Tectonic implications of a paleomagnetic study of the Sarmiento Ophiolitic Complex, southern Chile

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Abstract

A paleomagnetic study was carried out on the Late Jurassic Sarmiento Ophiolitic Complex (SOC) exposed in the Magallanes fold and thrust belt in the southern Patagonian Andes (southern Chile). This complex, mainly consisting of a thick succession of pillow-lavas, sheeted dikes and gabbros, is a seafloor remnant of the Late Jurassic to Early Cretaceous Rocas Verdes basin that developed along the south-western margin of South America. Stepwise thermal and alternating field demagnetization permitted the isolation of a post-folding characteristic remanence, apparently carried by fine grain (SD?) magnetite, both in the pillow-lavas and dikes. The mean "in situ" direction for the SOC is Dec: 286.9°, Inc: −58.5°, α95: 6.9°, N: 11 (sites).

Rock magnetic properties, petrography and whole-rock K–Ar ages in the same rocks are interpreted as evidence of correlation between remanence acquisition and a greenschist facies metamorphic overprint that must have occurred during latest stages or after closure and tectonic inversion of the basin in the Late Cretaceous.

The mean remanence direction is anomalous relative to the expected Late Cretaceous direction from stable South America. Particularly, a declination anomaly over 50° is suggestively similar to paleomagnetically interpreted counter clockwise rotations found in thrust slices of the Jurassic El Quemado Fm. located over 100 km north of the study area in Argentina. Nevertheless, a significant ccw rotation of the whole SOC is difficult to reconcile with geologic evidence and paleogeographic models that suggest a narrow back-arc basin sub-parallel to the continental margin. A rigid-body 30° westward tilting of the SOC block around a horizontal axis trending NNW, is considered a much simpler explanation, being consistent with geologic evidence. This may have occurred as a consequence of inverse reactivation of old normal faults, which limit both the SOC exposures and the Cordillera Sarmiento to the East. The age of tilting is unknown but it must postdate remanence acquisition in the Late Cretaceous. Two major orogenic events of the southern Patagonian Andes, in the Eocene (ca. 42 Ma) and Middle Miocene (ca. 12 Ma), respectively, could have caused the proposed tilting.

Keywords: Paleomagnetism; Ophiolite; South America; Patagonia; Orocline; Remagnetization

1. Introduction

The Andean orogen changes its strike at around 53°S from a roughly north–south direction to the north into an east–west orogen in the south. This bend is known as the Patagonian Orocline, after Carey (1955). As already pointed out by Cunningham et al. (1991), a yet unresolved problem in the evolution of the Southern Andes is the origin of such curvature. Paleomagnetism is a very powerful tool to reconstruct the kinematic evolution of an orocline both in space and time (see for instance Morris and Anderson, eds., 1998). Therefore, reliable paleomagnetic data from outcrops distributed along the whole Andean orogen between 50°S and 56°S would be significant for unravelling the tectonic evolution of this region.

Despite the fact that several different tectonic models have been put forward to explain the late Mesozoic–Cenozoic tectonic evolution of this part of the Andes, considering a full, partial or no oroclinal bending (e.g. Wilson, 1991; Cunningham, 1993, 1995; Diraison et al., 2000; Kraemer, 2003; Fildani and

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Hessler, 2005; Gighlione and Ramos, 2005, Gighlione and Cristallini, 2007), very few paleomagnetic studies have been carried out yet in the region (Dalziel et al., 1973; Burns et al., 1980; Cunningham et al., 1991; Rapalini et al., 2001; Baraldo et al., 2002; Iglesia Llanos et al., 2003). As recently pointed out by Rapalini (2007) the available database is insufficient to test different models of tectonic evolution of the Patagonian Orocline.

A transitional volcanic-rifted to back-arc basin developed along the southern continental margin of South America during the Late Jurassic to Early Cretaceous. This is generally known as the Rocas Verdes basin (e.g. Dalziel et al., 1974; Stern and De Wit, 2003) and is inferred from discontinuous ophiolitic complexes exposed along the present Pacific margin of the southern Patagonian and Fuegian Andes and in the northern Scotia Arc (Mukasa and Dalziel, 1996). The opening and subsequent closure of this basin is considered a major tectonic development of the South American margin that may have had a substantial impact in its present configuration (e.g.Burns et al., 1980; Kraemer, 2003).

In order to obtain new paleomagnetic data to constrain models of the kinematic evolution of the Patagonian orocline, a reconnaissance paleomagnetic survey was carried out on the northern seafloor remnant of the Rocas Verdes basin, the Sarmiento Ophiolitic Complex (SOC), as part of a multidisciplinary project. Our results suggest a complex tectonic and magnetic history of these rocks which are carrier of a characteristic remanence acquired after the main deformational event that closed and inverted the Rocas Verdes basin. Although a significant declination anomaly was found in these rocks, the simplest interpretation of the paleomagnetic results does not need any tectonic rotation around vertical axes that might be related to a secondary curvature of the orogen.

2. Geology and sampling

Seafloor remnants of the Rocas Verdes basin are exposed discontinuously from about 51°S (SOC) to 55°S (Tortuga Ophiolite) in southern South America (Dalziel et al., 1974; Stern and De Wit, 2003). Mafic metaigneous complexes comprise sills and dikes of amphibolitized gabbro, rare plagiogranites and amphibolites and a thick extrusive unit composed of pillow basalts and pillow breccias with intercalation of radiolarian bearing cherts and siltstones. The SOC bears bimodal extrusive and intrusive terrains that have been associated with the initial stages of lithospheric rupturing along a volcanic-rifted margin in Late Jurassic times (Calderon, 2006). This evolved into a back-arc basin in the Early Cretaceous (Wilson 1991). The Rocas Verdes basin was tectonically closed and inverted in several pulses starting in the Mid-Cretaceous (Dalziel, 1981; Kraemer, 2003).

The studied area comprises four main N–S trending and east-verging thrust sheets(Fig. 1), in which three of them form elongated mountain belts of supracrustal rocks and shallow intrusives, flanked to the west by granitic rocks of the South Patagonian batholith (Fig. 1). The westernmost thrust slice comprises Paleozoic metamorphic rocks of the Staines Complex (Forsythe and Allen, 1980; Hervé et al., 2003) which to the north at Seno Yussef are unconformably overlain by volcano-sedimentary rocks of the Jurassic Tobífera Formation. Part of the Tobífera Formation was deposited under relatively deep marine conditions (Allen, 1982; Wilson, 1991) and has an estimated minimum thickness of 1000 m (Allen, 1982). It is generally interpreted as deposits associated with the rift processes that preceded and accompanied the opening of the basin floored with quasi-oceanic crust. This quasi-oceanic crust is represented by the SOC, that is conformably overlain by the clastic Zapata Formation consisting of ammonite, belemnite and radiolarian bearing successions of siltstones and mudstones which reach a minimum thickness of 1000 m. Biostratigraphic age of the Zapata Formation is restricted to the Tithonian–Neocomian (ca. 150–125 Ma) according to Fuenzalida and Covacevich (1988). In the study area the Zapata Formation is exposed on top of the extrusives of the SOC, being affected by large scale folding and thrusting (Fig. 1).

The SOC is constituted by two imbricated N–S to NNW–SSE trending thrust sheets in a sub-vertical to east-verging fold and thrust belt. It is mainly exposed along the Cordillera Sarmiento, a NNW trending mountain block with peaks reaching over 2000 m above sea level and covered by thick caps of ice. It is limited to the east by the Canal de las Montañas, a straight, narrow depression along which one or more NNW–SSE thrust faults are inferred (Fig. 1). The Canal de las Montañas separates the Cordillera Sarmiento from the Cordillera Riesco on the East, mainly composed of foliated volcanosedimentary successions assigned to the Tobífera Formation (Galaz et al., 2005), upon which the SOC has been overthrust (Calderón et al., 2005). Folded shales of the Zapata Formation and sheared silicic tuffs of the Tobífera Formation are in turn cross-cut by a few sub-vertical and east–west trending lamprophyric dikes.

