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New South American record of the Cretaceous–Paleogene boundary interval (La Colonia Formation, Patagonia, Argentina)

W.C. Clyde [a, *], J.M. Krause [b, c], F. De Benedetti [b], J. Ramezani [d], N.R. Cúneo [b], M.A. Gandolfo [e], P. Haber [a], C. Whelan [a], T. Smith [a]

[a] Department of Earth Sciences, University of New Hampshire, Durham, NH, 03824, United States
[b] CONICET–Museo Paleontológico Egidio Feruglio, Avenida Fontana 140, Trelew, Chubut, 9100, Argentina
[c] Universidad Nacional de Río Negro, Av. Roca 1242, General Roca, Río Negro, 8332, Argentina
[d] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139, United States
[e] L. H. Bailey Hortorium, Plant Biology Section, School of Integrative Plant Science, Cornell University, Ithaca, NY, 14850, United States

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A B S T R A C T

The La Colonia Formation is an Upper Cretaceous to Paleogene shallow marine sedimentary unit in Chubut Province (Patagonia), Argentina that preserves important vertebrate and plant fossils. Despite good exposures and significant paleontological investigation, the precise age of the La Colonia Formation and its stratigraphic relationship to the Cretaceous–Paleogene (K–Pg) boundary are not well understood. The K-Pg boundary is associated with one of the largest mass extinctions in Earth's history yet there are few continental stratigraphic records of the boundary in South America, resulting in poor understanding of its effects there. This study combines magnetostratigraphy, detrital zircon uranium–lead (U–Pb) geochronology, and preliminary palynological results to constrain the age of the La Colonia Formation and its fossils more precisely and determine whether it preserves the K–Pg boundary. U–Pb ages of detrital zircons from the directly underlying Puntudo Chico Formation indicate that the base of the La Colonia Formation is younger than ~71.7 Ma. The studied palynological assemblage includes *Quadraplanus brossus*, which is restricted to the Maastrichtian in other southern hemisphere records. Paleomagnetic results show that the ~125 m Cerro Buitre Norte section of the La Colonia Formation and the overlying Cerro Bororó Formation has dominantly normal polarity except for a ~5 m zone of reversed polarity near the base that is interpreted to correlate to Chron C30R of the Geomagnetic Polarity Timescale (GPTS), and a ~13 m zone of reversed polarity near the top of the La Colonia Formation that is interpreted to correlate to Chron C29R. The presence of a magnetozone correlated to C29R in the La Colonia Formation suggests that it preserves the K–Pg boundary, making it an important target for continued paleontological collection to better understand the K–Pg extinction and recovery dynamics in South America.

1. Introduction

Stratigraphic records of extinction and recovery across mass extinctions provide important windows into biotic resiliency. The Cretaceous–Paleogene (K–Pg) boundary represents one of the largest mass extinction events in Earth history and is thought to have been primarily caused by the environmental effects of an extraterrestrial bolide impact at the Chicxulub site in the Yucatan Peninsula with potential contributions from massive volcanism associated with the Deccan Traps in India (Alvarez et al., 1980; Courtillot et al., 1986, 1988; Swisher et al., 1992; Chenet et al., 2009; Schulte et al., 2010; Renne et al., 2013; Schoene et al., 2019; Hull et al., 2020). Biotic extinction and recovery dynamics have been studied in great detail in many parts of the globe but few stratigraphic records of the K–Pg boundary have been reported from South America making the effects of the K–Pg environmental catastrophe and associated extinction poorly resolved on this continent (e.g. Figure 2A of Schulte (2010) showed South America as the only continent without a “key” K–Pg boundary site). Here, we

* Corresponding author.
E-mail address: will.clyde@unh.edu (W.C. Clyde).

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report new chronostratigraphic data from the Upper Cretaceous−−Paleogene La Colonia Formation to better resolve its age and determine whether it preserves the K−Pg boundary itself.

1.1. Geological context

The La Colonia Formation (Pesce, 1979; Ardolino and Delpino, 1987) is exposed along the southeastern margin of the Somún Curá Plateau in north-central Chubut Province, Patagonia, Argentina. Four regional geological maps coarsely define the extent of the formation between 42.30° and 43.35° S latitude, and 69.0°−66.30° W longitude (Ardolino and Franchi, 1996; Anselmi et al., 2004; Sacomani et al., 2007; Ardolino et al., 2017), with the most continuous outcrops distributed between Telsen and El Mirasol (Fig. 1). Outcrops of the La Colonia Formation were also recognized to the east of Telsen (Haller et al., 2005), although probably deposited within another contemporaneous depocenter.

The studied section at "Cerro Buitre Norte" is located in the area of Mirasol Chico creek, 7.5 km northeast of El Buitre hill (Fig. 1). Previously reported stratigraphic sections of the La Colonia Formation vary in thickness between ~40 and 205 m (Ardolino and Franchi, 1996). Stratigraphically, the La Colonia Formation overlies, through a low angle erosional surface, the Puntudo Chico Formation in the study area of Mirasol Chico creek (Ardolino and Franchi, 1996) or the Chubut Group in the Telsen area (Navarro et al., 2008, 2012). Overlying units include brackish paludal siliciclastic facies of the Paleocene Cerro Bororó Formation, basalts of the Paleocene−Eocene El Buitre Formation and Oligocene pyroclastic rocks of the Sarmiento Formation (Ardolino and Franchi, 1996; Anselmi et al., 2004; Sacomani et al., 2007; Navarro et al., 2008). Between 130 and 180 km south of our study site, strata corresponding to the Puntudo Chico Formation directly underlie the Danian Cerro Bororó Formation without intervening La Colonia Formation. This suggests that outside the marine depocenter, the upper part of the Puntudo Chico Formation is partially contemporaneous with the La Colonia Formation, in agreement with the interpretation of Page (1987) and Ardolino and Franchi (1996), based on lithofacies criteria in the Cerro Buitre area.

The La Colonia Formation was deposited during epeiric flooding that affected the continental margin of Argentina, and other regions of South America, during the Late Cretaceous and the earliest Paleogene (e.g. Riccardi, 1988; Uliana and Biddle, 1988 and citations therein). However, there are different interpretations of the specific depositional environments represented by the La Colonia Formation. Pascual et al. (2000) divided the La Colonia Formation into three facies associations, corresponding, from base to top, to fluvial, estuarine tidal flat or coastal plain, and upper tidal flats. Cúneo et al. (2013a, 2014) suggested an origin related to clastic coastal plains bathed by shallow seas and development of barrier island/lagoon complexes, without recognition of fluvial facies. For a La Colonia succession near our study section, Gasparini et al. (2015) interpreted a brackish to fresh water estuarine mixed-energy system. Navarro et al. (2008, 2012), Guler et al. (2014, 2019), and Borel et al. (2016) interpreted the La Colonia succession in the Telsen area as deposited in, from base to top, shoreface, offshore, mixed and mud tidal flat, and supratidal settings, defining an upward trend toward fresher water environments.

Several regional paleogeographic models proposed for the Late Cretaceous flooding of northern Chubut and southern Río Negro Provinces explain the deposition of the La Colonia Formation (Riccardi, 1988; Uliana and Biddle, 1988; Malumián, 1999; Franzese et al., 2003; Náñez and Malumián, 2008; Malumián and Náñez, 2011; Scasso et al., 2012; del Río and Martínez, 2015; Guler et al., 2019 and citations therein). Although there are some differences among them, particularly regarding the connection between the Cañadón Asfalto and the Golfo San Jorge basins, they all support the correlation of the La Colonia Formation with other adjacent units, such as the Lefipán, Los Alamitos and Coli Toro formations (Riccardi, 1988; Getino, 1995; Ardolino and Franchi, 1996) (Fig. 1).

1.2. La Colonia fossils

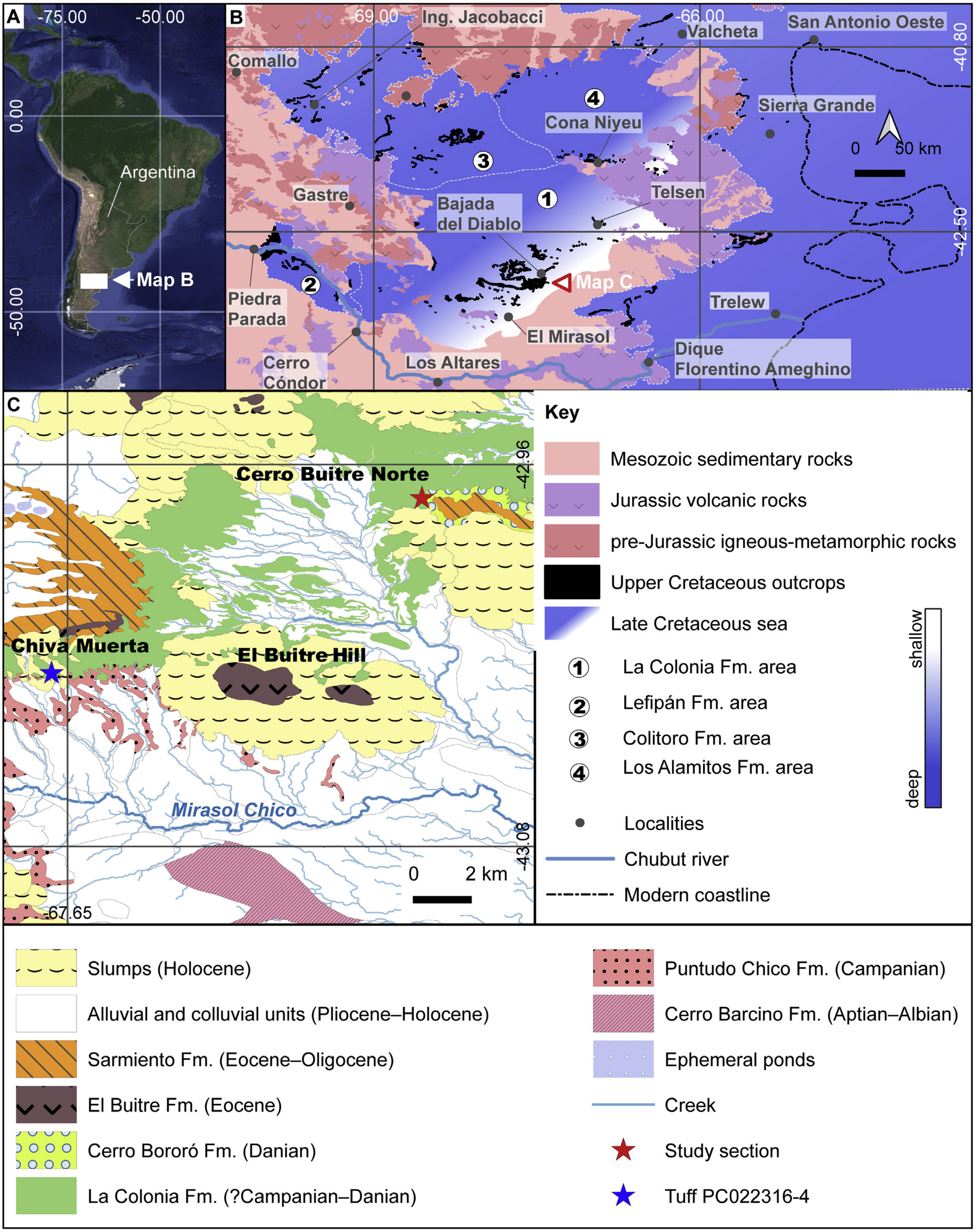
The La Colonia Formation has a rich paleontological history that includes the discovery of important vertebrate and plant fossils. Vertebrate fossils include non-avian dinosaurs (Bonaparte, 1985; Gasparini et al., 2015), birds (Lawver et al., 2011), plesiosaurs (Gasparini et al., 2001; O'Gorman and Gasparini, 2013; O'Gorman et al., 2013a, 2013b; Gasparini et al., 2015), turtles (Gasparini, 2000; Sterli and de la Fuente, 2012; Oriozabala et al., 2020), snakes (Albino, 2000; Gómez et al., 2019), fresh water fishes (Apesteguía et al., 2007), and mammals (Pascual et al., 2000; Kielan-Jaworowska et al., 2007; Rougier et al., 2009; Gasparini et al., 2015; Harper et al., 2019). Plant macrofossils and microfossils reported from the La Colonia Formation include aquatic ferns (Archangelsky et al., 1999; Cúneo et al., 2013a; Hermsen et al., 2014, 2019; De Benedetti et al., 2018), aquatic angiosperms (Gandolfo and Cúneo, 2005; Gallego et al., 2014) and a diversity of other plants (Cúneo et al., 2014; Gandolfo et al., 2014). Free floating microphytes and dinoflagellate cysts have also been reported (Cúneo et al., 2014; Guler et al., 2014; Borel et al., 2016). Taken together, these fossil assemblages indicate a diverse ecosystem and a warm, fresh water to brackish depositional environment.

