



## Revised timing of the South American early Paleogene land mammal ages



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### ABSTRACT

A new Ar/Ar date on the Las Flores Tuff (Río Chico Group, Las Flores Fm., central Patagonia, Argentina) yielded an age of  $49.512 \pm 0.019$  Ma. This tuff, which stratigraphically overlies the mammal-bearing deposits that produced the Las Flores fauna, helps constrain the age of the Itaboraian SALMA [South American Land Mammal Age] to which that fauna is referred. The new data also have implications for the age of succeeding mammal biochrons, such as the Riochican and “Sapoan” which are revised to being somewhat younger than previously interpreted. Although closer in age than formerly interpreted, they still are biotically distinct. Concomitant evaluations suggest that the Itaboraian SALMA is perhaps more contemporary with the EECO (Early Eocene Climatic Optimum) than previously considered. The Riochican may be interpreted as post-EECO, with its cooler climate consistent in that regard. A recent reconsideration of the chronology of elements of the Salamanca Formation resulted in the downward revision of the ages of the Peligran SALMA and the *Carodnia* Zone biochrons. These operations, together with our results, reflect a 9 m.y. gap in the late Paleocene and early Eocene land mammal record in South America.

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### 1. Introduction

The succession of South American Mammal Ages has been developed over several decades since the middle of the last century (Pascual et al., 1965; Simpson, 1971; Patterson and Pascual, 1972; Marshall et al., 1983). As summarized in Woodburne et al. (2014), those of the Paleogene are largely uncalibrated, with age estimations based on aspects of biochronology, stratigraphy and correlation to paleomagnetic scales.

Here we report on a new  $^{40}\text{Ar}/^{39}\text{Ar}$  date on the Las Flores Tuff that crops out near the middle of the Las Flores Formation (Río Chico Group, central Patagonia, Argentina). The new date ( $49.512 \pm 0.019$  Ma) provides an upper boundary for the underlying mammal-bearing deposits referred to the Itaboraian SALMA. The results of the present work suggest that the Itaboraian SALMA

likely ranges in age from about 53 – 50 Ma, somewhat younger than previously suggested (Woodburne et al., 2014), and also that the Riochican is no older than about 49 Ma. With the post-Riochican “Sapoan” fauna likely ranging from about 48.5 – 47 Ma (revised from Tejedor et al., 2009), it appears that the Riochican represents a relatively short interval of time, and that the “Sapoan” age may be revised as being somewhat younger than previously considered. Although not bracketed by calibrated dates, the new information provided in this work aids in narrowing the potential age range, and suggests a later beginning for the Riochican SALMA and the “Sapoan” local fauna. Geological investigations by Clyde et al. (2014) on the Salamanca Formation in the western part of the San Jorge Basin (from about CA – LF, with extension to about CH, Fig. 1b) results in a lowering of the Peligran SALMA and *Carodnia* Zone ages. The Tiupampan and Peligran SALMAs and the *Carodnia* Zone are contained within the Danian Stage. The result of these studies is that there now appears to be a nearly 9 m.y.-long, middle to late Paleocene, gap in the biochronology of the South American mammal fauna.

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### 1.1. Definitions and abbreviations

BNI	Banco Negro Inferior (Lower Black Bank, Hansen Member; uppermost Salamanca Formation).
EEOC	Early Eocene Climatic Optimum. This is the interval of highest mean ocean temperature of the Cenozoic Era (Wolfe, 1978; Zachos et al., 2001, 2008). It began about 53 Ma and persisted to about 50 Ma (Tsukui and Clyde, 2012), and occurred in the contexts of generally warm conditions that characterized the early Cenozoic Era from the Paleocene to about middle Eocene.
k.y.	A segment of geologic time one thousand years in duration or the age of an event (e.g., ten thousand years ago), without reference to a point or set of points on the radioisotopic time scale.
Ma	Megannum. One million years in the radioisotopic time scale (e.g., 10 Ma refers to the ten million year point on the time scale)
MAT	Mean Annual Temperature (as inferred from paleobotanical leaf margin and other data)
m.y.	A segment of geologic time one million years in duration or the age of an event (e.g., ten million years ago) without reference to a point or set of points on the radioisotopic time scale.
NALMA	North American Land Mammal Age (Woodburne, 2004); an interval of time based on North American mammalian biochronology. Use of NALMA indicates that the units are not formalized Ages of the International Stratigraphic Guide (Salvador, 1994).
NMGR	New Mexico Geochronological Research Laboratory, Socorro, New Mexico.
PETM	Paleocene-Eocene Thermal Maximum. A short-term hyperthermal pulse of global warming at the Paleocene-Eocene boundary (Zachos et al., 2008; McInerney and Wing, 2011). This is the earliest Eocene hyperthermal event, calibrated at 56.33 Ma (Westerhold et al., 2009). It had a duration of 120–220 k.y. (Murphy et al., 2010), with an initial pulse of about 10 k.y. during which global sea surface temperatures rose 5–9 °C.
SALMA	South American Land Mammal age; comparable to NALMA; see Pascual et al. (1965), Simpson (1971), Patterson and Pascual (1972), Marshall et al. (1983), Dunn et al. (2013), Woodburne et al. (2014). Units discussed here include Tiupampan, Peligran, <i>Carodnia</i> Zone, Itaboraian, Riochican, and “Sapোন fauna.” Units such as “Sapোন” are given (“”) due to their currently informal status. Nevertheless, both the <i>Carodnia</i> Zone and “Sapোন” are considered to represent distinct temporal intervals consistent with SALMA status.

## 2. Geological framework

The study area is located on the eastern margin of the San Bernardo fold belt, on the northern flank of the San Jorge Basin, Chubut Province, southeastern Argentina (Fig. 1a). This basin is an extensional intracontinental trough developed on a Paleozoic continental crust, linked to the Gondwana break-up and the opening of the South Atlantic Ocean during the Jurassic. The main deposits of the basin are pyroclastic and epiclastic sediments that range in age from Jurassic to the Miocene (Barcat et al., 1989; Fitzgerald et al., 1990). Several continental and marine successions from the Late Cretaceous to the middle Miocene are exposed in the north flank of the basin (Fig. 1b).

The San Jorge Basin record of the Salamanca Formation has been studied for over 70 years (Clyde et al., 2014). Bond et al. (1995) and Raigemborn et al. (2010) show that the formation occurs widely in the subsurface and outcrop from the Río Senguer in the west to the Atlantic Coast on the east (Fig. 1a, b). Clyde et al. (2014) focus on outcrops in the Sarmiento district from Palacio de los Loros (PL, Fig. 1b) to the vicinity of Las Flores (LF, Fig. 1b), but also extends to the east coast. Their discussion includes new paleomagnetic and radioisotopic data for the Salamanca and Peñas Coloradas Formations.

