4 A geochronology for the Sarmiento Formation at Gran Barranca

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Abstract

The Sarmiento Formation (middle Eocene – early Miocene) is a terrestrial pyroclastic succession in central Patagonia broadly recognized by its abundant fossil mammals which comprise the standard succession for the South American mammal record. Age calibration of each subdivision of the formation and the internal discontinuities have been controversial and in need of better resolution. Until now, few radiometric dates were available.

Age calibration of the Sarmiento Formation was obtained at the type locality at Gran Barranca in south-central Chubut Province where the most continuous exposures occur. This age calibration integrates information from Ar/Ar dates on plagioclase and volcanic glass mineral separations from ten levels in all six members and five magnetic polarity sequences at different stratigraphic profiles. With this information, ten bounding surfaces with different origins and geometries were correlated along the exposure. The Sarmiento Formation transitionally overlies the Koluel-Kaike Formation. At the top of Gran Barranca is a poorly preserved remnant of the marine Chenque Formation. There are six members of the Sarmiento Formation at Gran Barranca containing seven distinct mammal faunas. The Gran Barranca Member yields Barrancan age fossils and spans the temporal interval from 41.6 to 39.0 Ma or late Lutetian–Bartonian (Chron C19r to C18n.1n). The Rosado Member includes both transitional Barrancan–Mustersan and Mustersan age faunas and spans the interval from about 38.4 to 38.0 Ma or late Bartonian (Chron C18n.1n). The Lower Puesto Almendra Member contains Mustersan age fossils between 37.3 Ma and 36.58 Ma or early Priabonian (Chron C17n). The Vera Member includes Tinguiririca age mammals and spans the interval between 35.0 Ma and 33.3 Ma or Priabonian to early Rupelian (Chron C15n to C13n). Tinguiririca age assemblages within this member are between 33.7 and 33.3 Ma. The Upper Puesto Almendra Member contains a pre-Deseadan age fauna (GBV-19 "La Cantera") and poorly sampled faunules of more typical Deseadean aspect. The member comprises three units and spans an interval as old as 31.1 Ma to as young as 24.2 Ma or late Rupelian–Chattian (Chron C12n to C7n). GBV-19 is between 31.1 and 29.5 Ma, and the Deseadan assemblages are between 29.2 Ma and 26.3 or younger in age. The Colhue-Huapi Member with Colhuehuapian and Pinturan faunal zones spans the interval between 20.4 Ma and 18.7 Ma or late Aquitanian–Burdigalian (C6An.1r to Chron C6n). The Lower Fossil Zone of the Colhue-Huapi Member containing Colhuehuapian mammals is 20.4 Ma to 20.0 Ma and the Upper Fossil Zone containing Pinturan mammals is between 19.7 and 18.7 Ma.

Primary and secondary pyroclastic sedimentation spans nearly 23 million years in the vicinity of Gran Barranca. During this interval, 8.4 m.y. are not preserved mainly because of significant erosion events and subordinately by non-deposition and soil formation. Temporal hiatuses between members increase from 0.7 m.y. in the middle Eocene to 3.48 m.y. in the early Miocene, probably in response to progressively increasing tectonic and landscape instability.

Resumen

La Formación Sarmiento (Eoceno medio – Mioceno temprano) es una sucesión piroclástica terrestre de Patagonia central, ampliamente reconocida por sus abundantes mamíferos fósiles, que forman la sucesión estándar de los vertebrados cenozoicos sudamericanos. La definición de edades precisas para cada una de sus sub-unidades, así como de posibles discontinuidades y hiatos internos, ha sido un tema discutido y pendiente de resolución desde hace décadas, contándose hasta hoy con muy escasos y restringidos datos de edades absolutas.

Este nuevo ajuste temporal fue elaborado para la localidad tipo de Gran Barranca (centro-sur de la provincia de Chubut), donde se encuentran los afloramientos fosilíferos más extendidos y continuos. Esta calibración geocronológica integró la información procedente de Ar/Ar en plagioclasa y vidrio volcánico de muestras de diez niveles pertenecientes a los seis miembros, cinco perfiles de polaridad magnética y cinco superficies de discontinuidad litoestratigráfica de diferente origen, geometría y jerarquía que fueron correlacionadas a lo largo de la barranca.

La Formación Sarmiento suprayace transicionalmente a la Formación Koluel-Kaike. En el tope de la Gran Barranca hay un remanente pobremente preservado de la Formación

The Paleontology of Gran Barranca: Evolution and Environmental Change through the Middle Cenozoic of Patagonia, eds. R. H. Madden, A. A. Carlini, M. G. Vucetich, and R. F. Kay. Published by Cambridge University Press.

Chenque, de origen marino. En la localidad de Gran Barranca hay seis miembros de la Formación Sarmiento que contienen siete faunas distintas. El Miembro Gran Barranca contiene fósiles de la Subedad Barranquense y se extiende temporalmente entre los 41.6 y 39.0 Ma; Luteciano tardío – Bartoniano [Crones C19r a C18n.1n]. El Miembro Rosado incluye faunas transicionales Barranquense-Mustersense y Mustersense, y abarca el intervalo de 38.4 a 38.0 Ma; Bartoniano tardío [Cron C18n.1n]. El Miembro Puesto Almendra Inferior contiene fósiles de la SALMA Mustersense y se extiende entre los 37.3 Ma y 36.58; Priaborniano temprano [Chron C17n]. El Miembro Vera contiene mamíferos tinguiririquenses y abarca el intervalo entre 35.0 y 33.3 Ma; Priaborniano – Rupeliano temprano [Crones C15n to C13n]. En este miembro, las localidades tinguiririquenses están entre los 33.7 y 33.3 Ma. El Miembro Puesto Almendra Superior contiene una fauna pre-Deseadense (GBV-19) y fáunulas de aspecto Deseadense más típico, pero pobremente muestreadas. Este Miembro tiene tres unidades y se extiende por un intervalo tan viejo como 31.1 Ma a tan joven como 24.2; Rupeliano tardío – Chatiano [Crones C12n a C7n]. GBV-19 se encuentra entre los 31.1 y 29.5 Ma. Los fósiles deseadenses se encuentran entre los 29.2 y 26.3 Ma, o aún algo más jóvenes. El Miembro Colhue-Huapi, con niveles de faunas del Colhuehuapense y "Pinturense," se extiende por el intervalo entre los 20.4 y 18.7 Ma; Aquitaniano tardío – Burdigaliano [Crones C6An.1r a C6n]. La Zona Fosilífera Inferior, con mamíferos colhuehuapenses, está entre los 20.4 y los 20.0 Ma, mientras que la Zona Fosilífera Superior, con mamíferos del "Pinturense," se encuentra entre los 19.7 y 18.7 Ma.

La sedimentación piroclástica primaria y secundaria se prolongó en la región de Gran Barranca por casi 23 millones de años. Unos 8.4 m.y. de ellos no están registrados, principalmente debido a significativos eventos de erosión y, subordinadamente, por falta de depositación y pedogénesis. Los hiatus temporales entre los distintos miembros se incrementan de 0.7 m.y. en el Eoceno medio a 3.48 m.y. en el Mioceno temprano, probablemente como respuesta a una progresiva inestabilidad tectónica y del paisaje.

Introduction

Gran Barranca exposes the most complete sequence of middle Cenozoic fossil-mammal bearing rocks in South America and the only continuous continental fossil record anywhere in the southern hemisphere through the middle and late Eocene, across the Eocene–Oligocene transition (EOT), and into the early Miocene. The fossil mammal sequence at Gran Barranca is the standard of reference for the middle Cenozoic throughout South America and Western Antarctica. Wherever fossil mammals are collected in South America or Antarctica, comparisons are necessarily made to the standard sequence in Patagonia which in turn relies ultimately on the quality and resolution of the paleontology, stratigraphy, and geochronology at Gran Barranca.