In order to make a reconnaissance paleomagnetic study of the SOC, a regional sampling was carried out on 13 sites (98 samples) distributed along the whole exposure of the ophiolitic complex (almost 100 km long, see Fig. 1). Access to sampling localities was only possible by boat. Sampled lithologies comprised pillow and massive olivine–clinopyroxene basalts, sub-vertical dikes of amphibolitized fine gabbro and medium-grained gabbro sills. A lamprophyric dike was also studied. For the lavas, bedding attitude was estimated from overlying sediments of the Zapata Formation. Samples were collected with a gasoline-powered portable drill, and oriented both with sun and magnetic compasses whenever weather conditions permitted. At several sites, samples were also taken for radiometric dating through K–Ar whole-rock analysis (see Fig. 1).

3. Paleomagnetic results

Collected cores were sliced into standard 2.2 cm long specimens. At least one specimen per sample was submitted to full demagnetization following a stepwise procedure. All measurements were carried out at the Paleomagnetic Laboratory of the INGEODAV (University of Buenos Aires). Remanence was measured with a DC squids 2G cryogenic magnetometer. Demagnetization was performed either with a 3 axis automatic static degausser attached to the magnetometer or with a dual-

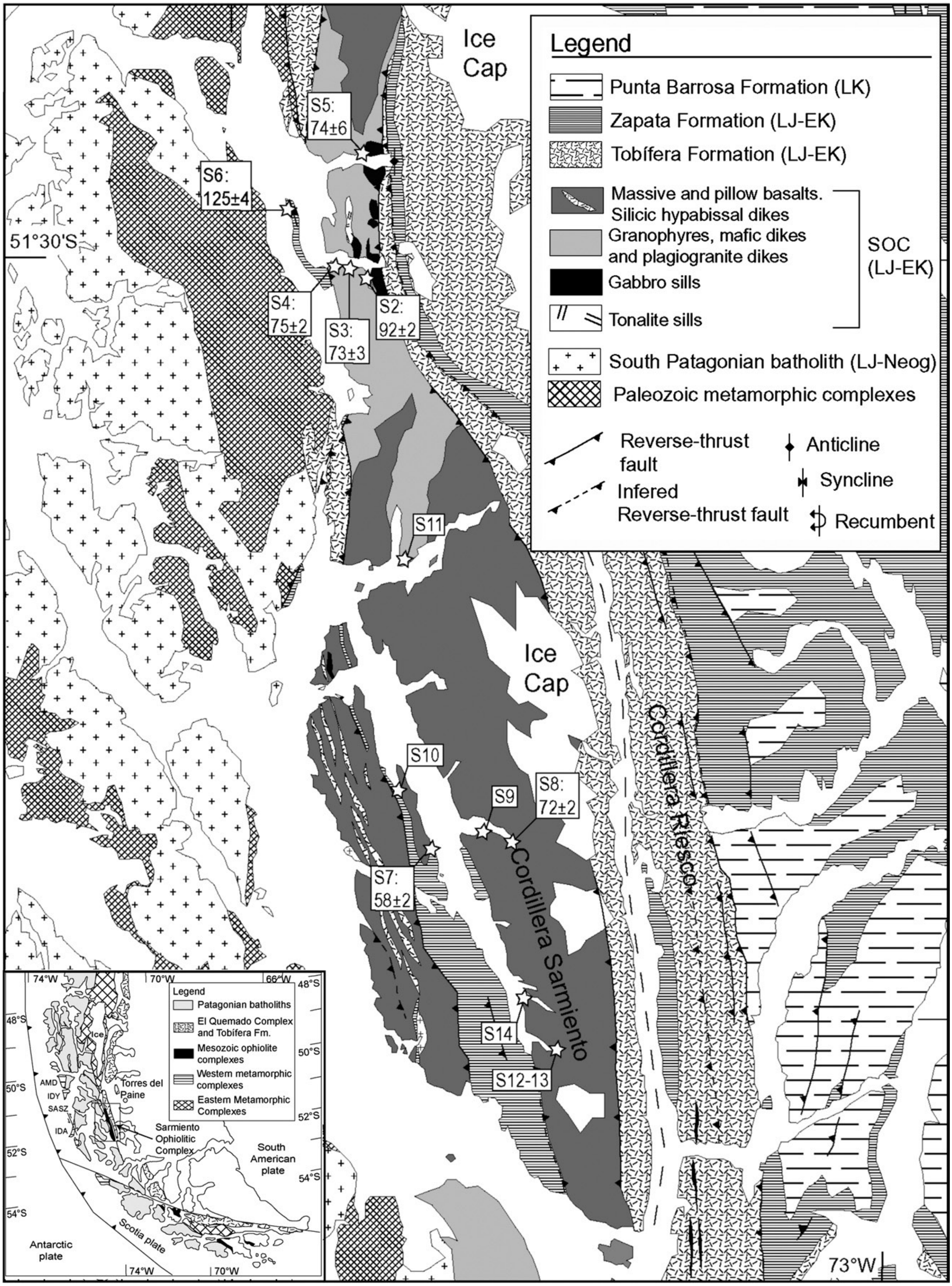

Fig. 1. Geologic map of the Cordillera Sarmiento and neighbouring areas in southern Chile. The paleomagnetic sampling sites and the K/Ar whole-rock ages (italics) are shown. Inset: main tectonic units of the southernmost Andes and location of the Sarmiento and other ophiolitic complexes.

chamber ASC non-magnetic furnace. The type of demagnetization applied was determined after evaluation of magnetic behaviour of at least 4 pilot specimens per site that were submitted either to thermal (two specimens) or AF (other two) cleaning (e.g. Butler, 1992) in twelve to sixteen steps. Maximum temperatures of 650 °C and magnetic fields of 140 mT were reached. Some examples of characteristic behaviours are presented in Fig. 2. Magnetic components were isolated by visual inspection of each specimen independently and computed by means of principal component analysis (Kirschvink, 1980). Maximum angular deviation (MAD) up to 15° was accepted, although 80% of components were determined with MAD values under 10°. Besides a very soft and random magnetic component of probable viscous origin that was erased in many samples at fields under 15 mT or temperatures below 250 °C, most sites presented a well defined, highly consistent magnetic component. This was not present at sites S-4 and S-7, which showed either very low coercive forces (S-4, Fig. 2D) or unstable behaviours (S-7). The characteristic component defined in all other sites was properly isolated both by AF and thermal cleaning (Fig. 2). AF demagnetization showed moderate coercive forces, which permitted definition of the component from 20 mT up to 75 or even 100 mT, while thermal treatment permitted isolation of the characteristic remanence from 200 °C up to 600 °C in many cases. The discrete unblocking temperatures found in many samples around 550–580 °C as well as the convex to concave up shape of the AF demagnetization curve (e.g. Fig. 2A, B) strongly suggest that single domain (SD) magnetite is the magnetic carrier in most sites (Dunlop and Özdemir, 1997). However, the possible presence of pirrhotite was inferred in site S-11 by discrete unblocking between 300 °C and 350 °C.

