New age constraints for the Salamanca Formation and lower Río Chico Group in the western San Jorge Basin, Patagonia, Argentina: Implications for Cretaceous-Paleogene extinction recovery and land mammal age correlations

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ABSTRACT

The Salamanca Formation of the San Jorge Basin (Patagonia, Argentina) preserves critical records of Southern Hemisphere Paleocene biotas, but its age remains poorly resolved, with estimates ranging from Late Cretaceous to middle Paleocene. We report a multi-disciplinary geochronologic study of the Salamanca Formation and overlying Río Chico Group in the western part of the basin. New constraints include (1) an 40Ar/39Ar age determination of 67.31 ± 0.55 Ma from a basalt flow underlying the Salamanca Formation, (2) micropaleontological results indicating an early Danian age for the base of the Salamanca Formation, (3) laser ablation HR-MC-ICP-MS (high resolution-multi collector-inductively coupled plasma-mass spectrometry) U-Pb ages and a high-resolution TIMS (thermal ionization mass spectrometry) age of 61.984 ± 0.041(0.074)[0.100] Ma for zircons from volcanic ash beds in the Peñas Coloradas Formation (Río Chico Group), and (4) paleomagnetic results indicating that the Salamanca Formation in this area is entirely of normal polarity, with reversals occurring in the Río Chico Group. Placing these new age constraints in the context of a sequence stratigraphic model for the basin, we correlate the Salamanca Formation in the study area to Chrons C29n and C28n, with the Banco Negro Inferior (BNI), a mature widespread fossiliferous paleosol unit at the top of the Salamanca Formation, corresponding to the top of Chron C28n. The diverse paleobotanical assemblages from this area are here assigned to C28n (64.67–63.49 Ma), ~2–3 million years older than previously thought, adding to growing evidence for rapid Southern Hemisphere floral recovery after the Cretaceous-Paleogene extinction. Important Peligran and “Carodnia” zone vertebrate fossil assemblages from coastal BNI and Peñas Coloradas exposures are likely older than previously thought and correlate to the early Torrejonian and early Tiffanian North American Land Mammal Ages, respectively.

INTRODUCTION

During the Paleocene Epoch (66.0–56.0 Ma; Gradstein et al., 2012), the Earth system experienced extreme variability that exposed it to unusual boundary conditions. The base of the Paleocene is characterized by recovery from a bolide impact and mass extinction associated with the Cretaceous-Paleogene (K-Pg) boundary (e.g., Schulte et al., 2010). Paleocene climates were characterized by gradual cooling to minimum values at 60–58 Ma, followed by long-term warming (Zachos et al., 2001). The Paleocene ended with the onset of an extreme,
yet transient, global warming event called the Paleocene-Eocene Thermal Maximum (PETM), which represents one of the largest perturbations to the carbon cycle of the last 100 million years (Kennett and Stott, 1991; Stuiver et al., 2007; McInerney and Wing, 2011). Understanding the causes and effects of such extreme Earth system variability in the geological past requires well-resolved stratigraphic records from all the major continents and oceans. Although the Paleocene of the South American continent is becoming better documented with respect to fossils and sedimentary environments, the chronostratigraphy of most units is poorly resolved, and thus the associated fossil and sedimentary records cannot be precisely compared to similar records from other parts of the world (Bond et al., 1995; Flynn and Swisher, 1995; Gelfo et al., 2009; Woodburne et al., 2013).

The shallow marine Salamanca Formation is the stratigraphically lowest Cenozoic geological unit in the San Jorge Basin of central Patagonia (Argentina) and has long been studied for its rich fossil record of marine microorganisms (Frenguelli, 1936; Camacho, 1954, 1967; Méndez, 1966; Masui, 1967; Bertels, 1975; Matheos et al., 2005), plants (Berry, 1937; Archangelsky, 1973, 1976; Petriella and Archangelsky, 1975; Archangelsky and Zamaola, 1986; Zamaola and Andreis, 1995; Matheos et al., 2001; Iglesias et al., 2007; Brea et al., 2008), mammals (Pascual et al., 1992, 2002; Bonaparte et al., 1993; Bonaparte and Morales, 1997; Gelfo and Pascual, 2001; Gelfo, 2007; Gelfo et al., 2007, 2008; Forasiepi and Martínez, 2003; Gurovich, 2008), reptiles (Bona and de la Fuente, 2005; Bona, 2007; Sterli and de la Fuente, 2012), and marine macrofaunas (Chebli and Serraio, 1974; Andreas, 1977; Parma and Casadio, 2005). Despite preserving one of the most complete Paleocene stratigraphic and paleontological records from all of South America, the Salamanca’s precise age remains poorly resolved. Some studies have suggested that its base ranges into the Cretaceous (e.g., Legarreta and Uliana, 1994; Gelfo et al., 2009), whereas others indicate that its top ranges up to the late Paleocene (e.g., Foix et al., 2012). Given that the Salamanca Formation is in places less than 50 m in total thickness, this represents significant chronostratigraphic uncertainty. Understanding the age of the Salamanca is complicated further by the great distances (>300 km) over which it is exposed and its transgressive character, creating the possibility of significant diachrony between different parts of the basin.

For this study, we gathered new field data and applied a wide variety of geochronological tools to better date the Salamanca Formation and lower Río Chico Group in the western part of the San Jorge Basin near the city of Sarmiento, where important paleontological sites are located (Berry, 1937; Matheos et al., 2001; Iglesias et al., 2007; Fig. 1). We compare these results with previous data from other areas of the basin to better define the time scale of biotic recovery in South America after the K-Pg mass extinction and help constrain the age of other important early Paleogene fossil sites, including vertebrate fossil assemblages known from exposures of these lithologic units farther to the east.

