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Palaeomagnetism of the Upper Carboniferous–Lower Permian transition from Paganzo basin, Argentina

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SUMMARY

A palaeomagnetic study of Upper Palaeozoic rocks was performed on Paganzo basin, central-western Argentina and its western extension, Río Blanco subbasin. The volcanic–volcaniclastic Río del Peñón and marine sedimentary Punta del Agua formations were sampled in the Rincón Blanco syncline. Both units represent the Upper Carboniferous–Lower Permian transition according to palaeontological and geochronological evidence. The Chancaní and Cerro Colorado-Caminiaga formations were sampled in their type localities, in the eastern Paganzo basin. All-reversed, pre-tectonic characteristic magnetizations were isolated in all three localities, spanning a wide lithological variation. Particularly in the Rincón Blanco syncline, the same reversed magnetization is observed in the entire 1500 m-thick sequence in volcanic and sedimentary rocks; at least part of the deformation there is thought to be Permian in age, related to the San Rafael orogenic phase (SROP). The palaeomagnetic poles are: Rincón Blanco (RB) Lat. 77°S, Long. 294°E, $N = 19$, $A_{95} = 4.9$, $K = 47$; Chancaní (CH) Lat. 85°S, Long. 359°E, $N = 3$, $A_{95} = 8.8$, $K = 196$; Cerro Colorado-Caminiaga (CC) Lat. 79°S, Long. 291°E, $N = 6$, $A_{95} = 8.0$, $K = 71$. Neither of the poles is coincident with expected Late Carboniferous–Early Permian directions according to accepted apparent polar-wander paths (APWPs) from South America and from other plates forming Pangaea in Late Palaeozoic times. This discrepancy could be the result of: (i) polar wander affecting the western Gondwana margin, probably related to SROP; (ii) tectonic rotations related to strike-slip faults active in the area since the Palaeozoic and controlling the position of the main depocentres; (iii) incorrect age assignment for the sedimentary sequences or for the remanence acquisition, i.e. local remagnetizations. Tectonic rotations and local remagnetization have both been proven in particular localities and further work needs to be done to establish the Late Palaeozoic APWP for South America, however, SROP seems to have played a major role controlling both processes, rotation and remagnetization.

Key words: block rotations, orogeny, palaeomagnetism, remagnetization, South America, Upper Palaeozoic.

INTRODUCTION

The poorly determined Carboniferous–Permian segment of the South American apparent polar-wander path (APWP) has played a crucial role in testing Pangaea reconstructions. The low quality and quantity of the Gondwanaland palaeomagnetic data has been repeatedly invoked as a strong limitation in assessing the Late Palaeozoic configurations for Pangaea (e.g. Van der Voo 1993). Many of the Carboniferous–Permian palaeomagnetic poles of South America have been obtained from Neopalaeozoic basins of central-western Argentina; particularly, an important set of palaeopoles are from the foreland Paganzo basin, developed east of a magmatic arc during the Late Carboniferous to Late Permian (Mpodozis & Ramos 1989; Azcuy *et al.* 1999) (Fig. 1). These poles define two distinct groups: the Late Carboniferous (Cu) group, reflecting a quasi-static period for South America, followed by the late Early Permian to Middle Jurassic (PJ) Group (Vilas 1981), with an intervening Late Carboniferous–Early Permian period of rapid polar wander. However, this geodynamic interpretation for the palaeopoles has become controversial because it is not reflected in the APWP from other plates forming Pangaea at those times (Smith 1999; McElhinny & McFadden 2000). In addition, many of these Paganzo palaeopoles

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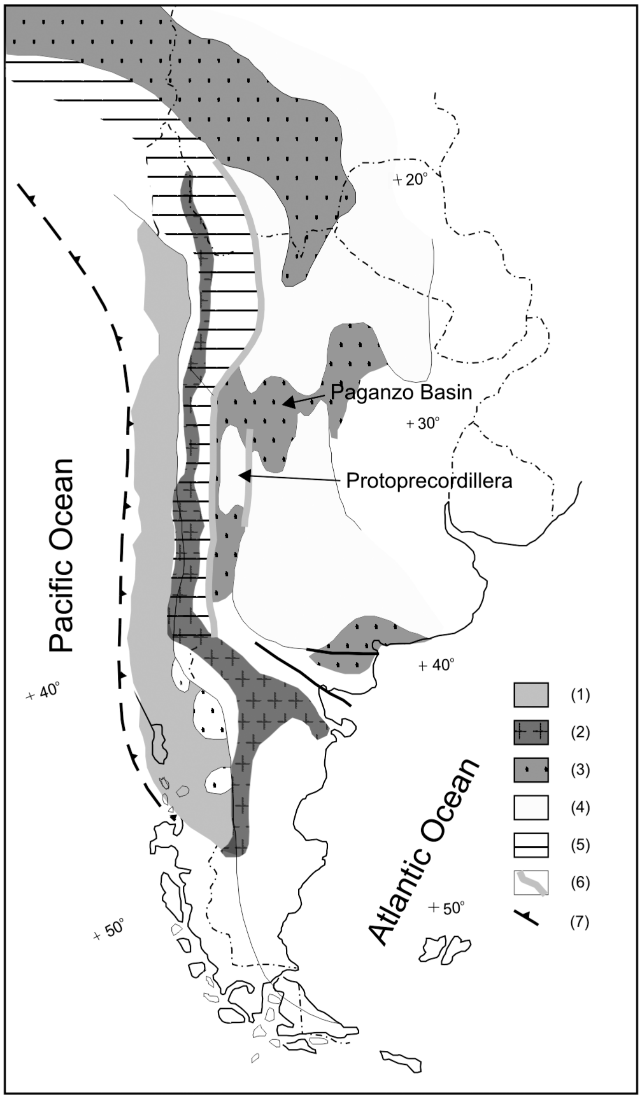

Figure 1. Location map of Paganzo basin in southern South America, and its tectonic setting (modified from Mpodozis & Ramos 1989): (1) accretionary prism and forearc assemblages; (2) magmatic arc; (3) terrestrial red beds; (4) uplifted area; (5) exotic terranes accreted to the South American margin before the Carboniferous; (6) suture zone; (7) inferred palaeotrench position.

come from continental red beds, which has raised suspicions of remagnetization (Smith 1999), inclination error or incorrect age assignment (Rochette & Vandamme 2001). The South American Late Palaeozoic APWP is then reduced to a very small number of reliable poles (see for example Tomezzoli 2001).

We performed new palaeomagnetic studies of Upper Palaeozoic localities of the Paganzo basin, located in different tectonic settings with a range of rock types. Volcanic and coastal sedimentary rocks were sampled from both limbs of the Rincón Blanco syncline, in the western extension of the basin (Fig. 2). Two additional studies were performed on small outcrops within the more stable (and poorly exposed) eastern area of the Paganzo basin.

The characteristic magnetization is exclusively of reversed polarity and pre-tectonic, and it is carried by different magnetic minerals, in a variety of lithologic types. At least part of the deformation in one of the localities is attributed to the San Rafael orogenic phase (SROP), Asselian in age, which implies a very early acquisition of the pre-tectonic remanence. The reversed polarity suggests that rocks were magnetized during the Permian–Carboniferous reverse superchron (PCRS, *ca* 317 to 265 Ma; Menning 1995; Opdyke *et al.* 2000 Fig. 3), in agreement with the Late Carboniferous–Early Permian age of the sampled sections.

By reviewing the Permian Paganzo poles using updated geological information, we established that localities of similar age have yielded different pole positions, forming two main groups. These groups may represent actual polar wander, with discrepancies as a result of inaccuracies in age assignations or local remagnetizations; or, they may be related to local tectonic rotations associated with strike-slip faults active in the area since the Palaeozoic (Fernández Seveso *et al.* 1990) and reactivated by Tertiary compressive tectonics in the adjacent Andean chain (Introcaso & Ruiz 2001).

Examples of both rotations and local remagnetizations are known, probably related to SROP. It seems clear that Permo-Triassic tectonic events (SROP) played a major role in the geological evolution of southern South America and its signature is usually present in the palaeomagnetic results of rock units older than Permian and close to the western margin of Gondwana.

GEOLOGICAL SETTING

Red beds, with scarce, thin intercalations of basaltic flows, constitute most of the Permian record in the foreland Paganzo basin. However, this basin was open to the Pacific ocean and shallow-marine sediments were preserved in its western extension. A record of simultaneous magmatic activity and Neopalaeozoic sedimentation (Caminos 1985) is present at Rincón Blanco (7 in Fig. 2), where lava flows are interbedded with shallow-marine and coastal sedimentary rocks.

A N–S trending structural high, the Protoprecordillera, partially separated the Paganzo basin from its marine extensions to the west: the Río Blanco and Calingasta-Uspallata basins (Limarino *et al.* 1996) (Fig. 2). The Paganzo basin itself can be divided into two areas: the eastern part, where the sedimentary cover is thinner and was deposited on Proterozoic igneous–metamorphic basement; and the western part, a narrow belt developed on more mobile areas, with thicker deposits upon metamorphic basement and Lower Palaeozoic sediments of the Precordillera (Azcuy *et al.* 1999). There is evidence of oblique convergence in the Late Palaeozoic subduction zone to the west (Mpodozis & Kay 1992; Kay 1993); strike-slip faults have controlled the development of the forearc basins (Fernández Seveso & Tankard 1995).

