REVISTA DE LA
ASOCIACIÓN GEOLÓGICA
ARGENTINA
www.geologica.org.ar
Volumen 77 (2)
Junio 2020

Large paleomagnetic declination anomalies in the Cerro Nevado (Snow Hill) Island, Antarctic Peninsula: evidence of hidden tectonic rotations?

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Editor: Diego A. Kietzmann

Recibido: 7 junio, 2019
Aceptado: 31 octubre, 2019

ABSTRACT

We report anomalous paleomagnetic directions obtained in magnetostratigraphic studies carried out on Cretaceous marine sedimentary rocks of the Marambio Group, southeast James Ross Basin, at the Sanctuary Cliffs Nunatak and the Spath Peninsula, located in the Cerro Nevado (Snow Hill) Island. Data quality and field tests suggest a primary origin of the magnetization, ruling out the possibility that directions have been affected by alteration or remagnetization processes related to the Miocene magmatism of the James Ross Island Volcanic Group. A counterclockwise tectonic rotation of 47.9° ± 20.0° of the whole Cerro Nevado Island can account for the paleomagnetic declination anomaly. The bedding of the Cretaceous units at and near the sampling localities show similar directional variations that those observed in paleomagnetic declinations, consistent with such interpretation. However, geological continuity between the exposed units at Marambio Island and the Spath Peninsula, the variable bedding strikes at different localities in the Cerro Nevado Island, plus geometric considerations strongly constrain any rigid body counterclockwise rotation of the whole island to a maximum of about 10°, around a vertical axis located close to the Picnic Passage (~64.4°S, 56.9°W). This indicates that most, if not all, of the hypothetical rotations suggested by the paleomagnetic data must occurred during the Eocene, before tectonic tilting of the Cretaceous units. This needs to be tested with new detailed structural and paleomagnetic studies at different localities along the Cerro Nevado Island as well as with geophysical surveys along the island and its marine surroundings.

Keywords: *Paleomagnetism, James Ross Basin, Marambio Group, James Ross Island Volcanic Group, Antarctica.*

RESUMEN

Grandes anomalías en la declinación paleomagnética en la isla Cerro Nevado, Península Antártica ¿evidencia de rotaciones tectónicas ocultas?

Estudios magnetoestratigráficos realizados en las sedimentitas cretácicas marinas del Grupo Marambio en el sector sudeste de la cuenca James Ross, arrojaron direcciones paleomagnéticas anómalas para el nunatak Sanctuary Cliffs y la península Spath (isla Cerro Nevado). La calidad de los datos y las pruebas de campo sugieren que la magnetización es de origen primario y que no fue afectada por procesos de alteración o remagnetización relacionados con la posterior actividad magmática. La variación en la declinación encontrada para el Cretácico de la isla Cerro Nevado se puede explicar a partir de una rotación tectónica antihoraria calculada en 47.9° ± 20.0°. La actitud de los estratos cretácicos en las localidades de muestreo, con rumbos que presentan variaciones en la misma dirección que la dirección paleomagnética, es consistente con esta interpretación. Sin embargo, la continuidad geológica que se observa entre las unidades aflorantes de la isla Marambio (Seymour) y de la península Spath, sumado a las variaciones locales de rumbo dentro de la propia isla, limita una hipotética rotación de un bloque rígido que comprenda a toda la isla a un máximo de ~10°

alrededor de un eje vertical ubicado en el Pasaje Picnic (~64.4°S, 56.9°O). Esto permite inferir que las hipotéticas rotaciones sugeridas por los datos paleomagnéticos debieron ocurrir durante el Eoceno, previamente a la estructuración de las unidades cretácicas. Este modelo requiere ser validado con nuevos estudios geológicos, paleomagnéticos y geofísicos en Cerro Nevado y en sus áreas marítimas vecinas.

Palabras clave: *Paleomagnetismo, Cuenca James Ross, Grupo Marambio, Grupo Volcánico James Ross Island, Antártida.*

INTRODUCTION

Dalziel and Elliot (1971) were among the first to propose that the large-scale curvature of the Antarctic Peninsula is a secondary feature and it makes it an orocline (*sensu* Carey 1955). According to these authors, the opposite curvatures of the Antarctic Peninsula and southern Patagonian - Fuegian Andes constitute the opposite limbs of a major orocline developed during the opening of the Drake Passage in Cenozoic times. Paleomagnetic studies in the Fuegian Andes (see Poblete et al. 2016, Rapalini et al. 2016 and references therein) have demonstrated that this orogen underwent significant counterclockwise rotations in Late Cretaceous times producing a true oroclinal bending of the southernmost Andes.

Since the first studies carried out by Valencio et al. (1980), however, paleomagnetic data from the Antarctic Peninsula suggested that its curvature is an original feature. This has been later confirmed with new and better paleomagnetic results by Grunow (1993), Poblete et al. (2016), Gao et al. (2018) and Milanese et al. (2019b), among others. Nevertheless, due to the large ice-coverage and to logistic and climatic difficulties for sampling, distribution of paleomagnetic studies in the Antarctic Peninsula is uneven and still scarce. This precludes ruling out the presence of rotated crustal blocks of few km to few tens of km large associated to the late Mesozoic to Cenozoic tectonic evolution of the Peninsula.

A systematic magnetostratigraphic study of the infill of the James Ross Basin, mainly the Marambio Group, has been carried out lately thanks to a cooperation of researchers from Caltech (California Institute of Technology), CADIC (Centro Austral de Investigaciones Científicas) and IGeBA (Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires). This has led to the publication of several partial magnetostratigraphic columns from successions exposed in the James Ross and neighboring islands (Milanese et al. 2019a, 2017, Tobin et al. 2012). From Late Cretaceous paleomagnetic directions from the James Ross Island, Milanese et al. (2019b) computed two paleomagnetic poles of ca. 80 and 75 Ma, respectively, for the Antarctic Peninsula, contributing to a better definition of its apparent polar wander path. However, paleomagnetic results from Cerro Nevado (Snow Hill) Island (Fig. 1) were excluded from this calculation due to their odd mean declination, which did not agree with those coming from James Ross Island or with previous Cretaceous reference paleomagnetic mean directions for Antarctica. Due to the high-quality paleomagnetic results that led to this anomalous declination and after discarding the main alternative sources that could produce a deviation of the expected paleomagnetic mean for the Late Cretaceous in the Antarctic Peninula, this anomalous direction will be discussed in this paper in terms of local tectonic rotations.

GEOLOGICAL SETTING

The Cretaceous infill of the James Ross Basin is subdivided into two groups: the Aptian-Coniacian Gustav Group and the Santonian-Danian Marambio Group. The coarse-grained, deep marine Gustav Group sediments were deposited in a normal fault-regulated submarine slope apron system located along the Prince Gustav Channel, which separates James Ross Island from the Antarctic Peninsula (Fig. 1). It represents an under-filled backarc basin generated to the East of the magmatic arc of the Antarctic Peninsula (Ineson 1989, Scasso et al. 1991). Its outcrops are restricted to western James Ross Island.

The fine-grained Marambio Group is more than 3 km-thick, encompassing marine shelf sediments formed during three main phases of shelf expansion: during the Santonian-Early Campanian, after the Coniacian inversion stage of the basin, and during the Maastrichtian – Danian, when the already fully developed shelf extended for more than 150 km into the Weddell Sea (Olivero 2012). The Marambio Group is exposed at many localities in the James Ross archipelago. At the southeast area of the James Ross Basin it is constituted, in stratigraphic order, by the basal Rabot Formation (Lirio et al. 1989, Marenssi et al. 1992, Martinioni 1992), the Snow Hill Island Formation (Pirrie et al. 1997), the Haslum Crag Formation, and the López de Bertodano and Sobral Formations (Figs. 1 and 2).

