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Late Cretaceous paleogeography of the Antarctic Peninsula: New paleomagnetic pole from the James Ross Basin

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ABSTRACT

Two paleomagnetic poles of 80 and 75 Ma have been computed from 191 to 123 paleomagnetic samples, respectively, of the marine sedimentary units of the Upper Cretaceous Marambio Group exposed in the James Ross Island, Antarctic Peninsula. Paleomagnetic behaviors during stepwise thermal demagnetization and rock magnetic analyses indicate that magnetization is likely primary and carried by SD-PSD detrital titanomagnetite. Application of an inclination shallowing correction by the elongation-inclination method yielded a significant inclination shallowing affecting the older (ca. 80 Ma) succession exposed in the northwest area of the island. However, the paleomagnetic directions computed from the younger (ca. 75 Ma) succession outcropping in the southeast corner of the island yielded an indeterminate result using the same analysis. The inclination shallowing-corrected 80 Ma paleopole position plus previous ones of ca.110, 90 and 55 Ma were used to construct the Apparent Polar Wander Path (APWP) for the Antarctic Peninsula during the Late Cretaceous-Paleocene. This path confirms that oroclinal bending of the Antarctic Peninsula as well as relative displacement with respect to East Antarctica are negligible since 110 Ma. Comparison with the apparent polar wander path for South America for the 130-45 Ma period suggests that this continent and the Antarctic Peninsula kept a very similar relative paleogeographic position since 110 Ma until 55 Ma, which likely meant a physical link between both continental masses. During that period, both continents underwent a relatively fast southward displacement of around 7° and a clockwise rotation relative to the Earth spin axis that can be bracketed between around 100 and 90 Ma. Oroclinal bending of the Fuegian Andes was likely due to tectonic interactions between the Patagonian-Fuegian Andes and the Antarctic Peninsula promoted, at least partially, by such displacements. By 55 Ma the Antarctic Peninsula probably was starting or about to start its final separation from South America.

1. Introduction

Some authors propose Antarctica as the nucleus of Gondwana dispersion, that started in the middle Jurassic (~167 Ma, Gao et al., 2018 and references therein) and, based in their geological similarities, there is consensus that the Antarctic Peninsula (AP) and Patagonia remained either attached or close to each other at least until the Late Cretaceous (Dalziel et al., 1973; Hathway, 2000; Hervé et al., 2006 and references therein). Different paleogeographic models have been proposed for the paleoposition of AP: while some authors establish a position to the west of Patagonia (Fig. 1A, Dalziel et al., 2013; Ghidella et al., 2002; Harrison et al., 1979; König and Jokat, 2006), others place it in linear continuity with southern South America (Fig. 1B, Poblete et al., 2011; Storey et al., 1996 and references therein). The former has been supported by detailed sea-floor magnetic anomalies interpretation in the Weddell Sea (Ghidella et al., 2002) which also suggests possible relative convergence between West and East Antarctica prior to 100 Ma. In any case, by Late Cretaceous time there is agreement that a position of AP to the west of Patagonia is no longer tenable (Dalziel et al., 2013; Ghidella et al., 2002; Poblete et al., 2011). Some paleomagnetic results support the lack of significant relative displacement between the AP and East Antarctica since ~100 Ma (Bakhmutov and Shpyra, 2011; Grunow,

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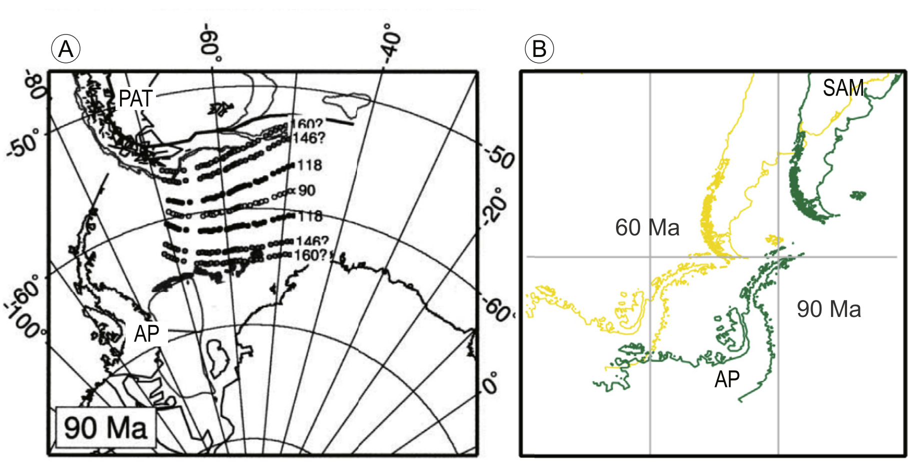

Fig. 1. Paleogeographic reconstructions of the Weddell Sea for the Late Cretaceous. A: Ghidella et al. (2002) propose a west position respect to Patagonia (PAT) for the Antarctic Peninsula (AP), based on the interpretation of marine magnetic anomalies. B: Reconstruction of the Antarctic Peninsula and South America (SAM) from paleomagnetic data. The relative positions in longitude of both SAM and the AP are arbitrary. Taken from (Poblete et al., 2011).

1993; Poblete et al., 2011). Unfortunately, much older paleomagnetic data is very scarce, in part due to a pervasive Late Cretaceous remagnetization affecting the Jurassic volcanic and older rocks of the AP (Poblete et al., 2011). This limits the interpretation of the pre-middle Cretaceous paleogeography for both the AP and Patagonia, where evidence of this remagnetization was also found (Poblete et al., 2016; Rapalini, 2007). The limited paleomagnetic data from Grunow (1993) suggest, however, a clockwise rotation and a later counter-clockwise rotation of the AP relative to East Antarctica between 175 and 130 Ma. Despite these limitations, previous paleomagnetic analyses strongly suggest that a clockwise rotation of the Antarctic Peninsula since Mid-Late Cretaceous is unlikely (Grunow, 1993; Milanese et al., 2017; Poblete et al., 2011; Watts et al., 1984). This is intrinsically related to the debate on whether the clockwise curvature of the northern Antarctic Peninsula is a secondary feature, and therefore an orocline, or it is a primary character (Dalziel and Elliot, 1973; Valencio et al., 1979). Most reconstructions of the relative paleogeographic evolution of AP and Patagonia are based on magnetic anomaly isochrons and fracture zones (Eagles, 2016; Eagles et al., 2005; Eagles and Jokat, 2014; Livermore et al., 2007, 2005; Lodolo et al., 2006) and the origin of the opposite curvatures of the northern AP and the southern tip of Patagonia is still under debate. A primary origin for the Patagonian curvature has been proposed by several authors (Diraison et al., 2000; Eagles, 2016; Ghiglione and Cristallini, 2007) while others preferred a secondary origin either related to the closure of the Late Jurassic "Rocas Verdes" back-arc basin (Kraemer, 2003) or to a complex system of strike-slip deformation (Cunningham et al., 1991). Recent paleomagnetic studies in Tierra del Fuego (Poblete et al., 2016; Rapalini et al., 2015 and references therein) strongly support an oroclinal bending of the southern Patagonian-Fuegian Andes that mainly occurred in Late Cretaceous times. However, an opposite conclusion has been obtained for the case of the AP curvature from paleomagnetic studies carried out in Western Antarctica (see Grunow, 1993, Poblete et al., 2011 and Gao et al., 2018 for a brief account). Reliable mean paleomagnetic poles for AP of ca. 110, 90 and 55 Ma have been recently obtained (Poblete et al., 2011; Gao et al., 2018). Comparison with coeval reference poles for South America (Somoza and Zaffarana, 2008) indicates that both continents apparently experienced moderate but significant geodynamic displacements between about 90 and 55 Ma that involved a southward movement of South America and a clockwise rotation of the AP (and the whole Antarctica?), prior to final separation and opening of the Drake Passage at some time between late Eocene and early Miocene times (Barker, 2001; Eagles et al., 2006; Lawver and Gahagan, 2003). According to Gao et al. (2018), this event was associated with a clockwise rotation of AP after 55 Ma. The lack of reliable poles for AP between about 90 and 55 Ma makes it difficult to constrain and understand its postulated Late Cretaceous clockwise rotation and its relationship with the southward displacement of South America and final stages of Patagonian orocline formation.

