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Paleomagnetism and tectonics of the South Shetland Islands and the northern Antarctic Peninsula

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ABSTRACT

New paleomagnetic data presented here from 61 sites in Paleozoic, Mesozoic and Cenozoic igneous and sedimentary rocks from the Antarctic Peninsula and the South Shetland Islands constrain the relative motion of the Antarctic Peninsula since the mid-Cretaceous and allow the quantification of tectonic rotation between the different blocks recognized within the area. Paleozoic and Jurassic results failed the fold test and suggest an important remagnetization in the area. The similarity between these results and those obtained from Cretaceous intrusives indicates a mid-Cretaceous age for the remagnetization. The paleopoles obtained for the different blocks and for different ages suggest that there is no relative rotation among them. These combined results allow us to obtain a Cretaceous (90 Ma) and Paleocene (60 Ma) paleopole.

These paleopoles document a very low apparent polar wandering of the Antarctic Peninsula for the last 100 Ma.

1. Introduction

During the Paleozoic, South America, Arabia, Africa and East and West Antarctica were part of the Gondwana supercontinent (Torsvik et al., 2008; Vaughan and Pankhurst, 2008). The breakup of Gondwana began around 167 Ma when north–south oriented separation between East Antarctica and Africa occurred, giving origin to the Mozambique Basin–Riiser-Larsen Sea, and the Somali Basin (König and Jokat, 2006). Subsequently, at 147 Ma the first true ocean floor associated with rifting between the Antarctic Peninsula and southernmost South America formed the Weddell Sea (König and Jokat, 2006). Whereas strong constraints exist on the movement between Africa and East Antarctica, a major problem concerns the geometrical fit and subsequent drift history between southernmost South America and the Antarctic Peninsula.

Proposed models have shown that at 160 Ma the Antarctic Peninsula may have been attached to Patagonia (Dalziel, 1982; Ghidella et al., 2002; König and Jokat, 2006; Livermore and Hunter, 1996; Martin, 2007; Miller, 1983; Norton and Sclater, 1979; Torsvik et al., 2008). However, the connection between Patagonia and the Antarctic Peninsula has been controversial within Gondwana breakup models. Some models have shown the Antarctic Peninsula attached to the eastern border of Patagonia (Dalziel, 1982; Norton and Sclater, 1979), whereas others place the Antarctic Peninsula attached to the western edge of Patagonia (Ghidella et al., 2002; Harrison et al., 1979; König and Jokat, 2006; Miller, 1983; Torsvik et al., 2008). It has also been suggested that the northern tip of the Antarctic Peninsula was joined to the southern edge of Patagonia (Dalziel and Elliot, 1972; Storey, 1991; Suárez, 1976).

Most paleogeographic reconstructions that include the Antarctic Peninsula and Patagonia are constrained by seafloor magnetic anomalies in the Weddel Sea. However, because of the tectonic complexity of the region, it is difficult to define isochrons accurately older than 83.5 Ma (Ghidella et al., 2002, 2007). In the plate tectonic reconstruction of Ghidella et al. (2002), where South America is fixed, the Antarctic Peninsula underwent a relative southward latitudinal motion from the breakup of Gondwana until about 118 Ma. Subsequently, since 90 Ma the Antarctic Peninsula went through an important clockwise rotation to finally arrive at its current position (Cunningham et al., 1995; Ghidella et al., 2002). The final separation between the Antarctic Peninsula and Patagonia occurred around 40 Ma when the Scotia Plate was formed (Barker, 2001).

Paleomagnetic studies have also been carried out to provide constraints on the relative positions between Patagonia, the Antarctic Peninsula and East Antarctica. According to Grunow (1993) the Antarctic Peninsula had undergone a clockwise rotation from 175 to 155 Ma and a counterclockwise rotation between 155 and 130 Ma.

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Grunow (1993) suggested that the clockwise rotation was related to the opening of the Weddell Sea. Although this interpretation is in good agreement with the age proposed for the opening of the Weddell Sea at about 160 Ma by Ghidella et al. (2002), it is slightly older than the age proposed by König and Jokat (2006). In the same way, Eagles and Vaughan (2009) proposed a tectonic model of the Weddell Sea using the constraints imposed by the opening of the South Atlantic and SW Indian oceans. Their results suggest that Gondwana broke up into just two plates by continental deformation in contrast to the three-plate breakup model proposed by König and Jokat (2006), and indicate no independent movements between the small plates during the Gondwana breakup. Several paleomagnetic studies have suggested that the Antarctic Peninsula would have had little latitudinal movement relative to East Antarctica since at least 100 Ma (Dalziel et al., 1973; Grunow, 1993; Kellogg and Reynolds, 1978; Valencio et al., 1979; Watts et al., 1984). These studies also suggest that the actual curvature of the Antarctic Peninsula is a structural feature already shaped by about 100 Ma.

In this contribution we present the results of an extensive paleomagnetic study during which more than 450 samples were collected from the South Shetland Islands and the Antarctic Peninsula. These new data, which are broadly consistent with previous results, are utilized to better constrain the tectonic model of this key region of Antarctica.

2. Tectonic setting

The Antarctic Plate is mostly surrounded by oceanic spreading ridges which define the boundaries of six neighboring tectonic plates (Fig. 1). Antarctica consists of two geologically distinct provinces, the East Antarctic Craton and the West Antarctic Rift System. The Transantarctic Mountains are one of the dominant features of the Antarctic continent and define the boundary between East Antarctica and the West Antarctic Rift System. East Antarctica is a Precambrian craton locally overlain by Devonian to Jurassic units (Fitzsimons, 2000; Harley, 2003). East Antarctica has remained stable around the South Pole since at least 75 Ma (Torsvik et al., 2008). West Antarctica is formed by a younger series of mobile belts which include at least four major crustal blocks (Antarctic Peninsula, Thurston Island, Ellsworth–Withmore Mountains and Marie Byrd Land) with independent Mesozoic and Cenozoic tectonic histories (Fig. 1). During the breakup of Gondwana these four crustal blocks moved relative to each other and to the East Antarctic Craton as rigid blocks (Dalziel and Elliot, 1982; Dalziel and Lawver, 2001). Some authors have subdivided these crustal blocks into minor terranes (Pankhurst et al., 1998; Vaughan and Storey, 2000; Vaughan et al., 2002). In the case of Marie Byrd Land, Pankhurst et al. (1998), on the basis of geochronological and geochemical data, divided the block into the Amundsen and Ross provinces. For the Antarctic Peninsula, this block is considered to be formed by three domains that amalgamated to each other during the mid-Cretaceous (Vaughan and Storey, 2000; Vaughan et al., 2002).

The northern Antarctic Peninsula has been part of the Pacific margin since before the breakup of Gondwana (Barker, 1982) although its pre-mid-Cretaceous history could be more complicated. A collision history, related to subduction process has been identified in the area. At least two or three terranes collided during the Palmer Land event, suggesting a progressive change in the Gondwana margin in that area (Vaughan and Livermore, 2005; Vaughan and Storey, 2000). Before the latter event, siliciclastic turbidite deposits of the Trinity Peninsula Group (Fig. 1, right), up to 3 km thick, were deposited during the Permian to Triassic in a marginal basin setting (Birkenmajer, 1994). An episode of deformation occurred during the

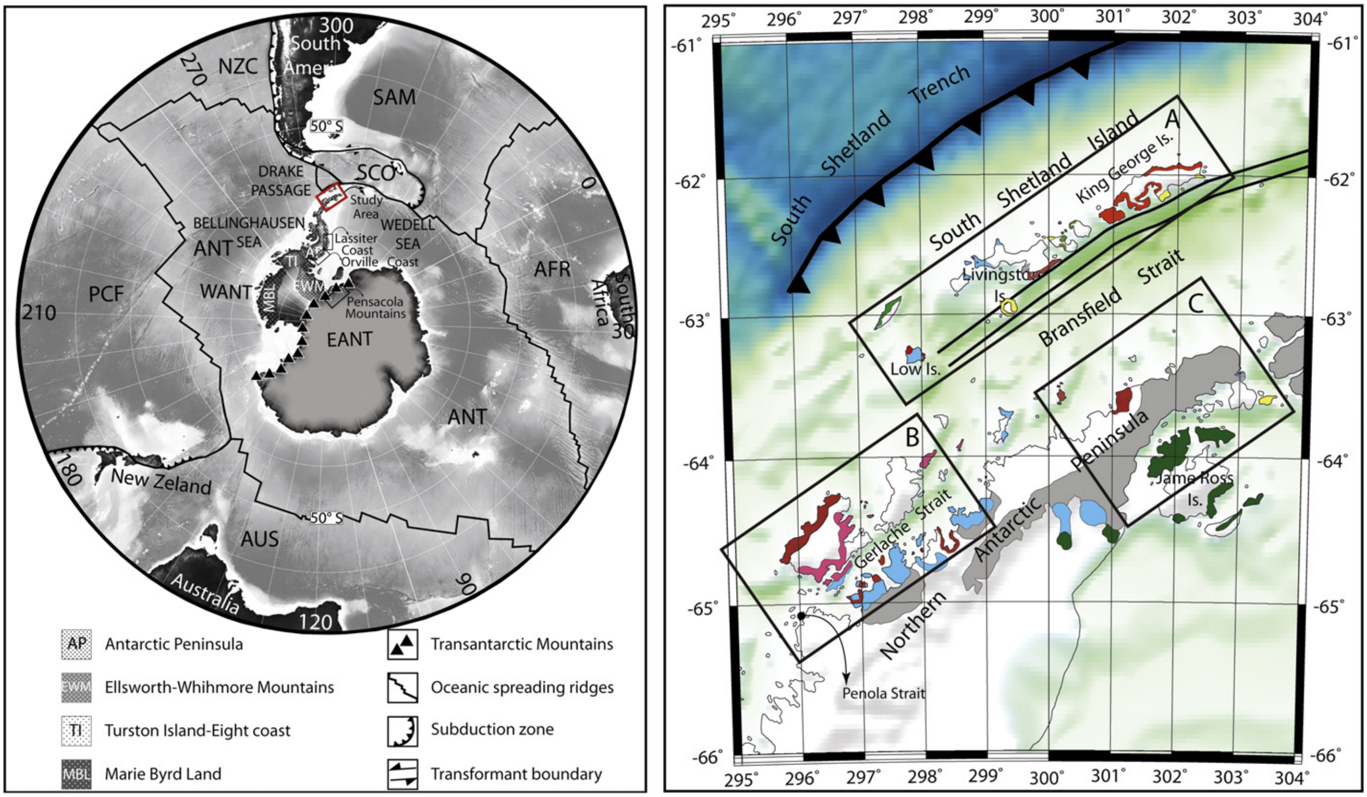

Fig. 1. (Left): Major plate organization around the South Pole. ANT (Antarctic) Plate is bounded by six plates: AUS (Australian), PCF (Pacific), SAM (South America), SCO (Scotia), NZC (Nazca) and AFR (African) Plates. Antarctica is subdivided into 2 provinces: West Antarctica (WANT) and East Antarctica (EANT) divided by the Transantarctic Mountains. West Antarctica consists of four major distinctive terranes: AP (Antarctic Peninsula), TI (Thurston Island Eights Coast), EWM (Ellsworth-Whitmore Mountain) and MBL (Marie Byrd Land) (Modified from Barker, 2001; Grunow, 1993; Klepeis and Lawver, 1996; Smalley et al., 2007; Torsvik et al., 2008). (Right): Simplified geological map (from British Antarctic Survey, 1985; Farquharson, 1982; Hervé et al., 2006a,b; Klepeis and Lawver, 1996; modified). Lithology is further described in the text. Legend and frames A, B and C are shown in Fig 2.

