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Notes

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Abstract: The South American record of remagnetizations is linked to specific events of its tectonic history stretching back to Precambrian times. At the Ediacaran–Cambrian time interval (570–500 Ma), the final stages of the western Gondwana assemblage led to remagnetization of Neoproterozoic carbonates within the São Francisco–Congo Craton and at the border of the Amazon Craton, along the Araguaia–Paraguay–Pampean Belt. From the late Permian to early Triassic, the San Rafaelic orogeny and the emplacement of the Choiyoi magmatic province was responsible for widespread remagnetizations in Argentina and Uruguay. Cretaceous remagnetization has also been documented in Brazil and interpreted to result from magmatism and fault reactivations linked to the opening of the South Atlantic Ocean. We present a review of these widespread remagnetization events principally based on palaeomagnetic data and, when available, on rock magnetic and radiogenic isotope age data. This study gives an overview of the geographical distribution of the remagnetization events in South America, and provides important clues to better understand the geodynamic evolution of the South American plate at these times. In addition, magnetic mineralogy data for the different case studies presented here constrain the physical–chemical mechanisms that led to partial or total resetting of magnetic remanences in sedimentary rocks.

Global plate tectonics reconstructions using palaeomagnetism are based on the record of the natural remanent magnetization (NRM) in rocks at the time of their formation. Consequently, secondary remanent magnetizations acquired late in the geological history of sedimentary and igneous rocks have long been considered as an obstacle for palaeogeographic reconstructions based on palaeomagnetism. Over the past two decades, a better understating of physical–chemical mechanisms responsible for magnetic resetting and the genesis of authigenic magnetic carriers, in addition to improvements in radiogenic isotope dating methods, permit the use of remagnetized rocks as a tool for the study of large-scale geological processes. Widespread remagnetization events linked to large-scale tectonic processes, such as formation of orogenic belts, deformation and metamorphism, are well documented in the literature for North America (e.g. McCabe & Elmore 1989; Elmore *et al.* 1993; Banerjee *et al.* 1997; Xu *et al.* 1998) and Europe (e.g. McCabe & Channell 1994; Katz *et al.* 2000; Jordanova *et al.* 2001; Weil & van der Voo 2002; Gong *et al.* 2009) but are still poorly constrained for the South American continent (D'Agrella-Filho *et al.* 2000; Trindade *et al.* 2004; Rapalini & Sánchez-Bettucci 2008; Tohver *et al.* 2010; Font *et al.* 2011) despite the important role they plays in global plate-tectonic reconstructions.

From Precambrian times until the end of the Cretaceous, the South American plate has experienced a significant number of tectonic events: the accretion of crustal blocks, opening and closing of ocean basins and large-scale magmatic and metamorphic processes. In early Cambrian times, during the final stages of assemblage of western Gondwana, the closure of the Clymene Ocean that separated the Amazon Craton from the São Francisco and Rio de

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la Plata blocks was apparently responsible for widespread remagnetizations along the Paraguay, Pampean and Dom Feliciano belts (e.g. D'Agrella-Filho *et al.* 2000; Trindade *et al.* 2003, 2004, 2006; Font *et al.* 2006; Rapalini & Sánchez-Bettucci 2008; Tohver *et al.* 2010, 2011). During the Permian, southern South America was affected by the San Rafaelic deformation and other approximately coeval tectonic events for which several genetic models have been proposed. Among them is accretionary tectonics, collision of the North Patagonian block and the contemporary to slightly younger felsic magmatic activity of the large Choiyoi province (Azcuy & Caminos 1987; Llambías & Sato 1995; Ramos 2008; Vaughan & Pankhurst 2008; Tomezzoli 2009; Rapalini *et al.* 2010). The timing of this orogenic event coincides with wide-scale remagnetizations in Argentina (Valencio *et al.* 1980; Rapalini & Tarling 1993; Tomezzoli & Vilas 1999; Rapalini *et al.* 2000; Tomezzoli 2001) and Uruguay (Rapalini & Sánchez-Bettucci 2008). Finally, a large-scale deformational event occurred during the Cretaceous in eastern Brazil due to intense volcanism and fault reactivation linked to the opening of the South Atlantic Ocean (Font *et al.* 2011), which also left an important imprint in the magnetic record of older rocks.

The purpose of the present contribution is two-fold: (1) to provide a review of the time and location of widespread remagnetization events that have affected South America since the Precambrian, and highlight evidence of their direct relationship with large-scale plate-tectonics events; and (2) to give a synthesis of the nature and origin of the physical–chemical mechanisms that lead to the partial or total magnetic resetting in these rocks. Beforehand, a synthesis of the apparent polar wander path (APWP) of South America, based on updated palaeomagnetic pole compilations, is presented and discussed to provide a useful palaeomagnetic background for comparison with the remagnetized poles described further.

APWPs of South America at Ediacaran–Cambrian, late Palaeozoic and Cretaceous times

Isotopic, palaeomagnetic and geochronological data suggest that the final assemblage of Gondwana was a long process spanning the Neoproterozoic and early Cambrian times, resulting from successive diachronic collisions involving major and minor blocks (Stern 2002; Cordani *et al.* 2003; Meert 2003; Trindade *et al.* 2006; Meert & Lieberman 2008; Vaughan & Pankhurst 2008; Cordani *et al.* 2009; Gray *et al.* 2009; Tohver *et al.* 2011). The APWP of Gondwana is anchored by a few palaeomagnetic poles for the 570–500 Ma interval (Fig. 1b, Table 1) (Tohver *et al.* 2006; Trindade *et al.* 2006; Moloto-A-Kenguemba *et al.* 2008), and the older portion of this period is probably marked by ongoing convergence of different cratonic blocks. No individual South American craton can be constrained by palaeomagnetic poles between the age of the Marinoan glaciation in the Amazon Craton (*c.* 635 Ma; Trindade *et al.* 2003; Font *et al.* 2005) and the age of the Nola dyke (571 ± 6 Ma; Moloto-A-Kenguemba *et al.* 2008) and the Sierra de Animas two poles (579 ± 2 Ma; Sanchez-Bettuci & Rapalini 2002; Oyhantçabal *et al.* 2007). For ages older than 580 Ma there are only two palaeomagnetic poles available, which are not well constrained. The first, the Playa Hermosa pole (Sánchez-Bettucci & Rapalini 2002), has a coherent position in the APWP of Gondwana (Fig. 1b) but is of low quality due to: (1) absence of radiometric isotope ages that may constrain the depositional age of the sediments; (2) low number of data (2 sites, 6 samples); (3) absence of field tests; and (4) absence of flattening inclination correction. However, new geochronological, magnetic fabric and palaeomagnetic results (Lossada *et al.* 2011) seem to ratify the pole position and its proposed age (around 595 Ma). The second pole from this interval is the Campo Alegre pole (D'Agrella-Filho & Pacca 1988) which has long been used for palaeogeographic reconstructions. This has recently been called into question however by its geographic proximity with the widespread remagnetization that affected the Itajaí basin during Permian or Cretaceous times (see below). The remanent magnetization of the Campo Alegre rocks is very stable and coherent, being carried by both magnetite and hematite, but only an incomplete baked contact test is reported in the original study of D'Agrella-Filho & Pacca (1988) which is insufficient to ascertain its primary nature. Re-evaluating the tilt correction applied to these rocks, it is observed that the *in situ* site mean characteristic component of the Campo Alegre rocks lies very close to the remagnetized Itajaí virtual geomagnetic poles (VGPs), suggesting that both results reflect a contemporaneous remagnetization (Font *et al.* 2011). At the other end of the APWP, starting from 525 Ma, a well-defined APWP for Gondwana can be traced along northern Africa until the early–mid-Ordovician (*c.* 500 Ma, see compilations by Meert 2003 and Trindade *et al.* 2006; Fig. 1c; Table 1).

The South American APWP for the time period from the Carboniferous (*c.* 350 Ma) until the Permo-Triassic (*c.* 250 Ma) is the subject of numerous controversies and has been at the core of the different Pangea models (i.e. Pangea A v. Pangea B, e.g. Wegener 1912; Bullard *et al.* 1965; Irving 1977;

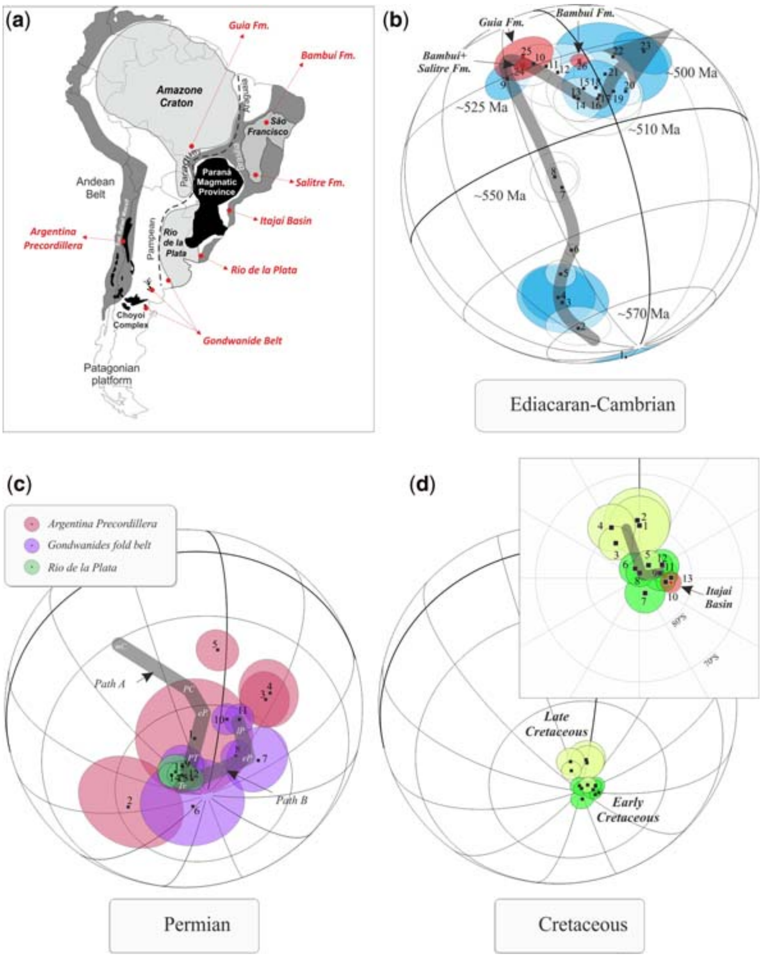


Fig. 1. (**a**) Geological map of South America (modified from Tohver *et al.* 2011) showing the location of the studied areas; Apparent Polar Wander Paths for the South American plate at (**b**) Ediacaran–Cambrian (poles from South America are highlighted in blue; see text for details); (**c**) Permian, showing a short Path A (Brandt *et al.* 2009) and a more conventional Path B (Tomezzoli 2009); (**d**) Cretaceous times (Font *et al.* 2009). Selected palaeomagnetic poles are referenced in Tables 1–3. Positions of the remagnetized formations synthetized in this work are also indicated: (b) Bambuí, Salitre and Guia Formations (in red); (c) Argentina Precordillera (in pink), Gondwanides Fold Belt (in purple) and Rio de la Plata (in green); and (d) Itajaí Basin (in green).

Morel & Irving 1981; Torsvik & Van der Voo 2002; Muttoni *et al.* 2003, 2009; Van der Voo & Torsvik 2004; Brandt *et al.* 2009; Domeier *et al.* 2011; Yuan *et al.* 2011). Ever since the publication of the first Late Palaeozoic APWP for South America (e.g. Vilas 1981), it has been observed that Late Carboniferous–Late Permian poles plot along a large loop. This trend has been subsequently confirmed by numerous palaeomagnetic studies (see Rapalini *et al.* 2006; Tomezzoli *et al.* 2009 for recent reviews; Fig. 1c). Most but not all of these results derive from the study of clastic sedimentary rocks. This loop indicates a relatively low-latitude position for the western areas of Gondwana in the Early Permian, which gives rise to an apparently large overlap of continental crust with southern Laurasia in a Wegener type Pangea A reconstruction. This palaeogeographic overlap was eliminated by Irving's (1977) proposal of a different Permian configuration for Pangaea (Pangea B) that transposed Gondwana to the east relative to Laurrussia. In order to restore Pangaea to its known configuration at the time of break-up (reconstructed from ocean floor magnetic anomalies), the Pangea model requires a

Table 1. *Selected palaeomagnetic poles for the calibration of the APWP of Gondwana during Ediacaran–Cambrian times*

Selected palaeomagnetic poles		P_{lat}	P_{long}	α_{95}	References
Gondwana APWP					
1	Praya Hermoza	−75	182	12	Sánchez-Bettucci & Rapalini (2002)
2	Nola Dolerite	−62	305	10.5	Moloto-Kenguemba *et al.* (2008)
3	Sierra de las Animas II	−49	312	15	Sánchez-Bettucci & Rapalini (2002)
4	Los Barrientos	−47	313	12	Rapalini (2006)
5	Sinyai dolerite	−40	321	5	Meert & Van der Voo (1996)
6	Mirbat SS	−34	330	2	Kempf *et al.* (2000)
7	Arumbera	−14	336	5	Kirschvink (1978)
8	Todd River	−10	335	8	Kirschvink (1978)
9	Itabaina dykes	29	330	8	Trindade *et al.* (2006)
10	Adma diorites	31	341	9	Morel (1981)
11	Ntonya Ring	28	345	2	Briden (1968); Briden *et al.* (1993)
12	Hawker Group	24	348	13	Klootwijk (1980)
13	Pertaoorta Group	12	351	8	Klootwijk (1980)
14	Madagascar vigration	13	350	14	Meert *et al.* (2003)
15	Kangaroo Island	15	354	12	Klootwijk (1980)
16	Billy Creek	11	358	14	Klootwijk (1980)
17	Carion Granite	14	358	11	Meert *et al.* (2001)
18	Juiz de Fora Complex	10	357	10	D'Agrella-Filho *et al.* (2004)
19	Giles Creek	11	3	10	Klootwijk (1980)
20	Sor Rondane	10	7	5	Zijderveld (1968)
21	Lower Lake Frome	18	3	10	Klootwijk (1980)
22	Sierras de la Animas I	24	9	19	Sánchez-Bettucci & Rapalini (2002)
23	Piquete Formation	24	22	10	D'Agrella-Filho *et al.* (1986)
Remagnetized poles					
24	Bambui + Salitre C	32	337	3	Trindade *et al.* (2004)
25	Araras Group B	36	338	10	Trindade *et al.* (2003)
26	Bambui B	26	357	3	D'Agrella-Filho *et al.* (2004)

Remagnetized palaeomagnetic poles of the Guia, Bambuí and Salitre formations are also shown. Palaeomagnetic poles were rotated using the Euler pole from Reeves *et al.* (2004) for South America: Lat = 43.017°N, Long = 329.935°E, Angle = 58.842°.

very long (3000 km or more) strike-slip displacement between Gondwana and Laurasia at some time during the Permian and/or the Triassic (Irving 2004). This palaeoreconstruction has attracted occasional support from palaeomagnetic studies from different areas of Gondwana such as Africa (Bachtadse *et al.* 2002), Adria (Muttoni *et al.* 2003) and Iran (Torcq *et al.* 1997). Amongst geologists, the enormous amount of displacement between Gondwana and Laurasia required by the Pangaea B configuration has been a source of scepticism. Several tests have demonstrated that large-scale and long-standing non-dipolar fields are not a plausible explanation for the apparent overlap between northern and southern continents (Muttoni *et al.* 2003, 2009; Tauxe 2005). Thus, palaeomagnetic objections to the Pangaea B configuration are related to artefacts or biases in the palaeomagnetic database, for example incomplete demagnetization, overprinted results, incorrectly dated rocks or the inclination error in sedimentary rocks (e.g. Rochette & Vandamme 2001; Weil *et al.* 2001; Torsvik & Van der Voo 2002). Recent palaeomagnetic results in Permian rocks for South America (e.g. Brandt *et al.* 2009; Domeier *et al.* 2011; Yuan *et al.* 2011; Fig. 1c; Table 2) have been in favour of a much shorter APWP path for South America between the Late Carboniferous and the Early Triassic that would be more compatible with a Pangea A reconstruction throughout the whole time span. To consider this proposal, most (if not all) the previously available poles must however be discarded, no matter whether they correspond to pre-tectonic, syn-tectonic or post-tectonic magnetizations. The short APWP is also incompatible with some poles based on magmatic rocks, which are intrinsically devoid of inclination-shallowing effects (Conti & Rapalini 1990; Tomezzoli *et al.* 2005, 2009). Which APWP is the most reliable still remains an open question.