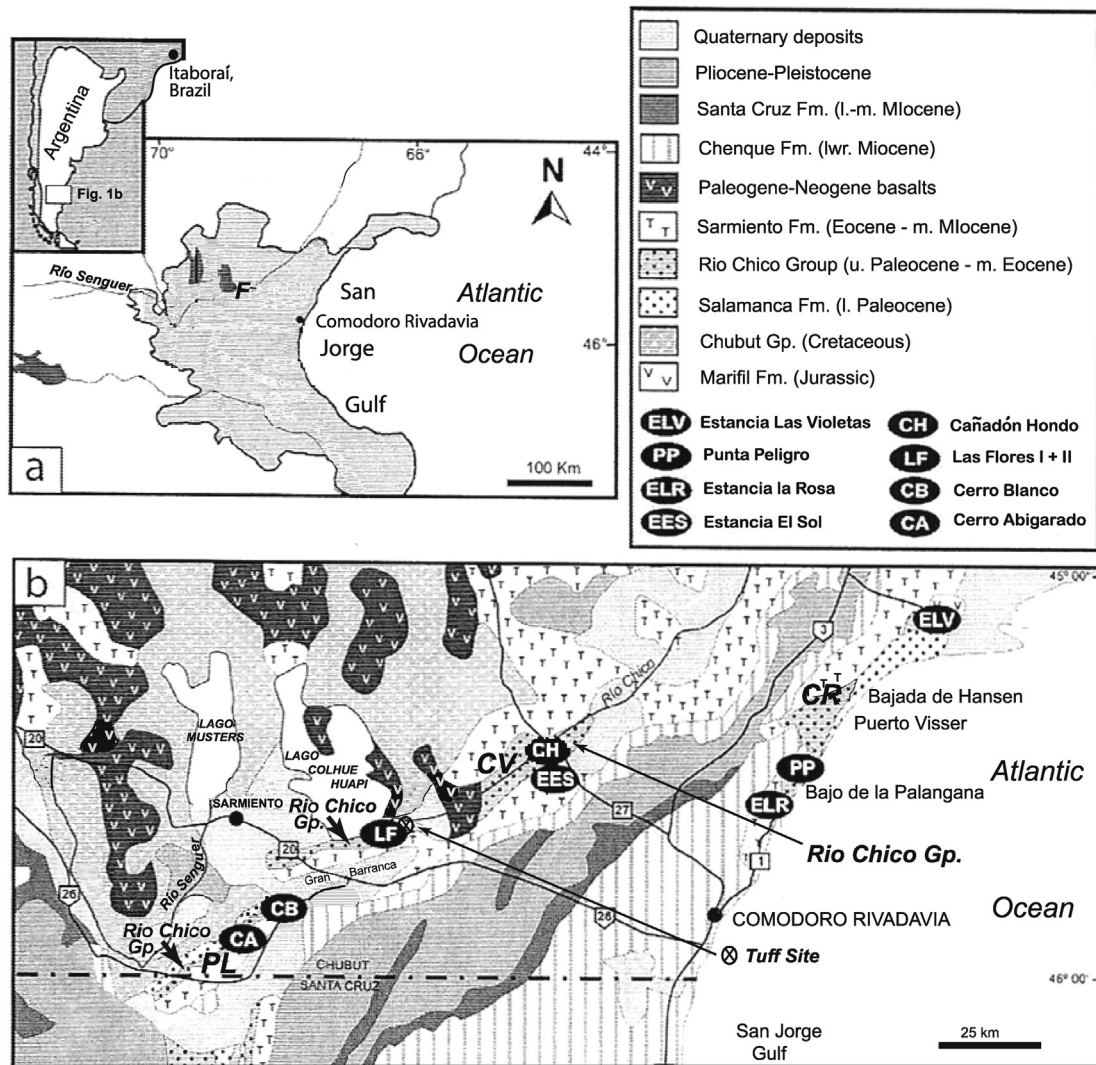
As upgraded by Clyde et al. (2014) the Salamanca Formation represents a shallow marine transgression composed mostly of sandstone, siltstone and mudstone. It ranges up to 150 m thick and unconformably overlies the Angostura Basalt, dated (Clyde et al., 2014) at 67.31 Ma (Fig. 2), with both units unconformably above

the continental deposits of the Chubut Group (early Campanian; Fig. 2). As indicated in Fig. 2, the Fragmentosa unit of the Salamanca Formation is unconformably overlain by the Banco Verde, and followed by the Hansen Member, also known as the Banco Negro Inferior (Bond et al., 1995; BNI, Fig. 2), a widespread dark paleosol that marks the transition from the shallow marine Salamanca Formation to the following nonmarine units of the Río Chico Group, of ?late Paleocene – early Eocene age (Feruglio, 1949; Legaretta and Uliana, 1994; Raigemborn et al., 2010), but see below for an early Paleocene base for the Río Chico Group. Raigemborn et al. (2010) also reported a transitional unit above the BNI, where the beds change from marine to nonmarine strata (Transitional beds, Fig. 3), and characterized the overlying Las Violetas and Peñas Coloradas as part of the transitional succession. In that Raigemborn et al. (2010; 243, and Fig. 6a and b) indicate an unconformable relationship between the Peñas Coloradas and the Transitional beds of the Salamanca Formation at Cerro Abigarrado and a site 20 km southwest of Punta Peligro, the physical contact with the Peñas Coloradas Formation is shown as an unconformity in Figs. 2 and 3. As discussed below, the revised chronology of the BNI bears on the age of the Peligran SALMA.

The Río Chico Group consists of an epiclastic and pyroclastic continental succession composed of fluvial, lacustrine, and eolian facies (Legaretta and Uliana, 1994), with major outcrops extending in a northeast direction from Cerro Abigarrado, through the Las Flores region north of the Gran Barranca, and along the Río Chico and to the coast (CA – ELV, Fig. 1b). The Río Chico Group forms four units which, from bottom to top, are the Las Violetas (not shown on Fig. 2), Peñas Coloradas, Las Flores, and Koluel-Kaike Formations (Raigemborn et al., 2010). The Río Chico Group is overlain by, and partly interfingers with, the middle Eocene – early Miocene loessic and fluvial Sarmiento Formation (Fig. 2) or is locally overlain unconformably by the early Miocene shallow marine Chenque Formation (Fig. 1b). A gradational relationship was observed between the units of the Río Chico Group on the north flank of the basin, with a lateral transition likely maintained between the Las Violetas and Peñas Coloradas Formations (see Krause and Piña, 2012; Fig. 2), and also partly between the Las Flores and Koluel-Kaike Formations (Raigemborn et al., 2010), as reflected in the stratigraphic relations shown in Fig. 2. For the purpose of this report we focus on the Peñas Coloradas, Las Flores and Koluel-Kaike Formations, with emphasis on the Las Flores.