The Snow Hill Island Formation is constituted, at southeast James Ross Basin, by the Hamilton Point, Sanctuary Cliffs and Karlsen Cliffs Members (Fig. 2), but only the upper two units are present in Cerro Nevado Island. The Sanctuary Cliffs Member is exposed exclusively in the namesake nunatak (Figs. 1 and

3a). It is composed of ~200 m of unconsolidated mudstones and sandstones with hummocky stratification, present as a thick (~25 m) and continuous package at the base of the section or as ~0.5 m-thick intercalated beds in the upper half. Its fossil content is very abundant, with the kossmaticeratid *Neograhamites* cf. *kiliani* Spath (late Campanian-early Maastrichtian) being especially frequent. The Karlsen Cliffs Member exposures are in Spath Peninsula, Ula Point, and Cockburn Island (Figs. 1 and 3b). It is a coarsening and thickening upward succession of mudstones and sandstones. A very distinctive character of this unit is its orange weathering color, given by clay levels with high pyrite content, and the presence of oblate calcareous concretions of ~30 cm in diameter. Figure 4a-d show views of the studied sections from Sanctuary Cliffs and Karlsen Cliffs Members, respectively.

The Haslum Crag Formation (Fig. 2), restricted to Cerro Nevado and Marambio (Seymour) Islands (Figs. 1, 2, and 3b), is a ~200 m package of highly bioturbated sandstones and glauconitic mudstones with heterolithic stratification. Its base is defined by an erosive unconformity that represents the incision and migration of channels during a forced regression. This unit represents the only known to date example of a basal erosion surface carved by tidal action and not by waves, having this case being previously established as a theoretical possibility only (Olivero et al. 2008, Posamentier et al. 1992). Figure 4c-d show different views of the contact between this unit and the Karlsen Cliffs Member. The contact with the López de Bertodano Formation in Spath Peninsula is shown in figure 4e.

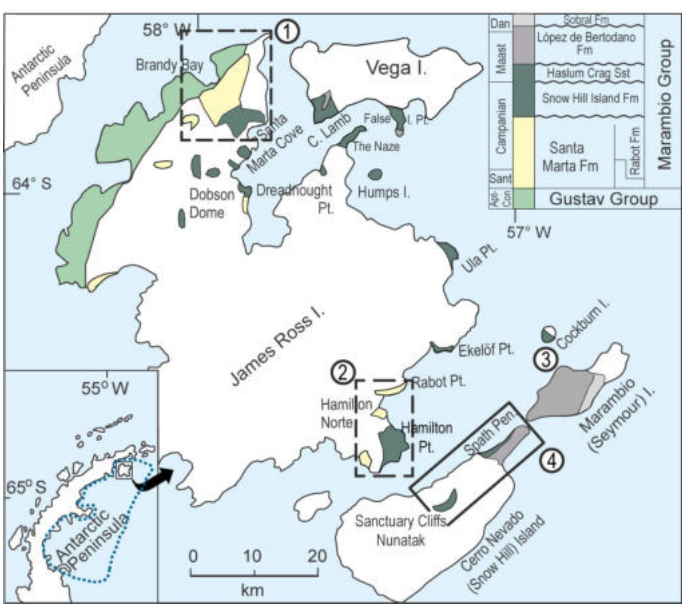

Figure 1. Geological map of the Cretaceous units of the James Ross Basin. Inset down left, in dotted line, inferred boundaries of the Larsen Basin. Localities 1 and 2 correspond to ca. 80 Ma and ca. 75 Ma paleomagnetic poles from Milanese et al. (2019b), respectively. Locality 3 correspond to Tobin et al. (2012). Locality 4 corresponds to the present study. Modified from Olivero (2012) and Pirrie et al. (1997).

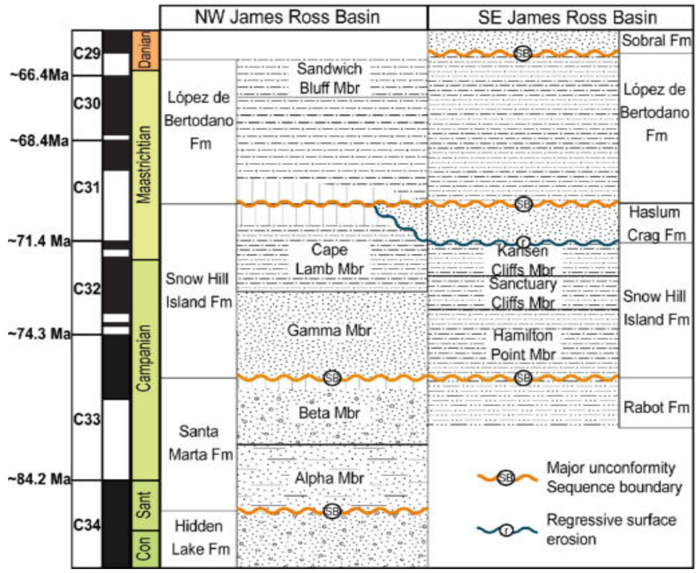

Figure 2. Chronostratigraphic chart of the Upper Cretaceous Marambio Group.

The López de Bertodano Formation (Figs. 2, 3b, and 4e) is mostly exposed in Cerro Nevado and Marambio Islands, but a small outcrop is located at Cape Lamb (Fig. 1). It is constituted by ~1,000 m of mudstones and very fine-grained sandstones, both mostly unconsolidated. Its base is an unconformity that in some areas cuts up to 60 m over the underlying Haslum Crag Formation. This incision is filled with lenticular channel bodies with heterolithic stratification, cross lamination, mud drapes and marine fossils that suggest tidal influence. This unit is highly fossiliferous, with several molluscs (bivalves, gastropods, cephalopods) and the serpulid *Rotularia*. Ammonite fauna is scarce, except for specific horizons abundant in the kossmaticeratid *Maorites tuberculatus* (middle Maastrichtian). This unit has been interpreted as estuarine and shallow marine transgressive deposits at this lower 500 m and as a transgressive shelf followed by a regressive trend in the uppermost part of the López de Bertodano Formation.

Cretaceous rocks exposed in the Spath Peninsula are intruded by SW-NE subvertical alkaline basaltic dykes (Figs. 3b, and 4d), that correspond to the Neogene magmatism of the James Ross Island Volcanic Group (Calabozo et al. 2015, Smellie et al. 2008). This magmatism is widely distributed as dykes and lava flows in all the James Ross Archipelago.

METHODOLOGY

The magnetostratigraphic sampling was designed for achieving a more robust and accurate geochronological framework for the Upper Cretaceous Marambio Group in southeast James Ross Basin (Milanese et al. 2019a). Localities 1 and 2 from figure 1 correspond to northwest and southeast James Ross Island and from which a ca. 80 and a 75 Ma paleomagnetic pole were, respectively, computed (Milanese et al. 2019b). Figure 2 shows a simplified stratigraphic scheme of the sampled units involved in the previous magnetostratigraphic studies, together with the general magnetostratigraphy for the basin. The paleomagnetic results analyzed in this paper correspond to the Sanctuary Cliffs and Karlsen Cliffs Members of the Snow Hill Island Formation, Haslum Crag Formation and López de Bertodano Formation, from which a total of 155 paleomagnetic samples were collected in two areas of the Cerro Nevado Island (Fig. 1, locality 4): Sanctuary Cliffs Nunatak (69 samples) and Spath Peninsula (86 samples). Together, both sections cover ~700 m of sedimentary thickness. Sampling at the Sanctuary Cliffs Nunatak (Fig. 3a) included the offshore mudstones and very fine-grained sandstones of the Sanctuary Cliffs Member (Fig. 2). At Spath Peninsula (Figs. 2, and 3b), we sampled the prograding deltaic wedge deposits of the Karlsen Cliffs Member, the forced-regressive sandstones of the Haslum Crag Formation and the lower levels of the estuarine mudstones and very fine-grained sandstones of the López de Bertodano Formation (up to Unit 5 from Macellari 1988) in an almost continuous section.