The Cretaceous APWP for South America is comparatively well established (Ernesto *et al.* 2002; Ernesto 2007; Somoza & Zaffarana 2008; Font *et al.* 2009) and is consistent with its North America counterpart after adequate rotation, at least for the mid- to late Cretaceous interval

Table 2. *Mean palaeomagnetic poles of the Path A (Brandt* et al. *2009) and Path B (Tomezzoli 2009) illustrated in Figure 1c*

Selected palaeomagnetic poles		P_{lat}	P_{long}	α_{95}	References
Mean palaeomagnetic poles					
Path A (Brandt *et al.* 2009)					
Middle Permian–early Triassic	−80	311	6.9		
Early Permian	−62.4	347.6	8.1		
Permian–Carboniferous	−54.3	341	12.4		
Middle Carboniferous	−31.6	317.5	8.3		
Path B (Tomezzoli 2009)					
Triassic	4	−81	279.5		
Late Permian	–	−72	39		
Early Permian	7	−64	14		
Remagnetized poles					
1	San Juan Formation	−70.2	337.8	19.2	Rapalini & Tarling (1993)
2	La Flecha Formation	−63.8	244.6	18	Rapalini & Astini (2005)
3	Ponón Trehue	−53.4	25	9	Truco & Rapalini (1996)
4	Alcaparrossa	−50.8	25.8	11	Rapalini & Tarling (1993)
5	Hoyada Verde	−41.9	356.2	7	Rapalini *et al.* (1989)
6	Gonzalves Chaves	−84	216	17	Tomezzoli & Vilas (1997)
7	San Roberto	−70	49	11	Tomezzoli *et al.* (2006)
8	Tunas II	−74	26	5	Tomezzoli & Vilas (1999)
9	Sierra Grande	−77	311	7	Rapalini (1998)
10	Rio Curaco	−64	5	5	Tomezzoli *et al.* (2006)
11	Tunas I	−63	14	5	Tomezzoli & Vilas (1999)
12	Cerro Victoria	−82.6	309.3	3.9	Rapalini & Sánchez-Bettucci (2008)
13	Yerbal	−77	298.4	5.9	Rapalini & Sánchez-Bettucci (2008)
14	Rocha	−76.6	291	4.2	Rapalini & Sánchez-Bettucci (2008)
15	Sierras Bayas Group	−79.3	300.9	4.8	Valencio *et al.* (1980)

Remagnetized palaeomagnetic poles of the Gondwanides Belt, the Argentina Precordillera and the Rio de la Plata Craton are also indicated.

(Tarduno & Smirnov 2001; Somoza & Zaffarana 2008). Future refinements to this section of the APWP should address age determinations and more complete geographic distribution for the mid- to late Cretaceous interval (Table 3). The compilation of Font *et al.* (2009) is based solely on poles from magmatic rocks, in order to minimize uncertainties in the palaeomagnetic record of sedimentary rocks due to problems of shallowing and time of magnetization (Fig. 1d; Table 3). The majority of high-quality palaeomagnetic poles are from the Paraná Magmatic Province of Brazil, with a few poles from other regions of South America. Of the thirteen palaeomagnetic poles selected by Font *et al.* (2009), eight are from Brazil (Table 3), four are from Argentina (Geuna & Vizán 1998; Geuna *et al.* 2000) including two from Patagonia (Butler *et al.* 1991; Somoza & Zaffarana 2008) and one is from Paraguay (Ernesto *et al.* 1996). The APWP of South America is better defined for the early Cretaceous interval from *c.* 135 to *c.* 125 Ma, where high-quality palaeomagnetic data based on a large number of independent sites are available from well-dated rocks by ^{40}Ar/^{39}Ar methods (see review in Ernesto 2007). Of particular interest are the Serra Geral Formation and the Ponta Grossa dykes from the Paraná Magmatic Province, dated at 133–132 and 131–129 Ma, respectively (Ernesto *et al.* 1990, 1999; Renne *et al.* 1992, 1996); and the Central Alkaline Magmatic Province, Brazil dated at 127–130 Ma (K–Ar method; Velázquez *et al.* 1992; Ernesto *et al.* 1996). From early- to mid-Cretaceous, South American poles cluster near the geographic pole (Fig. 1d). From mid- to late Cretaceous, the South American plate experienced southward continental drift associated with clockwise rotations (Ernesto *et al.* 2002). The transition is well constrained in the APWP by the high-quality palaeomagnetic pole from the Cabo Magmatic Province, NE Brazil ($Q = 5$), well dated at 102 ± 1 Ma (Font *et al.* 2009).

Table 3. *Selected palaeomagnetic poles for the calibration of the APWP of South America at the Cretaceous (modified from Font* et al. *2009)*

Formation	Pole number	Age (Ma)	Polarity	N	Long. (°E)	Lat. (°N)	References
South America (North Pole)							
Patagonian Basalts	1	64–79	N/R	18	178.4	78.7	Butler *et al.* (1991)
Itatiaia and Passa Quatro comb.	2	70–71	N/R	18	180.0	79.5	Montes-Lauar *et al.* (1995)
Poços de Caldas Complex	3	84	N/R	36	145.7	82.2	Montes-Lauar *et al.* (1995) recalc.
São Sebastião Dykes	4	80–90	N	26	151.3	79.0	Montes-Lauar *et al.* (1995)
San Bernardo	5	85–98	N	9	215.0	87.0	Somoza & Zaffarana (2008)
Cabo Magmatic Province, Brazil	6	100	N	24	155.9	87.9	This paper
Cerro Barcino, Argentina	7	112–130	N	16	339.0	87.0	Geuna *et al.* (2000)
Florianópolis Dykes, SE Brazil	8	119–128	N/R	65	183.3	89.1	Raposo *et al.* (1998)
Central Alkaline Province	9	127–130	N/R	75	242.3	85.4	Ernesto *et al.* (1996)
Ponta Grossa Dykes, SE Brazil	10	129–131	N/R	115	238.5	84.5	Ernesto *et al.* (1999)
Serra Geral Formation	11	133–132	N/R	392	269.2	84.1	Ernesto *et al.* (1990, 1999)
Cordoba Province, Argentina	12	133–115	N/R	55	255.9	86.0	Geuna & Vizán (1998)
Northeastern Brazil Magmatism	13	125–145	N/R	44	277.6	85.2	Ernesto *et al.* (2002)
Mean South America Poles							
Upper Cretaceous		65–80	N/R	4	165.2	80.2	$\alpha_{95} = 3.9$; $K = 552$
Middle Cretaceous		80–110	N	3	230.9	89.2	$\alpha_{95} = 4.9$; $K = 646$
Lower Cretaceous		110–140	N/R	6	254.8	86	$\alpha_{95} = 1.9$; $K = 1152$
Remagnetized Poles							
Itajaí Basin			R	95	277.5	84	Font *et al.* (2011)

Position of the remagnetized Itajaí pole is also shown.

Cambrian remagnetizations at the final assemblage of Western Gondwana

The Guia Formation

The Araras Group in the SE Amazon Craton (Fig. 1a) presents a peculiar case where both primary and secondary magnetic remanences are preserved within a single carbonate sequence. The stable and undeformed region near the city of Mirassol d'Oeste (MO), Mato Grosso state, Brazil presents well-preserved outcrops of the lower part of the Araras Group in the Terconi Quarry. Here, basal pink microbial dolostones (i.e. the so-called cap carbonates; Hoffman *et al.* 1998; Hoffman *et al.* 2007) of the Mirassol d'Oeste Formation and bituminous limestones of the Guia Formation cover the Marinoan (*c.* 635 Ma) glacial deposits of the Puga Formation (Nogueira *et al.* 2003, 2007; Trindade *et al.* 2003; Font *et al.* 2010).

The basal pink dolostone records a stable magnetization carried by hematite that yielded a palaeomagnetic pole, $P_{long} = 283.7°$, $P_{lat} = 83.5°S$ ($N = 51$; dp = 3.1°; dm = 5.3°; palaeolatitude = 21.2°), for the Amazon Craton at the end of the Neoproterozoic (Trindade *et al.* 2003; Font *et al.* 2005, 2010). The presence of geomagnetic reversals (Fig. 2a) and a positive fold test (Trindade, R., unpublished data) suggests a primary, detrital origin for the magnetization. The presence of at least four reversals within the 20 m of dolostones observed by Trindade *et al.* (2003) and Font *et al.* (2010) also suggests sedimentation over a much longer time period than that predicted by the original 'snowball Earth' hypothesis of Hoffman *et al.* (1998). In contrast, the bituminous limestones of the Guia Formation record a secondary, post-folding remagnetization (Fig. 2b; Trindade *et al.* 2003; Tohver *et al.* 2010). Rock magnetic properties are typical of those of remagnetized carbonates (Font

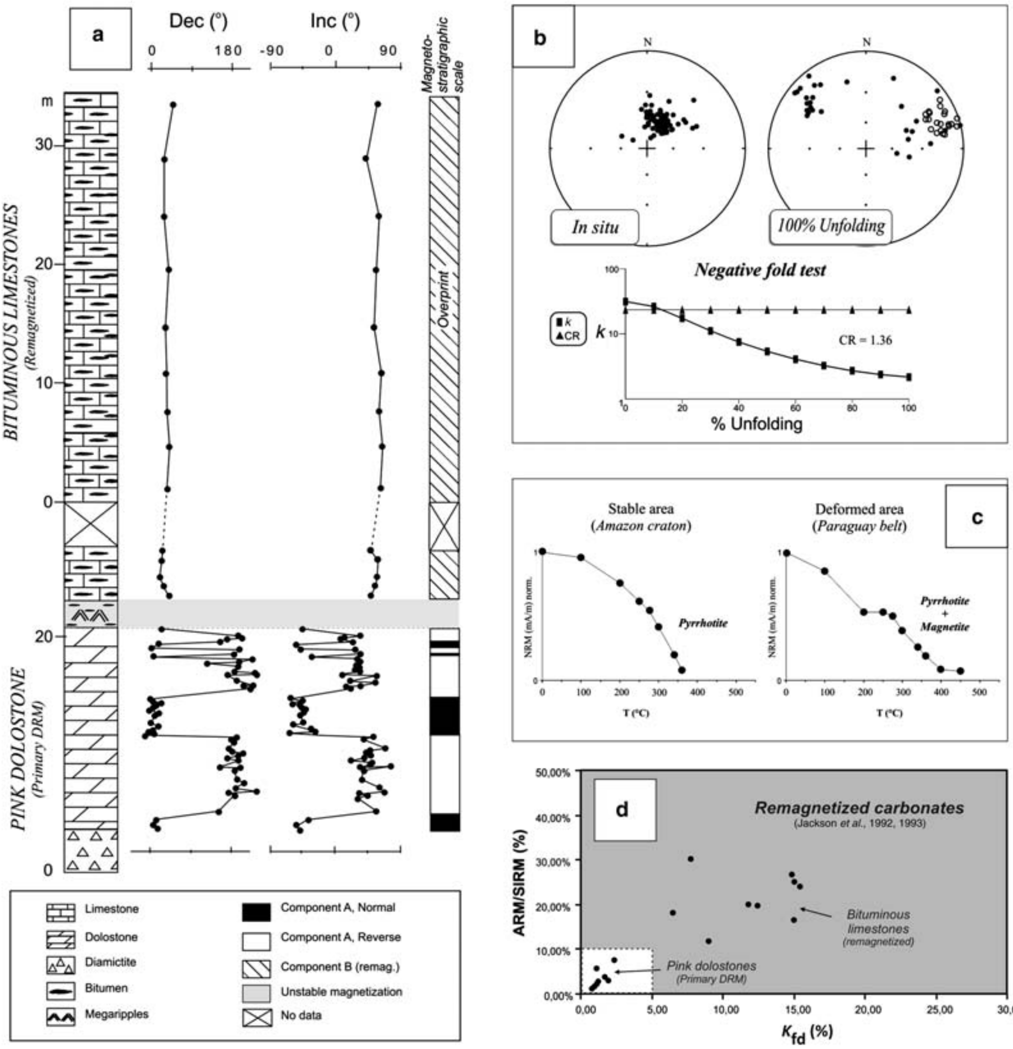


Fig. 2. (**a**) Magnetostratigraphic column of the Mirassol d'Oeste and Guia formations (Araras Group) showing primary (with geomagnetic reversals; A component) and secondary (B component) characteristic remanent magnetizations, respectively. (**b**) Negative fold test (McElhinny 1964) of the Guia limestones in the Paraguay Fold and Thrust Belt. Above: stereographic projections in geographic and tilt-corrected coordinates showing a divergence of magnetic directions after 100% unfolding; below: dispersion parameter k v. percentage of unfolding (CR represent the critical ratio at which k values become significant at the 95% confidence level for the number of data entries). (**c**) Thermal demagnetization curves of Guia limestones in stable (Amazon Craton) and deformed (Paraguay Belt) areas showing pyrrhotite and a mixture of pyrrhotite and magnetite as principal magnetic carriers, respectively. (**d**) Dominance of superparamagnetic particles in the remagnetized Guia limestones is indicated by high values of ARM/SIRM and K_{fd} (%), whereas the latter are absent in the preserved MO dolostones (typical values for remagnetized carbonates are from Jackson *et al.* 1992, 1993).

et al. 2006) and indicate magnetite and iron sulphides (mostly pyrrhotite) as principal magnetic carriers in these rocks (Fig. 2c, d).