1.3. Existing age constraints

Previous estimates of a Campanian−early Paleogene age of the La Colonia Formation have mostly relied on regional correlations and biochronological assessments, with little to no direct geochronological information (Pascual et al., 2000; O'Gorman et al., 2013a; Cúneo et al., 2014). The youngest unit directly underlying the La Colonia Formation throughout its known exposures is the Puntudo Chico Formation which is generally regarded as Middle Campanian to Lower Maastrichtian (Vera et al., 2019), although this age estimate is itself based largely on regional correlations and biochronology so not completely independent of previous La Colonia estimates. The oldest well-dated deposits that overlie the La Colonia Formation are basalts of El Buitre-El Canquel Formation which have been dated using the $^{40}Ar/^{39}Ar$ method to the lower Eocene (Alric and Massaferro, 2017). This constrains La Colonia to be between the Middle Campanian and Eocene, assuming the unit is relatively the same age across its entire lateral distribution. Despite the absence of biostratigraphic markers in the dinoflagellate and calcareous microfossil assemblages studied from the La Colonia Formation, a Maastrichtian−Danian age was suggested for the unit (Ardolino and Franchi, 1996; Page et al., 1999; Náñez and Malumián, 2008; Guler et al., 2014). This interpretation is consistent with age estimates for the Cerro Bororó Formation, which lies directly above the La Colonia Formation in the Cerro Buitre Norte section studied here and is considered Danian based on its micropaleontological assemblage and regional correlations to nearby, better-dated, units like the Lefipán and Salamanca formations (Andreis et al., 1973; Bertels, 1973; Scafati et al., 2009).

1.4. K−Pg boundary in South America

There are few known records of the K−Pg boundary in South America, so the biological and geological effects of the boundary events (e.g. Chicxulub impact and Deccan volcanism) are poorly understood on this continent (however see Stiles et al. (2020)). The Poty Quarry site in northeastern Brazil is reported to preserve a


A
-75.00
-50.00
0.00
-50.00
Argentina
Map B
B
-69.00
-66.00
-40.80
-42.50
Ing. Jacobacci
Valcheta
San Antonio Oeste
Comallo
Sierra Grande
Cona Niyeu
0
50 km
Gastre
Telsen
Bajada del Diablo
Map C
Trelew
Piedra Parada
El Mirasol
Dique Florentino Ameghino
Cerro Cóndor
Los Altares
C
Cerro Buitre Norte
-42.96
Chiva Muerta
El Buitre Hill
Mirasol Chico
-43.08
0
2 km
-67.65
Key
Mesozoic sedimentary rocks
Jurassic volcanic rocks
pre-Jurassic igneous-metamorphic rocks
Upper Cretaceous outcrops
Late Cretaceous sea
shallow
deep
1 La Colonia Fm. area
2 Lefipán Fm. area
3 Colitoro Fm. area
4 Los Alamitos Fm. area
Localities
Chubut river
Modern coastline
Slumps (Holocene)
Alluvial and colluvial units (Pliocene–Holocene)
Sarmiento Fm. (Eocene–Oligocene)
El Buitre Fm. (Eocene)
Cerro Bororó Fm. (Danian)
La Colonia Fm. (?Campanian–Danian)
Puntudo Chico Fm. (Campanian)
Cerro Barcino Fm. (Aptian–Albian)
Ephemeral ponds
Creek
Study section
Tuff PC022316-4

tsunami deposit, iridium anomaly, and dramatic turnover in ostracod assemblages marking the K–Pg boundary (Albertão and Martins, 1996; Rodrigues et al., 2014). Another tsunami deposit marking the K–Pg boundary has been identified in the Neuquén Basin in western Argentina and is one of the most distal sites reported to preserve a tsunami deposit (Scasso et al., 2005). No K–Pg boundary markers, such as iridium or shocked minerals, were present in this section, but microfossil assemblages found within the basin confirm the Cretaceous to Paleogene age of the sequence. Significant turnover in molluscan fossil assemblages was also observed and is consistent with a dramatic decline in mid-shelf primary productivity at the boundary (Aberhan et al., 2007). More recently, a South American record of the K–Pg boundary from Gorgonilla Island, Colombia (Bermúdez et al., 2016) was discovered. A glassy spherule layer at the Gorgonilla section yielded an $^{40}Ar/^{39}Ar$ age of 66.051 ± 0.031 Ma consistent with the Chicxulub impact event (Renne et al., 2018). Palynological, micropaleontological, and sedimentological data indicate that the site underwent dramatic paleoenvironmental changes at the K–Pg boundary, potentially related to impact-induced seismic activity (Renne et al., 2018). The K–Pg boundary sequence closest to the La Colonia site studied here is the Lefipán Formation, ~190 km to the west in Chubut Province (Patagonia, Argentina) (Barreda et al., 2012; Scasso et al., 2012). Although no K–Pg boundary layer is preserved within the Lefipán stratigraphic sequence, biostratigraphic data constrain the boundary to a ~4-m stratigraphic interval of the section. Palynological analysis of the Lefipán Formation showed a significant decrease in diversity and abundance of plants across the boundary, though few palynomorphs showed permanent extinction. This pattern is similar to other austral sites and suggestive of a southern hemisphere refugia from the impact (Vajda and Raine, 2003; McLoughlin et al., 2008).

1.5. Study area

The Cerro Buitre Norte (CBN) section (base at S42.97034, W67.54350, WGS84 datum; Fig. 1) is the primary stratigraphic section studied here. Some samples were also collected from the Chiva Muerta (CHM) area, located ~12 km southwest from the Cerro Buitre Norte section, and ~6 km west of El Buitre hill. The Cerro Buitre Norte section (also known colloquially as the "Plesiosaurio" section) represents one of the longest and most continuous exposures of the La Colonia Formation in the region, especially for the middle–upper parts of the unit. The lower 125 m of the Cerro Buitre Norte section was sampled for this study and spans the middle–upper La Colonia and lower Cerro Bororó formations. The contact between the La Colonia and Cerro Bororó formations occurs at the 108-m level in the section and is marked by a distinct red bed at the top of the La Colonia Formation suggesting slowed deposition or a hiatus of some duration at that time. The Cerro Buitre Norte section is located ~2 km to the southeast of the sections "Norte de Cerro Bayo 1" and "Norte Cerro Bayo 2" presented in Gasparini et al. (2015). The succession of sedimentary facies is very similar between the two areas, although the Gasparini et al. (2015) sections do not include the Cerro Bororó Formation.

2. Methods

2.1. Sedimentology, mapping, and paleogeographic reconstruction

The composite stratigraphic section at Cerro Buitre Norte was measured using a Jacob's staff and hand-held global positioning system (GPS). Field data were recorded in descriptive logs that included lithology, mean grain size, and sedimentary structures. Our descriptive logs were used to identify key horizons and correlate them to previously studied sedimentary successions of the La Colonia (Pascual et al., 2000; Cúneo et al., 2014; Gasparini et al., 2015). Additional observations on the basal part of the La Colonia Formation were made in the Chiva Muerta area (Figs. 1 and S1). A paleogeographic map of the region (Fig. 1B) was created using QGIS by compiling the outcrop area of Upper Cretaceous marine units based on regional geological maps (see the Supplementary Information for details regarding the construction of this map).

2.2. Zircon U–Pb geochronology

Multiple samples were collected from the La Colonia Formation and its underlying Puntudo Chico Formation for U–Pb zircon geochronology, the majority of which produced visibly detrital zircons unsuitable to constraining depositional ages. Euhedral zircons were separated from a sample of relatively uniform, buff-white, tuffaceous siltstone (sample PC022316-4) by standard techniques using magnetic separation and high-density liquids. The siltstone bed is ca. 10 cm thick and underlies the basal coarse sandstone of the La Colonia Formation at Chiva Muerta (Fig. S2). Twelve single zircons were selected based on grain morphology and analyzed by the U–Pb chemical abrasion isotope dilution thermal ionization mass spectrometry (CA–ID–TIMS) technique following the procedures described in Ramezani et al. (2011). All zircons were pre-treated by a chemical abrasion method modified after Mattinson (2005), which involved thermal annealing at 900 °C for 60 h, followed by partial dissolution in 29M HF at 210 °C for 12 h. After thorough fluxing in HCl/HNO_3 and rinsing with Millipore water to remove leachates, the grains were spiked with the EARTHTIME ET535 mixed ^{205}Pb–^{233}U–^{235}U tracer (Condon et al., 2015; McLean et al., 2015) prior to complete dissolution in HF (48 h). Purification of U and Pb was achieved by an HCl-based ion-exchange column chemistry using AG1-X8 anion resin and their isotopic analyses were made on an Isotopx X62 multi-collector thermal ionization mass spectrometer equipped with a Daly ion counting system at MIT. Data reduction including date calculation and propagation of uncertainties used computer applications and algorithms of Bowring et al. (2011) and McLean et al. (2011). Complete U–Pb data appear in the electronic supplementary material (Table S1).