The sampling was conducted with a portable gasoline-powered drill, collecting one sample per stratigraphic level, precisely determined using Jacob's staff. Although stratigraphic spacing between samples depended on the availability of beds suitable for drilling, samples were collected at an average rate of one every 4.5 m. Measurements were carried out in 5.5 cm^3 paleomagnetic specimens at the Paleomagnetic Laboratory of the California Institute of Technology using an automatic 3-axis DC-SQUID moment magnetometer system, housed in a magnetically shielded room. Based on previous experience in the sedimentary rocks from the Marambio Group, the demagnetization routine started with two low-temperature cycling steps (samples were cooled to 77 K in liquid N_2 in a low field environment), followed by three low-intensity alternating field (AF) steps (from 2 to 6.9 mT). 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 above 120 °C to minimize oxidation. A total of 134 samples were analyzed and characteristic remanence directions (ChRM) were obtained from all of them, calculated by means of principal components analysis (PCA, Kirschvink 1980). Only those with maximum angular deviation (MAD) values under 10° were accepted. In only five samples, great circle analysis (McFadden and McElhinny 1988) were performed to constrain the remanence direction along an arc. Analysis of palaeomagnetic data was conducted with PaleoMag 3.1 software (Jones 2002) and Paleomagnetism.org online portal (Koymans et al. 2016).

RESULTS

Rock magnetism

Figure 5 shows Zijderveld and demagnetization diagrams that summarize the paleomagnetic behavior of the samples from Snow Hill Island Formation (SCF40, SCF52, SP10) and from López de Bertodano Formation (SP47). Most samples had a single magnetic component, although in many cases, a small viscous remanence was removed with the first steps of low-temperature demagnetization, AF or thermal cleaning up to 150 °C. Thermal demagnetization could not proceed further than 400-480 °C in most cases, due to a random directional behavior acquired by the samples above those temperatures produced, most likely, by chemical changes in clay minerals upon heating (Pan et al. 2000).

Thermomagnetic curves from figure 6a show irreversible behaviors, where susceptibility (k) values are higher during cooling than during heating. The increase of k observed between 400 and 500 °C could indicate: a) primary (Ti) magnetite Curie's point or b) the formation of new mineral during heating. Whichever is the explanation, thermomagnetic curves indicate the absence of a mineral with Curie temperature (TC) below 400 °C. Most secondary magnetization common carriers (*e.g.*, greigite, phyrrhotite, etc) are characterized by TC < 400 °C.

Isothermal remanent magnetization curves from figure 6b show remanence coercivity (BCR) values of ~40-50 mT (this parameter is obtained from the intersection of the red curve with the abscissa axis). We know from previous studies (Milanese et al. 2019a, 2017, among others) that coercivity values (BC) are between 14 and 22 mT. Both BCR and BC of Cerro Nevado Cretaceous rocks are consistent with a ferrimagnetic mineral that could correspond to titanomagnetite (*s.l.*). Greigite has already been ruled out from magnetostratigraphic studies carried out in the Rabot Formation (Milanese et al. 2017).

Lowrie-Fuller test is designed to differentiate characteristic remanences carried by single- domain (SD) from those carried by multi-domain (MD) magnetite grains. Diagrams from figure 6c show that anhysteretic magnetization (ARM) is more resistant to AF demagnetization than isothermal remanent magnetization (IRMz), which is typical from SD or PSD grains, excluding multi-domain magnetite as main magnetic carriers in these sediments. These minerals are the most liable to be remagnetized after rock formation.

Directional analysis

Figure 1 shows the localities in the James Ross basin from which previous paleomagnetic mean directions were computed (1-2: Milanese et al. 2019b, 3: Tobin et al. 2012). Mean directions obtained at localities from figure 1 are presented in figure 7a and

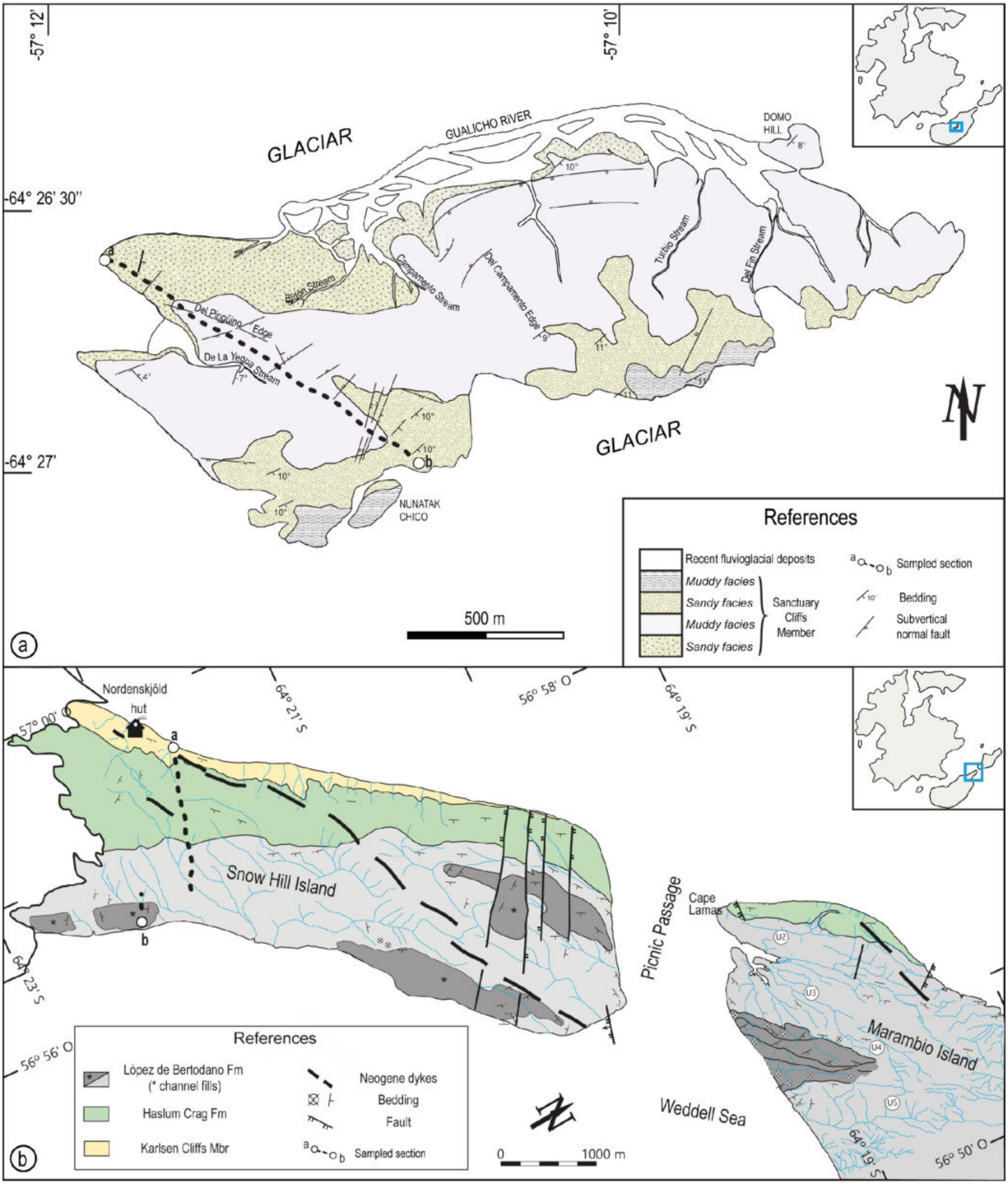

Figure 3. a) Geologic map of the Sanctuary Cliffs Nunatak. The sampled section is indicated in dotted line. Modified from Robles Hurtado (1992); b) Geologic map of the Spath Peninsula and southwest sector of the Marambio (Seymour) Island. The sampled section is indicated in dotted line. Modified from Olivero et al. (2008).