Terrigenous clastic fill of the Paganzo basin was originally subdivided into three stages referred to as Carboniferous, Permian and Triassic by Bodenbender (1911). Azcuy & Morelli (1970) assigned the name Paganzo group to the Carboniferous–Permian sections; the Triassic sequence (usually referred to as the Upper Paganzo Section or Paganzo III in former palaeomagnetic contributions) constitutes an independent cycle related to the development of Triassic extensional basins, following a tectonic inversion marked by a major unconformity that truncates Permian sequences (Fernández Seveso & Tankard 1995).

Upper Palaeozoic fill within the Paganzo basin (i.e. the Paganzo group) comprises four supersequences of mainly continental sediments (Fig. 3): Guandacol, Tupe, Lower Patquía-De La Cuesta and Upper Patquía-De La Cuesta (Fernández Seveso *et al.* 1990). A progressive continentalization culminates in Permian supersequences composed of continental red beds with records of extensive aeolian fields.

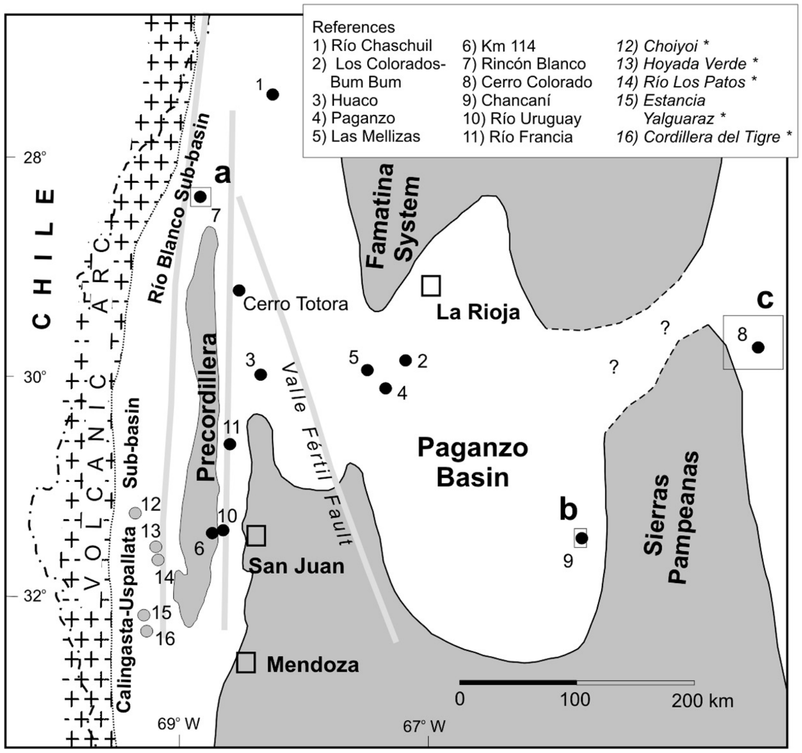

Figure 2. Sketch of Paganzo basin, with localities referred to in the text (modified from Azcuy *et al.* 1999). Location of maps in Fig. 4 are shown. Localities 12–16 correspond to palaeomagnetic studies from Valencio & Vilas (1985) and Rapalini & Vilas (1991), several of them resulting in tectonically rotated poles.

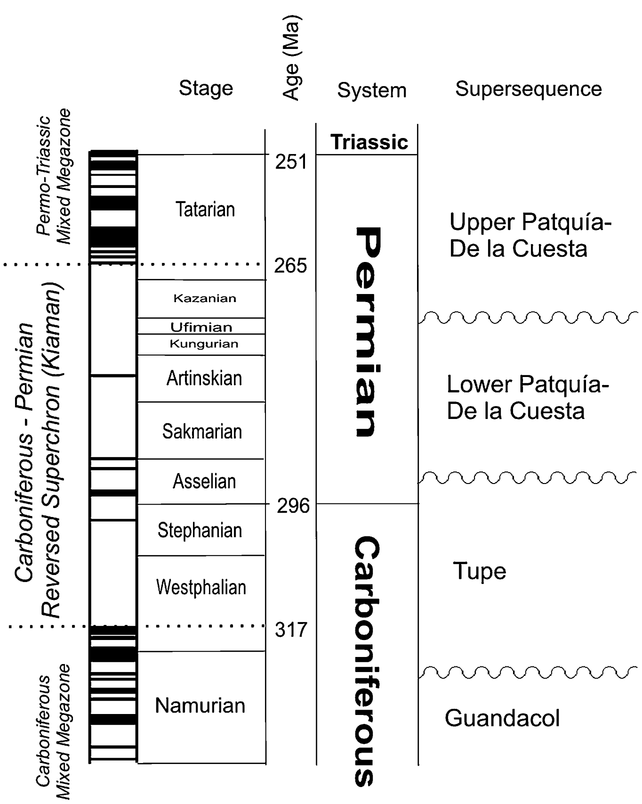

Figure 3. Megasequence framework for the Paganzo succession (from Fernández Seveso & Tankard 1995), referred to the modified Permian timescale of Menning (1995). The column to the left is the magnetostratigraphy, white (black) indicating reversed (normal) polarity zones.

Magmatic arc-related deposits in the western basin are linked with active subduction during the Late Palaeozoic, culminating in the San Rafael orogenic phase (SROP, Asselian, Llambías 1999). Effects of SROP in the western margin of Gondwana are reflected in a major erosion surface on which the Choiyoi magmatic province (280–240 Ma) developed. However, the SROP surface may not be readily identifiable where the Permian deformation is superimposed by Neogene (Andean) deformation, as in most of the western fringe of Argentina, especially where Choiyoi volcanics are absent. Recently Dávila *et al.* (2003) showed that cylindrical folding previously attributed to Andean deformation in the Famatina system (see location in Fig. 2), in fact, reflects episodic coaxial-coplanar fold amplification, Permian deformation being one of the most important episodes recorded. The SROP effects dilute eastwards and are limited to changes in subsidence rates in the eastern foreland basins (Fernández Seveso & Tankard 1995).

Extensional basins developed during the Triassic and Cretaceous (Uliana *et al.* 1990), after inversion at the end of the Permian. The Tertiary Andean orogeny created the present relief, in some cases by inversion of major structures and the development of tilt-block foreland basins with Neogene fill (Ramos 1999).

The burial depth of the Upper Palaeozoic sequences increases from east to west, as indicated by the thickness of overlying sequences and the compaction ratio. It correlates with a rise of diagenetic temperatures, as kaolinite, abundant in the eastern area, is replaced by a quartz, illite and chlorite-rich authigenic association in the west (Net 2002).

Permian sections of the Paganzo basin were sampled in two different settings (Fig. 2): two sections were located in the eastern Paganzo basin, on more stable areas of the craton, however, with limited exposures and poorly known ages. In contrast, a third section sampled in the Río Blanco depocentre is very well exposed and dated,