New fossil vertebrate collections are now much larger than ever before available and include new and diverse small mammals collected by both dry and wet screening. The new collections document 49 discrete fossil-mammal levels in the Sarmiento Formation, including levels never before sampled. The fossil content of these levels is described in this book.

This chapter establishes a chronology for the fossil-bearing rocks at Gran Barranca based on radiometric age determinations and magnetic polarity stratigraphy. Until now the geochronology of the Sarmiento Formation at Gran Barranca consisted of only a few $^{40}K/^{40}Ar$ dates on a basalt flow complex high in the section (Marshall *et al.* 1986) and $^{40}Ar/^{39}Ar$ determinations for a single tuff near the base of the section (Kay *et al.* 1999). Although some additional dates for other stratigraphic units were reported without comment by Kay *et al.* (1999), here we report many additional $^{40}Ar/^{39}Ar$ dates and a composite magnetic polarity stratigraphy based on five stratigraphic profiles extending between the west and east end of the continuous exposures at Gran Barranca and build a preliminary geochronologic framework for the Sarmiento Formation at Gran Barranca.

Methodology

During the Scarritt Expeditions of the American Museum of Natural History, George Gaylord Simpson measured and described some of the stratigraphic profiles used here (Simpson 1930; Cifelli 1985). Simpson recorded the position of many of the fossil mammal localities or levels where we have collected. Our geochronology is presented in the context of the physical stratigraphy of the Sarmiento Formation of Bellosi (this book) with reference to the profiles of Simpson and others at Gran Barranca. The new stratigraphy identifies ten temporally significant discontinuities (paleosurfaces, paraconformities, and erosional unconformities), six members and a number of lithostratigraphic subunits in the Sarmiento Formation (Bellosi Chapter 2, this book). The geochronology is organized and presented by lithostratigraphic unit, begininning with the oldest Gran Barranca Member at the base of the Sarmiento Formation and ending with the Colhue-Huapi Member at the top.

Due to their fine-grained texture, bulk plagioclase and glass mineral separations were analyzed using step-heating age spectrum methods. The glass samples were degassed in 8–12 heating steps in a double vacuum resistance furnace. Approximately 3–5 mg splits of plagioclase were analyzed in the laser furnace in 6–12 heating steps. Most step-heated plagioclase samples yielded plateau age spectra for 100 % of the ^{39}Ar released. In addition, some plagioclase samples were dated using the total laser fusion method.

Table 4.1. *Preferred ages tuffs for both glass and plagioclase of the Sarmiento Formation*

Tuff Name and Sample	Best Glass Age (error=1 sigma)	Best Plagioclase Age (error=1 sigma)	Tuff Mean Age (N)
Vilas & Re Silicified (VRS) Tuff			
GB 01-9		41.70 (0.38)	
Simpson Y Tuff			39.85 (3)
GB 01-5 (Profile N1)	39.45 (0.24)	40.24 (0.24)	
GB 99-7 (Profile MMZ)		39.87 (0.20)	
Mazzoni Tuff			39.08 (2)
GB 99-1	37.96 (0.34)	40.19 (0.58)	
Rosado Tuff			38.66 (3)
GB 99-4	38.55 (0.11)	39.40 (0.24)	
GB 99-6	38.03 (0.07)		
Kay Tuff			37.045 (2)
GB 99-3	37.21 (0.10)	36.88 (0.19)	
Carlini Tuff			33.995 (2)*
GB 02-01	30.15 (0.17)	34.08 (0.25)	
GB 02-02	28.30 (0.23)	31.86 (0.51)	
GB 99-8	33.91 (0.05)		
Big Mammal Tuff			19.75 (3)
RFK-1 (8953-01)	19.13 (0.17)	20.26 (0.70)	
RFK-1 (8953)		19.87 (0.33)	
Basal Colhue-Huapi Tuff			20.39 (3)
GB 01-8 (53459-01)	19.37 (0.08)	21.09 (0.30)	
GB 01-8 (53460)		20.73 (0.26)	
Monkey Tuff			19.81 (5)
RFK-2 (8954)	19.13 (0.16)	19.94 (0.28)	
RFK-2 (8954)		19.54 (0.20)	
GB 99-5	19.12 (0.05)	21.30 (0.28)	
MMZ 24.5 Tuff			19.295 (2)
GB 01-7	18.53 (0.24)	20.06 (0.12)	

Note: *Mean of concordant glass plateau and plagioclase laser fusion ages.

The results of our $^{40}Ar/^{39}Ar$ dating analyses include step-heating results for glass and plagioclase, laser fusion data for plagioclase are presented in Table 4.1. Laboratory results for the $^{40}Ar/^{39}Ar$ dates are available directly from MH at the Geochronology Research Laboratory of the New Mexico Bureau of Geology and Mineral Resources. The age interpretations made here depend on the integration of the physical stratigraphy, the $^{40}Ar/^{39}Ar$ dates and the magnetic polarity stratigraphy. Technical information about magnetic polarity sampling and the results of laboratory analyses are presented in a separate chapter (Ré *et al.* Chapter 3, this book). As reversed polarity sites are relatively rare in the sampled profiles, we critically evaluate the quality of the laboratory results for all reversed polarity sites prior to interpreting the age of the sediments. We organize the discussion of the geochronology of the Sarmiento Formation with reference to lithostratigraphy rather than fossil content, although noteworthy fossil mammal levels and zones are mentioned where appropriate.

General stratigraphy

Gran Barranca south of the Lake Colhue-Huapi is a continuous escarpment extending some 7 km between two basalt flow complexes, the west and east end basalts. The maximum height of the escarpment is about 200 meters at Profile MMZ near the western end and varies down to about 80 meters at its lowest point between Profiles J and K. The composite stratigraphy of the Sarmiento Formation along this escarpment is based on a series of profiles (Bellosi

Chapter 2, this book) from Profile A at the western end to Profile N at the eastern end. Additional exposures of the Sarmiento Formation occur in smaller isolated areas farther to the west (Profile AAC) and east (Las Flores) of the main escarpment. The stratotype section of the Sarmiento Formation is Profile MMZ near the west end of Gran Barranca (Spalletti and Mazzoni 1979).

In general, the Sarmiento Formation comprises fine-grained primary and reworked volcaniclastic sediments, including pyroclastic mudstones and siltstones, volcaniclastic sandstones, fine tuffs, and bentonitic claystones (Spalletti and Mazzoni 1979; Bellosi this book). These tephric materials originated as distal Plinian or Sub-Plinian pyroclastic ash fall deposits from magmatic arcs in northwestern Patagonia (Mazzoni 1985, Bellosi this book). Several basalt flows intercalate within this pyroclastic succession. Coarser-grained sediments do not occur at Gran Barranca, except as intraformational conglomerates with clasts mostly formed from autochthonous soil fragments and basalt breccias.

The mineral composition of Sarmiento Formation sediments at Gran Barranca is described in detail only for Profile MMZ (Spalletti and Mazzoni 1979). Simpson (1930) described the sediments observed in many additional profiles at Gran Barranca. Cifelli (1985) published new descriptions of the lithostratigraphy for the lower portions of Simpson's profiles, based on Simpson's observations. Simpson measured 11 partial or complete profiles along the continuous escarpment, his A-1, A-2, A-3, G, H, J, K, LB, M, N-1, and N-2 and three additional sections on isolated hills just north of the escarpment (Profiles B, I, and LA). Mazzoni and Spalletti measured two sections at the west end of Gran Barranca, a section described in 1977 (Spalletti and Mazzoni 1977) and a more complete and detailed section that we refer to as Profile MMZ (Spalletti and Mazzoni 1979). We extend measurement of Simpson's Profiles K, L, and M upwards to the top of the escarpment, and continue measurement of Profiles G and H downwards to the base of the exposed section. During the course of magnetostratigraphic work, we re-measured Profile MMZ and Simpson's Profiles A3, K, M, and N-1. Approximate GPS coordinates for the base and top of the profiles and their subdivisions is provided in Table 4.2.