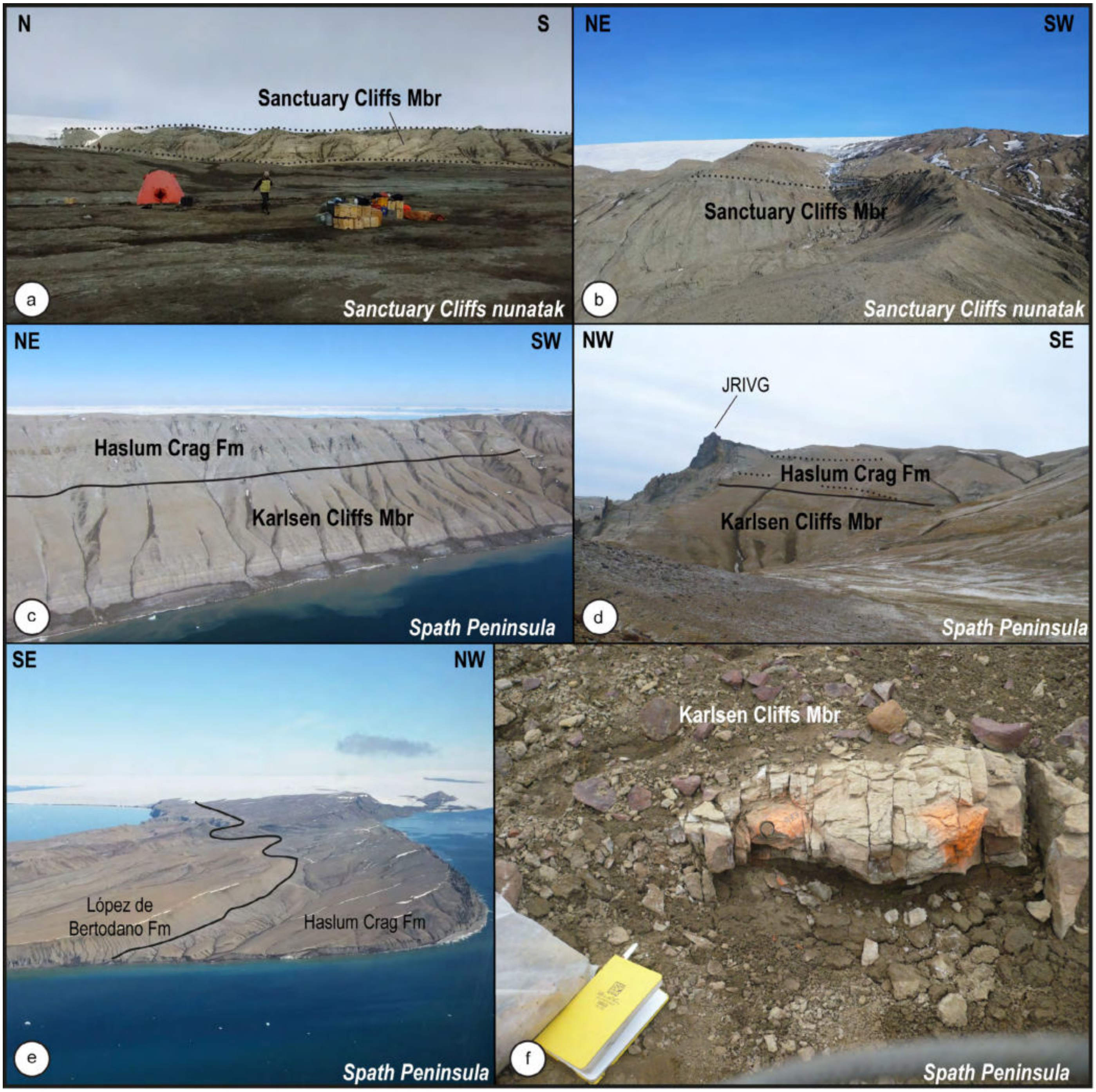

Figure 4. a-b) Outcrop views from Sanctuary Cliffs Member; c-d) Contact between Karlsen Cliffs Member and Haslum Crag Formation, and intrusive dykes of the James Ross Island Volcanic Group at Spath Peninsula; e) contact between Haslum Crag and López de Bertodano Formations; f) Sample collected from an oval concretion surrounded by unconsolidated mud in the Karlsen Cliffs Member at Spath Peninsula.

summarized in Table 1, and correspond to northwest and southeast James Ross Island and Marambio Island, respectively. The three means come from distributions that led to positive C-class reversal tests. Paleomagnetic directions from Cerro Nevado Island (Fig. 7b) yielded a positive reversal test (McFadden and McElhinny 1990, Table 1), but the obtained mean is considerably different from those from Late Cretaceous successions exposed in both James Ross Island locations and in Marambio Island. As also shown in figure 7a, it is anomalous with respect to other Late Cretaceous to early Paleogene directions from other areas of the Antarctic Peninsula (Gao et al. 2018, Poblete et al. 2011). All mean directions from figure 7a are represented in the upper hemisphere to facilitate their comparison. Direction values in geographic and bedding corrected coordinates are given in tables S1

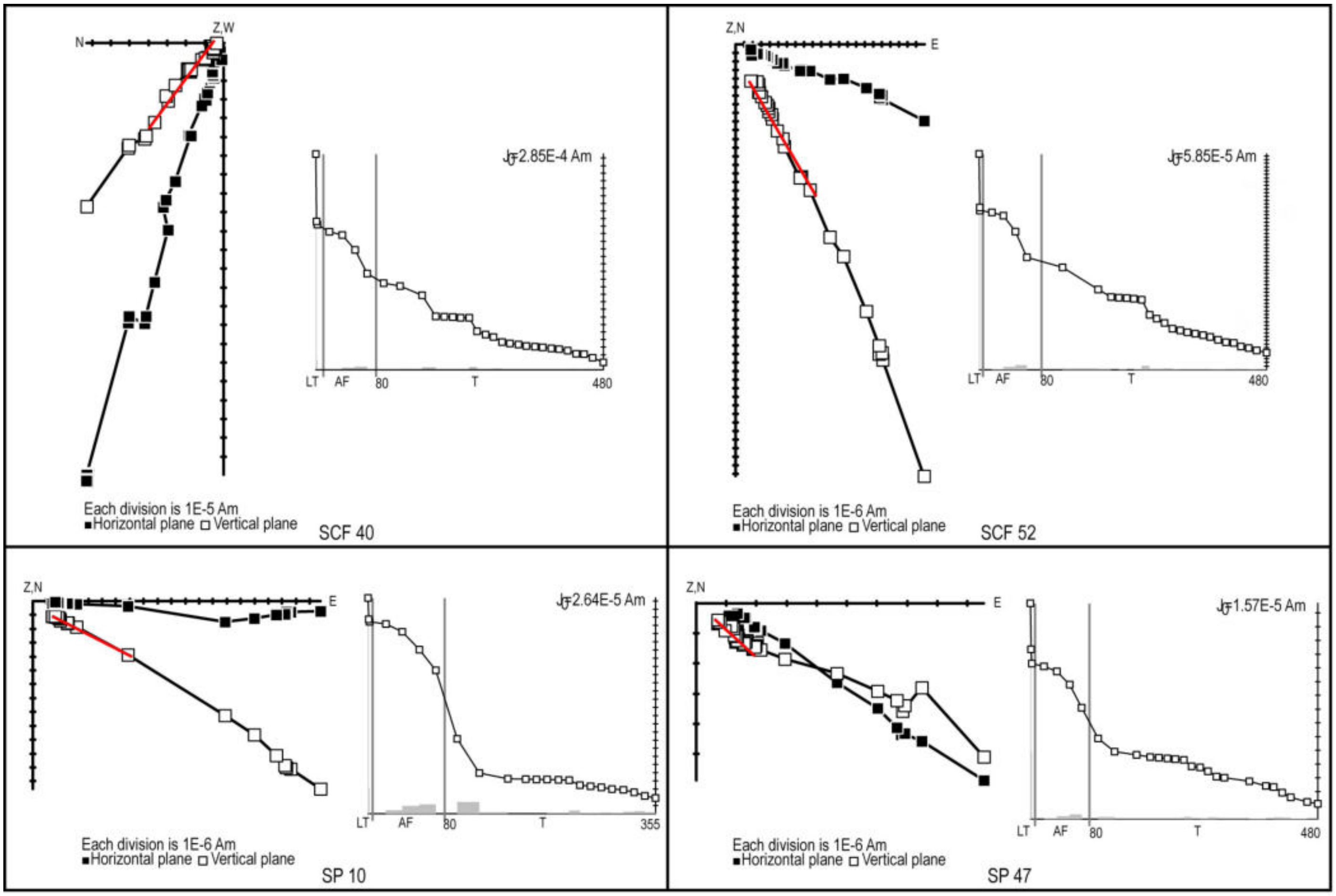

Figure 5. Zijderveld and demagnetization diagrams of the Sanctuary Cliffs Member (SCF40 and SCF52), the Karlsen Cliffs Member (SP10), and López de Bertodano Formation (SP47). Most samples have univectorial behavior. Red line indicates the characteristic remanent magnetization calculated by principal component analysis. Demagnetization processes did not go above 480 °C due to a random directional behavior acquired above that temperature. LT: low temperature; AF: alternating field; T: temperature. Magnetization (J) is normalized.

to S4 from supplementary material. Figure 7c shows the counter clock displacement from Cerro Nevado Island paleomagnetic pole (this work) respect to our reference paleomagnetic pole (Marambio Island, Tobin et al. 2012).