This secondary palaeomagnetic direction from the central portion of the Paraguay Belt reported by Trindade *et al.* (2003) yields a palaeomagnetic pole ($P_{\mathrm{long}} = 326.6°$; $P_{\mathrm{lat}} = 33.1°$N; $N = 74$; $dp = 3.3°$; $dm = 3.6°$; palaeolatitude $= 36.4°$) that plots on the APWP for West Gondwana (Fig. 1b) close to the high-quality 525 Ma Itabaiana pole of the Borborema Province, NE Brazil (Trindade *et al.* 2006). This observation indicates the palaeogeographic proximity between the Amazon Craton and the proto-Gondwana at the time of the Araras Group remagnetization and the intrusion of the Itabaiana dykes, an important constraint on the timing of the final collision between these two cratons during the assembly of Gondwana (Trindade *et al.* 2003, 2006). Further study along the entire >90° arc of the curved Paraguay Belt demonstrates a clear correlation between the declination of this secondary magnetization and the strike of the belt (Fig. 3; Tohver *et al.* 2010). This positive strike test, equivalent to a vertical axis fold test, indicates the secondary, oroclinal nature of the Paraguay Belt curvature. Thus, the >90° bend of the Paraguay Belt was created by large-scale tectonic rotations (principally of the *c.* 200 km long, east–west limb of the belt) after 525 Ma.

The Araras Group offers an excellent opportunity to study the interplay between carbonate rocks, hydrocarbons and the physio-chemical conditions that led to the complete resetting of their primary remanence.

Two different mechanisms have been proposed to account for the remagnetization of the Guia Formation: the maturation of organic matter (Font *et al.* 2006) and clay mineral transformations (Font *et al.* 2006; Tohver *et al.* 2010). In the first case, the maturation of hydrocarbons by microbial activity in sedimentary rocks and particularly in carbonates results in an anaerobic iron-reducing environment that favours the growth of authigenic magnetite and ferrous sulphide (e.g. Seewald 2001, 2003; Kao *et al.* 2004). The first evidence for a relationship between hydrocarbons and authigenic magnetite was reported by Elmore *et al.* (1987) and further confirmed by others workers (e.g. Benthien & Elmore 1987; Kilgore & Elmore 1989; Elmore & Crawford 1990; Suk *et al.* 1990; Blumstein *et al.* 2004; Font *et al.* 2006). Models for magnetite authigenesis in hydrocarbon-rich sediments invoke reducing conditions, induced by the release of H_2S from hydrocarbon maturation, leading to the transformation of primary iron oxides (e.g. Reynolds *et al.*

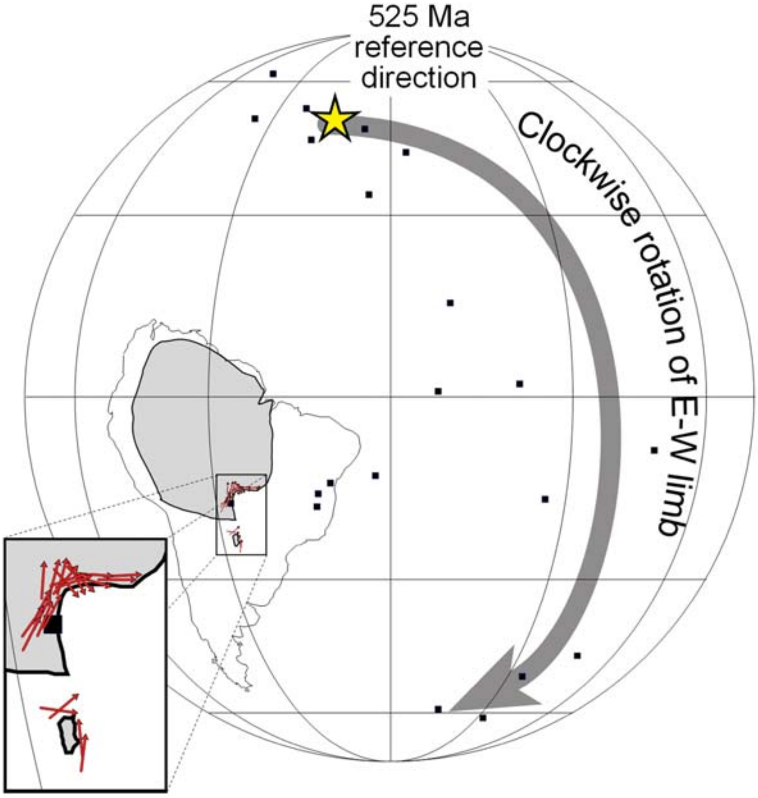


Fig. 3. Position of site mean VGPs from the Araras Group carbonates demonstrating divergence from the 525 Ma Itabaiana reference pole. Inset shows how the declination of site level directions varies with regional strike of the Paraguay Belt, with easterly declinations common in the east–west-trending portion of the belt, northeasterly declinations in the NE-trending hinge zone and northerly directions in the north–south-trending domain.

1990, 1991; Seewald, 2003; Kao *et al.* 2004). Once dissolved Fe^{2+} is available, authigenic magnetite can precipitate inorganically. However, the presence of spherical magnetite and framboids of pyrite/magnetite in several case studies suggested that microbial activity also plays an important role in the formation of new magnetic phases (e.g. Elmore *et al.* 1987; Elmore & Leach 1990; Brothers *et al.* 1996). Magnetite is not the solely magnetic carrier that can be produced by hydrocarbon–reservoir rock interactions. It may be partially or totally substituted by ferromagnetic iron sulphides, such as pyrrhotite and greigite, which contribute significantly to the chemical remanent overprint (e.g. Dekkers 1990; Rochette *et al.* 1990; Krs *et al.* 1992; Xu *et al.* 1998; Dunlop 2000; Zegers *et al.* 2003; Font *et al.* 2006). Greigite and pyrrhotite are generally metastable in sedimentary rocks, tending to transform into pyrite (i.e. pyritization), but may be preserved in (Total Organic Carbon) TOC-poor and reactive Fe-rich environments, where effective removal of reduced sulphur by precipitation of intermediate iron sulphides prevented pyritization (Kao *et al.* 2004). The presence of pyrrhotite in the remagnetized Araras Group rocks is evidenced magnetically by its characteristic Curie temperature at *c.* 280–320 °C (Rochette *et al.* 1990) (Fig. 2c). Scanning Electron Microscopy (SEM) coupled to Energy Dispersive Spectra (EDS) identified numerous iron sulphides in close association with bitumen, namely pyrrhotite and pyrite that precipitated in voids and microcracks of the rocks (Fig. 4a–d). Relics of pyritized bacteria are represented by framboids (Machel & Burton 1991; Fig. 4e).

The second mechanism for carbonate remagnetization relies on the link between clay mineral maturity and the presence of magnetite as a secondary by-product (McCabe *et al.* 1989; Katz *et al.* 1998, 2000; Gill *et al.* 2002; Woods *et al.* 2002; Blumstein *et al.* 2004; Moreau *et al.* 2005; Tohver *et al.* 2008). In the case of the Paraguay Belt, there appears to be a link between the host minerals of the stable

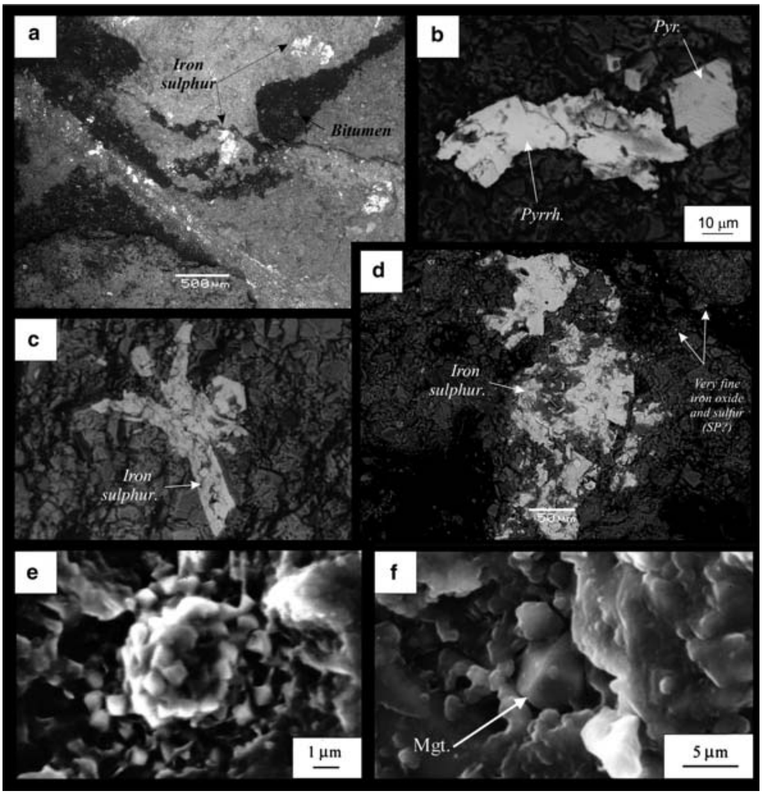


Fig. 4. Scanning Electronic Microscopy (SEM) photographs showing: (**a**) association of authigenic iron sulphurs with bitumen and fractures; (**b**) euhedral pyrite (diamagnetic) and probably pyrrhotite (ferromagnetic); (**c**) iron sulphur filling voids; (**d**) presence of large (>100 µm) iron sulphur and very fine (SP) iron oxides and sulphurs; (**e**) euhedral secondary magnetite; and (**f**) pyrite framboid.

magnetization and the site-level tectonic environment. For example, carbonate rocks located in the stable, that is cratonic, area (Terconi Quarry) contain essentially pyrrhotite whereas those located in the deformed area (Paraguay Belt) show a mixture of pyrrhotite and authigenic magnetite (Fig. 2c). Font *et al.* (2006) interpreted the lack of remanence signal in the upper levels of the dolostone (Fig. 2a) and the complete remagnetization of overlying limestones as a result of the higher organic matter content in these layers. In the more deformed portion of the Paraguay Belt, the higher metamorphic grade (higher illite crystallinity values of Alvarenga 1990) suggests the operation of the second clay-related mechanism of remagnetization. Here, authigenic magnetite occurs either as large euhedral crystals (i.e. palaeomagnetically irrelevant) or very fine, probably superparamagnetic, minerals (Fig. 4d, f). In their study of these remagnetized carbonates, Tohver *et al.* (2010) separated different size fractions of insoluble clay for ^{40}Ar/^{39}Ar encapsulation dating. The maximum age of remagnetization is indicated by the ages of the finest grain size aliquots, where the concentration of authigenic illite would be expected to be highest. The *c.* 530 Ma maximum age of remagnetization from three different sites of remagnetized limestone agrees with the *c.* 525 Ma age inferred from the aforementioned overlap in the palaeomagnetic pole position determined from the Araras Formation and the primary Itabaiana pole.

The Bambuí case

The São Francisco Basin covers *c.* 300 000 km^2 of the São Francisco Craton and comprises clastic and carbonate sediments of Neoproterozoic age, with a basal glacial unit (Macaúbas Group in the south, Bebedouro Formation in the north) covered by a thick carbonate succession (Bambuí Group in the south, Salitre Formation in the north) (Karfunkel & Hoppe 1988). The basal glacial unit comprises diamictites, clast-supported conglomerates, sandstones and pelites deposited in glacio-marine environments. The upper unit comprises mostly carbonate rocks with pelitic intercalations deposited along an extensive platform that comprised not only the craton margins but most of its inner part (Fig. 1a). The succession has experienced moderate to weak deformation inside the cratonic area as far-field response of the intense deformation that occurred along the encircling Brasiliano fold belts between 600 and 520 Ma (Inda & Barbosa 1978).

The maximum age of sedimentation for both the Bebedouro and Macaúbas glacial units were obtained from the U–Pb sensitive high-resolution ion microprobe (SHRIMP) dating of detrital zircons from both units with ages around 900 Ma (Pedrosa-Soares *et al.* 2000), which are corroborated by similar ages obtained for dykes that cut across the basement of the Neoproterozoic succession but do not reach it. Several attempts to date the upper carbonate succession using Pb–Pb and U–Pb methods were unsuccessful (Babinski *et al.* 1999; D'Agrella-Filho *et al.* 2000). Most ages cluster within 550–515 Ma with a peak at 520 Ma. Only two ^{207}Pb/^{206}Pb dates provide ages older than 650 Ma, thus approaching the sedimentation age of the carbonates at 686 ± 69 Ma (Babinski *et al.* 1999) and 740 ± 22 Ma (Babinski *et al.* 2007).

Palaeomagnetic data for the Bambuí Group and the Salitre Formation were reported by D'Agrella-Filho *et al.* (2000) and Trindade *et al.* (2004), respectively. In both regions, carbonate successions presented a very stable characteristic magnetic component with single polarity and tightly grouped directions across sedimentary sections hundreds of metres thick. In both regions, which are more than 600 km apart, directions were remarkably similar, comprising three magnetic components with similar palaeomagnetic poles obtained from magnetic components carried by similar magnetic carriers. The more stable components, B and C, are carried by monoclinic pyrrotite and magnetite, respectively. The corresponding palaeomagnetic poles coincide with reference poles for 520 Ma (Fig. 1b), which by its turn is the peak age obtained using Pb/Pb methods for the carbonates and Pb–Zn mineralization in the area, which is thus interpreted as the age of fluid migration across the whole São Francisco Craton (Trindade *et al.* 2004). In Salitre Formation rocks, in the northern sector of the basin, an additional component (named D) was obtained at very high unblocking temperatures, characteristic of hematite.