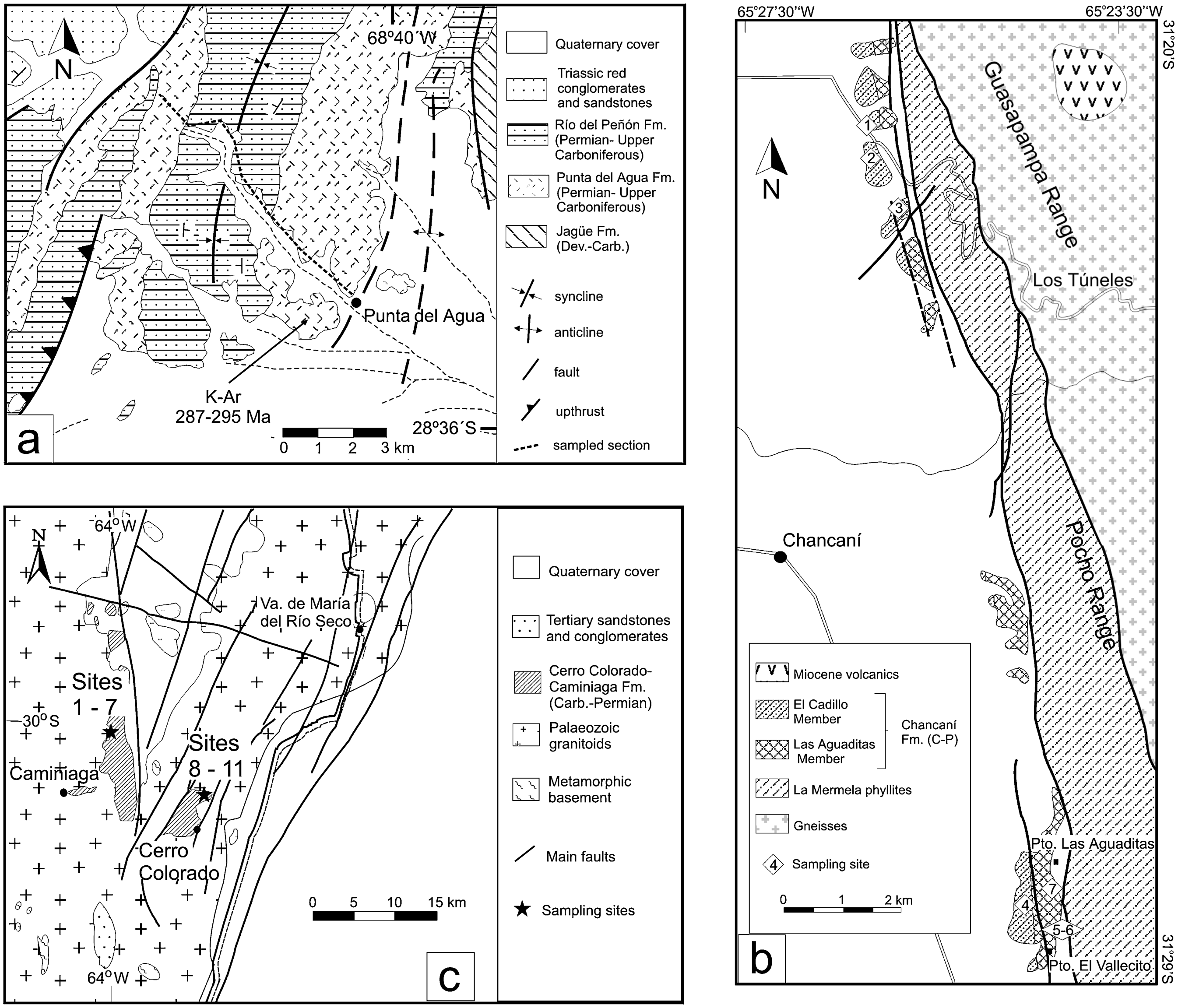

Figure 4. Geological maps, showing the location of the palaeomagnetic sections or sites: (a) Rincón Blanco syncline, modified from Fauqué *et al.* (1991); (b) Chancaní area, modified from Hünicken & Pensa (1980); (c) Cerro Colorado-Caminiaga area, modified from Lucero Michaut (1981).

however, situated in a less stable area, closer to the Palaeozoic–Present magmatic arc. More importantly, it contains an extensive record of a unique volcanic episode coeval with sedimentation.

Rincón Blanco syncline

The Río Blanco basin, a northwestern extension of the Paganzo basin (Fig. 2), has been active since the Early Carboniferous. Upper Carboniferous–Lower Permian units are clearly exposed in thick sequences, resting unconformably upon Lower Carboniferous marine sediments (Fig. 4a).

The Punta del Agua Formation (Aceñolaza *et al.* 1971) is a volcano-sedimentary complex interfingered near the base of the marine sedimentary rocks of the Río del Peñón formation (González & Bossi 1986) and represents one of the few records of simultaneous magmatic activity with the Upper Palaeozoic sedimentation (Caminos 1985). Although originally assigned to the Upper Carboniferous based on flora remains, an Early Permian age has been suggested recently, based on invertebrate fossil contents of Río del Peñón formation (Cisterna & Sabattini 1998) and on radiometric ages of 287 and 295 Myr for the uppermost andesitic flows of Punta del Agua formation (Fauqué *et al.* 1999). According to these, the sequence would represent the Upper Carboniferous–Lower Permian transition, or the western extension of the uppermost Tupe supersequence.

The Punta del Agua Formation is composed of andesitic and basaltic flows, with minor rhyodacite flows, volcanic breccias and agglomerates. The magmatic episode consists of an intrusive facies (represented by hypabyssal basic to intermediate bodies) and an effusive one, with more acidic products constituting a laterally discontinuous intercalation in the sedimentary sequence (Fauqué *et al.* 1991). Volcanic products are more abundant to the west, being replaced by volcaniclastic rocks to the east.

The Río del Peñón Formation begins with thick conglomeratic beds followed by coarse sandstones and siltstones. The sedimentary sequence is approximately 1200 m thick and it is composed of mudstones, fine sandstones and limestones, of characteristic greenish grey colour. The middle section exhibits a rich fauna constituting of brachiopods, bivalves, gastropods and ostracods. The upper section is distinguished by the presence of laminated black shales, lacking invertebrate remains.

The entire sequence was folded and is exposed now in the Rincón Blanco syncline. It is not clear whether the deformation was the result of the Andean orogeny (Tertiary) or to the SROP (Early Permian), however, the style of deformation, with broad folding, has led Caminos (1985), Fauqué *et al.* (1991) and Azcuy *et al.* (1999) to assign the deformation to the Permian.

Palaeomagnetic sampling was performed in the Rincón Blanco syncline, along the Peñón river (Fig. 4a). One hundred and twenty one hand samples were taken at 40 sampling sites, distributed over both limbs of the syncline (Fig. 4a). The Punta del Agua Formation sites were located in andesites, andesitic breccias and sandstones. The Río del Peñón Formation was sampled in the lower section, composed of mudstones and fine to mid-grained sandstones; a 70 m-thick dacitic sill intruding the lower sedimentary levels was sampled in the western limb of the syncline.

Chancaní

The Chancaní Formation outcrops in a narrow belt along the western border of the Córdoba Pampean ranges (Fig. 4b), in the footwall of the reverse fault that has thrust up the Pocho and Guasapampa ranges. The unit rests unconformably on phyllites of the La Mermela Formation (Precambrian) (Fig. 4b).

Two members have been recognized within the Chancaní formation: the lower one (Las Aguaditas Member) is composed of grey and greenish sandstones and mudstones and the upper one (El Cadillo Member) comprises mottled, red to pink quartz-sandstones. The Las Aguaditas Member contains plant remains of the Late Carboniferous and the colour variation along the members led Hünicken & Pensa (1980) to correlate them with the Paganzo I and II sections (Carboniferous Tupe and Permian Lower Patquía-De La Cuesta supersequences), respectively.

Outcrops, small and poorly exposed in a densely vegetated area, form a N–S trending asymmetric syncline, with axial plane inclined to the east (Hünicken & Pensa 1980). The thickest exposures, of 2–3 m, were found in small sandstone quarries.

Three sites were obtained in the lower grey section and four in the upper red one. Just one site could be recovered in the western limb of the syncline, gently dipping to the east; the other six sites were situated in the eastern limb, steeply dipping west. In addition, three sites were located within La Mermela phyllites.

Cerro Colorado-Caminiaga

Quartzitic red sandstones of the Cerro Colorado-Caminiaga formation (Lucero Michaut 1981) outcrop in Sierra Norte de Córdoba, covering approximately 60 km^2 (Fig. 4c). They are not fossiliferous, however, they have been considered temporal equivalents of the Chancaní Formation as a result of their lithological resemblance to the El Cadillo Member. However, the outcrops included in this unit are not homogeneous, but include a belt of grey and pink to reddish quartzitic sandstones in the east, bordering the range around Cerro Colorado, and red coarse sandstones in the west, near Caminiaga. Besides the darker colour, the latter differ from the former in being more friable and some authors have suggested that they could be younger (Cretaceous? Lucero Michaut 1981).

Oriented cylinders were drilled in a 50 m-thick outcrop in the eastern belt; the sequence here is mainly coarse-grained, however, four sites could be recovered in quartzitic mottled pink sandstones, massive or with crossed stratification. Another seven sites were obtained in the western area, near Caminiaga, five of them in friable coarse red sandstones and the remaining two in fine sandstones and brick-red mudstones.

LABORATORY PROCEDURES

Methods

At least three block samples or five core samples were taken from each site (lava flow or sedimentary bed). They were oriented using both Brunton and solar compasses whenever possible. Sedimentary units were used to determine the attitude of the sampled sections.

For palaeomagnetic measurements the samples were cut into specimens of 2.5 cm diameter and 2.2 cm length. Remanent magnetization was measured using a three-axis 2-G DC squid cryogenic magnetometer. Alternating field (AF) demagnetization was carried out to a maximum of 110 mT (peak) using a static 2G600 demagnetizer. Stepwise thermal demagnetization was performed using a Schonstedt TSD-1 thermal demagnetizer.

At least two specimens from each site were subjected to stepwise demagnetization, to examine the coercivity and blocking-temperature spectra of the natural remanent magnetization (NRM). As a general procedure, AF demagnetization was preceded by the application of heating to 150°C, to eliminate the effects of modern goethite, whereas thermal demagnetization was preceded by the application of low alternating fields (up to 10–20 mT) to minimize the soft components carried by multidomain magnetite. Bulk magnetic susceptibility was measured after each thermal step in order to monitor possible magnetic mineral changes.

The pilot specimens were used to determine which of the methods was the most effective for each site. At least three more specimens per site were treated to a minimum of five steps to determine the characteristic remanence magnetization (ChRM) by using principal component analysis (PCA, Kirschvink 1980).

A mean direction for each stratigraphic level was obtained by averaging magnetic components from specimens of each sedimentary bed or volcanic flow. In some cases, this procedure was performed by combining magnetic components with demagnetization circles (McFadden & McElhinny 1988). The single-stratigraphic-level directions within each section were averaged using standard Fisher (1953) statistics to obtain section-mean directions.

Isothermal remanent magnetization (IRM) up to 4 T was applied to selected samples to identify the minerals that carry the magnetization. In addition, hysteresis and low-field thermomagnetic curves were measured at the Instituto Astronomico e Geofisico, Universidade de Sao Paulo, Brazil. Hysteresis curves were measured at room temperature in a maximum field of 1 T, using a Molspin vibrating sample magnetometer; thermomagnetic curves were determined using a MS2WF furnace added to a MS2W Bartington susceptometer.