The alkaline magmatism from the Miocene-Holocene James Ross Island Volcanic Group (Concheyro et al. 2007, Ivany et al. 2006, Marenssi et al. 2010, Smellie et al. 2008) is represented in the Cerro Nevado Island as dykes elongated in a southwest-northeast direction (Figs. 3b, and 4d). Before attempting a tectonic interpretation of the anomalous paleomagnetic direction obtained from Cretaceous rocks of this island, it is necessary to rule out a possible remagnetization produced by this magmatic episode. Figure 7d shows that there is no overlap between the characteristic remanent directions obtained from the Miocene basaltic dikes (Milanese 2018) and those from Cretaceous sedimentary successions sampled in the Cerro Nevado Island, both *in situ* and after bedding correction. This rule out a remagnetization produced by the Neogene volcanism as a suitable explanation for the anomalous directions at this island. The possibility of this anomalous direction being due to a perturbation of the geomagnetic field is also ruled out, since geomagnetic excursions have been reported to last as much as 10 kyr (Roberts 2008) and our samples come from a ~700 m-thick section that covers at least 1.5 my and includes three polarity reversals (Milanese et al. 2019a).

We computed the anomalies in magnetic declination and inclination from Cerro Nevado Island with their respective confidence intervals, following Demarest (1983) and Beck (1989). Considering that there is stratigraphic overlap between the upper levels sampled at Snow Hill Island (Milanese et al. 2019a) and those studied at Marambio Island (Tobin et al. 2012), correspondent to the lower levels of the López de Bertodano Formation, we calculated the rotation (R) and flattening (F) of the Cerro Nevado paleomagnetic mean with respect to that of the Marambio Island (Figs. 1, and 7a). Being the reference declination D_r=352.5° and our declination D0=304.6, the rotation R of the Cerro Nevado mean is:

$$R = D_0 - D_r$$

$$\boldsymbol{R = -47.9° \pm 20.0°} \text{ (counterclockwise)}$$

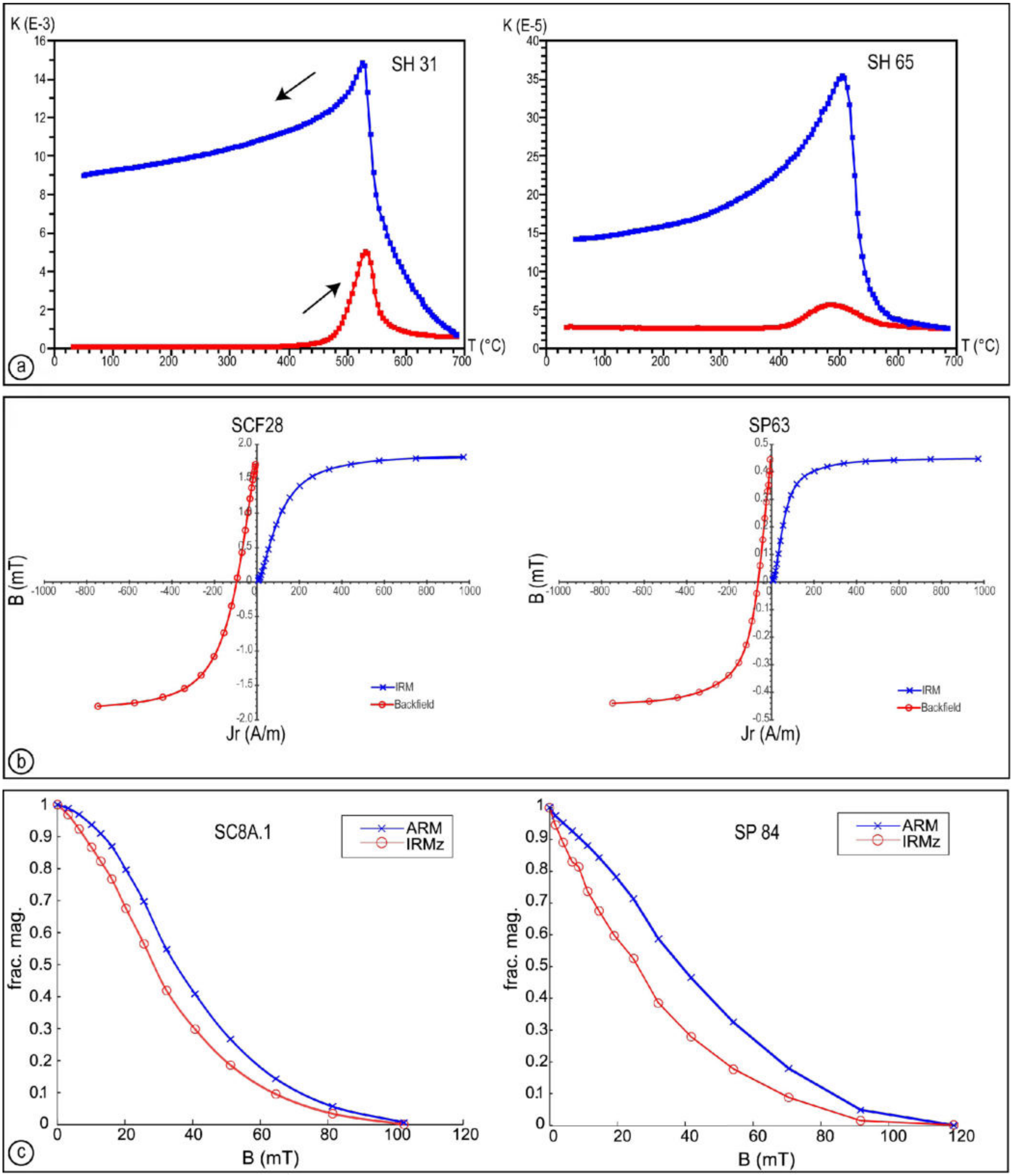

Figure 6. a) High-temperature thermomagnetic curves for samples from Karlsen Cliffs Member (SH31) and Haslum Crag Formation (SH65). Red is for heating and blue for cooling; b) IRM/Backfield curves for Sanctuary Cliffs Member (SCF28) and Haslum Crag Formation (SP63) samples. Saturation is reached at ~300 mT and remanence coercivity (BCR) is around 50 mT; c) Lowrie–Fuller tests of samples from Sanctuary Cliffs Member (SC8A.1) and Haslum Crag Formation (SP84). All units from Marambio Group show similar behaviour: ARM is more resistant than IRM to AF demagnetization. Taken from Milanese et al. (2019a).

Being the reference inclination I_r=-73.1° and our inclination I_0=-62.6°, the flattening F of the Cerro Nevado mean is:

$$F = I_r - I_0$$

$$\boldsymbol{F = -10.5° \pm 6.5°}$$

To check for the uncertainty calculation, we refer the reader to Beck (1989) and our Table 1.

The mean remanence direction obtained from the Late Cretaceous rocks exposed in Cerro Nevado Island, therefore, suggests a counterclockwise rotation of 47.9° ± 20.0° of the study successions around a vertical axis located at or very near the sampling localities. The flattening value given by this method (Beck 1989, Demarest 1983) has a significance of 4°.