Samples from both regions show all the rock magnetic characteristics typical of remagnetized carbonates. The hysteresis cycles are always wasp-waisted in shape, resulting from the mixture of soft and hard coercivity fractions. In addition, all samples show anomalously high H_c (coercivity) and H_{cr} (coercivity remanence) ratios when plotted in the Day *et al.* (1977) diagram (Fig. 5a), following the trend of remagnetized carbonates proposed by Jackson (1990). This trend has been interpreted by Dunlop (2002) as a result of the mixture of stable single-domain magnetite with superparamagnetic grains. Lowrie–Fuller Cisowski tests were also performed in both collections (Fig. 5b). In this test, samples are alternating field (AF) demagnetized, are then given an anhysteretic remanent magnetization (ARM) at a peak field of 200 mT, demagnetized again and finally given a stepwise isothermal remanent magnetization (IRM) up to 200 mT, which is subsequently AF demagnetized. The resulting curves show the same behaviour presented in other

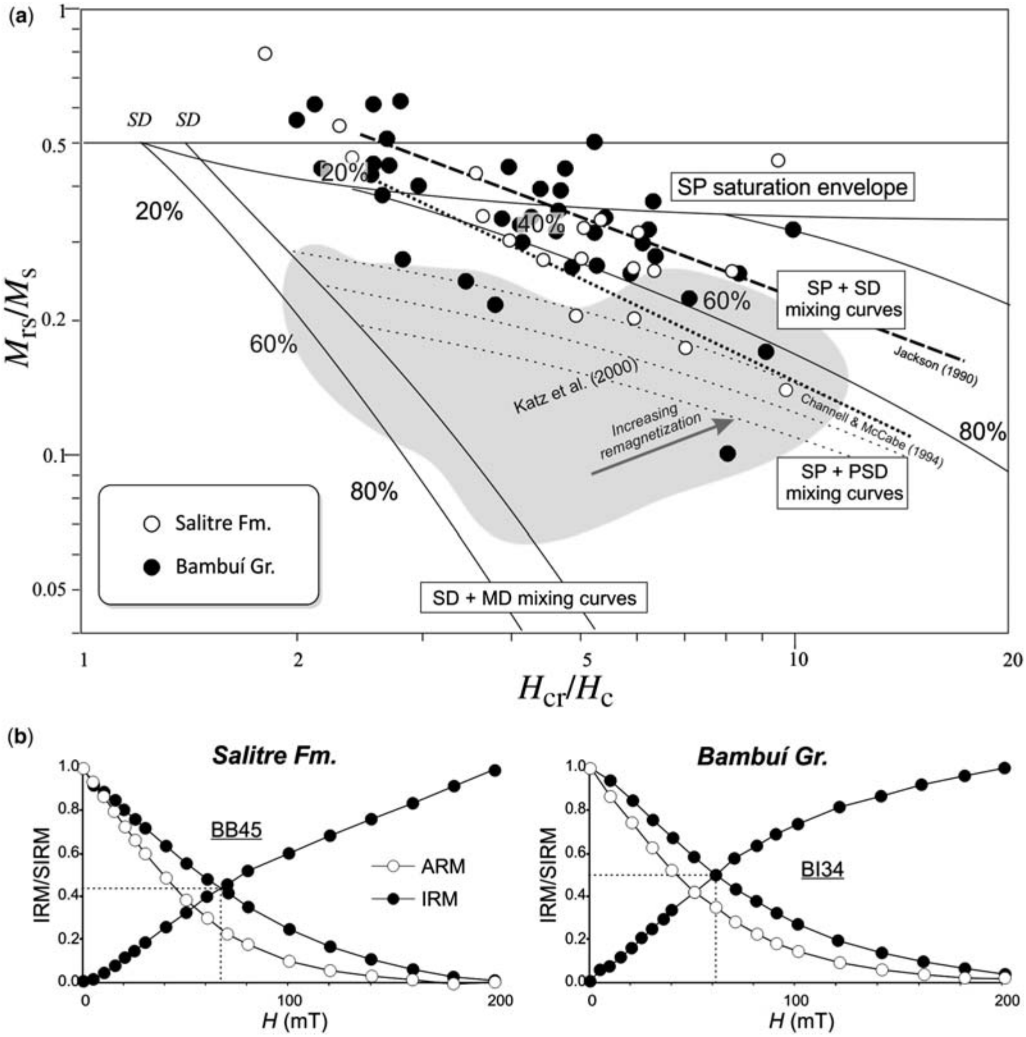


Fig. 5. (**a**) Hysteresis data from the Bambuí Group and Saltire Formation (Trindade *et al.* 2004) plotted on the theoretical unmixing diagram of Dunlop (2002) and showing a mixture of SD + SP typical of remagnetized carbonates (Jackson 1990). (**b**) Lowrie-Fuller (Johnson *et al.* 1975) and Cisowski (1981) tests of representative samples from the Bambuí Group and the Salitre Formation. Results are similar to the contradictory behaviour observed in other remagnetized carbonates (Jackson 1990; McCabe & Channell 1994; Huang & Opdyke 1996).

remagnetized successions (McCabe & Channel 1994; Huang & Opdyke 1996). In these curves, the symmetrical behaviour of IRM acquisition and demagnetization curves indicates that single-domain particles are non-interacting (Cisowski 1981). This contrasts with the fact that ARM is weaker than IRM to AF demagnetization, a behaviour more akin to that of multi-domain magnetite grains (Johnson *et al.* 1975) but also typical of remagnetized carbonates (McCabe & Channel 1994). Given the coincidence in magnetic directions, unblocking temperatures and magnetic carriers across a broad cratonic region, the single-polarity and tightly grouped nature of magnetic components and the rock magnetic properties typical of remagnetized carbonates, we interpreted these rocks to have been affected by a widespread remagnetization event. The age of the event can be constrained by both the coincidence of the Bambuí and Salitre poles with reference Cambrian poles for the Gondwana supercontinent, and the 520 Ma Pb/Pb ages obtained systematically in the two regions. Since this age corresponds to the final assembly of the Gondwana supercontinent, we have suggested that a large-scale brine migration has affected most of the São Francisco Basin promoting pervasive remagnetization of the carbonates, resetting of their Pb isotopic system and also a concentrating of base metals which formed widespread Pb–Zn mineralization found all along the region (e.g. Misi & Veizer 1998; Monteiro *et al.* 1999).

Late Palaeozoic remagnetizations

The San Rafaelic remagnetization of the Argentine Precordillera

Rapalini & Tarling (1993) reported for the first time the presence of a widespread remagnetization affecting areas of the exposed Cambro-Ordovician carbonate platform of the Argentine Precordillera. This was inferred to have occurred in the Permian on the basis of the corresponding pole positions and their exclusively reversed polarity (i.e. Kiaman Reverse Polarity Superchron). The main carrier of this remagnetization is the Early Ordovician San Juan Limestone (e.g. Benedetto 1998), which is largely exposed along the Eastern and Central Precordillera in the provinces of San Juan, La Rioja and Mendoza. Rapalini & Tarling (1993) included within the same remagnetizing event the syn-tectonic magnetization observed in the Carboniferous Hoyada Verde clastic sediments (Bobbio *et al.* 1990) as well as their reinterpretation of the original Alcaparrosa Formation pole (Vilas & Valencio 1978) which, according to the authors, does not reflect the original remanence but a syn-tectonic (44% unfolding) magnetization during Permian times. The original work of Rapalini & Tarling (1993) was continued by Truco & Rapalini (1996) who found a syn-tectonic magnetization affecting the Middle Ordovician limestones of the Ponón Trehué Formation, exposed in the San Rafael Block, some 400 km south from the previous study zone. More recently, Rapalini *et al.* (2000) and Rapalini & Astini (2005) carried out new palaeomagnetic studies at different localities along the Eastern and Northern Precordillera, where several localities showed a similar magnetic component to that found in the previous study. This allowed the study area affected by the remagnetization to be expanded both geographically (San Rafael Block, Eastern and Northern Precordillera) as well as stratigraphically along the carbonatic sequence. Some areas were however found to be unaffected by the remagnetization, which was apparently due to a lithological control. Rocks that showed no evidence of remagnetization were characterized by either a primary remanence or unstable or incoherent magnetizations.

Figure 6a, b shows the distribution of localities where the remagnetizing event has been found as well as those where it is apparently absent. It is clear from the figure that no single geographic pattern arises from this distribution. The lithological control is clear in the extreme north of Precordillera, where the Early Cambrian Cerro Totora Formation made up of red sandstones and siltstones records a primary magnetization (Rapalini & Astini 1998), and the limestones of the Late Cambrian La Flecha Formation, exposed less than 3 km away from the former, have been remagnetized.

The Argentine Precordillera is part of the Andean Chain that was uplifted, mainly by east-verging thrusts, in the Late Tertiary (Jordan *et al.* 1983; Allmendinger *et al.* 1990). As such, ‘syn-tectonic’ or ‘post-tectonic’ magnetizations may have undergone Andean tilting, which in most cases is not well constrained. In the case of the calcareous rocks exposed in the Eastern Precordillera, a large tilting of around 40° of the whole sequence since remanence acquisition was inferred from the remanent magnetization directions (Rapalini *et al.* 2000). In other cases (Rapalini & Tarling 1993; Truco & Rapalini 1996; Rapalini & Astini 2005), very minor if any significant Andean tilting has been observed from pole positions (Fig. 1c; Table 2), the distribution of which is consistent with magnetization being acquired during the Early–Late Permian. Three units (Hoyada Verde, Alcaparrosa and Ponón Trehue Fms) present a syn-tectonic magnetization that is close to Early Permian reference directions. All these units were affected at that time by a major deformational phase that affected the Precordillera and other neighbouring geologic provinces in Argentina called the San Rafaelic tectonic phase (Azcuy & Caminos 1987), hence the term ‘San Rafaelic Remagnetization’ (Table 2). Rapalini & Astini (2005) have speculated on some progressive migration of the remagnetizing ‘front’. According to their consideration, the units located towards the west (i.e. The Hoyada Verde and the Alcaparrosa Formation) underwent syn-tectonic magnetizations during folding at *c.* 300–285 Ma. Meanwhile, units located more to the east were remagnetized at a later time. The La Flecha Formation exposed in the Northern Precordillera was apparently remagnetized not before *c.* 263 Ma as inferred from its pole position and the presence of mixed polarities. In any case, there seems to be little doubt on the relation of this event and deformation assigned to the San Rafaelic tectonic phase.

Detailed and systematic rock-magnetic studies on the remagnetized rocks mentioned above are lacking. Rapalini *et al.* (2000) performed hysteresis studies on samples from the La Flecha, La Silla and San Juan formations from Eastern Precordillera (Fig. 6c). When plotted together with unmixing theoretical curves for carbonates (Dunlop 2002), unremagnetized limestones fall within the single- and multi-domain (SD + MD) which is characteristic of primary magnetic mineralogy. Remagnetized carbonates however show a typical trend from SD + MD to pseudo-single- and single-domain (PS + SD) mixture. Geuna & Escosteguy (2006) have recently performed a magnetic mineralogy study on the Late Ordovician Alcaparrosa Formation, originally studied by Vilas & Valencio (1978) and re-interpreted by Rapalini & Tarling (1993) as an Early Permian syn-tectonic remagnetization. The new study reveals that the magnetization in the basaltic pillow lavas and dolerites of this unit is mainly carried by pyrrhotite with minor and sporadic amounts of magnetite. Geuna & Escosteguy (2006) were able to prove that the remanence is secondary and related to neoformation of magnetic minerals in the alteration halo associated with the intrusion of a small porphyritic body (Pórfiro Alcaparrosa) that has been dated as 270 Ma (Sillitoe 1977). The natural remanence and magnetic susceptibility is significantly higher inside the contact aureole surrounding the intrusion, and decreases progressively away from the contact aureole. A few kilometres from the aureole, the Alcaparrosa volcanic and sedimentary rocks are paramagnetic with unstable remanence. Geuna & Escosteguy (2006) interpreted that the original magnetic minerals in these basic volcanic rocks were altered by ocean floor metamorphism. Secondary pyrrhotite and sporadic magnetite in the rocks are almost exclusively found inside or very close to the alteration halo of the intrusive body.

Rapalini & Tarling (1993) proposed that the San Rafaelic remagnetization found in the Argentine Precordillera was a chemical remagnetization linked to tectonically expelled fluids from the orogen towards the foreland ('the migrating fluids model' of Oliver 1986). Conversely, Geuna & Escosteguy (2006) suggested that other sources of remagnetization were also active at those times and cast doubts on the validity of a single and simple model to explain the whole remagnetizing event. However, detailed rock magnetic studies are poorly documented for these remagnetized rocks, making the identification of the corresponding remagnetizing processes difficult to establish. Future magnetic mineralogy investigations in these formations will probably provide better insights to study the mechanisms of remagnetization in the Argentine Precordillera.

Remagnetizations in the Gondwanides Fold Belt

In the late Palaeozoic, the southern margin of Gondwana was characterized by a large orogenic belt that

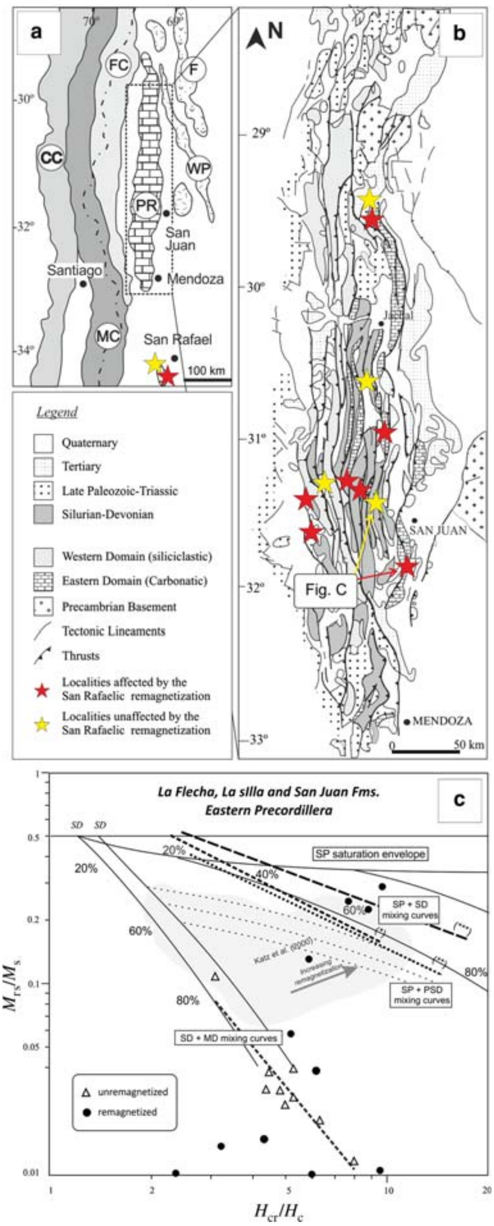


Fig. 6. (**a**, **b**) Distribution of remagnetized (red stars) and unremagnetized (yellow stars) rocks from the Argentina Precordillera. CC, Cordillera de la Costa; MC, Cordillera Principal; FC, Cordillera Frontal; PR, Precordillera; F, Famatina; WP, Sierras Pampeanas (modified from Rapalini & Astini 2005). (**c**) Hysteresis data from La Flecha, La Silla and San Juan formations (Rapalini *et al.* 2000), plotted on the theoretical unmixing diagram of Dunlop (2002) and showing a typical SD + MD mixture for unremagnetized carbonates and a SD–SP trend for remagnetized limestones. Envelope curves typical of remagnetized carbonates are also shown (*, Trindade *et al.* 2004; **, Channel & McMabe 1994; and ***, Jackson 1990; see graph curves for asterisks).

extended nearly 13 000 km across South America, southern Africa, Antarctica and eastern Australia. This belt was originally defined by Du Toit (1937) as the 'Samfrau Geosyncline' and is also known as-the 'Gondwanides Belt' (Keidel 1916). The Sierras Australes Fold and Thrust Belt of the Buenos Aires province (Argentina), also widely known as Sierra de la Ventana Fold Belt (e.g. Harrington 1947; Fig. 7), has been interpreted as the result of crustal collision between Patagonia and southern South America (Ramos 2008) or as the result of accretionary tectonics (e.g. Cawood & Buchan 2007). In the last decade, large palaeomagnetic studies were carried out on the youngest (i.e. Permian) clastic sedimentary units of the stratigraphic sequence exposed along this belt and, in particular, in the Sierra Australes (Tomezzoli 2001), the Carapacha Basin (Tomezzoli *et al.* 2006) and the North Patagonian Massif (Rapalini 1998).