$^{40}Ar/^{39}Ar$ geochronology

The basalts in the Sarmiento Formation at Gran Barranca and elsewhere in Patagonia (Windhausen 1924; Feruglio 1949) that have a direct relationship to fossil mammal levels were the first to be dated by isotopic methods (Marshall *et al.* 1977). While basalts are resistant to erosion and are fairly widespread throughout Patagonia, the episodic nature of basalt production, mostly during a short interval in the Oligocene (Bellosi 1995) has limited their application to the geochronology of mammal-bearing units. The West End Basalt Complex (WEBC) comprises several stacked basalt flows that outcrop immediately west of Profile A. The eastern edge of the WEBC is clearly within the Upper Puesto Almendra Member, a stratigraphic relationship similar to the basalts in Profiles A-2 and H. The East End Basalt at the top of Profile N appears to be a single thick flow, although sampled for magnetic polarity at several different levels.

Table 4.2. *Approximate GPS coordinates for the base and top of profiles of the exposed Sarmiento Formation at Gran Barranca (in decimal degrees South latitude; West longitude)*

Profile	Base	Top
A (Simpson)	45.70588; 68.73935	45.71083; 68.74260
A-1 (Simpson, Colhue-Huapi Mbr)	45.71065; 68.74418	45.71083; 68.74260
G (Simpson)	uncertain	45.71105; 68.74142
I (Simpson)	45.70674; 68.72939	45.70942; 68.73108
MMZ (Mazzoni)	45.70998; 68.73487	45.71024; 68.74400
H (Simpson)	45.71315; 68.73658	45.71358; 68.73788
J (Cifelli 1985 Section II)	45.71430; 68.72855	45.71683; 68.72970
K (Cifelli 1985 Section III)	45.71255; 68.69875	45.71440; 68.69635
LA (Simpson)	45.71953; 68.69304	45.71055; 68.69329
LB (Simpson)	45.72102; 68.69692	45.72000; 68.70110
M (Cifelli 1985 Section V)	45.72242; 68.67763	uncertain
N1 (Simpson)	45.72721; 68.65905	45.72862; 68.65740
N2 (Simpson)	45.72107; 68.65443	45.72363; 68.65593
Las Flores	45.72600; 68.62116	45.72635; 68.63137

With the advent of $^{40}Ar/^{39}Ar$ dating of airborne tephra, additional levels of the Sarmiento Formation have become suitable for radioisotopic age determination. Tuffaceous sediments of the Sarmiento Formation are widespread in Patagonia (Mazzoni 1985; Franchi and Nullo 1986) and extend geographically and temporally beyond the limits of available basalts. The tuffaceous sediments of the Sarmiento Formation at Gran Barranca have a composition consistent with silicic subduction zone volcanic rocks and a presumptive source area in Neuquen and Rio Negro Provinces (Mazzoni 1979, 1985; Franchi and Nullo 1986).

Despite some complexities in the argon results, both glass and plagioclase provide useful constraints for the interpretation of the local magnetic polarity stratigraphy, the age of members and subunits of the Sarmiento Formation, and the duration of temporal hiatuses identified in the lithostratigraphy. The preferred results of $^{40}Ar/^{39}Ar$ analyses on Sarmiento Formation tuffs (Table 4.1) are concordant with stratigraphic superposition. Discrepancies between plagioclase and glass ages are found for most of the tuffs in the Sarmiento Formation, with dates for argon consistently younger than those for plagioclase. We attribute part of this discrepancy to argon loss. In some cases, age discrepancies or polymodalities are found in the same mineral and between samples of the same tuff. For example, polymodality is suggested by the plagioclase results for the Monkey Tuff and the Rosado Tuff, and in glass for the Carlini Tuff, the Rosado Tuff, and Simpson's Y Tuff. Thus, sediment reworking and xenocrystic mixing are indicated. Relatively few of the dated tephra are primary air-fall deposits. Most of them show evidence of secondary reworking, such as variable thickness, discontinuity, and inclusion of fragmented and entire clasts, and inclusion of fossils. In general, with the exceptions of the Simpson's Y Tuff, Mazzoni Tuff, and Kay Tuff in the Gran Barranca Member and the MMZ 24.5 Tuff in the Colhue-Huapi Member, all other dated samples at Gran Barranca are from laterally discontinuous local concentrations of tuffaceous material.

The Gran Barranca Member

The Gran Barranca Member is the most widely distributed lithologic unit of the Sarmiento Formation at Gran Barranca. The member is composed of thick, white, massively bedded pyroclastic mudstones, olive-green bentonites, and poorly developed paleosols. The basal contact of the Gran Barranca Member on the Kolhue-Kaike Formation is obscured by the incoherence of the lowermost strata and the low topographic relief of the flatland extending northward from the foot of Gran Barranca. At the Las Flores locality, a distinct exposure 1 km to the east of Profile N-2, the basal contact is well exposed and transitional (Bellosi Chapter 2, this book). Within this member, Simpson identified a richly fossiliferous tuff called "Bed Y," which is the only continuous marker bed extending unbroken the full length of Gran Barranca. Bed Y rests on Discontinuity 1 (D1). The upper boundary of the Gran Barranca Member is defined by Discontinuity 2. In addition to highly fossiliferous Bed Y, this member contains several other levels with fossil mammals both above and below D1. These assemblages are relatively uniform in composition and form the basis for the recognition of the Barrancan subage of the Casamayoran South American Land Mammal Age (SALMA) (Cifelli 1985). Three pyroclastic mudstones within the Gran Barranca Member have been dated and the $^{40}Ar/^{39}Ar$ results are discussed here, beginning with the stratigraphically lowest dated level.

VRS or Vilas and Ré Silicified Tuff The lowest pyroclastic mudstone sampled and analyzed from the Sarmiento Formation at Gran Barranca is the VRS Tuff near the base of Profile N-1. The VRS Tuff is below D1 and just overlies the lowest fossil-bearing level at Gran Barranca. A plagioclase laser fusion mean age of 41.70 ± 0.38 Ma was obtained from the VRS Tuff (Table 4.1).

Simpson's Y Tuff Simpson's Y Tuff (also Y Tuff or Bed Y) immediately above D1 has been dated at two different locations along Gran Barranca, at Profile MMZ (sample GB 99–7) and at Profile N-1 (sample GB 01–5). There is close agreement between the plagioclase plateau age (39.87 Ma) and laser fusion mean age (40.24 Ma). Glass results are inconsistent between samples and are younger than the plagioclase results in both samples, suggesting argon loss. The glass plateau age of sample GB 99–7 is much younger than the glass plateau age for GB 01–5. This anomalous result is discounted in the computation of an arithmetic mean age for the Y Tuff. The mean age of 39.85 Ma for Simpson's Y Tuff uses the three preferred results (the GB 01–5 glass plateau and plagioclase laser fusion mean ages plus the GB 99–7 plagioclase plateau age (Table 4.1)).

Mazzoni Tuff The Mazzoni Tuff is a thin dark pyroclastic mudstone just above Simpson's Y Tuff on Profile A-3 and is the "prominent thin hard steely-grey band" of Simpson (1930). A total gas age of 37.7 Ma for glass and a furnace argon total gas age for plagioclase of 37.9 Ma were reported by Kay *et al.* (1999) on samples collected from Profile MMZ. Another sample of the Mazzoni Tuff (GB 99–1) yielded a glass plateau age of 37.96 Ma and a plagioclase plateau age of 40.19 Ma. The arithmetic mean age of the Mazzoni Tuff based on this sample is 39.08 Ma.

