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Mid-Cretaceous polar standstill of South America, motion of the Atlantic hotspots and the birth of the Andean cordillera

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ABSTRACT

A paleomagnetic study on mid-Cretaceous rocks from the San Bernardo foldbelt (Patagonia) yields high unblocking temperature and high-coercivity magnetizations. The results indicate absence of relative vertical-axis rotations during development of the foldbelt, with the associated pole position being highly concordant with coeval poles from Brazil and Patagonia. Taken together, mid-Cretaceous poles derived from studies in widely distributed localities provide supportive evidence that South America was essentially motionless with respect to the paleomagnetic axis from ca 125 to at least 100 Ma. The paleolatitudes of South America are not consistent with the occurrence of mid-Cretaceous true polar wander, suggesting that the previously observed discrepancy between the paleomagnetic and the fixed Indo-Atlantic hotspot reference frames be related to motion of the Atlantic hotspots. In agreement with this, the discrepancy is diminished by half when the Cretaceous poles of the Americas are observed in a moving-hotpots reference frame, with the residual offset being comparable to that seen for younger time intervals. The South American paleopoles and the moving-hotspot framework provide a kinematic scenario that allows relating the extensional tectonics in the early stages of Andean evolution with episodic divergence between the trench and the continental interior. Likewise, the beginning of contractional events correlates with model-predicted westward acceleration of South America in the Late Cretaceous, suggesting that the continent episodically overrode the Andean trench by those times. We argue that this change in Andean tectonic regime is associated to major plate reorganization at ca 95 Ma.

1. Introduction

The mid-Cretaceous geological record documents major geodynamic events such as fast seafloor spreading, huge upwelling of mantle derived magmas, relative motion between paleomagnetic and fixed hotspot reference frames, and a >37 m.y. interval of uniform geomagnetic polarity. During the mid-Cretaceous occurred the final dismembering of Gondwana leading to consolidation of the major present-day continents and oceanic basins. A further peculiar characteristic in those times is that North America and Eurasia were essentially motionless with respect to the paleomagnetic axis, and similar behavior seems to have experienced the mid-Cretaceous Pacific (Tarduno and Sager, 1995; Sager, 2006).

In this paper we report new paleomagnetic data from mid-Cretaceous rocks in the San Bernardo foldbelt, Patagonia. The results, together with others from stable areas of South America, provide supportive evidence for an almost polar standstill between 125 and at least 100 Ma, a behavior that resembles that of the above mentioned plates. The stability of the Americas with respect to the spin axis in the mid-Cretaceous suggests that the previously observed discordance between the paleomagnetic and the fixed Indo-Atlantic hotspots frameworks (e.g. Andrews, 1985; Van Fossen and Kent, 1992; Prévot et al., 2000; Besse and Courtillot, 2002; Torsvik et al., 2002) is related to motion of the Atlantic hotspots. In agreement with this, applying new reconstructions with respect to a moving IAHS framework (O'Neill et al., 2005) significantly reduces the offset between Cretaceous poles from the Americas and the spin axis, suggesting that models that allow the sublithospheric melting anomalies to move and deform in response to flow in the surrounding mantle should be considered to assay tectonic and geodynamic models.

We further observe that both the moving-hotspot reference frame and the South American paleomagnetic poles provide a kinematic scenario that is compatible with the change in tectonic style recorded in the Andean margin during the mid- to Late Cretaceous. It is argued that this event is associated to major mid-Cretaceous plate reorganization.

2. Sampling in the San Bernardo foldbelt

The San Bernardo fold belt (Fitzgerald et al., 1990; Peroni et al., 1995; Figari et al., 1999) is a N–S band of compressional structures that transverses the intracratonic Golfo San Jorge basin (Fig. 1). It was

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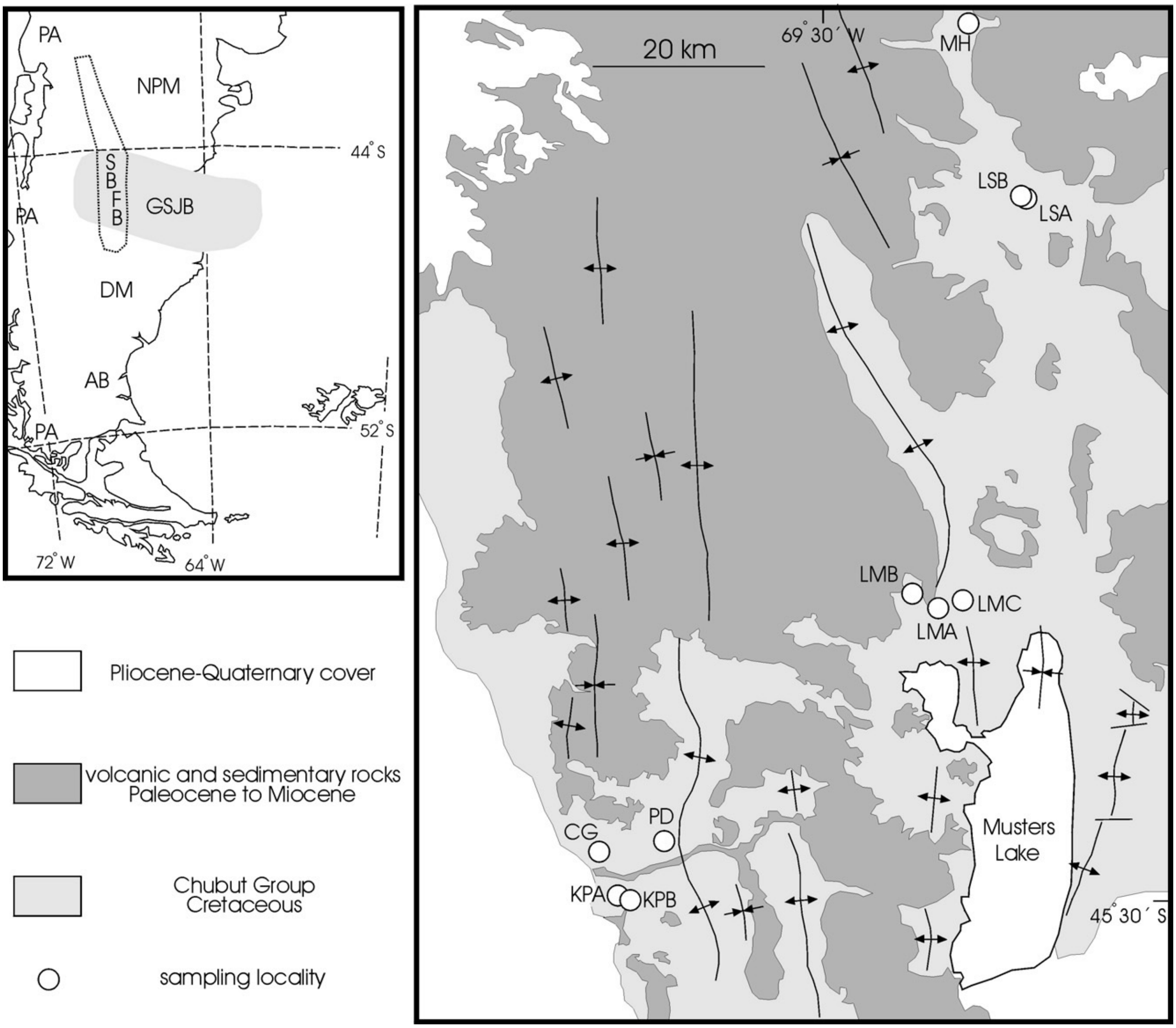

Fig. 1. The studied sector of the San Bernardo foldbelt (modified from Paredes et al., 2007). Upper left corner shows the location of the Golfo San Jorge basin (GSJB), the San Bernardo foldbelt (SBFB), and the outline of the Bernárdides (dotted line). The location of the North Patagonian Massif (NPM), the Deseado Massif (DM), the Austral Basin (AB) and the Patagonian Andes (PA) are also shown.

formed by middle Miocene tectonic inversion of Mesozoic extensional structures, producing long anticlines, broad synclines, and a variety of associated faults (Barcat et al., 1984; Peroni et al., 1995), showing an overall morphology of anticlinal mountains separated by broad synclinal valleys (Fig. 1).