The Sierras Australes. The Tunas Formation has a broad geographical extension in the region and is the youngest and less-deformed unit of the Carboniferous–Permian Pillahuincó Group. It is composed of 1200 m of silicified fine pale-green sandstones, lithic feldsarenites interbedded with red clay-siltstones and shale which were part of a deltaic complex prograding towards the NE (Harrington 1947). A variable degree of tectonic deformation is observed along the succession of the Tunas Formation, with higher deformation at the base than at the top (e.g. Harrington 1947; Buggisch 1987).The palaeofloral associations of *Glossopteris* attest to a Permian age for these rocks (Archangelsky & Cúneo 1984). Some vitric tuffaceous interbeds of the upper half of Tunas basin were dated at 274 ± 10 Ma (U–Pb, Tohver *et al.* 2007).

For the palaeomagnetic study, more than 600 specimens were collected from 55 sites in 8 localities in the eastern parts of the belt (Sierra de las Tunas to the north and Sierra de Pillahuincó to the south; Tomezzoli 1997; Fig. 7a). Magnetic patterns were similar in all localities and showed well-defined unblocking temperatures between 550 and 680 °C and a gradual quasi-linear decay towards the origin. The isolated characteristic remanent magnetization (ChRM) shows positive (downwards) inclinations and good within-site directional consistency ($\alpha_{95} < 15^\circ$ and $k > 20$) in at least 44 sites. Exclusive reverse polarity suggests magnetization acquired during the Kiaman Reverse Polarity Superchron (Opdyke & Channell 1996). High unblocking temperatures suggest hematite as the main magnetic carrier. A syn-tectonic origin for the remagnetization is suggested by a negative fold test (McFadden 1990) where minor scattering in magnetic directions is reached after partial unfolding (Fig. 7). At the base of the sequence from the Sierra de las Tunas (San Carlos, Toro Negro and Golpe de Agua localities; Tomezzoli & Vilas 1999), the results of the fold test provides best grouping at an average of 42% unfolding (Fig. 7b). Younger sequences from the Sierra de Pillahuincó (Dos de Mayo, Las Lomas-La Susana, Arroyo Paretas and Las Mostazas localities; Tomezzoli 2001) however demonstrated a magnetization acquired with an average of 90% unfolding (Fig. 7c). Magnetization was likely acquired during the Kiaman Reverse Polarity Superchron, based on the fact that only a reversed magnetic polarity is observed in these rocks. A significant duration is envisioned for the remagnetization event (i.e. syn-tectonic magnetic overprint proceeding from the base to the top), estimated to *c.* 20 Ma (Fig. 7d; Tomezzoli 1999). These results are grouped into two palaeomagnetic poles called Tunas I (Tomezzoli & Vilas 1999) and Tunas II (Tomezzoli 2001) that are consistent with previous poles from South America assigned to the Permian (Fig. 1c). The Early Permian deformation responsible for the magnetization described here may correspond to the activity of the San Rafaelic orogenic phase already mentioned (Azcuy & Caminos 1987). The beginning of the San Rafaelic orogenic phase according to Llambías & Sato (1995) in the Cordillera Frontal of Argentina was during the Asselian (earliest Permian). The positions of Tunas I and II poles follow a consistent trend within their stratigraphic position in the Tunas Formation. According to a traditional Late Palaeozoic APWP for South America (Brandt *et al.* 2009; Tomezzoli 2009; Domeier *et al.* 2011), an Early Permian age for Tunas I and a Permian age for Tunas II is likely (Fig. 1c).

No detailed rock magnetic studies were carried out for these rocks. Demagnetization patterns strongly suggested hematite as the principal remanence carrier. In the Tunas Formation, some beds have red spots both in the pigment and detrital grains which are interpreted as diagenetic hematite. These rocks have not been significantly metamorphosed, having suffered only moderate diagenetic changes (Cobbold *et al.* 1986; Buggisch 1987). The magnetization is believed to be mainly syndepositional to syndiagenetic. This suggests that deformation occurred very soon after deposition of the Tunas Formation started and continued during sedimentation. Deformation appears to be diachronous, being older in the western areas of the Tunas depositional basin while deposition was starting to take place in eastern areas (Fig. 7c). For that reason, the degree of deformation diminishes substantially both stratigraphically (towards younger levels) and geographically (eastwards). This is probably why magnetization is truly syn-tectonic in the western Sierra de las Tunas (lower levels) and almost pre-tectonic in the Sierra de Pillahuincó

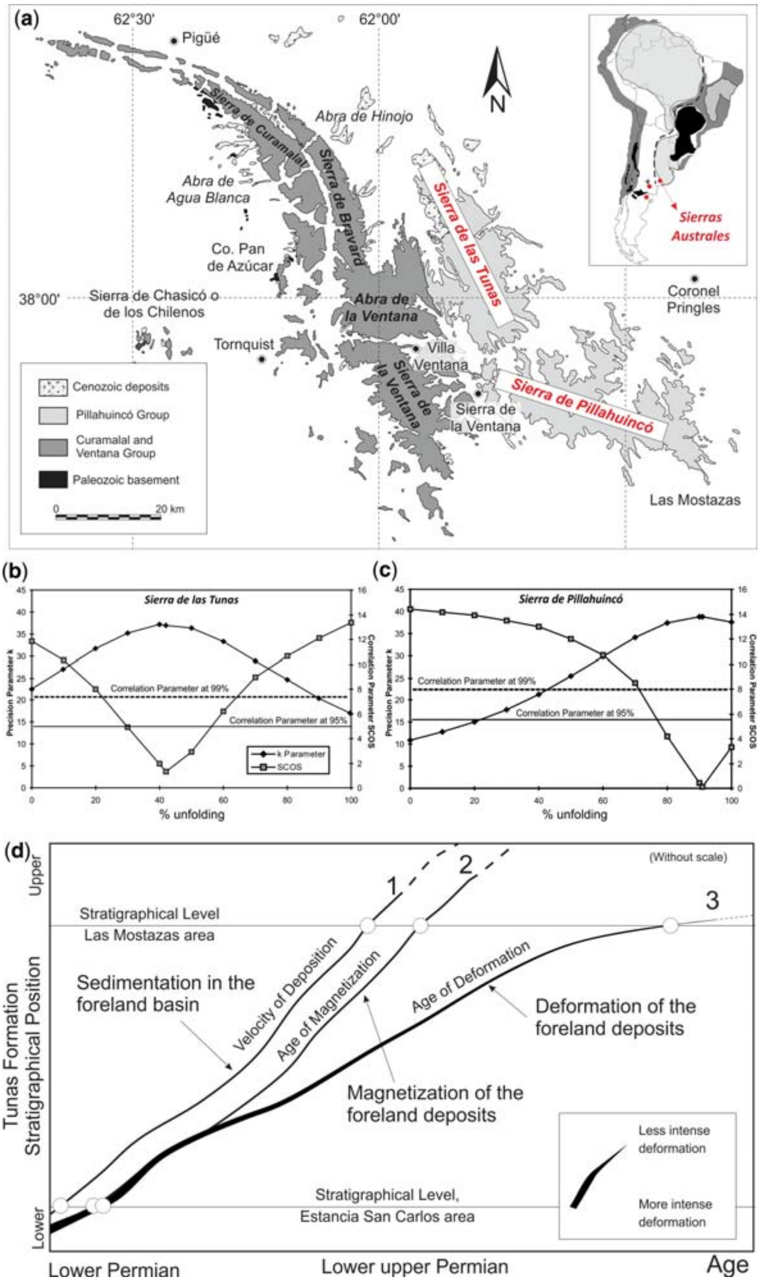
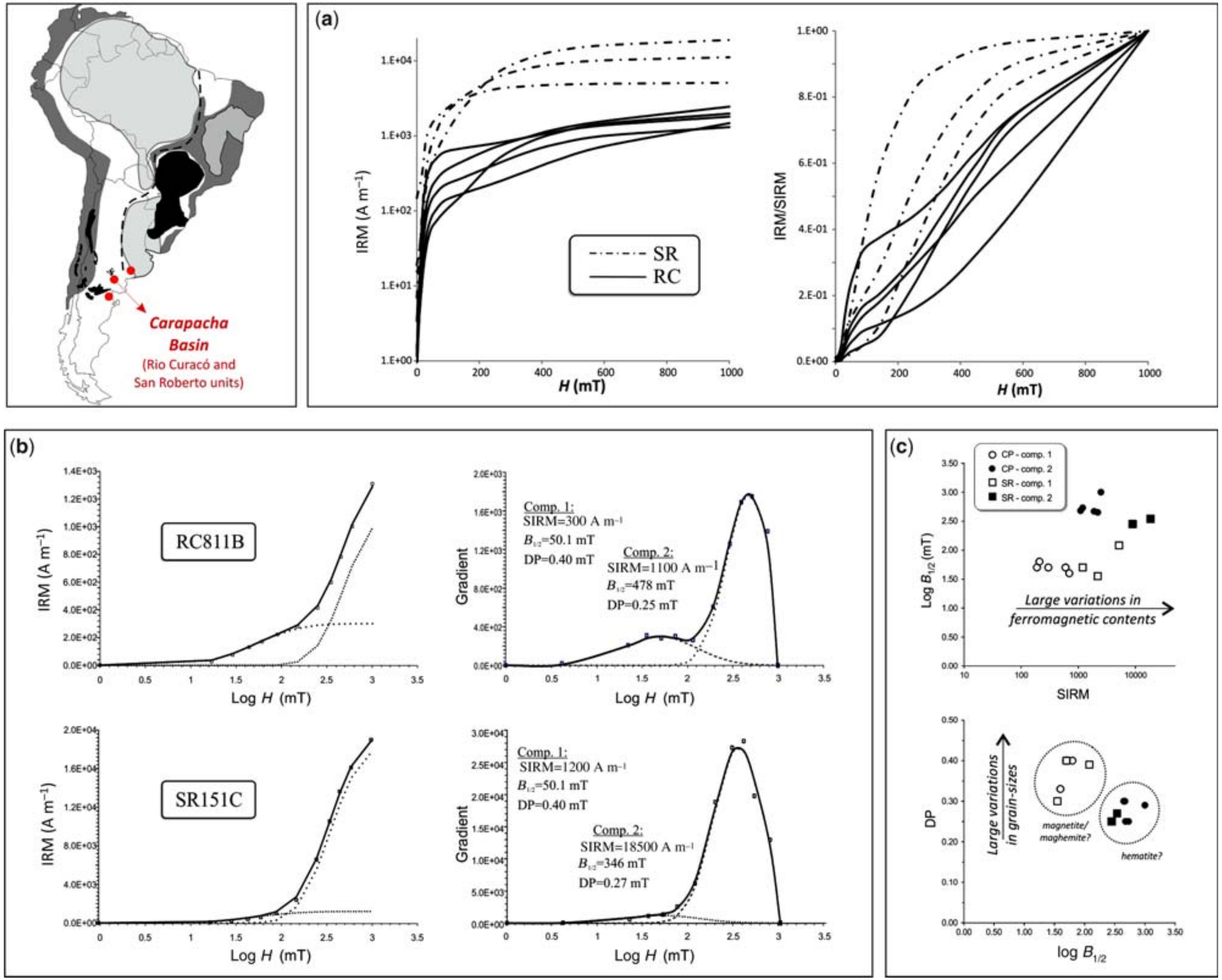


Fig. 7. (**a**) Geological map of the Sierras Australes, Argentina. Plots of the statistical parameters *k* (Fisher 1953) and the SCOS (correlation parameter of McFadden 1990) for the Tunas Formation in the (**b**) Sierra de las Tunas and (**c**) Sierra de Pillahuincó v. percentage unfolding (Tomezzoli & Vilas 1999; Tomezzoli 2001). Both units showed a syn-folding origin for the remagnetization. (**d**) Schematic relationship of sedimentation, magnetization and deformation for different stratigraphic levels of the Tunas Formation (Tomezzoli 1999).

(upper levels). It must be noted that the Sierra de Pillahuincó retains the same orientation of the structures as the Sierra de las Tunas, with wider folds and smoother topography, indicating that they were affected in different degrees by the same tectonic process.


Carapacha Basin
(Rio Curacó and San Roberto units)
(a)
IRM (A m⁻¹)
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
0
200
400
600
800
1000
H (mT)
SR
RC
IRM/SIRM
0.E+00
2.E-01
4.E-01
6.E-01
8.E-01
1.E+00
H (mT)
(b)
RC811B
IRM (A m⁻¹)
Log H (mT)
Gradient
Comp. 1:
SIRM=300 A m⁻¹
B1/2=50.1 mT
DP=0.40 mT
Comp. 2:
SIRM=1100 A m⁻¹
B1/2=478 mT
DP=0.25 mT
SR151C
Comp. 1:
SIRM=1200 A m⁻¹
B1/2=50.1 mT
DP=0.40 mT
Comp. 2:
SIRM=18500 A m⁻¹
B1/2=346 mT
DP=0.27 mT
(c)
○ CP - comp. 1
● CP - comp. 2
□ SR - comp. 1
■ SR - comp. 2
Log B1/2 (mT)
SIRM
Large variations in ferromagnetic contents
DP
log B1/2
Large variations in grain-sizes
magnetite/ maghemite?
hematite?

The Carapacha Basin. The Carapacha Basin is a continental half-graben of Permian age located in southern La Pampa province, central Argentina (Melchor 1999; Fig. 8), along the trend of the Gondwanides Belt, some 500 km west from the Sierras Australes. The basin filling is up to 630 m thick and entirely composed of fluvial and subordinate lacustrine deposits assigned to the Carapacha Formation for which a mid-Permian age have been attributed from the presence of *Glossopteris* flora (Melchor & Césari 1997). The base of the Carapacha Formation is not exposed and the uppermost part is intruded by andesites and small rhyolitic dykes, believed to be associated with Permian volcanic rocks of the Choiyoi Group. Due to the large regional distribution of these eruptive units and to the paucity of precise radiogenic isotope age data, their regional distribution is hard to establish. Basement rocks include Upper Cambrian–Lower Devonian metamorphic rocks and Late Palaeozoic granite and orthogneisses (Cerro de los Viejos Complex) that crop out in south-eastern La Pampa province. Magnetic fabrics of the Cerro de los Viejos Complex are characterized by two distinct foliations dated between 280.4 ± 2.3 Ma and 261 ± 13 Ma (Tomezzoli *et al.* 2003).