### 2.1. Peñas Coloradas Formation

The Peñas Coloradas Formation is composed of fine-grained conglomerate, very fine to very coarse sandstone, and massive mudstone, of volcanoclastic as well as siliclastic composition, of gray to reddish color. This unit has an average thickness of 40 m and represents a fluvial system of low to moderate energy. Where studied by Clyde et al. (2014), the Peñas Coloradas unconformably overlies the transitional units of the Salamanca Formation (Figs. 2 and 3). Clyde et al. (2014) interpreted an early Paleocene age for the formation in the western part of the basin, with its base being about 62.4 Ma, and tuffs near the top of the unit assessed at 61.51 ± 0.88 Ma. The *Carodnia* Zone, which is defined (Simpson, 1935) at Bajo de La Palangana (Fig. 1b), is interpreted as being contained within these limits (Fig. 2). The implications of these data for the ages of the Tiupampan and Peligran SALMAs and the *Carodnia* Zone are discussed below. Clyde et al. (2014) also implied the presence of an unconformity at the top of the formation, with the overlying Las Flores Formation being correlated with chron C26n, or about 59.2 Ma. We arbitrarily (Fig. 2) use this as the base of the Las Flores Formation, so that the Peñas Coloradas extends upward to that date, past the upper boundary indicated by Clyde et al.



**Fig. 1.** Distribution map of Río Chico Group and associated geological units, Chubut and Santa Cruz provinces, northern Patagonia. a. San Jorge Gulf and inset for Argentina, with Las Flores, Patagonia (F) and Itaboraí, Brazil (I) indicated. b. Map of geology of study region, with site for dated tuff indicated. After Raigemborn et al. (2010, Fig. 1).

(2014). Fig. 2 indicates the extension of the Peñas Coloradas Formation to the Las Flores on one hand, but also that the contact is unconformable.

## 2.2. Las Flores Formation

As seen in the north flank of the basin, the Las Flores Formation is composed of epiclastic and pyroclastic sediments that range in thickness from less than 20 m–44 m over an area of 70 km in a north-south direction and 160 km east-west (southern-most outcrops not shown on Fig. 1b). The formation exhibits a variety of facies arrangements and stratigraphic relationships at different locations in the basin (Raigemborn et al., 2010, Fig. 3 here).

Toward the western part of the north flank of the basin (e.g., Cerro Blanco; Figs. 1 and 3) the Las Flores Formation is 33–44 m thick, and is composed of a homogenous, greenish-gray muddy, epiclastic and pyroclastic, sequence. The characteristic facies consist of laterally continuous sheets of massive mudstone, with common biogenic and pedogenic structures. In addition, some tabular or lenticular beds of massive tuffaceous sandstone, tuffs, and laminated siltstones are present. The Las Flores Formation facies reflect a distal floodplain setting where materials settle from

suspension during sheet flood and stream-flow episodes. Pyroclastic ash-fall events and small, very shallow-water, bodies were developed in this floodplain. The Las Flores Formation in this area of the basin represents a broad epiclastic to pyroclastic muddy distal floodplain of the sinuous fluvial system developed to the east (Raigemborn, 2008).

Microfossils of the Las Flores Formation in the western area include mainly arboreal phytoliths with palm and, to a lesser extent, herbaceous components characteristic of humid subtropical to tropical conditions (Raigemborn et al., 2009), as do fossil lauraceae leaves at the base of the unit. This is compatible with crocodilian coprolites recorded at the basal levels of the unit in the coastal area that also suggest a subtropical-tropical climate (Krause and Piña, 2012). The base of the Las Flores Formation is not well exposed in this area. Elsewhere in the basin it is unconformable above the Peñas Coloradas Formation and in other places may be gradational (Figs. 2 and 3). Legaretta and Uliana (1994) also noted a discordant contact in the coastal region, with a sharp color change in the Estancia Las Violetas section (ELV, Fig. 1b), although Krause and Piña (2012) regarded the two units to be essentially coeval. In Fig. 3 the Las Flores Formation unconformably overlies the Las Violetas Formation at the ELV, in that the Peñas Coloradas