Results

Rincón Blanco

A total of 242 specimens (five to eight per site) were treated by alternating magnetic fields (AF) or thermal demagnetization. NRM intensities ranged between 2×10^{-2} and 5×10^{-1} A m^{-1} for the volcanics, 5×10^{-3} and 4×10^{-2} A m^{-1} for the volcaniclastics, and between 1×10^{-5} and 4×10^{-2} A m^{-1} for the sedimentary rocks.

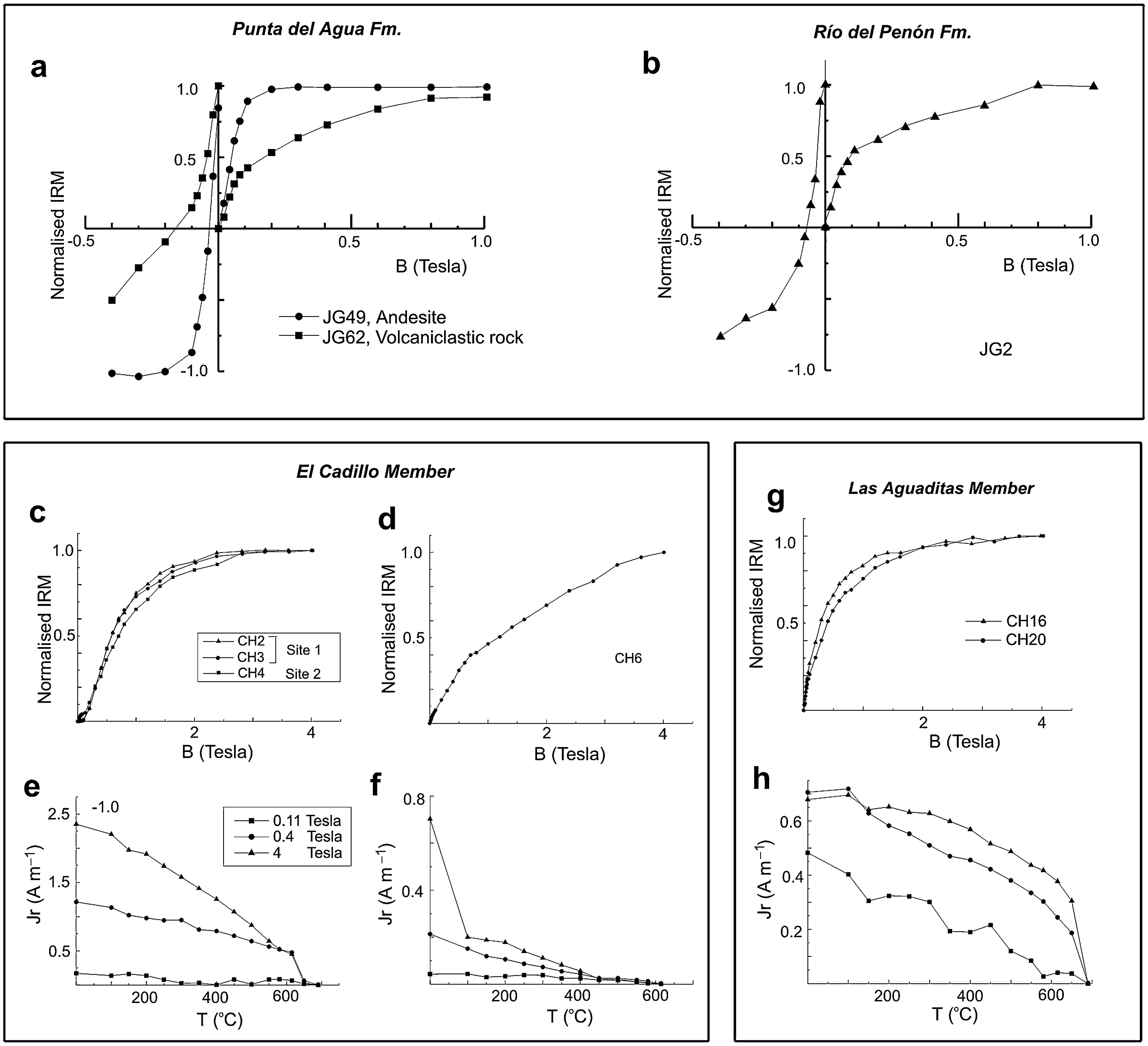

Figure 5. (a), (b), (c), (d) and (g) show acquisition of isothermal remanent magnetization and backfield demagnetization of SIRM for selected specimens, showing different combinations of magnetite and haematite as magnetic carriers; (d) is a sample containing goethite; (e), (f) and (h) show thermal demagnetization of composite IRM applied along three orthogonal axes (after Lowrie 1990) showing haematite, goethite and magnetite+goethite as carriers, respectively.

Volcanic and volcaniclastic rocks have magnetite as the main mineral carrier of the magnetization, with remanent coercive forces (Hcr) between 30 and 50 mT, and saturation isothermal remanent magnetization (SIRM) between 5 and 120 A m^{-1}. However, some samples have a high-coercivity phase as the main carrier and both phases (low and high coercivity) were observed in several sites (Fig. 5a). The dacitic sill intruded into the sedimentary Río del Peñón Formation (site 29 in Table 1) is strongly chloritized and kaolinized, and this is reflected in a very low SIRM (*ca* 0.2 A m^{-1}). This high alteration degree seems to be restricted to the sill, while no other site showed this alteration assemblage. Characteristic hysteresis and thermomagnetic curves are shown in Figs 6(a)–(b) and 7(a)–(b), respectively.

Sedimentary rocks of the Río del Peñón Formation are weakly magnetic. Magnetic response is controlled essentially by the paramagnetic fraction. They show a slight wasp-waisted loop after paramagnetic correction, reflecting a mixture of minerals (Fig. 6c). SIRM usually ranged between 0.05 and 0.2 A m^{-1} and most of the samples showed two-fraction IRM curves with a low and a high coercivity phase, interpreted as magnetite and haematite, respectively (Fig. 5b). The latter becomes dominant in the top of the sampled sequence, which progressively reddens upwards.

Both demagnetization methods (thermal and AF) revealed two components of NRM: a component (B) removed early and coincident with the present magnetic field, and a second more stable component (A) of positive inclination (Figs 8a–f). The A component usually showed coercive forces of up to 100 mT and unblocking temperatures of 580°C (magnetite). However, in several sites the same component showed higher unblocking temperatures, indicating that haematite is carrying the same characteristic direction (Fig. 8e). In

Table 1. Palaeomagnetic data from Rincón Blanco (La Rioja Province, lat. 28.6°S, long. 68.6°W).

Site	Li	Co	Cl	N	*In situ*		Strike/Dip	Palaeohorizontal		α_{95}	K	VGP	
					Dec.	Inc.		Dec.	Inc.			Lat. S	Long. E
					Punta del Agua Formation (volcanic-volcaniclastic rocks)								
S29	DS	A	1	9	249.3	34.7	20/56	186.4	56.4	8.4	38.2	−79.6	258.7
S28	AN	A	1	6	263.0	37.9	20/56	181.8	67.9	7.7	76.2	−67.7	288.1
S27	AB	A	2	5	214.8	59.7	20/56	146.8	36.3	19.2	34.6		
S26	AN	A	1	6	265.3	40.3	20/56	175.9	69.2	6.5	115.7	−65.2	298.4
S25	AN	A	2	6	272.7	31.3	20/56	207.1	75.4	8.3	82.7		
S24	AN	A	2	3	266.9	29.8	20/56	205.3	70.1	12.3	101.9		
S23	AN	A	1	6	256.1	32.8	20/56	192.4	61.8	10.8	42.8	−72.3	259.0
Mean*				4/7	258.1	36.7	20/56	184.3	63.4	7.6	146.9		
S21	AN	A	1	4	139.5	35.5	190/49	194.1	58.6	10.6	76.3	−74.7	250.5
S22	AN	A	2	5	151.9	59.8	190/49	238.9	53.2	12.1	62.4		
S20	FGS	A	1	6	127.0	41.7	190/49	201.8	69.8	9.0	60.8	−60.6	265.8
S19	AN	A	2	3	145.7	40.5	190/49	205.6	55.7	27.2	21.6		
S18	LP	A	1	6	127.9	42.1	190/49	202.0	69.1	7.1	88.5	−60.8	263.3
S17	LP	A	1	4	148.8	23.9	190/49	182.9	46.0	4.3	448.5	−87.3	176.0
S16	AN	A	1	6	130.5	18.3	190/49	158.4	54.9	11.9	32.6	−70.2	354.1
S15	LP	A	2	3	124.1	45.7	190/49	214.1	72.0	18.2	46.8		
S14	LP	A	1	7	126.1	50.7	190/49	228.0	69.5	10.6	33.5	−47.8	250.7
Mean*				6/9	134.2	35.8	190/49	189.8	62.5	12.2	31.0		
Mean Punta del Agua Fm.*													
	In situ			10	176.1	55.6				33.6	3.0		
	Corrected			10				187.6	62.9	7.0	48.9		
					Río del Peñón Formation (sedimentary rocks)								
S40	FGS	A	1	6	262.2	48.3	20/56	157.7	64.9	14.3	22.8	−64.3	329.9
S35	BM	A	1	5	251.4	52.2	20/56	155.1	56.8	9.9	64.5	−67.0	351.7
S39	MGS	A	1	6	231.9	42.9	20/56	170.6	44.6	14.1	23.6	−81.5	35.5
S37	MGS	A	2	2	258.2	32.6	20/56	193.1	63.4	–	–		
S38	MGS	A	2	2	263.6	29.4	20/56	205.6	67.3	–	–		
S32	CGS	A	2	2	239.7	23.9	20/56	199.3	45.6	–	–		
S31	BM	A	1	8	273.9	46.1	20/56	150.6	72.9	7.7	51.9	−54.0	317.7
Mean*				4/7	254.5	48.3		160.0	59.2	14.6	40.4		
S1	FGS	A	1	6	145.3	25.0	190/49	181.0	49.5	4.9	189.5	−88.1	257.6
S2	FGS	A	1	6	137.8	27.9	190/49	179.3	56.4	10.9	38.4	−81.5	296.2
S3	FGS	A	2	2	145.0	31.2	190/49	189.1	52.7	–	–		
S4	FGS	A	2	6	161.4	23.8	190/49	191.2	36.9	11.3	41.1		
S6	FGS	A	1	6	135.3	26.2	190/49	173.6	57.5	8.5	63.1	−79.4	317.1
S7	FGS	A	2	4	173.2	36.6	190/49	211.5	34.8	23.6	56.9		
S8	FGS	A	2	5	142.7	53.5	190/49	227.4	58.9	12.4	49.9		
S9	FGS	A	1	4	137.2	35.6	190/49	192.3	60.8	12.6	60.2	−73.9	258.1
S10	FGS	A	1	6	132.6	26.9	190/49	173.1	59.5	11.2	36.5	−76.6	316.3
S11	FGS	A	2	2	101.5	23.5	190/49	106.2	72.9	–	–		
Mean*				5/10	137.6	28.5		179.5	56.4	5.7	182.9		
Mean Río del Peñón F.*													
	In situ			9	173.7	53.3				33.2	3.4		
	Corrected			9				171.7	58.7	6.7	39.4		
Mean West Limb*				8	256.5	42.5		171.4	61.9	7.9	49.9		
Mean East Limb*				11	135.8	32.4		184.6	59.8	6.7	47.8		
Total mean*:													
	In situ			19	174.9	54.5				21.8	3.4		
	Corrected			19				179.3	60.8	4.9	47.2	−77.0	294.0