2.3. Palynology

The palynomorphs studied herein were recovered from samples collected at two localities: Cerro Buitre Norte (CBN) and Chiva Muerta (CHM) (Fig. 1). Samples from CBN were collected simultaneously with those for paleomagnetic analyses (see below), although only 22 samples labeled LCP231-248 and LCP1801-1804 were examined for palynology. In CHM, 6 samples labeled CHM923–928 were collected from the lower 30 m of grey mudstones located above the basal sandstone of the La Colonia Formation (Fig. S2). The samples were mechanically disaggregated and treated with hydrofluoric acid (70%) and hydrochloric acid (30%). The residue was decanted and washed several times, and then filtered with 150 μm sieves to separate out megaspores and 10 μm sieves for pollen/spore analyses. For light microscopy (LM) observations, the residues were mounted on slides with glycerin jelly. For

Fig. 1. Maps showing the location of the study area and key localities referenced in the text. (A) Regional setting of the study area in Argentina. The white area encompasses map in B. (B) Paleogeographic reconstruction for the Upper Cretaceous sea in southern Río Negro and northern Chubut provinces (see text and supplementary materials for details). (C) Detailed geologic map of the Mirasol Chico Creek area where study sites are located.

quantitative analyses a minimum of 300 palynomorphs were counted per slide. LM observations were made with a Nikon Eclipse 80i microscope coupled with a Nikon DS-L4 camera (Nikon Corp., Minato, Tokyo, Japan) at the Museo Paleontológico Egidio Feruglio (MEF) Trelew, Chubut Province, Argentina. Coordinates of each photographed palynomorph correspond to this microscope. All images were edited using Adobe Photoshop CS6 (Adobe, San José, California, USA). The studied slides are housed at the palynological collection of the MEF, under the repository initials MPEF-PA (Table S2).

2.4. Isothermal remanent magnetization

Isothermal remanent magnetization (IRM) data were collected for six samples representing different lithologies from the La Colonia Formation (4 samples) and the overlying Cerro Bororó Formation (2 samples) to better understand the mineralogy governing the magnetic remanence in the Cerro Buitre Norte section. The IRM samples were first cut into cubes of ~1 cm^3. The x-axis of each cube was then subjected to a magnetic field of increasing strength within an ASC Scientific IM-10 impulse magnet at discreet steps from 0 T up to 1.1 Tesla (T) and measured in the 2G magnetometer after each step. After reaching the 1.1 T step, the samples were then subjected to a backfield applied in the opposite direction in steps of 100 and 300 mT. This was done to isolate the proportion of bulk remanence held by the soft ferrimagnetic (e.g., magnetite, maghemite) and hard antiferromagnetic (e.g., hematite, goethite) components. The backfield data were used to calculate the S-Ratio (Stober and Thompson, 1979; Bloemendal et al., 1992; Maxbauer et al., 2016) which is defined as half of the difference between the saturation isothermal remanent magnetization (SIRM) and the IRM at 300 mT (IRM_300mT) divided by the SIRM (Maxbauer et al., 2016). Samples were then subjected to the three-axis IRM method of (Lowrie, 1990) where a field of 1.1 T was applied to the x-axis, 0.4 T to the y-axis, and 0.12 T to the z-axis of the samples to separate the magnetization of mineral fractions of different coercivities along each axis. The samples were then subjected to thermal demagnetization at the following temperature steps (°C): 25, 50, 75, 100, 125, 150, 200, 250, 275, 300, 325, 350, 375, 400, 500, 540, 560, 580, 600, 620, 650, and 680. The magnetic intensities of the three orthogonal axes were measured at each step and compiled into three-axis IRM demagnetization curves.

2.5. Paleomagnetism

Paleomagnetic samples were collected from the Cerro Buitre Norte section during three field trips. In 2010, 76 samples from 19 sampling sites (labeled with LCP2 prefix) were collected through the first 100 m of section. Based on promising initial results from these samples, additional sampling was carried out in 2017 (80 samples, 19 sites; labeled with LP17 prefix) and 2018 (37 samples from 9 new sites, labeled with LP18 prefix, and 5 additional samples from 2 previous sites) that increased the sampling resolution and extended the sampling higher in the section. There are three overlapping sampling transects (referred to here as A, B, C; see inset map in Fig. 2) along different ridges that make up the Cerro Buitre Norte section. During the field trip in 2018, it became clear that the upper part of the A transect was part of a slump, so data from previously collected samples from that part of the section (sites LP1703–LP1708) were discarded in the subsequent analyses.

Sampling through the section targeted the relatively homogenous well-indurated gray mudstones that dominate this part of the La Colonia Formation. GPS locations and stratigraphic levels within the Cerro Buitre Norte section were recorded for all samples. Oriented hand samples were collected in the field and subsequently cut into approximately 8 cm^3 cubes preserving the oriented face as one of the faces of the cube. Samples were analyzed at the University of New Hampshire Paleomagnetism Lab using a 2G superconducting rock magnetometer, a Molspin tumbling alternating-field demagnetizer, and an ASC Model TD48 SC thermal demagnetizer.

At least three samples from each site were analyzed using stepwise (11–19 steps) thermal demagnetization up to 630 °C and/or alternating field (AF) demagnetization up to 100mT to characterize the characteristic remanent magnetization (ChRM) of each sample. Demagnetization steps were applied until the natural remanent magnetization (NRM) fell below the detection level of the magnetometer or the NRM no longer decreased in intensity.

All sample data were analyzed using the PuffinPlot paleomagnetic data program (Lurcock and Wilson, 2012). Samples with three or more sequential demagnetization steps exhibiting linear or quasi-linear decay to the origin were characterized using principle component analysis (PCA) (Kirschvink, 1980). Only those samples with a PCA line with maximum angular deviation of $\leq 20°$ were included. Some samples with overlapping unblocking spectra displayed a demagnetization path that was best characterized by a great circle. Alpha sites for this study are described using Fisher statistics and defined as sites that pass the Watson test for randomness with the requisite *R*-value (Watson, 1956) and included three or more samples whose ChRM was defined by principle components analysis. Beta sites are sites that have three or more reliable sample directions but include at least one sample characterized by great circle analysis (McFadden and McElhinney, 1988).

3. Results

3.1. General facies and zircon U–Pb geochronology

The base of the La Colonia Formation in the Mirasol Creek area is represented by a ravinement surface, over which shoreface deposits were deposited (Fig. S1), similar to the Telsen area (Navarro et al., 2008, 2012; Guler et al., 2014; Borel et al., 2016). The overlying facies are constituted by muddy and heterolithic deposits, arranged in a continuous, prograding tidal succession, as described in previous studies (Guler et al., 2014; Gasparini et al., 2015; Borel et al., 2016). The base of the red siltstone located in the upper Cerro Buitre Norte section, here considered as the top of the La Colonia Formation, is a surface probably related to a pause in sedimentation, before the deposition of the overlying Cerro Bororó Formation. Besides these basal and uppermost key surfaces, no evident discontinuities are present within the studied sections of the La Colonia Formation in this area.

The 12 analyzed zircon grains from the uppermost Puntudo Chico Formation range in $^{206}Pb/^{238}U$ dates (2σ internal uncertainties) from 468.4 ± 1.0 Ma to 71.71 ± 0.33 Ma (Table S1), indicating a mixed age population of predominantly detrital origin. Therefore, 71.71 ± 0.33 Ma serves only as a maximum age estimate for the base of the La Colonia Formation at Chiva Muerta (Table S1). This means that the La Colonia Formation must be Maastrichtian or younger in age, based on the latest calibration of the geologic time scale (Ogg and Hinnov, 2012; Cohen et al., 2013). Two dominant age groups are present among the analyzed detrital zircons; the Early Permian (Cisuralian) and Early Jurassic (Pliensbachian), which suggest detrital origin from the crystalline basement and the Las Leoneras/Lonco Trapial formations (Cúneo et al., 2013b), respectively.

3.2. Palynology

Of the 28 processed samples, 23 were fertile for palynomorphs, most of them bearing abundant, diverse, and well-preserved

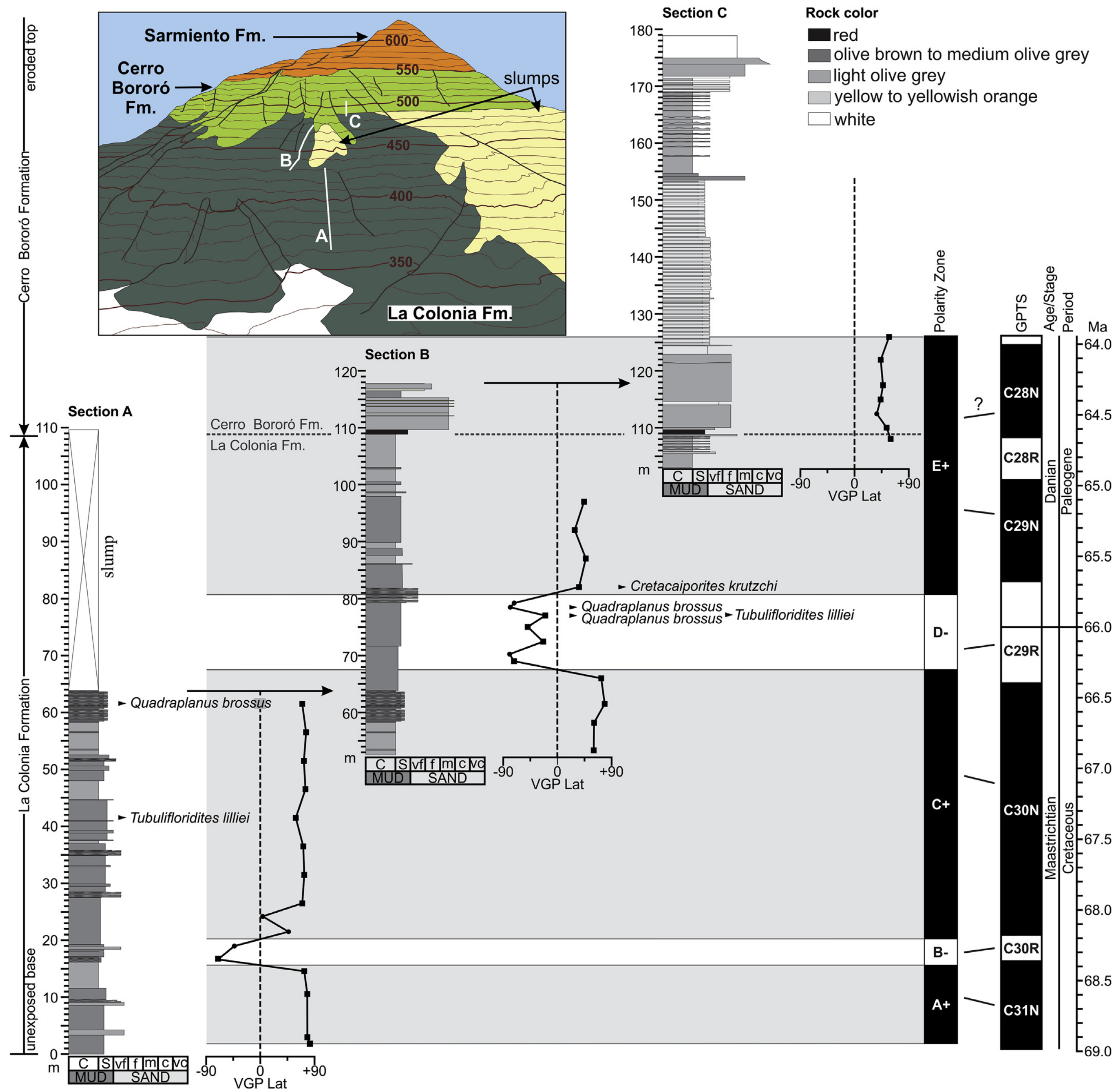
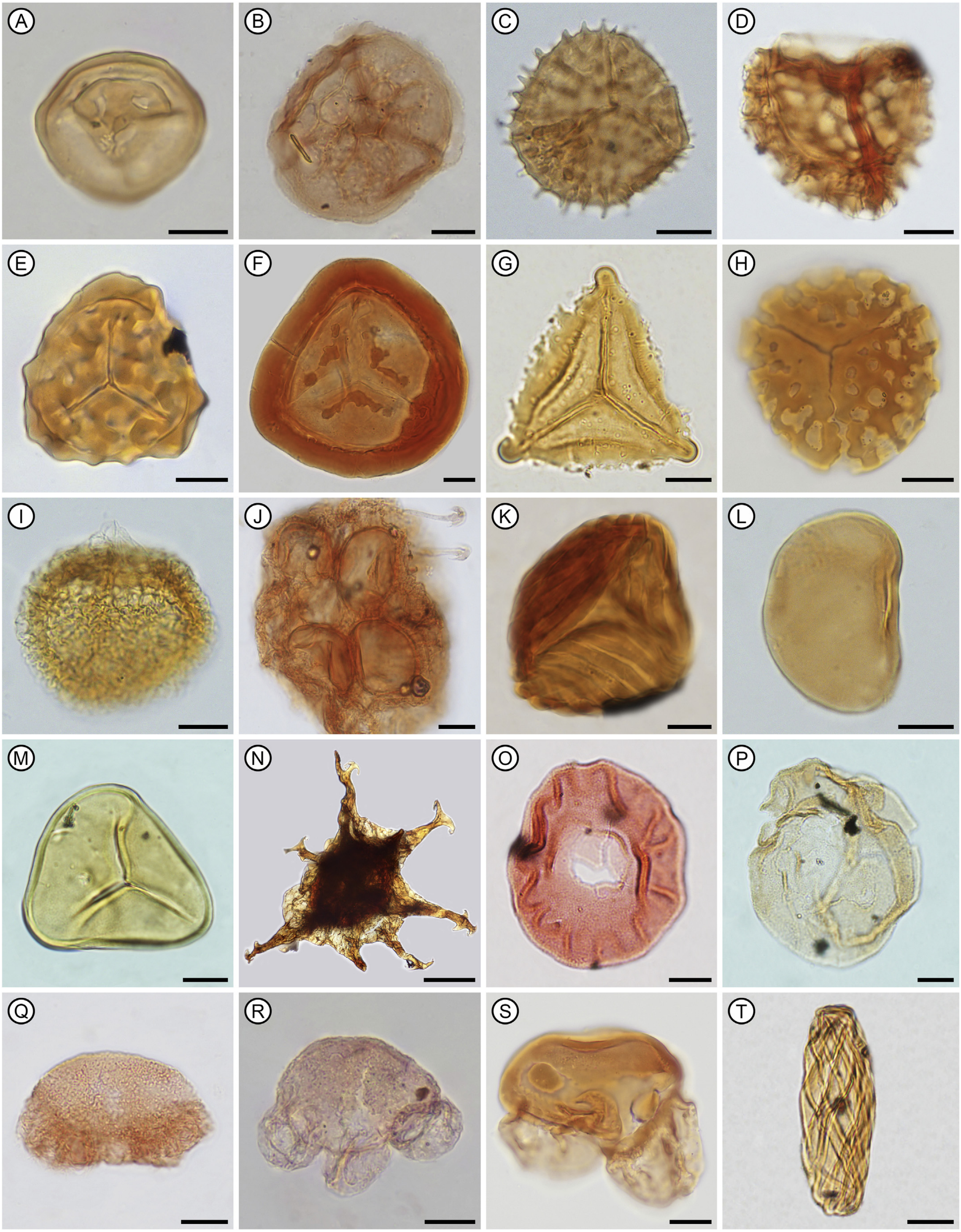