In order to fill the gap of paleomagnetic data between 90 and 55 Ma and to contribute to the reconstruction of the paleogeography of the AP, in this work we will attempt to obtain latest Cretaceous (ca. 80 to 75 Ma) reliable paleomagnetic poles for the AP, coming from a continuous succession of fine-grained clastic rocks that make up the infill of the James Ross Basin (uppermost part of the Gustav Group and the Marambio Group). Even sedimentary rocks are sometimes considered less reliable for paleomagnetic pole calculations, due to possible inclination errors and a more problematic determination of remanence age, the available paleomagnetic database for the AP is based solely on magmatic rocks that in several cases may have not averaged PSV and/or show dubious paleohorizontal determinations. These sources of uncertainties will be absent in our study. As a result, a more robust Late Cretaceous apparent polar wander path for the AP can be constructed and its paleogeographic and tectonic implications explored.

2. Geological setting and methodology

The James Ross Basin (JRB) is located in the northeastern tip of the Antarctic Peninsula (Fig. 2) and comprises more than 6 km of marine clastic and volcaniclastic strata, ranging from Early Cretaceous (Barremian) to Paleogene (Eocene) (Del Valle et al., 1983; Francis et al., 2006; Olivero, 2012). The best exposures are located on James Ross, Snow Hill, Seymour (Marambio), and Vega Islands as well as on other smaller islands of the James Ross archipelago. The Cretaceous infill of the JRB is subdivided into two major groups: the Aptian-Coniacian Gustav Group and the Santonian-Danian Marambio Group. The coarse-grained, deep marine Gustav Group represents deposition in a normal fault-regulated submarine slope apron system located along the Prince Gustav Channel, which separates James Ross Island from the Antarctic Peninsula mainland (Fig. 2). It represents an under-filled back-arc basin generated to the East of the magmatic arc of the Antarctic Peninsula (Ineson, 1989; Ineson et al., 1986; Riding et al., 1998; Riding and Crame, 2002; Scasso et al., 1991; Whitham et al., 2006). Outcrops of the Gustav Group are restricted to the northwest margin of James Ross Island. The fine-grained Marambio Group is more than 3 km thick, encompassing marine sediments formed during the shelf expansion in an inversion stage of the basin, when the already fully developed shelf extended for more than 150 km into the Weddell Sea (Olivero, 2012). Our study was carried out on the higher levels of the Gustav Group and the lower to middle levels of the Marambio Group exposed on James Ross Island. Paleomagnetic sampling was carried out with the main purpose of constructing local magnetostratigraphic columns for the Upper Cretaceous infill of the James Ross Basin (Milanese, 2018). Partial magnetostratigraphic results have already been published

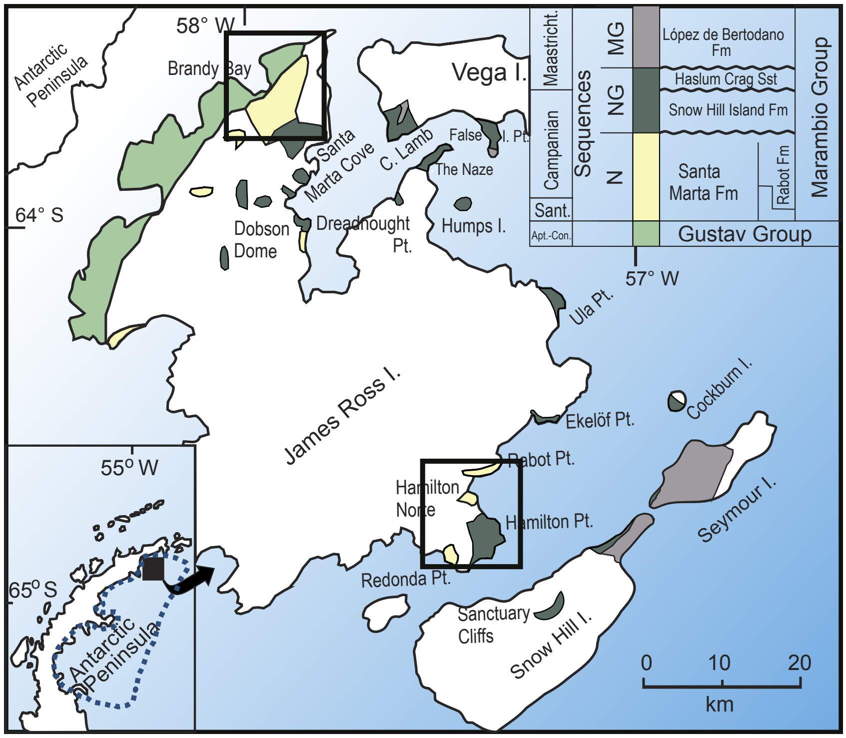

Fig. 2. Geological sketch of Cretaceous outcrops of the James Ross Basin.). Inset down left, in dotted line, inferred boundaries of the Larsen basin. The study areas are shown in the black boxes. Adapted from Pirrie et al. (1997) and Olivero (2012).

(Milanese et al., 2017; Tobin et al., 2012) or are being worked on. The abundant paleomagnetic directions obtained in these studies, the very accurate correlation found with the Global Magnetic Polarity Scale (e.g. Ogg et al., 2016) and the recording of paleomagnetic directions encompassing several million years give the possibility of computing two paleomagnetic poles of slightly different ages for the Antarctic Peninsula. Magnetostratigraphic sampling was carried out in two areas located on the NW and SE of the James Ross Island, respectively. Sampling near Brandy Bay and Santa Marta Cove (Fig. 3) targeted the Hidden Lake (Gustav Group) and Santa Marta formations. Younger rocks are exposed on the southeast of James Ross Island at Rabot Point, Hamilton Norte, Redonda Point and Hamilton Point areas and include the Rabot Formation (partially equivalent to the Beta Member of the Santa Marta Formation, see Olivero, 2012) and the basal unit of the Snow Hill Island Formation: the Hamilton Point Member (Fig. 4). The magnetostratigraphic sampling covered a total of ~2500 m of sedimentary thickness, sometimes with stratigraphic overlap between sections. The sampled sections are indicated in Figs. 3 and 4. The basal Santa Marta Formation is exposed in the northwest of the JRB (Olivero, 1988, 1984; Olivero et al., 1986; Scasso et al., 1991) and its partially equivalent Rabot Formation outcrops to the southeast (Lirio et al., 1989; Marenssi et al., 1992; Martinioni, 1992). The Snow Hill Island Formation (Pirrie et al., 1997) overlies both the Santa Marta and Rabot formations in both studied areas, but it is represented by different lithologies in the NW and SE sectors. Overlying the Santa Marta Formation, the dinosaur bone – bearing sandstones of the Gamma Member are found, while the Rabot Formation is overlain by the transgressive off-shore unconsolidated mudstones of the Hamilton Point Member (Pirrie et al., 1997). The relative age of the sampled sections is well determined by ammonite associations (Olivero, 2012 and references therein) and finely calibrated by magnetostratigraphy (Milanese, 2018; Milanese et al., 2017), as well as chemostratigraphic and micropaleontologic data (Crame et al., 2004; McArthur et al., 2000; Pirrie et al., 1997). Combining these different sources of information highlights that the strata sampled in the northwest area were deposited between ~85 and 78 Ma, while those in the southeast region can be bracketed between ~80 and 74 Ma. Outcrops are exposed in both the northwest and southeast areas of the island as largely homoclinal successions dipping gently towards the southeast. Strata dips were measured accurately at each sampling point and values do not exceed 10-15° along the entire composite section.

Sampling was carried out using a portable gasoline-powered drill. We collected a total of 424 standard paleomagnetic cores oriented with sun and magnetic compasses, each of them corresponding to a discrete stratigraphic level, precisely determined using Jacob's staff. Stratigraphic separation between adjacent samples varied from few centimeters to a maximum of 10 m (Milanese, 2018). Sampling was carried out at a rate of one sample per level, along eleven cross-sections that could be correlated with sufficient certainty in both areas. Although lithologies of the Gustav and Marambio groups are mostly unconsolidated, hard fine-grained sandstone beds and isolated spherical concretions allowed a successful sampling. There were two reasons for not collecting more than one sample per level. First, there are not continuous sandstone or limestone beds along all sections (especially in Hamilton Point locality) of the James Ross Basin. Actually, small concretions are more common than continuous beds and they were the main font of sampling. Taking more than one sample in the scarce continuous beds and not in the rest of the concretion-sampled levels, it would have introduced a serious statistical bias. Second, this sampling rate allowed us to span more than ~2000 m of sedimentary thickness, as a part of the original goal of the sampling: to achieve the complete magnetostratigraphy of the basin (Milanese, 2018; Milanese et al., 2017) and not to obtain paleogeographic results.