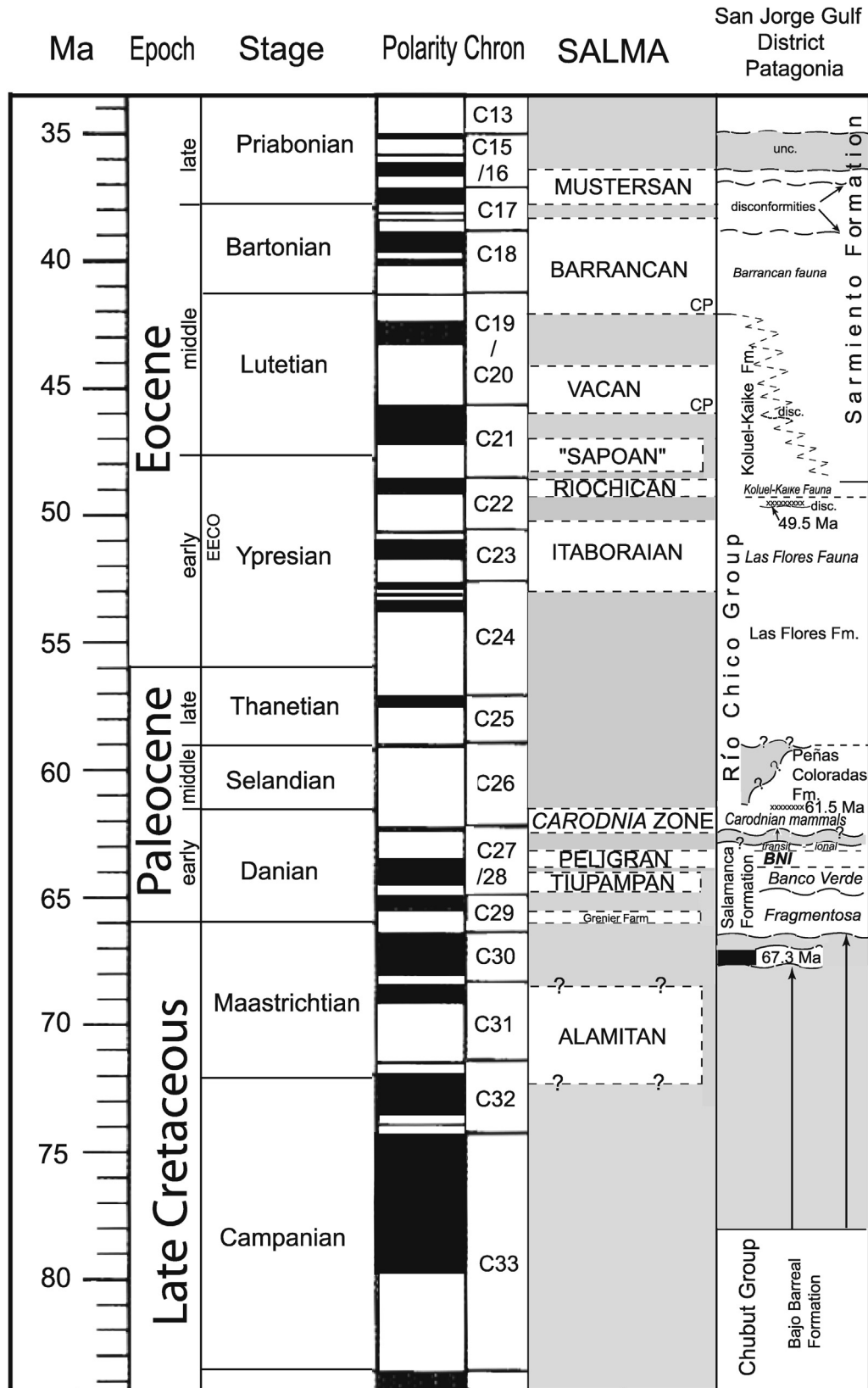
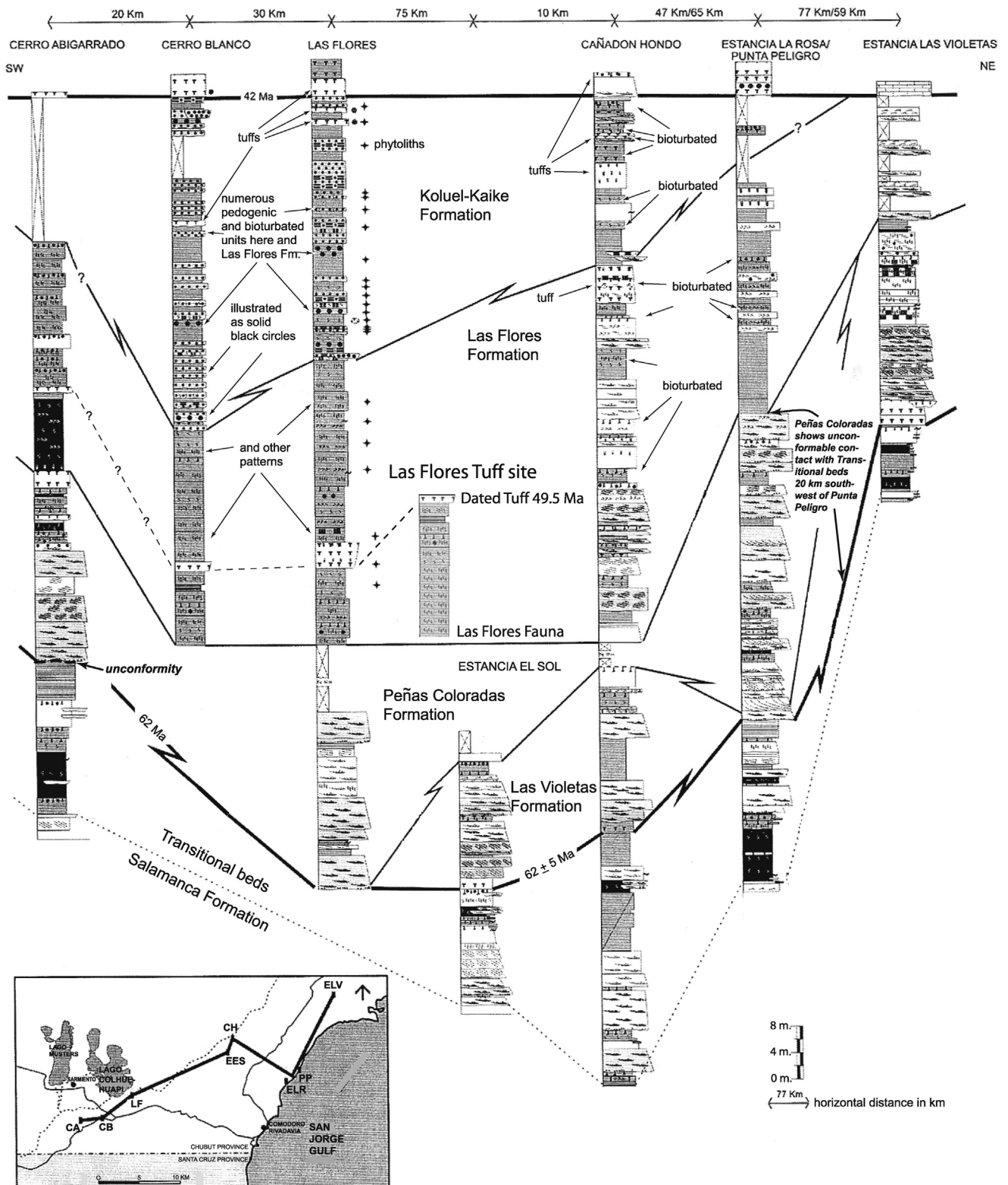


Fig. 2. Stratigraphic relationships of late Cretaceous and Paleogene SALMAs. Chubut Group and Salamanca Formation updated from Clyde et al. (2014). Rio Chico Group discussed in the text. Mammal biochrons of the Sarmiento Formation after Woodburne et al. (2014). Global time scale after Vandenberghe et al. (2012). EECO after Hyland et al. (2013). Termination of right-hand border of Grenier Farm and indicated SALMAs shows lack of representation in San Jorge Gulf District. CP in Barrancan and Vacan indicates their being parts of the former Casamayoran SALMA.



**Fig. 3.** Stratigraphic sections of the Río Chico Group, Chubut Province, Argentina. After Raigemborn et al. (2010, Fig. 3), with Las Flores Tuff site added, along with labeled indications of bioturbation. CS, CB, LF, ESS, CH, ELR and ELV as in Fig. 1b. Horizontal separation of the Las Flores Tuff site section is not to scale. Raigemborn et al. (2010; 243, and Fig. 6a and b) indicate an unconformable relationship between the Peñas Coloradas and the Transitional beds of the Salamanca Formation at Cerro Abigarrado and a site 20 km southwest of Punta Peligro, as shown here.

Formation is missing. Las Flores fossil mammals from ELV show affinity with those of the Itaboraian and “Sapoan” biochrons (Gelfo et al., 2010; Zaidman et al., 2013), compatible with the correlations shown in Fig. 2. In addition, the Las Flores Formation underlies

transitionally tuffaceous paleosols of the Koluel-Kaike Formation (Raigemborn et al., 2010, Fig. 3 here).

In the easternmost part of the Lago Colhué-Huapi (LF, Fig. 1b), the Las Flores Formation is 44 m thick (Fig. 3) and crops out in

greenish-gray rounded hills covered by a weathered layer several centimeters thick, in a typical badland landscape. At the basal-middle section there a distinctive white tuffaceous unit has been dated herein at  $49.512 \pm 0.019$  Ma (see below). The tuff apparently once extended over an area at least about 70 km long, with outcrops represented to the southwest in the Cerro Blanco and, possibly, the Cerro Abigarrado sections (Fig. 3) The dated tuff does not seem to be represented in the Cañadón Hondo, Estancia La Rosa and Estancia Las Violetas sections to the northeast.

Locally, the tuff is a relatively laterally continuous bed about 1 m thick, with an overall lenticular shape in cross section. It consists of massive, medium grain-sized reworked vitric tuff, in which vitreous components are pumice fragments and planar and cusped glass shards. Less abundantly present are crystals of euhedral monocrystalline embayed quartz, sanidine and partly altered plagioclase. The minor lithic fragments are represented by rounded and partially altered particles with a felsic and pilotaxitic texture. Crystals and glass shards are frequently replaced by clay minerals, such as kaolinite and smectite, by opal-CT, and less frequently by zeolites (clinoptilolite). The pore space is filled with the same authigenic minerals. This tuffaceous level represents the filling of a shallow channel in floodplain deposits. Compositional features suggest that the principal source was a volcanic eruption. As indicated in Fig. 3, the Las Flores fauna site occurs about 20 m below the dated tuff.