Late Triassic and affected the Trinity Peninsula Group. This event has been considered as part of the Gondwanian orogeny by Smellie (1991) and Birkenmajer (1994), but might well correspond to the Peninsula Orogeny of Miller (1983) and Vaughan and Livermore (2005) particularly if its timing extends into the earliest Jurassic.

In the Antarctic Peninsula, magmatism has been active at least since the Jurassic (Leat et al., 1995). It is possible to distinguish two magmatic stages (Fig. 1, right; second stage a and b in Fig. 2). During the first stage, and related to acid volcanism, three extensive episodes of plutonism have been identified at 188–178 Ma, 172–162 Ma, and 157–153 Ma (Pankhurst et al., 2000). This magmatic province, known as the Chon Aike Province (Pankhurst et al., 1998) has a crustal signature and has been related to the Gondwana breakup (Hervé et al., 2007; Pankhurst et al., 2000). In the second stage a, magmatism with a tholeiitic to calc-alkaline signature, started to develop during the Early Cretaceous and migrated to outer positions during the Late Cretaceous to Miocene (Birkenmajer, 1994; Kraus, et al., 2008; Machado et al., 2005; Willan and Kelley, 1999). From Late Miocene to Recent times, the Bransfield Rift, a back-arc basin, developed at the north-western margin of the Antarctic Peninsula as a result of transtensional processes and the roll-back of the Phoenix Plate beneath the South Shetland Island (Barker, 1982; Barker et al.,

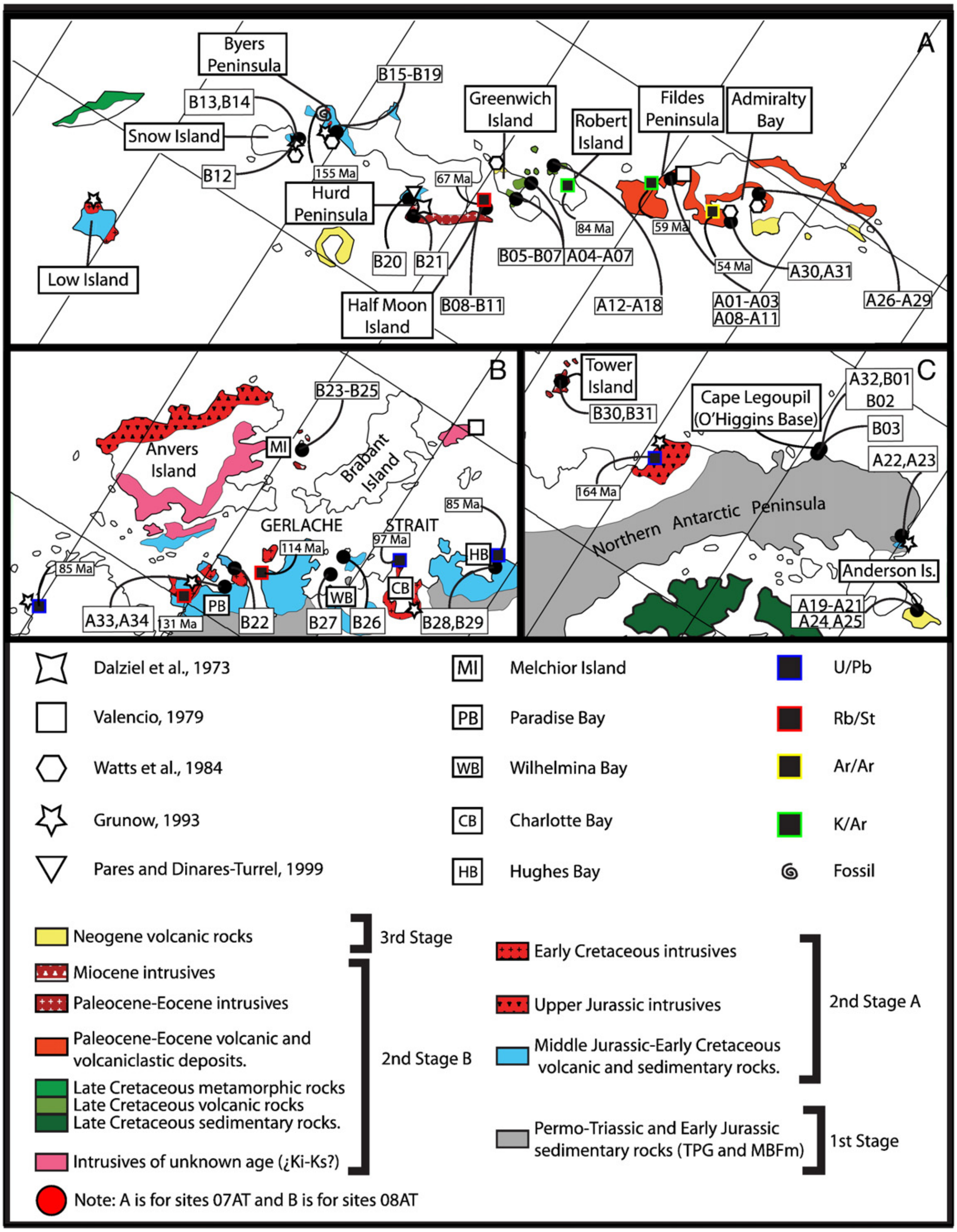

Fig. 2. Magnified areas from northern Antarctic Peninsula. Locations of frames A, B and C are shown in Fig 1. Sampling site locations for this study are indicated by black dots. Geochronology and paleomagnetic data for previous studies published in the area are also shown.

2003; Solari et al., 2008). However, Birkenmajer (1994), extends the initial rifting back to the Oligocene.

3. Paleomagnetic sampling and procedures

Paleomagnetic sampling was undertaken in the austral summers of 2006/2007 and 2007/2008, during which we collected more than 450 oriented cores. We sampled the South Shetland Islands (41 sites) and the northern Antarctic Peninsula (23 sites). The locations of paleomagnetic sites are given in Table A (see supplementary data) and shown in Fig. 2. Within the South Shetland Islands most samples are from the Upper Cretaceous Coppermine Formation (~85 Ma), which consists of olivine basaltic and basaltic andesite lava flows, as well as polymictic lappilli-stones and agglomerates with multiple intrusions (Hervé and Araya, 1965; Machado et al., 2005) and from the Fildes Peninsula Formation (~55 Ma) basalts, andesites and volcaniclastic rocks (Birkenmajer, 2001; Smellie et al., 1984). Several samples were also drilled in dikes from the Admiralty Bay Group and from basalts, andesites and basaltic andesite rocks of the Marlet Inlet Group (~55 Ma) in Admiralty Bay. A few are from mudstones and sandstones in the Upper Jurassic Anchorage Formation (~150 Ma) in the Byers Peninsula and from sedimentary rocks in the Lower Cretaceous Chester Cone Formation (~140 Ma) and Eocene intrusives (~55 Ma) on Snow Island (Hathway and Lomas, 1998; Watts et al., 1984).

In the Gerlache Strait and the northern part of the Antarctic Peninsula most samples are from siliciclastic turbidites of the Permo-Triassic Trinity Peninsula Group and from Cretaceous and Miocene intrusives ranging between diorite and granite. A few are from Jurassic volcanic–volcaniclastic and Neogene volcanic rocks.

Samples were, at most sites, cored with a portable drill and orientated by both sun and magnetic compasses. Only two sites (08AT30-08AT31) were sampled using oriented block samples due to access problems. Samples were analyzed in paleomagnetic laboratories at the Universidad de Chile and the Université de Rennes. For most samples, one specimen was subjected to stepwise thermal demagnetization (10–15 steps) in an ASC Scientific furnace where the residual field was less than 10 nT. Magnetic susceptibility was measured after each thermal demagnetization step, in order to check magnetic mineralogical changes upon heating. Remanence was measured with either a spinner magnetometer (Molspin or AGICO JR5A) or a 2 G cryogenic magnetometer. To better investigate the origin of the remanent magnetization, stepwise alternating field (AF) demagnetization using a Molspin AF instrument or the 3 axis AF degausser online with the 2 G magnetometer was also performed on some samples.

Characteristic remanence (ChRM) component directions were determined using principal component analysis (Kirschvink, 1980). Site-mean directions were defined using classical Fisher statistics or a combination of individual components and remagnetization circles where necessary (McFadden and McElhinny, 1988). For typical (and some atypical) samples, the magnetic carriers of the ChRM were investigated further by means of IRM acquisition and demagnetization experiments. Additionally, thin and polished sections of the studied rocks were microscopically analyzed by transmitted and reflected light in order to identify the magnetic minerals and their paragenesis.

Radiometric age control is based on a compilation of previously published data (see supplementary data, Table sd4) and on unpublished U–Pb zircon results from some paleomagnetic sites by Calderón et al. (unpublished data).

4. Paleomagnetic results

The following results are summarized in Table 1 and organized according to the age of the rock units.