Measurements were carried out in 5.5 cm^3 paleomagnetic specimens at the Paleomagnetics and Biomagnetics Laboratory of the California Institute of Technology, using an automatic 3-axis DC-SQUID moment magnetometer system, housed in a magnetically shielded room. Demagnetization routine started with two low-temperature cycling steps (samples were cooled to 77 K in a field free environment), followed by three low-intensity alternating field (AF) steps (from 2.3 to 6.9 mT) to remove secondary magnetizations acquired during collection and transportation of samples. Based on experience from previous

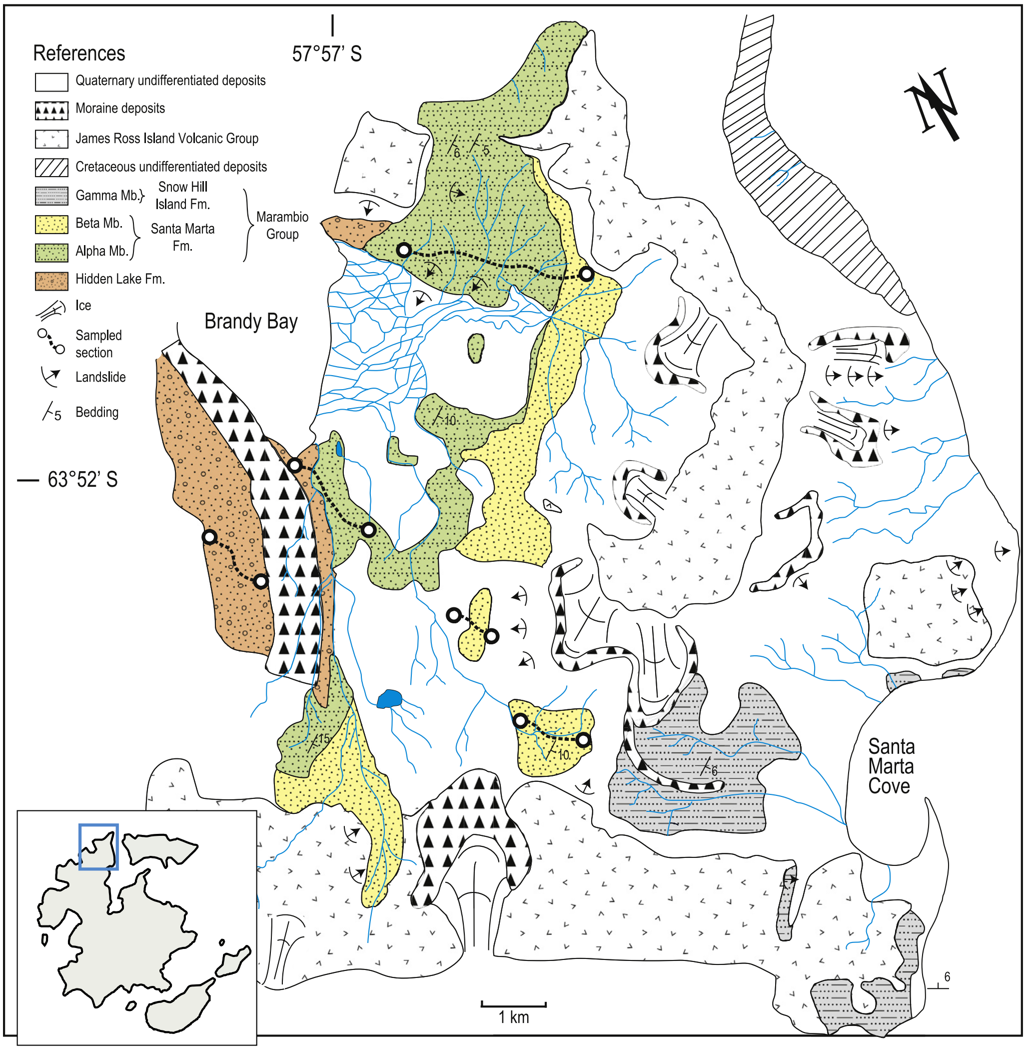

Fig. 3. Geological scheme of Brandy Bay and Santa Marta Cove area, NW James Ross Island. Partial sampling sections are indicated in dashed lines. Modified from Olivero (1992).

studies in the Marambio Group, the main demagnetization process was thermal from 80 °C to 575 °C in 15–10 °C steps, with samples being demagnetized in a trickle of N_2 gas above 120 °C to minimize oxidation.

Demagnetization results were interpreted using principal component analysis (Kirschvink, 1980) and Fisherian statistics (Fisher, 1953) were applied to average paleomagnetic directions.

3. Results

The primary nature of the isolated Characteristic Remanent Magnetization (ChRM) directions of these samples have been demonstrated in previous magnetostratigraphic works (Milanese, 2018; Milanese et al., 2017) based on several rock magnetic analyses (such as thermomagnetic curves, hysteresis cycles, IRM/Backfield curves, Lowrie Fuller tests and Day Plots) on samples from all units mentioned above, as well as from the consistent magnetostratigraphic columns obtained in both areas. Fig. 5 shows two examples of IRM/Backfield curves (A) and a Day diagram (B) modified by Dunlop (2002), which, among other rock magnetism analyses previously carried out in samples from the Marambio Group, strongly suggest pseudo-single domain (PSD) Ti-poor magnetite as the main ChRM carrier.

Only those ChRMs obtained by Principal Component Analysis (PCA, Kirschvink, 1980) with a MAD under 10° were accepted for computing the paleomagnetic poles. Additionaly, components obtained using great circle analysis (McFadden and McElhinny, 1988), that were used in the magnetostratigraphic analyses (Milanese, 2018; Milanese et al., 2017) were discarded from these calculations. Directional analysis was performed using PaleoMag (Jones, 2002) and Paleomagnetism.org (Koymans et al., 2016) softwares. In many cases, a small viscous remanence was removed within the first demagnetization steps (below 150 °C). Thermal demagnetization did not proceed further than 500–550 °C in most cases, due to a random directional behavior above those temperatures produced, most likely, by chemical changes in clay minerals upon heating (Pan et al., 2000). Examples of typical paleomagnetic behaviors are given in Fig. 6.

3.1. Northwest area of James Ross Island

Samples collected at this locality span more than 1000 m of sedimentary thickness and probably more than 6 Ma. Although 180 reliable directions (see supplementary material) were found, those include great circle analysis so only 139 ChRM directions from the succession in northwest James Ross Island were used (Fig. 7). Dispersion is higher than usual probably due to the high paleolatitude as well as to the fact that each direction corresponds to an individual sample. To get rid of paleomagnetic directions corresponding to excursions or acquired during reversals of the Earth Magnetic Field, the Vandamme (1994) filter was applied to the data in order to remove outliers (20 out of 139