The mean characteristic remanence direction for each site is presented in Table 1. Moderate to high directional consistency is observed in the eleven sites. These directions, both before and after bedding correction are presented in Fig. 3. Bedding correction was applied solely to the data belonging to lavas, since paleohorizontal data for sampled dikes was not available. They were considered initially unaffected by significant tectonic tilting due to their sub-vertical attitude. Comparison of statistical values of the mean site direction before and after correction indicates a negative result for the fold test. Stepwise application of bedding correction yielded the best grouping of site directions at 0% unfolding. These results indicate that the

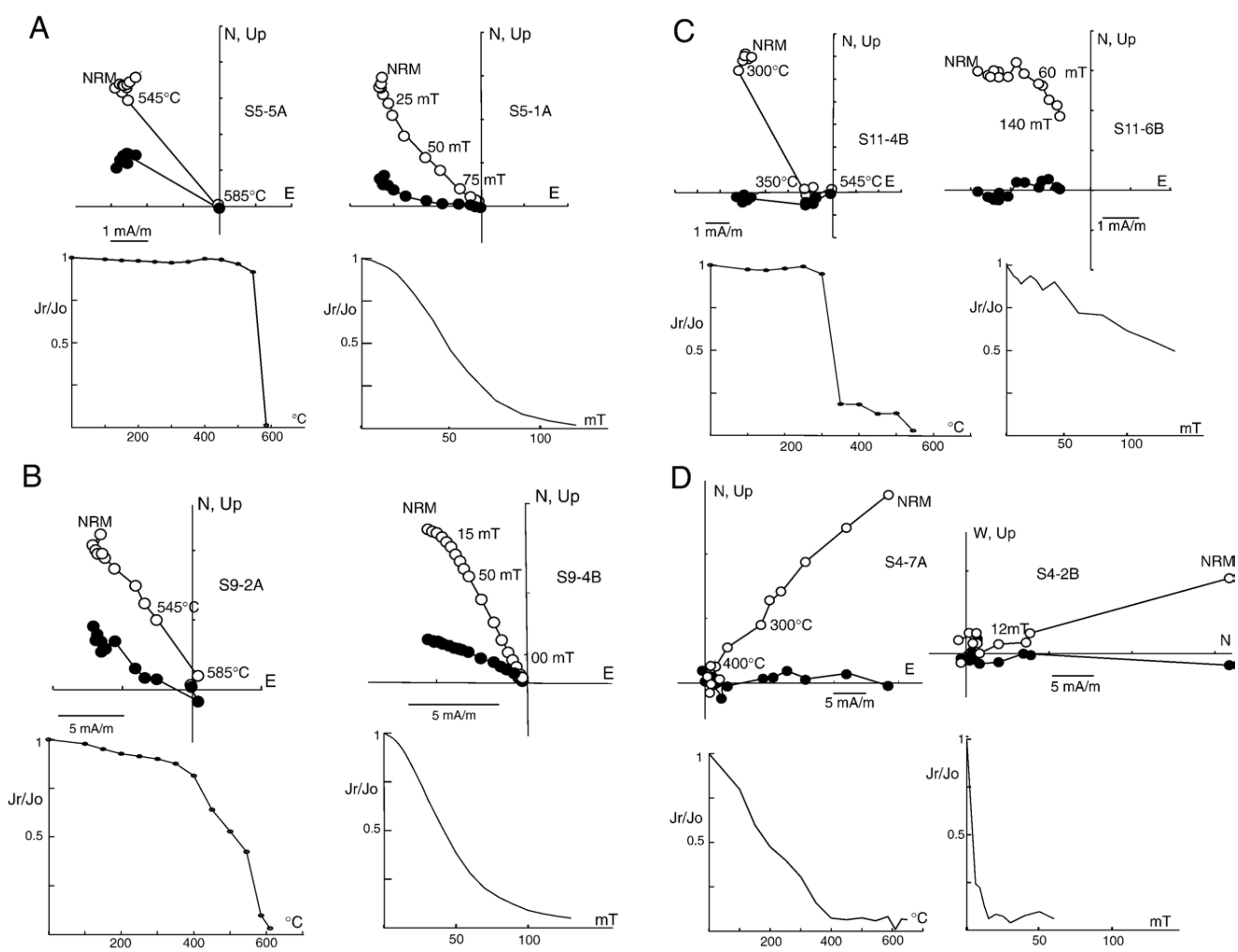

Fig. 2. Representative demagnetization behaviour of samples from different lithologic units of the SOC shown by Zijderveld diagramas and normalized demagnetization curves. In each case the response of specimens from the same site to AF and thermal cleaning is shown. In the Zijderveld plots, projection on the horizontal (vertical) plane is represented by full (open) symbols. More details in the text.

Table 1
Site mean remanence directions isolated from dikes and pillow-lavas of the Sarmiento Ophiolitic Complex (SOC)

Site	Lithology	*n* (*N*)	Dec (°)	Inc (°)	α95 (°)	Bedding correction Strike;dip	Dec* (°)	Inc* (°)	α95 (°)
S-2	Sheeted dyke	6	237.2	−63.9	11.6	0;0	237.2	−63.9	11.6
S-3	Sheeted dyke	7	312.4	−58.7	11.0	0;0	312.4	−58.7	11.0
S-5	Sheeted dyke	7	298.7	−51.6	3.5	0;0	298.7	−51.6	3.5
S-6	Dyke	7	134.7	72.1	9.5	0;0	134.7	72.1	9.5
S-8	Pillow-lava	7	289.1	−52.7	7.2	180;30	333.7	−77.2	7.2
S-9	Pillow-lava	8	295.7	−56.5	3.4	180;30	356.7	−76.1	3.4
S-10	Pillow-lava	7	283.4	−56.0	7.9	170;52	48.2	−66.0	7.9
S-11	Sheeted dyke	5	271.5	−62.0	11.8	0;0	271.5	−62.0	11.8
S-12	Pillow-lava	7	279.1	−53.0	9.0	52;12	287.6	−43.6	9.0
S-13	Pillow-lava	7	285.0	−45.9	10.9	335;68	272.5	13.2	10.9
S-14	Pillow-lava	7	286.5	−56.7	5.5	72;35	310.5	−30.0	5.5
Mean in situ		11	286.9	−58.5	6.9				
Mean corrected		11					297.8	−60.4	19.7

Site S-6 corresponds to a ca. 80 Ma lamprophyric dike intruding the folded Zapata Fm. *n* (*N*): number of samples (sites) considered for the mean; bedding correction values are expressed following the right-hand rule; no bedding correction was applied to remanence directions from dikes; Dec* and Inc* correspond to declination and inclination values after bedding correction.

characteristic remanence found in the SOC is a post-tectonic magnetization. Application of McElhinny's (1964) fold test indicates that this result is statistically significant at a 99% confidence. The overall mean direction for the SOC is: Dec: 286.9°, Inc: −58.5°, α95: 6.9°, N (sites): 11.

Ten out of eleven sites present a west-directed upward magnetization, while a single site (S-6) corresponding to a discordant sub-vertical lamprophyric dike intruding folded shales of the Zapata Formation shows a direction of opposite polarity.

The origin and tectonic implications of the paleomagnetic data obtained are analyzed below.

4. Rock magnetism and petrographic observations

In order to constrain the magnetic mineralogy of the SOC and its origin a series of rock magnetic measurements as well as microscopic observations of thin and polished sections of representative samples were performed.