Fig. 2. Litho- and magnetostratigraphy of the La Colonia and Cerro Bororó formations at Cerro Buitre Norte section. Biostratigraphically significant pollen occurrences are shown next to each of the three overlapping segments of the stratigraphic section (A, B, C). Local polarity zones defined by intervals of normal polarity (positive virtual geomagnetic pole latitudes [VGP lat]) and reverse polarity (negative VGP lat). Inferred correlation of local magnetostratigraphic zones to the Geomagnetic Polarity Timescale (GPTS(Gradstein et al., 2012);) shown at right is supported by graphic correlation shown in Fig. 8; Inset, three-dimensional geological map of Cerro Buitre Norte showing the position of the three segments of the stratigraphic section (A, B, C).

palynofloras. A total of 189 pollen and spore taxa were recognized. Presence/absence data of the identified palynomorphs from the CBN and CHM localities are provided in Table S3. Relative abundance data for samples LCP240 to LCP247 from the CBN section are provided in Table S4 and plotted in Fig. S3.

Spores of bryophytes (Figs. 3A, 4B) and lycophytes (Fig. 3C, 3D) were recorded in most of the studied samples but always in low frequencies (1%–10%). Most of the La Colonia palynological assemblages are dominated by ferns (mean 37%, up to 68% in sample LCP243), which are represented by members of the families Dicksoniaceae (Fig. 3E, 3F), Gleicheniaceae (Fig. 3G), Lygodiaceae (Fig. 3H), Marsileaceae (Fig. 3I), Salviniaceae (Fig. 3J), Schizaeaceae (Fig. 3K), Polypodiaceae (Fig. 3L), among others (Fig. 3M, 3N). Pollen of *Classopollis* (Pflug) Pocock and Jansonius (Fig. 3O), produced by members of the extinct family Cheirolepidiaceae, is the most abundant type in samples LCP240 (~34%), LCP1801 (~29%) and LCP1802 (~28%), and it is a frequent taxon in all the studied palynological assemblages (mean 22%). Other gymnosperms represented by pollen of Araucariaceae (Fig. 3P), Podocarpaceae (Fig. 3Q–3S), and Ephedraceae (Fig. 3T) were also recorded. Green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algae, particularly *Botryococcus* Kützing (Fig. 4A), *Pseudopediastrum* Hegewald (Fig. 4B), and Zygnemataceae spores (Fig. 4C, 4D) are highly abundant in samples LCP240 (~25%), LCP241 (~72%) and LCP242 (~60%) but were also sparsely reported in all of the studied samples. Angiosperms are represented by members of the families Arecaceae (Fig. 4E–4H), Asteraceae (Fig. 4I), Ericaceae (Fig. 4J), Liliaceae (Fig. 4K), Gunneraceae (Fig. 4L), Proteaceae (Fig. 4M–4P), and Typhaceae (Fig. 4Q) among others (Fig. 4R, 4S). Angiosperms is the second major group in diversity, but they have low frequencies in all of the studied samples (mean 9%). Dinoflagellate cysts were scarcely recorded (mean 0.5%), whereas fungal remains (spores, hypha, and fruit bodies) occur commonly in most of the studied samples and they are particularly abundant in sample LCP243 (~8%).

The presence of *Botryococcus*, *Pseudopediastrum*, and Zygnemataceae and salvinialean spores in all of the studied samples indicates that freshwater conditions were frequent in the La Colonia Formation at the Mirasol Chico Creek area. On the other hand, the presence of pollen grains of the genus *Spinizonocolpites* Muller, that probably represents the marine coastal palm *Nypa* Wurmb, and the high abundance of *Classopollis* pollen, a genus commonly inhabiting nearshore marine lagoon environments indicates close proximity of a shoreline. The palynological assemblages reported here support previous paleoenvironmental interpretations for lagoon systems occurring along irregular coastal plains with the frequent development of freshwater conditions (Cúneo et al., 2014).

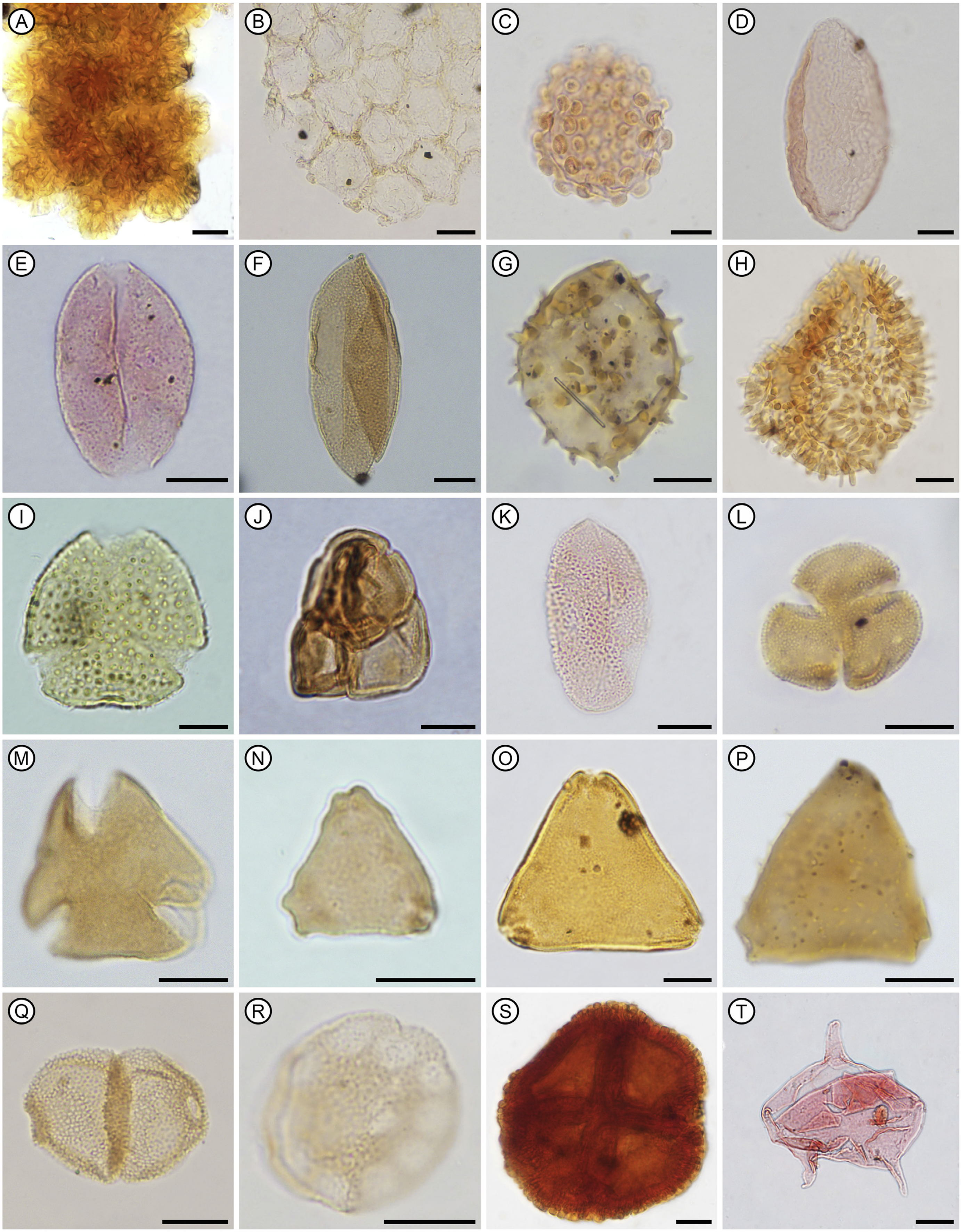
Biostratigraphically relevant palynomorphs identified in the samples studied here from the La Colonia Formation include *Quadraplanus brossus* Stover and Partridge (Fig. 4S) and *Tubulifloridites lilliei* Farabee and Canright (Fig. 4I). *Q. brossus* is restricted to the Late Maastrichtian while *T. lilliei* is only found in the Late Campanian–Late Maastrichtian, and both taxa were previously reported to become extinct at the K–Pg boundary in southern Australia, New Zealand, Antarctica, and Patagonia (Stover and Partridge, 1973, 1984; Sepúlveda et al., 1989; Askin, 1990a, 1990b; Papú, 1993; Vajda and Raine, 2003; Partridge, 2006; Vallati, 2010; Barreda et al., 2012, 2015; Raine and Schiøler, 2012; Povilauskas, 2017; Vallati et al., 2020). The palynological assemblage of the La Colonia Formation also includes some elements typically recorded in Brazil and Africa, like *Cretacaeiporites krutzschi*, *Gabonisporis vigourouxii*, *Spinizonocolpites* pollen-type, and other thermophilous taxa, which are all distinctive of the Late Cretaceous paleotropical Palmae Province (Table S3) (Boltenhagen, 1967; Herngreen, 1980; Herngreen and Chlonova, 1981; Herngreen et al., 1996; Vajda-Santivanez, 1999; Vajda and Bercovici, 2012; Ibrahim et al., 2017). Although dinoflagellates were scarcely recorded, we recognized the presence of "?*Morkallacysta* spp." (Fig. 4T), which was previously documented from the San Miguel section of the La Colonia Formation in the Telsen area, located approximately 100 km east of the CBN section (Guler et al., 2014). Guler et al. (2014) suggested a Danian age for the San Miguel section, and according to these authors, dinocysts of "?*Morkallacysta* spp." could be important paleoenvironmental markers for the Paleocene in northeastern Patagonia.