The age of the Gran Barranca Member

Magnetic polarity stratigraphies are available for the Gran Barranca Member at four profiles (MMZ, K, M, and N-1).

Of these, the most densely sampled (Profile MMZ) is used to establish the upper age boundary of the Gran Barranca Member. Profile N-1 magnetostratigraphy extends down to the contact with the underlying Koluel-Kaike Formation and is used to establish the age of the base of the Gran Barranca Member, and thus, the age of the base of the Sarmiento Formation at Gran Barranca.

Profile MMZ local normal interval N2, represented by single site (Site X12) is sandwiched between two narrow reversed polarity intervals R2 (Site 06) and R3 (Site 07) likewise supported by single sites. We have some reservation about the behavior of the five cores drilled at Profile MMZ Site 6. Profile MMZ local zone R2 (Site 06) was sampled in Simpson's Y Tuff, a horizon that elsewhere yields only normal polarity (the Y Tuff at Profile K yielded normal polarities for five sites sampled at less than 1 meter intervals). For the age interpretation, we ignore this local reversed polarity zone. Profile K polarity stratigraphy for the Gran Barranca Member yields a complex local polarity sequence. Of these local polarity zones, only R2 is supported by more than one site. Profile K local polarity zones N1, R1, and N2 are supported by single sites, but we are confident about these results. There are no obvious discontinuities and few sharp contacts in the lower part of the Gran Barranca Member at Profile K.

At Profile M magnetic polarity stratigraphy for the member is uniformly normal polarity except for a single site (GBM-03–06 or MI06) stratigraphically just above the Y Tuff. This site is at a stratigraphic level equivalent to Site 7 at Profile MMZ which also yielded reversed polarity, and thus this reverse polarity zone is recognized in the age interpretation. Profile N-1 was sampled at rather coarse density and the analyses for the lower sites reveals a long reverse polarity interval supported by multiple levels.

Judging from the $^{40}Ar/^{39}Ar$ results for the three tuffs and the local magnetic polarity stratigraphy, Chrons 19, 18, and 17 of the GMPTS (Gradstein *et al.* 2004) are the most likely correlatives of the Gran Barranca Member. The simplest interpretation of the age of the Gran Barranca Member begins by noting that at Profile N-1 the VRS Tuff (41.70 Ma) falls in a zone of reversed polarity that we conclude corresponds to Chron 19r calibrated to between 40.671 and 41.590 Ma (Gradstein *et al.* 2004). Simpson's Y Tuff (mean age 39.85 Ma) and the Mazzoni Tuff (mean age 39.08 Ma) both fall in local zones of reversed polarity in Profile MMZ. This suggests that Simpson's Y Tuff identifies Chron C18r at Profile MMZ, and the Mazzoni Tuff may identify Chron C18n.1r. However, Simpson's Y Tuff has been sampled for magnetic polarity stratigraphy at Profiles K, M, and N-1, and in all three profiles, it has normal polarity. This normal polarity is especially significant at Profile K where eight sample sites have been analyzed (K03, K03A through K03G). In all profiles sampled for magnetostratigraphy, all sites above the Mazzoni Tuff yield normal polarity. Assuming continuous deposition, this normal polarity zone represents Chron C18n.1n and indicates that the age of the top of the Gran Barranca Member is between 38.032 and 38.975 Ma.

In summary of the above, the base of the Gran Barranca Member is within Chron 19r (40.671–41.590 Ma) and its top within Chron C18n.1n (38.032–38.975 Ma). Cifelli's (1985) Barrancan fauna from localities within the Gran Barranca Member falls within the interval between about 41.6 and 38.7 Ma, the age of the Rosado Tuff (see below).

The Rosado and Lower Puesto Almendra Members

The Rosado Member is a 7-m thick pinkish tuffaceous calcic paleosol that outcrops discontinuously between Profiles J and M. Its base is Discontinuity 2, which separates it from the underlying Gran Barranca Member, and its top is the irregular Discontinuity 3. By contrast, the Lower Puesto Almendra Member is a 30-m thick succession of volcaniclastic sandstones, the "Lower Channel Beds" of Simpson (1930), pyroclastic mudstones, bentonites, and paleosols (Bellosi this book) widely exposed west of Profile J and bounded by Discontinuity 3 and Discontinuity 5. One tuff within the Rosado Member and another within the Lower Puesto Almendra Member have been dated.

Rosado Tuff The Rosado Tuff occurs within the Rosado Member just west of the axis of Profile J along a badly eroded and unserviceable road that ascends Gran Barranca. The Rosado Tuff (sample GB 99–4) glass plateau age is somewhat younger than the plagioclase result, an age disparity consistent with argon loss typically observed in Sarmiento Formation tuffs. Sample GB 99–6 yielded a plateau age for glass of 38.03 Ma, close but not within the 2-sigma margin of error of GB 99–4 glass. The arithmetic mean of the $^{40}Ar/^{39}Ar$ results is 38.66 Ma, the age of the Rosado Tuff (Table 4.1).

Kay Tuff The Kay Tuff occurs within the Lower Puesto Almendra Member. It is a thick conspicuous whitish tuff outcropping discontinuously between Profiles A and J. The Kay Tuff rests directly on the surface of a distinct stratum known as Mazzoni Bed 10 in the upper part of the Lower Puesto Almendra Member. In Simpson's Profile A-2, the Kay Tuff corresponds to the "massive grey tuff" (Simpson 1930) about 2 m above a channel bed and Discontinuity 4. The dated sample (GB 99–3) was collected from an exposure about 75 meters east of the axis of Profile A-2 and yielded nearly concordant glass and plagioclase plateau ages of 37.21 and 36.88 Ma, respectively. The arithmetic mean age of the Kay Tuff is 37.05 Ma (Table 4.1).

The age of the Rosado and Lower Puesto Almendra Members

Magnetic polarity stratigraphies are available separately for the Rosado and Lower Puesto Almendra Members. (Ré *et al.* [Chapter 3, this book] report not sampling the Rosado Member at Profile J but they did sample it in Profile M.) All sampled sites in both members have normal polarity. The age of the Rosado Tuff falls within the calibrated age range of Chron C18n.1n from 38.032 to 38.975 Ma (Gradstein *et al.* 2004). Therefore we hypothesize that the Rosado Member represents a portion of the upper part of Chron C18n.1n. The upper Gran Barranca Member represents the lower portion of the same polarity chron. Discontinuity 2 at the contact between the Gran Barranca and Rosado members had little temporal duration. The age of the Kay Tuff (37.05 Ma) falls within C17n.1n from 36.512 to 37.235 Ma (Gradstein *et al.* 2004). Discontinuity 3 at the top of the Rosado Member represents a temporal hiatus related to pedogenesis of the Rosado palaosol and subsequent fluvial erosion. This surface encompasses at least the interval between Chron C18n.1n and Chron C17n.1n, that is, from 37.235 to 38.032 Ma. An estimate of the duration of the temporal hiatus represented by Discontinuity 6 at the top of the Lower Puesto Almendra Member can only be established by considering the age of the overlying Vera Member (see below).

The Rosado and Lower Puesto Almendra members include all levels containing fossils assigned to the Mustersan SALMA. Notably, another locality in the Rosado Member, GBV-60 "El Nuevo," has a distinct faunal composition *intermediate* between temporally adjacent Barrancan and Musteran levels. Chron 18n.1n is a roughly 1-million-year interval. The lower part of this chron is represented by a Barrancan fauna in the Gran Barranca Member. The upper part of the same chron is represented by the Rosado Member, which in its lower parts contains a transitional Barrancan–Mustersan fauna (GBV-60 "El Nuevo"), while the upper part contains a Mustersan fauna (GBV-3 "El Rosado"). We tentatively conclude that the Mustersan SALMA at Gran Barranca must begin towards the end of Chron C18n.1n, slightly older than 38.0 Ma, and can be no younger than the top of C17n.1n at 36.5 Ma.