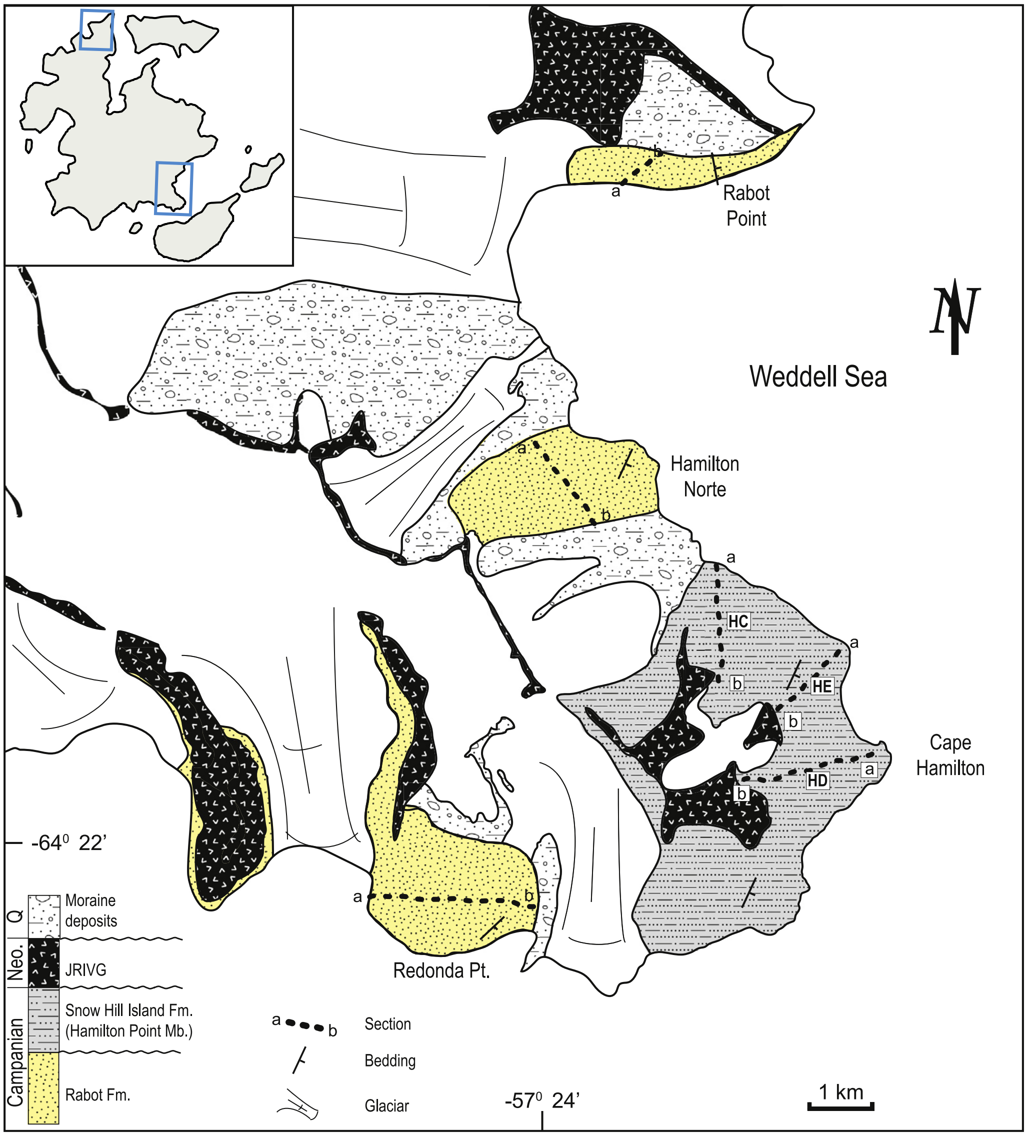

Fig. 4. Geological scheme of Rabot Point, Hamilton Norte, Redonda Point and Hamilton Point area, SE James Ross Island. Sampling sections are indicated in dashed line. *HC*, *HE* and *HD* are Hamilton Point Member partial sections in upward stratigraphical order. JRIVG and Neo. are abbreviations for James Ross Island Volcanic Group and Neogene, respectively.

original directions). Thus, the mean bedding corrected direction obtained for the northwest area of James Ross Island is: Dec.: 2.7°, Inc.: −65.5°, α_{95}: 3.8°, n: 119 samples. Note that applying bedding corrections does not change significantly the grouping of directions due to the homoclinal disposition and shallow dips of the sampled rocks. However, inclination shallowing (see below) and several rock parameters that suggest detrital titanomagnetite as the main carrier of magnetization point towards a primary and therefore pre-tectonic magnetization. Additionally, as presented in Fig. 7, ChRM record both polarities. Performance of a reversal test (McFadden and McElhinny, 1990) a positive result (Classification C), but no tilt or fold test could be performed.

Several authors have suggested that paleomagnetic poles computed from sedimentary rocks may be biased systematically due to inclination shallowing produced by compaction of the sediments during burial (Kodama, 2012). In order to determine if these sections were affected by such process, we performed the elongation-inclination test (E/I, Tauxe and Kent, 2004) to the observed paleomagnetic directions using the Paleomagnetism.org portal (Koymans et al., 2016; Tauxe et al., 2008). This test indicates that the sections exposed in the northwest area of the James Ross Island are affected by significant inclination shallowing (f = 0.54) and its correction yields a mean corrected inclination of −76.1°. The value of inclination shallowing found is within that expected for titano-magnetite carrying rocks (see Huang et al., 2013; Kodama, 2009 and references therein). Every ChRM was corrected for the calculated factor and a virtual geomagnetic pole computed from each. Considering the inclination shallowing corrected ChRM directions, the paleomagnetic pole falls at Lat: −88.7°, Long: 302.2°, A_{95}: 5.0°, n: 119 samples. According to the age of the sampled unit (Milanese, 2018), this paleopole is considered to be of ca. 80 Ma. In situ and bedding corrected mean directions, paleopole position and reversal test results are given in Table 1. Individual sample directions in situ, after bedding correction and after correction for inclination shallowing and the corresponding VGPs are presented as Supplementary material.

3.2. Southeast area of James Ross Island

Sampling at this locality comprised six different partial cross sections that were stratigraphically correlated. They span from the middle section of the Rabot Formation (Milanese et al., 2017) up to the lower

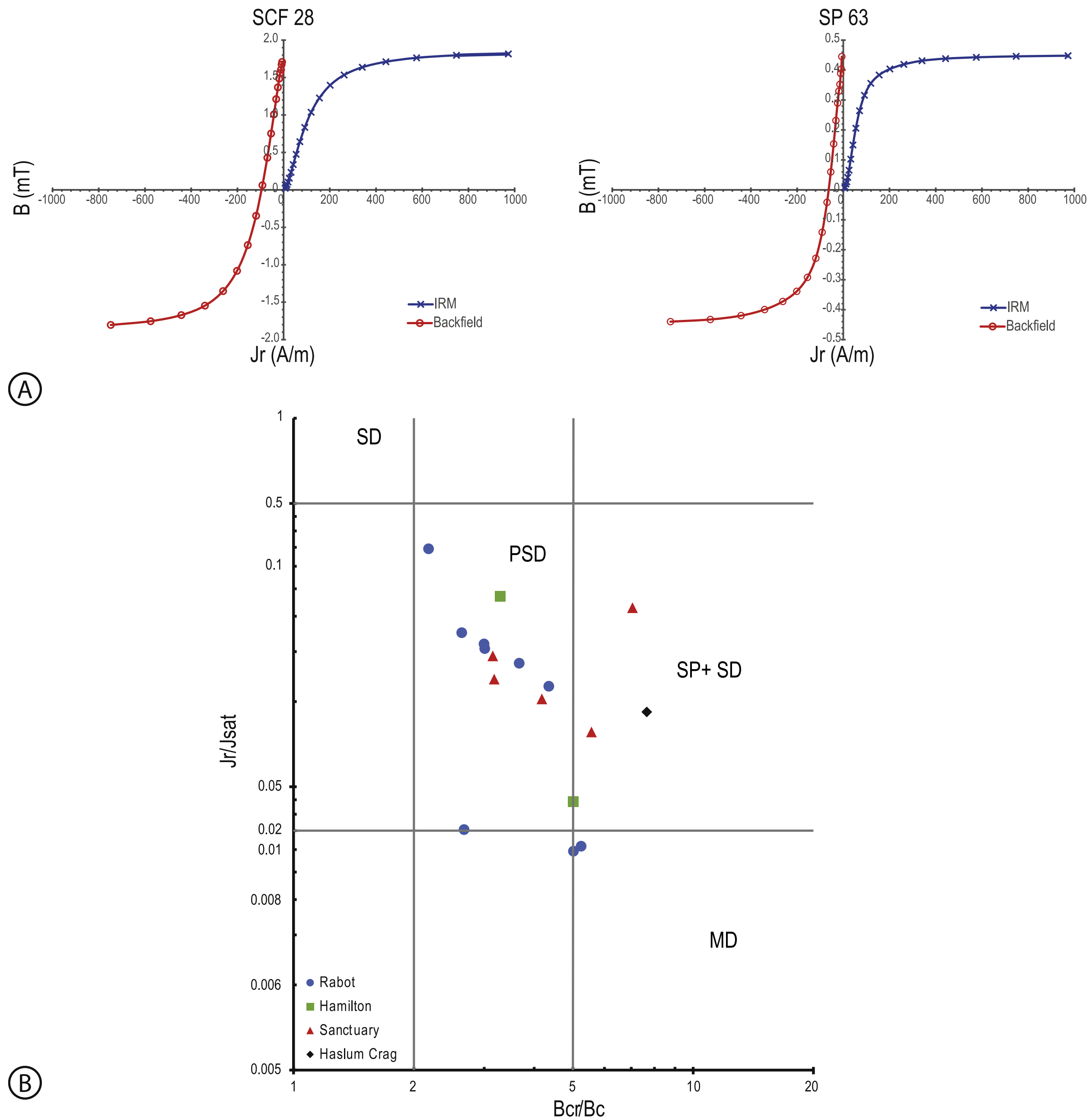

Fig. 5. IRM/Backfield curves and Day diagram. IRM/Backfield curves and (A) and Day diagram modified by Dunlop (Dunlop, 2002) from Marambio Group samples (B). Both analyses suggest that the ChRM carrier is the pseudo-single-domain (PSD) Ti-poor magnetite. Jr/Jsat = Remanent magnetization/Saturation magnetization, Bcr/Bc = coercivity of remanence/coercivity, SD = single-domain, SP = Superparamagnetic, MD = multi-domain For more detailed information see (Milanese, 2018; Milanese et al., 2017).