Several other taxa that have been used to correlate local sequences from the Late Cretaceous and Paleocene of Patagonia were also recorded from the La Colonia Formation. *Triporopollenites ambiguus* (Stover) Stover and Partridge (Fig. 4P) and *Spinizonocolpites hialinus* Archangelsky and Zamaloa (Fig. 4G), which have been recorded from the Late Cretaceous and Paleocene of Patagonia (Archangelsky and Zamaloa, 1986; Baldoni and Askin, 1993; Papú, 2002; Povilauskas et al., 2008; Scafati et al., 2009; Barreda et al., 2012; Povilauskas, 2013, 2017), and *Spinizonocolpites riochiquensis* Vallati and De Sosa Tomas (Fig. 4H), that was recently described from the Maastrichtian of southern Chubut Province (Vallati et al., 2020), were also recorded. *Longapertites patagonicus* Archangelsky (Fig. 4F), which was previously recorded from Maastrichtian to Danian deposits of Patagonia (Archangelsky, 1973; Baldoni and Askin, 1993; Povilauskas, 2017) is also present. Another relevant species that has been recorded in the CHM locality is *Grapnelispora loncochensis* Papú (Fig. 4N) is restricted to the Campanian-Maastrichtian of Argentina (Palamarczuk and Gamerro, 1988; Sepúlveda et al., 1989; Papú, 1993, 1997, 2002; Papú and Sepúlveda, 1995; Marenssi et al., 2004; Vallati, 2010; Puebla et al., 2015).

Palynological assemblages similar to the La Colonia Formation assemblage have been reported from the Maastrichtian of the Lago Colhué Huapi Formation (Vallati et al., 2020), the Maastrichtian-Danian of the Lefipán Formation (Barreda et al., 2012), and the Maastrichtian-Danian of the Monte Chico Formation (Povilauskas, 2017), which are located approximately ~100 km south, ~200 km west, and ~600 km southwest from the CBN section respectively. Among the most relevant taxa shared with the La Colonia palynological assemblages are *Quadraplanus brossus*, *Tubulifloridites lilliei*, *Triporopollenites ambiguus*, *Spinizonocolpites* spp., *Longapertites patagonicus*, *Arecipites minutiscabratus* McIntyre (Fig. 4E), *Liliacidites variegatus* Couper (Fig. 4K), *Peninsulapollis gillii* (Cookson) Dettmann and Jarzen (Fig. 4M), *Proteacidites* spp. (Fig. 4O), and *Tricolpites reticulatus* Cookson ex Couper (Fig. 4L). Given the known biochrons for all of these taxa and the similarities found with other contemporary formations, a Maastrichtian age (probably Late Maastrichtian) is suggested for the La Colonia Formation palynological assemblages.

Finally, the presence of *Tripunctisporis maastrichtiensis* (Krutzsch) Herngreen et al. (Fig. 3A) from the La Colonia Formation could also be biostratigraphically relevant. Notably, in Australian and New Zealand basins (e.g. Gippsland Basin and Taranaki Basin respectively) the boundary between the early Late Maastrichtian and the middle Late Maastrichtian (~67 Myr old) is defined by the first appearance datum (FAD) of *T. maastrichtiensis* (Partridge, 2006; Raine and Schiøler, 2012; Carpenter et al., 2015). In Patagonia, *T. maastrichtiensis* has been recorded from the Maastrichtian of the Loncoche Formation (Papú, 2002) and the Late Maastrichtian of the Lefipán Formation (Barreda et al., 2012). In the present study, *T. maastrichtiensis* was recorded in the entire CBN section but not from those samples collected from the first 30 m of mudstones of the La Colonia Formation at the CHM locality, where the zircon sample of the underlain Puntudo Chico Formation was dated as ~71.7 Ma. Although Australian zonations cannot be directly applied, this taxon could also be locally useful in Maastrichtian Patagonian

Fig. 3. Pollen and spores recovered from the La Colonia Formation. A. *Tripunctisporis maastrichtiensis* (Krutzsch) Herngreen et al., 1986Herngreen, MPEF-PA 803, 23.4/109. B. *Zlivisporis reticulatus* (Pocock) Pacltová and Simoncsics, 1970, MPEF-PA 822, 45.4/98.6. C. *Ceratosporites equalis* Cookson and Dettmann, 1958, MPEF-PA 874, 23.6/98.6. D. *Retitriletes austroclavatidites* (Cookson) Döring et al., 1963, MPEF-PA 752, 43.2/99.1. E. *Cibotiidites auriculatus* Archangelsky and Villar de Seoane, 1998, MPEF-PA 874, 26.5/103.5. F. *Cyatheacidites annulatus* , MPEF-PA 820, 28.2/104.3. G. *Clavifera triplex* (Bolkhovitina) Bolkhovitina, 1966, MPEF-PA 870, 37.8/101.2. H. *Klukisporites variegatus* Couper, 1958, MPEF-PA 835, 50.8/98.7. I. *Crybelosporites pannuceus* (Brenner) Srivastava, 1977, MPEF-PA 753, 28.1/109.8. J. *Azolla coloniensis* De Benedetti and Zamaloa emend. Hermsen et al. 2019, MPEF-PA 767, 18.6/92.7. K. *Cicatricosisporites* sp. 1, MPEF-PA 933, 43.2/113. L. *Laevigatosporites ovatus* Wilson and Webster, 1946, MPEF-PA 803, 31.8/106.2. M. *Cyathidites minor* Couper, 1953, MPEF-PA 922, 27.2/110.5. N. *Grapnelispora loncochensis* Papú 1997, MPEF-PA 206 (now in SEM stub). O. *Classopollis* sp. 1, MPEF-PA 857, 21.2/108.8. P. *Araucariacites australis* Cookson, 1947, MPEF-PA 925, 41/104.9. Q. *Lygistepollenites florinii* (Cookson and Pike) Stover and Evans 1973, MPEF-PA 804, 28.9/98.4. R. *Microcachryidites antarcticus* Cookson, 1947, MPEF-PA 819, 40.3/99. S. *Phyllocladidites mawsonii* Cookson, 1947, MPEF-PA 793, 26.6/100.3. T. *Ephedripites jansonii* (Pocock) Muller, 1968, MPEF-PA 871, 28.6/95.5. Scale bars = 10 μm, except in figure N where the scale bar is equal 40 μm.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palynofloras. Unfortunately, previous stratigraphic sampling of this taxon is limited, so its biostratigraphic significance remains hard to evaluate.

3.3. Isothermal remanent magnetization

IRM acquisition curves for all samples except LP1713B show steep increases in intensity up to ~200 mT and very high (>0.95) S-Ratios, consistent with these samples being dominated by low-coercivity minerals such as magnetite, titanomagnetite, and maghemite (Figs. S4 and S5; Tables S5 and S6). Sample LP1713B, which is from the red siltstone to very fine sandstone directly above the top of the La Colonia Formation, exhibits a shallower IRM acquisition curve and a S-ratio of 0.54 indicating it is characterized by a mix of low-coercivity minerals and high coercivity minerals (e.g. hematite, goethite). The three-axis IRM thermal demagnetization data indicate that IRM in four of the La Colonia samples is strongly concentrated in the soft (0.12 T) axis and is completely demagnetized by 580 °C indicating magnetite is the dominant mineral carrying remanence in most La Colonia samples. The IRM in sample LP1713B from the uppermost part of the La Colonia Formation is shared between the soft (0.12 T) and hard (1.1 T) axes and demagnetizes at 600 °C suggesting a mixture of low coercivity magnetite with higher coercivity phases like hematite, maghemite, or titanohematite which probably formed during post-depositional oxidation of the detrital mineral assemblage possibly during pedogenesis. The IRM of Sample LP1719A from the Cerro Bororó Formation (tan, very fine sandstone) is shared by the soft (0.12 T) and medium (0.4 T) axes and is almost completely demagnetized at 580 °C suggesting the sample is dominated by magnetite with minor amounts of an intermediate coercivity mineral like maghemite that may have been formed during oxidative diageneses or recent weathering. These results point to a relatively homogenous NRM behavior likely driven by detrital magnetite in most of the facies of the La Colonia Formation with more complex magnetic mineral assemblages carrying the NRM in the uppermost red bed from the La Colonia Formation and the overlying facies of the Cerro Bororó Formation.

3.4. Paleomagnetism

Most samples responded well to AF and/or thermal demagnetization (Figs. 5 and 6; Table S7). Of the 139 samples that were analyzed (not including the 19 samples analyzed from sites LP1703–1709 that were later discovered to be in a slump), 122 exhibited stable demagnetization that could be used to interpret polarity. The remaining samples exhibited chaotic demagnetization behaviors and could not be used for polarity determinations (Fig. 5F). The ChRM for 107 of the stable samples were characterized by PCA (average MAD of PCA lines = 5.2°) and the remaining 15 stable samples were characterized by great circle analysis.

Of the 41 total sites that were sampled in the Cerro Buitre Norte section (excluding sites LP1703–LP1709 that were part of the slump), 31 sites met the criteria for alpha sites and 7 sites met the criteria for beta sites (Fig. 6; Table 1). The remaining 3 sites did not meet the criteria for alpha or beta sites and were not considered further. The mean declination and inclination for the 26 normal polarity alpha sites is 337.1/-45.0 ($\alpha_{95} = 7.0$) and the mean for the 5 reversed polarity alpha sites is 134.2/37.7 ($\alpha_{95} = 26.5$). The alpha sites passed the parametric bootstrap reversal test of Tauxe et al. (2018) at the 95% confidence level as signified by the overlap of the α95s of the two populations of directions (Fig. 7).