During the mid- to Late Cretaceous the San Jorge basin was fulfilled by continental strata grouped into the Chubut Group (Lesta and Ferrello, 1972; Figari et al., 1999; Paredes et al., 2007), which are overlain by Lower Tertiary marine and continental strata and Cenozoic basalts. The fold belt constitutes the only area in the basin where the Chubut Group is exposed, being represented, from old to young, by low to moderate sinuosity fluvial systems of the Matasiete Formation and low sinuosity fluvial systems with wide alluvial plains and shallow-lacustrine deposits of the Castillo and Bajo Barreal formations (Sciutto, 1981; Paredes et al., 2007). The uppermost Cretaceous strata in the area comprise stacked paleosols formally named as the Laguna Palacios Formation, which constitute proximal facies of the upper Bajo Barreal fluvial system. Compositionally, the rocks of the Chubut Group are strongly dominated by volcaniclastic material (tuffs and tuffaceous sandstones and siltstones) provided from the west by the Andean magmatic arc.

The aim of this paleomagnetic study in the San Bernardo foldbelt was recognizing possible vertical-axis rotations associated with Cenozoic tectonic inversion. Sampling was performed on siltstones and fine-grained sandstones of the Castillo (62 samples from 4 sections) and Bajo Barreal (53 samples from 3 sections) formations, and on paleosols of the Laguna Palacios Formation (46 samples from 3 sections). The sampled sections have variable thickness, ranging from 20 m (PD section in the Castillo Formation) to 90 m (KPB section in the Laguna Palacios Formation). $^{40}Ar/^{39}Ar$ ages from tuffs in the three sampled units range from 97.9 to 85.1 Ma (Bridge et al., 2000), indicating that sampling covered the Cenomanian to Coniacian stratigraphic interval according to the timescale of Gradstein et al. (2004).

3. Paleomagnetic results

The high bulk magnetic susceptibility in these sedimentary rocks (mean value 2 10^{-3} SI) suggests an important participation of magnetite in their composition. Despite that the conformably overlying Paleogene units show a similar overall composition (tuffs and tuffaceous rocks), they show a bulk magnetic susceptibility one order of magnitude smaller than that observed in the studied Cretaceous rocks, suggesting that magnetite in the Chubut Group is of Cretaceous age.

A roughly direct proportionality is observed between the intensity of natural remanent magnetization and the magnitude of the bulk magnetic susceptibility. Stepwise thermal and alternating field demagnetization allowed observing, in all of the samples, a high-temperature, high-coercivity magnetization of normal polarity carried by magnetite (e.g. Fig. 2a–d). However, only those components defined by a maximum angular standard deviation ≤10° were considered for further analysis, resulting in the rejection of results from ten samples. Paleomagnetic results from the remaining samples are listed in Table 1. A positive tilt test (Fig. 2e) constraints the age of the isolated remanences to be older than folding (i.e. middle Miocene).

Anisotropy of the magnetic susceptibility (AMS) measurements on samples from fluvial and lacustrine facies of the Bajo Barreal and Castillo formations define a good cluster of minimum susceptibility axes almost perpendicular to bedding plane (e.g. Fig. 2f), indicating the predominance of sedimentary magnetic fabric in these units. In contrast, the magnetic fabric observed in paleosols from the Laguna Palacios Formation shows an important scatter of the minimum susceptibility axes (Fig. 2g) which we attributed to disturbance of the primary sedimentary fabric by bioturbation. Despite these differences in the magnetic fabrics, the isolated remanences are indistinguishable from each other when compared at unit-level (see CT, BB and LP means in Table 1). Considering that magnetite is both the main carrier of remanence and the likely mineral that governs the magnetic fabric, the contrasting paleomagnetic and AMS results may imply the occurrence of either a regional remagnetization during some Late Cretaceous–Early Cenozoic normal polarity chron or a protracted acquisition of remanence in the paleosols, with the final magnetization lock-in occurring very late in the pedogenesis. The possibility of regional remagnetization during a normal polarity chron younger than the Cretaceous Superchron may be ruled out due to the fact that magnetostratigraphic studies in Paleogene rocks from the San Bernardo foldbelt area (35 km SE of the Musters Lake, see Fig. 1) show the presence of well defined, regionally continuous normal and reversed polarity zones (Ré et al., in press), as expected for recordings of the Early Cenozoic geomagnetic field. Likewise, the South American apparent polar wander (APW) curve discussed below indicates that any remagnetization during a Campanian or Maastrichtian normal polarity chron should show steeper inclinations than those actually observed. Thus, the exclusive presence of normal polarities in agreement with the stratigraphic and isotopic ages of the rocks, the Cretaceous age of the carrier of remanence above discussed, and the lack of evidence for regional remagnetization strongly suggest that the observed remanences were acquired close to the time of deposition.

It is widely recognized that the record of paleofield in sedimentary rocks can be biased by inclination flattening, which is commonly attributed to either deposition of elongate magnetic particles (e.g. detrital hematite, see Tauxe, 2005) or post-depositional burial compaction, particularly in clay rich sediments (e.g. Anson and Kodama, 1987; Kim and Kodama, 2004). In the case of this study, however, we think that the isolated remanences may represent accurate records of the mid-Cretaceous magnetic field due to: 1) the fact that the paleomagnetic behavior indicates almost absence of hematite in the studied rocks (e.g. Fig. 2b, d); 2) the fact that the aggradation process documented by the tuffaceous, vertically-stacked