4.1. Bulk susceptibility (k)

Bulk susceptibility of each specimen was measured with a Bartington MS-2 susceptometer. The geometric average value for each site is presented in Table 2. With the exception of site

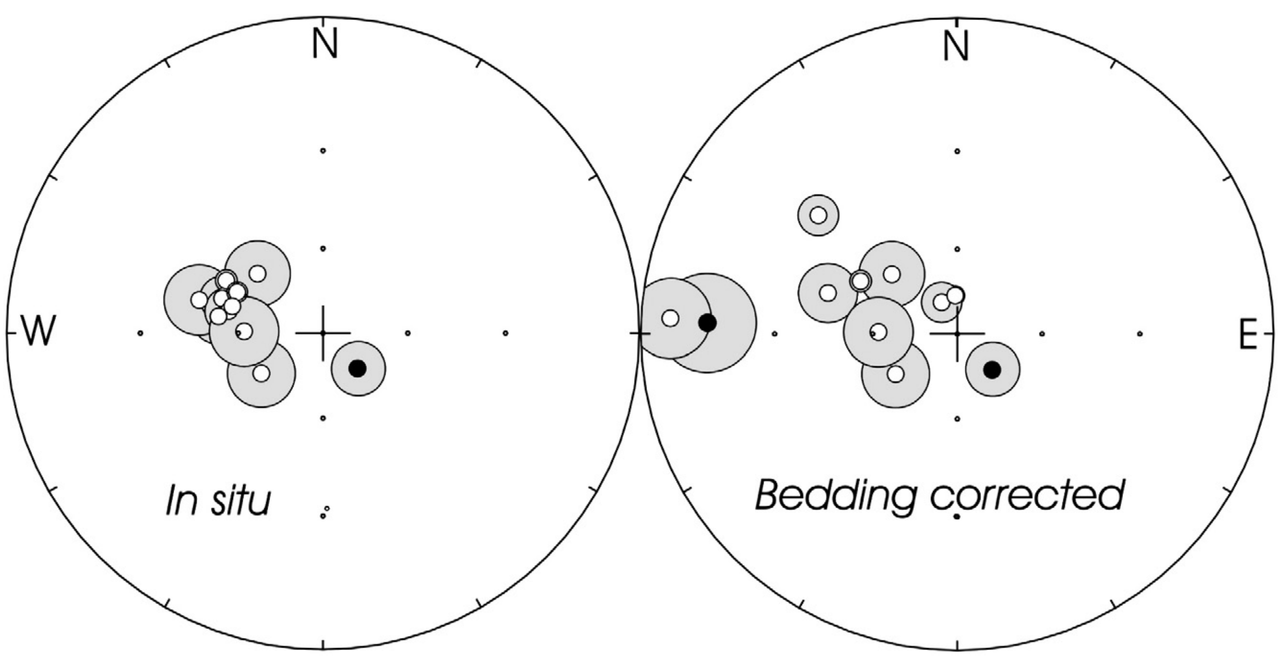

Fig. 3. Site mean remanence directions for the Sarmiento Ophiolitic Complex also presented in Table 1, both in situ (A) and after bedding correction (B). Note the negative fold (tilt) test. Each mean direction is represented with its correspondent α95 (grey circles). Open (full) symbols represent negative (positive) inclinations. Note the only site with an opposite polarity (S-6), corresponding to the ca. 80 Ma lamprophyric dike.

Table 2
Mean site magnetic susceptibility and classification

Site	K mean (10^5 SI)	Standard deviation	Type of rock and magnetic classification
S-2A	246	50	Gabbro, weakly ferromagnetic
S-2B	84	13	Dyke cutting gabbro, paramagnetic
S-3	88	12	Sheeted dyke, paramagnetic
S-4	468	175	Sheeted dike, moderately ferromagnetic
S-5	49	14	Sheeted dyke, paramagnetic
S-6	63	4	Lamprophyric dyke, paramagnetic
S-7	57	–	Pillow-lava, paramagnetic
S-8	59	11	Pillow-lava, paramagnetic
S-9	66	5	Pillow-lava, paramagnetic
S-10	49	4	Pillow-lava, paramagnetic
S-11	64	2	Sheeted dyke, paramagnetic
S-12	68	5	Pillow-lava, paramagnetic
S-13	61	16	Pillow-lava, paramagnetic
S-14	48	5	Pillow-lava, paramagnetic

S-4 and subsite S-2A (correspondent to a gabbro), which show moderately high k values, all remaining sites show low k values approximately between 5 and 8×10^{-4} SI. These values correspond to susceptibility dominated by paramagnetic minerals (Tarling and Hrouda, 1993). The homogeneous low values found both in dikes and lavas along near 100 km indicate that this is a characteristic feature of the SOC. The fact that the only significantly different site (S-4) presented as well a different character of the remanence, compatible with large magnetite grains, suggests that a secondary geologic event may have produced both this homogenization and the post-folding remanence. The paramagnetic character of most of the SOC rocks is consistent with the magnetic response of basalts and upper level of dike complexes of ophiolites and from drill cores of altered oceanic crust (e.g. Frey and Robinson, 1998). As shown before, virtually all sites showing this paramagnetic susceptibility also presented evidence of a characteristic remanence carried by magnetite. It is interpreted that a secondary process may have produced breakdown of the original iron oxides in most sites (except S-4) and that a very limited but widespread secondary formation of small size magnetite grains occurred afterwards generating the acquisition of a post-folding magnetization.

4.2. Isothermal remanent magnetization (IRM)

Normalized IRM acquisition curves were obtained for one specimen per site of the SOC up to maximum fields of 1 T with an ASC pulse magnetizer. They are illustrated in Fig. 4. All curves indicate that the remanence is dominated by a ferrimagnetic mineral. Relatively high coercivities in sheeted dikes and to a lesser extent in pillow-lavas (50% of saturation IRM acquired between 45 and 100 mT) is consistent with SD magnetite as the carrier as suggested by demagnetization behaviours. The much lower coercivity showed by site S-4 (50% of saturation IRM at around 30 mT) points to a significant presence of MD magnetite, consistent with high k values and the absence of the characteristic post-tectonic remanence.

4.3. Hysteresis cycles

Hysteresis curves were obtained from crushed samples from sites S-3, S-5, S-6, S-8 and S-10. Measurements were made with a Molspin VSM at the Instituto de Geociencias, Universidade de Sao Paulo (Brasil), with a maximum applied field of 1 T. In all cases an overwhelming paramagnetic signal was observed with no reliable isolation of any ferromagnetic (s.l.) contribution. These somewhat contradictory results with the already mentioned IRM curves can be explained by the presence of a very small fraction of a ferrimagnetic mineral that is obscured by the paramagnetic response in the hysteresis experiments.

4.4. Petrography

From petrographic evidence, the metamorphic evolution of the Sarmiento Ophiolitic Complex is far from simple. According to Elthon and Stern (1978), after its magmatic formation in the Late Jurassic, the SOC underwent a hydrothermal and non-deformative ocean floor metamorphism, prior to its uplift, which developed secondary mineral assemblages in a steep vertical metamorphic gradient passing from zeolite to greenschist facies, followed by a transition to amphibolites and fresh gabbros. The overprint of this metamorphism is characterized by irregular grain boundaries and disequilibrium retrograde effects. These authors explain the observations with a model governed by the interaction of the igneous pseudostratigraphy, the geothermal gradient and hydrothermal circulation. Recent studies allowed the recognition of kilometre wide sheared belts in the SOC and the Tobífera Formation (Galaz et al., 2005; Calderón 2006), which are probably associated with processes of ophiolite over-thrusting. Syntectonic mineral assemblages in foliated mafic metaigneous rocks and geothermobarometric calculations in sheared felsic rocks allowed these authors to constrain a greenschist facies metamorphic