At this point, the stratigraphic relationships indicate that the Las Flores mammals are older than 49.5 Ma, but their actual age is still unresolved. At present, and based on the following discussion of the age of the Itaboraí mammals of Brazil, the Las Flores mammal fauna is suggested as being between 53 and 50 Ma in age. As discussed below the boundary between the Itaboraian and Riochican SALMAs apparently is bracketed in the Las Flores Formation (Fig. 2).

### 2.3. Koluel-Kaike Formation

Koluel-Kaike Formation is between 35 and 55 m thick. It is transitional above the Las Flores Fm., and overlain by the Sarmiento Fm. (Fig. 2). In the sections shown in Fig. 3, the contact seems to reflect a sharp change in lithology, with basal Sarmiento tuffs in four of the six sections displayed. At Bajo de la Palangana, on the slopes of Pico Salamanca Hill, near Punta Peligro (PP, Fig. 1b), the Koluel-Kaike Formation contains the *Ernestokokenia* faunal zone (Simpson, 1935), now recognized as the Riochican SALMA (Fig. 2). As discussed below, the Koluel-Kaike Formation is in part disconformable with, and in part interfingers with, the overlying Sarmiento Formation, with the youngest contact being about 42 Ma (see also Bellosi and Krause, 2014, Fig. 2). The Las Flores Tuff (below) provides a potential upper limit for the Las Flores Fauna on the one hand and a potential lower limit for the Koluel-Kaike fauna on the other. The Riochican age of the Las Flores Fauna is constrained to be older than the “Sapooan” fauna of Fig. 2, which likely is no older than about 48.5 Ma (see below). The interfingering of the Koluel-Kaike and Sarmiento Formations reflects actual data (Bellosi, 2010) as well as the physical contact between the Koluel-Kaike and local bases of the Sarmiento Formation of Barrancan and Vacan ages. The numerous tuffaceous, bioturbated, and pedogenetically altered units in the Koluel-Kaike, the numerous phytoliths seen especially in the Las Flores section, and the lack of physical continuity of beds between the various stratigraphic sections (Fig. 3) attest to the dynamic episodic-depositional floodplain environment that likely also included numerous discontinuities comparable to those of the Sarmiento Formation.

### 2.4. Sarmiento Formation

The Sarmiento Formations occurs widely in the Gran Barranca region eastward to the coast, and reaches a thickness of 319 m (Bellosi, 2010; Bond et al., 1995). In contrast to the underlying Koluel-Kaike Formation the Sarmiento is composed of poorly sorted pyroclastic mudstones, paleosols, cross-bedded sandstones, intraformational conglomerates, and local basalts (Bellosi, 2010), who also reported a 10 m thick transitional and interbedded interval between the Koluel-Kaike and Gran Barranca member of the Sarmiento Fm. at Las Flores and Cerro Blanco. At least ten intraformational discontinuities and unconformities are recognized, with some being of significant duration. Fig. 2 shows the Eocene portion of the Sarmiento Formation (it ranges to the early Miocene), and potential interfingering relationships with the Koluel-Kaike Formation, up to the base of the Barrancan SALMA. The unconformity at the base of the Vacan section at Cañadón Vaca (Cifelli, 1985; CV, Fig. 1b) is indicated. Bellosi and Krause (2014) note this as a paraconformity. Andreis (1977) also indicated a local unconformity between these units at Cañadón Hondo (CH, Fig. 1b).

## 3. Age of Las Flores tuff

This is based on NMGR Internal Report IR-802, provided by Dr. Heizler. According to that report, the tuff sample provided by M.O. Woodburne was processed to isolate alkali-feldspar grains that were irradiated for 20 h at the USGS TRIGA reactor in Denver, Colorado, along with the standard Fish Canyon tuff sanidine as a neutron flux monitor. Single crystals were dated by the laser fusion method using a CO<sub>2</sub> laser to heat the crystals. A summary of the analytical methods is provided in Table 1 and details regarding the overall operation and data handling methods employed by the NMGR can be downloaded from the Internet site <http://geoinfo.nmt.edu/publications/openfile/argon/home.html>, also discussed by Steiger and Jäger (1977), Taylor (1982), and Renne et al. (1998).

Thirteen individual crystals were fused and show an age range between ~76.5 and 49.5 Ma (Fig. 4). The data tend to cluster at

**Table 1**  
Summary of analytical methods and instrumentation.

Sample preparation and irradiation:
Alkali-feldspar mineral separate obtained by standard magnetic, heavy liquid and hand-picking techniques.
Samples were loaded into machined Al discs and irradiated for 20 h, USGS TRIGA Reactor, Denver, CO
Neutron flux monitor Fish Canyon Tuff sanidine (FC-2). Assigned age = 28.02 Ma (Renne et al., 1998)
Instrumentation:
Thermo-Fisher Scientific ARGUS VI mass spectrometer on line with automated all-metal extraction system.
System = Jan
Multi-collector configuration: 40Ar-H1, 39Ar-Ax, 38Ar-L1, 37Ar-L2, 36Ar-L3
Amplification: H1, L1, L2 1E12 ohm Faraday, AX 1E13 ohm Faraday, L3 – CDD ion counter, deadtime 14 nS.
Laser heating:
Single crystals fused with a 55 W Photon-Machines CO <sub>2</sub> laser.
Reactive gases removed by 2.5 min reaction with 1 SAES D-50 getter operated at 250 °C.
Gas also exposed to aW filament operated at ~2000 °C.
Analytical parameters:
Mass spectrometer sensitivity = 5E-17 mol/fA
Total system blank and background: 15 ± 4%, 0.13 ± 70%, 0.1 ± 100%, 0.16 ± 75%, 0.05 ± 3.6%, x 10–17 mol for masses 40, 39, 38, 37, 36, respectively.
J-factors determined to a precision of ~± 0.02% by CO <sub>2</sub> laser-fusion of 6 single crystals from each of 10 radial positions around a 20-hole irradiation tray.
Correction factors for interfering nuclear reactions were determined using K-glass and CaF <sub>2</sub> and are as follows: (40Ar/39Ar)K = 0.008236 ± 1.3e-4; (36Ar/37Ar)Ca = 0.000273 ± 0.0000002; and (39Ar/37Ar)
Ca = 0.000698 ± 0.0000078.

~49.5, 51, and 61 Ma and K/Ca values are between 0.3 and 99 (Fig. 4; Table 1). The lower K/Ca values (0.34–2.9) are within the anorthoclase group whereas higher values are sanidine and/or plutonic K-feldspars. Radiogenic yields are also variable and fall between ~60 and 99%. The three youngest grains have a weighted mean age of  $49.512 \pm 0.019$  Ma.

The youngest age population of  $49.512 \pm 0.019$  Ma is interpreted to record the depositional age of the Las Flores tuff. Older grains are likely inherited during post-depositional reworking and/or were incorporated during eruption. The age of 49.5 Ma is considered to be a maximum date for the Las Flores tuff, and conforms to the constraint of the underlying fauna that requires ash deposition subsequent to 53 Ma.