member (Hamilton Point Member) of the Snow Hill Island Formation, encompassing 1300 m of stratigraphic thickness. We were able to compute reliable ChRM directions from 128 samples (see tables in supplementary material). The homoclinal character of the outcrops of these rocks does not allow for performance of a valid tilt or fold test. However, a reversal test yields a positive result (Classification C, (McFadden and McElhinny, 1990). Milanese et al. (2017) and Milanese et al. (2018) provided detailed rock magnetic results suggesting that remanence is carried by detrital titanomagnetite along these sections too. A successful magnetostratigraphic correlation also points towards a primary nature of the remanence. Again, several million years are represented along the sections sampled. Fig. 8 shows the ChRM directions determined in this locality and its mean in bedding corrected coordinates. After applying the Vandamme (1994) filter, five out of the 128 remanence directions were ruled out. The mean bedding-corrected direction obtained from the remaining 123 samples of the southeast area of James Ross Island is: Dec.: 14.1°, Inc.: −73.4°, α_{95}: 5.7°, n: 123. Computing of I/E parameters for this section yields an undefined result. This could be due to a larger than expected dispersion, which again is probably the product of the single sample per stratigraphic level. Conservatively, we applied the same inclination shallowing factor computed for the NW area section (0.54) to each ChRM direction and computed a VGP for each. This mean corresponds to the inclination-corrected pole position at Lat: −79.6°, Long: 276.5°, A_{95}: 6.0°. According to the sampled units (Milanese, 2018), the assigned age to this paleopole is of ca. 75 Ma. In situ and bedding corrected mean directions, paleopole positions and reversal test results are given in Table 1.

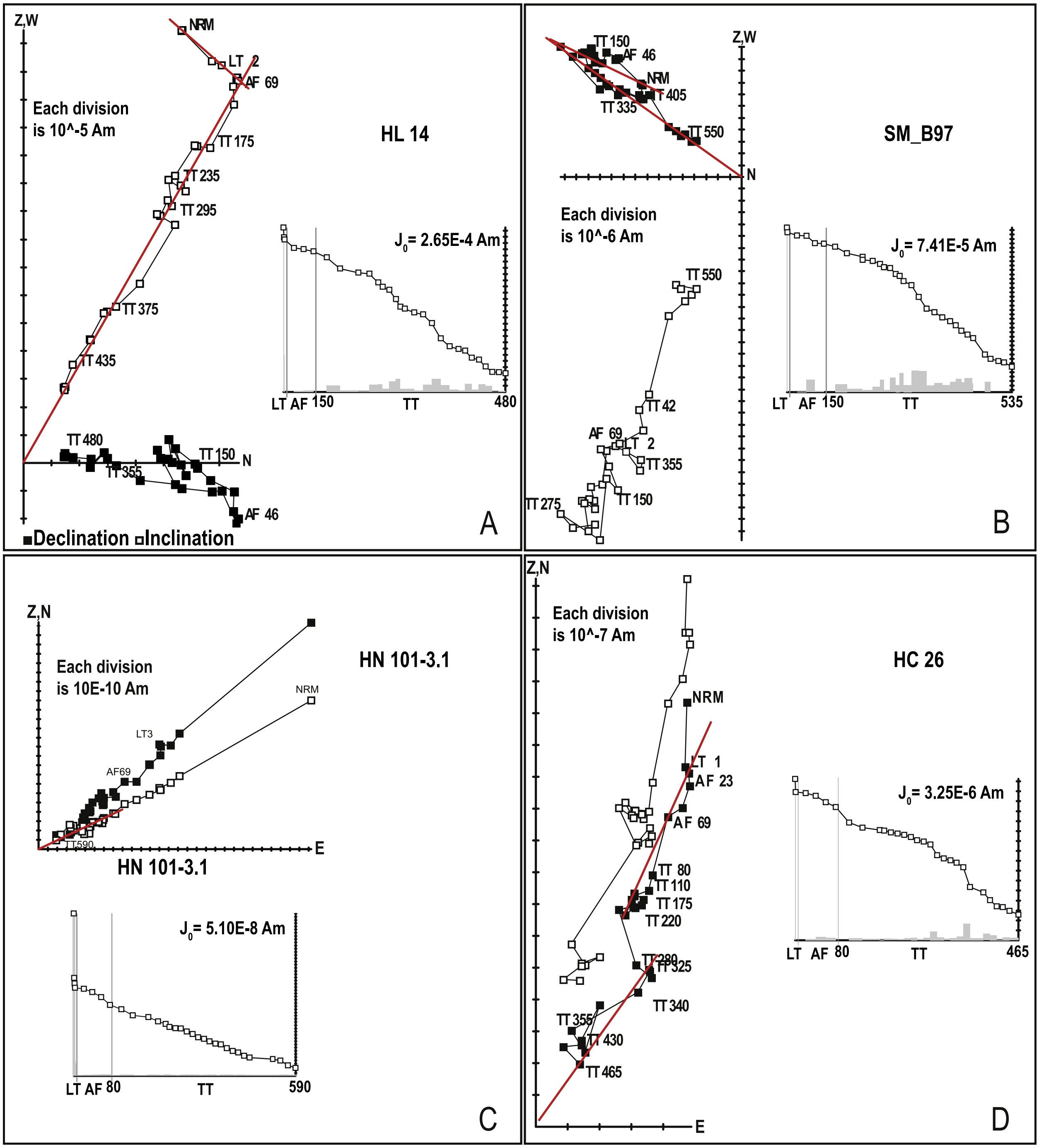

Fig. 6. Paleomagnetic behaviors. Orthogonal vector plots and demagnetization diagrams of samples from Hidden Lake (A), Santa Marta (B), Rabot (C) and Snow Hill Island (D) formations. Component directions (schematically drawn in red) were obtained by PCA. In some cases, a viscous component was removed with the first demagnetization steps. The directions are given in bedding-corrected coordinates.

4. Discussion

Fig. 9A illustrates the two paleomagnetic poles obtained in our study from the infill of the James Ross Basin, the ca. 80 Ma pole from the Santonian-Early Campanian succession exposed in NW James Ross Island and the ca.75 Ma pole from the Middle to Late Campanian succession sampled in SE James Ross Island. Pole positions, both before and after correction for inclination shallowing of the sample remanences, following the elongation-inclination model (Tauxe and Kent, 2004) are presented. They are shown together with previous reference poles for the Antarctic Peninsula. This compilation includes two paleopoles (110 and 55 Ma) obtained by Gao et al. (2018), who combined their own data from King George (25 de Mayo) Island with previous data from several authors from the South Shetland Islands plus some sites in the northern Antarctic Peninsula (Bakhmutov and Shpyra, 2011; Grunow, 1993; Nawrocki et al., 2010; Poblete et al., 2011; Watts et al., 1984). It also includes the 90 Ma paleomagnetic pole obtained by Poblete et al. (2011) in volcanic rocks from South Shetland Islands and the northern Antarctic Peninsula and the 65 Ma paleopole calculated by Tobin et al. (2012) from the Upper Marambio Group (Seymour Island, James Ross Basin). With no correction for inclination shallowing, the 80 Ma pole falls quite apart from previous Late Cretaceous to Paleocene

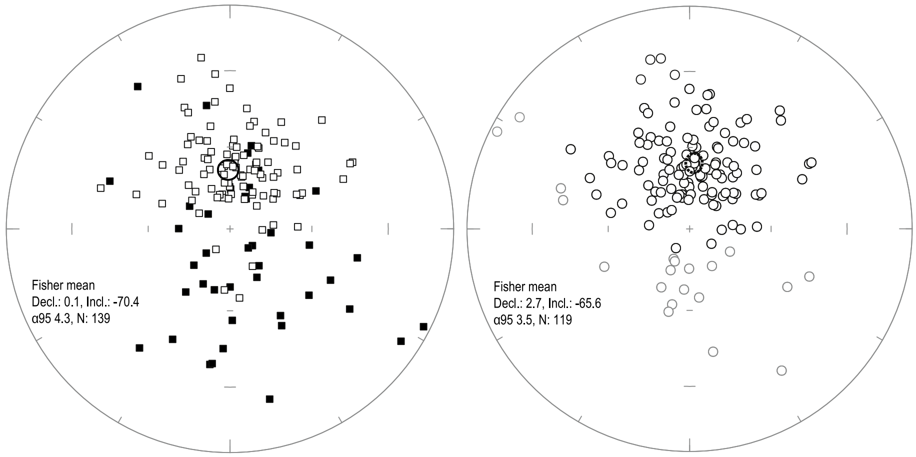

Fig. 7. Paleomagnetic directions from northwest James Ross Island. Mean direction (left) and mean direction after turning reverse directions to upper hemisphere (right). In gray color those samples discarded from the mean calculation according to Vandamme (1994) criteria: this distribution leads to a positive reversal test. All directions are given in paleogeographic coordinates. Geographic and Paleogeographic mean directions, reversal test results and the calculated paleopole are given in Table 1.