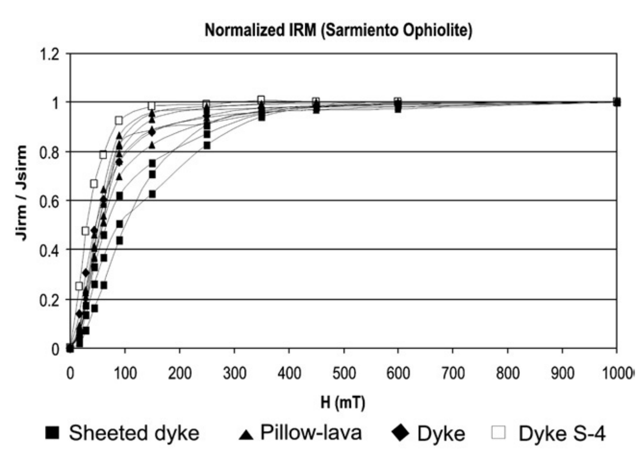

Fig. 4. Normalized acquisition curves of isothermal remanent magnetization (IRM) for representative samples of the Sarmiento Ophiolitic Complex. Note that all samples reach saturation before 500 mT indicating a ferrimagnetic phase (magnetite?) as principal magnetic carrier. The lower coercive force of site S-4 is consistent with its demagnetization behaviour suggestive of MD magnetite (Fig. 2D). More details in text.

event that may have occurred before the latest Cretaceous (ca.75 My, according to radiometric ages presented in this paper). In order to know the incidence of the mentioned metamorphic processes on the natural remanent magnetization of the SOC a study of ferromagnetic (s.l.) minerals, carriers of such magnetization, was performed. A description of the major iron-bearing phases can be found in Stern et al. (1976) and Elthon and Stern (1978).

The studied rocks show metamorphic assemblages consisting of actinolite, titanite, epidote, chlorite/smectite, quartz and carbonates in mafic dikes and gabbros. In mafic lavas and dikes, from the southern area (Fig. 1), epidote, chlorite/smectite, titanite, pumpellyite, rare actinolite and carbonates are common metamorphic phases. Magnetic minerals were identified by microscope observations under reflected and transmitted light, and in some cases by energy dispersive X-ray spectrometry (EDAX). According to microscopic observations, the gabbroic sills (site 2A,B) are composed of medium- or fine-grained amphibolitized gabbro with abundant hemo-ilmenites. The opaque minerals are dominated by ilmenite which precipitated as rod-shapes and along the cleavage planes of metamorphic amphibole (Fig. 5A, B, C), and as crystals rimmed by titanite, the latter stable in lower grade metamorphism. In some specimens magnetite–ilmenite intergrowths are observed (Fig. 5E). These oxides seem to have been formed by replacement of pyroxene by amphibole during water-fluxed (hydrothermal) metamorphism. Pseudomorphs of amphibole are considered as ghost crystals of pyroxene (Fig. 5F).

The sheeted dikes were either of fine-grained amphibolitized gabbros (sites 3 and 4) or diabase (sites 5 and 11). In the former ilmenite is generally replaced by titanite, in some cases as pseudomorphs. Site 4 presents large (≥ 50 μm) titanomagnetite and ilmenite crystals. The diabase dikes contain no Fe–Ti oxides visible under the microscope. They present sulphides (pyrrhotite–pentlandite? and chalcopyrite) grains rimmed by goethite of possible meteoric origin. The lavas (sites 7, 8, 9, 10, 12, 13 and 14) consist of pillow and massive fine-grained basalts with no Fe–Ti oxides visible under the microscope (Fig. 5I). Sulphides are chalcopyrite, pyrrhotite–pentlandite?, pyrite and marcasite as pyrite pseudomorph.

The lamprophyre (site 6) is a porphyritic and fine-grained amphibole-bearing dike that intrudes folded shales of the Zapata Formation (Figs. 1, 5G, H). Fe–Ti oxides are not observable under the microscope. Sulphides are abundant (chalcopyrite grains rimmed by goethite and pyrrhotite–pentlandite?). A Mn–Fe oxide of the spinel group (probably jacobsite) is recognized too.

4.5. Analysis of magnetic susceptibility and petrography

Most sites show similar bulk susceptibility values (Table 2), independent of lithology. These values are consistent with the microscopic observations indicative of metamorphic processes that have performed strong effects on ferromagnetic minerals. These metabasites are distinctly poor in titanomagnetites, as indicated by their low magnetic susceptibilities, except for the metagabbro and some dikes crosscutting gabbroic sills. The later show higher susceptibilities due to both ilmeno-magnetite and hemo-ilmenite generated by uralitization of pyroxenes during ocean floor metamorphism (see also Stern et al., 1976). Dikes and lavas show low susceptibilities controlled by paramagnetic minerals, consistent with greenschist facies metamorphism that tend to destroy most magnetic minerals (Clark and Emerson, 1991). It is likely that chloritization (Eggleton and Banfield, 1985), a common process in all components of SOC, was responsible for generating almost pure microcrystalline (SD) magnetite as shown by IRM analyses and demagnetization behaviour.

5. Radiometric dating

Whole-rock K–Ar determinations were carried out on dikes of amphibolitized microgabbro at sites S-2, S-3, S-4 and S-5, and on pillow-lavas at sites S-7 and S-8. An additional amphibole-bearing lamprophyric dike at S-6, intruding the Zapata Formation, was also dated. The dating was carried out at the Center for Geochronological Research of the University of São Paulo. Laboratory procedures for potassium and argon analyses are virtually the same as previously described by Amaral et al. (1966). Argon is extracted by means of total fusion of the samples in a molybdenum-crucible by induction heating in an ultra-high vacuum system. A pure ^{38}Ar spike, taken from a pipette-driven reservoir, is used for the isotope dilution measurement, carried out in a Reynolds-type pyrex glass mass spectrometer. Potassium analysis is done by flame photometry, and all samples are run in duplicate, with a degree of reproducibility usually within 1.0%. The precision of the argon analyses depends on the quality of the mass spectrometer isotopic measurements, the ^{38}Ar spike calibration against standard samples, and also on the atmospheric argon content of each individual extraction. For normal determinations, the total analytical error, calculated considering error propagation, is around 3% at the 2 σ level. Potassium decay constants are after Steiger and Jaeger (1977).

The analytical details for the seven K–Ar measurements are presented in Table 3. It shows that all dikes present relatively low K amounts, between 0.3 and 1.0%, quite normal for mafic magmas. One of the pillow-lavas (ST0240A) showed a slightly higher K content. ^{40}Ar measurements were of adequate analytical quality, with atmospheric argon always below 60%. With the exception of sample ST0236B, with a higher value, all the others showed experimental errors within about 3%.

Pillow basalts and sheeted dykes of the SOC were formed during the Late Jurassic (ca. 150 Ma; Calderón et al., 2004). Therefore, the obtained K–Ar whole-rock ages found in our study clearly indicate a rejuvenation of the isotopic system in these rocks.