GEOLOGICAL SETTING

The San Jorge Basin is situated in Chubut and Santa Cruz Provinces of Argentina, between 44° and 47°S and 66° and 71°W (Fig. 1). The basin is bounded to the north by the Somuncura massif, to the south, the Deseado massif and the continental margin of the Atlantic Ocean to the east (Syllwan, 2001). Formation of the San Jorge Basin is associated with the Jurassic initial breakup of Gondwana, producing an east-west-oriented extensional intracratonic trough formed on Paleozoic continental crust (Fitzgerald et al., 1990; Spalletti and Franzese, 2007). Infilling of half grabens with volcaniclastic and lacustrine sediments led to the formation of the Jurassic Marifil Complex and Lower Cretaceous Las Heras Group. Continued extension during the rest of the Cretaceous resulted in the deposition of the Chubut Group (Figari et al., 1999; Spalletti and Franzese, 2007; Foix et al., 2012).

The shallow marine Salamanca Formation overlies the Chubut Group, representing a Paleocene transgression of the Atlantic Ocean (Fig. 2). It consists dominantly of sandstones (some glauconitic), siltstones, and mudstones and varies in thickness between <50 m to >150 m (Feruglio, 1949; Andreis et al., 1975; Matheos et al., 2005; Comer, 2011). Feruglio (1949) recognized four
Several important fossil plant collections have been reported from the Salamanca Formation. These collections include the original, small compression flora from Palacio de los Loros composed of 11 species (Berry, 1937), several palynological and fossil wood studies (Romero, 1968; Archangelsky, 1973; Archangelsky and Romero, 1974; Petriella and Archangelsky, 1975; Archangelsky and Zamaloa, 1986; Brea et al., 2005, 2008; Matheos et al., 2005), and most recently, two large, quantitatively sampled compression floras from the Palacio de los Loros section (Iglesias et al., 2007; Escapa et al., 2013). These last collections show that floral diversity in this part of South America had already risen well above that documented for comparable assemblages in North America by Salamanca time. Also of great interest is that abundant fossil vertebrates are preserved in the BNI along the present-day coast (Pascual et al., 1992, 2002; Bonaparte et al., 1993; Bonaparte and Morales, 1997; Gelfo and Pascual, 2001; Bona and de la Fuente, 2005; Bona, 2007; Gelfo, 2007; Gelfo et al., 2007, 2008; Gurovich, 2008; Sterli and de la Fuente, 2012). The unique mammalian assemblages from the BNI include an immigrant monotreme, non-therians from endemic survivor lineages of the Cretaceous, marsupials, and placentals, thus representing one of the most informative records of vertebrate evolution from the early Paleogene of South America and forming the basis of the Peligran South American Land Mammal Age (SLAMA; Bonaparte et al., 1993; Gelfo et al., 2009).

Previous studies of the Salamanca Formation have indicated a mid-to-late Danian age (foraminiferal Zone PIC) based on planktonic foraminiferal assemblages found at the Puerto Visser and Punta Peligro localities in the eastern part of the basin, near the modern-day coast (Méndez, 1966; Bertels, 1975). Barcat et al. (1989), however, assigned a Maastrichtian age to the base of the Salamanca Formation based on calcareous nanofossils from a drill hole located in the center of the basin near the coast (Lomita de la Costa). This is based on fossil identifications in an internal oil company report, making them difficult to verify, and the reported taxa are not convincingly age diagnostic. Attempts to refine the age of the Salamanca using radiometric and paleomagnetic techniques have thus far yielded ambiguous results. Marshall et al. (1981) used K-Ar ages of 64.0 ± 0.8 Ma and 62.8 ± 0.8 Ma for a basalt flow underneath the base of the Salamanca (re-dated here) and paleomagnetic data to correlate the BNI to Chron C26r at the Cerro Angostura and Punta Peligro localities along the coast, indicating an approximate age for the BNI of 64 Ma. These results were reinterpreted by Bonaparte et al. (1993) who suggested that the BNI correlates to somewhere within Chron C27, with the middle of C27r as their best estimate. Moreover, Somoza et al. (1995) found the BNI to be characterized by normal polarity at the Las Violetas and El Gauchito localities (north of Cerro Redondo and Punta Peligro on the coast; Fig. 1) and correlated it to Chron C27n. Updated time scales have also significantly changed the estimated ages for the chron boundaries since these original studies were published (Gradstein et al., 2012). In summary, a range of age estimates for the upper and lower limits of the Salamanca Formation (including the BNI) have been proposed, extending from the Maastrichtian to the Eocene (ca. 60–67 Ma).

Results reported here come from the western part of the basin near the city of Sarmiento (Fig. 1). Motivations for working in this area include (1) the presence of macrofloras in the studied sections that appear to be unique on the Gondwanan continents for their combination of early Paleocene age (tested here), excellent preservation and abundance, and unusually high diversity for the time period (Iglesias et al., 2007; Brea et al., 2008), and (2) the need to develop a stratigraphic anchor for the extensive, and long-studied, overlying sequence of Cenozoic vertebrates in the BNI, Río Chico Group, and Sarmiento Formation, which is the richest in the Southern Hemisphere (Ameghino, 1906; Simpson, 1935a, 1935b, 1950, 1980; Madden et al., 2010; Woodburne et al., 2013). Our study is based on (Fig. 1): two adjacent, correlated stratigraphic sections at Bosque Petrifizado José Ormaechea (OR; Dromedary Hill and Cerro Colorado); two adjacent, correlated sections at Palacio de los Loros (PLa and PLb); isolated sections of Salamanca Formation at Rancho Grande (RG) and Peñas Coloradas Formation at Las Flores (LF), which each contain important (currently unpublished) macrofloras that extend the knowledge of plant evolution in the region (Iglesias, 2007); and a new isotopic age determination for the basalt near Estancia La Angostura that was first analyzed by Marshall et al. (1981).

METHODS

Microfossil Biostratigraphy

Foraminifera

Samples from the Dromedary Hill section at Ormaechea (OR1013–OR1019) and the Rancho Grande section (RG1001–RG1003)
were soaked and manually disaggregated in a beaker of tap water, washed over a 63 μm sieve, and dried in a convection oven at 50 °C. After initial searches on the picking tray for foraminifera, the sieved residue (~2–3 g) was poured and stirred in a beaker containing carbon tetrachloride, and the heavy liquid float was decanted into filter paper that, once dried, was scanned to identify and pick biogenic material. Scanning electron microscopy (SEM) was performed on a Phillips XL-30 ESEM with a LaB6 electron source at the U.S. National Museum of Natural History.