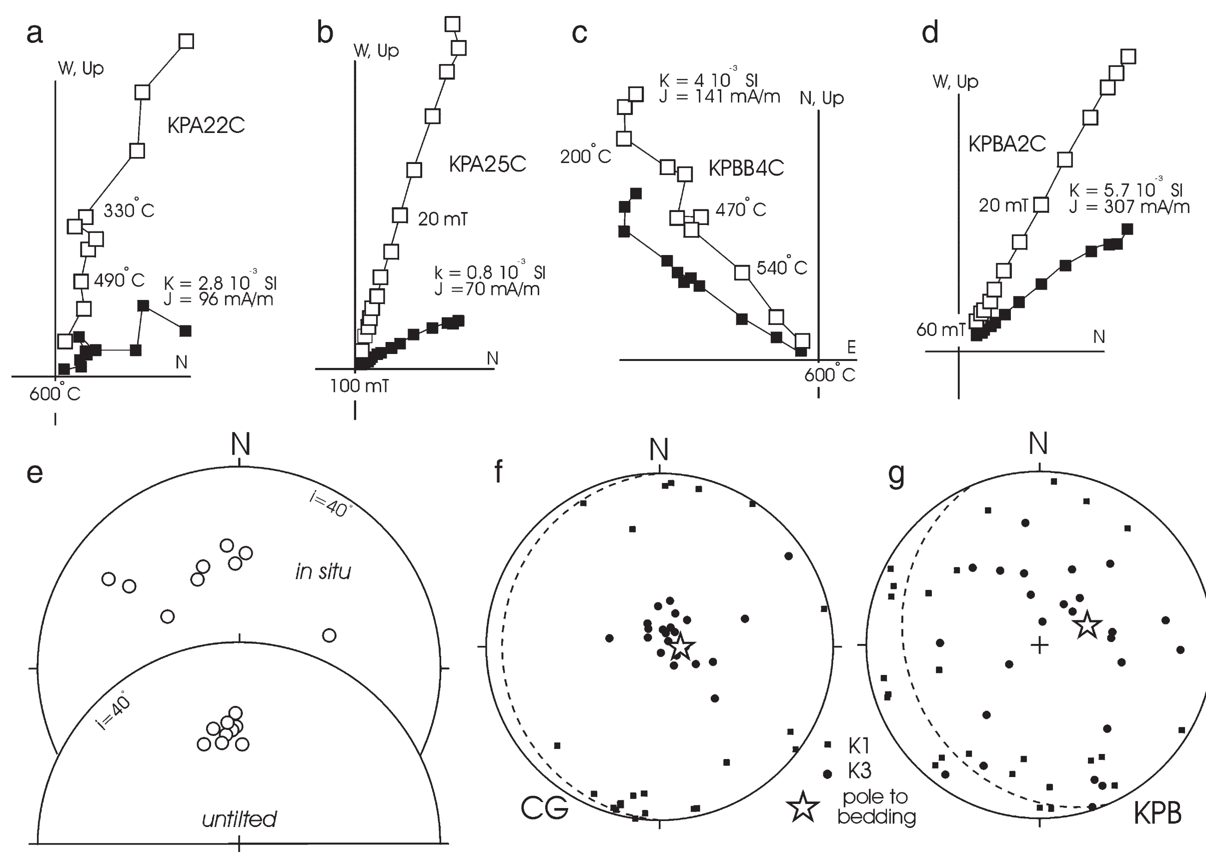

Fig. 2. Representative vector component diagrams (a–d) of progressive demagnetization of natural remanent magnetization (see text for description). Close (open) symbols representing projections onto the horizontal (vertical) plane. e) stereograms showing the time averaged vector from each of the studied sections in geographic and stratigraphic coordinates. f) anisotropy of the magnetic susceptibility results from fluvial-lacustrine rocks of the Bajo Barreal Formation (section CG in Fig. 1). K1 and K3 are maximum and minimum susceptibility axes, respectively. Lower hemisphere projection. g) anisotropy of the magnetic susceptibility results from paleosols of the Laguna Palacios Formation (section KPB in Fig. 1). Note the scatter of minimum susceptibility axes (K3), arguing against important post-paleosol compaction (see main text for further discussion).

Table 1
Paleomagnetic results

Section (unit)	Lat. (°S)	Long. (°W)	n	Decl.$_G$	Incl.$_G$	α_{95}	k	Bedding plane	Decl.$_S$	Incl.$_S$	α_{95}	k
KPA (CT)	45.48°	69.73°	15	336.2	−67.6	3.9	100	161/6	358.6	−62.9	3.9	100
KPA (BB)	45.48°	69.73°	12	333.5	−65.3	3.2	191	161/6	354.1	−61.3	3.2	191
KPA[2] (CT+BB)	45.48°	69.73°	27	335.2	−66.6	2.5	127	161/6	356.5	−62.2	2.5	127
KPB (LP)	45.49°	69.73°	21	306.5	−56.8	3.9	21	157/24	347.4	−61.3	3.9	21
CG (BB)	45.42°	69.75°	20	340.5	−64.2	2.9	123	180/10	1.9	−65.8	2.9	123
PD (CT)	45.45°	69.66°	11	358.7	−64.8	2.6	307	Subhoriz	340.5	−64.2	2.9	307
LMA (CT)	45.17°	69.28°	20	71.1	−66.8	3.2	77	46/36	358.3	−58.1	3.2	77
LMB (LP)	45.16°	69.31°	11	304.1	−51.6	7.7	36	171/30	350.5	−65.1	7.7	36
LMC (CT)	45.20°	69.26°	13	305.0	−68.9	4.2	99	135/21	353.0	−63.3	4.2	99
LSA (BB)	44.83°	69.23°	9	359.8	−64.8	6.0	76	11/1	357.8	−64.6	6.0	76
LSB (BB)	44.83°	69.23°	9	7.1	−59.8	3.8	188	20/5	359.1	−58.3	3.8	188
LSA,B[2] (BB)	44.83°	69.23°	18	3.8	−62.3	3.5	98	Variable	358.5	−61.4	3.5	97
MH (LP)	44.53°	69.26°	10	354.6	−60.3	4.1	143	Subhoriz	354.6	−60.3	4.1	143
Mean sections			9	339.0	−66.9	11.1	22		355.6	−62.8	2.0	659
CT mean			4						353.0	−62.3	5.4	291
BB mean			3						358.0	−62.9	4.7	676
LP mean			3						351.1	−63.1	4.1	902
Mean units			10						353.9	−62.7	2.2	498
Pole position (section level): Lat. 86.8° S; Long. 35.2° E; A95 = 2.8°; K = 346; N = 9												

Section (unit) denote geographic locality (sampled unit, where CT is Castillo F., BB is Bajo Barreal F. and LP is Laguna Palacios F). Lat., Long. indicate geographic coordinates of the section. n is the number of samples involved in statistics. Decl.$_G$, Incl.$_G$ are declination and inclination of paleomagnetic vector in geographical coordinates; α_{95} is the cone of 95% confidence level around mean direction; k is the fisherian precision parameter; bedding plane is donned as strike of bedding and dip measured 90 degrees clockwise from strike; Decl.$_S$, Incl.$_S$ are declination and inclination referred to the paleohorizontal. "2" indicates that the two preceding unit mean-directions have been averaged into a combined value which represents the section-mean used for tectonic analysis.

(locally up to 200 m) mature paleosols of the Laguna Palacios Formation points to a protracted history of ash fall and subsequent pedogenesis, attesting for a low subsidence, tectonic stability and the prevailing of diastems, all of them contrasting with the relatively fast burial of sediments that may favor compaction and associated inclination flattening; 3) the latter is further supported by the presence of undeformed ichnofossils (Genise et al., 2002) and by the fact that the magnetic foliation from many samples of these paleosols strongly departs from the bedding plane (Fig. 2g), suggesting that the last important modification in their primary sedimentary fabric is related to bioturbation associated with pedogenesis instead to post-paleosol compaction linked to burial. These points indicate that the paleomagnetic record in the Laguna Palacios paleosols is likely unaffected by significant inclination flattening. The fact that the inclination of the time-averaged paleomagnetic vector from these paleosols is indistinguishable from both the mean paleomagnetic inclination observed in the underlying sedimentary units (compare CT, BB and LP means in Table 1) and the paleomagnetic inclination predicted in the study area by results from older (125–100 Ma) magmatic rocks in Brazil (see below), points to negligible inclination flattening for all of the studied rocks.