The Vera Member

The Vera Member is a thick, homogeneous, and poorly stratified succession of pyroclastic mudstones exposed between Profile M and Profile J. This distinctive member is bounded at its base by Discontinuity 5 and at its top by Discontinuity 6. There are no obvious discontinuities within this member. The absence of the Vera Member at Profile MMZ and the obscure contacts at Profile J engender some difficulty interpreting its stratigraphic relationships. The Vera Member includes two localities at the same stratigraphic level yielding fossil mammals assigned to the Tinguiririan SALMA. These include the faunal assemblage from GBV-4 "La Cancha" and the mammals from GBV-28, a screenwash site (Carlini *et al.* this book; Reguero and Prevosti this book; Goin *et al.* this book).

The only dated rock in the Vera Member is the Carlini Tuff, a pyroclastic mudstone located in the middle part of the member at Profile K. The age of the Vera Member is constrained by $^{40}Ar/^{39}Ar$ dates from this tuff (Table 4.1). Samples of the Carlini Tuff at Profile K come from 1–3 m below the fossil level GBV-4. The "La Cancha" bed (including the dated sample and the fossiliferous bed) is a consolidated pale to pinkish tuffaceous mudstone rich in carbonate and manganese nodules. Numerous fragmentary fossil mammal remains have a characteristic crust or patina of manganese oxide. The Carlini Tuff provides a maximum age for the fossil mammal assemblage at GBV-4 and an age for the base of the local N4 normal polarity interval in Profile K (see below).

Our interpretation of the age of the Carlini Tuff is based on glass ages from samples GB 99–8, GB 02–01, and GB 02–02, and plagioclase results from samples GB 02–01 and GB 02–02. Glass plateau ages range between 28.30 and 33.91 Ma, with no overlap at 2-sigma error. Plagioclase laser fusion results are consistently older than the glass results but show a slightly more constrained age range. The arithmetic mean of the $^{40}Ar/^{39}Ar$ results is 31.66 Ma. The multimodal ages of the $^{40}Ar/^{39}Ar$ results suggest the Carlini Tuff preserves minerals from distinct eruption events, but the age disparities in the $^{40}Ar/^{39}Ar$ results seem inconsistent with the form of the Carlini Tuff in the field, where it appears as a discrete horizon, although of limited lateral extent, and nodular in part suggesting local reworking. The only concordance among the $^{40}Ar/^{39}Ar$ results is found between the best glass plateau age (33.91 Ma) and the plagioclase laser fusions mean age (34.08 Ma) giving a mean age of 34.0 Ma (Table 4.1). An improved constraint on the age of this tuff is suggested by the uniformly normal magnetic polarity of samples from Vera Member sediments adjacent to the "La Cancha" bed and Carlini Tuff. Only one normal interval occurs within the range of dates we have for this tuff. Chron C13n ranges between 33.27 and 33.74 Ma, our preferred age range for the Carlini Tuff.

Age of the Vera Member

Profile K polarity stratigraphy is based on an average sampling interval of 3.78 m for the 131-m portion of the profile sampled. This interval includes the Vera Member in the highest 106 m of the profile. In this interval, there are two normal local polarity zones (N3 and N4) and one reversed zone (R3). Profile M polarity stratigraphy is based on an average sampling interval of 4.13 m for the highest 141 m of the profile above the base of Simpson's Y Tuff. The unconsolidated nature of Vera Member sediments beneath the "La Cancha" level in Profile M obliged a coarser sampling density along this profile. The Vera Member at Profile M includes three local polarity zones, N2 at the base, R2 supported by a single site, and N3 extending through most of the thickness of the member.

The polarity of most sites in both profiles is normal, as is the Carlini Tuff, a finding that is informative given the uncertainty of the $^{40}Ar/^{39}Ar$ results for the Carlini Tuff and the temporally dominant reversed polarity of Chrons C13, C12, and C11 around the Eocene–Oligocene boundary and into the early Oligocene (Gradstein *et al.* 2004).

The distinctive "La Cancha" bed is a poorly developed paleosol that extends laterally between Profile K and Profile M. As mentioned above, at Profile M, a fluvial channel incises the "La Cancha" bed. The unconformity observed by Simpson at the base of this fluvial channel cannot be traced laterally. A single long normal polarity zone extends below and above the "La Cancha" level and Carlini Tuff and is interpreted to represent the same normal polarity chron, Chron C13n (33.266–33.738 Ma: Gradstein *et al.* 2004), the closest normal polarity interval in the age range of the Carlini Tuff. This correlation and the assumption of nearly continuous deposition imply that the Vera Member represents much of Chron C13 (including all of C13r) and extends down to include some portion of Chron C15n.

As for the age of the base of the Vera Member, the mean age of the Kay Tuff (37.05 Ma) and correlation of the Lower Puesto Almendra Member normal polarity with Chron C17n.1n reveals something about the duration of the temporal hiatus represented by Discontinuity 5. The base of the Vera Member must be between 34.782 and 35.043 Ma and the temporal hiatus between the Lower Puesto Almendra Member and the base of the Vera Member is on the order of 1.5 to 2 m.y. The age of the top of the Vera Member, if only Chron C13n is represented, is no younger than 33.26 Ma. The composition of the fossil assemblage from GBV-4 "La Cancha" suggests a correlation with the Tinguiririca SALMA, which is concordant with our age interpretation, and somewhat older than the minimum age of the type fauna from central Chile.

The Upper Puesto Almendra Member

The Upper Puesto Almendra Member consists of three units: numbers 3, 4, and 5 of Bellosi's scheme (Bellosi this book). The basal Unit 3 rests on Discontinuity 6. Discontinuity 7 within Unit 3 is an erosional surface upon which rests basalt flows. On top of the basalts is another erosional surface (Discontinuity 8) that marks the top of Unit 3 and the base of Unit 4. In turn, the top of Unit 4 is marked by Discontinuity 9 and the top of Unit 5 by Discontinuity 10. Thus, all the basalts at Gran Barranca occur above Discontinuity 7 within Unit 3 of the Upper Puesto Almendra Member. Marshall *et al.* (1977) reported $^{40}K/^{40}Ar$ dates for basalt samples collected in 1975 and samples collected in 1981 by Marshall and Drake as reported by Marshall (1985). On the age of these basalts, Marshall concluded "apparently only one flow is represented, in which case the best approximation of its apparent age is the date of 28.8 Ma obtained on the least-weathered sample" (Marshall 1985). The dated basalts correspond to those observed by Simpson in Profiles A, H, and N. "[T] he base of each basalt lies within 2 meters of each other relative to either the 'X' or 'Y' marker tuffs, a relationship which demonstrates that all three basalts occur at the same stratigraphic level relative to these lower marker tuffs" (Marshall *et al.* 1986). Our observations do not confirm Marshall's single-flow hypothesis. We have several dates from these flows and it seems probable they erupted over a period of several million years.

Gran Barranca basalts represent flows with baked zones at their lower contact but not at their tops. The Profile H Basalt, West End Basalt, East End Basalt (in Profile N-2), and the Profile A-2 basalt occur within fluvial deposits of Unit 3 of the Upper Puesto Almendra Member. However, stratigraphic relationships clearly indicate that multiple flows are represented, so relatively brief periods of local erosion must have intervened between them. Erosive discontinuity surfaces also occur at the base and top of the basalts (Bellosi this book). Discontinuity 7, on which most of the basalts rest, is an extensive surface related to fluvial channel erosion. Discontinuity 8 is another irregular erosion surface truncating the top of the lenticular basalts at Profiles A-2 and H, and in some places extending down to the level of the Discontinuity 7 (or possibly lower). Discontinuity 8 is covered by a residual breccia composed of weathered basalt blocks in a white tuffaceous matrix (Bellosi this book).