4.1. Results from Permo-Triassic and Jurassic rocks

All samples from sites within fine-grained sandstones, mudstones and metasandstones of the Trinity Peninsula Group (Hope Bay, Legoupil and Paradise Harbor Formations), sandstones and mudstones of the Anchorage Formation, and metasandstones of the Miers Bluff Formation, have relatively low values of susceptibility (between 10^{-3} and 10^{-4} SI units) and NRM intensities range from 2×10^{-2} to 5×10^{-4} A m^{-1} (Table A; see supplementary data).

All samples from sites 07AT32 and 07AT34 in the Legoupil and Paradise Harbor Formations have characteristic magnetizations with a narrow unblocking temperature range near 300 °C (Fig. 3A). IRM acquisition indicates the presence of a magnetic phase with magnetic saturation above 300 mT, indicating that this phase is not titanomagnetite (Fig. 3A). Microscopic observations in reflected and transmitted light from thin-polished sections of the Trinity Peninsula Group at the O'Higgins Base (07AT32) at Cape Legoupil confirm that pyrrhotite is the main magnetic carrier. The opaque mineral in the fine sandstone occurs mainly in veinlets: chalcopyrite in chlorite veinlets and fine pyrrhotite (less than 10 μm) in biotite veinlets (Figs. sd1a and sd1b, see supplementary data). From site 07AT34 (Trinity Peninsula Group) in Paradise Bay the very fine-grained nature of the mudstone restricted our observations on the magnetic mineralogy, which are therefore not conclusive.

Unfortunately, at all other sites drilled in sedimentary rocks in Legoupil (08AT01, 08AT02), and Hope Bay (07AT22, 07AT23) the magnetization was unstable during thermal or AF demagnetization and it has been impossible to determine a characteristic remanent magnetization.

Jurassic deposits were sampled at 4 sites from Start Hill (08AT15 to 08AT18). Sites 08AT15 and 08AT17 correspond to thin-bedded, fine-grained deposits. Microscope observations of samples from site 08AT15 show numerous small lithic plagioclases suggesting that the fine mudstone and sandstone are intercalated with finer-grained ash deposits (Fig. sd1c, see supplementary data). Within the thin tuff we observed pyrrhotite as the main magnetic carrier and small rutiles which could reflect disequilibrium in the rock (Fig. sd1d, see supplementary data). The two other sites correspond to thicker beds with a larger grain size. A characteristic direction was determined in only 3 samples at site 08AT15 and in 3 samples at site 08AT18. The magnetization could be of primary origin but the limited data preclude further interpretation.

Three sites were drilled in rocks attributed to the Antarctic Peninsula Volcanic Group (APVG). Univectorial magnetizations are observed with high unblocking temperatures (Fig. 3B) and magnetite grains (<10 μm) as the main magnetic carrier. At *in situ* coordinates, the magnetization is well grouped and strongly scattered after bedding correction. A possible explanation for this behavior is that the magnetizations are secondary due to hydrothermal alteration, despite the strong (above 1 A/m) and stable magnetizations going through the origin during the demagnetization, which suggests a primary origin instead.

Microscope observations also support a secondary origin for the magnetization. At site 08AT22 subhedral–anhedral magnetite is recognized to be predominately concentrated in the lithic components of tuffs, diminishing gradually towards the groundmass whose texture is partially obliterated (Fig. sd1e and sd1f, see supplementary data). In the crystal-rich lithic tuff sampled at site 08AT29, however, the original texture of the rock is recognized in fine-grained biotitization and chloritization affecting the groundmass. Magnetite and sulphides are identified as well. Finally, at site 07AT33 (basaltic andesitic lava flow) we recognized a chloritization event affecting the whole rock that is associated with chlorite-epidote-anhydrite veinlets. The brownish color of the chlorite suggests that this event superimposed its effect on a previous biotitization event.

The characteristic directions in Permo-Triassic and Jurassic rocks (07AT32, 07AT33, 07AT34, 08AT22, 08AT29, except at sites in the Anchorage Formation at Start Hill) are well grouped in *in situ*

Table 1
Paleomagnetic results.

In situ	Bed correction								
Site	Lithology	N/n	Dec	Inc	Dec	Inc	α95	Kappa	Type/Age
Permo-Triassic and Jurassic rocks:									
O'Higgins Base									
07AT32	Sedimentary	9/6	358.2	−74.1	141.8	−63.0	1.8	1454	B/Kmed
Gerlache Strait									
08AT22	Volcanic	8/7	7.5	−71.6	106.9	−38.6	4.9	155	B/Kmed
08AT29	Volcanic	6/6	345.8	−67.7	140.3	−30.1	1.8	1133	B/Kmed
07AT33	Volcanic	9/8	334.2	−71.1	334.2	−71.1	5.3	112	B/Kmed
07AT34	Sedimentary	7/4	355.2	−67.4	348.6	2.2	6.3	213	B/Kmed
Start Hill, Byers Peninsula									
08AT15	Sedimentary	6/3	279.3	−69.0	346.5	−63.1	16.1	60	B/Kmed
Cretaceous intrusive and volcanic rocks:									
O'Higgins Base									
08AT03	Sill	6/6	348.2	−79.2	348.2	−79.2	3.6	350	A/Kmed
Gerlache Strait									
08AT26	Intrusive	9/8	357.9	−72.8	357.9	−72.8	2.1	722	A/Kmed
08AT28	Intrusive	8/6	345.3	−72.7	345.3	−72.7	2.5	730	A/Kmed
Start Hill, Byers Peninsula									
08AT18	Sill	5/3	273.0	−71.7	350.9	−68.1	11.7	113	A/Kmed
Cerro Negro Hill, Byers Peninsula									
08AT19	Weld. Ign	9/7	2.6	−60.3	340.0	−30.5	3.3	334	A/Kmed
Robert Island									
07AT12	Volcanic	5/4	4.2	−72.7	4.2	−72.7	12.9	52	A/Ksup
07AT14	Volcanic	6/6	359.2	−73.4	359.2	−73.4	5.3	158	A/Ksup
07AT15	Volcanic	4/4	355.8	−70.9	355.8	−70.9	5.9	245	A/Ksup
07AT16	Volcanic	5/5	359.1	−65.1	359.1	−65.1	4.3	319	A/Ksup
07AT17	Volcanic	5/5	29.4	−82.9	29.4	−82.9	2.4	785	A/Ksup
07AT18	Volcanic	5/5	349.8	−77.1	349.8	−77.1	3.0	644	A/Ksup
Greenwich Island									
07AT04	Volcanic	7/6	3.3	−73.6	3.3	−73.6	2.6	670	A/Ksup
07AT05	Volcanic	10/8	232.4	−72.6	174.9	−78.9	2.7	413	A/Ksup
07AT06	Volcanic	6/5	41.8	−66.3	41.8	−66.3	10.0	59	A/Ksup
08AT05	Volcanic	7/7	1.4	−63.2	1.4	−63.2	3.1	369	A/Ksup
08AT06	Volcanic	8/7	3.3	−79.8	3.3	−79.8	1.6	1487	A/Ksup
08AT07	Volcanic	10/5	338.9	−72.4	338.9	−72.4	8.8	77	A/Ksup
Paleocene igneous and volcanic rocks:									
Torres Island									
08AT30	Intrusive	7/4	169.0	74.2	169.0	74.2	14.8	143	A/KT
08AT31	Intrusive	6/6	135.9	71.9	135.9	71.9	2.8	592	A/KT
Snow Island									
08AT13	Sill	6/5	335.3	−73.0	335.3	−73.0	3.0	647	A/PalEoc
08AT14	Sill	5/4	339.0	−78.6	339.0	−78.6	2.6	1261	A/PalEoc
08AT12	Sedimentary	15/10	230.3	68.3	162.8	87.8	4.0	144	A/PalEoc
Half Moon									
08AT08	Volcanic	7/5	174.0	67.4	174.0	67.4	5.1	228	B/KT
08AT09	Volcanic	6/4	153.9	76.5	153.9	76.5	6.4	205	B/KT
08AT10	Intrusive	10/8	147.1	74.8	147.1	74.8	4.5	152	A/KT
08AT11	Volcanic	5/5	135.7	72.1	135.7	72.1	6.1	61	B/KT
King George Island									
07AT01	Volcanic	4/4	314.1	79.7	91.7	75.7	6.6	197	A/PalEoc
07AT08	Dyke	6/5	206.8	73.3	206.8	73.3	6.2	154	A/PalEoc
07AT09	Volcanic	7/4	359.4	−72.2	359.4	−72.2	5.1	320	A/PalEoc
07AT11	Volcanic	6/5	288.5	68.0	320.2	72.3	4.1	401	A/PalEoc
Admiralty Bay									
07AT30	Dyke	6/5	250.5	76.1	250.5	76.1	8.8	89	A/PalEoc
Miocene Intrusive rocks:									
Gerlache Strait									
08AT23	Intrusive	8/5	39.5	−70.9	339.5	−70.9	14.2	30	A/Miocene
08AT24	Intrusive	10/7	7.1	−70.3	7.1	−70.3	6.8	81	A/Miocene
Pliocene–Pleistocene Volcanic rocks:									
Anderson Island									
07AT19	Volcanic	4/4	155.5	75.8	175.7	77.1	5.6	364	A/Pli
07AT20	Volcanic	6/5	157.7	78.8	184.0	79.7	3.9	392	A/Pli
07AT24	Volcanic	4/4	130.6	71.0	138.8	73.7	2.1	1968	A/Pli
07AT25	Volcanic	6/6	125.1	80.2	151.3	83.7	5.0	179	A/Pli

Antarctic Peninsula site mean directions arranged according to age and location. N/n Number of samples v/s number of samples used in the calculation of the mean direction; Dec, inc mean declination and inclination *in situ* and after bedding correction; α95 semi-angle at the 95% confidence level; Kappa Fisher's precision parameter; Type/Age type of magnetization where A is of primary and B of secondary age, and the postulated age of the magnetization.

coordinates and show very large scatter upon tilt correction (Fig. 3C). This observation suggests a contemporaneous time for the acquisition of the characteristic magnetization and the emplacement of the intrusives (see below).

4.2. Results from Cretaceous intrusive and volcanic rocks

All sites have high magnetic susceptibility values (>0.01 SI) (Table A; see supplementary data) and unblocking and Curie temperatures (Fig. 4A and Fig. sd4, see supplementary data), indicating that magnetite is the dominant magnetic carrier in most of these rocks.