4. Regional tectonic implications: further evidence for absence of crustal-scale rotations in Patagonia since mid-Cretaceous

As mentioned above, the magnetizations isolated in the San Bernardo foldbelt are indistinguishable from each other when compared at unit-level (Table 1), suggesting no discernible changes

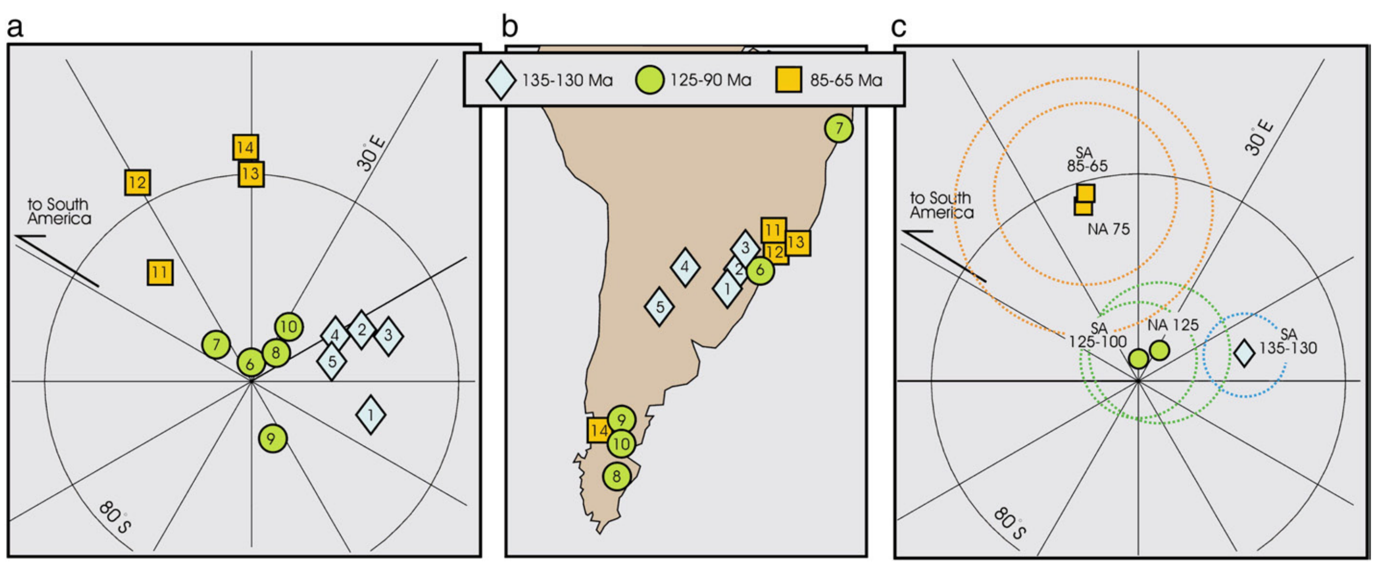

Fig. 3. a, b) Cretaceous paleomagnetic pole determinations for stable South America and localities where each study was done. Symbols separate the poles by age-group, numbers connect the paleopoles with sampling locations and with the "code" column in Table 2. c) SA denotes mean South American pole positions from the dataset in (a), NA denotes North American poles. NA125 corresponds to the mid-Cretaceous pole of Tarduno and Smirnov rotated to South American coordinates by combining M0 reconstruction in the central Atlantic (Klitgord, and Schouten, 1986) and South America–West Africa fit in the Equatorial Atlantic (Nürnberg and Müller, 1991). NA75 is a 75 Ma synthetic North American pole (Torsvik et al., 2001, spline method) transferred to South America by the North America to South America anomaly C33 finite rotation of Müller et al. (1999).

in the local geomagnetic field during the time span encompassing the deposition of the Castillo Formation and the development of paleosols in the Laguna Palacios Formation. Likewise, the tight cluster of time-averaged vectors in Fig. 2e indicates that the tectonic inversion in the basin did not produce relative vertical-axis rotations between the sampling localities. This allows using the directional dataset to calculate a paleomagnetic pole, which was done by conversion of each section-mean magnetization into its associated virtual paleomagnetic pole (VGP). The mean age (92.5 Ma) resulting from averaging the six $^{40}Ar/^{39}Ar$ dates available from the units in the study area constitutes a workable age for the obtained paleopole. Fig. 3a shows that the paleopole from the San Bernardo foldbelt is concordant with mid-Cretaceous poles from Brazil (see also Table 2), indicating that the folded area did not rotate as a whole with respect to stable South America.

The San Bernardo foldbelt is located in the southern part of the Bernárdides, a 600 km long and 100 km wide, NNW–SSE trending band of Miocene compressional structures that transverses the Patagonian foreland (Fig. 1). Somoza (1994) and Geuna et al. (2000) discussed paleomagnetic results from the Aptian Cerro Barcino Formation in the North Patagonian Massif (Fig. 1, Table 2), including several sites from the northern sector of the Bernárdides. The paleopole from the Cerro Barcino Formation is also concordant with Brazilian poles of similar age, although the paleomagnetic inclination of its observed time-averaged vector is a little shallower (~2°) than that predicted by those Brazilian poles. Nevertheless, the Cerro Barcino and San Bernardo paleopoles strongly suggest absence of vertical-axis rotations associated with the Miocene tectonic inversion in the Bernárdides. Taken together, the paleomagnetic dataset in the region indicates that the mid-Cretaceous and younger paleomagnetic record from Patagonia is suitable for constraining the South American APW curve.

5. The Cretaceous apparent polar wander path of South America

We agree with Ernesto et al. (2002) in that the Cretaceous APW path for South America is now well established. Indeed, an APW curve clearly emerges when Cretaceous pole positions derived from studies in widespread, mostly magmatic localities are plotted together (Fig. 3a, b). This APW implies that the Cretaceous continental motion with respect to the pole may be described as an episodic southward drift with an intervening period, from ca 125 to at least 100 Ma, of roughly APW standstill (see also Ernesto et al., 2002), which is further supported by the new results in the San Bernardo foldbelt (Fig. 3a). Despite this, we notice that the mid-Cretaceous mean-pole used in this paper (Fig. 3c) corresponds to the average of those poles derived from stable areas only, since including the poles from studies in the Bernardides does not change the computed pole position (compare South America mid-Cretaceous A with South America mid-Cretaceous B in Table 2).

The mid-Cretaceous interval of little South American motion with respect to the spin axis resembles the well known mid-Cretaceous polar standstill of North America (Van Fossen and Kent 1992; Tarduno and Smirnov, 2001). Fig. 3c shows the tight fit between the mid-Cretaceous South American mean-pole and the coeval North American mean-pole computed by Tarduno and Smirnov (2001) when the latter is rotated to South American coordinates by applying appropriate plate reconstructions. The angular difference between these mid-Cretaceous poles in Fig. 3c (1.1° ± 3.2°) illustrates the accurateness of both paleomagnetic determinations and plate tectonic reconstructions in the frame of a dominantly geocentric, axial and dipolar geomagnetic field, further supporting previous analyses of the mid-Cretaceous geodynamo (e.g. Tarduno et al., 2002).

The Late Cretaceous mean-pole for South American in Fig. 3c is less defined than the older paleopoles. It is evident, however, that late in the Cretaceous the continent experienced southward motion associated with some amount of clockwise rotation with respect to the geomagnetic axis (see also Ernesto et al., 2002). Available paleomagnetic data indicate that this episode of continental drift may be confidently bracketed between ca 100 (90?) and ca 75 Ma (Fig. 3a, c; Table 2). Albeit additional studies are necessary to refine the path and associated timing of the South American drift during those times, we highlight that 5°–7° southward motion during the Late Cretaceous seems to be inescapable on paleomagnetic grounds.