Four new radioisotopic dates for the basalts are fairly close in age. $^{40}Ar/^{39}Ar$ plateau ages for two basalt flows, one at the West End (27.87 ± 0.13 Ma) and another at the East End (27.76 ± 0.08 Ma) suggest these represent the same eruption event. The range of $^{40}Ar/^{39}Ar$ ages for the West End (27.87 ± 0.13, 29.18 ± 0.38 Ma), East End (27.76 ± 0.08 Ma), and Profile H Basalt (26.34 ± 0.32 Ma) point to multiple eruption events with intermittent periods of deposition and erosion. The ~26.3-Ma Profile H Basalt provides an upper boundary for the age of the basaltic eruption activity at Gran Barranca.

The Upper Puesto Almendra Member has two different fossil-bearing levels. The lower level GBV-19 "La Cantera" occurs near the base of Unit 3 below Discontinuity 7. GBV-19 yields a distinctive assemblage with some Deseadan elements and some elements more reminiscent of the Tunguiririca SALMA. Above D7 in more direct stratigraphic relationship with the basalts are fossil mammals more typical of the Deseadan SALMA. Deseadan age mammals are found in close or even direct association with the basalts and their associated erosional surfaces near the top of Profile J, and in the exposures between Profiles H and A at the west end of Gran Barranca.

Age of the Upper Puesto Almendra Member

The age of the Upper Puesto Almendra Member can be established only in relation to the basalts. The oldest sediments of the Upper Puesto Almendra Member (Unit 3, between Discontinuities 6 and 7) are constrained in age by the lower contact and overlying basalts. The same basalts provide a basal age for Unit 4. The youngest sediments of the Upper Puesto Almendra Member, Unit 5, are constrained in age by the underlying basalts and the age of the overlying Colhue-Huapi Member.

The age of the fossil-bearing sediments of GBV-19 "La Cantera" in Unit 3 between Discontinuity 6 (the contact with the Lower Puesto Almendra Member) and Discontinuity 7 at the base of the basalts hinges on three sorts of information: (1) the stratigraphic relationship of the Kay Tuff in the Lower Puesto Almendra Member to Discontinuity 6 and GBV-19 in Profile A-2, (2) the magnetic polarity stratigraphy of Unit 3, and (3) the age of the basalts.

With respect to the first point, the Vera Member thins west of Profile J and pinches out where the plane of Discontinuities 5 and 6 converge and become coplanar at a level above the Kay Tuff. From this point westward between Profiles I and A-2, the Vera Member cannot be recognized. Between Profiles J and A-2, the Kay Tuff has a discontinuous distribution, but is well exposed below the coplanar Discontinuities 5 and 6 at Profile G and again at Profile A-2. The fossil locality GBV-19 "La Cantera" occurs within a pale grey tuffaceous mudstone in the lowermost part of the Unit 3 of the Upper Puesto Almendra Member, stratigraphically just above Discontinuity 6. Thus, Discontinuity 6 occurs stratigraphically between the Kay Tuff and GBV-19 "La Cantera."

As to the second point, we have five magnetostratigraphic sites in Unit 3 below Discontinuity 7 (the lowest of the units of the Upper Puesto Almendra Member) at Profile MMZ (sites 10.3, 10.5, 11, 12, and 12.7) yield normal polarity. Given our best estimate of the age of the Carlini Tuff in the Vera Member and the overlying basalts in Unit 3 above Discontinuity 7, the Unit 3 normal polarity zone could correspond to either Chron C13n (33.266–33.738 Ma), C12n (30.627–31.116 Ma), C11n.2n (29.853–30.217 Ma), or C11n.1n (29.451–29.740 Ma) following Gradstein *et al.* (2004). Given the apparent magnitude of erosion represented by Discontinuity 6, we consider it unlikely that this is the same normal polarity interval as that sampled by the Vera Member (i.e. Chron C13n). Therefore, the fossil mammals at GBV-19 "La Cantera" (Goin *et al.* this book; Carlini *et al.* this book; Vucetich *et al.* this book; Lopez *et al.* this book; Ribeiro *et al.* this book) must belong to one of the remaining three chrons of normal polarity. The most precise age we can establish for the fossil-bearing sediments of the lower part of Unit 3 is that they must be younger than 31.1 Ma and older than 29.5 Ma. This interpretation also accords with the ages of the basalts (the third point), all of which are younger than 29.18 Ma.

Upper Unit 3 of the Upper Puesto Almendra Member includes the basalts (29.18–26.34 Ma) above Discontinuity 7 and below Discontinuity 8. Deseadan age mammals occur often along the erosional surfaces distal to the tops of the basalts. If the tops of all the basalts were weathered at the same time, i.e. a single Discontinuity 8, then the Deseadan age assemblages at Gran Barranca must be younger than the youngest basalt. Thus, the Deseadan faunules at Gran Barranca would be younger than about 26.3 Ma. If, on the other hand, there were multiple erosional discontinuities within Unit 3 associated with the tops of several basalt flows of different ages, then some of the Deseadan mammals at Gran Barranca could be slightly younger than 29.2 Ma and some within Unit 4 above Discontinuity 8 could be younger than 26.34 Ma. The beds are not sufficiently well exposed nor the faunas of Deseadan aspect well enough preserved to select among these alternatives.

Unit 5 of the Upper Puesto Almendra Member has no dated rock, so it is constrained only by the age of the underlying Unit 4 basalts and their associated discontinuities and the contact between Unit 5 and the overlying Colhue-Huapi Member. However, the sediments resting on Discontinuity 8 and extending up to Discontinuity 10 at the base of the overlying Colhue-Huapi Member include three normal and two reversed magnetic polarity intervals at Profile MMZ, suggesting this unit extends in age up to Chron 7.

The Colhue-Huapi Member

The Colhue-Huapi Member outcrops only at the west end of Gran Barranca in a single exposure at the top of the escarpment. Two measured stratigraphic profiles extend up through the Colhue-Huapi Member; Profile A-1 at Colhue-Huapi West (CHW) and Profile MMZ at Colhue-Huapi East (CHE). Four tuffs in the Colhue-Huapi Member have been dated. Three of the tuffs occur in the lower section of the Colhue-Huapi Member, distinguished lithologically by more finely stratified low-energy fluvial depositional cycles of intraformational conglomerates, pyroclastic mudstones, and paleosols (Bellosi this book). The fourth and highest of the dated tuffs, the MMZ 24.5 tuff in upper part of the member, is a conspicuous whitish pyroclastic mudstone that forms a distinct laterally continuous stratum of variable thickness. All other tuffs occur as stratiform but laterally discontinuous concentrations of relatively pure fine-grained volcaniclastic material.

Big Mammal Tuff The Big Mammal Tuff occurs on Profile A-1 about 6 meters above the basal Discontinuity 10 of the member and is the stratigraphically lowest of the dated tuffs in the Colhue-Huapi Member. The arithmetic mean age of the Big Mammal Tuff is 19.75 Ma (Table 4.1).

Basal Tuff The Basal Tuff in Profile MMZ at Colhue-Huapi East (CHE) occurs about 10 m above Discontinuity 10 near the axis of the profile. Glass and plagioclase plateau ages for sample GB 01–8 are 19.37 ± 0.08 Ma and 21.09 ± 0.30 Ma (1-sigma error), respectively (Table 4.1). Another sample of the same tuff yielded a plagioclase plateau age of 20.73 ± 0.26 Ma (1-sigma error). The arithmetic mean age of all three determinations is 20.39 Ma (Table 4.1).