Looking at Table 3, a regional Late Cretaceous thermal event seems to be indicated by a cluster of apparent K–Ar ages between 72 and 75 Ma, obtained on three of the sheeted dikes from sites S-3, S-4 and S-5, as well as from the pillowed basalt at site S-8. The present mineralogy of these rocks (see "Petrography") includes the already mentioned low grade metamorphic

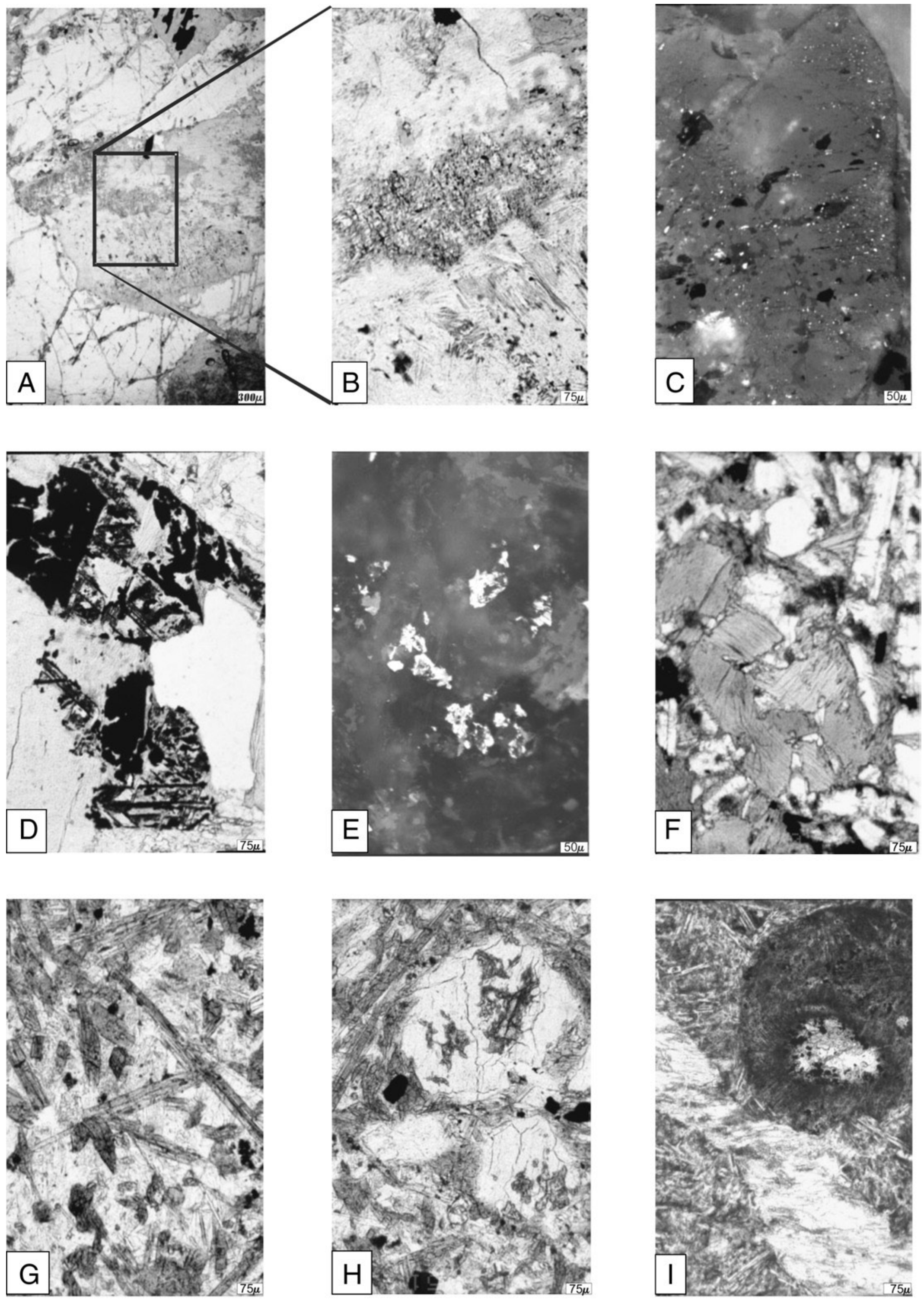

Fig. 5. Photomicrographs of selected samples from the Sarmiento Ophiolitic Complex under transmitted and reflected light. A, B and C (site 2A) show rods of ilmenite (black dots in B and white dots in C) formed by replacement of pyroxene by amphibole in a gabbro during water-fluxed (hydrothermal) metamorphism. D (site 2A) Oxide precipitates along cleavage planes of metamorphic amphibole. E (site 2B), magnetite–ilmenite intergrowths from a dike of fine-grained amphibolitized gabbro, possibly with the same metamorphic origin as in site 2A. F (site 2B), Metamorphic fibrous amphiboles in a dyke of fine-grained amphibolitized gabbro. G. Euhedral amphiboles from a lamprophyric dyke (Site 6). H. Euhedral olivine phenocrysts from site 6 mainly replaced by chlorites. I. A typical microscopic texture of a pillow-lava with no Fe–Ti oxides visible under the microscope. Scales are shown in the low right corner.

assemblages, in which the mineral phases containing potassium could be identified as white micas and also biotite as in sample ST0233B. Such minerals are known to retain argon well at low temperatures, and as a consequence they seem to bring evidence for a Late Cretaceous regional thermal episode.

Table 3
Basic experimental data for K–Ar and Ar–Ar analyses

Site	Sample (lab number)	Lithologic type	K (%)	Ar^{40} Rad ccSTP/g ($*10^{-6}$)	Ar^{40} Atm (%)	Age (Ma)
S-6	ST02-25 (7882)	Lamprophyric dyke	0.4054	2.04	24.94	125.2±3.7
S-2	ST02-29B (7883)	Microgabbro	0.7268	2.66	22.06	91.8±2.5
S-3	ST02-32B (7884)	Microgabbro (dyke)	0.3269	0.94	50.10	72.7±3.2
S-4	ST02-33B (7885)	Microgabbro (dyke)	0.9476	2.82	37.36	75.0±2.3
S-5	ST02-36B (7886)	Diabase	0.4161	1.22	51.59	74.4±5.6
S-8	ST02-40A (7888)	Basaltic pillow-lava	1.1324	3.24	15.65	72.1±2.1
S-7	ST-02-39D (7887)	Basaltic pillow-lava	0.5418	1.24	32.40	58.2±2.2

K–Ar age determinations on whole-rock samples from the SOC. Potassium decay constants are the ones recommended by Steiger and Jaeger (1977).

The remaining apparent ages of Table 3 seem to lack direct geological significance.

The age of the pillow basalt from site S-7 is clearly too young, reflecting argon loss from the less retentive mineral phases. Hydrothermal veins and complete replacement of olivine with carbonate were observed at this site.

A microgabbroic dike intruded within a deeper level of SOC, sampled at S-2, yielded an apparent age about 20 m.y. older than those of the sheeted dikes, indicating that perhaps argon degassing may not have been complete during the postulated Late Cretaceous thermal event.

The lamprophyre dike from site S-6, differently from the SOC sheeted dikes, shows a reversed magnetic polarity and intrudes the Zapata Formation, whose depositional age is at least Neocomian. It shows brown amphibole crystals which are preserved with just a narrow rim of actinolite, and it does not bear clear diagnostic evidence for a greenschist facies metamorphism. Its apparent K–Ar age is much older (Table 3), and may indicate that this sample was not seriously affected by the Late Cretaceous thermal event. Folded shales, intruded by this dike, however, bear low grade metamorphic assemblages consisting of prehnite, albite and carbonates suggesting that intrusion took place after this metamorphic event and that the 125 Ma dating cannot be assumed as the intrusion age of the dike. In any case, reliable dating of the lamprophyric dikes awaits a systematic geochronologic work.

In conclusion, although interpretation of whole-rock K–Ar dating is complicated by several variables that are difficult to take into account, the clustering of a few dates around 74 Ma, in the Late Cretaceous, seems to constrain an age for a resetting episode of the K–Ar systems. In the Late Cretaceous, a regional thermal episode, attaining about 400 °C in the area of sampling, may have produced complete argon loss and consequent rejuvenation of the isotopic systems. In effect, this thermal event may be related to a tectonic episode of thrusting and folding observed regionally and associated with final stages of closure and inversion of the Rocas Verdes marginal basin (e.g. Kraemer, 2003). The apparent K–Ar ages could be considered as labelling the time of regional uplift and consequent cooling that occurred subsequently. The widespread post-tectonic remagnetization observed in the lavas and dikes of the SOC can be tentatively assigned to the same episode of metamorphic overprint and following cooling.