Table 2
Cretaceous poles for South America and North America (in South American coordinates)

Paleopole	Code	Age (Ma)	Lat. (°S)	Long. (°E)	A95	Source
Southern Paraná LIP	1	133 [1]	84.0	106.2	1.5	a
Central Paraná LIP	2	132 [1]	84.1	64.4	2.3	a
Northern Paraná LIP	3	132 [1]	83.0	71.4	2.4	a
Paraguay alkaline province	4	~129 [2]	85.4	62.3	3.1	a
Sierras Pampeanas in Córdoba	5	~130 [2]	86.0	75.9	3.3	b
Florianolopolis Dykes	6	~121 [1]	89.1	3.3	2.6	c
Baqueró Group	8	119 [1, 3]	88.2	42.7	5.5	d
Santo Agostinho Lavas	7	102 [1]	87.6	315.0	4.5	e
Cerro Barcino Formation	9	Aptian [3]	87.0	159	3.8	f
San Bernardo Foldbelt	10	~92 [1]	86.8	35.2	2.8	g
Poços de Caldas Complex	11	84 [2]	83.2	320.1	2.7	h
São Sebastião Island	12	81 [2]	79.4	331.9	4.9	h
Passa Quatro – Itataia complexes	13	70 [2]	79.5	360.0	5.7	h
Patagonian Basalts	14	80–65 [2]	78.7	358.4	6.3	i
South America Early Cretaceous [4]		135–130	84.7	76.4	2.0	g
South America mid-Cretaceous A [5]		125–90	89.1	33.8	2.4	g
South America mid-Cretaceous B [6]		125–100	88.7	354.0	2.3	g
South America Late Cretaceous [7]		85–65	80.6	345.1	4.3	g
North America mid-Cretaceous [8]		125–100	88.3	37.1	3.4	j
North America 75 Ma [9]		75	81.2	343.6	6.2	k

Code connects the listed pole positions with Fig. 3a. Source: a, Ernesto et al. (1999); b, Geuna and Vizán (1998); c, Raposo et al. (1998); d, Somoza et al. (2005); e, Schult and Guerreiro (1980); f, Geuna et al. (2000); g, this paper; h, Montes Lauar et al. (1995); i, Butler et al. (1991), j, Tarduno and Smirnov (2001); k, Torsvik et al. (2001). 1, Ar^{40}/Ar^{39}; 2, K/Ar; 3, paleontology; 4, mean of code 1 to 5 poles; 5, mean of code 6 to 10 poles; 6, mean of code 6 to 8 poles (undeformed areas only); 7, mean of code 11 to 14 poles; 8, transference using Klitgord and Schouten (1986) and Nürnberg and Müller (1991) rotations (see main text); 9, transference using Müller et al. (1999) rotation (see main text).

6. The Cretaceous paleomagnetic and Indo-Atlantic hotspot frameworks as seen from the Americas

Strong debate has been carried out in the last years about the origin of the discrepancy between paleomagnetic and Indo-Atlantic hotspot (IAHS) reference frames for the 130–110 Ma time interval (Prévot et al., 2000; Tarduno and Smirnov, 2001; Camps et al., 2002; Tarduno and Smirnov, 2002; Torsvik et al., 2002; Besse and Courtillot, 2002). The analyses involved in most of these studies comprise large paleomagnetic dataset and hotspot (HS) models (Müller et al., 1993) that consider the Indo-Atlantic plumes to be fixed in the mantle. In all of the cases, the reconstruction to the fixed IAHS framework shows a significant offset between the 130–120 Ma paleomagnetic poles and the spin axis, which may be corrected by applying 15°–12° clockwise rotation about an equatorial pole at 20°E longitude (Torsvik et al., 2002). Conversely, the 100–90 Ma and younger paleopoles tend to agree with the spin axis when observed in fixed-IAHS coordinates (Van Fossen and Kent 1992; Tarduno and Smirnov, 2001; Torsvik et al., 2002).

Prévot et al. (2000) and Besse and Courtillot (2002) interpreted the mismatch between the 130-110 Ma paleopoles in fixed-IAHS coordinates and the spin axis as evidence for a 130–100 Ma true polar wander (TPW) event, a geodynamic process that involves rotation of the whole rigid Earth about a nearly equatorial axis (Goldreich and Toomre, 1969). Conversely, others authors suggested that the main cause of the discordance is related to motion of the Atlantic HS during the mid-Cretaceous (Van Fossen and Kent 1992; Tarduno and Gee, 1995; Tarduno and Smirnov, 2001; Tarduno and Smirnov, 2002;

Torsvik et al., 2002). In particular, the little North American APW between 125–100 Ma has been interpreted as either evidence against the occurrence of mid-Cretaceous TPW (Tarduno and Smirnov, 2001; Tarduno and Smirnov, 2002) or a fortuitous coincidence (Camps et al., 2002) due to North American lithospheric motion in the opposite direction of that of predicted by the TPW event.

Paleomagnetism and plate tectonics indicate that the Americas rotated (with different angular rates) about the paleomagnetic axis during the mid-Cretaceous. Fig. 4a uses a North American test locality (nearby Baltimore) to show that the superposition of the motions predicted by the fixed-IAHS framework and the hypothetical TPW event conducts to a displacement compatible with that is indicated by paleomagnetism, illustrating the fortuitous coincidence invoked by Camps et al. (2002). Nevertheless, it must be noted that the history depicted in Fig. 4a would involve gradual, rather slow (0.6°/Myr) TPW during the 120–100 Ma time interval, since a sudden TPW event (Prévot et al., 2000) superimposed to the much slower North American continental drift should have produced an abrupt change in the APW curve (Tarduno and Smirnov, 2002; Torsvik et al., 2002). In contrast with the ambiguity in the North American scenario, a similar analysis on a locality from NE Brazil points to failure of the TPW hypothesis (Fig. 4b), favoring the claim (Tarduno and Gee, 1995; Tarduno and Smirnov, 2001; Tarduno and Smirnov, 2002; Torsvik et al., 2002) that the discordance between the paleomagnetic and fixed-IAHS reference frames in the mid-Cretaceous is mostly related to drift of the Atlantic HS.

O'Neill et al. (2005) used mantle convection models and dipole paleolatitudes to construct a moving IAHS framework back to 120 Ma. Somoza (2007) has shown that this moving HS model predicts the Late Cretaceous to Eocene APW curve of South America much better than the fixed-IAHS model does. In Fig. 5 we compare the consistency between both these HS models and the Cretaceous paleomagnetic poles from the Americas. Such comparison involves rotation of the paleopoles to each HS framework (Fig. 5a, b) and then averaging the distances from the reconstructed paleopoles of a given age to the spin axis, an approach named great circle distance (GCD) by Torsvik et al. (2002).

Applying the restricted (but accurate) set of paleopoles from the Americas resembles the results obtained from larger paleomagnetic datasets when subjected to fixed-IAHS reconstructions (see GCD box in Fig. 5), in agreement with the observation that the mid-Cretaceous discrepancy between the paleomagnetic and the fixed-IAHS reference frames is almost independent of the used paleomagnetic dataset (Torsvik et al., 2002). In particular, the position and distance (about 13°) to the spin axis of the 120 Ma poles in fixed-HS coordinates (Fig. 5a) agree with the offset observed in previous studies. This misfit is reduced to one-half when the paleopoles are rotated to the moving-IAHS framework (Fig. 5b), an improvement that would be partly related to the fact that this model is calibrated by paleomagnetic latitudes. On the other hand, the residual discrepancy (~6–7°) is similar to the average offset (~5°) that results when a larger dataset from Cenozoic paleopoles is observed in moving-IAHS coordinates (Torsvik et al., 2002). However, we emphasize that the small Cenozoic values are variable in direction and difficult to distinguish from noise sources (uncertainties in hotspot locations and paleomagnetic data).