Monkey Tuff The Monkey Tuff occurs about 22 m above the base of the member and outcrops in a limited area in close proximity and at the same stratigraphic level (Level C) where most of the fossil primates have been recovered at Colhue-Huapi West (Kay this book). Samples RFK-2 and GB 99–5 yielded an age range between 19.12 and 21.30 Ma. Furnace argon isotopic plateau ages for plagioclase (19.94 and 21.30 Ma) are uniformly older than glass ages (19.13 and 19.12 Ma) for the same samples; however, the glass ages of the two samples are essentially identical, whereas the plagioclase plateau ages differ by about 1.3 m.y. The arithmetic mean of all five determinations (including the laser argon results for RFK-2) is 19.81 Ma (Table 4.1).

MMZ 24.5 Tuff MMZ 24.5 Tuff is a conspicuous 2-m thick impure white pyroclastic mudstone near the top of the northernmost exposures of the Colhue-Huapi Member on Profile MMZ. It occurs about 48.5 m above the base of the member at a level between two discrete biozones; the Lower Fossil Zone with at least 17 distinct fossil-bearing levels of Colhuehuapian age, and the Upper Fossil Zone with two or three levels, a "Pinturan age" correlative. The age of the MMZ 24.5 Tuff falls between the Colhuehuapian and "Pinturan" levels, so it provides age constraints for both ages. The arithmetic mean age of two determinations is 19.30 Ma (Table 4.1).

The age of the Colhue-Huapi Member

Sediments of the Colhue-Huapi Member were sampled for magnetic polarity stratigraphy at sites along two measured sections; Profile A-1 at CHW on the west side of the exposure, and Profile MMZ at CHE on the east side. The Colhue-Huapi Member at Profile A-1 measures 63 m in total thickness, from the basal contact to the top of consolidated sediments of the upper section of this member. The exposures of the Colhue-Huapi Member along Profile MMZ measure about 48.5 m in thickness. The lowest strata of the Colhue-Huapi Member are found above Discontinuity 10 at CHE. The top of the member at CHE is truncated by erosion and obscured by plant cover. Magnetostratigraphic sampling intervals were spaced along Profile A-1 at an average interval of 2.1 m. This represents a closer sampling interval than along Profile MMZ where sampling achieved an average interval of 4.4 m (Ré *et al.* Chapter 3, this book). There are two normal polarity zones in the Colhue-Huapi Member, with a reversed zone at the base and another near the middle of the member.

Arithmetic mean ages for Colhue-Huapi Member tuffs range between 20.39 and 19.30 Ma, a range of about 0.9 m.y., and well within the 2-sigma errors of the individual estimates.The age range for preferred plagioclase results extends from 21.30 to 19.54 Ma and for glass from 19.37 to 18.53 Ma, with glass ages uniformly younger for all samples and all tuffs.

The temporal interval of the GMPTS (Gradstein *et al.* 2004) between 20.39 and 19.30 Ma (between C6An.1r and C6n) is dominantly normal polarity, but includes two reversed polarity intervals. There is strong evidence for two reversed-polarity intervals in the Colhue-Huapi Member (Ré *et al.* Chapter 3, this book). The lowest sites sampled in both Profiles A-1 (CHW) and MMZ (CHE) yielded reverse polarity with high-quality site mean direction and thus we assume that the base of the long local normal polarity interval N1 of Profile MMZ and the lowest local normal polarity site of Profile A-1 provide a useful time horizon. The second interval of reversed polarity occurs just above the highest fossil mammal level of the Lower Fossil Zone (see below), and was detected with confidence only in Profile MMZ.

Two different interpretations of the age of the Colhue-Huapi Member are possible:

(1) The arithmetic mean age of the Basal Tuff (20.40 Ma) indicates the long normal interval N1 of Profile MMZ (CHE) may represent Chron C6An.2n (20.439–20.709 Ma) and the arithmetic mean age of MMZ 24.5 Tuff (19.30 Ma) assigns the highest normal polarity interval N2 of Profile MMZ to Chron C6n (18.748–19.722 Ma).

(2) The arithmetic mean ages of the Big Mammal (19.75 Ma) and Monkey (19.81 Ma) tuffs fall within the age range of reversed polarity chron C6r (19.722–20.040 Ma). However, the normal polarity of the sediments bracketed by these two tuffs indicates they more likely correspond to C6An.1n (20.040–20.213 Ma) than to C6n (18.748–19.722 Ma). The correlation to C6An.1n agrees better with the plagioclase results for these two tuffs and implies that R1 represents C6An.1r (20.213–20.439 Ma) and R2 represents C6r (19.722–20.040 Ma).

Of the two possibilities, we prefer the second. The first interpretation posits that the interval between 19.722 and 20.439 Ma is not preserved in the Colhue-Huapi Member at Gran Barranca.The second requires no significant temporal hiatus within the member, more in agreement with field

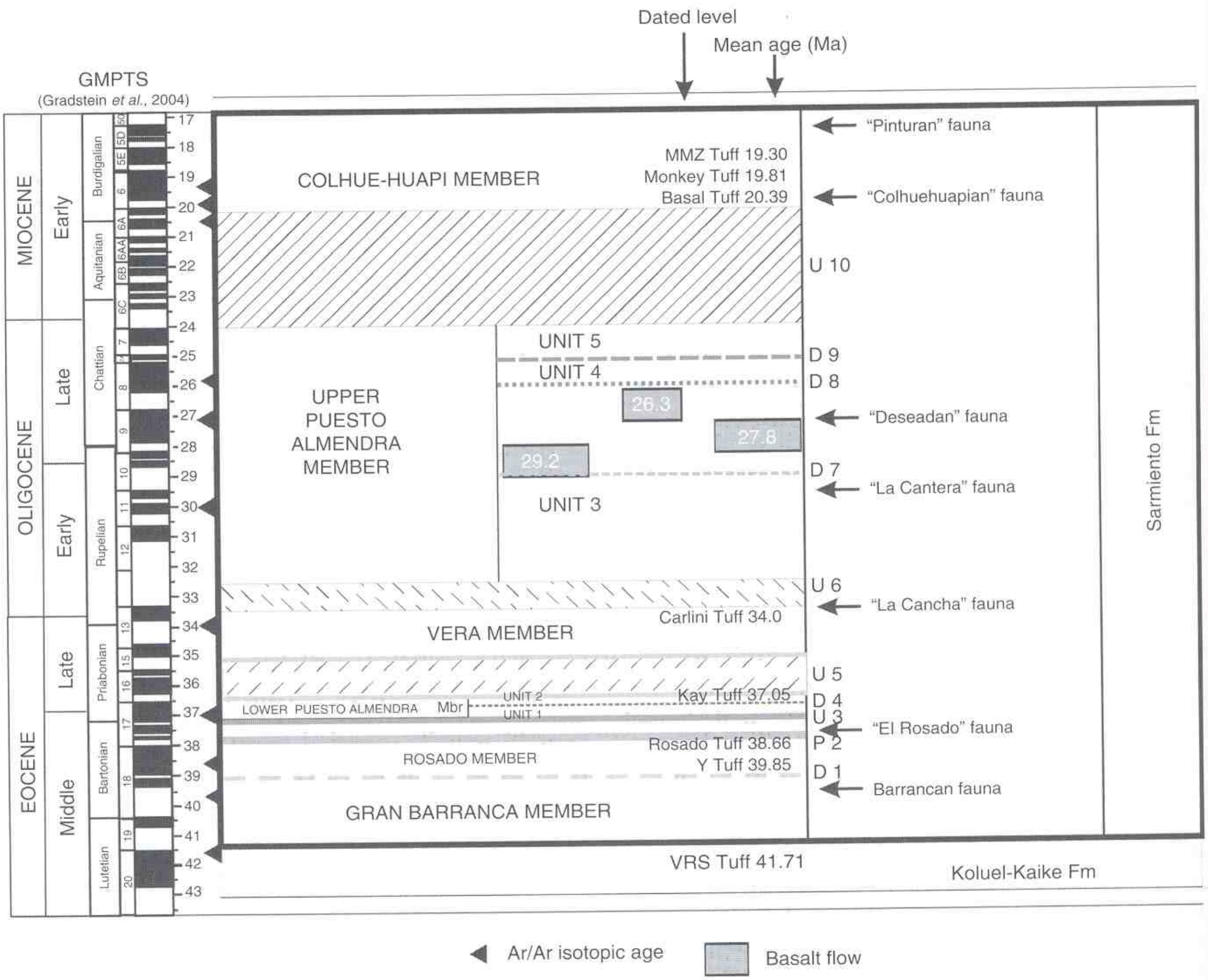

Fig. 4.1. Summary of the geochronology of the Sarmiento Formation at Gran Barranca, indicating temporal hiatuses and stratigraphic discontinuities.

observations of depositional continuity. An assignment of the lower normal polarity interval of the Colhue-Huapi Member to Chron C6An.1n and the upper normal polarity interval to Chron C6n seems to best fit the available evidence.