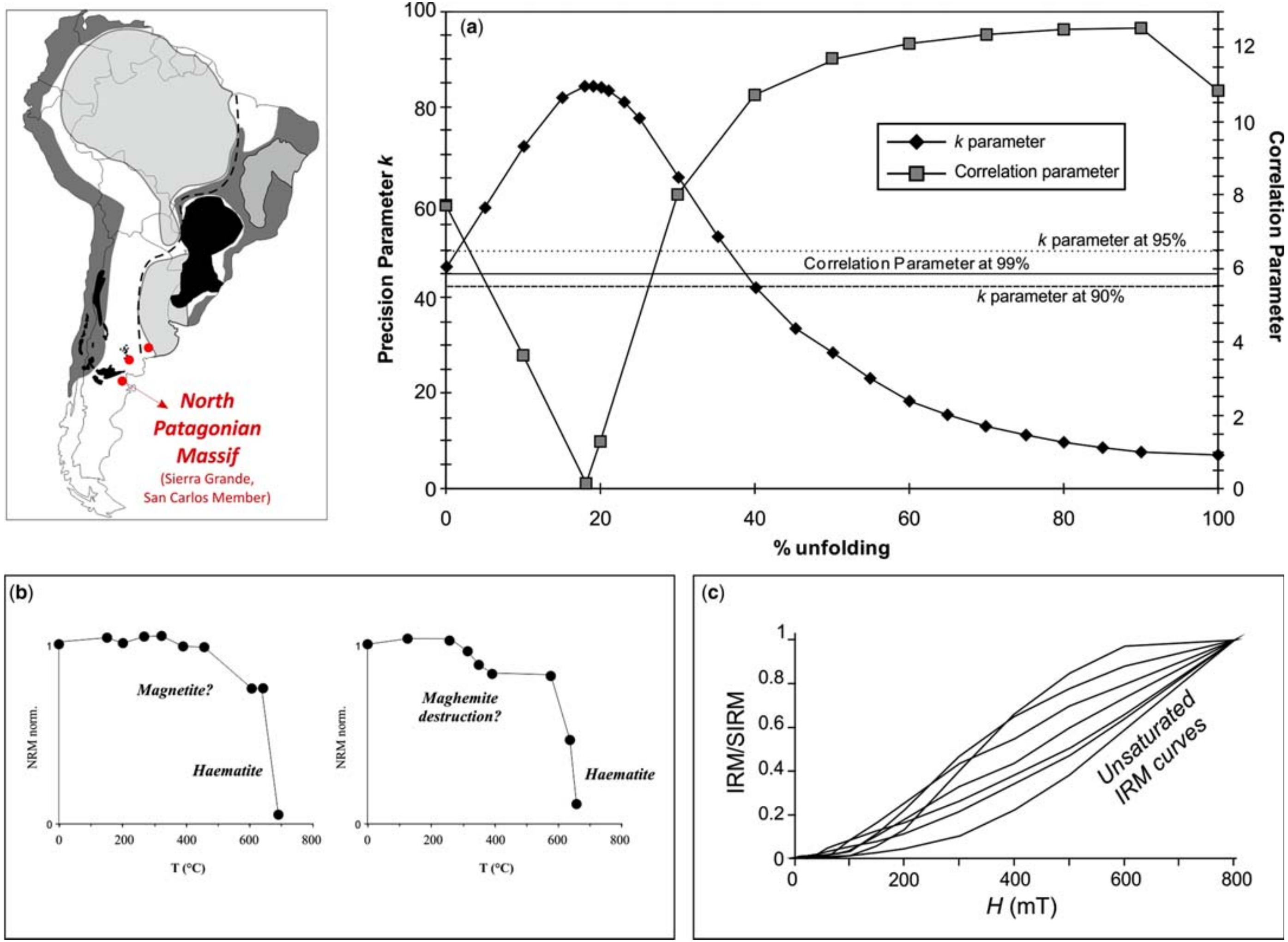
The Carapacha Formation comprises red, brown or grey arkosic or lithic mudstones, siltstones and fine-grained sandstones and massive or laminated and scarce conglomerates. It has been divided into two members separated by an unconformity: the Urre-Lauquen Member, which crops out along the Río Curacó as gently folded strata, and the homoclinal sequence of the Calencó Member (Melchor 1999). However, poor exposure of the rocks precludes a more definite determination of the tectonic structure here.

For the palaeomagnetic study, more than 250 specimens were collected from 24 sites at the two localities, with different structural attitudes (Tomezzoli *et al.* 2006). Most samples carry a single component of magnetization with positive inclination and good statistical values ($\alpha_{95} < 15^\circ$ and $k > 20$ for site-based mean directions). Stepwise unfolding of remanence directions showed a better clustering before un-tilting, that is, negative fold test, suggesting a post-folding age for the magnetization in the Carapacha basin (Tomezzoli *et al.* 2006). Unblocking temperatures of *c.* 680 °C suggested hematite as the principal magnetic carrier in these rocks (Fig. 9). In some samples, however, unblocking temperatures ranging from 450 to 580 °C were suggestive of magnetite or titanomagnetite. A mixture of hematite and magnetite corroborates IRM curves that remain unsaturated at 1 T (Fig. 8; Tomezzoli *et al.* 2006). IRM data was treated by the cumulative log-Gaussian function (Robertson & France 1994) using the software of Kruiver *et al.* (2001). Results show a clear contribution of hematite (65–95%) over magnetite (5–25%) in both the Rio Curacó and San Roberto units. Large values of saturation IRM (SIRM) and dispersion parameter (DP) suggest a heterogeneous (probably secondary) population of magnetic carriers in terms of concentration and/or grain size (Fig. 8).

The two different palaeomagnetic poles calculated from the Río Curacó (lower member) and San Roberto (upper member) are located at different positions in the APWP of South America (Fig. 1c). The San Roberto deposits that are less deformed occupy a younger position in the APWP while those from the Río Curacó deposits, that are older and more deformed, fall within an older section of the APWP (Tomezzoli *et al.* 2006; path B of Fig. 1c). The apparent age difference between the two poles, as judged by their relative positions along the APWP, is large enough to suggest a long period of several million years for the remagnetization phases. These results agree with those obtained in the same area from the Sierra Chica volcanic units (Tomezzoli *et al.* 2009) and for the Sierras Australes mentioned above.

Geological evidence indicates that sedimentation in Sierra de la Ventana was partially coeval with deformation and that this deformation advanced from west to east (Tomezzoli & Vilas 1999). The San Roberto pole presented here is thought to represent a younger remagnetization age, equivalent to the Tunas II palaeomagnetic pole (Tomezzoli 2001). Since the direction of the maximum compression is from SW to NE, it is logical that the age of the deformation is older to the west than to the east as seen in the Sierras Australes from the Buenos Aires Province where the time-transgression of the deformation is clearly evidenced by the palaeomagnetic study. Overall, the whole remagnetization process is broadly coeval with the San Rafael orogenic phase (Azcuy &

Fig. 8. IRM data for the Rio Curacó and San Roberto units, Carapacha Basin (Tomezzoli *et al.* 2006). (**a**) Raw (left) and normalized (right) IRM curves of SR (San Roberto units) and RC (Rio Curacó) samples. Data show that most samples did not reach saturation at 1 T, suggesting the resence of hematite. Differences in the shape of the IRM curves indicate wide ranges of ferromagnetic content and coercivity spectra. (**b**) Cumulative log-Gaussian treatment of representative samples using the software of Kruiver *et al.* (2001). Results show a characteristic bimodal distribution of coercivity spectra corresponding to a mixture of a low (magnetite?) and high (hematite?) coercive ferromagnetic phase. (**c**) Log $B_{1/2}$ v. SIRM and DP v. log $B_{1/2}$ plots showing large variations in ferromagnetic content and grain size.


North Patagonian Massif
(Sierra Grande, San Carlos Member)
(a)
Precision Parameter *k*
Correlation Parameter
% unfolding
k parameter
Correlation parameter
k parameter at 95%
Correlation Parameter at 99%
k parameter at 90%
0
20
40
60
80
100
2
4
6
8
10
12
(b)
NRM norm.
T (°C)
Magnetite?
Haematite
Maghemite destruction?
Haematite
0
200
400
600
800
1
(c)
IRM/SIRM
H (mT)
Unsaturated IRM curves
0.2
0.4
0.6
0.8

Caminos 1987), which may link the magnetization characteristics in La Pampa and Sierra de la Ventana to those found in the Precordillera and San Rafael Block. However, this is still speculation and a thorough investigation of the processes responsible for this regional feature is needed.

The North Patagonian Massif. Rapalini (1998) investigated the palaeomagnetism of the Siluro-Devonian clastic sedimentary rocks of the Sierra Grande Formation, exposed in the northeastern corner of the North Patagonian Massif (41.6°S, 65.3°W, Fig. 9). This unit is well known for the presence of two ferriferous horizons called the Rosales (San Carlos Member) and the Alfaro (Herrada Member) horizons (Zanettini 1981). Near the town of Sierra Grande, these horizons have been affected by thermal metamorphism caused by the intrusion of a Late Palaeozoic granitic body which led to the formation of secondary magnetite that was commercially exploited for many years in the Hiparsa mine. Rapalini & Vilas (1991) presented the first palaeomagnetic data for these rocks, originally interpreting palaeomagnetic remanences from the Rosales horizon as primary, an assessment that was later discarded (Rapalini 1998). The upper Herrada Member however preserves a likely primary palaeomagnetic direction. Preliminary results on sandstones of the San Carlos Member, not including the Rosales horizon, showed a probable Permian remagnetization. A more detailed study by Rapalini (1998) on the sandstones of the San Carlos Member concluded that these rocks have been syn-tectonically remagnetized. Eighty-eight samples from 13 sites located along a syncline–anticline structure on these rocks presented a characteristic remanence with the best directional grouping obtained after 19% of partial unfolding (Fig. 9a). The partially corrected remanence yielded a pole position for the syn-tectonic magnetization of the Sierra Grande Formation at 77.3°S, 310.7°E ($\mathrm{dp} = 7.7°$, $\mathrm{dm} = 6.6°$, $N = 13$). The position of this palaeopole is coincident with late Early–early Late Permian poles of South America (Fig. 1c), giving a minimum age for deformation in this area. The exclusive reverse polarity found in the San Carlos Member was interpreted by the author as suggesting acquisition of remanence before the end of the Kiaman Superchron, which is older than 265 Ma (Gradstein *et al.* 2004; Ogg *et al.* 2008).

Detailed rock magnetic or petrographic studies have not been carried out on these rocks. However, high unblocking temperatures over 650 °C and the ineffectiveness of AF demagnetization strongly suggest hematite as the principal magnetic carrier of the remanence in the San Carlos Member, with probable minor additions of magnetite/maghemite (Fig. 9b). The presence of oolitic hematite has been confirmed in samples located few tens of kilometres from the metamorphic zone. Normalized IRM acquisition curves (IRM/SIRM) show a lack of low-coercivity fraction and unsaturated state at 1 T (Fig. 9c), which supports the theory that remanence is essentially carried by hematite. However, the presence of magnetite has been reported by Zanettini (1981) in the lower Rosales horizon. Detailed rock magnetic or petrographic studies have not been carried out on these rocks.

The syn-tectonic magnetization found in the Sierra Grande sediments may be caused by the same regional tectonic process evidenced from thrusting and folding in the North Patagonian Massif (von Gosen 2002, 2003; López de Luchi *et al.* 2010) and the Sierras Australes Fold Belt (Harrington 1947; von Gosen *et al.* 1990; Tomezzoli & Cristallini 1998) in the Permian. As such, the remagnetization of the Sierra Grande sediments may be associated directly with authigenic precipitation of iron oxides (mainly hematite) during deformation. Tomezzoli *et al.* (2010) have recently found that Early Ordovician granitoids exposed in the Sierra Grande area with little or no evidence of internal deformation have also been remagnetized in the Permian, thus suggesting that deformation is not the sole cause of remagnetization. Widespread Permian magmatism is observed in the North Patagonian Massif (see Pankhurst *et al.* 2006) and, in particular, in the Sierra Grande area where Varela (2009) have recently dated different plutons at 263 ± 9, 262 ± 6 and 260 ± 3 Ma by Rb–Sr isochrones. Considering that the Sierra Grande Formation has been severely overprinted by contact metamorphism with Permian plutons in some areas, chemical remagnetization is evidently linked to increased thermal gradient and fluids associated with the intrusions. Since deformation and magmatism were relatively contemporaneous, the syn-tectonic nature of the magnetization should not be mistaken for 'syndeformational'; in other words, deformation may not be the sole cause of magnetic memory resetting in the studied rocks.

The Río de la Plata Craton

The presence of a widespread remagnetization during the Permian and/or Triassic in the Rio de la Plata Craton has been recently reported in the

Fig. 9. (**a**) Negative fold test (McFadden 1990) of the San Carlos Member, Sierra Grande, North Patagonian Massif (Rapalini 1998); (**b**) thermal demagnetization diagram; and (**c**) IRM curves of the San Carlos sediments showing dominance of an antiferromagnetic fraction as principal magnetic carrier of the secondary magnetization (Rapalini 1998).

limestones from the Cerro Victoria Formation (Late Ediacaran–Early Cambrian), the late Ediacaran clastic Yerbal Formation and the Ediacaran clastic Rocha Formation (Rapalini & Sanchez-Bettucci 2008). These units are exposed in different tectonostratigraphic terranes of Uruguay. While the Cerro Victoria and Yerbal Formations are exposed in the Nico Perez terrane, the Rocha Formation belongs to the Punta del Este (or Cuchilla Dionisio terrane, e.g. Basei *et al.* 2005). In all cases, a well-defined dual polarity magnetization that does not pass the fold test indicated a post-tectonic remagnetization (Fig. 10). Rapalini & Sanchez-Bettucci (2008) also claimed that this secondary direction is indistinguishable from that found in the La Tinta Formation from the Tandilia region of Argentina (Valencio *et al.* 1980), thus invalidating the use of the La Tinta Formation palaeomagnetic pole for late Precambrian palaeogeographic reconstructions. As shown in Figure 1c, the pole positions belonging to the Cerro Victoria, Yerbal, Rocha and La Tinta Formation coincides within their uncertainties. The new palaeomagnetic pole from the Sierras Bayas Group (ex-La Tinta Formation) is also shown, with no significant discrepancy from the other. The post-tectonic nature of the magnetization of these rocks indicates a dual-polarity secondary magnetization that is probably latest Permian–Early Triassic in age. Because the APWP for South America since late Permian times shows very slow and short displacements the pole positions cannot be unambiguously assigned to the Permo-Triassic, and the latest Cretaceous–Early Tertiary portion of the APWP also presents a viable, alternative age for the remagnetization. A Late Permian–Early Triassic age is however favoured from the number of syn-tectonic magnetizations of such age found along the Gondwanides Belt (already mentioned) and from the recent report of an age of 254 ± 7 Ma for diagenetic processes in the Sierras Bayas Group (Zalba *et al.* 2007). Conversely, Rapalini & Sánchez-Bettucci (2008) reported a less conspicuous Cambrian remagnetization (see above) in the latest Ediacaran–Cambrian Polanco Formation and a couple of sites from the Cerro Victoria Formation.