Steinberger and O'Connell (1998) noticed that the mantle flow constraints they applied to determine plume-advention ignore diffusion, viscous dissipation, adiabatic heating and cooling effects, further commenting that this simplification may be justified for Cenozoic times and recognizing that its impact on Mesozoic modeling is uncertain (see also Steinberger, 2000; O'Neill et al., 2005). Hence, the 7–5° offset observed when Cretaceous–Cenozoic poles in moving-HS coordinates are compared with the spin axis could be partly related to unaccounted factors in plume-motion modeling, as well as some other factors including the exact location of the hotspot relative to its surface expression, and the age of the hotspot track (e.g. Baksi, 1999).

7. Motion of South America and tectonic regimes in the Andean region

The Andean magmatic arc that parallels the western margin of South America was almost permanently active since at least the Early Jurassic, pointing out a long-lived subduction history. The coeval evolution of the continental margin may be divided into two periods

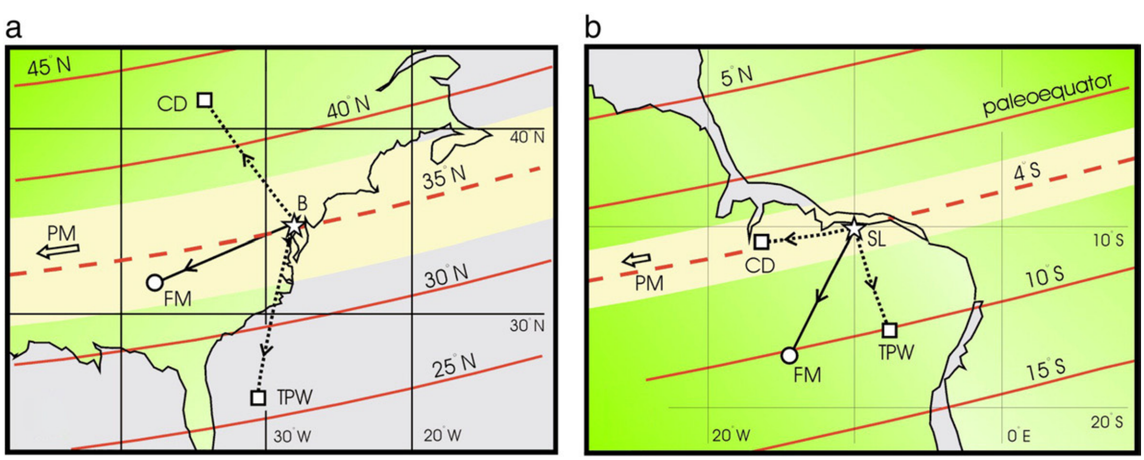

Fig. 4. a) North America and its associated paleomagnetic field rotated back to 120 Ma in the fixed Indo-Atlantic hotspot framework of Müller et al., 1993. Paleomagnetism and plate tectonics indicate that the continent moved westward (PM arrow) parallel to its paleolatitudes (some of them are shown in red). Red dashed line represents the 120–100 Ma paleolatitude for a test locality (star) near Baltimore (B) and yellow zone depicts its 95% confidence interval. Square (CD) is the 100 Ma position that the test locality would have reached in absence of TPW (continental drift only). Triangle (TPW) is the 100 Ma position that the test locality would have reached under the effects of TPW only (i.e. no continental drift). Since both rotations would have occurred in unison, the predicted path is that leads "B" to the 100 Ma position "FM" (circle). Note that this path is compatible with the paleomagnetically derived path (dashed line). The rotation from "B" to CD (after Müller et al., 1993) is 47.47° N; 16.64° E; angle = −12.09° (negative = clockwise). The rotation from "B" to "TPW" (after Torsvik et al., 2002) is 0° N; 20° E; angle = 11.9°. The composite rotation (from "B" to "FM") is 71.36° N; 205.61° E; angle = −10.04°. In order to minimize the effects of the non commutative property of rotations, the latter was calculated summing up 10 alternating rotations, five times 0° N; 20° E; angle = 2.38° and five times 47.47° N; 16.64° E; angle = −2.42°. b) The same framework as in 4a. Paleomagnetism and plate tectonics indicate that mid-Cretaceous South America also moved parallel to its paleolatitudes (PM arrow), possibly westward but slower than North America did. Star (SL) represents a test location near São Luis, other elements are equivalent than those in Figure 4a, and the analysis follows the same procedure as well. SL-CD rotation is 32.89° N; 340.68° E; angle = −9.14°; SL-FM rotation is 33.61° N; 238.66° E; angle = −9.16°. Note that, in this case, incorporating the TPW rotation conducts to wrong paleolatitudes, strongly suggesting that the TPW hypothesis is an artifact of HS motion.

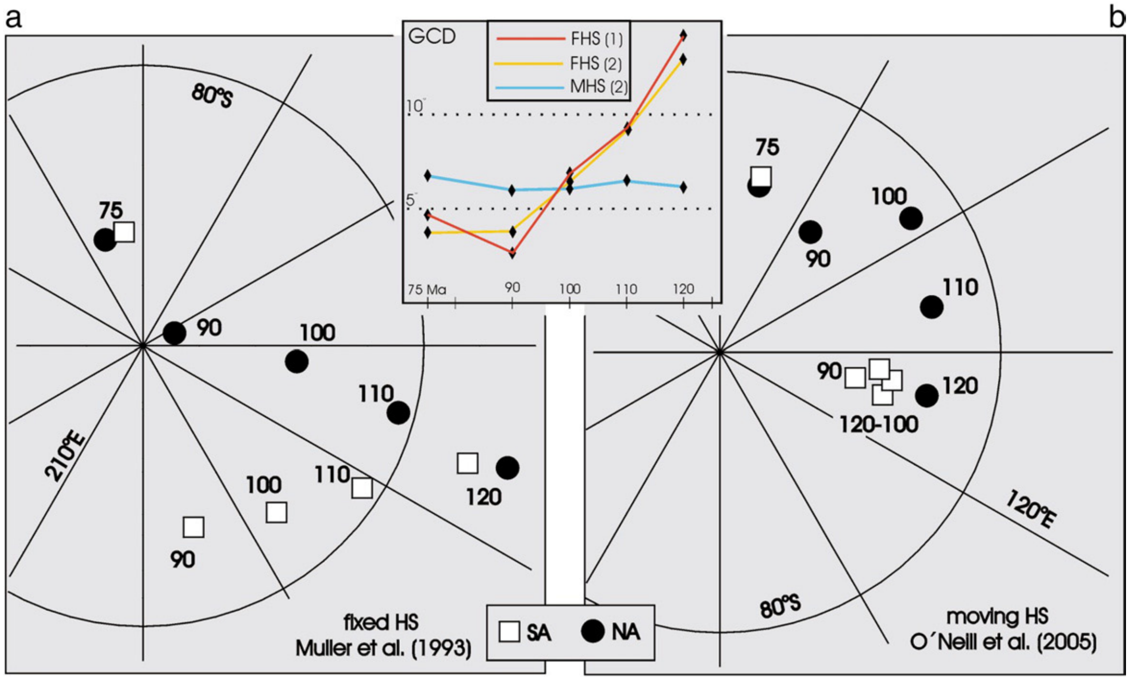

Fig. 5. The Cretaceous poles from the Americas in a) fixed-IAHS and b) moving-IAHS coordinates. The box shows the great circle distance curves (GCD, see main text), where the red curve FHS (1) represents GCD from paleomagnetic dataset of Torsvik et al. (2002) in the fixed-HS framework; the orange curved FHS (2) represents GCD from paleopoles of the Americas in fixed-IAHS coordinates; and the blue curve MHS (2) represents GCD from paleopoles of the Americas in moving-IAHS coordinates. Note coincidence between curves FHS (1) and FHS (2) (red and orange, respectively), supporting that the paleopoles from the Americas are representative of larger datasets. Applying the moving-IAHS framework reduced by 50% the amount of the mid-Cretaceous discrepancy between paleomagnetic and fixed-IAHS reference frames (blue curve), with the residual offset being comparable with that is observed when large paleomagnetic datasets for the Cenozoic are observed in moving-IAHS coordinates (e.g. Torsvik et al. (2002)).