**4. Implications for ages of Paleogene SALMAs**

Woodburne et al. (2014) discussed the ages of the Tiupampan through Deseadan SALMAs, and utilized an age of about 64 Ma for the Tiupampan SALMA. This is not modified here.

**4.1. Peligran**

The fossil mammals designated as the Peligran SALMA (Bonaparte et al., 1993) were recovered from the Banco Negro Inferior of the Salamanca Formation in the eastern part of the basin. As indicated in Fig. 2, Clyde et al. (2014, Fig. 10) illustrated that the BNI ranges in age

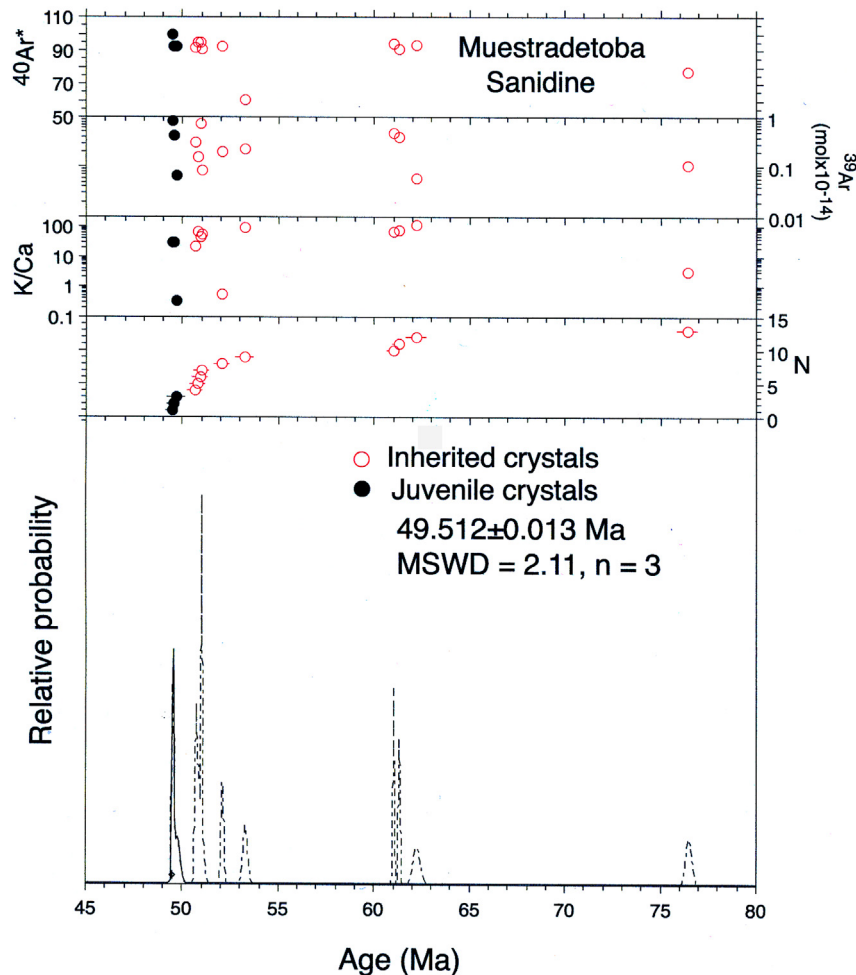
from about 63.2 to 63.8 Ma (and youngest to the east), so the Peligran SALMA is considered to be contained within this interval. That is about 1.5 m.y. older than proposed in Gelfo et al. (2009) and Woodburne et al. (2014) and is so modified here. The new Peligran age does not change its position relative to the older Tiupampan SALMA. This revision is compatible with that for the Carodnia Zone.

**4.2. Carodnia Zone**

The Carodnia Zone is contained within the Peñas Coloradas Formation (Bond et al., 1995; Pascual and Ortiz-Jaureguizar, 2007), and was considered to be about 59 Ma old (Woodburne et al., 2014). As updated by Clyde et al. (2014), the Peñas Coloradas Formation is correlated at ca 62 Ma, based on paleomagnetism and tuffs dated in the lower and upper parts of the formation at Ormaechea and Palacio de los Loros (about 5 km NE and SW, respectively, of Cerro Abigarrado, CA, Fig. 1b).

Clyde et al. (2014, Fig. 10) indicated that the Peñas Coloradas Formation extends into the eastern coastal area, but did not illustrate or discuss its upper contact with the Las Flores Formation other than to note that its base can be correlated with Chron 26n (ca 59 Ma) based on paleomagnetism. This leaves an undocumented upper extension of the Peñas Coloradas Formation, as shown in Fig. 2.

The Carodnia Zone was defined (Simpson, 1935) at Bajo de La Palangana (PP, Fig. 1b), as being located 19–20 m above the Banco Negro Superior (essentially transitional beds above the BNI in



**Fig. 4.** Age probability diagram for sanidine results with supporting diagrams of K/Ca values, <sup>39</sup>Ar signal intensity and radiogenic yield. The youngest population is interpreted to record the depositional age of the ash.

Fig. 2), and correlated with fossils found at the base of unit h in a measured section at Cerro Redondo (CR, Fig. 1b). Simpson (1935, p. 9) noted the unit h level as being “somewhat, but perhaps not significantly, earlier than the horizon of *Carodnia* in the Palangana basin” (Simpson, 1935, p. 8).

For this report, we correlate the *Carodnia* Zone at about 62 Ma. In that the Las Flores.

Formation may be in part gradational with the top of the Peñas Coloradas Formation (discussed above), we portray that contact at about 59 Ma, as being possibly as old as chron 26n (Clyde et al., 2014). We conservatively consider this more likely than their suggestion that the basal contact could be considerably younger, with the next youngest normal chron, c24n.3n being about 53–54 Ma in age (Luterbacher et al., 2004; Vandenberghe et al., 2012).

Here, we recognize the presence of an upper unconformable contact for the Peñas Coloradas in the eastern area where the *Carodnia* Zone was defined (Legaretta and Uliana, 1994; Bond et al., 1995) and, lacking evidence for a younger age there, assign a time comparable to the 61.5 Ma dated ash as recorded by Clyde et al. (2014) and as extended by them to the eastern coastal area. We consider that this correlation likely would be compatible with that proposed by Marshall et al. (1997), but recognize that the sections illustrated therein lack necessary stratigraphic details.