No detailed rock magnetic studies have yet been carried out on these rocks, limiting the identification of the remagnetization processes. Additionally, the rocks on the craton do not show any macroscopic evidence of deformation during the Late Palaeozoic. Preliminary magnetic mineralogy data included IRM acquisition curves that showed a dominant signal from hematite consistent with their NRM demagnetization behaviour, suggesting a CRM origin for the remagnetization. A CRM overprint agrees well with uplift and inversion of the sedimentary column which led to the formation of a very large fore-deep (Claromecó fore-deep) towards the NE (e.g. Ramos 2008) which could expell fluids from the orogen towards the foreland, similar to that described by Oliver (1986, 1992) for eastern

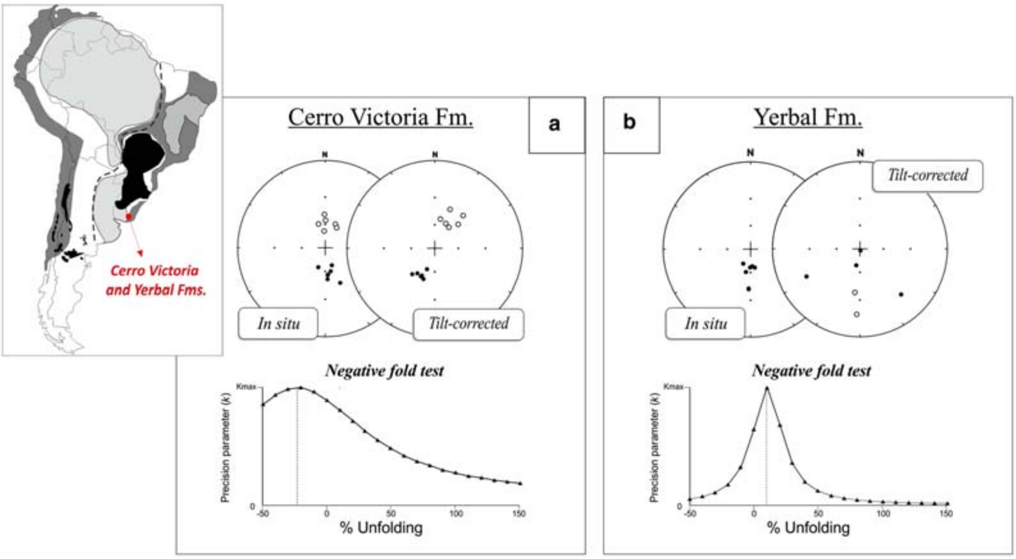


Fig. 10. Fold test (McFadden 1990) of the (**a**) Cerro Victoria and (**b**) Yerbal formations, Rio de la Plata, Uruguay (Rapalini & Sánchez-Bettucci 2008). Above: stereographic projections in geographic and tilt-corrected coordinates; below: dispersion parameter *k* v. percentage of unfolding. In both cases, data show a higher dispersion *k* after tilt correction and gave a negative (i.e. post-folding) response in the test.

North America. However, as in the case of the San Rafaelic remagnetization, a possible mineralogical control on the remagnetization is evident. Rapalini (2006) have reported Ediacaran–Cambrian red clastic sediments in the Tandilia system that have escaped remagnetization. Results of similar studies on the calcareous and clastic sediments of the Sierras Bayas Group (Augusto Rapalini, pers. comm., 2011) also indicate both hematite and magnetite in the remagnetized as well as in the unremagnetized samples. These observations highlight the importance of future detailed rock magnetic studies to unravel the nature and origin of the remagnetizing events in this area.

Cretaceous overprint link to the opening of the Atlantic Ocean: the Itajaí Basin case

The Itajaí Basin is located in the state of Santa Catarina, Brazil, and borders the Dom Feliciano orogenic belt which is coeval with the collision that sutured the Congo, Kalahari and Rio de la Plata cratons at the end of the Neoproterozoic and Early Cambrian. It was interpreted as a collision-related foreland basin (Gresse *et al.* 1996; Rostirolla *et al.* 1999). This syn-orogenic origin has been questioned since sedimentary features indicate a quiescent environment (Almeida *et al.* 2010). The Itajaí Group is composed of detrital sediments intruded by granites and capped by rhyolites. Its age was set between 563 ± 3 Ma, corresponding to the age of the sandstone deposition, and 549 ± 4 Ma for the intrusion of rhyolites (U–Pb dating, Guadagnin *et al.* 2010).

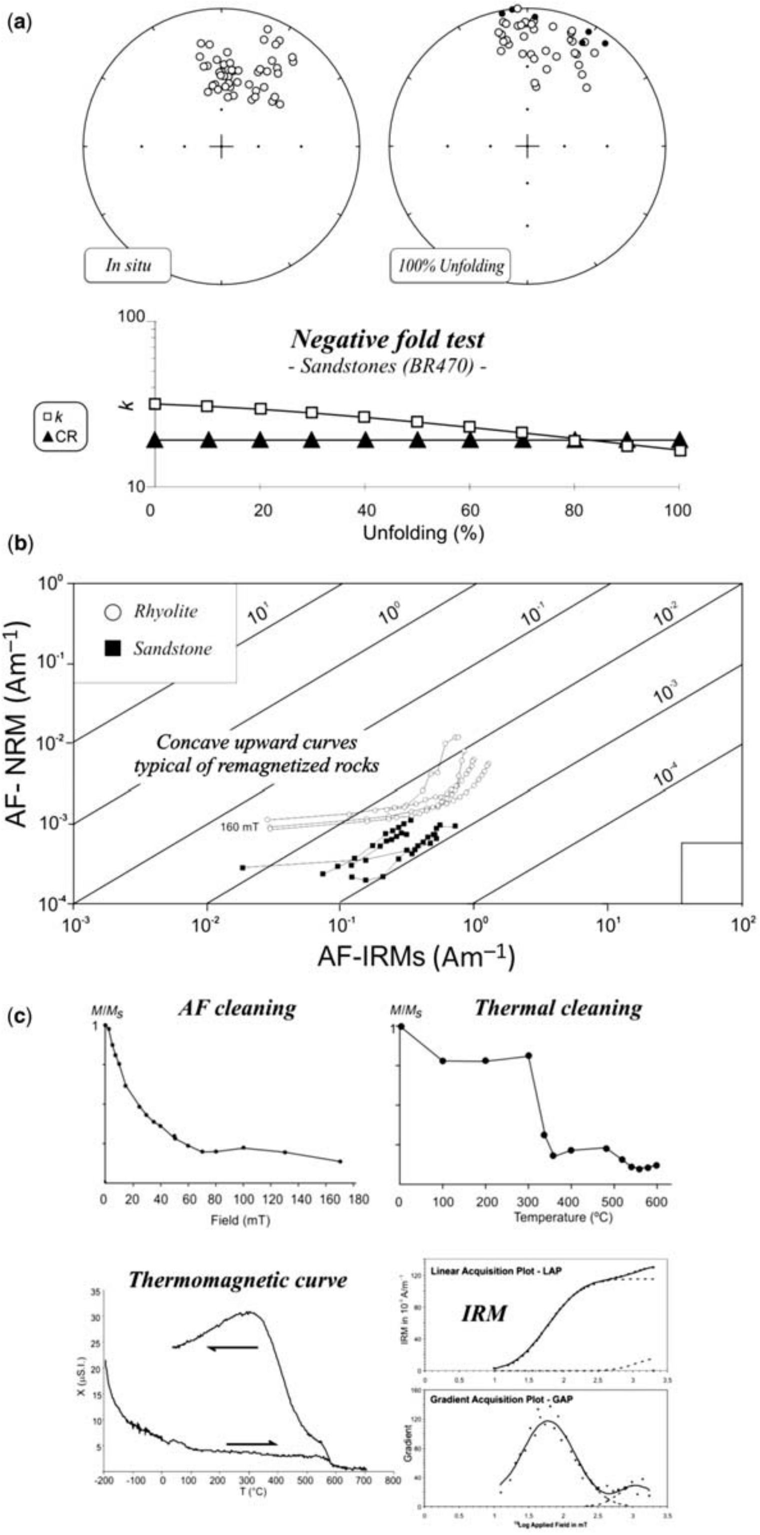
Rhyolites and sandstones share the same mean characteristic remanent magnetization and the coordinates of the corresponding palaeomagnetic pole ($\mathrm{P_{long}} = 277.5°\mathrm{E}$, $\mathrm{P_{lat}} = 84.0°\mathrm{S}$, $\alpha95 = 2.0$) plot close to the current geographic pole (Font *et al.* 2011). Once rotated to African coordinates using the 'tight fit' Euler poles (Trindade *et al.* 2006), the Itajaí pole (IT) is located far away from the APWP of Gondwana for the 570–500 Ma interval (Fig. 1d); this suggests that the remagnetization took place well after the final assemblage of the Gondwana supercontinent. The Itajaí pole is statistically more similar to the Lower Cretaceous poles than to the Permian portion of the APWP, suggesting that remagnetization took place at this later time (Fig. 1d).

The secondary origin for the magnetization of the Itajaí Group was suggested by a negative fold test (McElhinny 1964) performed on the sandstones (Fig. 11a; Font *et al.* 2011). It matches results of the Fuller *et al.* (2002) diagram that shows a concave-upwards NRM:IRMs diagram typical of remagnetized rocks (Fig. 11b). Principal magnetic carriers are represented by a mixture of authigenic magnetite ($T_{\mathrm{Curie}} = 580\ °\mathrm{C}$), maghemite ($T_{\mathrm{destruction}} = 350\ °\mathrm{C}$), goethite ($T_{\mathrm{C}} = 100\ °\mathrm{C}$) and hematite ($T_{\mathrm{Néel}} = 680\ °\mathrm{C}$) (Fig. 11c). The presence of superparamagnetic minerals was evidenced by the frequency-dependent susceptibility (K_{fd}) which takes values within the range 4–11%. SEM analysis indicates that most of the sandstone samples contain strongly altered iron oxides frequently associated with hydrothermal elements such as Ba and Mn, suggesting severe chemical alteration by fluid circulation (Fig. 12). Maximum demagnetization temperatures for the ChRMs of both rhyolites and sandstones are too high for these components to have been acquired by thermoviscous processes (Pullaiah *et al.* 1975). Alternatively, evidence of hydrothermal circulation via fault reactivation suggests a chemical origin for the remagnetization.

The Rio de la Plata Craton is bounded everywhere by strike-slip faults of late Neoproterozoic–early Palaeozoic ages originated by sinistral transpression during the closure of the southern Adamastor Ocean (e.g. Oyhantçabal *et al.* 2011; Rapela *et al.* 2011). During the Mesozoic opening of the South Atlantic, reactivation of ancient NE–SW faults in the Dom Feliciano Belt, such as the Perimbó Shear Zone (PSZ) that separates the Itajaí Basin from the Neoproterozoic Brusque Complex and the Major Gercino Shear Zone (MGSZ), resulted in extensional deformation (Moulin *et al.* 2010; Passarelli *et al.* 2010). These events may have facilitated hydrothermal circulation, leading to the formation of Au-rich quartz veins and Pb, Zn and Cu mineralization in the Itajaí Basin and playing an important role in the remagnetization processes. Early and Late Cretaceous dykes related to reactivation of WNW–ESE faults are compatible with this NE–SW extension and are related to the opening of the South Atlantic Ocean (R. Almeida, pers. comm.).

Summary

Until the last decades, the paucity of palaeomagnetic data in South America severely limited our capacity to reconstruct the palaeogeography of the South American plate in crucial phases of its evolution, whether in the context of the Gondwana assemblage (e.g. Meert & Powel 2001) or in that of the Pangaea (e.g. Ernesto 2007; Brandt *et al.* 2009; Font *et al.* 2009; Tomezzoli 2009; Domeier *et al.* 2011; Yuan *et al.* 2011). Significant improvements have since been made and a globally well-defined APWP is currently available and presented here for the Precambrian–Ediacaran (570–500 Ma), the Permo-Triassic (300–250 Ma) and the Cretaceous (140–65 Ma) interval. However, few reliable


(a)
In situ
100% Unfolding
Negative fold test
- Sandstones (BR470) -
□ k
▲ CR
k
100
10
0
20
40
60
80
100
Unfolding (%)
(b)
○ Rhyolite
■ Sandstone
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Concave upward curves typical of remagnetized rocks
160 mT
AF- NRM (Am^{-1})
AF-IRMs (Am^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
(c)
AF cleaning
M/M$_S$
1
0
20
40
60
80
100
120
140
160
180
Field (mT)
Thermal cleaning
M/M$_S$
1
0
100
200
300
400
500
600
Temperature (°C)
Thermomagnetic curve
X (µS.I.)
35
30
25
20
15
10
5
-200
-100
0
100
200
300
400
500
600
700
800
T (°C)
Linear Acquisition Plot - LAP
IRM
IRM in 10^{-1} A/m^{-1}
0
40
80
120
0
0.5
1
1.5
2
2.5
3
3.5
Gradient Acquisition Plot - GAP
Gradient
0
40
80
120
160
^{10}Log Applied Field in mT

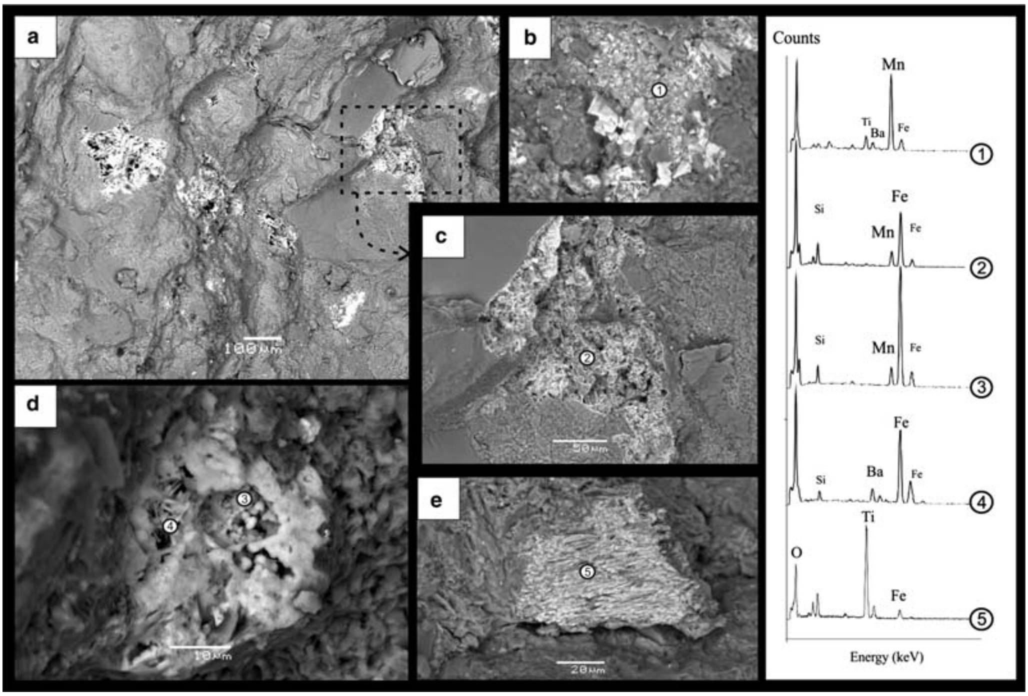


Fig. 12. SEM photographs and corresponding Energy Dispersive Spectra (EDS) of the remagnetized sandstones of the Itajaí Basin showing: (**a**–**d**) large ($>100\mu$m) and severely altered iron oxides associated with hydrothermal elements such as Mn and Ba; (**e**) Ti-rich altered iron oxide (hematite?).

palaeomagnetic poles exist between these time intervals and further palaeomagnetic investigations are still needed to reconstruct the missing pieces of the puzzle. One of the principal limitations resides in the episodic occurrence of widespread remagnetizations linked to major plate-tectonics events. A review of where, when and how these remagnetizations led to partial or total magnetic resetting of South American rocks is therefore summarized here (Fig. 13).