**Calcareous Nanofossils**

Sample OR1016 was also prepared for analysis of calcareous nanofossils at Pennsylvania State University following Bown and Young (1998). This sample was chosen because SEM images of the planktonic foraminifera showed preserved nanofossils, many in attachment to the studied foraminifera. In addition to the SEM images, small amounts of the sediment were disaggregated and suspended in buffered (pH ~8) distilled water. This suspension was allowed to settle for 1–2 min for sand- and silt-sized particles to separate from the solution. A microscope slide was made from the resulting suspension, which was observed under cross-polarized light at different magnifications (1000×–1600×) for at least five random transects of the slide (>100 fields of view) to increase the likelihood of detecting very rare taxa.

**Dinoflagellate Cysts**

Twenty palynological samples from all four sections at Ormaechea and Palacio de los Loros were processed for dinoflagellate cysts. Sample processing followed standard protocols of the Laboratory of Palaeobotany and Palynology of Utrecht University (see GSA Data Repository for details1).

**Terrestrial Palynomorphs**

A set of 24 samples from the four sections at Ormaechea and Palacio de los Loros were processed using standard palynological techniques (HCl, HF, heavy liquid ZnCl₂, and HNO₃) and mounted in polyvinyl alcohol at Universidad de Buenos Aires. Observational and photographic equipment included a Dialux 20 microscope with a Leica EC3 digital camera at the Universidad de Buenos Aires, and a Philips XL 30 scanning electron microscope at the Museo Argentino de Ciencias Naturales “Bernardino Rivadavia”. Slides and residues are archived in the palynological collection of the Departamento de Ecología, Genética y Evolución, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, as BAFCB p.m. 254–258.

**Isotope Geochronology**

 Marshall et al. (1981) first reported a basalt flow above the Bajo Barreal Formation (Chubut Group), but below the unconformable contact with the Salamanca Formation, in the area along the Río Chico, just east of its outflow from Lake Colhué Huapi (Fig. 1). Whole rock ⁴⁰Ar/³⁹Ar isotopic geochronology on two samples from this basalt previously yielded ages reported as 64.0 ± 0.8 Ma and 62.8 ± 0.8 Ma (Marshall et al., 1981). We resampled this same basalt, here called La Angostura Basalt, in order to determine a modern ⁴⁰Ar/³⁹Ar laser incremental heating age for this unit, given its ability to provide a firm maximum age for the Salamanca and the large uncertainties associated with the original ⁴⁰Ar/³⁹Ar ages. Our sample (LF1007) came from very close to Estancia La Angostura at the outflow of Lake Colhué Huapi (Table DR1). Although we did not observe the contact between the basalt and the overlying Salamanca Formation in this area, subsurface resistivity logs from nearby oil wells are consistent with a laterally discontinuous basalt flow between the Salamanca and underlying Bajo Barreal, supporting the stratigraphic placement shown in Marshall et al. (1981). Samples of purified groundmass were incrementally heated using the methods of Smith et al. (2006). Argon isotope analyses were done using a MAP 215-50 mass spectrometer at the University of Wisconsin, and the data were reduced using Ar40Calc software version 2.5 (http://earthref.org/Ar40Calc/). The age uncertainties reported here reflect analytical contributions only, at the 2σ level; the decay constants used are those of Min et al. (2000; see Supplementary Methods for details).

**U-Pb CA-TIMS**

The eleven zircons selected on the basis of the LA-ICP-MS results from the PL-1 tuff sample were subjected to a modified version of the chemical abrasion TIMS method of Mattinson (2005). U-Pb dates and uncertainties were calculated using the algorithms of Schmitz and Schoene (2007) and the U decay constants of Jaffey et al. (1971). Quoted errors are 2σ in the form ±X[Y][Z], where X is solely analytical uncertainty, Y is the combined analytical and tracer uncertainty, and Z is the combined analytical, tracer, and ⁴⁰Ca decay constant uncertainty (see Supplementary Methods for additional details).

**Paleomagnetism**

Paleomagnetic samples were collected from 60 sample sites within the stratigraphic sections at Ormaechea, Palacio de los Loros, Rancho Grande, and Las Flores. Formations sampled...
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included the upper Bajo Barreal (Chubut Group), Salamanca, Peñas Coloradas, and Las Flores. Stepwise alternating field (AF) and thermal demagnetization methods were used on a preliminary set of samples and indicated that AF demagnetization with a peak field of 100 mT was successful at isolating natural remanent magnetization (NRM) components in the majority of samples. However, samples from oxidized red beds within the Río Chico Group were stepwise thermally demagnetized up to 690 °C. Magnetic mineralogy was determined by acquisition of isothermal remanent magnetization (IRM) up to a peak field of 1.1 T, followed by stepwise demagnetization of three orthogonal IRMs of 1.1 T, 0.4 T, and 0.12 T up to 690 °C (Lowrie, 1990). Paleomagnetic analyses were performed using an HSM2 SQUID cryogenic magnetometer, a Molspin tumbling AF demagnetizer, an ASC Model TD48-SC thermal demagnetizer, and an ASC IM10 impulse magnet in the paleomagnetics lab at the University of New Hampshire.

RESULTS

Microfossil Biostratigraphy

Foraminifera

Extremely rare but very well-preserved foraminifera were found only in samples OR1016 and RG1002 (Table 1). The silty claystone sample OR1016 (basal Salamanca Formation in Ormaechea Park; Table DR2) yielded one benthic foraminifer assigned to Gyroidinoides nitidus (Fig. 3.1) and eight planktonic specimens assigned to Globonamolina planocompressa (6 specimens; Figs. 3.2, 3.4), Dipsidripella? sp. (1 specimen; Fig. 3.3), and one unknown taxon. Co-occurrence of the foraminifera with common tri-radiate sponge spicules, and their extraordinarily good preservation, indicate that these specimens were deposited in situ within a shelfal marine depositional environment. The small sizes of the planktonic foraminifera and the patchy distribution of wall pores in the G. planocompressa specimens indicate they did not reach reproductive maturity, which is consistent with the interpretation that they were deposited in a shallow marine setting. In the clay-rich siltstone sample RG1002, several large-sized benthic specimens were found (e.g., Fig. DR2), but no planktonic foraminifera or other microfossil constituents were observed. The large (0.4–0.6 mm diameter) and robust shells, absence of shell infilling or recrystallization, and occurrence with silt-sized grains and authigenic glauconite argue that the specimens were not reworked from a significantly older, lithified sediment source. Nonetheless, abrasion of the final chambers may indicate some degree of local sediment reworking. The specimens are tentatively assigned to Cribrotrilocula?, but the presence of deeply incised umbilical sutures and raised spiral sutures, as well as the reported stratigraphic age range of this genus from the late Eocene through middle Miocene (Loeblich and Tappan, 1988), suggest this may belong to a different, but related taxon. Nonetheless, this form is characteristic of species found only in shallow, inner to middle shelf paleo-environments.