DISCUSSION

Paleomagnetic directions used to calculate the tectonic rotation led to a positive reversal test which, together with rock magnetic analysis that indicate a ferrimagnetic SD or PSD phase as the characteristic magnetization carrier, suggest that the magnetization of the Cretaceous units from Cerro Nevado Island is primary. Inclination errors in remanence directions in clastic sedimentary rocks are frequent (see a review of this subject in Kodama 2012). This bias, that produces remanence inclination values systematically lower than the magnetic field in which they were recorded, is called "inclination shallowing" and is the effect of the depositional processes affecting the detrital ferromagnetic (*s.l.*) grains and/

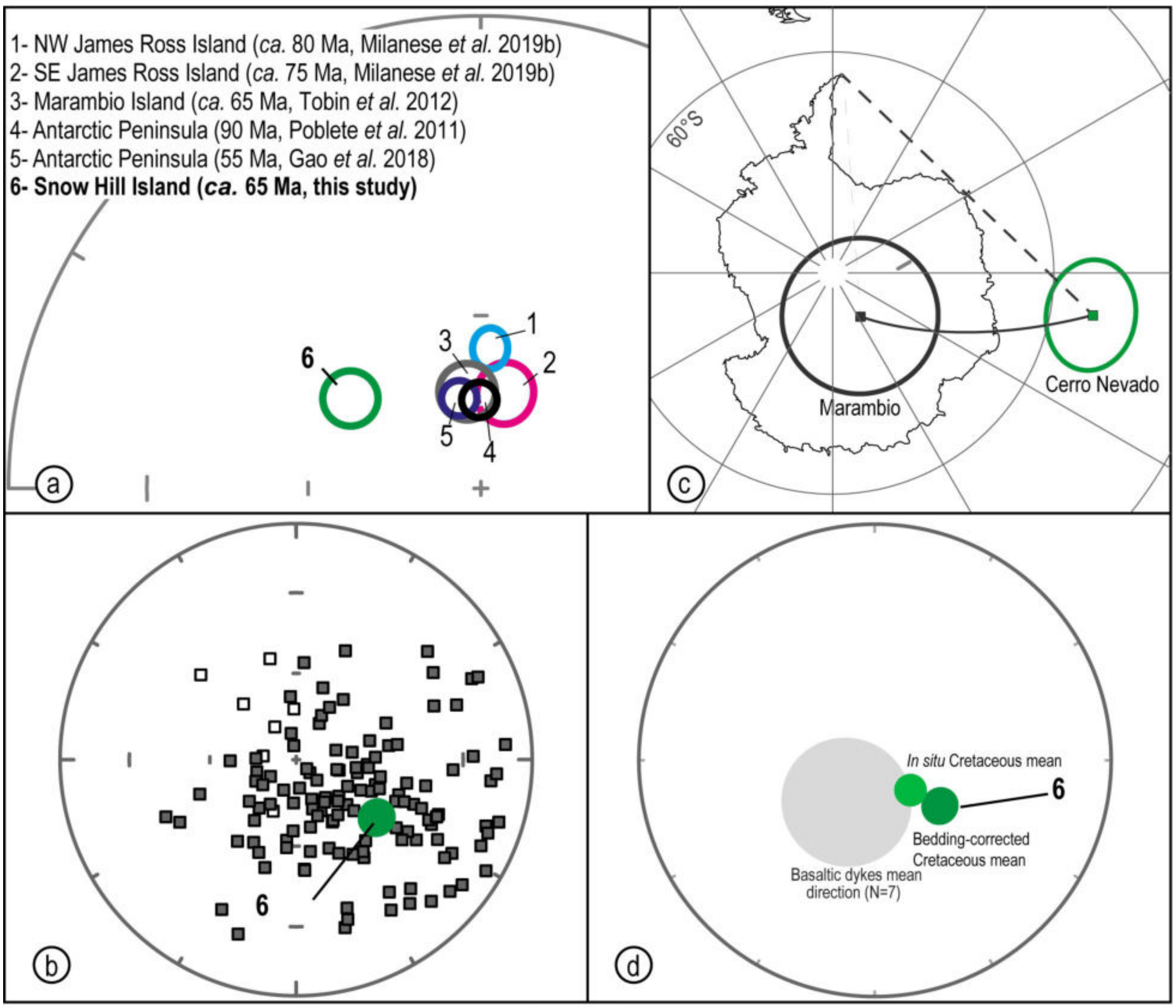

Figure 7. a) Mean directions of previous studies carried out in the James Ross Basin and other areas of the Antarctic Peninsula, and from the present study. All directions are plotted in the upper hemisphere; b) Paleomagnetic directions from Cerro Nevado Island yield a positive reversal test (see Table 1). All stereographic plots are in bedding-corrected coordinates; c) Rotation of the Cerro Nevado paleomagnetic pole (calculated from mean 6) respect to Marambio reference paleopole; d) Miocene basaltic dykes mean paleomagnetic direction, together with *in situ* and bedding-corrected Cretaceous paleomagnetic means from Cerro Nevado Island.

Table 1. Paleomagnetic means of the James Ross Archipelago and the Antarctic Peninsula.

Northwest James Ross Island (ca. 80 Ma)					
	Dec (°)	Inc (°)	α95	N	
In situ mean	26.0	-70.5	3.4	119	
Bedding-corrected mean	2.7	-65.5	3.5	119	
Southeast James Ross Island (ca. 75 Ma)					
	Dec (°)	Inc (°)	α95	N	
In situ mean	52.6	-73.6	5.6	123	
Bedding-corrected mean	14.1	-73.4	5.7	123	
Cerro Nevado Island (ca. 65 Ma)					
	Dec (°)	Inc (°)	α95	N	
In situ mean	131.2	73.9	5.2	133	
Bedding-corrected mean	124.7	62.6	5.3	133	
	Critical Angle (°)		Obeserved Angle (°)		Condition
Reversal test from bedding-corrected mean	19.5		11.3		Positive. Class C
Miocene basaltic dykes					
	Dec (°)	Inc (°)	α95	N	
In situ mean	214.0	72.3	22.4	7	
Antarctic Peninsula 90 Ma (Poblete et al. 2011)					
	Dec (°)	Inc (°)	α95	N	
Bedding-corrected mean	359.5	-74.7	3.4		
Antarctic Peninsula 55 Ma (Gao et al. 2018)					
	Dec (°)	Inc (°)	α95	N	
Bedding-corrected mean	347.1	-74.0	3.4		
Marambio Island ca. 60 Ma (Tobin et al. 2012)					
	Dec (°)	Inc (°)	α95	N	
Bedding-corrected mean	352.5	-73.1	5.4	60	
Sanctuary Cliffs					
	Dec (°)	Inc (°)	α95	N	
In situ mean	101.3	76.7	8.4	52	
Bedding-corrected mean	107.1	65.8	8.7	52	
	Critical Angle (°)		Obeserved Angle (°)		Condition
Reversal test from bedding-corrected mean	24.5		15.2		Indeterminate
Spath Peninsula					
	Dec (°)	Inc (°)	α95	N	
In Situ mean	142.9	71.1	6.6	82	
Bedding-corrected mean	132.8	60.0	6.6	82	
	Critical Angle (°)		Obeserved Angle (°)		Condition
Reversal test from bedding-corrected mean	69.1		4.8		Indeterminate

or due to compaction during diagenesis. In fact, the mean direction computed from the lower Marambio Group (*ca.* 80 Ma) from northwestern James Ross Island (Milanese et al. 2019b, Fig. 7a), was corrected by an inclination shallowing factor *f* of 0.54 computed through the elongation-inclination method (Tauxe et al. 2008) before calculating the corresponding paleomagnetic pole. Given this scenario, the minor inclination anomaly (significance of 4°) obtained in the upper Marambio Group using Beck (1989)