(e.g. Ramos and Aleman, 2000). During Jurassic to Early Cretaceous times most of the margin was very close to sea level, with backarc shallow seas and extensional basins. In contrast, the Late Cretaceous to Recent interval is characterized by rising of arc massifs and increasing predominance of horizontal shortening, leading to progressive crustal thickening, uplift, development of thrust belts and associated foreland basins. Thus, the Andean region experienced a change in tectonic regime from distension to compression that could have been roughly coeval with the Atlantic HS motion slowdown.

The results in Fig. 5 allow considering that moving-IAHS (O'Neill et al., 2005) may provide a workable kinematic model to predict the mid-Cretaceous motion of the continents with respect to the underlying mantle. The synthetic flowlines describing the motion of Africa with respect to the moving-IAHS framework for the 120–100 Ma time interval (Fig. 6) suggest that slab pull force in the eastern Tethys subduction zone was an important factor in controlling the motion of that continent. By those times South America was physically connected to northwest Africa throughout an incipient extensional region in the present day equatorial Atlantic (Fig. 6). This way, South America must have felt both the slab pull force at the Tethys trench and the competing force derived from suction at the Andean subduction zone (Fig. 6). The moving-HS model predicts that about 75% of the 120–100 Ma full spreading in the South Atlantic Ocean is associated with African “absolute” motion, implying eastward motion of the young mid-ocean ridge and, by inference, little (~1.5 cm/yr average in the model) westward motion of South America. This scenario, with South America experiencing little motion with respect to the mantle, allows considering the possibility of episodes in which oceanward motion of the Andean trench due to slab rollback was faster than westward continental motion, yielding a mechanism to account for the extensional conditions in the western continental margin during the considered time interval. Although no moving-HS reconstructions older than 120 Ma are available, it is worth noting that South America experienced counterclockwise rotation about a northern pole between 135–125 Ma (Fig. 3c), suggesting that the continent moved away from its western subduction zone in those times, also consistent with development of extensional conditions at the Andean margin. Hence, paleomagnetic and moving-IAHS kinematics allow interpreting the development of extensional tectonics in the early Andean margin as the product of episodic divergence between the trench and the continental interior.

Extensional conditions dominated in Perú and central-northern Chile until the Cenomanian (Cobbing et al., 1981; Åberg et al., 1984; Atherton and Webb, 1989; Mpodozis and Allmendinger, 1993). On the other hand, the firsts contractional events in the Andean Cycle seem to have occurred in Santonian–Campanian times (Mégard, 1984, 1987; Scheuber et al., 1994; Ladino et al., 1999; Tomlinson et al., 2001), suggesting that they began a little later than the final disconnection between Africa and South America in the present day Equatorial Atlantic.

Rifting in the sheared Equatorial Atlantic margins (Fig. 6) started in Aptian times and complete continental disconnection occurred sometime during the Cenomanian–Turonian (Basile et al., 1998), although it seems that deepwater connection between central and south Atlantic was not established until Turonian–Coniacian (Wagner and Plesch, 1999) or even Santonian (Moullade et al., 1998) times. The moving-IAHS model predicts that the westward motion of South America substantially increased (Central Andean average ~4.5 cm/yr between 90–60 Ma) after the final continental disconnection in the Equatorial Atlantic region (inset “a” in Fig. 6). This faster westward drift likely led to episodes in which the continent effectively overrode the Andean trench, in agreement with the development of compressive events at its leading edge. However, the moving-IAHS framework further implies that increasing westward motion of South America was not simply due to open South Atlantic spreading after complete continental disconnection, as has been previously envisaged (Mpodozis and Ramos, 1989; Somoza, 1996; Ramos and Aleman, 2000; Jaillard et al., 2000). Instead, it seems to be actually associated with a