6. Interpretation

Most studied rocks of the SOC are carriers of a post-folding remanent magnetization of exclusive normal polarity. According to our interpretation this remanence was acquired by small quantities of SD (?) magnetite formed during a metamorphic overprint in the final stages of or after closure of the Rocas Verdes back-arc basin in the Late Cretaceous. A cluster of whole-rock K–Ar ages around 74 Ma is consistent with a resetting of the K–Ar system associated with that event and is interpreted as its approximate age. The exclusive normal polarity observed in the SOC rocks is consistent with the long normal polarity C33n chron between 79 and 73 Ma (Gradstein et al., 2005) and the dominantly normal polarity C32 chron between 73 and ca.70 Ma. Lack of significant metamorphic overprint and the reverse polarity recorded by the lamprophyric dike intruding the Zapata Fm. at site S-6 suggests a younger age for this dike, despite the 125 Ma whole-rock K–Ar age obtained.

Mean site directions were presented in Table 1 and are plotted in Fig. 6 (after inversion of direction from S-6). Overall mean direction is anomalous with respect to the expected direction for the Cretaceous or Cenozoic of South America. A significant anomaly in declination is observed with a much less significant anomaly in inclination. Considering the evidence presented before it is likely that the magnetization was acquired in the Late Cretaceous. Therefore, a Late Cretaceous reference pole for South America (80.6°S, 344.2°E, $\alpha 95$: 4.4°, Somoza and Tomlinson, 2002) was used to compute the respective anomalies in declination and inclination, as well as their uncertainties, following Demarest (1983) and Beck (1989). The computed anomalies are R (anomaly in declination) = 58.8° ± 12.4° (ccw) and F (inclination anomaly) = 12.9° ± 6.0° (positive means lower than expected inclination). Both parameters are significant, although R is the most striking. The high consistency of mean site directions along the whole extension of the SOC exposures suggests that the SOC behaved as a basically rigid tectonic block with minor or no relative rotation or tilting between sites.

Previous studies in the region have reported significant ccw rotations (Rapalini et al., 2001; Iglesia Llanos et al., 2003), both to the NW and NE of the SOC. It may well be speculated that a similar ccw rotation around a vertical axis affected the studied outcrops of the SOC. Fig. 6B presents the location of previous paleomagnetic studies in the region that have detected ccw rotations around vertical axes. For a more detailed analysis of the paleomagnetic database of the region see Rapalini (2007). As can be seen in the figure, the declination anomaly found in the SOC is virtually identical to those found in the Jurassic El Quemado volcanics exposed to the NE on the Argentine side of the southern Patagonian Andes. This may lead easily to

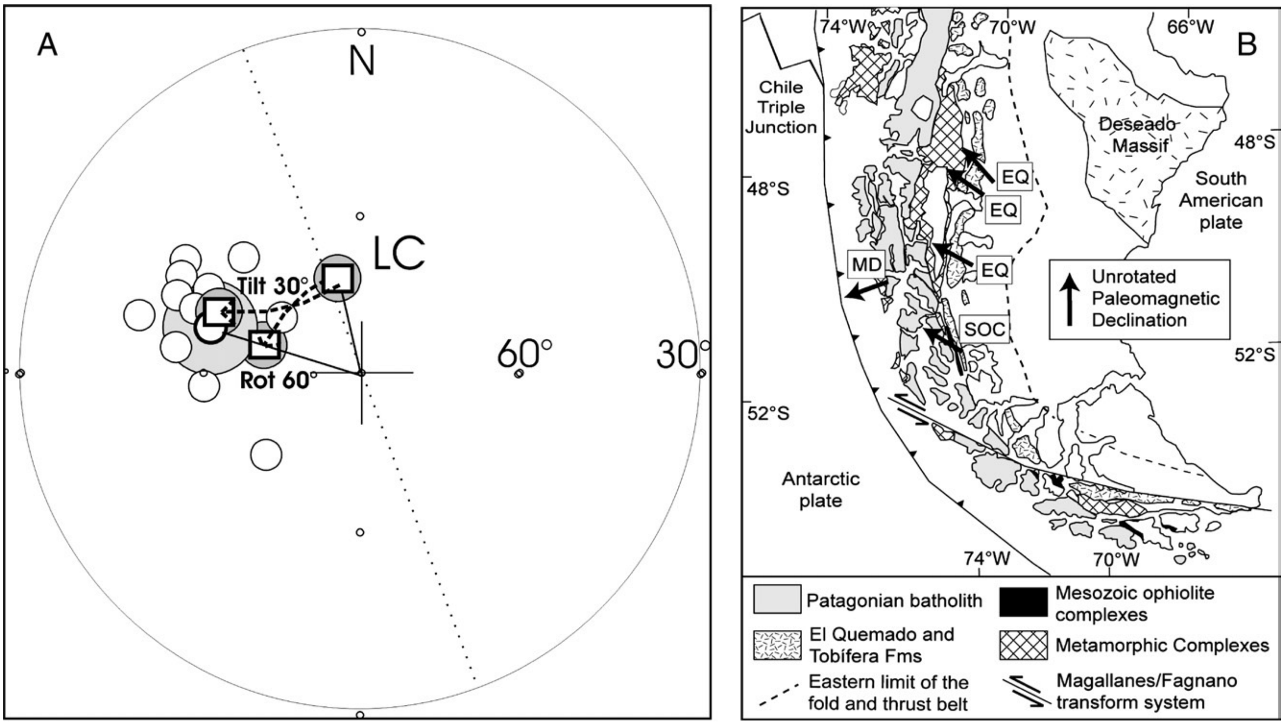

Fig. 6. A. Site mean remanence directions of SOC and its overall average shown by its α95 (grey circles). Antipodal direction from site S-6 has been plotted to keep all directions in the same hemisphere. Squares (and small grey circles) are the Late Cretaceous expected direction at the sampling area (and its α95) and their positions after 60° ccw rotation around a vertical axis or after tilting westward around a horizontal axis trending N340°E (shown as a dotted line) B. Paleomagnetic declinations obtained in previous studies in the region compared with those obtained in the present study. MD: Madre de Dios (Denaro and Tarlton Complex, Rapalini et al., 2001), EQ: El Quemado volcanics (Iglesia Llanos et al., 2003), SOC: Sarmiento Ophiolitic Complex (present study). Note the apparently systematic ccw rotations and the nearly identical values of declination anomalies obtained at SOC and EQ.

speculate on a single (and simple?) tectonic process that has produced identical ccw rotations on a scale of a few hundred kilometres, either as a single rigid-body or as systematic rotations of several smaller blocks (in a domino-like system?). However, such a significant rotation faces several important problems: i) it must postdate closure and inversion of the back-arc basin, due to the post-tectonic nature of the remanence, which rules out a feasible mechanism for producing a significant rotation of a large tectonic block; ii) it implies a very complex paleogeographic scenario with an originally NE–SW oriented basin, probably unconnected to other coeval outcrops of the Rocas Verdes basin located to the south; and iii) it does not explain the minor inclination anomaly.

Since the characteristic remanence of the SOC is post-folding, paleohorizontal control is lacking and a declination anomaly can also be caused by rotation around a horizontal or an inclined axis. A simple tectonic way to interpret the declination anomaly found in the SOC is a rigid-body tilting around a NNW horizontal axis. Fig. 6A shows that a 30° tilting of the whole block towards the west around a horizontal axis trending N20°W produces an agreement with the Late Cretaceous South American reference direction.