The occurrence of G. planicompressa in sample OR1016 indicates an early Danian age based on its recorded range from upper planktonic foraminifer Zone P2 through middle Zone P1c (Olsson et al., 1999). Although G. planicompressa has not been recorded elsewhere in Patagonia, its occurrence in the Ormaechea section is consistent with reports of Danian planktonic foraminifera, including Parasubbotinita pseudobulloides, Subbotina triloculinae, and Globoconusa daubjergensis, from the Salamanca Formation in the eastern coastal region of Chubut (Méndez, 1966; Masuik, 1967; Bertels, 1975). Absence of these latter species in sample OR1016 may have been the result of shallower marine conditions in the shoreward region of the San Jorge Basin, or facies progradation across the basin causing the Salamanca Formation to be somewhat time-transgressive from west to east. Assignment of the specimen illustrated in Figure 3.3 to Dipsidripella? is based on the presence of a strongly muricate wall texture, incised sutures, and extra-umbilical position of the aperture. If this taxonomic placement is correct, this occurrence considerably predates the age range for the oldest species of the genus, Dipsidripella danvillensis, which is from the middle-upper Eocene (Pearson et al., 2006). In summary, the foraminiferal data from sample OR1016 in the lower Salamanca Formation at Ormaechea indicate an early Danian age (Zone Ptc-middle Zone P1c).

Calcareous Nannofossils

Nannofossils are present but very rare and poorly preserved in sediment sample OR1016. Calcisphaera (thoracosphaeres) fragments were the most commonly observed nannofossils (Fig. DR3A). Coccolithus cavus, Cruciplacolithus primus, and Prinsiis dimorphous are also present at very rare abundances (Figs. DR3B–DR3D respectively; Table 1). The presence of these taxa indicates an early Danian age for the sediment, likely in the NP2 biozone (Martini, 1971). Nannofossils observed in the SEM micrographs also support the early Danian age assessment. Although distinct nannofossil biostratigraphic indicator taxa are lacking in these images, Zeugohabditus sigmoide, Cyclagelosphaera sp., and Biscutum sp. were observed (Figs. DR3E–DR3F), all known K-Pg survivors (e.g., Bown, 2005). Several securely Cretaceous taxa are also present in the SEM micrographs, including Nephroleithus frequens and Staurolithites (Fig. DR3F).

Dinoflagellate Cysts

Of the 20 samples processed for dinocysts, only two were productive. Sample OR1016 contains, along with pollen and spores (see next section), an abundant and diverse dinocyst assemblage. Age-diagnostic species include Cyclapophysis monmouthensis, Senianisphaera inornata, Damassadinium californicum, Trihyroidinium evitti, and Palaeoperidinium pyrophorum (Table 1; Fig. DR4). These species together are typical for earliest Danian strata worldwide (Williams et al., 2004). Other species present in this sample are Lentinia sp., Cerodinium sp., Palaeocystodinium golzowense, Areoligeria tauloma, Glaphyrocysta pastielisi, Tanyosphaeridium sp., and Spiniferites sp. The abundant dinocysts in sample OR1016 comprise an assemblage that is typical for an earliest Danian marine shelf (Pross and Brinkhuis, 2005) and suggest a major transgression in this area by the earliest Danian (Scasso et al., 2012). Normal marine conditions prevailed, however nutrient

TABLE 1. BIOSTRATIGRAPHICALLY SIGNIFICANT MICROFOSILS RECOVERED FROM THE BASAL SALAMANCA FORMATION NEAR SARMIENTO, ARGENTINA, INDICATING AN EARLY DANIAN AGE

| Sample | Dinoflagellates | Foraminifera | Calcareous nannofossils |
|--------|----------------|--------------|------------------------|
| OR1016 | Senonisphaera inornata, Cyclapophysis monmouthensis, Damassadinium californicum, Trihyroidinium evitti, Palaeoperidinium pyrophorum, Tanyosphaeridium, Spiniferites, Cerodinium, Lentinia, Palaeocystodinium | Gyroidinoides nitidus, Dipsidripella sp., Globonamolina planicompressa | Coccolithus cavus, Cruciplacolithus primus, Prinsiis dimorphous, Zeugohabditus sigmoide, Cyclagelosphaera, Biscutum, Nephroleithus frequens, Staurolithites |
input was probably large given the relatively high abundance of (presumed heterotrophic) peridinioid dinocysts, such as Cerodinium, Len- tinia, and Palaeocystodinium compared to (presumed autotrophic) gonyaulacoid cysts (Sluijs et al., 2005). Sample PL1019 (basal Peñas Coloradas Formation, Palacio de los Loros; Table DR2) is dominated by terrestrial palynomorphs and the green alga Pediasastrum (see next section), but the dinocyst Senegalinum is also common. In this sample, the abundant pollen and spores in combination with the high abundance of Pediasastrum suggest a high input of terrestrial and aquatic organic matter, but the presence of Senegalinum suggests continued marine influence, albeit at low salinities (Brinkhuis et al., 2006; Sluijs and Brinkhuis, 2009). The absence of dinocysts in all other samples is probably due to syndepositional overexposure to oxygen and physical abrasion associated with very shallow or non-marine environments.
Terrestrial Palynomorphs

Six of the 24 samples yielded terrestrial palynomorphs, and five of those had abundant, diverse, and well-preserved palynofloras (Table 2, Fig. 4). A total of 63 pollen and spore taxa were recognized. Angiosperm pollen was highly diverse at all levels examined and represents more than 50% of the total taxa; pteridophyte and bryophyte spores represent ~30% and gymnosperm (conifer) pollen represents ~13%.