* Mean based only on class 1 sites (ChRMs determined by PCA, sometimes combined with remagnetization circles, see text).
Li: lithology; AN: andesitic flow; AB: andesitic breccia; DS: dacitic sill; LP: lapillite; CGS: coarse gray sandstone; MGS: medium grey sandstone; FGS: fine gray sandstone; BM: brown mudstone.
Co: magnetic component; Cl: classification of magnetic behaviour (see text); N: number of specimens used in statistics; strike and dip by right-hand convention; α_{95}: 95 per cent confidence circle; K: Fisher (1953) precision parameter; VGP: virtual geomagnetic pole.

these cases, the directions of the magnetite and haematite components are indistinguishable.

The direction of the A component was determined with a maximum deviation angle of 10° in 132 specimens (55 per cent of the collection; Table 1). In another 31 specimens, the A and B components could not be completely resolved and demagnetization circles were used. The circles were combined with the remanence directions obtained in other specimens by the McFadden & McElhinny (1988)

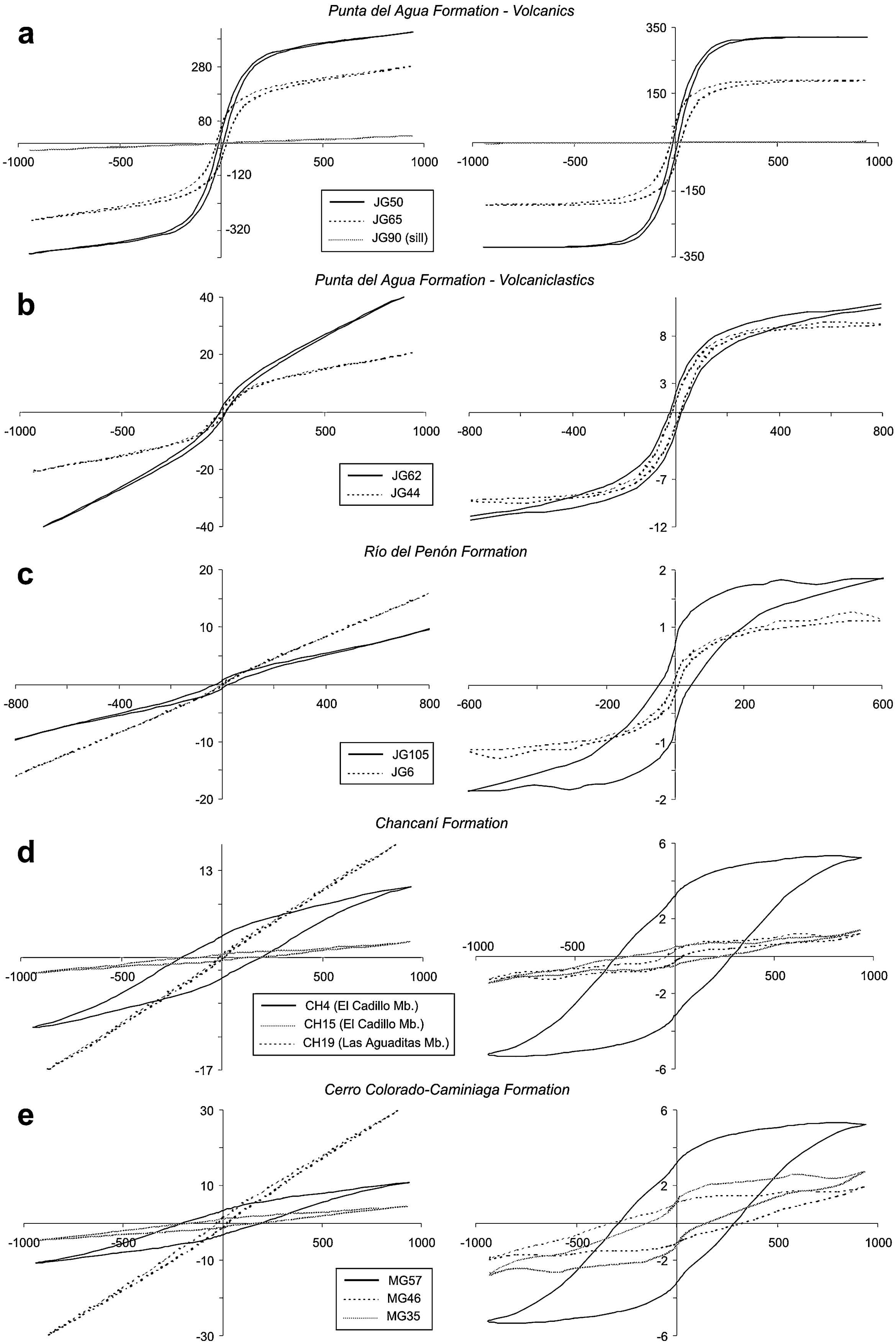

Figure 6. Typical hysteresis curves: (X-axis) applied field in millitesla; (Y axis) magnetic moment in μ A m^2. Curves to the right are corrected for paramagnetic content.

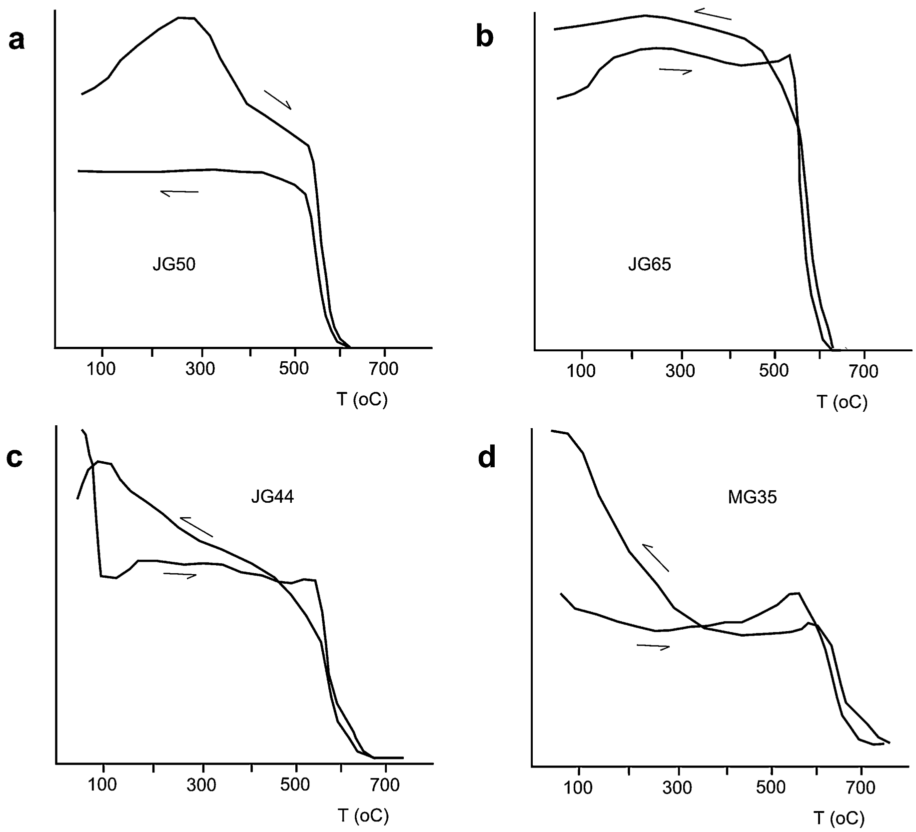

Figure 7. Typical low-field thermomagnetic (k-T) curves, with a heating rate of 30° min^{-1}. Heating and cooling thermomagnetic curves after subtraction of paramagnetic susceptibility. (a) and (b) Volcanic rocks from Punta del Agua Formation. (c) Volcaniclastic rock from Punta del Agua Formation. (d) Pink quartz-sandstone from Cerro Colorado-Caminiaga Formation.

method. The 79 remaining specimens (33 per cent of the processed specimens) did not provide stable directions. These are mainly sedimentary specimens whose magnetization intensities fell quickly below 10^{-7} A m^{-1}.