All sites have normal polarity (Fig. 4B) in agreement with radiometric dating, suggesting that most of these intrusive rocks were emplaced during the long normal Cretaceous superchron (Pankhurst, 1982; Tangeman et al., 1996). A single component of magnetization is observed after removal of a small, soft component of likely viscous origin (Fig. 4C). A bedding correction was tentatively estimated from fiamme elongation in the welded ignimbrite at site 08AT19, but the *in situ* direction is in better agreement with the other directions indicating a post-tectonic remagnetization, or that the bedding correction was poorly defined.

In intrusive rocks from the Gerlache Strait, microscopic analysis confirms the presence of magnetite as the main magnetic carrier (Fig. sd2, see supplementary data). At site 08AT28, two families of Fe–Ti oxides are recognized. The first family corresponds to fine subhedral–euhedral magnetite with a grain size smaller than 10 μm. This mineral is hosted mainly within euhedral mafic minerals. The second family of Fe–Ti oxides also corresponds to magnetites, however with a grain size exceeding 50 μm. This mineral is recognized principally within mafic mineral borders and in association with chlorite. For the first family of magnetite, the shape and location within other silicate minerals (mainly pyroxene) suggest that this magnetite is related to a magmatic crystallization process, as also suggested by Evans and McElhinny (1966). On the other hand, the second family of magnetite could be related to post-

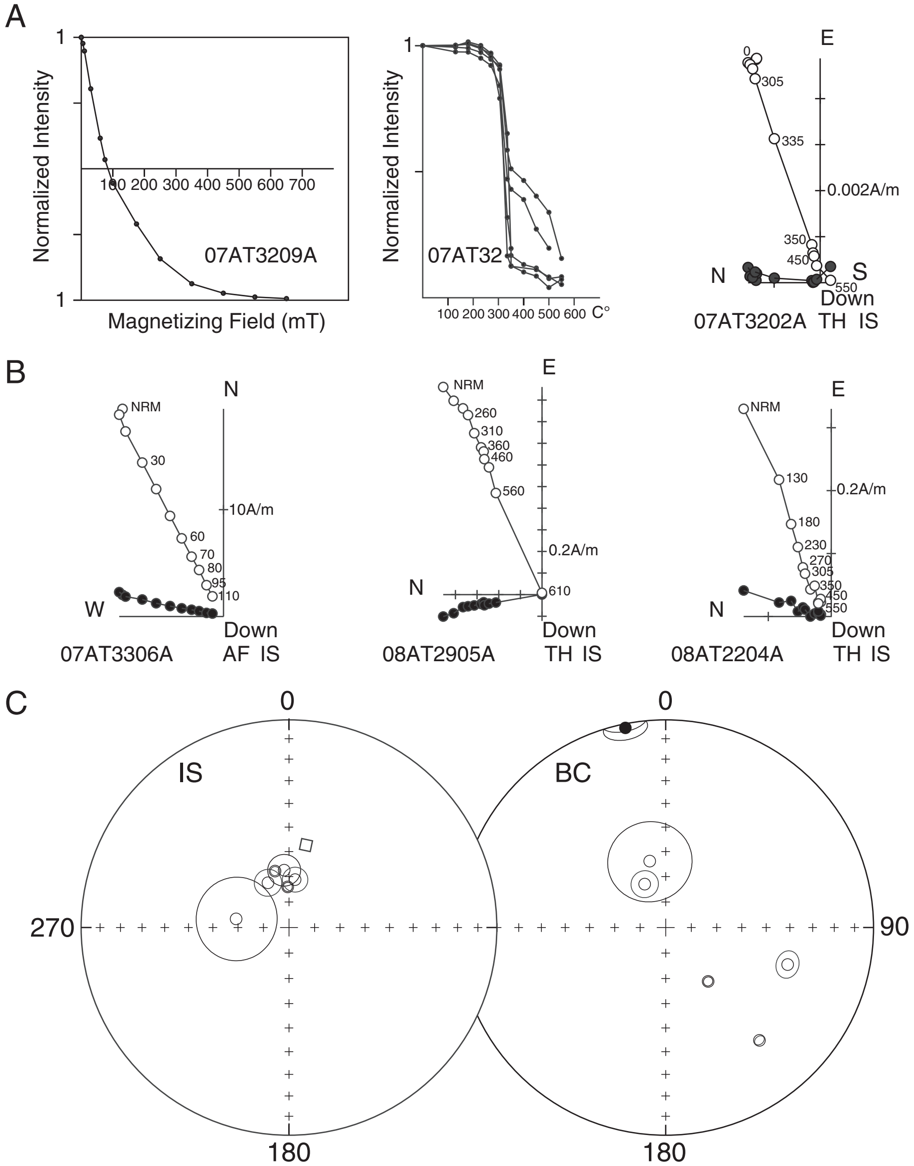

Fig. 3. A-left: Reverse field IRM acquisition for one sample from Permo-Triassic sedimentary rocks (TPG). A-mid: Variation of the intensity of remanent magnetization during thermal demagnetization. Most of the magnetization is lost between 300 ° C and 350 °C for site 07AT32. A-right: Representative thermal demagnetization Zijderveld diagram. Solid (open) circles correspond to projection onto the horizontal (vertical) plane. The characteristic magnetization was determined in the temperature range 200–450 °C. B: Orthogonal projections of *in situ* vector endpoint diagrams of thermal (TH) (temperatures in °C) or alternating field (AF) (steps in mT) demagnetization. Characteristic component goes through the origin. C: Equal-area projection for Permo-Triassic and Jurassic sites. Sites are well grouped in *in situ* coordinates while they are highly scattered after bedding correction. Solid (open) symbols correspond to projection onto the lower (upper) hemisphere. IS (BC) *in situ* (bedding corrected) coordinates.

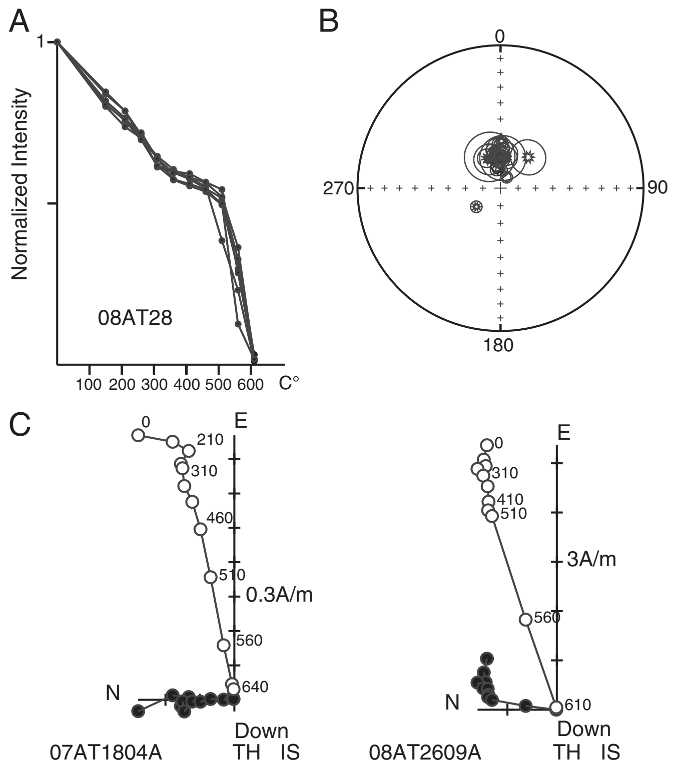

Fig. 4. (A): Variation of the intensity of remanent magnetization during thermal demagnetization for samples from site 07AT28, showing that more than 50% of the magnetization has unblocking temperatures above 500 °C. B. Equal-area projection for Cretaceous igneous sites. Almost all sites are well grouped and have normal polarity. Solid (open) symbols correspond to projection onto the upper (lower) hemisphere. C. Representative orthogonal projections of *in situ* vector endpoint diagrams of thermal (temperatures in °C) demagnetization. Characteristic component goes directly through the origin in both volcanic (left) and plutonic (right) rocks. Solid (open) circles correspond to projection onto the horizontal (vertical) plane.

magmatic alteration because of its mineral association (magnetite + chlorite + biotite?) (See Evans and McElhinny, 1966) related to the same process. It is likely that those early and post-magmatic processes happened in a short period of time, since silicate-hosted magnetite records stable remanent magnetization and is well isolated from hydrothermal processes (Astudillo et al., 2010; Evans and McElhinny, 1966; Feinberg et al., 2005; Renne, et al., 2002), while both families of magnetite record the same magnetic field. This suggests that for intrusive rocks in the Gerlache Strait the magnetization is primary and mainly related to the fine silicate-hosted magnetite.

In volcanic rocks from the South Shetland Islands, microscopic analysis confirms the presence of magnetite as the main magnetic carrier. At site 07AT18, magnetite grains exceeding 20 µm are recognized in addition to numerous small grains. It is most likely that the small grains (<10 µm) recorded the stable remanent remagnetization.

4.3. Results from Paleocene–lower Eocene intrusive and volcanic rocks

Reverse polarities are predominant in Paleocene–lower Eocene volcanic rocks from Torres Island, Half Moon Island and King George Island (Fig. 5B). These sites have high values of both magnetic susceptibility (ranging from 10^{-1} to 10^{-2} SI units) and NRM intensities between 10 and 1×10^{-1} A m^{-1} (Table A; see supplementary data).

High unblocking temperatures and univectorial magnetizations suggest that the magnetizations are primary and were acquired during the emplacement of the volcanic rocks (Fig. 5A). At all sites but those of Half Moon Island, optical observations confirm the lack of hydrothermal alteration. The lava flows from the Half Moon Island sites have been hydrothermally altered and record the same direction as that determined in an intrusive stock at site 08AT10. Thus, although unaltered and altered rocks share similar good magnetic characteristics (i.e. univectorial magnetization during the demagnetization, the same range of NRM intensity and magnetic susceptibility, and a similar unblocking spectrum), we cannot discard the hypothesis that the magnetization from sites 08AT08, 09 and 11 might be secondary. Microscopic observation at site 08 (Half Moon Island) indicates that subhedral–anhedral magnetite, the main magnetic carrier, is located in clasts of the lithic tuffs and is also associated with the mineral assemblage silica–muscovite–chlorite-clay. The aforementioned with its highly obliterated texture (Fig. sd3, see supplementary data) supports the hypothesis of a secondary magnetization for this site. The reverse polarity of the characteristic remanent magnetic direction obtained at site 08AT10 does not agree with the 105 K/Ar age, but is in agreement with the Rb/Sr isochrons between 76 and 66 Ma reported by Parica and Remesal (2007).