In spite of the relatively low diversity of conifer species, two different species (and probably new species) of Classopolis (Figs. 4E–4F), pollen produced by members of the extinct family Cheirolepidaeae, are the most abundant type in almost all the assemblages and dominate in several basins of the region, including a similar “Classopolis spike” found in early Danian littoral sediments of the Lefipín Formation in northwestern Chubut (Barreda et al., 2012). The high palynological diversity and good preservation of the analyzed assemblages indicate a local source of the pollen and spores, which were produced by trees, shrubs, and herbs growing inland and near the shore. The mixture of the aquatic components (green algae) and marine dinoflagellates is consistent with an estuarine or other river-influenced shallow shelf environment for the Salamanca Formation (Comer, 2011).

Isotope Geochronology

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

The incremental heating experiment on the sample LF1007 from the basalt intercalated between the Bajo Barreal and Salamanca Formations yielded a well-defined plateau with a weighted mean age of 66.95 ± 0.37 Ma, which comprises ~97% of the $^{39}$Ar release (Fig. 5; Table DR3). The initial five heating steps of the experiment gave ages that were slightly younger, possibly indicating a small degree of radiogenic argon loss. The 17-step isochron defined an age of 67.31 ± 0.55 Ma with a MSWD of 0.31 and an initial $^{40}$Ar/$^{39}$Ar ratio of 294.7 ± 0.9. This isochron is preferred, rather than the apparent plateau age, because it takes into account the potential for a non-atmospheric trapped component. This $^{40}$Ar/$^{39}$Ar age (67.31 ± 0.55 Ma) for the La Angostura basalt is significantly older than the K-Ar dates previously reported for the same unit (64.0 ± 0.8 Ma and 62.8 ± 0.8 Ma; Marshall et al., 1981), probably reflecting inaccurate measurement of $^{40}$Ar or K content of the extremely large whole-rock samples that were melted for the original K-Ar analyses.

U-Pb LA-ICP-MS

Results from the twenty zircons that were analyzed from each of the tuff samples using the LA-ICP-MS method are shown in Table DR4. Calculated ages for Peñas Coloradas Formation samples from the PL-1 (Palacio de los Loros), OR-20, and OR-21 (Ormaechea) tuffs all overlapped within analytical uncertainty, thus supporting the idea that they represent coeval phases of volcanism in these two, 15.4-km-apart sampling areas and provide an important new chronostratigraphic marker. The age of igneous crystallization for the PL-1 tuff was estimated by this method to 61.48 ± 0.66 [0.82] Ma from 19 equivalent $^{206}$Pb/$^{238}$U dates (MSWD = 0.26; Fig. 6A), later refined by the CA-TIMS analyses discussed below. The OR-20 tuff yielded an age of 62.08 ± 0.83 [0.98] Ma (n = 16; MSWD = 0.41; Fig. 6C), while that of OR-21 was estimated to 61.51 ± 0.88 [1.00] Ma (n = 16; MSWD = 0.34; Fig. 6D). The sample from the upper Salamanca Formation at Ormaechea (OR-Tuff-2012.1) had zircons with a wide range of calculated ages from 67.9 to 194.6 Ma, with two main clusters of 100–120 Ma and 140–150 Ma (Fig. DR5). These results for OR-Tuff-2012.1 are consistent with the zircons in this sample being detrital in origin, thus providing sedimentary provenance information for the Salamanca Formation rather than direct geochronological constraints. The younger cluster of zircons is consistent with a source in the lower part of the underlying Cretaceous Chubut Group, and the older, Late Jurassic–Early Cretaceous cluster could be associated with unroofing of arc volcanic rocks far to the west (Barcat et al., 1989; Sylwan, 2001; Spalletti and Franzese, 2007).

Paleomagnetism

The acquisition of IRM in samples from the Salamanca Formation (OR1016 and OR1019) and Banco Negro Inferior (OR1022) showed rapid increases in intensity with saturation occurring around 0.2 T, indicating that the magnetic mineralogy is dominated by a low-coercivity mineral like magnetite or greigite (Fig. DR6A). Demagnetization curves showed a gradual decrease in intensity with final unblocking temperatures of 580 °C, suggesting that magnetite is the dominant carrier of magnetic remanence in these samples (Figs. DR6B–DR6D).

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**TABLE 2. TERRESTRIAL PALYNOMORPHS RECOVERED FROM SAMPLES IN THE SALAMANCA FORMATION NEAR SARMIENTO, ARGENTINA**

| Sample | Section/level† | Bryophytes/pteridophytes | Gymnosperms | Angiosperms | Algae |
|--------|----------------|--------------------------|-------------|-------------|-------|
| PL002  | PL(a)/1.4 m    | Ceratosporites equalis Cookson & Dettmann 1958 | Classopollis | Ailanthipites cf marginatus Frederiksen 1983* | Pediastrum boryanum | x — taxon present. |
| PL011  | PL(a)/30.4 m   | Cicatricosisporites sp.* | Dacrydiumites praecupressinoides (Couper) Truswell 1983 | Arecipites minutiscabratus | Zygnemataceae | x — taxon present. |
| OR1015 | DH/3.3 m       | Clavilera tripex (Bolkhovitina) Bolkhovitina 1966 | Microcachrydites antarcticus Cookson 1947 | Haloragacidites sp. | Dinoflagellate cysts | x — taxon present. |
| OR1016 | DH/5.1 m       | Kuyisporites waterbolkii Potonié 1956* | Phyllocladidites mawsonii Cookson ex Couper 1953* | Liliacidites variegatus Couper 1953 | x — taxon present. |
| OR1023 | CC/–8.3 m      | Cyathidites waterbolkii Potonié 1956* | Podocarpidites elegans Romero 1977 | Liliacidites vermireticulatus | Psilatifricolporites sp. | x — taxon present. |