The dacitic sill and its country rock recorded the same characteristic downward-inclination component as the rest of the sequence. Unfortunately, the medium to coarse sandstones surrounding the sill carried A and B components with overlapping unblocking-temperature spectra. The precise unblocking temperature of component A in these sandstones could not be resolved by thermal demagnetization and no baked-contact test was possible.

Thirty-three sites carried an A component as a characteristic remanence, the remaining sites carrying unstable or present magnetic field (PMF) magnetization. However, an A component could be more confidently isolated in some sites by using combined minimum least squares and remagnetization circles (group 1, Table 1). Sites named 2 in Table 1 are those with a high number of specimens discarded, or in which just demagnetization circles were used (with no determination of reference direction by PCA). Because the Group 2 directions have a higher dispersion than Group 1, only the latter were used for the following analysis (Table 1).

Fig. 9(a) shows the directions of the A components, sites of Group 1 quality, before and after restoration to the palaeohorizontal. The fold test (McFadden & Jones 1981) is clearly positive, which indicates that the beds acquired their magnetization before they were folded. The mean direction after unfolding is Dec. 179.3, Inc. +60.8, α_{95} 4.9 and the corresponding palaeomagnetic pole is Lat. 75°S, Long. 291.5°, $A_{95} = 6.7$, $N = 19$ [Rincón Blanco (RB) in Fig. (10)].

Chancaní

Sixty-five standard specimens were demagnetized. NRMs usually ranged between 1.5×10^{-4} and 8×10^{-3} A m^{-1} for the Chancaní Formation, with site 1 (western limb) having the highest NRM values, between 5×10^{-3} and 2×10^{-2} A m^{-1}.

IRM curves indicated haematite as the magnetic mineral in the red El Cadillo Member (Figs 5c and e) except for site 3, which contained goethite (Figs 5d and f) and haematite plus magnetite as carriers in the grey Las Aguaditas Member (Figs 5g–h). Thermal demagnetization of composite IRM applied along three orthogonal axes (Lowrie 1990) shows that the magnetite fraction is virtually absent in the El Cadillo Member, however, it is present in the Las Aguaditas Member (Figs 5e and h).

Demagnetization procedures on El Cadillo samples isolated a characteristic magnetic component of high unblocking temperature, between 650 and 680°C (A), after removing a very soft component (which will be called C) in fields lower than 10 mT (Fig. 11a). In contrast, Las Aguaditas samples carried a soft magnetic component (C), superimposed on a very stable component that could not be successfully removed as a result of the formation of a new magnetic phase above 580°C, as reflected in a sudden increase of the magnetic susceptibility (Figs 11b and d, Table 2).

The only site recovered in the western limb of the syncline (site 1) showed a characteristic magnetization with negative inclination, near to the PMF direction; goethite-bearing site 3 showed unstable behaviour. Only two sites of the El Cadillo Member (sites 2 and 4) showed a remanence direction that recorded an ancient magnetic field. As for the Las Aguaditas Member, we could not determine

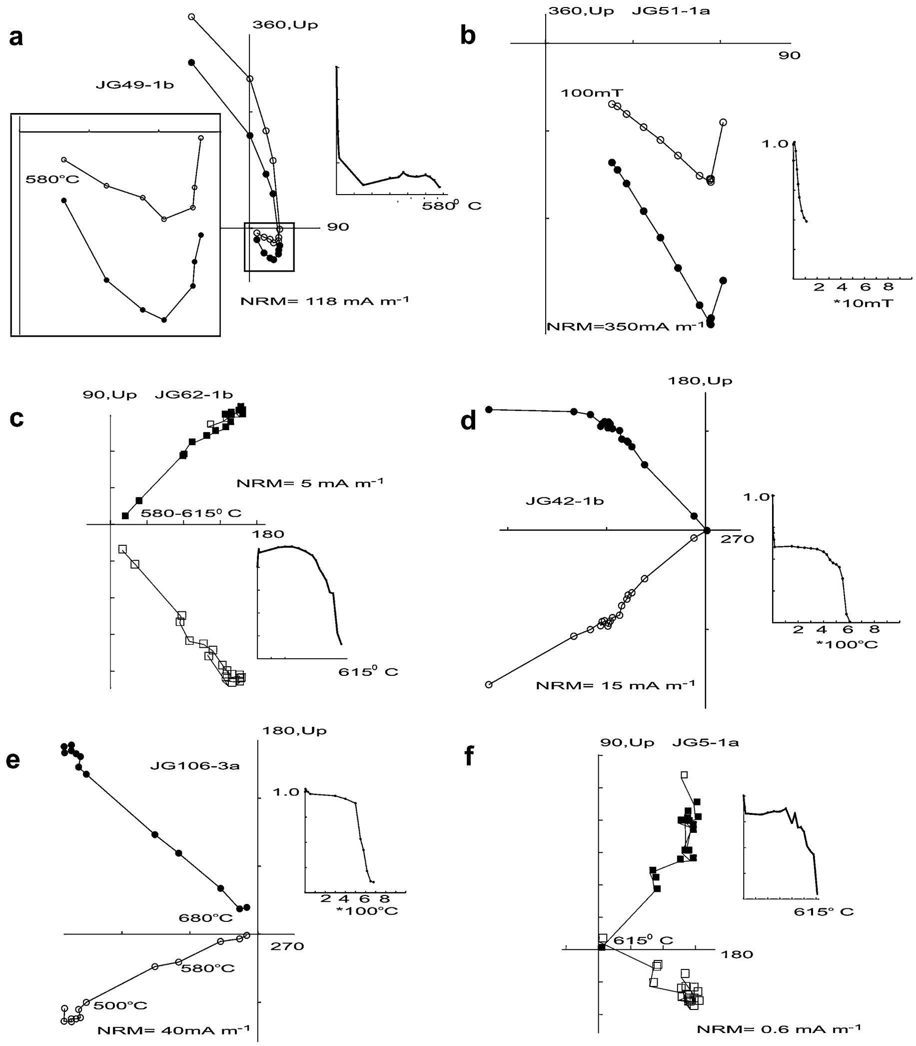

Figure 8. Examples of typical demagnetization behaviour in the Rincón Blanco area. Open (solid) symbols indicate projection onto the vertical (horizontal) plane. (a) and (b) Volcanic rocks from Punta del Agua Formation. (c) and (d) Volcaniclastic rocks from Punta del Agua Formation. (e) and (f) Sedimentary rocks from Río del Peñón Formation (JG106, reddened sandstone).

ChRMs decreasing towards the centre of the coordinate system, as a result of the growth of a new magnetic phase. Instead, we obtained very stable directions above 400°C (Fig. 11b). Site 5, consisting of coarse sandstones, showed very scattered directions, and site 7 (mudstones) showed a single component with low unblocking temperatures and low coercive force (C). For all the sites, the A and C components were roughly opposite (not antipodal) in the NW and SE quadrant of the Wulff projection, as seen in Fig. 9(b). These results are discussed below.

La Mermela phyllites unconformably underly the Chancaní strata and were sampled to evaluate the possibility of remagnetization with the overlying unit. They showed a characteristic magnetic component contained in the foliation plane and near the lineation direction, isolated using either AF up to 100 mT or thermal demagnetization up to 580°C. A second magnetic component in the direction of PMF, presumably carried by goethite, was eliminated by 150°C.

Cerro Colorado-Caminiaga

Seventy one specimens were submitted to thermal demagnetization, after establishing that AF treatment was ineffective in demagnetizing the NRMs, which had intensities ranging between 3×10^{-3} and 10^{-1} A m^{-1}. The characteristic magnetization in all of the samples was unblocked between 640 and 680°C, which points to haematite as the carrier mineral of the remanence. However, Cerro Colorado sandstones showed discrete unblocking temperatures, while Caminiaga sandstones exhibited a steady decrease in intensity above 500°C until the final drop-out (Figs 11e–f).

Directions of characteristic magnetization were clearly distinct: Cerro Colorado sandstones showed very low in-site dispersion, with steep positive inclinations. On the other hand, Caminiaga coarse sandstones carried more dispersed magnetizations with shallower negative inclination. Magnetic directions from the two lithologic groups are not antipodal (Fig. 9c): moreover, some of the samples from Caminiaga appear to carry a subtle high-temperature component that could not be properly isolated. Conversely, the two fine-grained sites from Caminiaga showed the same positive inclination magnetization direction found in Cerro Colorado sandstones (Fig. 9c, Table 3).