Significantly larger paleosecular variation is recorded in the early Paleogene rocks than in the Cretaceous rocks. This is especially clear in VGP coordinates where 4 sites out of 8 from King George Island indicate a latitude lower than 45° (Fig. 5B2).

On Snow Island, two sites (08AT13 and 08AT14) were drilled in Eocene sills, for which an age of 54 Ma was reported by Watts et al. (1984). These two sites have a normal polarity magnetization. At site 08AT12, 12 samples were drilled in sediments and three samples in an intercalated thin sill. All samples record a very stable reverse polarity magnetization. Despite the low magnetic susceptibility, the high intensity of the NRM (up to 0.5 A/m) in the deposits indicates that they were remagnetized at the time of sill emplacement. The characteristic directions from the remagnetized deposits were thus averaged with the results from the volcanic unit. A bedding correction was estimated (~ 20° to the northeast) but it is unclear whether the sills intruded after or before the light deformation of the area. Watts et al. (1984) do not mention any tilt correction, whereas Grunow (1993) reports a negative fold test based on three sites.

4.4. Results from Miocene–Pliocene intrusive and volcanic rocks

On Anderson Island, results were obtained from 4 out of 5 sampled sites. All of these show reverse polarity magnetization (Fig. 6A). Both sites sampled in palagonite-bearing rocks have low NRM values (Table A; see supplementary data). A low temperature component of magnetization was determined in four samples from site 07AT19 (Fig. 6B). The reverse polarity of this magnetization and the very low unblocking temperatures support the hypothesis that this magnetization was acquired during emplacement and possible rapid cooling under water and that it is not a recent viscous overprint. Samples from the other site (07AT21) indicated a more unstable behavior and the results were discarded. A characteristic reverse polarity magnetization was determined at higher temperatures for the three other sites from basaltic olivine lava flows (Fig. 6C). Three sites were also drilled in the Miocene intrusive stock at Melchior Island. These rocks have very soft NRMs with an MDF lower than 5mT. We tentatively determined a characteristic direction for two sites (Fig. 6D).

5. Tectonic Implications and APWP for the Antarctic Peninsula

Paleomagnetic results for the Antarctic Peninsula have already been reported in a number of studies (Blundell, 1962; Dalziel et al., 1973; Grunow, 1993; Kellog, 1980; Kellogg and Reynolds, 1978; Longshaw and Griffiths, 1983; Parés and Dinarès-Turell, 1999; Valencio et al., 1979; Watts et al., 1984). However, only Watts et al. (1984) and Grunow (1993) provide detailed paleomagnetic and geologic information that facilitate the combination of our data with these previously published results.

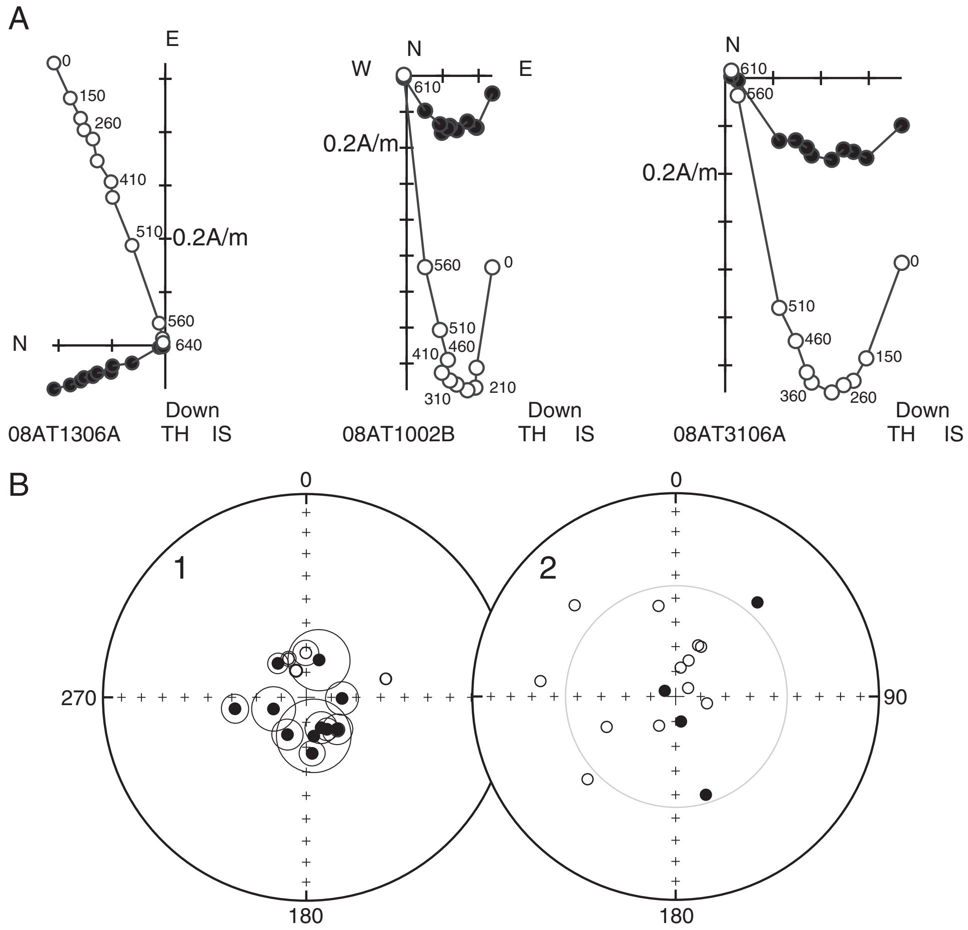

Fig. 5. A: Orthogonal projections of *in situ* vector endpoint diagrams of thermal (temperatures in °C) demagnetization. Characteristic component goes directly through the origin in sample 08AT13 (Snow Island) while a low temperature is erased in both 08AT1002B (Half Moon Island) and 08AT3106A (Torres Island) samples. Solid (open) circles correspond to projection onto the horizontal (vertical) plane. B: Equal-area projection for mean directions (left) and paleopoles (right) at Paleocene sites. In contrast to Cretaceous rocks, in this case the sites record both normal and reverse polarities and show an important scatter probably due to secular variation. Open (solid) symbols correspond to projection onto the upper (lower) hemisphere. Small grey circle is the 45° limit.

A poor paleomagnetic record in the TPG deposits combined with widespread remagnetization impedes the determination of the APWP for the Antarctic Peninsula during the late Paleozoic. Evidence for remagnetization was also reported for a number of localities by Grunow (1993).

Remagnetization could reflect an important tectonic event during Cretaceous time in the northern Antarctic Peninsula. This event could be associated with the well-documented mid-Cretaceous Palmer Land Event in the southern part of the Antarctic Peninsula (Palmer Land) (Vaughan et al., 2002). On the other hand, Cretaceous remagnetization has also been reported in southern Patagonia (Rapalini, 2007), suggesting that this region was close to the Antarctic Peninsula during the Mid-Cretaceous and that both were affected by the same event (Vaughan and Livermore, 2005). The normal polarity observed in the remagnetization can also be correlated with widespread early Late Cretaceous magmatism. Indeed all sites sampled in these rock units record normal polarity magnetization.

The most significant results correspond to the early Late Cretaceous and to the Paleocene–early Eocene interval. Taking into account the curved shape of the Antarctic Peninsula and the suggested block segmentation of the Antarctic Peninsula proposed by Hawkes (1981), we first test the possible existence of relative rotations associated with subduction, exploring the possible deformation associated with differential subduction obliquity along the South Shetland Arc. We then discuss the APWP of the Antarctic Peninsula.

5.1. Are there relative block rotations within and between the South Shetland Arc and the Antarctic Peninsula?

The subduction of the Phoenix Plate, divided by important fracture zones, below the Antarctica Plate (Barker, 1982) has been related to segmentation of the Antarctic Peninsula into different tectonic blocks (Barker, 1982; Hawkes, 1981) which could have undergone relative movement among them. On the other hand, the opening of the Bransfield Strait, active since the early Pliocene (Barker, 1982; Solari et al., 2008), could have induced relative rotation between the different blocks forming the Shetland Islands.

Most of the paleomagnetic results in previously published studies as well as in the present study come from volcanic or intrusive rocks. Some of the mean poles previously published for different localities correspond to a low number of sites. Secular variation is probably not fully averaged in each individual study and there are also uncertainties about bedding. Instead of comparing the mean poles published in different studies, we thus combine individual results from Grunow (1993) and Watts et al. (1984) with our new results to provide a mean paleopole for each locality of the Shetland Islands, the area of the Gerlache Strait and the northern tip of the Antarctic Peninsula (Fig. 2, frames a, b and c in Fig. 1). Most of the available paleomagnetic results correspond to two main age groups; one yielding ages of about 60 ± 10 Ma and the other of about 90 ± 10 Ma. For example, Grunow (1993), Watts et al. (1984) and the present study provide respectively 3, 10 and 3 results from Snow Island with an