*Indicates first record in Salamanca Formation.
†Indicates the local section and stratigraphic level for each sample (see Fig. 9 and Table DR2 for reference [see footnote 1]). PL—Palacio de los Loros; DH—Dromedary Hill; CC—Cerro Colorado.
Figure 4. Microphotographs of selected terrestrial palynomorphs, Salamanca Formation. (A) Kuylisporites waterbolkii. (B) Clavifera triplex with scanning electron microscope (SEM). (C) Dictyophyllidites concavus. (D) Trilites parvalatus. (E–F) Classopollis sp., F with SEM. (G) Dacrydiumites praecupressinoides. (H) Podocarpidites marwickii. (I) Podocarpidites rugulosus with SEM. (J–K) Arecipites minutiscabratus, K with SEM. (L) Liliacidites vermireticulatus. (M) Proxapertites sp. (N) Ulmoideipites patagonicus. (O) Peninsulapollis gillii with SEM. (P) Tricolpites anguloluminosus with SEM. (Q) Tricolpites communis. (R) Psilatricolporites sp. (S) Proteacidites sp. (T) Pediastrum boryanum with SEM. Scale bars = 10 µm.
IRM analysis of samples from the red beds in the Peñas Coloradas Formation was not conducted, but high unblocking temperatures of the NRM in these samples indicated hematite was the dominant magnetic carrier in these samples.

Characteristic remanent directions were calculated using least squares analysis for samples where linear decay toward the origin was observed (Kirschvink, 1980; Figs. 7A–7C). However, several samples showed an initial decay followed by clustering of vector endpoints, and in these cases a Fisher mean was calculated to determine the characteristic direction of the sample (Fig. 7D). Characteristic directions were determined for three samples from each site, and a site mean was computed. The Watson (1956) test for randomness was then used to identify sites with significantly clustered sample directions (Table DR2). All results are reported in geographic coordinates, giving that they are antipodal and that secondary magnetizations in these samples.

Site mean directions reveal four polarity intervals in the measured sections from Ormaechea and Palacio de los Loros (Fig. 9). The Dromedary Hill section in Ormaechea Park contains a reversed and a normal polarity interval in the Bajo Barreal Formation and a normal polarity interval in the Salamanca Formation that extends up through the BNI. The Cerro Colorado section in Ormaechea shows normal polarity for the upper Salamanca Formation and BNI with a reversal in the lower half of the Peñas Coloradas Formation, though the position of this reversal is not well constrained due to sparse sampling in this part of the section. A normal polarity interval is then observed, beginning in the base of the Las Flores Formation. Correlative sections at Palacio de los Loros (a and b, see Fig. 9) show a very similar reversal pattern, with normal polarity for the uppermost Bajo Barreal Formation and the full Salamanca Formation (up through the BNI) followed by a reversal in the lower Peñas Coloradas Formation (Fig. 9). Results from the Las Flores area are also consistent with the Ormaechea record in having a normal polarity site in the upper Bajo Barreal Formation (just below the dated basalt) and two normal polarity sites in the lower Peñas Coloradas Formation, where a macrofloral site is located (Table DR2). Results from two sites in the Salamanca Formation from the Rancho Grande section, containing another paleobotanical locality, are indicative of normal polarity, and thus consistent with results from Ormaechea and Palacio de los Loros, but these do not pass the Watson test for randomness and so are less reliable.

DISCUSSION

Chronostratigraphy

The new magnetostratigraphic, biostratigraphic, and geochronological data reported here can be combined with other published information within a sequence stratigraphic framework to correlate the Bajo Barreal–Salamanca–Río Chico succession in the study area to the geomagnetic polarity time scale (GPTS; Gradstein et al., 2012; Fig. 10). The existence of a lithologic unconformity at the contact between the Bajo Barreal Formation and the overlying Salamanca Formation, as well as the lack of evidence for a reversed polarity interval that could correspond to Chron 29r (which spans the K-Pg boundary), makes it almost certain that the normal polarity associated with those two units represents different chron units separated by a hiatus. The Bajo Barreal Formation is poorly constrained in time but is generally thought to be Campanian–Turonian in age based on $^{40}$Ar/$^{39}$Ar ages reported from it and the overlying Laguna Palacios Formation (Bridge et al., 2000), as well as its dinosaur fauna (Lamanna et al., 2002; Casal et al., 2009; Navarrete et al., 2011). Our results indicate a reverse-to-normal polarity transition in the uppermost Bajo Barreal in the study area. Because the Cretaceous Normal Superchron (C34n) lasts from the Aptian to the Santonian–Campanian boundary and does not contain any known reversals within it that are younger than the Albian (ca. 100 Ma), the reversal in our section of the Bajo Barreal must be Campanian or younger in age, suggesting that the upper Bajo Barreal Formation in this area is younger than generally thought. This is supported by nearby dinosaur fossils from the upper Bajo Barreal that suggest a Campanian–Maastrichtian age (Casal et al., 2007; Ibiricu et al., 2010). Given these various age constraints, we correlate the polarity reversal in the upper Bajo Barreal Formation to the C33r–C33n reversal but acknowledge that it could be a younger, Campanian or Maastrichtian reversal.

The early Danian foraminifera, calcareous nanofossils, and dinoflagellates reported here from the base of the Salamanca Formation indicate that the normal polarity interval in the lower part of the Salamanca Formation is Chron C29n (65.69–64.96 Ma). The U-Pb age of 61.98 Ma from the overlying Peñas Coloradas Formation indicates that its reversed polarity zone (which contains the dated tuffs) is most likely Chron C26r (62.22–59.24 Ma; Fig. 9) with the
normal polarity interval at the base of the Peñas Coloradas Formation in all likelihood correlating to C27n (62.52–62.22 Ma) given the general stratigraphic continuity within this formation. The intervening strata of the upper Salamanca Formation and BNI are all normal polarity and lack additional chronologic constraints, meaning that they belong to some combination of C29n, C28n, and/or C27n and that at least one, and probably more, significant unconformities must be present that erased two corresponding reversed polarity intervals (C28r and C27r). The most likely positions for large unconformities are within the upper Salamanca Formation (between the Fragmentosa and the Banco Verde beds) and between the BNI and the overlying Peñas Coloradas Formation. These two erosional surfaces have been clearly identified in coastal successions (Legarreta et al., 1990; Legarreta and Uliana, 1994; Bond et al., 1995), and our own observations suggest they are developed in the study area as well (Comer, 2011).