DISCUSSION

The positive inclination of the directions of magnetic remanence in Rincón Blanco reflects a reversed polarity of the geomagnetic

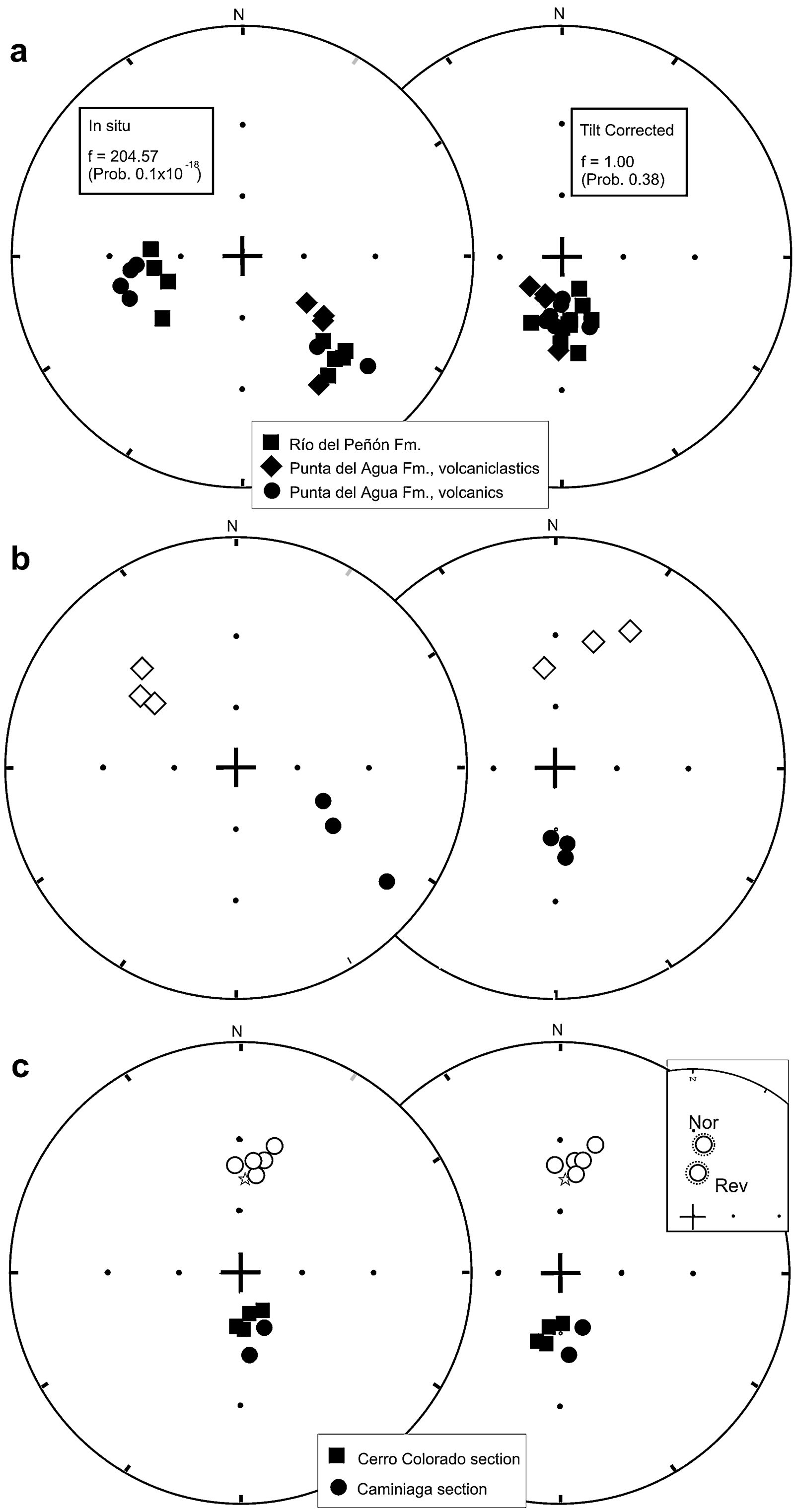

Figure 9. Palaeomagnetic directions, A component before (left) and after (right) structural correction to restore them to palaeohorizontal. (a) Rincón Blanco syncline. (b) Chancaní. Diamonds: C component (see text). (c) Cerro Colorado-Caminiaga. Inset depicts a negative reversal test for these palaeomagnetic data (reversed directions inverted into normal directions). The star indicates the present field dipole.

field, consistent throughout the whole studied succession (volcanics and sedimentary rocks). The positive fold test (Fig. 9a) clearly indicates that the remanence was acquired before the deformation. If we follow Caminos (1985), Fauqué *et al.* (1991) and Azcuy *et al.* (1999), considering that at least part of the folding was produced by SROP (Early Permian), the remanence would have been acquired very early and should be considered primary. However, if the folding was entirely caused by the Andean orogeny (Tertiary), we cannot rule out a pre-folding remagnetization based only on the positive fold test.

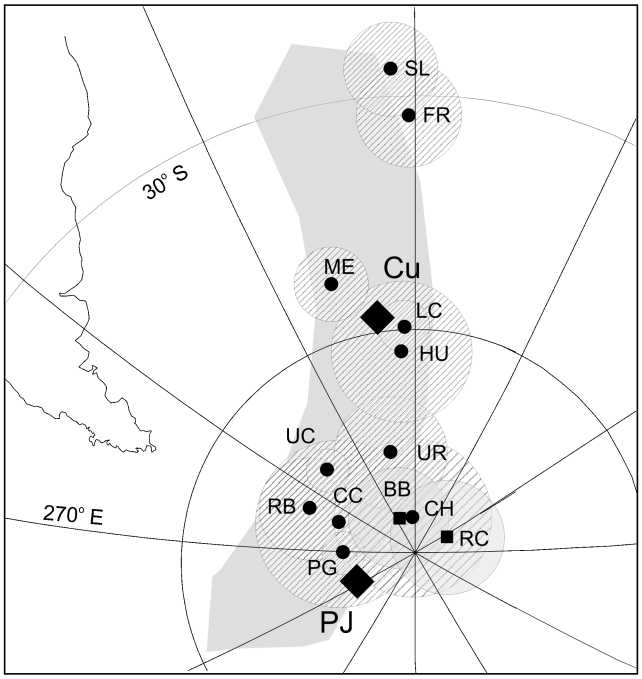

Figure 10. Palaeomagnetic poles of CPRS age from the Paganzo basin, including A_{95} confidence circles. See pole labels from Table 4. Wulff projection, southern hemisphere. Circles belong to all-reversed polarity localities; squares (BB and RC) are poles based on two polarities, interpreted here as remagnetized poles. Diamonds are Cu group (Late Carboniferous–Early Permian) and PJ group (Permo-Jurassic) from Vilas (1981). Shaded arc is the approximate small circle described by applying a rotation around a vertical axis situated in Paganzo basin.

Burial diagenesis has been connected to remagnetization, either by viscous overprinting at elevated temperatures or by the creation of a CRM residing in authigenic magnetite related to the alteration of smectite to illite (Katz *et al.* 1998). Illite has been described by Net (2002) as cementing the sandstones of Río del Peñón Formation. No systematic difference in inclinations was observed between sedimentary and volcanic rocks, which means either that there was no inclination-shallowing induced by compaction, or that magnetite is not detrital, but related to illite authigenesis. The age and duration of diagenetic processes are not documented: however, the characteristic reverse magnetic direction is carried by either magnetite or haematite in all of the present lithologic types and along the whole stratigraphic column (1500 m-thick), suggesting that the magnetization process was entirely completed during the Permo-Carboniferous reverse superchron (PCRS).

The Chancaní Formation yielded a small number of useful sites. A fold test is not significant in this situation, however, it is noticeable that K improves with fold correction for the high temperature component (A). This is not so for the low temperature C directions, however, it is noteworthy that *in situ* C directions do not match any possible direction of the magnetic field younger than Late Palaeozoic: instead, tilt-corrected C directions are closer to Mesozoic and younger directions of magnetization (Fig. 9b). We, thus, suspect that both components are pre-tectonic and consequently pre-date the Andean orogeny. We cannot establish whether they are primary or secondary. The underlying La Mermela phyllites show a different magnetic carrier (magnetite) whose direction of remanence is strongly influenced by the metamorphic fabric, acquired during the Cambrian following Rapela *et al.* (1998).

In the Cerro Colorado-Caminiaga Formation, we also found two components of magnetization, one of them, of positive inclination, present in finer-grained or well-cemented sites, and the other, of negative inclination, present in coarse and poorly-cemented red sandstones. The two components are not antipodal. We, thus, interpret that coarser grained rocks, because of higher permeability, have been remagnetized. The site means of the positive-inclination component are strikingly coincident with those from the stratigraphically correlative Chancaní Formation (Fig. 9c).

The reverse polarity suggests that rocks from the three localities sampled acquired their remanence during the PCRS (*ca* 315 to 265 Ma; Menning 1995) (Fig. 3). The geological age of the Río del Peñón and Punta del Agua Formations is Late Carboniferous–Early Permian on the basis of fossils and radiometric studies (Tupe supersequence); Chancaní and Cerro Colorado-Caminiaga Formations are considered to be Carboniferous–Permian on the basis of plant remains from Las Aguaditas Member (Tupe and Lower Patquía-De la Cuesta supersequences).