At least three widespread remagnetization events linked to global plate tectonics are identified in South America from Precambrian to Cretaceous times. Early Cambrian remagnetization of the neoproterozoic carbonates from the Amazon (Guia Formation) and Congo-São Francisco (i.e. Bambuí and Salitre formations) cratons, now well dated at *c.* 520 Ma, marked the closure of the Clymene Ocean and the formation of the Paraguay and Araguaia thrust and fold belts at the final stages of the west Gondwana assemblage (Fig. 1; D'Agrella-Filho *et al.* 2000; Trindade *et al.* 2003, 2004; Tohver *et al.* 2010, 2011). Two remagnetized poles of possible Cambrian age from the Cerro Victoria and Polanco formations are also documented in Uruguay (Rapalini & Sánchez-Bettucci 2008), suggesting that the Cambrian remagnetization also spread to the Dom Feliciano orogen at the eastern margin of the Rio de la Plata Craton. The age of the Paraguay Belt overlaps with that of the Pampean Orogeny, suggesting a coeval closure for the Clymene Ocean separating Amazonia from the São Francisco and Rio de Plata cratons (Tohver *et al.* 2010). The Guia, Bambuí and Salitre

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Fig. 11. (**a**) Stereographic projections of magnetic data from the neoproterozoic sandstones of the Itajaí Basin in geographic and tilt-corrected coordinates (above) and dispersion parameter *k* v. percentage of unfolding. Results give a negative (i.e. post-folding) response in the fold test (McElhinny 1964). (**b**) Diagram of AF demagnetization of NRMs v. AF demagnetization of IRMs. The concave-upwards shape of the curves is typical of remagnetized rocks (Fuller *et al.* 2002). (**c**) Above: AF and thermal demagnetization; below: thermomagnetic curve and IRM data of representative samples of the Itajaí sandstones. Data show a mixture of magnetite and hematite (and/or goethite).

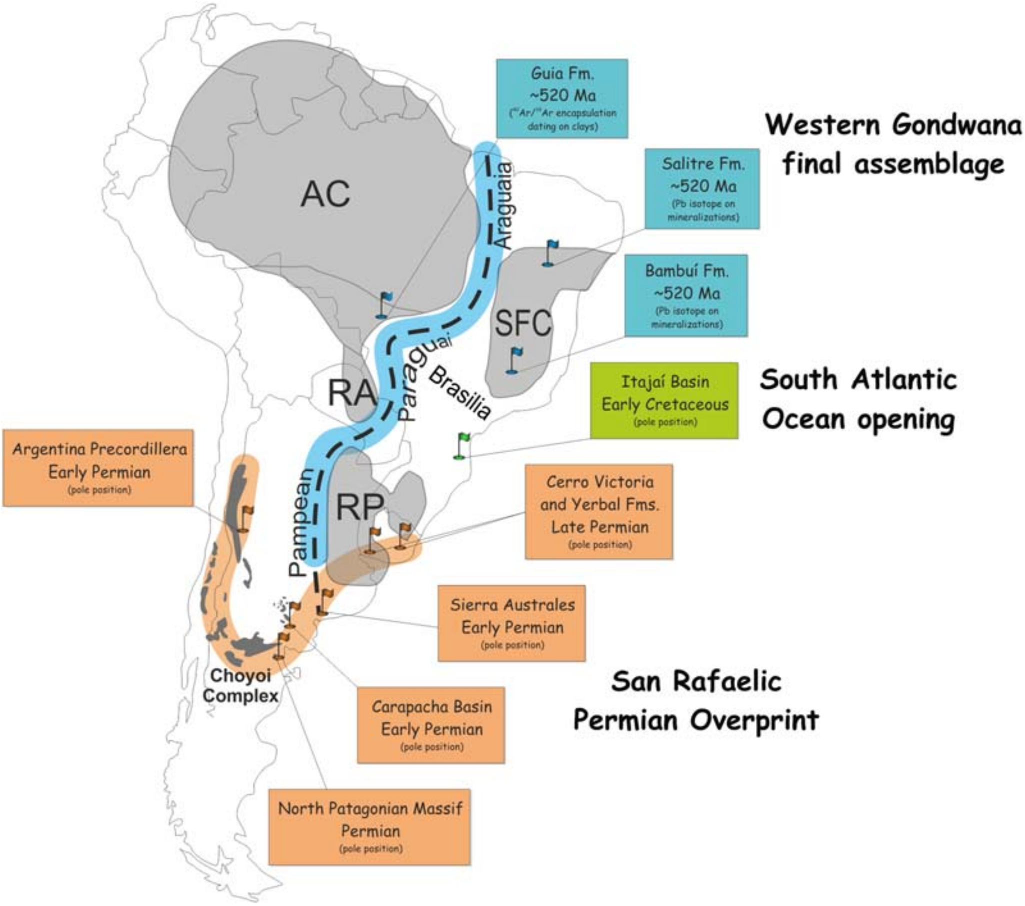

Fig. 13. Summary of remagnetized areas in South America showing age and dating methods of remagnetized poles.

formations are all composed of carbonates that are known to be easily prone to remagnetization through acquisition of a chemical remanent magnetization. In all cases, the secondary origin of the remanence is proved by negative fold tests. A CRM origin for the magnetization is well evidenced here by rock magnetic properties and mineralogical features where authigenic magnetite, and pyrrhotite in the case of hydrocarbon-rich sediments (i.e. Guia Formation), carried the secondary magnetization. The most probable remagnetizing mechanism is suggested here to be linked to smectite–illite transformation even if organic matter maturation by sulphato-reducing bacteria played an important role in the non-deformed Guia Limestones. Indeed, the smectite–illite transformation liberates free iron for latter magnetite authigenesis (e.g. Hirt *et al.* 1993; Katz *et al.* 2000; Gill *et al.* 2002; Zegers *et al.* 2003; Blumstein *et al.* 2004; Moreau *et al.* 2005; Tohver *et al.* 2008, 2010). There is some experimental evidence for a magnetite-producing reaction related to the breakdown of Fe-rich smectite to form Fe-poor illite and Fe-oxides (Hirt *et al.* 1993; Cama *et al.* 2000). Presumably, the liberation of Fe from smectite breakdown in a sulphur-rich environment would result in the formation of sulphides such as pyrrhotite in lieu of magnetite. Indeed, tests for the correlation between the age of remagnetization and the age of illitization have shown some recent success (Tohver *et al.* 2008; Zwing *et al.* 2009; Tohver *et al.* 2010). The genetic link between fine-grained illitic clay and its authigenic by-product magnetite provides a clear example of an amenable target for geochronology (Tohver *et al.* 2008; Zwing *et al.* 2009; Tohver *et al.* 2010). The age of the finest-grained material, dominated by authigenic illite (polytype $1M_d$), is determined by $^{40}Ar/^{39}Ar$ encapsulation dating.

Since this neoformed population is created by the same reactions that create authigenic magnetite, this technique can directly establish the age of remagnetization or, conversely, test for the likelihood of a primary magnetization.

The Permian was a period of intense volcanism along the continental margin of SW Gondwana where the Choiyoi magmatic belt emplaced a huge volume of rhyolites and granites in Chile and Argentina (Llambías *et al.* 2003). This period of intense volcanism is mostly coeval with the San Rafael Orogeny that affected the SW margin of Gondwana (Kleiman & Japas 2009) and was responsible for widespread remagnetization that affected the Rio de la Plata Craton (Rapalini & Sánchez-Bettucci 2008) from southern Brazil to central Argentina (Sierra Australes: Tomezzoli & Vilas 1999; Tomezzoli 2001; Sierra Chica: Tomezzoli *et al.* 2009). For instance, the age of the remagnetization in Argentina and Uruguay is estimated by the similarity of the corresponding poles with younger references, whereas no detailed magnetic mineralogy and/or radiometric dating for the magnetic overprint still exist. The case studies presented here however show good examples of remagnetization where lithology plays an important role. Indeed, in the Precordillera, the remagnetization is principally associated with carbonates of the La Flecha and San Juan formations whereas sandstones and siltstones of the Cerro Totora Formation preserved a primary magnetization in the same geographic area (Rapalini & Astini 1998). The distinction between preserved and remagnetized rocks is evidenced here by hysteresis data plotted together with theoretical unmixing curves for remagnetized carbonates (Fig. 6c; Dunlop 2002). The typical trend from SD + MD to SD + SP (single domain to superparamagnetic) is interpreted to have resulted from the CRM overprint. In the San Roberto and Rio Curacó formations in the Carapacha Basin, systematic dominance of hematite contents over magnetite as well as large SIRM and DP values point to a CRM acquisition via precipitation of authigenic magnetic carriers (Fig. 8). Similar interpretations have been made for the San Carlos Member sandstones of the Sierra Grande Formation, in the North Patagonian Massif, based on dominance of hematite over magnetite (Fig. 9).

The Cretaceous was a period of unusually active tectonics where ocean crust formation rate and off-ridge volcanism were greater than at any time since and where shallow and deep connections between the South Atlantic and North Atlantic ocean basins opened (e.g. Larson 1991; Poulsen *et al.* 2001; Phipps Morgan *et al.* 2004; Eagles 2007; Moulin *et al.* 2010). In southern Brazil, the accommodation of the extensional deformation resulting from the opening of the South Atlantic Ocean involved the reactivation of ancient faults and the genesis of a considerable quantity of ore deposits (Biondi *et al.* 1992, 2001; Basei *et al.* 2000; Passarelli *et al.* 2010). The best example is the Major Gercino Shear Zone (MGSZ), a Proterozoic lithospheric-scale discontinuity within the Dom Feliciano Belt which extended from southern Brazil to Uruguay (e.g. Passarelli *et al.* 2010). The main transpressive phase of the MGSZ was constrained by U–Pb analysis from multi-crystal zircon fractions at 614 ± 2 and 609 ± 16 Ma; recent K–Ar ages from biotites in mylonites however indicate ages of 206 and 230 Ma (Passarelli *et al.* 2010). The Perimbó Shear Zone (PSZ) is another large-scale fault zone which limits the Itajaí Basin from the Neoproterozoic Brusque Complex (Rostirolla *et al.* 2003). A fluid circulation via fault reactivation scenario is an excellent candidate to account for the remagnetization of the Neoproterozoic Itajaí Basin (Font *et al.* 2011). Contrary to the previous case, the Itajaí Basin is composed of rhyolites and sandstones, for which remagnetization proxies are still badly known and where no direct evidence between the age of the remagnetization and the nature and origin of the processes that led to total magnetic resetting are documented. Nevertheless, the position of the palaeomagnetic pole plots close to the Lower Cretaceous referenced poles (Fig. 1; Table 3). A negative fold test indicated a post-folding age for the remagnetization (Fig. 11). Principal magnetic carriers are authigenic magnetite, hematite (pigmentary) and goethite that are ubiquitously associated with hydrothermal elements such as barium and manganese (Fig. 12). In addition, taking into account that maximum demagnetization temperatures for the ChRMs of both rhyolites and sandstones *c.* 680 °C (hematite) are too high for these components to have been acquired uniquely by thermoviscous overprint (Pullaiah *et al.* 1975), a CRM origin is here preferred. However, more insights are needed to clearly state the links between faults reactivation, volcanism and fluid circulation of this area in the context of the South Atlantic opening.

In conclusion, the review of remagnetized South America formations presented here indicated at least three widespread remagnetization events linked to major plate tectonics, namely:

- the *Ediacaran–Cambrian remagnetization* that affected the Paraguay and Dom Feliciano belts and for which radiometric ages of 520–500 Ma marked the collision of the Amazon, Congo-São Francisco, Kalahari and Rio de la Plata cratons at the final stages of the western Gondwana assembly;
- the *San Rafaelic Permian Overprint* that affected Argentina and Uruguay during the emplacement of the Choiyoi Magmatic Province; and

- the *Lower Cretaceous remagnetization* associated with the South Atlantic opening that affected the Itajaí Basin bordering the Dom Feliciano Belt by fault reactions and fluid circulation.

In most cases, the origin of the remagnetization both in sedimentary (carbonates, siliciclastics) or magmatic rocks is interpreted as a chemical remanent magnetization. In the remagnetized carbonates of the Guia, Bambuí and Salitre formations, models invocated organic matter (hydrocarbon) maturation, smectite–illite transformations and migration of mineralizing fluids through basement faults. The genetic link between fine-grained illitic clay and its authigenic by-product magnetite provides a clear example of an amenable target for geochronology. However, in the case of the San Rafaelic Permian overprint and the Cretaceous remagnetizations, the ages of the remagnetization are only constrained by pole position and further detailed magnetic mineralogy analysis, coupled with radiometric dating of authigenic magnetic carriers, is needed to better constrain the timing and duration of these widespread remagnetizations.

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