The stratigraphic position of unconformities and intervening sedimentary systems tracts can be combined with the updated chronologic data and a global eustatic sea level curve to develop a sequence stratigraphic interpretation for the Salamanca Formation that provides an internally consistent chronostratigraphy of early Paleocene deposition in the study area (Comer, 2011;
Fig. 10. It is assumed in this analysis that the San Jorge Basin was slowly but continuously subsid- ing during this time. The unconformity between the Bajo Barreal and the Salamanca Formation was likely associated with non-deposition and erosion during the Late Cretaceous when eustatic sea level was moderately low (Kominz et al., 2008; see sequence boundary SB-1 in Fig. 10). Salamanca deposition began during Chron C29n in the study area, during the early Danian marine transgression, but likely initiated earlier in the east, as would be expected for a transgressive systems tract (Fig. 10). The sequence boundary between the Fragmentosa and Banco Verde facies (SB-2 in Fig. 10) likely formed during a mid-Danian fall of eustatic sea level (Kominz et al., 2008) that resulted in a eustatic lowstand in Chron 28n. The combination of constant eustatic sea level at lowstand and basin subsidence created net accommodation space that allowed a lowstand systems tract of the Banco Verde to form. The subsequent eustatic sea level rise and highstand created the overlying transgressive (uppermost Banco Verde) and highstand (BNI beds) systems tracts of the upper Salamanca Formation. The BNI represents a prograding coastal swamp deposit that has traditionally been associated with shoreline regression (Legarreta and Uliana, 1994; Bellosi et al., 2000; Bond et al., 1995; Matheos et al., 2001, 2005; Raigemborn et al., 2010; Comer, 2011). This is consistent with a highstand systems tract interpretation in which sediment accommodation space is created slowly and the coastal deposits prograde. We see no evidence that this is a falling stage systems tract created by a forced regression. A third eustatic sea level fall created a third sequence boundary (SB-3) that separates the Banco Negro Inferior from the superjacent Peñas Coloradas Formation. The onset of Peñas Coloradas deposition in Chron C27n represents the end of marine deposition in the San Jorge Basin until at least the Oligocene (Legarreta and Uliana, 1994). The sequence stratigraphic interpretation shown here represents the best match to the updated chronological data and to existing understanding of Late Cretaceous–Paleocene eustatic sea level changes, but other interpretations are also possible. To fully test these alternatives, a more precise age estimate for the upper Salamanca Formation and BNI will need to be determined via further geochronological, paleomagnetic, and biostratigraphic analyses in other areas of the basin (especially along the coast).

**Paleobiological Implications**

Iglesias et al. (2007) estimated the age of the fossil floras from Palacio de los Loros to be ca. 61.7 Ma, primarily based on the occurrences of Danian Zone P1C foraminifera in coastal sections of the Salamanca Formation (Bertels, 1975). Zone P1C spans part of C28n and all of C27r, ending near the Danian-Selandian boundary (ca. 61.7 Ma in the 2004 geologic time scale [GTS] used at the time), which, in the absence of
other constraints, Iglesias et al. took as a conservative age estimate for the floras. Our new age constraints, and especially the normal polarity results for their stratigraphic interval, indicate that the fossil plant compression assemblages from Palacio de los Loros are probably entirely from Chron C28n (64.67–63.49 Ma in the 2012 GTS; Gradstein et al., 2012), which means these comparatively high-diversity floras are ~2–3 million years older than previously thought and indicate an even faster post–K-Pg recovery. In addition, our results indicate a likely age within C28n for the compression flora from an isolated outcrop at Rancho Grande (Fig. 1; Iglesias, 2007), correlative with the floras at Palacio de los Loros and Ormaechea, and an age within C27n (late Danian) for the fossil flora in the lower Peñas Coloradas Formation in the Las Flores section (Fig. 1; Iglesias, 2007). Despite being ~1.5 m.y. younger and coming from a very different, fluvo-volcanic deposi-
tional environment, the Las Flores flora has very similar composition to those from Palacio de los Loros and Ormaechea (Iglesias, 2007), showing continuity through time of this coastal forest floral association.

The relatively high plant diversity during the early Paleocene observed here is consistent with recent palynological results from the Lefi pán Formation (~350 km north of the study area), where a short-term microfloral turnover and decline in species richness at the K-Pg boundary was rapidly followed by a rebound in diversity during the Danian to levels similar to the Maastrichtian (Barreda et al., 2012). The Salamanca macrofloral diversity pattern that is implied by the new age constraints reported here adds to the growing evidence for lower extinction at, and more rapid Southern Hemisphere biotic diversification after, the K-Pg extinction compared to the Northern Hemisphere (Case and Woodburne, 1986; Wolfe, 1987; Askin, 1988; Vajda and McLoughlin, 2007; Jiang et al., 2010; Wilf et al., 2013). Whether this trend is associated with greater distances from the Chicxu-
lub impact site, differences in biogeographic dynamics such that Southern Hemisphere continents acted as refugia, or something else, remains unknown.

Our new chronostratigraphic interpretation for the Salamanca Formation also provides important temporal constraints on the Banco Negro Inferior and its fossil assemblages. Marshall et al. (1981) analyzed the paleomagnetism of the BNI along the coast (Punta Peligro and Cerro Redondo) and found it to be characterized by reversed polarity. The BNI is shown here to...
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be normal polarity in the Sarmiento area, which means that it is definitely a time-transgressive unit (see also Soomza et al., 1995). Our new chronologic constraints and sequence stratigraphic interpretation suggest that the BNI is progradational from west to east and correlates to the top of Chron C28n near Sarmiento and to the base of Chron C27r (63.49 Ma) along the coast (Fig. 10). This interpretation makes the BNI, and associated Peligran SALMA, significantly older than the early Selandian (ca. 62–60 Ma) age that it was previously assigned (Marshall et al., 1981; Soomza et al., 1995; Bonaparte et al., 1993; Gelfo et al., 2009). The Peligran SALMA is then correlative with the early Torrejonian North American Land Mammal Age (NALMA) and Shanghuan Asian Land Mammal Age (ALMA; Clyde et al., 2010). These results also imply that the Peligran SALMA is closer in age to (or possibly older than) the Tiupampan SALMA. The Tiupampan SALMA has most recently been referred to as earliest Paleocene and correlated with the Puer- can NALMA, but is based entirely on a mammal fauna from the poorly dated Santa Lucía Forma- tion in Bolivia that has been variously attributed to the Upper Cretaceous through Selandian (see discussion in Gelfo et al., 2009).