3.5. Magnetostratigraphy

Plotting of the vgp latitudes for alpha and beta sites against stratigraphic level in the Cerro Buitre Norte section reveals a clear polarity pattern (Fig. 2). The lower ~15 m of the section are normal polarity (Zone A+), followed by ~5 m interval of reversed polarity (Zone B-), followed by a ~47 m interval of normal polarity (Zone C+), followed by a ~13 m interval of reversed polarity (Zone D-), and ending at the top of the section with a ~45 m interval of normal polarity (Zone E+).

4. Discussion

4.1. Chronostratigraphy

The new U–Pb radioisotopic, palynological, and magnetostratigraphic data presented here provide the most precise age constraints currently known for the La Colonia Formation. The U–Pb age of ~71.7 Ma for the youngest detrital zircon in a sample from the underlying Puntudo Chico Formation indicates that the La Colonia Formation must be Maastrichtian or younger. This agrees well with previous biostratigraphic estimates that support a Maastrichtian–Danian age for the La Colonia Formation (Ardolino and Franchi, 1996; Page et al., 1999; Náñez and Malumián, 2008; Guler et al., 2014). The palynoflora recovered at the Cerro Buitre Norte section supports this age. The key species *Quadraplanus brossus*, restricted to the Maastrichtian in other places of the southern hemisphere (e.g. Australia, New Zealand, Antarctica and other Patagonian localities), was found in several samples from this section. Based on these age constraints, there is only one viable correlation between the magnetostratigraphy reported here for the Cerro Buitre Norte section and the GPTS (Gradstein et al., 2012). The first half of the Maastrichtian is almost entirely characterized by reverse polarity (C31r), but the polarity of the La Colonia at Cerro Buitre Norte is almost entirely normal polarity (Zones A+, C+, E+) with two short intervals of reverse polarity (Zones B-, D-). The GPTS polarity pattern for the upper half of the Maastrichtian and lowermost Danian (Chrons C31n–C29n) matches the polarity pattern of the La Colonia Formation very closely (Fig. 2). Based on this match, we correlate Zone A+ to C31n, B- to C30r, C+ to C30n, D- to C29r, E+ to C29n (Fig. 8). Alternative magnetostratigraphic correlations to the GPTS would either place the La Colonia Formation in the Campanian or lower, which does not agree with the U–Pb or palynological data, or in the Danian or higher which does not agree with existing biostratigraphy. It is possible that the uppermost Zone E+ is a composite magnetozone and correlates to both C29N and C28N, with the short C28R being removed by an unrecognized

Fig. 4. Pollen and spores recovered from the La Colonia Formation. A. *Botryococcus* sp., MPEF-PA 752, 51/95. B. *Pseudopediastrum brevicorne* (A. Braun) Jena and Bock (in Jena et al., 2014), MPEF-PA 929, 35.4/108.7. C. *Catinipollis geiseltalensis* Krutzsch, 1966, MPEF-PA 819, 44.8/99.1. D. *Ovoidites ligneolus* (Potonié) Thomson and Pflug, 1953, MPEF-PA 820, 27.7/108.5. E. *Arecipites minutiscabratus* McIntyre, 1968, MPEF-PA 751, 32.4/97.1. F. *Longapertites patagonicus* Archangelsky 1973, MPEF-PA 872, 41.2/112.7. G. *Spinizonocolpites hialinus* Archangelsky and Zamaloa 1986, MPEF-PA 788, 39.4/106.7. H. *Spinizonocolpites riochiquensis* Vallati and De Sosa Tomas (in Vallati et al., 2020), MPEF-PA 938, 27.1/107.6. I. *Tubulifloridites lilliei* (Couper) Farabee and Canright, 1986, MPEF-PA 922, 38.4/100.2. J. *Ericipites* sp., MPEF-PA 923, 28.6/106. K. *Liliacidites variegatus* Couper 1953, MPEF-PA 808, 49.9/106.4. L. *Tricolpites reticulatus* Cookson ex Couper, 1953, MPEF-PA 927, 41.7/114.2. M. *Peninsulapollis gillii* (Cookson) Dettmann and Jarzen, 1988, MPEF-PA 872, 21.7/112.5. N. *Propylipollis lateflexus* (Archangelsky) Baldoni and Askin 1993, MPEF-PA 925, 41.6/101.9. O. *Proteacidites* sp. 2, MPEF-PA 870, 36/103.6. P. *Triporopollenites ambiguus* (Stover) Stover and Partridge 1973, MPEF-PA 750, 30/99.8. Q. Dyad of *Sparganiaceaepollenites* sp., MPEF-PA 929, 45.2/102.8. R. *Cretacaeiporites krutzschi* (Boltenhagen) Ibrahim et al., 2017, MPEF-PA 931, 33.1/106.7. S. *Quadraplanus brossus* Stover (in Stover and Partridge 1973), MPEF-PA 827, 33.7/94.8. T. *Morkallacysta* sp.?, MPEF-PA 821, 54.1/98.8. Scale bars = 10 μm, except in figure T where the scale bar is equal 20 μm.

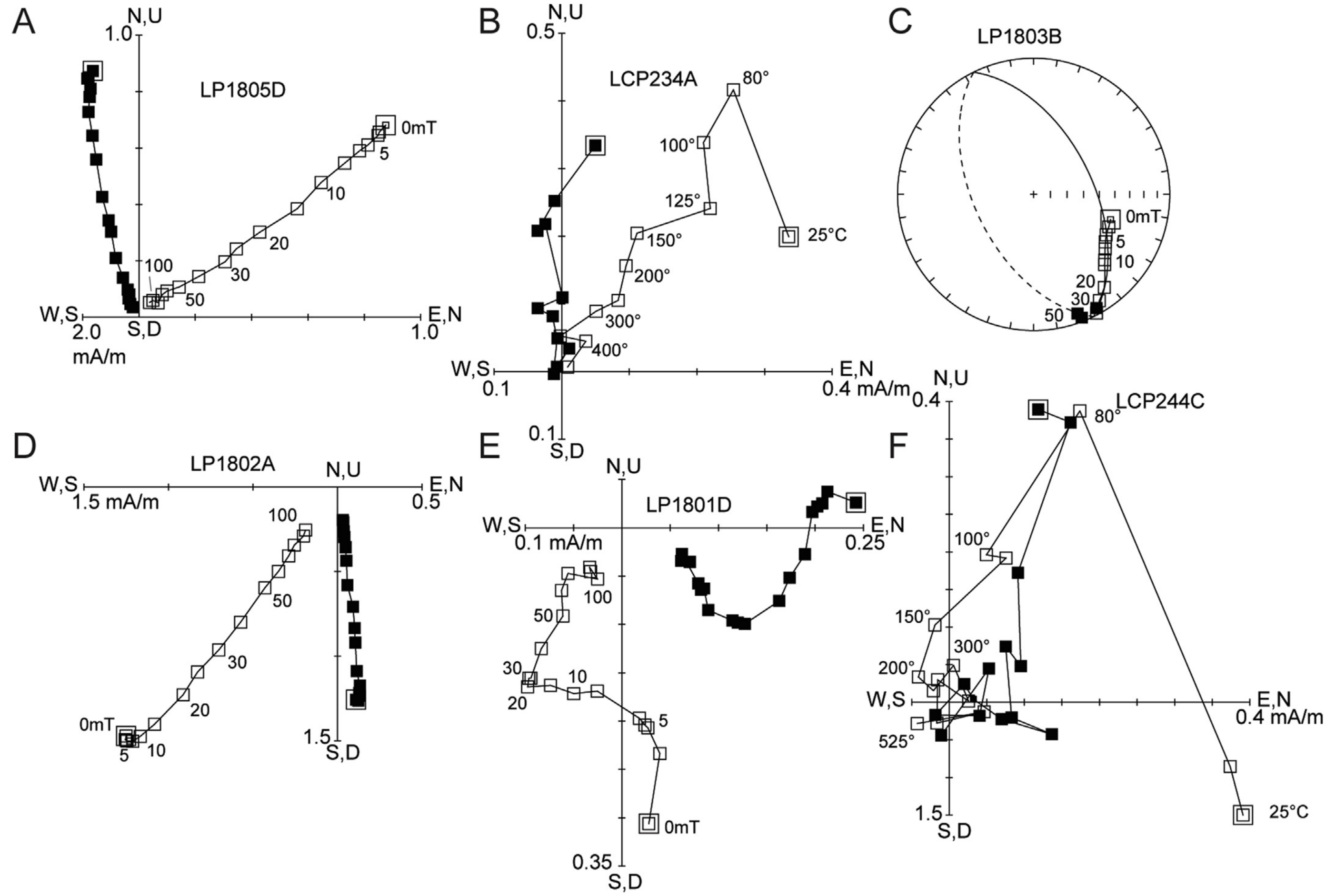

Fig. 5. Representative vector endpoint diagrams for selected paleomagnetic samples. Vector endpoints are labeled with alternating field intensity in milliTesla (mT) or temperature in degrees Celsius (°C). Scales on all axes are mA/m. **A,** LP1805D shows AF demagnetization of a normal polarity sample exhibiting a direction best characterized by PCA. **B,** LCP234A shows thermal demagnetization of a normal polarity sample exhibiting a direction best characterized by PCA. **C,** LP1803B shows AF demagnetization of a reversed polarity sample exhibiting a direction best characterized by a great circle. **D–E,** LP1802A and CB1801D show AF demagnetization of reverse polarity samples exhibiting a direction best characterized by PCA. **F,** LCP244C is a sample exhibiting chaotic demagnetization behavior and was not able to be characterized using PCA or great circle analysis.

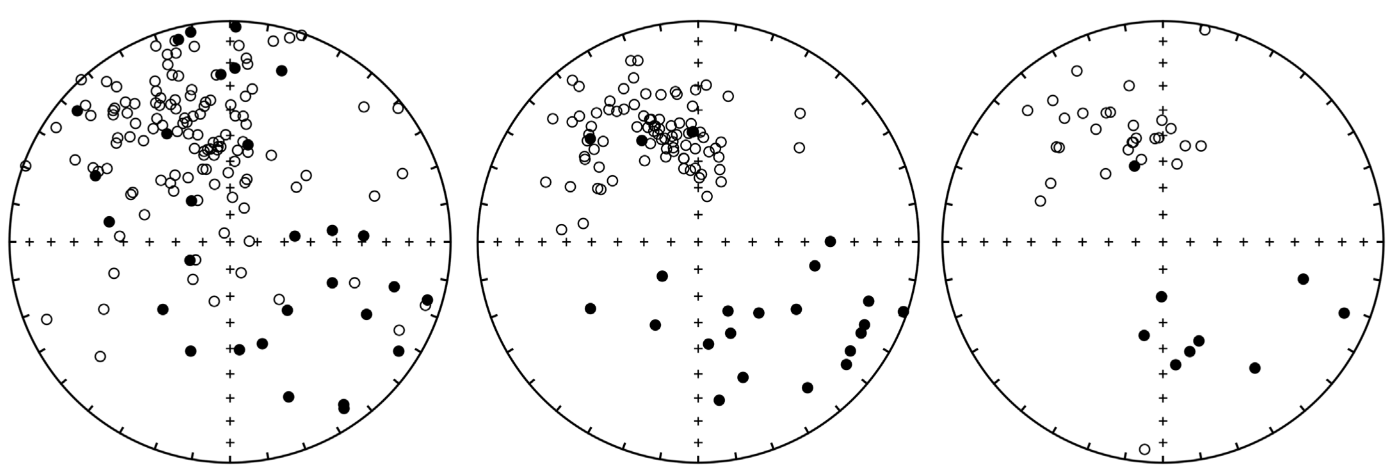

Fig. 6. Equal area projections for paleomagnetic samples and alpha site directions. **A**, Equal area projections of all NRM paleomagnetic sample directions. **B**, ChRM directions for paleomagnetic samples with stable demagnetization behavior. **C**, Alpha site mean ChRM directions. Open (closed).symbols are on the upper (lower) hemisphere. Directions are shown in geographic coordinates because strata are essentially flat-lying.

unconformity near the boundary of the La Colonia and Cerro Bororó formations (Fig. 2).