poles of the Antarctic Peninsula and the 75 Ma pole falls near the 110 Ma (Gao et al., 2018) and far apart from the 90, 65 and 55 Ma poles. In both cases their departure from the trend determined by previous paleomagnetic poles is consistent with inclination-shallowing affecting the remanence directions. As discussed above, an inclination-shallowing factor of 0.54 was computed from the distribution of remanence directions applying the elongation-inclination model for the ca. 80 Ma succession exposed in northwest James Ross Island. When corrected for this factor the modified pole position (Fig. 9A) falls close to the 90 Ma pole computed by Poblete et al. (2011) from volcanic and igneous rocks, suggesting negligible apparent polar wander during that period. Application of the same correction factor to the remanence directions of the younger sequence yields an inclination-shallowing corrected pole for ca. 75 Ma that looks overcorrected. It is interesting to note that the 0.54 factor was computed for the older succession while the younger one produced an undetermined result in the E/I analysis. The simplest explanation is that the correction factor overestimates the inclination-shallowing in the sections sampled in the southeast area of James Ross Island. As described by Milanese et al. (2018, 2017), magnetostratigraphic sampling of the Rabot and Snow Hill Island formations included a significant number of concretions, as the sediments are unconsolidated in most outcrops. This may explain why less-significant inclination-shallowing probably affected this succession, and produce an over-correction of its pole position, as concretions are likely to undergo less compaction effects than claystone and siltstone beds. Tobin et al. (2012) published a magnetostratigraphic study of the upper sections of the Marambio Group exposed along the Seymour (Marambio) Island. This section corresponds mainly to the middle and upper parts of the López de Bertodano Formation (Rinaldi et al., 1978) that includes the Cretaceous-Paleocene boundary. The paleomagnetic pole computed from that study, to which we assigned an approximate age of 65 Ma is also depicted in Fig. 9A. This pole falls somewhat in between the 80 and 90 Ma poles on one side and the 55 Ma pole on the other, however its large A95 precludes a rigorous analysis of its position in relation with older and younger poles. Considering the large confidence circles of the 65 Ma and 75 Ma poles and the uncertainty regarding any inclination-shallowing correction for the latter, we have excluded both from further analysis and in Fig. 9B, four paleomagnetic poles for the Antarctic Peninsula, corresponding to 110, 90, 80 and 55 Ma are presented. They are the most reliable pole positions available to date for the Late Cretaceous-Paleocene and depict a slow but nonetheless significant apparent polar wander of the Antarctic Peninsula. Poblete et al. (2011) published a ca. 60 Ma pole for the Antarctic Peninsula based on results from volcanic and intrusive rocks from the South Shetland Islands. Their pole falls farther apart from the older poles (see Fig. 9A). Gao et al. (2018) presented new results from the King George (25 de Mayo) Island and recomputed a mean pole for late Paleocene-early Eocene of the Antarctic Peninsula. Their new pole included those sites form the study of Poblete et al. (2011) and previous ones. Their ca. 55 Ma pole position (Fig. 9) is closer to the older poles than that of the

Table 1
Paleomagnetic means, reversal tests and paleopole coordinates for Northwest and Southeast James Ross Island. The used inclination value for NW area paleomagnetic pole was −76.13°, after inclination shallowing correction.

NW Area (ca. 80 Ma)					
	Dec (°)	Inc (°)	α_{95}	N	
In situ mean	26.0	−70.5	3.4	119	
Bedding-corrected mean	2.7	−65.5	3.5	119	
	Critical Angle (°)		Observed Angle (°)		Condition
Reversal test from beding-corrected mean	10.90		8.90		Positive. Class C
	Lat (°)		Long (°)		A_{95}
Paleomagnetic Pole (before inclination shallowing correction)	−73.81		128.5		5.0
Paleomagnetic Pole	−88.7		302.2		5.0
SE Area (ca. 75 Ma)					
	Dec (°)	Inc (°)	α_{95}	N	
In Situ mean	52.6	−73.6	5.6	123	
Bedding-correctedmean	14.1	−73.4	5.7	123	
	Critical Angle (°)		Obeserved Angle (°)		Condition
Reversal test from bedding-corrected mean	19.7		17.1		Positive. Class C
	Lat (°)		Long (°)		A_{95}
Paleomagnetic Pole (before inclination shallowing correction)	−81.64		181.7		9.5
Paleomagnetic Pole	−79.6		276.5		6.0

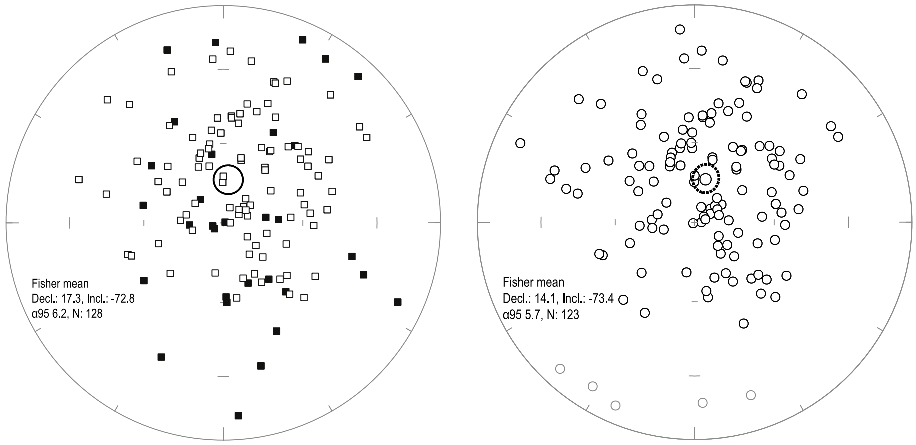

Fig. 8. Paleomagnetic directions from southwest James Ross Island. Mean direction (left) and mean direction after turning reverse directions to the upper hemisphere (right). In gray color those samples discarded from the mean calculation according to Vandamme (1994) criteria: this distribution leads to a positive reversal test. All directions are given in paleogeographic coordinates. Geographic and paleogeographic mean directions, reversal test results and the calculated paleopole from this mean are given in Table 1.

former authors, even though the A95 is larger. It is noteworthy that Nawrocki et al. (2010) proposed the existence of tectonic block rotations along the South Shetland Islands, a hypothesis ruled out by Poblete et al. (2011) arguing that in the previous study paleosecular variation had not been appropriately averaged, but this could cause the difference in pole position. Considering all these factors, we follow the conservative procedure of using the latest computation by Gao et al. (2018) as superseding the 60 Ma pole by Poblete et al. (2011).

It has been accepted for decades (see Poblete et al., 2011; Watts et al., 1984 and references therein) that the Antarctic Peninsula did not undergo significant tectonic displacements with respect to East Antarctica since at least the middle Cretaceous. This is strongly supported by similar paleomagnetic pole positions between both crustal masses since those times (Fig. 10A and B). Our preliminary APWP for the Antarctic Peninsula shows very similar positions for coeval poles with respect to that from East Antarctica. However, no individual reliable paleomagnetic poles are available for this continent for the Late Cretaceous to Paleocene times and its path has been computed from a global paleomagnetic database rotated into East Antarctica coordinates by ocean floor magnetic anomalies and geodynamic models that account for mobility of the Indo-Atlantic hot-spots (Torsvik et al., 2012). Nevertheless, consistency between both paths confirms lack of significant relative displacement and present-day relative position of Antarctic Peninsula with respect to East Antarctica can be accepted for the Late Cretaceous. This has already been proposed by many authors before us (Gao et al., 2018; Grunow, 1993; Poblete et al., 2011), and it is consistent with Weddell Sea magnetic anomalies interpretations that suggest that convergence between East and West Antarctica was prior to 100 Ma (Ghidella et al., 2002).