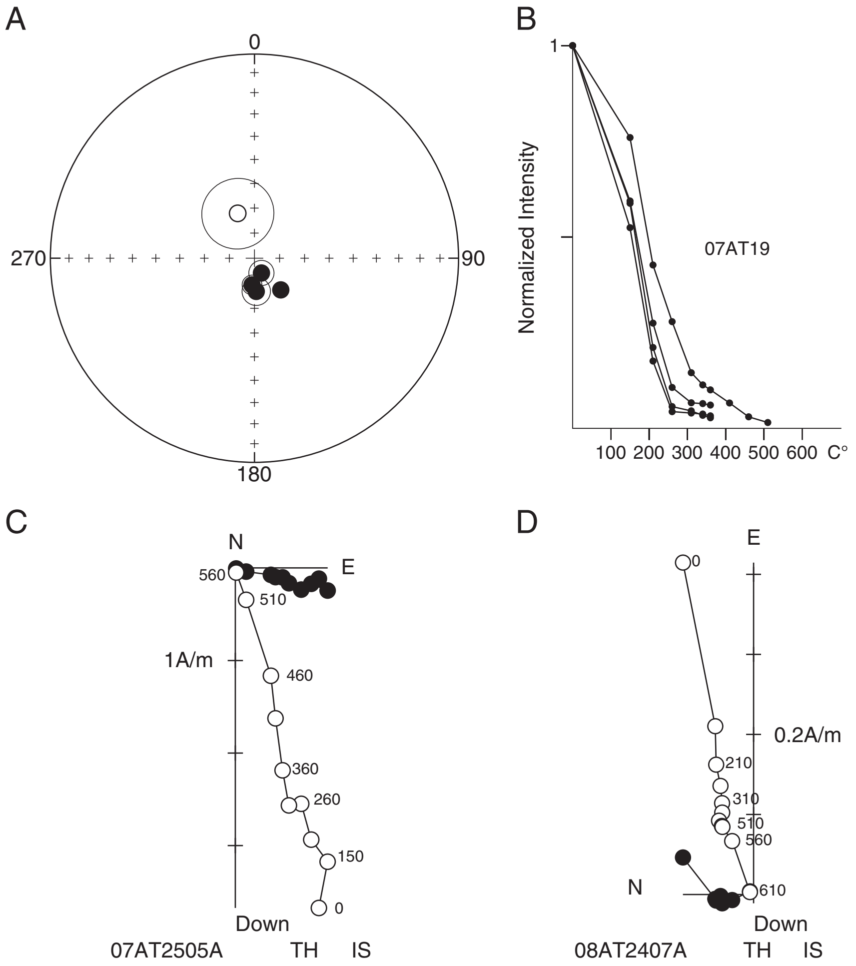

Fig. 6. A: Equal-area projection for mean directions in volcanic rocks from Anderson Island. Open (solid) symbols correspond to a projection onto the upper (lower) hemisphere. B: Variation of the intensity of the remanent magnetization during thermal demagnetization for site 07AT19. The magnetization is almost completely erased after 300 °C. C and D: Orthogonal projections of *in situ* vector endpoint diagrams of thermal (temperatures in °C) demagnetization for a sample from Anderson Island (C) and a sample from Melchor Island (D). Characteristic component goes directly through the origin in the sample, but unlike site 07AT19 the characteristic direction is obtained at higher temperatures.

attributed Eocene age. We thus combine these 16 sites to provide a mean pole (Fig. 7A, left; Table 2). Further north, we obtained a pole from 8 sites on King George Island while Watts et al. (1984) report 21 results in lower Eocene rocks from the same localities. We obtained a pole combining the 29 sites. There are no statistical differences between the mean poles except that more secular variation appears to be registered on King George Island (Fig. 7B, left; Table 2).

The same direction is also recorded in Paleocene rocks from Half Moon Island. This confirms the lack of detectable relative rotation between the Shetland blocks. Two Paleocene sites from Torres Island on the Antarctic Peninsula also have a similar direction to those on Half Moon Island, suggesting no rotation between the Shetland Islands and the main part of the Antarctic Peninsula (Fig. 7C, left; Table 2). To test this hypothesis, we define three main localities with paleomagnetic data in early Late Cretaceous rocks. The locality in the central part of the South Shetland Islands is constituted by our results from the Robert and Greenwich Islands and the results from Watts et al. (1984) from Greenwich Island (Fig. 7A, right; Table 2). The two other localities are on the Antarctic Peninsula. The southern one corresponds to the Gerlache and Penola Straits and include our data and those of intrusive rocks from Cape Tuxen (Grunow, 1993) dated by U–Pb at 85 Ma (Tangeman et al., 1996). We also sampled one site (08AT26) in a gabbro dated at 85 Ma by U–Pb (Calderón et al., unpublished data). Three sites in Jurassic volcanic and sedimentary rocks at Paradise Bay and one site at Charlotte Bay record magnetizations showing strong scatter upon tilt correction and a remagnetization by nearby intrusives is likely. Grunow (1993) also reports results from poorly dated intrusives at Charlotte Bay and we concur with this author that the age of the magnetization may be around 85 Ma. We thus have two sets of data for the Gerlache and Penola Straits, one corresponding to dated units around 85 Ma (Fig. 7B, right; Table 2) and the other with the postulated age of remagnetization at 85 Ma (Fig. 7C, right; Table 2).

In the northern Antarctic Peninsula, all the results of our study, together with those of Watts et al. (1984) and Grunow (1993) correspond to remagnetized sedimentary or undated igneous rocks. However, zircon fission track ages of 80, 87, and 91 Ma reported by Faúndez et al. (2003) corroborate the Rb–Sr age in a granodiorite of 92 Ma (Pankhurst, 1982) and confirm an early Late Cretaceous magmatic event in this part of the Antarctic Peninsula. Therefore we propose that results from remagnetized and intrusive rocks can possibly be assigned an age of about 90 Ma. We do not take into account the low inclination data obtained by Watts et al. (1984) in four sites from the Wide Open Islands gabbro (Fig. 7D, right; Table 2).

Both the Paleocene and early Late Cretaceous group of paleomagnetic poles confirm that the Antarctic Peninsula has been at nearly the same high paleolatitude for the last 100 my. The high inclination (~70–75°) makes it difficult to determine *in situ* block rotations. For the Paleocene group of poles, the difference in declination between the northern block

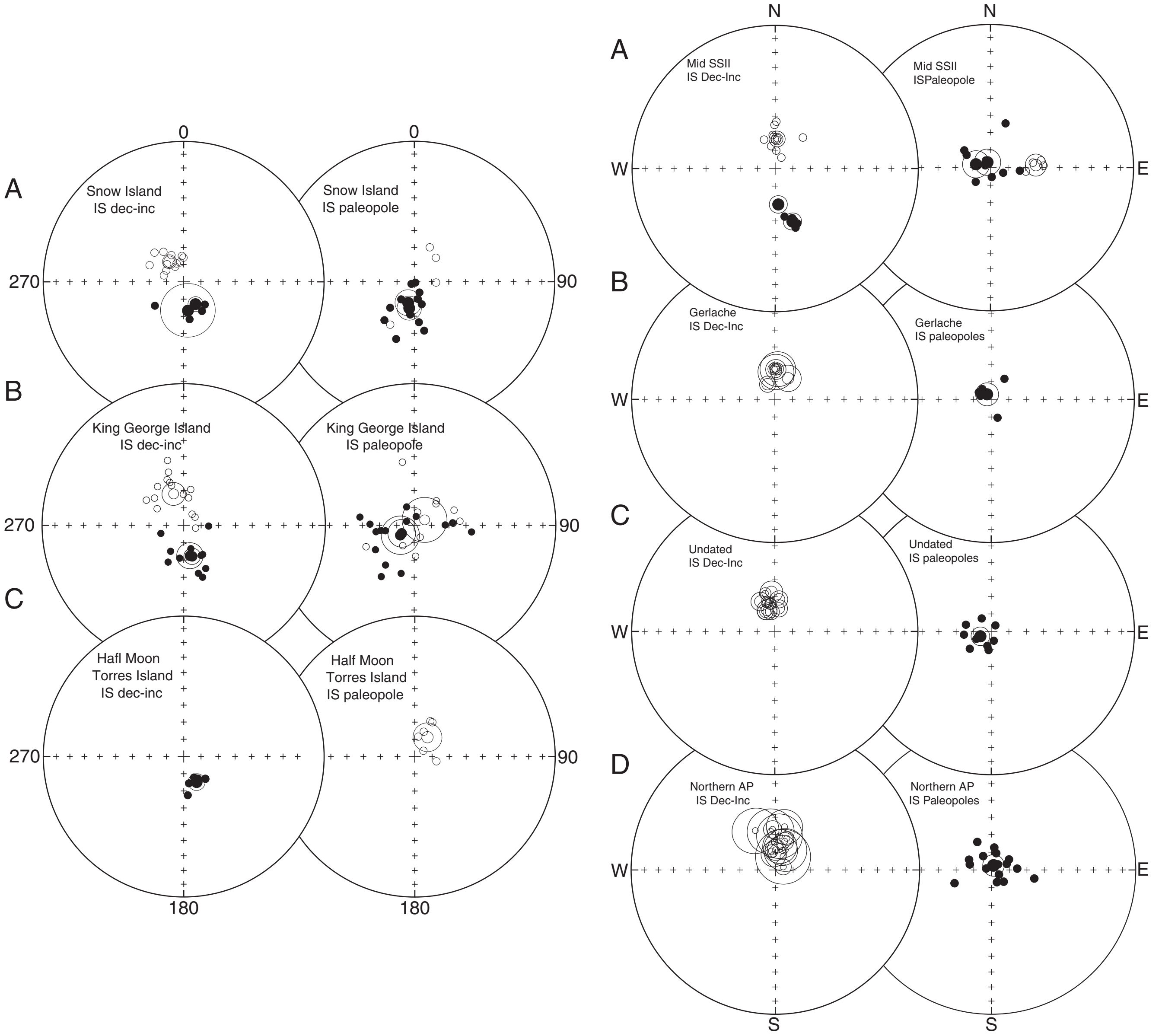

Fig. 7. Left) Equal-area projection for mean site directions and paleopoles for all sites on the South Shetland Islands and all samples on King George Island. In contrast to Cretaceous rocks, in this case the sites record both normal and reverse polarities and show an important scatter probably due to secular variation. Solid (open) symbols correspond to projection onto the lower (upper) hemisphere. IS (*in situ* results). Right) Equal-area projection for mean directions at *in situ* (IS) coordinates (left) and for paleopoles (right) for Cretaceous blocks in the Antarctic Peninsula and the South Shetland Islands. Open (solid) symbols correspond to projection onto the upper (lower) hemisphere.

(King George Island) and the southern block of the Shetland Islands is only 12° and both directions are not statistically different at the 95% confidence level.

For the early Late Cretaceous groups of directions, there is no statistical evidence for relative rotation between the different localities.

Our study contradicts the interpretation of Nawrocki et al. (2010) suggesting local rotations in early Eocene volcanic rocks from the central part of King George Island. These authors report new paleomagnetic data from different sections separated by only a few kilometers. Because their paleomagnetic sampling was mainly done with single oriented blocks in different units, they only provide a mean result from different sections. Nawrocki et al. (2010) interpreted the paleomagnetic differences between the localities as local tectonic rotations. However, except with the possible exception of Herve Cove, secular variation is clearly not averaged even at localities where the number of samples is large, such as Paradise Cove (k = 86 with n = 24). Thus it is necessary to average all the localities and the mean value is not statistically different from the direction expected for the early Paleocene reference pole calculated in the present study. We can thus discard any paleomagnetically detectable rotation within King George Island.