The preferred chronostratigraphic correlation outlined above implies that the uppermost La Colonia Formation is Danian and that Chron C29r, which includes the K–Pg boundary, lies between ~67.5 and 80-m level of the Cerro Buitre Norte section. This would make it one of very few stratigraphic sections in South America preserving C29r and the K–Pg boundary. Although there is no clear outcrop

Table 1
Site calculations for sites that passed the Watson test Watson, 1956. Sites are listed in superposition by section. **Site Lat/Long**– GPS latitude and longitude of site relative to WGS 84 Datum; **Strat Level (m)** – stratigraphic level in meters from base of composite section; **α/β**– site reliability level (alpha/beta site - see text); **PCA/GC**–indicates number of PCAs (principle component analyses) and/or great circles (respectively) used to characterize a site; **Dec/Inc**– declination and inclination of site mean vector; **α95**– 95% confidence interval of site mean; **k**– precision parameter; **n**– number of samples used in site statistics; **R**– length of the resultant vector; **VGP Long/Lat**–site virtual geomagnetic pole latitude and longitude.

Site	Section	Site Lat (°)	Site Long (°)	Strat Level (m)	α/β	PCA/GC	Dec.	Inc.	a95	k	n	R	VGP Long (°)	VGP Lat (°)
LP1809	A	−42.97034	−67.54350	1.8	α	3/0	10.2	−60.6	9.6	165.4	3	2.99	15.5	82.3
LP1810	A	−42.97037	−67.54337	3.0	α	3/0	345.4	−58.3	9.0	189.6	3	2.99	217.4	78.3
LCP233	A	−42.97039	−67.54300	10.6	α	3/0	355.6	−51.2	27.9	20.6	3	2.90	273.6	78.4
LCP234	A	−42.97039	−67.54261	14.6	α	3/0	359.5	−44.1	20.4	37.4	3	2.95	290.9	72.9
LP1701	A	−42.97039	−67.54251	16.8	α	3/0	160.0	50.5	21.0	35.4	3	2.94	52.4	−70.3
LP1808	A	−42.97042	−67.54241	19.0	β	0/3	185.0	−6.3	na	21.7	3	2.98	119.4	−43.6
LCP235	A	−42.97044	−67.54239	21.5	β	4/3	11.2	−2.4	44.3	2.8	7	5.38	309	47
LP1702	A	−42.97063	−67.54233	24.2	β	0/3	339.4	59.9	100.1	56.8	3	2.99	277	4.2
LCP236	A	−42.97047	−67.54233	26.5	α	3/0	21.7	−51.3	42.4	9.5	3	2.79	356.9	69.7
LCP237	A	−42.97050	−67.54200	31.5	α	3/0	345.6	−49.8	19.4	41.3	3	2.95	244.9	73.1
LCP238	A	−42.97056	−67.54172	36.5	α	3/0	339.4	−53.2	10.2	147.0	3	2.99	225.4	71.5
LCP239	A	−42.97058	−67.54144	41.5	α	3/0	320.0	−56.8	38.6	11.3	3	2.82	199.2	59.2
LCP240	A	−42.97044	−67.54136	46.5	α	3/0	4.1	−47.3	25.0	25.4	3	2.92	306.6	75.1
LCP241	A	−42.97056	−67.54103	51.5	α	3/0	342.9	−51.0	11.9	107.7	3	2.98	236.6	72.4
LP1805	B	−42.96958	−67.53956	53.4	α	3/0	347.8	−28.4	22.0	32.4	3	2.94	268.2	60.3
LCP242	A	−42.97053	−67.54078	56.5	α	3/0	13.1	−53.1	50.3	7.1	3	2.72	344.5	76.2
LP1807	B	−42.96973	−67.53951	58.2	α	3/0	337.9	−36.7	10.6	136.8	3	2.99	246.1	60.8
LCP243	A	−42.97067	−67.54036	61.5	α	3/0	345.8	−44.7	10.1	151.0	3	2.99	253.1	69.7
LP1709	B	−42.96992	−67.53999	61.5	α	5/0	357.7	−51.0	8.5	82.4	5	4.95	282.5	78.6
LP1710	B	−42.97009	−67.53941	66.0	α	3/0	343.4	−51.1	13.4	86.0	3	2.98	237.4	72.8
LCP244	B	−42.97017	−67.53936	69.0	α	3/0	166.2	47.6	50.5	7.0	3	2.72	70.1	−71.9
LP1801	B	−42.97018	−67.53928	70.2	β	2/1	181.5	69.8	44.3	11.7	3	2.87	287.7	−79.3
LP1711	B	−42.97020	−67.53924	72.5	α	3/0	104.8	34.5	30.9	17.0	3	2.88	17.9	−23.5
LP1802	B	−42.97022	−67.53919	75.0	α	3/0	143.9	29.9	45.1	8.5	3	2.77	52.5	−49.2
LCP245	B	−42.97028	−67.53917	77.0	α	3/0	111.4	12.7	15.8	62.2	3	2.97	32.6	−20
LP1803	B	−42.97028	−67.53908	78.5	β	0/3	191.4	54.4	na	14.5	3	2.97	164	−78.1
LP1712	B	−42.97029	−67.53908	79.2	β	2/1	174.1	43.4	135.9	2.4	3	2.36	95.3	−71.7
LCP246	B	−42.97033	−67.53903	82.0	α	3/0	297.6	−42.1	22.0	32.5	3	2.94	201.5	36.1
LCP247	B	−42.97039	−67.53889	87.0	α	3/0	321.5	−29.1	20.6	36.9	3	2.95	230.4	47.3
LCP248	B	−42.97056	−67.53850	92.0	α	3/0	288.4	−41.1	16.5	56.9	3	2.96	196.2	29
LCP249	B	−42.97061	−67.53831	97.0	α	3/0	312.3	−36.6	12.2	103.2	3	2.98	216.7	44.3
LP1713	C	−42.97161	−67.53710	108.0	α	4/0	336.3	−36.3	17.2	29.4	4	3.90	243.9	59.8
LP1714	C	−42.97170	−67.53698	110.0	α	3/0	328.1	−31.9	20.1	38.7	3	2.95	236.1	52.7
LP1715	C	−42.97187	−67.53675	112.4	β	3/1	314.1	−15.6	46.6	5.3	4	3.52	229.9	36.8
LP1716	C	−42.97185	−67.53667	115.0	α	3/0	311.7	−35.5	7.6	263.3	3	2.99	216.9	43.4
LP1717	C	−42.97183	−67.53664	117.4	α	3/0	333.3	−14.3	17.9	48.5	3	2.96	251.4	47.3
LP1718	C	−42.97177	−67.53655	122.0	α	3/0	322.1	−19.8	24.3	26.7	3	2.93	235.9	43.6
LP1719	C	−42.97175	−67.53649	126.0	α	3/0	329.3	−40.3	31.3	16.6	3	2.88	230.8	57.7

scale lithological evidence for a K–Pg boundary layer being preserved in this particular section, additional microstratigraphic sampling within the C29r interval could provide additional details and test the proposed correlation.

The presence of the Maastrichtian restricted *Quadraplanus brossus* in palynological samples spanning paleomagnetic zones A+ to D-from the Cerro Buitre Norte section provides biostratigraphic evidence supporting our preferred magnetostratigraphic correlation to the GPTS. Unfortunately, palynological assemblages with typical elements of a Danian age were not recorded in the studied samples of the magnetozone E+ (samples LCP246 and LCP247), which is correlated to Chron C29n. However, the Cretaceous taxa *Q. brossus* and *T. lilliei* were not recorded in the magnetozone E+. The last appearance of *Q. brossus* in the CBN section occur in the sample LCP1803 whereas the last occurrence of *T. lilliei* was in the sample LCP1802. Therefore, the absence of these Cretaceous taxa could be indicative for the presence of the Danian, although further analyses on samples near the boundary with the overlying Cerro Bororó Formation are needed to test this hypothesis.

This favored magnetostratigraphic correlation, however, also suggests that the taxon *Cretacaeiporites krutzschi* (Boltenhagen) Ibrahim et al. is recorded in the magnetozone correlated to Chron C29n. Previous reports of this taxon are restricted to the Upper Albian–Santonian of central west Africa, Brazil, and the southwestern Atlantic Ocean (Boltenhagen, 1975; Ioannides and Colin, 1977; Lawal and Moullade, 1986; Salard-Cheboldaeff, 1990; Ibrahim et al., 2017). This is the first record of *C. krutzschi* in Argentina and constitutes the most austral and youngest record for this species. This could be another example of a typically Mesozoic plant lineage surviving across the K–Pg boundary and might be further evidence for southern regions as biodiversity refugia during the end-Cretaceous global crisis (Vajda and Raine, 2003; McLoughlin et al., 2008; Barreda et al., 2012). However, because only a few specimens of this taxon were recovered, it is also possible that they could be reworked.