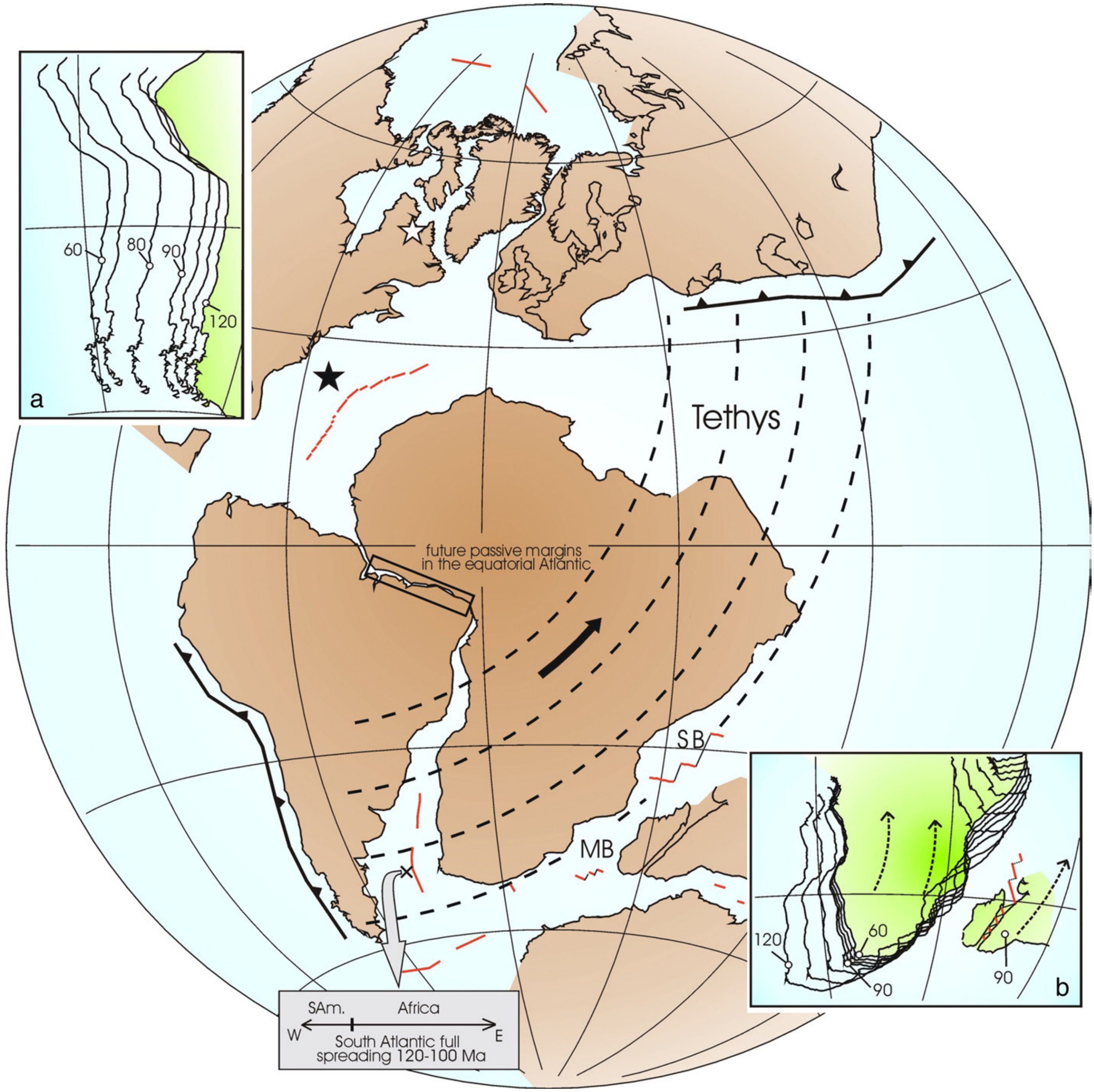

Fig. 6. 124 Ma (Gradstein et al., 2004) reconstruction to the moving-IAHS framework. Oceanic spreading systems (mainly based on identifications of the M0 magnetic anomaly) are shown in red. SB and MB depict Somali and Mozambique basins, respectively. Northern star (white) is the 124–100 Ma stage pole for Africa-South America relative motion. Southern star (black) is the pole describing the motion of Africa with respect to the moving-IAHS between 124 and 100 Ma (dashed small circle sectors being the associated synthetic flowlines). Box in the lower part of the draw show the Africa-South America divergence (at the "X" site) decomposed into motion of each one of these continents relative to the moving-HS framework. Inset "a" depicts the westward motion of the Andean region between 120 and 60 Ma (South America to Africa reconstructions: Nürnberg and Müller (1991), Eagles (2007) and Müller et al. (1999)). Note acceleration between 90 and 80 Ma, coincident with the beginning of compressive tectonics in the Andes. Inset "b" shows the motion of Africa with respect to the moving-HS between 120 and 60 Ma, note the motion slowdown after 90 Ma. Dashed lines represent the 90–60 Ma synthetic flowlines of the motion of Africa and India with respect to the moving-HS. India and Madagascar are reconstructed at 90 Ma in order to show the paleogeography at the beginning of spreading in the Central Indian Ocean.

deceleration of African drift at about 90 Ma (inset "b" in Fig. 6). This African motion slowdown and the continued expansion in the South Atlantic imply that the spreading ridge must have began to move westward with respect to the mantle, substantially increasing the westward drift of South America. In particular, a velocity increment of ~200% is predicted between 90 and 80 Ma (inset "a" in Fig. 6), a time interval that includes the beginning of contractional deformation in the Andes.

The ca 90 Ma African motion slowdown predicted by the moving-IAHS model seems to be almost coeval with Atlantic HS slowdown, suggesting a possible relation between them. Available data allow envisaging a kinematic scenario where, prior to 90 Ma, northeastern Africa and northern India (or Greater India) represented the leading edges of these independently drifting landmasses towards the eastern Tethys trench (Fig. 6). African motion slowdown and continued subduction at the Tethys trench may have led to the breakup of India and Madagascar, dated at ~90–88 Ma (Storey et al., 1995; Torsvik et al., 2000; Raval and Veeraswamy, 2003), and the associated development of the Central Indian oceanic ridge (inset "b" in Fig. 6). In this context, after 90 Ma the slab pull force in the eastern Tethys subduction zone mostly affected the Indian continent, whereas the development of the central Indian oceanic ridge led to Africa to be almost surrounded by plate-border-parallel spreading ridges, greatly inhibiting its motion excepting towards the Mediterranean region, the only remaining "free face" of Africa in the Late Cretaceous. Thus, the establishment of an almost complete girdle of spreading systems around Africa may be observed as a plate tectonics mechanism to account for the African motion slowdown at 90 Ma. In any case, such African slowdown with respect to the mantle and continued accretion of oceanic lithosphere at its eastern and western margins resulted in a relatively fast motion of both India and South America because the spreading ridges also moved apart from the then leisurely drifting Africa.

8. Concluding remarks

New paleomagnetic results from mid-Cretaceous rocks in Patagonia provide further evidence for absence of crustal scale rotation in the region since Aptian times. Mid-Cretaceous pole determinations derived from studies in Brazil and Patagonia are indistinguishable from each other and almost coincident with the present day geographic pole, indicating that 1) mid-Cretaceous South America was at the same latitudes than today and 2) the continent was essentially motionless with respect to the paleomagnetic axis from ca 125 to at least 100 Ma. Considering the coeval polar standstill of North America it is possible to visualize a scenario where two mid-Cretaceous plates, covering a wide paleolatitudinal range (~130°) along a relatively small (~50°) paleolongitudinal stripe, rotate about the paleomagnetic axis. It is shown that these kinematic-paleogeographic constraints disagree with the predictions of the mid-Cretaceous TPW hypothesis, suggesting that the latter is an artifact derived from considering fixity of the Atlantic HS during those times. In agreement with this, reconstruction of paleopoles from the Americas with respect to a moving-hotspot reference frame diminishes by half the paleopole-spin axis offset observed in fixed-IAHS coordinates, illustrating in turn the success of the models that allow sublithospheric melting anomalies to move and to deform in response to flow in the surrounding mantle. The remaining discrepancy may be due to limitations in mantle modeling, and our knowledge of the age and locations of Cretaceous hotspots tracks. Further data from submarine chains and developments in mantle modeling will certainly improve the knowledge on the mantle–lithosphere relationships.

The moving-hotspot framework predicts little 120–100 Ma motion of South America with respect to the sublithospheric mantle, whilst paleomagnetism indicates anticlockwise rotation of South America between 135–125 Ma. Taking into account such kinematic background and considering some foundational ideas on geodynamics and plate tectonics (e.g. Elsasser 1971; Forsyth and Uyeda, 1975; Chase, 1978; Dewey, 1980; Royden, 1993) it is possible to suggest a likely scenario to account for the Cretaceous evolution of the Andean margin. The extensional conditions in the Early Cretaceous may be related to episodic divergence between the continental interior and the trench related to both subduction hinge retreat and continental motion away from the trench. The moving-HS framework further predicts that South America increased its westward drift after the Cenomanian, bringing about episodes in which the continental leading edge effectively overrode the Andean trench leading to the development of contractional deformation. The latter tectonic behavior dominated the Late Cretaceous to Recent evolution of the margin, resulting in an important (predominant?) factor for mountain building in the Andean region.

The final separation between South America and Africa appears to have been part of a plate tectonic reorganization that particularly affected the former Gondwana region. Precise dating of this widespread event is precluded by the lack of seafloor magnetic anomalies from 120 (124?) to 84 Ma. However extrapolated ages of 95±5 Ma have been assigned to several changes in relative plate motion such as a subtle swing in the trend of South Atlantic Ocean fracture zones (Eagles, 2007), a notable kink in Weddell Sea fracture zones (Livermore and Hunter, 1996), a cusp in the southwest Indian Ocean fracture zones (Bernard et al., 2005), and a pronounced bend in the southeast Indian Ocean fracture zones (Müller et al., 2000). By those times Australia broke away from Antarctica and India from Madagascar (Veevers, 1986; Tikku and Cande, 1999; Torsvik et al., 2000; Raval and Veeraswamy, 2003). The latter event was followed by the fast northward drift of India (accounting for almost the whole oceanic expansion in the early Central Indian ridge, see above) that culminated with its collision with Asia and the associated formation of the Himalayas. On the other hand, by ~90 Ma Africa began to converge with Europe (Dewey et al., 1989; Ziegler, 2005; Stampfli and Kozur, 2006) leading to the development of magmatic arcs and the build-up of regional compressional stresses and associated metamorphic events (Ziegler, 1988; Okay et al., 2001; Carrapa and Wijbrans, 2003; Ziegler, 2005). Thus, this major plate reorganization in the mid-Cretaceous triggered the beginning of Andean and Alpine orogenies as well as the plate tectonic conditions that led to the formation of the Himalayas.

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