5.2. The apparent polar wandering path of the Antarctic Peninsula

We have shown that there is no evidence for relative rotation between the different blocks that constitute the northern Antarctic Peninsula. We can thus determine the APWP by combining data from different blocks.

We calculate two paleopoles at ~90 ± 10 Ma and ~60 ± 10 Ma, respectively. For the 90 Ma paleopole, we combined VGPs from the northern Antarctic Peninsula, the Gerlache Strait, and Robert and Greenwich Islands in the central part of the South Shetland Island group. This paleopole is statistically similar to that expected for East Antarctica from either the Besse and Courtillot (2002) or Torsvik et al. (2008) global APWP data (Fig. 8A; Table 2). For the 60 Ma paleopole, we used poles from sites sampled on the South Shetland Islands, at King George, Snow and Half Moon Island and from Tower Island in the central part of the northern Antarctic Peninsula. This paleopole does not differ strongly, even though it is at a slightly lower latitude, from that expected for East Antarctica according to the global APWP of Besse and Courtillot (2002) (Fig. 8A; Table 2).

Watts et al. (1984) and Grunow (1993) report numerous results from Lower Cretaceous rocks at Byers Peninsula on Livingstone Island (South Shetland Islands). Grunow (1993) sampled sedimentary rocks and lava flows from the Byers Group (145–125 Ma) as well as some intrusive units. Results from 9 sites in sedimentary rocks failed the fold test (k decreases from 130 to 34). Of 11 results from the lava flows, only one is of reverse polarity and the directions of the normal polarity lava flows are better grouped for *in situ* results than after bedding correction. The mean direction for the lavas is the same as that determined for results from intrusive dikes and plugs, all of them having a normal polarity magnetization. Radiometric K–Ar whole rock ages between 116 and 77 Ma were also reported by Pankhurst et al. (1979). All these observations indicate that the magnetization was most likely acquired during the Cretaceous Normal Chron. We tentatively attribute a mean age of 100 Ma to these results (Fig. 8A, Table 2). Because of the uncertainties in the exact age of the main event of remagnetization, we suggest that only the mean result determined from the intrusive units may be used.

On the Antarctic Peninsula at Penola Strait, Grunow (1993) reports results from intrusive units at Moot Point and on Rasmussen Island dated respectively by U–Pb at 107 Ma and 117 Ma. We combined the high temperature component A from Moot Point with results from Rasmussen Island to provide a mean pole at 112 Ma. At Mt. Banck, Grunow (1993) reports results from a 130 Ma intrusive, but in this case the A component does not correspond to high temperature-characteristic magnetization, in contrast to that determined at Moot Point. We therefore do not take this result into account.

Grunow (1993) reports results from a 160 Ma pink granite and 2 mafic dykes at Bone Bay. This pole is very different from that expected for either the Besse and Courtillot (2002) or Torsvik et al. (2008) global APWP data for East Antarctica (Fig. 8; Table 2). The difference between the master curves and the 160 paleopoles supports the idea of tectonic translation for some parts of the Antarctic Peninsula prior to about 105 Ma. Finally, the oldest VGP available for the Antarctic Peninsula is the 175 Ma pole determined by Longshaw and Griffiths (1983) and for which very few analytical details were given (Fig 8A; Table 2).

Results from mid-Cretaceous rocks along the Lassister coast in the southern part of the Antarctic Peninsula (Kellogg and Reynolds, 1978) are in good agreement with results from the northern part of the peninsula. These results come from rocks that intruded the Gondwana margin and are inboard of the eastern Palmer Land shear zone, which probably constitutes the major boundary between allochthonous and autochthonous parts of the margin (Vaughan and Storey, 2000). However, Kellogs (1980) found evidence of clockwise rotation along the Orville coast about 300 km from the Lassister coast sites. These results were interpreted as evidence of oroclinal bending due to the collision of a western block (Alexander Island block, Kellogs, 1980). The characteristic directions in both studies were determined by Fisher statistics at one level of AF demagnetization. Further work with thermal demagnetization might be needed to confirm these results. Again, in both studies, the magnetization is of normal polarity, and K–Ar ages of 95–104 Ma in biotites from intrusive rocks (Kellogg and Reynolds, 1978) along the Lassister coast as well as whole rock Rb–Sr ages of 103 and 109 Ma at the Orville coast, confirm that widespread magmatic activity took place in the Antarctic Peninsula during the long normal Cretaceous superchron.

5.3. The apparent polar wandering path of the Marie Byrd Land and Thurston Island

The AP is part of West Antarctica and paleomagnetic results for the Marie Byrd Land block have been reported by DiVenere and Kent (1994), DiVenere et al. (1995). Results from Thurston Island are also reported by Grunow et al. (1991). DiVenere and Kent (1994), DiVenere et al. (1995) studied volcanic and plutonic rocks from the eastern part of Mary Bird Land, and provided two mean poles, one for units with an assigned age of 100 Ma and another for an assigned mean age of 117 Ma. As observed in the AP, because of remagnetization due to widespread plutonism and the difficulty in determining bedding attitude or possible tilts in intrusive rocks, we concur with DiVenere et al. (1995) that it is not completely straightforward to obtain a representative mean paleopole. These authors tentatively

Table 2
Mean Paleomagnetic results and apparent polar wander path for the Antarctic Peninsula.

	Direction			VGP			
Block	Dec	Inc	a95	Long	Lat	a95	N
Results with an attributed Paleocene age							
Snow Island	152.1	75.4	4.3	196.2	77.3	7.6	16
King George Island	163.9	71.4	4.9	236.2	81.0	8.2	25
Half Moon and Torres Island	153.2	73.4	4.9	213.3	76.6	8.3	6
Results with an attributed Cretaceous age							
Gerlache Strait Known Age	3.3	−74.9	3.6	321.1	86.3	6.5	7
Gerlache Strait Unknown Age	349.5	−73.8	3.1	246.6	83.3	5.3	10
Northern AP Unknown Age	6.8	−76.0	3.6	17.0	86.9	5.4	18
Robert and Greenwich Island	355.0	−69.5	5.0	283.0	81.6	7.7	15

Apparent polar wander path for the Antarctic Peninsula

Time	Long	Lat	a95	R ± ∂R	Lat ± ∂L	Location	Basis for Pole
60 Ma	36.1	−79.6	4.5	−9.7 ± 8.4	1.6 ± 4.2	South Shetland Island	1,2,3
90 Ma	113.0	−86.8	3.4	−4.0 ± 9.5	−1.5 ± 5.0	Antarctic Peninsula	1,2,3
100 Ma	162.3	−79.6	8.5	3.3 ± 16.0	6.5 ± 8.7	Byers Peninsula	1
112 Ma	172.8	−77.4	6.4	−6.3 ± 10.5	4.6 ± 6.1	Gerlache Strait	1
160 Ma	125.4	−64.5	8.2	−45.3 ± 10.5	15.8 ± 7.7	Byers Pen. and Bone Bay	1
175 Ma	237.0	−46.0	6.4	16.5 ± 10.8	0.0 ± 6.7	East Graham Land	4

Block mean directions. Dec, Inc and α95 the declination and inclination parameters and the semi-angle at the 95% level of confidence, respectively; Long, Lat longitude and latitude for the paleopoles; N the number of sites used in the calculation of the mean paleopole for apparent polar wander path of the Antarctic Peninsula; Long, Lat longitude and latitude for the paleopoles; α95 is the semi-angle at the 95% level of confidence. Rotation and latitudinal displacement with respect to East Antarctica are calculated from the APWP of Besse and Courtillot (2002) for a site located at 62°S and 60°W. (1) data from Watts et al., 1984; (2) Grunow, 1993; (3) This Study; (4) Longshaw and Griffiths, 1983.