**Table 2**  
Metatherian mammalian taxa found at Itaboraí and Las Flores.

Genus	Itaboraí	Las Flores	References
Metatheria			
Sparassodonta			
<i>Patene</i>	X	?	Oliveira (1998)
<i>Nemolestes</i>	X		Oliveira (1998)
“Didelphimorphia”			
<i>Carolocoutoia</i>	X	X	Goin et al. (1998)
<i>Guggenheimia</i>	X	X	Oliveira (1998)
<i>Protodidelphis</i>	X	X	Oliveira (1998)
<i>Periprotodidelphis</i>	X		Oliveira and Goin (2011)
<i>Zeusdelphys</i>	X		Oliveira (1998)
<i>Derorhynchus</i>	X	X	Oliveira (1998)
Derorhynchidae, gen. nov. 1	X	X	Oliveira (1998)
Derorhynchidae, gen. nov. 2	X	X	Oliveira (1998)
<i>Minusculodelphis</i>	X		Oliveira (1998)
<i>Monodelphopsis</i>	X	X	Oliveira (1998)
<i>Eobrasilia</i>	X		Oliveira (1998)
<i>Caylordia</i>	X		Oliveira (1998)
<i>Marmosopsis</i>	X	X	Oliveira (1998)
<i>Carolopaulacoutoia</i>	X	X	Oliveira (1998), Oliveira and Goin (2011)
<i>Didelphopsis</i>	X	X	Oliveira (1998)
<i>Itaboraidelphys</i>	X		Oliveira (1998)
<i>Procaroloameghinia</i>	X	X	Oliveira (1998)
Peradectidae gen. nov. 3	X	X	Oliveira (1998)
Pediomyidae gen. nov. 4	X	X	Oliveira (1998)
Fam. indet. gen. nov. 5	X	X	Oliveira (1998)
Paucituberculata			
<i>Riolestes</i>	X		Goin et al. (2009)
<i>Bardalestes</i>		X	Goin et al. (2009)
Polydolopimorphia			
<i>Bobbschaefferia</i>	X	X	Oliveira (1998), Oliveira and Goin (2011)
<i>Mirandatherium</i>	X	X	Oliveira (1998), Oliveira and Goin (2011)
<i>Epidolops</i>	X	X	Goin and Candela (1995)
<i>Gashthermia</i>	X		Goin and Oliveira (2007)
<i>Pliodolops</i>		X	Chornogubsky (2010)
Polydolopidae, gen. nov. 6		X	Chornogubsky (2010)
Microbiotheria			
<i>Woodburnodon</i>		X	Goin and Oliveira (2007)
Total number of metatherian taxa	27	21	
Percent shared	63	81	

#### 4.3. Itaboraian

The Itaboraian SALMA was based on the mammal fauna from the fresh water travertine deposits at São José de Itaboraí, Brazil (Fig. 1a) and conventionally considered to be about medial Paleocene in age (e.g., Marshall, 1985). Later studies led to a re-evaluation of the age of the Itaboraian SALMA, considering it as medial to late Paleocene (Oliveira, 1998; Medeiros and Bergqvist, 1999) or latest Paleocene – early Eocene (Marshall et al., 1997; Gelfo et al., 2009; Oliveira and Goin, 2011). Apart from the age considerations developed from the evolutionary stage of the mammals, several other sources of evidence concur in assessing an early Eocene age for the Itaboraian deposits. Riccomini and Ridrigues-Francisco (1992; also Gomes Sant’ Anna and Riccomini, 1992) dated the Itaboraí ankaramite flow that occurs at the northern border of the basin as early Eocene ( $52.6 \pm 2.4$  Ma), and may postdate the Itaboraí fissure fillings. This event is part of a regional volcanic episode, recorded in the Mucuri and Espirito Santo basins and dated as 59–37 Ma (K–Ar, Mohriak, 2006) and 54–44 Ma (Ar/Ar, K–Ar, Geraldès et al., 2013).

Pollen guide-species for both the Paleocene and Eocene have been recovered in the lower calcareous levels of the Itaboraí sequence (Lima and Cunha, 1986). The pollen fossils were taken from Sequence S1, Facies B (lignites) of Medeiros and Bergqvist (1999). This sequence underlies Sequence S2, from which most of the Itaboraian mammals were recovered.

Woodburne et al. (2014) considered the mammal-bearing deposits to be close in age to the locally erupted basalts as proposed by Gomes Sant’ Anna and Riccomini (2001), and thus about 53 Ma in age. Bond et al. (1995) and Goin et al. (1997) allocated the Las Flores mammal fauna at Yacimiento Las Flores in Gran Barranca to the Itaboraian SALMA and noted the Patagonian presence of that mammal biochron. Other works advocating this correlation include Oliveira (1998), Goin and Oliveira (2007), Gelfo et al. (2009), Oliveira and Goin (2011), Woodburne et al. (2014), and literature cited therein. Tables 2 and 3 summarize our current knowledge of the taxa in common between the Las Flores and Itaboraí mammal faunas. The 17 metatherians shared between the two (Table 2), represents 63% of the Itaboraí fauna, and 81% of that from Las Flores. Comparable figures for placental mammals (Table 3) are 38% and 38%, respectively, based on 5 shared taxa. Considering the total numbers from each fauna, Table 3 yields 55% and 58%, respectively, of 22 shared genera. These data, including notes in Table 3, demonstrate a strong faunal similarity between Las Flores and Itaboraí mammals and strongly supports their correlation. Woodburne et al. (2014; 51) noted that the sharing of many taxa between the Las Flores and Brazilian sites suggests that the two regions also shared warm humid, subtropical, conditions. As indicated in Tables 2 and 3, the mammalian diversity and structure of the two regions appears to have been basically similar.

The present radioisotopic date from a tuff bed 20 m above the Las Flores fauna provides a potential upper limit for the Itaboraian, but does not closely constrain it. The tuff clearly was deposited on an open environmental surface that represents a disconformity of unknown duration within the Las Flores Formation. As noted above, the tuff is present in southwestern outcrops of the formation, but not to the northeast. In Fig. 2 an age of about 53 – 50 Ma is retained for the Itaboraian SALMA, with dashed upper and lower boundaries reflecting uncertainty (as for all SALMAS in Fig. 2).

#### 4.4. Riochican

The Riochican SALMA must be chronologically distinct from the Itaboraian because of the stratigraphic framework of the Las Flores and Koluel-Kaike Formations (Bond et al., 1995; this paper). Figs. 2



**Table 3**  
Placental mammals at Itaboraí and Las Flores and comparison of the entire mammalian fauna.

Genus	Itaboraí	Las Flores	References
Placentalia			
Cingulata			
<i>Riostegotherium</i>	X		Bergqvist et al. (2004)
Astrapotheria			
<i>Trigonostylops</i>		X	Bond et al. (1995)
<i>Tetragonostylops</i>	X		Price and Paula Couto (1950) <sup>a</sup>
<i>Shecenia</i>		X	Bond et al. (1995)
Didolodontidae			
<i>Ernestokokenia</i>		X	Bond et al. (1995)
<i>Lamegoia</i>	X		Paula Couto de (1952)
<i>Depaulacoutoia</i>	X		Cifelli and Ortiz Jaureguizar (2014) <sup>d</sup>
Litopterna			
<i>Miguelsoria</i>	X		Paula Couto de (1952) <sup>b</sup>
<i>Protolipterna</i>	X		Cifelli (1983)
<i>Asmithwoodwardia</i>	X	X	Cifelli (1983)
<i>Anisolambda</i>		X	Bond et al. (1995)
<i>Paranisolambda</i>	X		Cifelli (1983) <sup>c</sup>
<i>Victorlemoinea</i>	X	X	Bond et al. (1995)
Notoungulata			
<i>Henricosbornia</i>		X	Bond et al. (1995)
<i>Peripantostylops</i>		X	Bond et al. (1995)
<i>Camargomendesia</i>	X	X	Paula Couto de (1978), Bond et al. (1995)
<i>Isotemnus</i>		X	Bond et al. (1995)
<i>Colbertia</i>	X	X	Bond et al. (1995)
<i>Itaboraiterium</i>	X	X	Bond et al. (1995)
<i>Kibenikhoris</i>		X	Bond et al. (1995)
Xenungulata			
<i>Carodnia</i>	X		Paula Couto de (1952)
Total number of placental taxa	13	13	
Percent shared	38	38	
Total number of mammalian taxa	40	34	
Total percent shared	55	58	

<sup>a</sup> Originally described as a species of *Trigonostylops*.