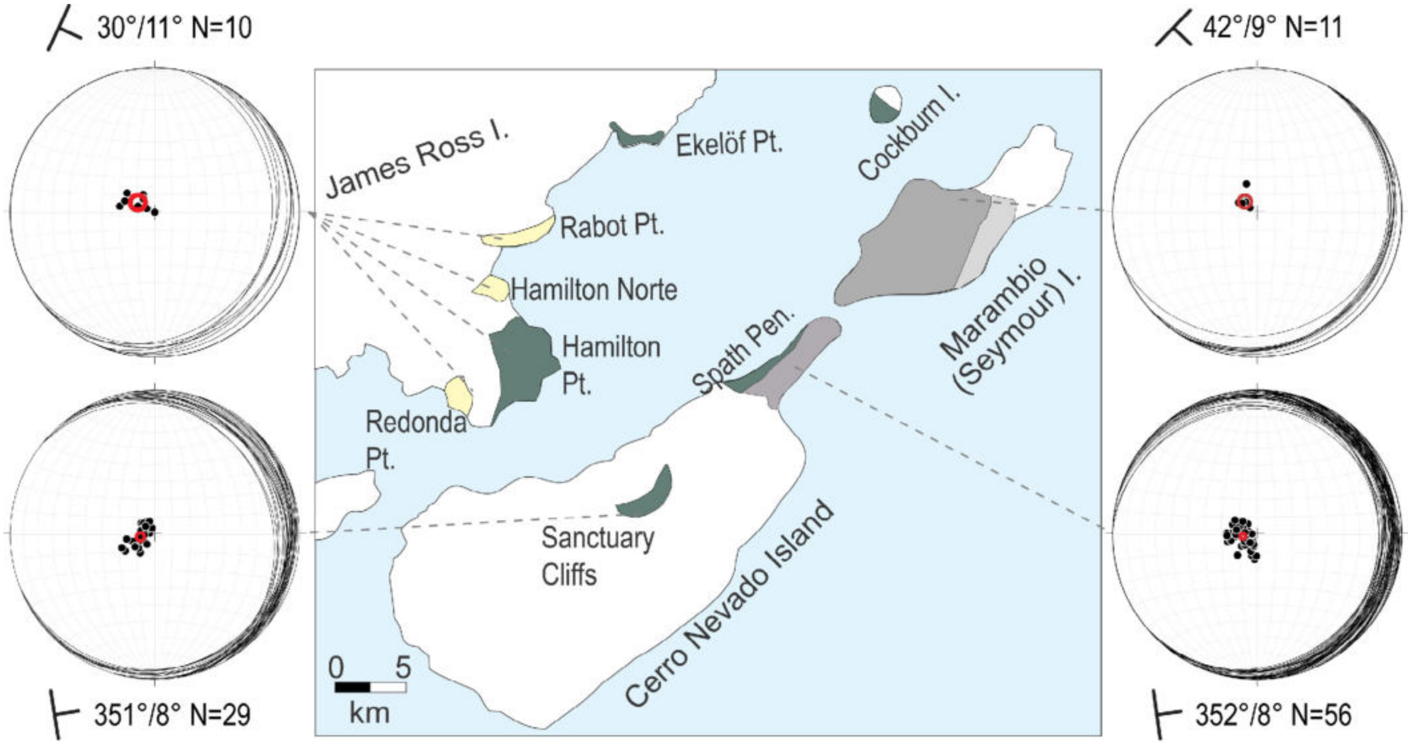

Figure 8. Bedding distribution in Sanctuary Cliffs, Spath Peninsula and southeast James Ross Island. Data from Marambio Island belong to Maestro et al. (2008) and Tobin et al. (2012). Bedding values are given in Table S5 (supplementary material).

and Demarest (1983) method can be speculatively attributed to an inclination shallowing effect due to compaction of clastic sediments during diagenesis. An attempt was made to compare this flattening value with the one obtained through elongation/inclination method (Tauxe et al. 2008), but Cerro Nevado Island Cretaceous paleomagnetic directions could not be compared with the TK03.GAD field model used by Paleomagnetism.org online platform (Koymans et al. 2016, Tauxe et al. 2008) in part due to the fact that mean direction from Spath Peninsula show significant different declination than that from Sanctuary Cliff which forbids using both datasets together for this calculation. This 4° inclination anomaly cannot be attributed to a latitudinal variation of Cerro Nevado, because it would imply a northern displacement of the island in the past while Marambio Island stood still, as indicated by its paleomagnetic pole (Fig. 7c).

Bedding does not seem to considerably change in the James Ross Basin, and a nearly homoclinal succession dipping ~10° to the E-SE has been always considered as the main attitude for the Cretaceous strata of the whole basin, despite local variations (e.g., Marenssi et al. 1998, Olivero 1998, Olivero et al. 2008). Shallow dipping of James Ross Basin sedimentary beds hampers the recognition in the field of tectonic rotations. Figure 8 summarizes the mean bedding attitudes of the Late Cretaceous-Paleocene successions of southeast James Ross Basin localities. Information of bedding planes of the López de Bertodano Formation at Marambio Island were obtained from Maestro et al. (2008) and from the original data used by Tobin et al. (2012). It is necessary to state that considering the shallow dips, bedding strikes vary consider-

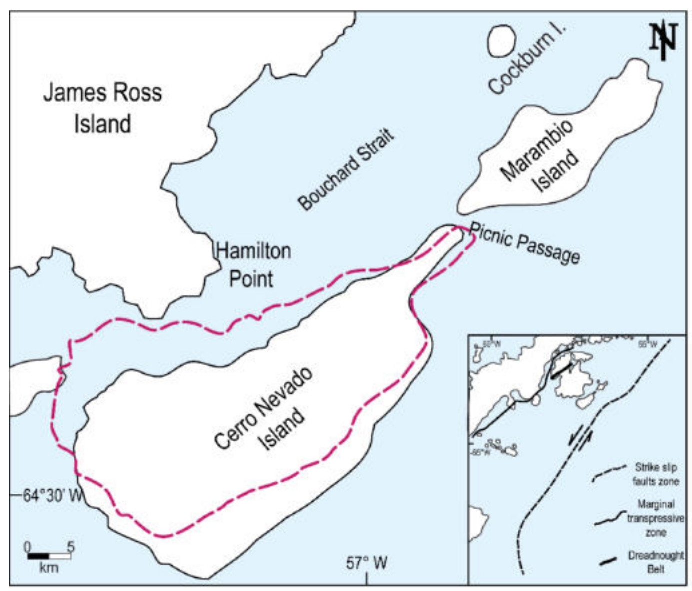

Figure 9. Hypothetical counterclockwise rotation of the Cerro Nevado Island of ~10°, around an axis located near the Picnic Passage. At the lower right, the major NE-SW strike-slip regional fault zone described by Sloan et al. (1995) and Ghidella et al. (2013) is indicated in dotted line. Other fault zones were described across the James Ross Island and in the Antarctic Peninsula (del Valle and Miller 2001, Strelin et al. 1992). See discussion in the main text.

ably between localities or even along a sequence. Olivero (1998) attributes some of these variations in the López de Bertodano Formation to the presence of large mud-filled tide channels that cut the tabular geometry of this unit (see dark gray units in figure 3b). Data coming from these channels have been excluded from bedding comparisons shown in figure 8, since strike variations in these cases can be of depositional origin, due to tilting and rotation, or a combination of both. In any case, it must be taken into account that paleomagnetic sampling at Spath Peninsula was carried out having special care to avoid these channels. Notwithstanding that data are still scarce, we can observe in figure 8 that mean bedding strikes from localities sampled at Cerro Nevado Island, both at Sanctuary Cliffs Nunatak and at Spath Peninsula, are NNW, meanwhile those at Marambio Island and southeast James Ross Island are NNE to NE. This systematic difference is consistent with a counterclockwise rotation of Cerro Nevado outcrops with respect to the Marambio and James Ross Islands as indicated by paleomagnetic mean directions. Bedding values are available in table S5 of the supplementary material.