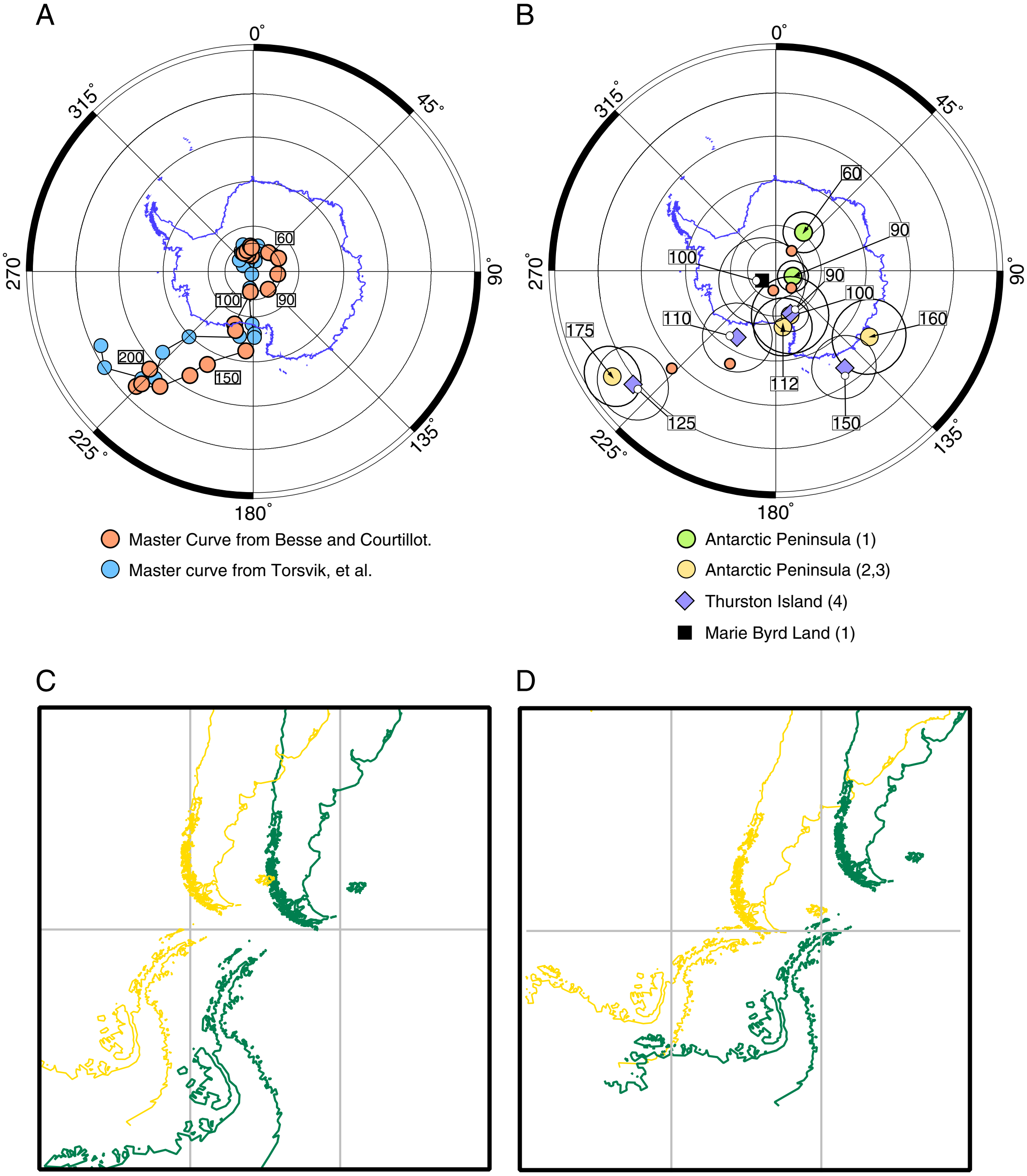

Fig. 8. A: Apparent polar wandering paths for East Antarctica from Besse and Courtillot (2002) (orange dots) and Torsvik et al. (2008) (blue dots). B: Virtual geomagnetic poles obtained in this study and others (1, This study; 2, Grunow, 1993; 3, Longshaw and Griffiths, 1983; 4, Grunow et al., 1991). Paleopoles obtained at 90 Ma does not differ significantly from those obtained by Besse and Courtillot (2002) while the pole at 60 Ma is slightly offset with respect to the Besse and Courtillot APWP (10 Ma window). The paleopole from Marie Byrd Land was recalculated as explained in text. The references poles at 60, 90, 100, 150 and 200 Ma from Besse and Courtillot (2002) are shown in orange circles. C: Reconstruction of the Antarctic Peninsula and South America at 95 Ma (green) and 65 Ma (orange) using the Gplate software and the plate circuit used by the Earth Byte Group. Reconstructions are made using the moving IAHS frame of O'Neill et al. (2005). D: Reconstruction of the Antarctic Peninsula and South America from paleomagnetic data only using the mean Late Cretaceous and mid Cretaceous poles determined for South America by Somoza (2008) and using our two poles at 60 and 90 Ma for the Antarctic Peninsula. The relative positions in longitude of both South America and the Antarctic Peninsula are arbitrary in these two reconstructions. The reconstructions are valid only for the paleolatitude and rotation of the plates. Same color code as in (C).

proposed a pole at 117 Ma based on results from six sites of Le Masurier volcanics. The high Fisher value (k = 193) and the fact that the *in situ* direction is not far from the expected 100 Ma direction suggest that this magnetization could also be a remagnetization. We thus discard a reference pole at 117 Ma that DiVenere and Kent (1994) calculated from intrusive rocks dated around 100 Ma. Although the evidence for tilting is very difficult to establish, a tilt correction was applied for localities at Ickes Mountain. Since remagnetization in volcanics is also widespread, we decided to combine the results from remagnetized localities (DiVenere et al., 1995) with those from intrusives rocks of 100 Ma without tilt correction.

Müller et al. (2007) reanalyzed the late Tertiary geometry of the West Antarctic rift system and proposed a new pole of rotation between West and East Antarctica to take extension into account. This study suggests a major dextral strike–slip boundary connected to the South Shetland subduction zone. The rotation of the Marie Byrd Land block thus does not apply to the AP block but may well apply to the Thurston Island block. Our calculated pole for Marie Byrd Land before correction for the extension in the Antarctic rift is 235.5°E, 86.1°S, A95 = 9.5 and after correction with the pole of rotation from Müller et al. (2007) (lat: −71.10, long: −22.80 and angle: 3.43) is −87.2°S, 227.1°E.

6. Discussion

The post-folding characteristic directions in Permo-Triassic and Jurassic rocks are not statistically different from the characteristic direction for early Late Cretaceous rocks. This remagnetization event during the early Late Cretaceous precludes the possibility to decipher the late Paleozoic and early Mesozoic APWP of the Antarctic Peninsula. This event of remagnetization coincided with the Palmer Land orogeny in the southern part of the Antarctic Peninsula (Vaughan et al., 2002), the closure of the Rocas Verdes Basin at the southern tip of South America (Klepeis et al., 2009, 2010) and a thermal event associated with widespread early Late Cretaceous magmatism concomitant with the accretion of the Scotia Metamorphic Complex (Brix et al., 2007; Hervé et al., 2006a,b). Thus, it seems that the whole area was affected by an important tectonic event during the early Late Cretaceous and prior to the opening of the Drake Passage. There is reasonably good evidence that this early Late Cretaceous event is more than just developed in the Antarctic Peninsula and Patagonia, but that it has a possible Pacific-wide context (Vaughan and Livermore, 2005).

When combining site poles from the different blocks, the paleomagnetic poles obtained in this study show little apparent polar wandering for the Antarctic Peninsula since the early Late Cretaceous. The pole determined at ~60 Ma indicates however about 20° counterclockwise rotation to its present position. Besse and Courtillot (2002) and Torsvik et al. (2008) provided updated master apparent polar wandering curves derived from a global compilation of the paleomagnetic poles from different plates and sea-floor spreading history to reconstruct the global curve. There are slight differences between both APWPs, but when compared with these APWPs our result indicates only about 10° counterclockwise rotation for the Antarctic Peninsula with respect of East Antarctica and a slightly more northerly position (Fig. 8). Unfortunately, there are no paleomagnetic data available directly for East Antarctica for the Late Cretaceous–Paleocene. However, there are sufficient paleomagnetic data available to establish an APWP for South America without the need to transfer poles from other plates. Somoza (2007) and Somoza and Zaffarana (2008) calculated a new APWP for the South American plate with a mid-Cretaceous polar standstill and a well-defined Late Cretaceous–Eocene reference pole. We made reconstructions using the Gplate software (Earthbyte Group) at 65 Ma and 95 Ma with the moving Indo-Atlantic Hotspot reference frame (moving IAHS) of O'Neill et al. (2005) (Fig. 8C) and using our new paleomagnetic poles for the AP and the two poles from Somoza and Zaffarana (2008) (Fig. 8D). The angular departure of about 7° observed by Somoza and Zaffarana (2008) for the late Cretaceous paleomagnetic pole of South America in the moving IAHS reference frame corresponds to a nearly 15° counterclockwise rotation for the Antarctic Peninsula. The paleomagnetic reference frame is likely more appropriate than the Hotspot frame for paleolatitude determination and paleogeographic purpose.

In the Late Cretaceous and early Tertiary, the South American Plate was nearly 5° farther south than its present position. The observed inclinations at 60 and 90 Ma are within ~2° of the expected inclinations determined from the master curves of Besse and Courtillot (2002) or Torsvik et al. (2008) and this confirms the lack of latitudinal displacement of the Antarctic Peninsula with respect of East Antarctica that can be determined by paleomagnetic methods. The separation of the southern tip of South America from the northern tip of the Antarctica Peninsula, which led to the opening of the Drake Passage, was thus due to northward drift of South America rather than southward drift of the Antarctic Peninsula, as also suggested by Somoza (2007).

The northern tip of the Antarctic Peninsula and south Patagonia present oppositely curved shapes. This important feature of the Patagonian margin is a key factor for refining both the connection between the Antarctic Peninsula and Patagonia before and during the Gondwana breakup and also for the opening of the Drake Passage. If the margin was straight we can explain approximately 2° of separation between the Antarctic Peninsula and Patagonia with no relative movement between them. This would involve at least a quarter of the opening of the Drake Passage as well. Also important is that when a straight margin is considered, an important overlap between the Antarctic Peninsula and Patagonia must have occurred, especially in models that place the Antarctic Peninsula along the western edge of Patagonia. In this context, Cunningham et al. (1991) suggests that Southernmost Patagonian bending began during or after the Andean orogeny and preceding the opening of the Drake Passage.

In the case of the Antarctic Peninsula, its present shape suggests a possible clockwise rotation if a more linear original shape is assumed, but this possibility is ruled out by our paleomagnetic data for the last 100 Ma.

The new ~100 Ma mean South Pole determined for Mary Bird Land is not statistically different from our AP 90 Ma pole and not different from those for Thurston Island (Grunow et al., 1991). The small amount of displacement between West and East Antarctica during the Tertiary is likely not discernible by paleomagnetism. On the other hand, the low number of poles determined for rocks older than 100 Ma makes it difficult to reconstruct the paleographic and tectonic history of the blocks constituting West Antarctica prior to the mid-Cretaceous.

7. Conclusions

The paleomagnetic results obtained in this study allow the following conclusions:

1.- Paleomagnetic results from Permo-Triassic and Jurassic rocks show evidence of remagnetization. This result does not allow us to determine a paleopole for the Antarctic Peninsula before the mid-Cretaceous. However, a similar characteristic direction was obtained in Cretaceous igneous rocks, which suggests a common origin for their magnetization.
2.- Magnetization in Cretaceous and Cenozoic rocks is mainly primary. When combining these results with previously reported results it is possible to determine that there was no relative motion between the southern and northern part of the South Shetland Islands, and between the South Shetland Islands and the Antarctic Peninsula.
3.- The paleopoles obtained for the Cretaceous and Paleocene indicate that the Antarctic Peninsula did not undergo latitudinal displacement since 90 Ma. The apparent counterclockwise rotation >15° of the Antarctic Peninsula since 60 Ma is largely a global feature also observed in the paleomagnetic data of the South American plate when compared to the moving IAHS reference frame (Somoza and Zaffarana, 2008).
4.- The available paleomagnetic data for the Antarctic Peninsula are not sufficient and reliable enough to document precisely the tectonic evolution and possible rotations of the Antarctic Peninsula prior to the mid-Cretaceous.

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