<sup>b</sup> Originally described as a species of *Ernestokokenia*.

<sup>c</sup> Originally described as a species of *Anisolambda*.

<sup>d</sup> *Depaulacoutoia* has close affinity with *Ernestokokenia* specimens from Las Flores (unpublished). Thus, even as currently separate genera, these taxa additionally support a strong Itaboraí – Las Flores correlation.

and 3 indicate that the Koluel-Kaike Formation occurs transitionally above the Las Flores Formation from Cerro Abigarrado to Cañadon Hondo, and also post-dates the 49.5 Ma tuff. Fig. 3 indicates that the Koluel-Kaike Formation extends about 25 m above the dated tuff. Based on these data, the base of the Koluel-Kaike Formation – and its fauna – is taken at about 49 Ma.

#### 4.5. “Sapoan.”

The upper limit of the Riochican is taken here as pre-“Sapoan” (also Woodburne et al., 2014). As discussed by Tejedor et al. (2009), the Paso del Sapo fauna occurs about 35 m stratigraphically above an ignimbrite dated at  $49.51 \pm 0.32$  Ma. In that the “Sapoan” mammal fauna is derived relative to that from the Koluel-Kaike Formation, our interpretation is that the “Sapoan” must be post-Riochican. The lower age for the “Sapoan” is here suggested as being on the order of 48.5 Ma, with its upper age of about 47 Ma (Fig. 2) being guided by the  $47.82 \pm 1.21$  Ma age of the Huancache Andesite that overlies the Laguna Fria mammal site, also considered to be of “Sapoan” age (Tejedor et al., 2009).

The preceding discussion thus results in a downward revision of the ages of the Peligran SALMA and *Carodnia* Zone, no major change in the Itaboraian, and an upward modification of the ages of the

Riochican and “Sapoan” SALMAs in comparison to their interpretations in Woodburne et al. (2014).

## 5. Paleofaunal ramifications

Woodburne et al. (2014) pointed out the taxonomic novelties presented by the Itaboraian mammals. These include both Itaboraí and Las Flores taxa (Table 2), and show the first protodidelphids (*Carolocoutoia*, *Guggenheimia*, *Protodidelphis*, *Periprotodidelphis*, and *Zeusdelphis*), an early diversity of sternbergiids (*Carolopaulacoutoia*, *Didelphopsis*, and *Itaboraidelphis*), the first caroloameghiniid (*Procaroloameghinia*), basal paucituberculatans (*Riolestes*, *Bardalestes*), one of the oldest microbiotheres (*Woodburnodon*) and a beginning diversity of polydolopimorphians (six genera).

Metatherian diversity is positively correlated with ambient temperatures (Birney and Monjeau, 2003). Zimicz (2012), Woodburne et al. (2014) and Goin et al. (in press) reviewed South American metatherian macroevolutionary events throughout the Paleogene. They recognized that, at least for metatherians, the Itaboraian SALMA was the main radiation event of the whole Cenozoic Era. This major event is not only verified in the diversity peak of Itaboraian metatherians, but also in that the main ecological niche filled by these mammals was that of frugivorous adaptive types, which reach their climax by the Itaboraian (see also Oliveira and Goin, 2011; Goin et al., in press). This agrees with extended tropical-subtropical environments throughout South America, under a general warm climate and high precipitations. Our correlation here of the Itaboraian SALMA with the EECO fits well with these inferences.

Itaboraian placental mammals (Table 3) are represented by South America's oldest cingulate dasypodid, *Riostegotherium*, as well as basal astrapotheres *Trigonostylops*, *Tetragonostylops*, and *Shecenia*. The first members of several other groups include protolipternid (*Miguelsoria*, *Protolipterna*, *Asmithwoodwardia*) and sparnotheriodontid (*Victorlemoinea*) litopterns, and the oldfieldthomasiid notoungulates (*Colbertia*, *Itaboraiterium*) New diversity is also indicated by two didolodontid ‘condylarths’ (*Depaulacoutoia*, *Lamegoia*), the above diversity of litopterns (including the anisolambdid, *Anisolambda*), and another notoungulate, *Camargomendesia*. In addition, the two oldfieldthomasiids round out Itaboraian innovations.

The numerous innovations of the Itaboraian contrast sharply with the precursor SALMAs, now made even more striking in view of the ca 9 m.y. gap in the South American mammal record (Fig. 2). We look forward to the time when this gap is filled in and expect to see a more gradual modernization of South America's land mammals recorded therein. Recovery of the PETM, in particular, would be a very welcome addition to the record and an additional test of global influence of that pattern.

## 6. Climatic implications

The downward revision of the ages of the Peligran SALMA and the *Carodnia* Zone mammals is still compatible with their living in subtropical conditions as discussed above and in Woodburne et al. (2014). The Itaboraian SALMA correlation with the EECO is maintained, as well, and recognition of its fauna representing a major modernization of South American mammals (Woodburne et al., 2014) is reiterated. An upward revision of the Riochican SALMA indicates a somewhat closer correlation to the onset of cooler climates after the EECO relative to that discussed in Woodburne et al. (2014), and is compatible with the available faunal data.

## 7. Conclusions

The work of Clyde et al. (2014) on the Salamanca Formation has resulted in our revising downward the ages of the Peligran SALMA

and the mammals of the *Carodnia* Zone. That work also suggests that the *Carodnia* Zone is no younger than about 61.5 Ma. For the moment, at least, these temporal changes are still compatible with the subtropical affinities of those mammal biochrons and the floras and other taxa with which they are associated.

Taking in account all arguments and evidence here considered, we conclude that the Itaboraian SALMA may be younger than previously thought, probably ranging from 53 to 50 Ma. That is, within the range of the Early Eocene Climatic Optimum. The adaptations and life histories inferred for taxa from the two associations referable to this age (The Las Flores and Itaboraí faunas) agree well with the global climatic and environmental scenarios inferred for the EECO.

The new date here reported, obtained from a tuff that occurs stratigraphically 20 m above the Las Flores mammal fauna, resulted in an upward revision of the age of the Riochican SALMA, and the base of the “Sapoan” fauna. These revisions reinforce the correlation of these biochrons with post-EECO, cooler climatic conditions. Also, they highlight the existence of a major (around 9 m.y.) gap in the South American terrestrial fossil record, from the medial Paleocene (early Selandian) to the earliest Eocene (early Ypresian).

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