Tectonic interplay between the Antarctic Peninsula and the southern tip of South America since the Cretaceous was probably rather complex. The precise position of the Peninsula with respect to Patagonia in pre-Cretaceous times is not firmly established, although a location of northern AP to the west of the southern Patagonian present-day margin has been favored for many years (Barron et al., 1981; Ghidella et al., 2002; Hervé et al., 2006; Lawver et al., 1992). Some authors, however, disagree and prefer a pre-Cretaceous position of the AP as a southward continuation of the Patagonian-Fuegian Andes (e.g. Vérard et al., 2012). However, it is reasonably well-established that the Drake Passage was fully opened by the latest Oligocene or Early Miocene, with complete physical separation between the southern tip of South America and the northern tip of AP occurring after ca. 40 Ma (Eagles and Jokat, 2014; Lagabrielle et al., 2009; Livermore et al., 2005; Lodolo et al., 2006; Scher and Martin, 2006). Based on high quality paleomagnetic data, Somoza (2007) demonstrated that the opening of the Drake Passage occurred after 45 Ma and was due to a northward drift of SAM of about 5–7°. This northward drift to attain the present position was preceded by a southward displacement of SAM, which according to Somoza and Zaffarana (2008) must have occurred at some time loosely bracketed between ca. 100 and 75 Ma. Previous to that, between around 125 and 100 Ma SAM experienced a standstill period with respect to the rotation axis (Ernesto et al., 2002; Somoza and Zaffarana, 2008).

The nearly 90 degrees of curvature shown by the Patagonian-Fuegian Andes, known as the Patagonian Orocline, has been shown by systematic paleomagnetic studies (Poblete et al., 2016; Rapalini et al., 2015) to be a true orocline, meaning that the present shape was attained by bending of the orogen. Poblete et al. (2016) presented evidence that oroclinal bending mainly occurred during the Late Cretaceous, and that most, if not all, of the curvature had already been in

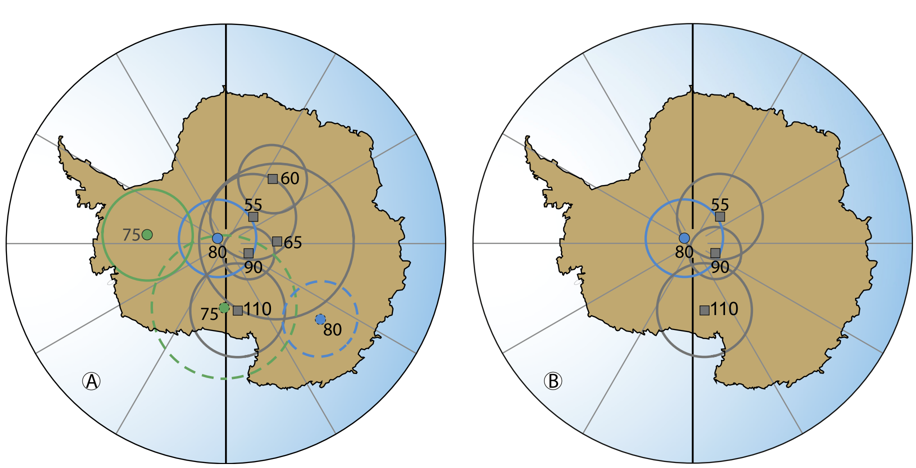

Fig. 9. Paleomagnetic poles. Polar stereographic projection of the paleomagnetic poles calculated in this work (blue and green) and other selected paleopoles for AP (A) and paleopoles selected as the most reliable for Late Cretaceous – Paleocene of AP (B). Each pole is represented with its corresponding A95. Numbers indicate the most likely approximate age for each one. Pole of 80 Ma (75 Ma) corresponds to the succession exposed in northwest (southeast) James Ross Island. Poles computed from Inclination-shallowing corrected remanence directions are presented with their A95 circle in continuous line. Uncorrected paleopoles with A95 in dotted line. 110 and 55 Ma paleopoles are from Gao et al. (2018) and 90 Ma from Poblete et al. (2011). More references and explanations in the text.

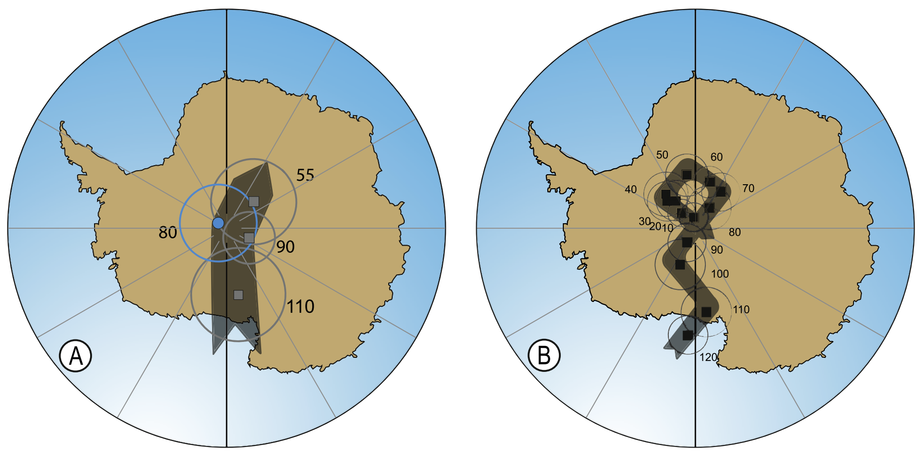

Fig. 10. Apparent polar wander tracks. Proposed apparent polar wander track for AP between 110 and 55 Ma based on previous reference poles plus the 80 Ma pole presented in this paper (A) and synthetic apparent polar wander path for East Antarctica from Torsvik et al. (2012) since 120 Ma (B).

place by the Paleocene. These recent results are of utmost importance as they unlink the opening of the Drake Passage from the curvature of the Patagonian-Fuegian Andes.

On the other hand, the opposite curvature shown by the northern Antarctic Peninsula has been suggested to be an original feature, as no significant different paleomagnetic directions have been found in Cretaceous and younger rocks between the southern and northern AP domains (see Grunow, 1993; Poblete et al., 2011). Comparison of Fig. 10A and B confirms that if any clockwise oroclinal bending of the northern AP occurred since Late Cretaceous times it must have been quite small since it is under the resolution of the available data.

Comparison of our schematic apparent polar wander path for the Antarctic Peninsula between 110 and 55 Ma and that from SAM between 130 and 45 Ma (Fig. 11) may help constrain the interplay

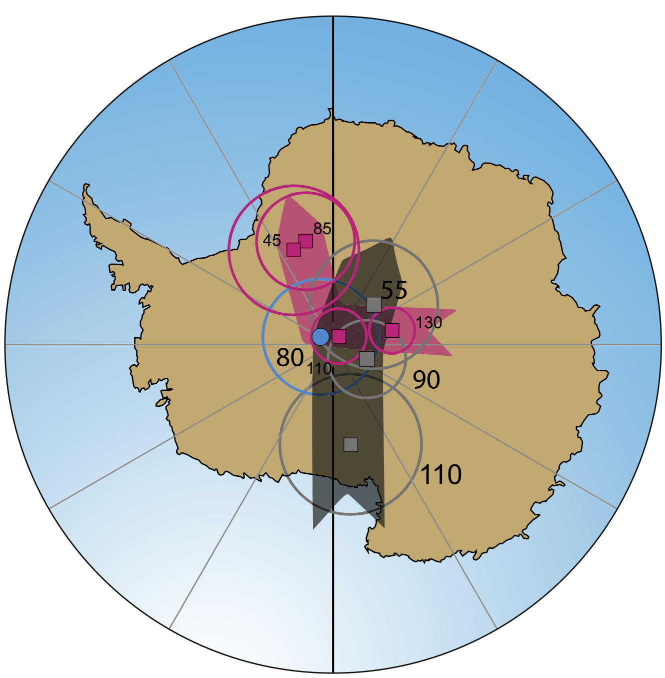

Fig. 11. Reference paleomagnetic poles. Middle-Late Cretaceous to Paleogene reference paleomagnetic poles for AP (dark grey), as presented in this paper and SAM according to Somoza and Zaffarana (2008) (pink). Our calculated AP paleomagnetic pole, from ca. 80 Ma is differentiated in light blue. Approximate ages of the poles are indicated in Ma. Arrows show the broad displacements of both continents as indicated by their APWP. Poles are plotted in present-day coordinates.

between these two plates during formation of the Patagonian Orocline and prior to opening of the Drake Passage. Fig. 12A shows that both paths can be overlapped between 110 and 80 Ma and even to 55 Ma considering the uncertainty margins of the pole of this age for the AP. Superposition of both paths produce a paleogeographic reconstruction as that shown in Fig. 12A for 110 Ma, with the northern tip of the AP in physical continuity with southern Patagonia. It must be considered that most of the oroclinal bending of the Fuegian Andes had not occurred at those times yet, producing a nearly linear and virtually continuous land mass between both continents. Somoza and Zaffarana (2008) stated that SAM experienced a southward displacement after a quasi-stationary period between at least 125 and 100 Ma followed by another quasi-static period between at least 75 and 45 Ma. The southward displacement, however, could only be loosely bracketed as occurring between “100 (90?) and 75 Ma”. Since from our data we can consider SAM and AP as a single plate from 110 to 80 (or 55) Ma, this permits us to bracket more precisely the SAM displacement as occurred before 90 Ma. This is consistent with the major change in plate kinematics inferred by Somoza and Zaffarana (2008) for those times consisting in an increased displacement of SAM towards the west (with no rotational or latitudinal movements) and a major slow-down of the displacement of Africa towards the NNE due to start of collision with the European platform.