The fern-spore spike is a recognized palynological event associated with the K-Pg boundary worldwide and is recorded at a single stratigraphic interval that can be as thin as 1 cm (Vajda et al., 2001; Vajda and Raine, 2003; Nichols and Johnson, 2008; Vajda and Bercovici, 2014). In Patagonia, the K-Pg transition has been reported from the littoral sediments of the Lefipán Formation (Barreda et al., 2012). In the Lefipán Formation, a fern-spore spike has not been recorded, but a similar "*Classopollis* spike" found at the beginning of the Danian has been documented (Barreda et al., 2012). In the La Colonia Formation palynological assemblages there is no evidence of a fern-spore spike or "*Classopollis* spike." Quantitative results show that there are no significant variations in the palynological content of each lithological unit spanning the

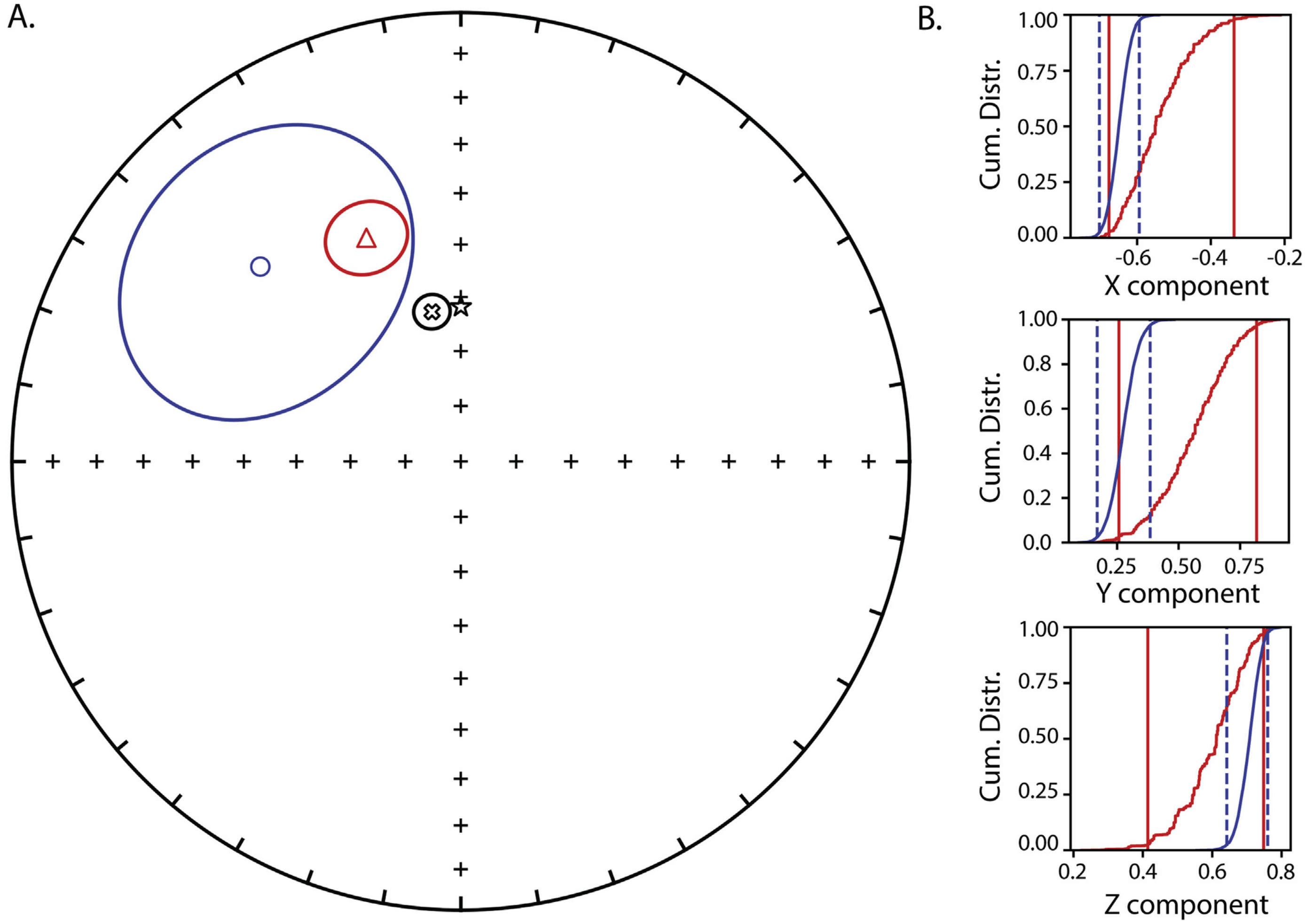

Fig. 7. A, Mean ChRM directions of alpha normal polarity sites (red) and alpha reversed sites flipped to antipodal direction (blue) with overlapping α_{95} confidence ellipses. The cross represents the expected 65 Ma direction (with α_{95} confidence ellipse) for this site from Besse and Courtillot (2002) and the star represents the present day direction. B, Results of the parametric bootstrap reversal test of Tauxe et al. (2018) showing the overlap of X, Y, and Z components in Cartesian coordinates. Solid red and dashed blue lines correspond to the α_{95} confidence interval for normal and reversed sites, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

magnetozone D- (samples LCP244 to LCP1804) and *Classopollis* pollen was relatively abundant in all of the studied samples (Table S4; Fig. S3). However, the sampling interval of ~1.5 m in the paleomagnetic zone D-may have been insufficiently close to detect a fern spore or *Classopollis* abundance anomaly. It is also possible that the interval was eroded or represents a hiatus in the CBN section. Similar results were found from the Monte Chico Formation in southern Patagonia, where a disturbance in the vegetation across the K-Pg transition has not been recorded (Povilauskas, 2017). Future micro-sampling through the D-magnetozone in the La Colonia Formation will help further investigate this question.

These chronostratigraphic results are some of the first direct age constraints on La Colonia Formation; however they are from a geographically limited area and thus do not necessarily represent the entire formation, which outcrops over a large area extending along an ~100 km NE—SW transect. For instance, it is possible that the La Colonia Formation is somewhat time-transgressive, especially given its highly variable thickness (25 to >200 m) and its association with a regional marine transgression (Navarro et al., 2012). Additional chronostratigraphic data from other sites with exposures of the La Colonia Formation will be needed to test this in detail.

4.2. Paleogeography

The La Colonia Formation correlates in time — at least partially — to several adjacent marine units including the Lefipán Formation, from the mid Chubut river area (Riccardi, 1988; Ardolino and Franchi, 1996; del Río and Martínez, 2015), Los Alamitos and Coloro formations from southern Río Negro Province (Riccardi, 1988; Getino, 1995; Ardolino and Franchi, 1996; Page et al., 1999; del Río and Martínez, 2015; Harper et al., 2019), and to the Jagüel Formation from Neuquén Basin (Riccardi, 1988; Ardolino and Franchi, 1996; Musso et al., 2012; del Río and Martínez, 2015) (Fig. 1). Both the Lefipán and Jagüel formations are reported to include the K—Pg boundary (Musso et al., 2012; Scasso et al., 2012). Our paleogeographic reconstruction coarsely matches previous paleogeographic reconstructions (Uliana and Biddle, 1988; Malumián, 1999; Page et al., 1999; Franzese et al., 2003; Náñez and Malumián, 2008; Malumián and Náñez, 2011; Scasso et al., 2012; del Río and Martínez, 2015; Guler et al., 2019), but it presents one noticeable difference. Since no outcrops of Upper Cretaceous or Danian marine units are recognized southward of Cerro Cóndor and Los Altares (Fig. 1), we show no direct connection between the Lefipán and La Colonia depocenters to the north and the other more southern depocenters like the Golfo San Jorge Basin. Instead, we

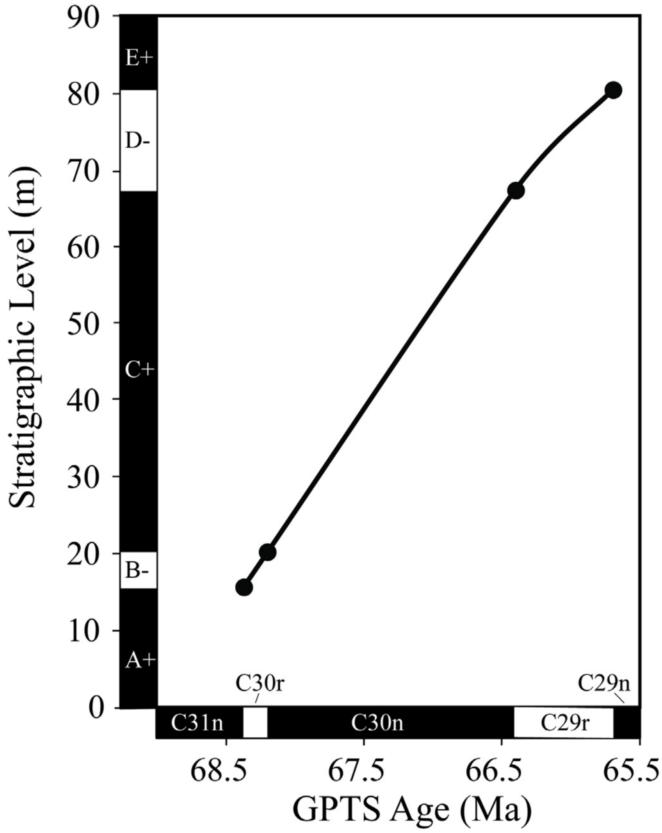

Fig. 8. Graphic correlation showing the excellent match between the stratigraphic record of local magnetic polarity zones and the C31n to C29n interval of the Geomagnetic Polarity Timescale (GPTS; (Gradstein et al., 2012).

interpret the presence of a regional embayment enclosing the depocenters of the Lefipán, Colitoro, La Colonia, and Los Alamitos formations (Fig. 1). The likely reason for this difference with other paleogeographic interpretations, is that our map focuses on Upper Cretaceous marine units and not on Danian ones, and thus some of the areas we interpret to be 'emerged lands' correspond to 'islands' in Scasso et al. (2012).

Our paleogreographic configuration indicates the presence of a Late Cretaceous SW–NE shoreline located along the El Mirasol–Bajada del Diablo–Telsen transect (Fig. 1) with the depocenters of the La Colonia and Lefipán formations adjacent to each other to the west (compatible with the 'Paso del Sapo Embayment' of Scasso et al., 2012). The strong similarity in facies arrangement observed in the La Colonia Formation at both Mirasol Chico Creek (our study area) and Telsen is consistent with a single coastline (Navarro et al., 2008, 2012; Guler et al., 2014; Borel et al., 2016). The Telsen area contains a much condensed section of the La Colonia Formation (only 10% the thickness of sections in the Mirasol Chico Creekarea). However, this can be explained by its proximity to 'emerged lands' represented by volcanic Jurassic rocks, which act as the basement supporting overlying Cretaceous and Cenozoic successions within the Chubut river region. Proximity to the 'emerged' Jurassic rocks in the Telsen area indicates the presence of a topographically higher basement, and thus shallower waters, in this area relative to outcrops to the west. The stratigraphic correlation between the Cerro Buitre Norte and the sections near Telsen is significant because the occurrence of dinoflagellate cyst assemblages and green algae in the latter, support a Maastrichtian – Paleogene age for the La Colonia Formation there as well (Guler et al., 2014; Borel et al., 2016). Our results also suggest that the Cerro Buitre Norte section studied here is correlative with the nearby 'Norte de Cerro Bayo 1 and 2' sections that preserve important vertebrate fossils (Gasparini et al., 2015). The youngest unquestionable Cretaceous vertebrate from the Norte de Cerro Bayo 2 section (an elasmosaurid from ~62 m level in that section) comes from a wavy heterolithic interval that likely correlates to a similar heterolithic interval recognized between 59 and 64 m in our Cerro Buitre Norte section, and thus would correlate to just below our polarity interval D- (Chron C29r).

5. Conclusions

New U–Pb geochronologic, biostratigraphic, and magnetostratigraphic data indicate that the La Colonia Formation, a richly fossiliferous tidally influenced marine-brackish succession in Chubut province of Argentina (Patagonia), is Maastrichtian – lower Danian in age and preserves Chron C29r which is the ~700,000 year-long interval of reversed polarity containing the K–Pg boundary. No outcrop scale K–Pg boundary layer is observed, and a major turnover in vegetation across the K-Pg transition was not recorded, suggesting that the mass extinction event may be less impactful in the southern hemisphere compared to similar sequences in the northern hemisphere. These new age constraints should provide a better chronostratigraphic framework for interpreting the evolutionary and biogeographic significance of the diverse vertebrate and plant fossil assemblages from the La Colonia Formation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cretres.2021.104889.