The Colhue-Huapi Member has many fossil bearing levels. More than 16 of them in the Lower Section are grouped together into the Lower Fossil Zone. All occur in the lower interval of normal polarity. The highest levels at the top of the Upper Section in Profile A-1 comprise the Upper Fossil Zone in the upper normal polarity interval. The fauna of the Lower Fossil Zone is the type fauna for the Colhuehuapian SALMA, and that of the Upper Fossil Zone is correlated with the Pinturan (see Kramarz and Bellosi 2005; Kramarz *et al.* this book). The Colhuehuapian SALMA at Gran Barranca is interpreted to represent 20.0 and 20.2 Ma (Chron C6An.1n). The Upper Fossil Zone has a more derived fauna (Kramarz *et al.* this book) and would be within C6n, between 18.7 and 19.7 Ma in age.

Summary and implications

The geochronology of the Sarmiento Formation at Gran Barranca, including its temporal hiatuses and stratigraphic discontinuities, is summarized in Fig. 4.1.

Gran Barranca Member The base of the Gran Barranca Member is within Chron 19r (40.671–41.590 Ma) and its top within Chron C18n.1n (38.032–38.975 Ma). Chrons 18 and 19 encompass the latest Lutetian and most of the Bartonian (Gradstein *et al.* 2004). This interval of the late middle Eocene that includes the Middle Eocene Climate Optimum (MECO), a stable isotope anomaly of transient high pCO_2 levels in the Indian (Kerguelen Plateau) and Atlantic (Maud Rise) sectors of the Southern Ocean (Bohaty and Zachos 2003; Luterbacher *et al.* 2004; Jovane *et al.* 2007). The Barrancan mammal fauna at Gran Barranca (Cifelli 1985) would thus fall within the interval between about 41.7 and 39.0 Ma.

Rosado and Lower Puesto Almendra Members The Rosado and Lower Puesto Almendra Members have a temporal duration equal to or less than the interval from near the top of Chron C18n.1n to the top of C17n.1n, that is, from slightly older than 38.0 to younger than 36.5 Ma. The Rosado Member contains a fauna transitional between the Barrancan and Mustersan SALMAs as well as a slightly younger Mustersan fauna. Faunas of Mustersan aspect also occur in the Lower Puesto Almendra Mamber. We tentatively conclude that the Mustersan SALMA at Gran Barranca may have a temporal duration equal to or less than the interval from near the top of Chron C18n.1n to the top of C17n.1n, that is, from slightly older than 38.0 to younger than 36.5 Ma. The Rosado and Lower Puesto Almendra members represent part of the late Bartonian (late middle Eocene) and Priabonian (late Eocene). The Mustersan SALMA temporal interval at Gran Barranca occurs at the beginning of a marked decline in atmospheric carbon dioxide concentrations following the MECO (Pagani *et al.* 2005) (although not documented from South Atlantic DSDP/ODP cores 511 and 513) and part of the post-MECO cooling of both surface and intermediate waters documented in the Atlantic and Indian sectors of the Southern Ocean (Bohaty and Zachos 2003). Discontinuity 3 between the Rosado Member and Lower Puesto Almendra Member represents a temporal hiatus encompassing at least the interval from 37.235 to 38.032 Ma.

Vera Member The base of the Vera Member is between 34.8 and 35.0 Ma. The age of the top of the Vera Member is no younger than 33.3 Ma. A temporal hiatus between the Lower Puesto Almendra Member and the base of the Vera Member is on the order of 1.5 to 2 m.y. The age of the Tinguiririca n fauna from GBV-4 "La Cancha" is between 33.3 and 33.7 Ma. The marked increase in sedimentation rate observed between C13r and C13n in the Vera Member corresponds to the oxygen isotope excursion of the Eocene–Oligocene transition into the Oi-1 glaciation of C13n as understood in the Southern Ocean deep sea record (Zachos *et al.* 1996; Salamy and Zachos 1999). At the western end of Gran Barranca, nearly all of the Vera Member was removed by erosion associated with Discontinuity 6, the erosional unconformity corresponding to the Oi-1 glaciation, with its inferred consequences for intensification of Southern Ocean circulation, atmospheric circulation over Patagonia, and continental shelf exposure off Patagonia. Correlation of the upper part of the Vera Member to C13n would attribute their stratigraphy and sedimentology to gradually increasing rates of eolian sediment deposition through C13r, followed by accelerating deposition into C13n, and eventually by still further increases in wind intensity at the erosional unconformity represented by Discontinuity 6 at the top of the Vera Member.

Upper Puesto Almendra Member The Upper Puesto Almendra Member is composed of three units. The lowest Unit 3 below Discontinuity 8 at the top of the basalts and above Discontinuity 6 has normal polarity. Given our best estimate of the age of the Vera Member and the age of the basalts, the Unit 3 normal polarity zone below the basalts and Discontinuity 7 corresponds to Chron C12n, C11n.2n, or C11n.1n. Thus, lower Unit 3 and the contained fossil mammals at GBV-19 "La Cantera" are between 31.1 and 29.5 Ma in age. The upper part of Unit 3 could be as young as 26.3 Ma. Units 4 and 5 are not dated. The top of the Upper Puesto Almendra Member must be younger than the age of the basalts at the top of Unit 3, and older than the age of the base of the overlying Colhue-Huapi Member (20.4 Ma). It is not established whether the Deseadan faunules at Gran Barranca are found in upper Unit 3 or at the base of Unit 4, or both. Deseadan assemblages at Gran Barranca could be as old as 29.2 Ma and as young a 26.3 Ma. Unit 3 sediments represent the beginning of the long 5-million-year period of sustained low atmospheric carbon dioxide concentrations that lasted through much of the Oligocene (DeConto *et al.* 2008), the temporal interval extending into the time when Units 4 and 5 were deposited.

Colhue-Huapi Member There are two normal polarity zones in the Colhue-Huapi Member, with a reversed zone at the base and another near the middle of the member. The reversed polarity interval at the base of the Member is C6An.1r (20.2–20.4 Ma). The lowest normal polarity interval represents Chron C6An.1n (20.0–20.2 Ma). The fauna of the Colhuehuapian SALMA at Gran Barranca is contained within this lower normal interval. The age of MMZ 24.5 Tuff (19.29 Ma) places the highest normal polarity interval to Chron C6n (18.748–19.722 Ma). The fauna of this interval has been correlated with that of the lower faunal levels in the vicinity of the Rio Pinturas. This temporal interval corresponds to the beginning of the Miocene Climate Optimum (Zachos *et al.* 2004).

ACKNOWLEDGEMENTS

The paleomagnetics laboratory was supported by grant UBACyT to Juan F. Vilas. Field research was supported by US National Science Foundation grants EAR-0087636, BCS-0090255, and DEB-9907985 to Richard F. Kay and Richard H. Madden.

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