Calderón et al. (2005) have described a couple of high-angle reverse N–S to NNW–SSE faults dipping to the west and limiting both the SOC outcrops and the Cordillera Sarmiento on the East (Fig. 7). It is likely that the SOC block was rigidly uplifted along one or more high-angle reverse faults during Andean shortening. These are likely Mesozoic normal faults, developed during the earliest stages of basin formation, reactivated with inverse displacements during the Andean orogeny. In such model, listric normal faults reactivated during a compressional event may easily produce a rotation of the uplifted block around a nearly horizontal axis parallel to the strike of the fault (Fig. 7).

This interpretation is consistent with the high topographic relief of the Cordillera Sarmiento and field observations of strata of the Zapata Formation on top of the SOC lavas dipping around 30° to the west (see also Allen, 1982). It is also consistent with structural interpretation of seismic data reported by Harambour (2002) who suggested that deeply rooted Late Jurassic normal faults inverted during the Andean orogeny are responsible for the uplift of the Magallanes fold and thrust belt. These faults would be rooted into a single decollement situated at around 5 s (two way time) in the seismic sections and would have caused an uplift of at least 6 km in the Torres del Payne National Park, to the north of the study area, since the Miocene.

Previous estimates have considered total thickness of pillow-lavas in the SOC as not exceeding 2 km (e.g. Barker and Dalziel, 1983; Stern and De Wit, 2003), but unless undetected tectonic repetition affects the outcrops, tilting of ca. 30° to the west would imply a higher thickness for this layer. This may be explained by tectonic stacking during closure of the Rocas Verdes basin. Kraemer (2003) and Galaz et al. (2005) have suggested that this marginal basin was closed by westward subduction of oceanic

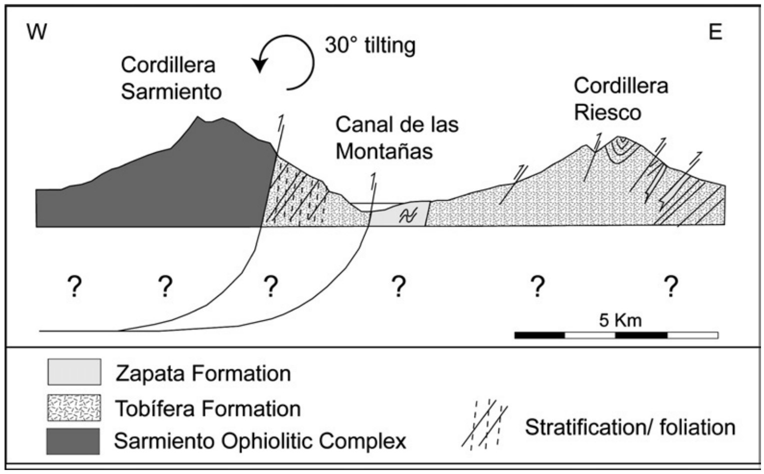

Fig. 7. Interpreted E–W cross-section at about 52°S showing the proposed westward tilting of the SOC outcrops due to tectonic inversion of normal listric faults associated with Andean reactivation. More details in text.

crust. This may have produced stacking of oceanic crust as has been long recognized in other ophiolitic complexes (e.g. Gealey, 1980). Tilting of sampled dikes was not expected at time of sampling as most selected dikes were sub-vertical. The lamprophyric dike intruding the Zapata Formation after folding is vertical but it trends towards azimuth 255°, which turns it orthogonal to the horizontal rotation axis inferred from the paleomagnetic results. Under these circumstances, tilting will be undetected in the field. Dike sampled at site S-11 dips 78° towards Az. 255°. This is consistent with an originally sub-vertical dike tilted some 15° towards the West, close to the tilting of the SOC inferred from the paleomagnetic data. On the other hand, sheeted dikes sampled in the northern sector show different strikes. Those with strikes that form high angles with respect to the 340° direction will show a very minor angle with respect to the vertical due to a 30° westward tilting. In any case the dikes may have been tilted first eastwards during subduction and closure of the marginal basin, acquired then their magnetization and finally tilted westward in the Cenozoic. Finally, sampling bias towards sub-vertical dikes in a large population of tilted dikes cannot be completely ruled out as a systematic measuring of dike attitudes has not been carried out yet in the region.

Age of the proposed rigid-body tilting of the SOC is constrained to be younger than the main deformational event, which has been associated with closure and inversion of the basin during Mid- to Late Cretaceous times (e.g. Dalziel, 1981; Wilson, 1991; Fildani et al., 2003; Kraemer, 2003; Stern and De Wit, 2003; Fildani and Hessler, 2005). Considering our interpretation of remanence acquisition in the Late Cretaceous, the time for tilting is restricted to the latest Cretaceous and Cenozoic.

The southern Patagonian continental margin was affected by two main deformational events in the Cenozoic, at ca 42 Ma and ca. 12 Ma (Kraemer et al., 2002), that have been correlated with ridge collisions (Ramos, 2005). Cande and Leslie (1986) proposed that the Miocene collision affected almost simultaneously a large section of the South Patagonian margin between 48° and 52°S in the interval of 14–10 Ma. According to Harambour (2002), the latter should be responsible for the uplift of the Torres del Paine granitic complex due to a thick-skin mechanism that produced a minimum of 6 km uplift. However, Thomson et al. (2001), based upon numerous zircon and apatite fission-track ages along the southern Patagonian Chilean margin, just north of the studied area, suggested that ridge collisions had no significant effect on the topographic relief, defining an event of accelerated cooling and high denudation (high topographic relief) in the western part of the Patagonian Andes at about 30 to 23 Ma, due to accelerated convergence between the Nazca and South American plates. This effect would migrate towards the east to be located on the eastern side (close to present divide) between 12 and 8 Ma.

The main tectonic trends and structures at the latitude of the SOC exposures, around Az. 340°, indicate ca. 20° of ccw deflection with respect to structures north of 50°S. Considering the lack of a primary remanence in the SOC rocks, use of our paleomagnetic results to test a secondary curvature of the orogen is ambiguous. Nevertheless, the analysis of the results already exposed indicates that they can be reconciled with the reference data of South America with no need for a post-Late Cretaceous secondary curvature of the orogen of about 20°.

7. Conclusions

A first paleomagnetic study on the Late Jurassic Sarmiento Ophiolitic Complex (SOC) exposed along the southern Chilean margin of South America was carried out. A widespread remagnetizing event has been found affecting both pillow-lavas and dikes of the SOC. Rock magnetic properties and petrographic observations suggest that the remagnetization was associated with a metamorphic overprint that pervasively affected these rocks. Whole-rock K–Ar reconnaissance dating produced systematically rejuvenated ages, which tend to cluster around 75 Ma, despite significant dispersion. A post-tectonic metamorphic overprint possibly associated with final stages of closure and inversion of the Rocas Verdes marginal basin during the Late Cretaceous (79–70 Ma?) is consistent with the geologic, paleomagnetic and radiometric evidence. The calculated post-folding mean remanence direction for the SOC is anomalous with respect to the expected reference directions of South America for the Late Cretaceous or Cenozoic. A significant ccw anomaly in declination of over 50° found for these rocks is very similar to ccw rotations found in the Jurassic El Quemado Fm., in the Argentine side of the South Patagonian Andean fold and thrust belt, over a 100 km to the NE of the study area. However, a similar interpretation that suggests a major ccw rotation of the whole SOC cannot be easily reconciled with the geologic evolution of the region and poses significant paleogeographic problems. On the other hand, considering the lack of paleohorizontal control that affects all post-folding remanence, a simpler model of 30° westward tilting of the whole SOC is preferred. This tilting must have taken place during a compressive event that produced the inversion of high-angle listric normal faults that were developed during opening of the basin. The proposed tilting is consistent with most field observations and may have occurred during an important Andean orogenic event, either in the Eocene or in the Miocene.

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