Fig. 12B shows a paleomagnetically controlled paleogeographic reconstruction of southern SAM and AP for 90 Ma. This probably remained unchanged until at least 75 Ma and perhaps up to 55 Ma (note that the 55 Ma for AP overlaps partially with those of 75 and 45 Ma of SAM). Paleogeographic change between 110 and 90 Ma consisted in a southward displacement and clockwise rotation of both SAM and the AP. Considering that AP was already attached to East Antarctica, the latter must have experienced a similar movement. This displacement is coeval with the period of major oroclinal bending of the Fuegian Andes (Poblete et al., 2016) suggesting a causal link between both. Southward displacement and clockwise rotation may have developed a sinistral transpressive tectonic environment at the boundary between southern SAM and the Antarctic Peninsula able of producing the orocline. This kinematic behavior is also coeval with closure of the Rocas Verdes back-arc basin in southern Patagonia with obduction and underplating along the western margin of southern SAM (Menichetti et al., 2008; Torres Carbonell et al., 2014). However, rotation of the Fuegian Andes continued after 90 Ma, until about 60 to 50 Ma (Poblete et al., 2016; Rapalini et al., 2015), even though southward displacement of SAM and AP had already stopped. It is likely that the following westward movement of SAM produced a continuation of the sinistral transpressive to transtensional tectonics between both continents (although there is no paleomagnetic evidence since their pole of rotation would

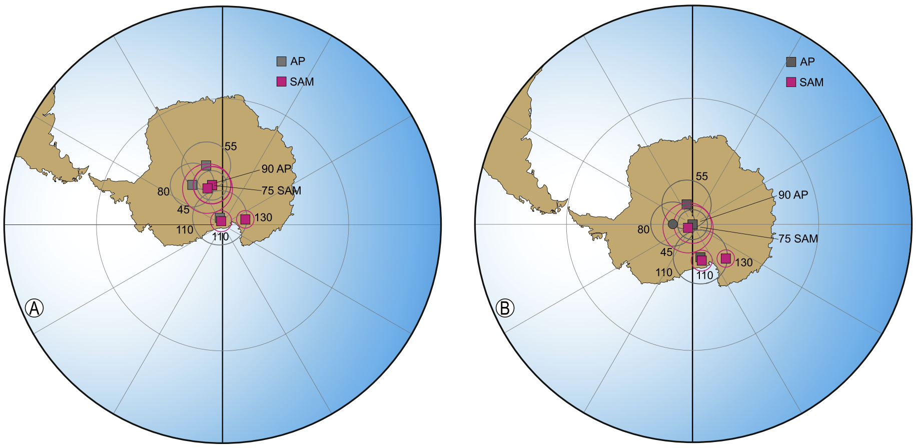

Fig. 12. Paleomagnetic reconstructions. A: Paleogeographic reconstruction of AP and southern SAM at 110 Ma. Consistency of poles from both continents between 110 and 80 Ma suggests that this relative position was virtually unchanged during much of the Late Cretaceous. Paleomagnetic poles from SAM are according to Somoza (2007) and Somoza and Zaffarana (2008). B: Paleomagnetically controlled paleogeographic reconstruction of AP and southern SAM for the latest Cretaceous (ca. 75 Ma). Note that both continents maintain the same relative position but have moved southward and rotated clockwise. The 55 Ma pole for AP allows this reconstruction to be valid even during the Paleogene, although overlapping of this pole with respect to the 45 Ma of SAM is only partial and suggests that the Antarctic Peninsula might have experienced some displacement with respect to the Earth's spin axis while South America remained unchanged.

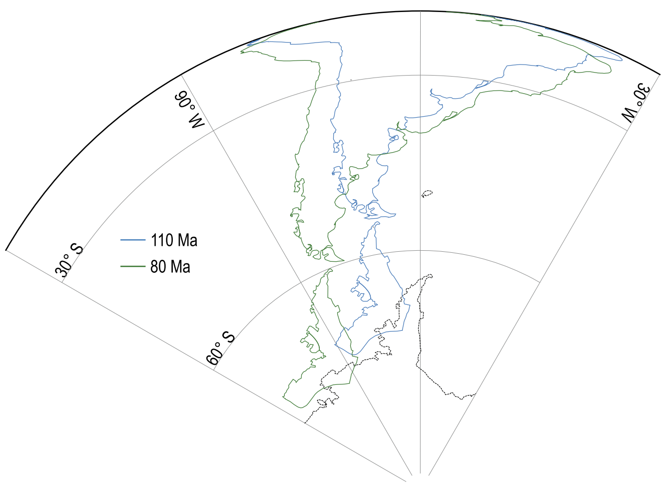

Fig. 13. Paleogeography. Paleoposition of South America (SAM) and the Antarctic Peninsula (AP) for early (110 Ma, blue line) and late (80 Ma, green line) Cretaceous. Present-day position of AP in dotted black line. South America is located today as it was at 110 Ma.

have been basically the Earth's spin axis). Ending of the oroclinal bending probably marks the end of the direct tectonic interplay between them and the start of a full process of drifting apart. As such, the partially deviated 55 Ma pole position from the AP with respect to the 75-45 Ma mean poles of SAM, although still not statistically significant, may be indicating their incipient relative movements, in accordance with data from magnetic anomalies in the Wedell Sea (Livermore et al., 2005). A better-defined paleomagnetic pole of that age is needed for AP to confirm or rebute this hypothesis. Later sinistral displacement between both continents to reach present day positions was achieved mainly by westward movement of SAM and southward displacement of Antarctica during creation and development of the Scotia plate. Fig. 13 summarizes and shows an augmented vision of the relative positions of AP and SAM at crucial times during this evolution.

Relative positions of AP and SAM are unconstrained by direct paleomagnetic data from these continents prior to 110 Ma. Different trends for the 130-110 Ma APWP between SAM and East Antarctica (compare Figs. 10B and 11) suggest that the relative paleogeographic reconstruction between AP and SAM shown in Fig. 12A may not be extrapolated back in time significantly.

5. Conclusions

Two paleomagnetic poles for the Late Cretaceous of the Antarctic Peninsula were computed from 119 to 123 paleomagnetic samples of the Late Cretaceous James Ross Basin, assigned to the uppermost Gustav Group and the lower and middle Marambio Group. The study was carried out at two localities on the northwest and southeast sectors of James Ross Island. Previous successful magnetostratigraphic and rock-magnetic results (Milanese, 2018; Milanese et al., 2018, 2017) strongly support a primary origin for the characteristic remanence and highlight that there is a complete averaging of paleosecular variation (PSV).

Homoclinal successions precluded the performance of a tilt test but a reversal test was positive in both localities. Demagnetization behaviors and different rock-magnetic studies also suggest that remanence is primary.

Inclination shallowing tests were performed by the elongation-inclination method and yielded a significant inclination shallowing (f: 0.54) for the succession exposed in the northwest area. indeterminate results were found when the test was applied to the other sector.

An inclination-shallowing corrected paleomagnetic pole was computed for the Santonian-Early Campanian succession in the northwest area, assigned with a putative 80 Ma age. This pole falls very close to the 90 Ma reference pole computed for the Antarctic Peninsula based on volcanic and intrusive rocks. A ca. 75 Ma paleomagnetic pole was computed for the southeast sector which falls far away from the 80 Ma pole and from other younger poles from the Antarctic Peninsula; however, application of the same inclination-shallowing correction as the northwest area appeared to over-correct the pole position.

An apparent polar wander path for the Antarctic Peninsula is proposed based on the 80 Ma pole plus previous ones of ca. 110, 90 and 55 Ma. This path confirms that oroclinal bending of the Antarctic Peninsula as well as relative displacement with respect to East Antarctica are negligible since 110 Ma. Comparison with the apparent polar wander path for SAM for the 130-45 Ma period suggests that both masses kept a very similar relative paleogeographic position since 110 Ma until 55 Ma. During that period both continents underwent a relatively fast southward displacement of around 7° and a clockwise rotation relative to the Earth spin axis that can be bracketed between 100 and 90 Ma as shown in this study.

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