Our results from the western San Jorge Basin also have implications for the age of important fossiliferous units of the Río Chico Group and their associated SALMAS. Based mostly on fos- sil localities near the coast, Simpson (1935b) first divided Río Chico stratigraphy into three mammalian faunal zones (Carodnia, Kibenikhoria, and Ernestokokenia), which correlate with the three lithological units exposed there (Peñas Coloradas, Las Flores, and Koluel-Kaike Formations, respectively, as near Sarmiento). The Kibenikhoria zone of the Las Flores Forma- tion is often referred to the Itaboraian SALMA, and the Ernestokokenia zone of the Koluel-Kaike Formation forms the basis of the Ríochican SALMA (Bond et al., 1995). The “Carodnia” zone is based on very few taxa found in Peñas Coloradas exposures near the coast (e.g., Carodnia feruglioi and Notoetayoa gargantua) and thus has not been elevated to Land Mammal Age status, but it is still thought to represent a distinct period of South American faunal evolution. The possible correlation of the “Carodnia” zone assemblage (as well as the Kibenikhoria zone as mentioned) to the poorly dated fissure-fill assemblages at Itaborai in Bra- zil is often discussed (Simpson, 1935a, 1935b; de Paula Couto, 1952; Bond et al., 1995; Marshall et al., 1997; Gelfo et al., 2009). Our new U-Pb isotopic date of 61.98 Ma from the upper Peñas Coloradas Formation near Sarmiento, as well as its dominantly reversed magnetic polar- ity (as it is near the coast; Marshall et al., 1981), indicates that it falls mostly within C26r (62.22– 59.24 Ma) and is thus latest Danian in age. This makes the “Carodnia” zone (at ca. 62 Ma) sig- nificantly older than generally thought (e.g., Thianetian, ca. 58–56 Ma; Gelfo et al., 2009) and equivalent to, or at least overlapping with, the early Tiffanian SALMA and Nongshanian ALMA (Clyde et al., 2010). Given the possi- bility for diachrony within Río Chico facies, direct testing of this correlation will require geo- chronological results from the coastal sections of the Peñas Coloradas Formation that actually produced the “Carodnia” zone fossils.

The original Kibenikhoria zone fossils described by Simpson (1935a, 1935b) were recovered from Río Chico facies at Cañadón Honda, which lies about halfway between Sarmiento and the modern coast. Legar- reta and Uliana (1994) and Bond et al. (1995), who recognized distinct, sequence-bounded litho-biostratigraphic packages within the early Paleogene stratigraphy of the San Jorge Basin, associated this fauna with the Las Flores For- mation. Additional vertebrate specimens from the Las Flores Formation are now known from east of Sarmiento city at the eastern tip of Gran Barranca (Cione et al., 2011) and along the coast near Comodoro Rivadavia (Krause and Piña, 2012). Our results indicate that the bottom part of the Las Flores Formation south of Sarmiento is characterized by normal polarity, which must represent Chron C26n or younger based on the new geochronological results for the underly- ing Peñas Coloradas Formation presented here. Currently, the only reliable age constraint from above the Las Flores Formation comes from the Sarmiento Formation, which lies above the Koluel-Kaike Formation and is correlated to Chron C19r at its base (42.30–41.39 Ma; RÉ et al., 2010; Dunn et al., 2012). This means that the Las Flores Kibenikhoria fauna (likely equivalent to, or overlapping with, the Itaboraian SALMA) and the Ríochican SALMA could theoretically be anywhere from late Paleocene to middle Eocene in age. Additional geochronolog- ical studies of the Las Flores and Koluel-Kaike Formations are clearly needed to better resolve the age of these units and their associated faunas. This is particularly important given the likelihood of large unconformities within this interval and the importance of determining the position of the Paleocene-Eocene boundary in the San Jorge Basin stratigraphy.

CONCLUSIONS

New biostratigraphic, radioisotopic, and paleomagnetic data from the fossiliferous Bajo Barreal Formation, Salamanca Formation, and overlying Río Chico Group in the Sarmiento area of Chubut, Argentina (central Patagonia), are placed in a sequence stratigraphic framework to develop a revised chronostratigraphy for the Late Cretaceous–early Paleogene deposits of the San Jorge Basin. Implications of this new chronostratigraphy are that (1) the Bajo Barreal Formation in this area ranges up to at least the Campanian (i.e., <83.6 Ma), (2) the Salamanca Formation (including the BNI) in the study area ranges from early to middle Danian (early Paleocene; ca. 65.7–63.5 Ma), and (3) the Peñas Coloradas Formation is latest Danian in age (ca. 62.5–61.6 Ma). Previously reported diverse fossil plant assemblages from the same sections studied here are from Chron C28n (64.67–63.49 Ma) and thus ~2 million years older than previously thought, supporting recent results suggesting a more rapid Southern Hemisphere biotic recovery from the K-Pg extinction compared to the Northern Hemi- sphere. Important fossil vertebrate faunas from the Banco Negro Inferior (Peligran SALMA) and Peñas Coloradas Formation (“Carodnia” zone) from areas farther to the east are also interpreted to be considerably older than generally acknowledged, correlating to the early Torrejonian NALMA/Shanghuan ALMA and the early Tiffanian SALMA/Nongshanian ALMA respectively.

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New biostratigraphic, radioisotopic, and paleomagnetic data from the fossiliferous Bajo Barreal Formation, Salamanca Formation, and