It is necessary to constrain both the timing and configuration of the hypothetical rotation calculated. In first place, a small offset in the contact between Haslum Crag and López de Bertodano Formation at both sides of the Picnic Passage is observed (Fig. 3b). There is a group of WNW-ESE extensional faults at the northern tip of Spath Peninsula, whose trend coincides with the WNW-ESE oriented straight coastlines of both north Spath Peninsula and south Marambio Island (Pirrie 1997). This straightness could be the expression of the submarine continuity of this extensional fault system, responsible for the observed offset. A rigid body rotation of the Cerro Nevado Island could also be explained as a result of this fault system, but the offset is not large enough to justify the paleomagnetic results, especially if the vertical rotation axis is placed in the island center. Relative positions of the northern margin of the Spath Peninsula and the southern one of the Marambio Island should not change significantly from the present one, which suggests that the rotation pole should be near the Picnic Passage. A rough trigonometric calculation, keeping the present geographic configuration and assuming an undisturbed and unrotated homoclinal succession dipping 5° to the SE across the Bouchard Strait (Fig. 9), gives a minimum of ~800 m of sedimentary thickness missing between SE James Ross Island and Sanctuary Cliffs (Fig. 1). However, a much shorter stratigraphic gap between these outcrops has been confirmed recently with magnetostratigraphic data by Milanese et al. (2019a). This could be explained by a rigid body counterclockwise rotation of 10° of the Cerro Nevado Island around a vertical axis located at ~64° 24' S, 56° 24' W, as illustrated in figure 9. Unrotating the island would juxtapose its southwestern margin with southeastern James Ross Island (Hamilton Point area). This reduces the potential stratigraphic gap between Cretaceous strata exposed at Hamilton Point (SE James Ross Island) and at Sanctuary Cliffs and maintains the small offset between Spath Peninsula and Marambio Island as much as possible.

Several problems arise from the hypothetical rotation shown in figure 9. In first place, it accounts only for one third of the magnitude indicated by the paleomagnetic data. Besides, although the sampled sections show significant differences in the bedding strikes than those observed at Marambio and southeast James Ross Islands, other authors have reported NNE strikes in other areas at Sanctuary Cliffs (Robles Hurtado 1993), Spath Peninsula and southwestern Marambio Island (Olivero et al. 2008, Pirrie et al. 1997, see Fig. 3), including those recognized as due to original configuration of the tidal channels fill (Olivero 1998). In our case a simple relationship between bedding strikes and paleomagnetic declination would suggest that those outcrops with NNE strikes (SE James Ross Island and Marambio Island) did not undergo significant rotations while the others did (Sanctuary Cliffs and Spath Peninsula, see figure 7). Cerro Nevado Island ice-cover and the lack of detailed geophysical surveys are further problems for attempting a comprehensive tectonic model that can account for the anomalous paleomagnetic directions and the known structural-stratigraphical features. To further complicate a simple rigid-body rotation of the Cerro Nevado Island, if the mean paleomagnetic directions computed at Sanctuary Cliff Nunatak and Spath Peninsula are considered independently, different rotations respect to Marambio Island are inferred for each area: -65.4° ± 25.8° for Sanctuary Cliffs and -39.7° ± 18.5° for Spath Peninsula. Therefore, even if an hypotethical rigid-body counter-clockwise rotation of *ca.* 10° is accepted for the whole Cerro Nevado Island (Fig. 9), most of the declination anomalies found, including possible relative rotations between Sanctuary Cliffs and Spath Peninsula successions, must have occurred while the successions were still subhorizontal. Regional tilting to the SE plus further local tilting in other directions must have occurred after most of the proposed tectonic rotations took place. The nearly homoclinal tilting of the James Ross Basin infill has been assigned to the early Eocene before deposition of the La Meseta Formation (Marenssi et al. 2012, Smellie et al. 1988). Therefore, the above cited hypothetical rotations must have occurred in pre-Eocene times, and more precisely between the early Paleocene – early Eocene.

Crame et al. (1991) suggested synsedimentary faulting activity during final stages of deposition of the Marambio Group sediments. Pirrie and Riding (1988) described Late Cretaceous small synsedimentary faults producing flower-type structures in Humps Island and indicative of strike-slip deformation along faults trending NE-SW. The study of Maestro et al. (2008) in the Marambio Island determined that the southeast James Ross Basin was affected since at least the Paleocene by NW-SE extensional stress, that may have been active even in Cretaceous times, associated to the development of the back-arc basin and the opening of the Weddell Sea. This was superimposed by a NE-SW extensional stress regime in Eocene-Oligocene times presumably associated to the opening of the Powell Basin that produced NW-SE directed fault-bounded incised valleys. According to Maestro et al. (2008), the presence of several NW-SE normal faults along the Spath Peninsula (Fig. 3b) is an indication of such regime. These data point to a complex extensional, or perhaps transtensional, tectonic regime for the whole Cenozoic in the study region. Sloan et al. (1995) describe the presence of a major NE-SW directed strike-slip regional fault zone of over 100 km long some 30 km to the southeast of Marambio and Cerro Nevado Islands (Fig. 9). Ghidella et al. (2013) confirmed the presence of such zone on the basis of aeromagnetic surveys. According to these authors, that zone experienced left lateral transcurrent movements and may indicate some relative displacement between the Larsen Basin and the Weddell Sea in early Cenozoic times. Other fault zones subparallel to this have been described across the James Ross Island, like the Dreadnought Belt (Strelin et al. 1992, Fig. 9). Although no structural data are available from the bottom of the Bouchard Strait, it is parallel to those major structures and submarine strike-slip and/or normal faults cannot be ruled out with the available geophysical data. A tectonic context as that present in early Cenozoic times in the region is compatible with counterclockwise tectonic rotations of some blocks due to local or regional sinistral transtensional stress regimes. However, our speculations need to be tested with new detailed paleomagnetic studies at different localities along Cerro Nevado Island as well as geophysical surveys along the island and its marine surroundings.

CONCLUSIONS

The paleomagnetic results obtained along two sections of the Late Cretaceous Marambio Group at Cerro Nevado Island (Sanctuary Cliffs Nunatak and Spath Peninsula, ~72 to 70 Ma) showed anomalous mean paleomagnetic declinations suggesting a counterclockwise tectonic rotation of 47.9°±20.0° with respect to Marambio Island, and a flattening value of -10.5°±6.5°, probably due to an inclination shallowing produced during sediments deposition and /or compaction. The correlation of the paleomagnetic declination anomalies with mean NNW bedding strikes at the sampling localities is consistent with such tectonic rotation, since unrotated localities as SE James Ross Island and Marambio Island show NE bedding strikes. The very low dip of the sequences turns the identification of tectonic rotations from the structural attitudes uncertain. However, rough correlation of outcrops from Sanctuary Cliffs with SE James Ross Island and from northern Spath Peninsula with those from southern Marambio Island constrain a hypothetical rigid body rotation of the island to a maximum of 10° and around an axis located close to the Picnic Passage. NNE bedding strikes reported at several other localities in Cerro Nevado (not sampled for paleomagnetic studies) also pose difficulties for a large (over 10°) rigid body rotation of the island. Smaller block rotations promoted by a long-lasting regional sinistral transtensional regime affecting the James Ross Basin is proposed as a working hypothesis to find viable mechanisms for the rotations found. These should have occurred before main tilting event of the Marambio Group sediments during the Eocene. Further paleomagnetic studies in other localities of the Snow Hill Island and detailed geophysical surveys in and around the island are needed for a more robust tectonic model.

ACKNOWLEDGEMENTS

To the Instituto Antártico Argentino for the logistic support during the Antarctic field seasons, and the NSF Office of Polar Programs (NSF grant 1341729 to JLK) for support of the laboratory work at Caltech. Grants from Universidad de Buenos Aires (UBACyT 20020130100465BA to A. Rapalini) provided additional support for this research. Thanks are due to Daniel Yagupsky for the very useful scientific debates. Ana Lossada, Lucía Sagripanti and Florencia Boedo's opinions were very helpful during the last stage of the correction. A critical lecture by Eduardo Olivero is deeply acknowledged. Florencia Milanese would like to specially thank to the US vessel crew Gould for the shower taken aboard during their one-day visit to Cerro Nevado Island in 2011. Sadly, samples collected that day showed an unusual magnetic instability and were ruled out from further analysis. Constructive critical reviews by M.P. Iglesia Llanos and A. Goguichaishvilli are gratefully acknowledged.

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