMA boundaries, illustrated in Figure 7. Often, the uncertainty, that is, the gap between well-dated faunal levels, is on the order of several million years. This makes it impossible in many cases to reject (or support) a hypothesis of coincidence. To illustrate this point further, we provide a comparison between SALMAs as temporally revised herein and the seven NALMAs that occur during the mid-Cenozoic (Woodburne, 2004; Albright et al., 2008) (Fig. 7). The comparison shows that, in most cases, because of missing data from South America, we simply cannot say whether the boundaries occur simultaneously. For example, whereas the lower and upper boundary of the Tinguirirican falls within the Orellan and Whitneyan, respectively (Fig. 7), more research might show that the Tinguirirican boundaries do coincide with the base of the Orellan and the top of the Whitneyan. In other cases, boundaries appear coincident at our current state of knowledge, such as the start of the Pinturan and Hemingfordian (Fig. 7), but because of a gap in the fossil record, the Pinturan might have started a million years earlier. Conversely, some turnover events are clearly disjointed between continents. The Orellan-Whitneyan boundary falls in the middle of the Tinguirirican SALMA, and the Uintan-Duchesnean boundary falls within the Barrancan.

Another problem when directly comparing land mammal age boundaries on different continents is the lack of consistent criteria for defining them. Therefore, it might be necessary to take a more detailed look at faunal evolution to test intercontinental patterns. For example, a recent study used factor analysis to discover "evolutionary faunas," which only in part corresponded to traditionally defined NALMAs, and argued that global climate helped control the dynamics of these faunas (Figueirido et al., 2011). Such a detailed comparison is not yet possible in South America, but we offer one example intercomparing faunal change dynamics between North and South America. The Uintan-Duchesnean boundary occurs at ca. 39.74 Ma (Prothero and Swisher, 1992) and corresponds approximately to the Simpson's Y Tuff (39.861 Ma) level at Gran Barranca, during the Barrancan land mammal age. The Duch-

esnean NALMA marks the first appearances of *Hyaenodon*, *Duchesneodus*, *Duchesnehippus intermedius*, *Amynodontopsis*, *Eotylopus* (Robinson et al., 2004), *Pterodon*, Leptomerycidae, and Anthracotheriinae (Robinson et al., 2004; Woodburne, 2004). Half of these first appearances are Asian or European immigrants into North America, but many others probably mark in situ evolution. There are no identified dispersal events in Patagonia during the Barrancan nor do faunal compositions change across the numeric age of the Uintan-Duchesnean boundary, i.e., faunal turnover in North America is countered by faunal stasis in South America.

Finally, we find no direct evidence as yet for changes to SALMAs in response to global climate change. Late Oligocene warming occurred within the Deseadan, and late Eocene cooling occurred with no obvious change to faunas during the Barrancan. On the other hand, it is possible that Tinguirirican faunas evolved in response to the Eocene-Oligocene transition—a hypothesis that can be tested with fossiliferous strata of the lower Vera Member that assuredly predate the Eocene-Oligocene transition.

Although we find little support for the climate-faunal evolution hypothesis in South America, we reiterate that additional chronologies and paleontological investigations could provide superior data sets for testing it, either across the continent or in targeted strata such as the lower Vera Member. Conversely, further chronologic and faunal analysis of Pinturan strata elsewhere in South America might elucidate processes of faunal change during a time when global climate was nearly invariant. Such studies will require, however, accurately dated horizons for which stratigraphic and chronologic relationships to faunally distinctive strata are clear.

#### CONCLUSIONS

Our U-Pb dates, combined with the magnetostratigraphic section of Ré et al. (2010a) and correlation to the time scale of Pálike et al. (2006), provide a precise age model for present and future high-resolution paleoecological studies testing hypotheses about rates of ecological and/or evolutionary change in South America. Additionally, since Gran Barranca is the reference section for the middle Cenozoic SALMAs for all of South America and Western Antarctica, the dates help refine the ages of the SALMA occurrences and their durations. To this end, latitudinal differences in faunal occurrences can be studied in more detail.

The analysis of tuffs from the Sarmiento Formation at Gran Barranca yielded weighted  $^{206}\text{Pb}/^{238}\text{U}$  mean ages of:  $39.861 \pm 0.037$  Ma

(Simpson's Y Tuff);  $37.000 \pm 0.014$  Ma (Bed 10 Tuff);  $33.581 \pm 0.015$  Ma (La Cancha Tuff);  $20.890 \pm 0.033$  Ma (Big Mammal Tuff); and  $19.041 \pm 0.027$  Ma (CHW01–24.5 Tuff). Maximum ages for four other tuffs were determined from the youngest one or two zircon ages: 38.03 Ma (Rosado Tuff); 36.73 Ma (Kay Tuff); 30.77 Ma (Cantera Tuff); and 23.13 Ma (Carbon Tuff).

These dates combined with magnetostratigraphic correlation indicate the following maximum and minimum durations for the members of the Sarmiento Formation: Gran Barranca: 42.11–38.16 Ma and 41.7–38.45 Ma; Rosado: 38.16–37.96 Ma and 38.03–37.96 Ma; Lower Puesto Almendra: 38.03–36.73 Ma and 37.52–36.73 Ma; Vera: 35.25–33.23 and 34.15–33.58 Ma; Upper Puesto Almendra: 30.77–21.11 Ma and 30.77–22.06 Ma; and Colhue-Huapi: 21.11–18.62 Ma and 20.89–19.04 Ma.

Because the Sarmiento Formation at Gran Barranca contains the type sections of the Barrancan, Mustersan, and Colhuehuapian SALMAs, refinements of these and the age boundaries of the Vacan, Tinguirirican, Deseadan, and Pinturan SALMAs are best addressed in this succession. By compiling the new dates from Gran Barranca with other dated vertebrate assemblages in South America, we propose the following durations for the middle Cenozoic SALMAs: 41.7–39.0 Ma (Barrancan); 38.2–38.0 Ma (Mustersan); 33.6–31.3 Ma (Tinguirirican); 29.4–24.2 Ma (Deseadan); 21.0–20.1 Ma (Colhuehuapian); and 19.0–17.5 Ma (Pinturan).

The pre-Deseadan, post-Tinguirirican faunas found at the La Cantera site, Gran Barranca, are between 30.77 and 30.62 Ma. This new age constraint is significant because it shows that this fauna, distinctive from either Tinguirirican or Deseadan faunas, postdates the Tinguirirican and pre-dates the Deseadan. Thus, it is reasonable that the La Cantera fauna could be proposed as its own SALMA if similar faunal assemblages are found elsewhere in Patagonia. However, to date, the La Cantera fauna is unique to Gran Barranca.

The Vera Member preserves the only known fossil-bearing, terrestrial record of the Eocene-Oligocene transition in the Southern Hemisphere. The record at Gran Barranca during this interval indicates that atmospheric temperatures remained constant across the climatic event, and that vegetation, based on a record of phytoliths, did not change substantially in composition. In addition, the faunal record at Gran Barranca shows that taxonomic turnover postdates the Eocene-Oligocene transition event. Finally, our dates confirm the long-standing hypothesis that hypsodonty increases seen at Gran Barranca occurred significantly earlier than on other continents.

Although precise dating of biostratigraphically important beds will eventually allow intercontinental comparisons of turnover events, we conclude that the current state of knowledge of the boundaries of SALMAs does not permit such studies except in a few cases. Work seeking to fill in the gaps in the faunal record will be necessary before such a comparison is possible.

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