The expected pole position for this time period is difficult to assess because of the scarcity of reliable poles (Fig. 12a). However, most of the African and Australian poles from the PCRS fall near the Late Carboniferous (Cu) Group identified by Vilas (1981) when rotated to South American coordinates using the parameters of Lottes & Rowley (1990) and Ricou *et al.* (1990), respectively (Figs. 12b and c).

The palaeomagnetic poles obtained for the A component from Rincón Blanco (RB), Chancaní (CH) and Cerro Colorado-Caminiaga (CC) do not agree with the Cu position (Fig. 10). Instead, they are closer to other poles calculated on all-reverse polarity sequences from stable areas of the adjacent Paganzo basin: Upper Los Colorados (UC, Embleton 1970a) and Paganzo village (PG, Valencio *et al.* 1977). These poles have been previously considered younger than the quasi-static group, reflecting a period of fast displacement of west Gondwana (Oviedo & Vilas 1984; Rapalini & Vilas 1996) before the end of the PCRS, in the late Early Permian.

This fast displacement during the Early Permian does not seem to be reflected either in the African or in the Laurasian APWP. Laurasian poles follow a smooth pattern without quasi-statics, as it was noted by Smith (1999) and McElhinny & McFadden (2000).

Instead, RB, CH, CC, UC and PG poles resemble a younger position when compared with the presently accepted South American APWP, suggesting remagnetization as invoked by Smith (1999) and McElhinny & McFadden (2000). However, younger positions are not consistent with a PCRS age based on the all-reverse magnetostratigraphy.

This contradiction can be resolved by re-analysing carefully the PCRS poles (Late Carboniferous-Early Permian) in the Paganzo Basin, in the light of updated geological information.

PCRS Paganzo palaeopoles

The PCRS is a long interval of about 50 Myr, during which the geomagnetic field maintained nearly constant reverse polarity. Recent workers place the lower limit of the PCRS between 318 and 311 Ma (Opdyke *et al.* 2000; Buchan & Chandler 1999) and the upper limit at approximately 265 Ma (Westphalian to Early–Late Permian; Menning 1995) (Fig. 3). Thus, deposition of the Tupe, Lower Patquía-De la Cuesta and part of the Upper Patquía-De la Cuesta supersequences in the Paganzo basin (Fig. 3) occurred entirely within the PCRS. In fact, just one pole (Bum Bum Mine, Thompson 1972) was

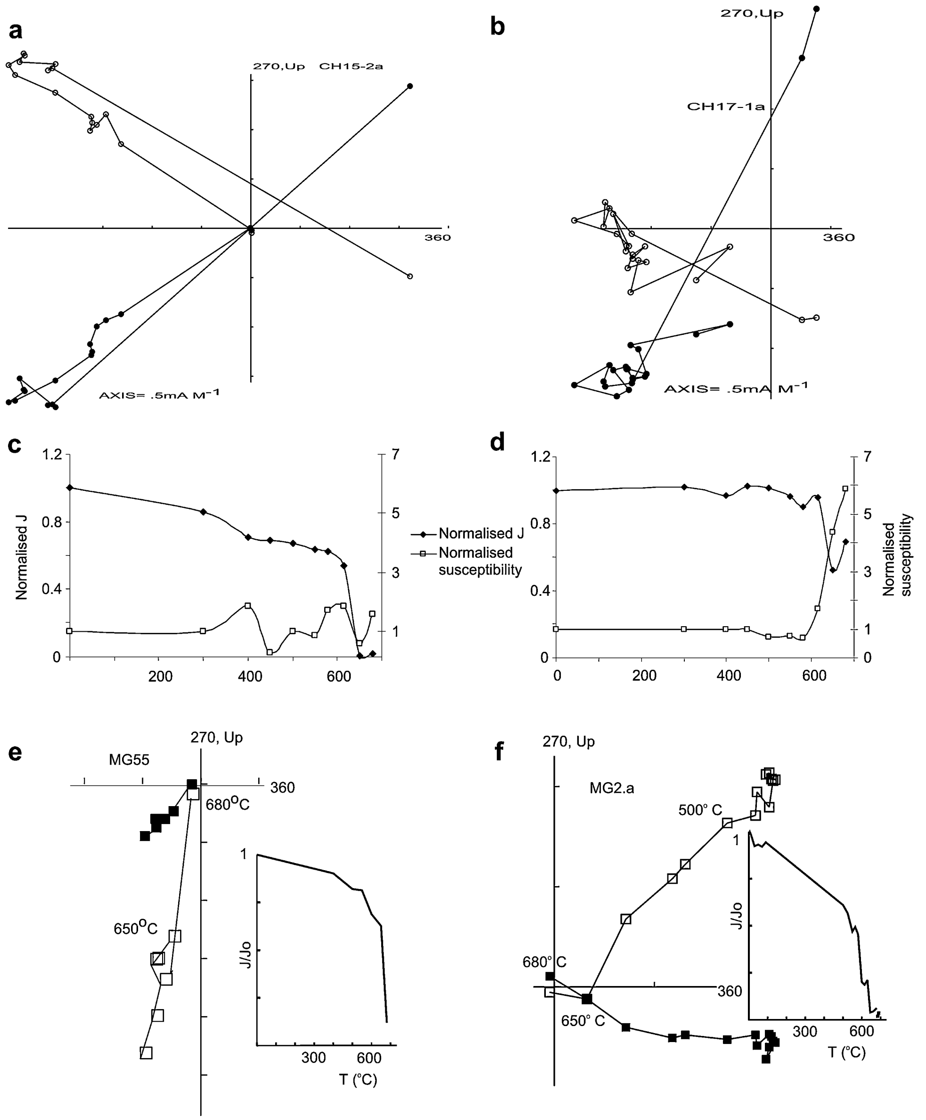

Figure 11. Examples of typical demagnetization behaviour in Chancaní and Cerro Colorado-Caminiaga areas. Open (solid) symbols in orthogonal diagrams indicate projection onto the vertical (horizontal) plane. (a) Pink mottled sandstone from El Cadillo Member. (b) Grey sandstone from Las Aguaditas Member. (c) and (d) Variation of magnetic susceptibility with temperature along the demagnetization of (a) and (b), respectively. (e) Pink quartz-sandstone from Cerro Colorado area. (f) Red sandstone from Caminiaga area.

calculated for the Tupe supersequence, the remaining poles belonging to palaeomagnetically more suitable red beds from Lower Patquía-De la Cuesta supersequence.

The PCRS poles of the Paganzo basin are summarized in Table 4. Most of the poles were published 30 yr ago and many are based on relatively scarce sampling, or not well documented demagnetization procedures. However, several of the localities show well-grouped NRMs with reversed polarity (e.g. Huaco and Los Colorados, Embleton 1970a) and the remanence directions do not change during demagnetization. Strikingly, Huaco (HU) and Lower Los Colorados (LC) poles are the only PCRS poles from the Paganzo basin falling near the expected direction, around the Cu group, *ca* 350°E and 60°S (Fig. 10).

Some other poles [Río Francia (FR) and Km 114 (SL)] can only be explained as a product of tectonic rotations, as was pointed out by Buggisch *et al.* (1993) and Rapalini & Mena (2001). Both poles come from the present Precordillera (Fig. 2), an area subjected to important thin-skin deformation since the Late Palaeozoic and, particularly, during the Andean orogeny. These poles will not be analysed further.

The remaining PCRS poles are suspiciously concentrated around the geographic pole, which has been the basis for remagnetization hypotheses. However, most of them are based on exclusively reverse polarity sequences, some of them of considerable thicknesses. The discrepancy among poles is especially striking in two cases: (i) Lower versus Upper Los Colorados (Embleton 1970a; Thompson 1972), (ii) Paganzo Village (Thompson 1972; Valencio *et al.* 1977) vs. Las Mellizas Mine (Sinito *et al.* 1979).

Los Colorados

Embleton (1970a) obtained 53 hand samples along a continuous homoclinal red-bed section in La Colina Formation (Permian). He noted a change in the directions of magnetization about halfway

Table 2. Palaeomagnetic data from Chancaní (Córdoba Province, lat. 31.3°S, long. 65.4°W).

Site	Li	Co	Cl	N	*In situ*		Strike/Dip	Palaeohorizontal		α_{95}	K	VGP	
					Dec.	Inc.		Dec.	Inc.			Lat.	Long.
El Cadillo Member (pink and reddish sandstones)													
S1	MRS	B#	1	10	350.2	−47.9	5/27	327.9	−35.7	3.8	163.1		
S2	MRS	A	1	4	127.6	10.5	181/69	170.2	53.3	9.2	101.1	−81.4	4.9
S4	MRS	A	1	7	122.0	38.2	157/50	173.0	48.0	9.5	41.6	−85.4	28.6
S4	MRS	C	1	7	315.7	−29.1	157/50	27.7	−24.2	4.6	169.2	−58.4	174.5
Las Aguaditas Member (grey and greenish sandstones and siltstones)													
S6	FGS	A	1	9	112.3	45.8	157/50	182.3	56.7	11.1	25.8	−83.7	277.7
S5	FGS	A	2	4	144.1	26.3	157/50	170.6	26.0	17.2	29.3	−70.4	86.5
S5	FGS	C	1	8	304.5	−35.1	157/50	349.9	−44.9	5.9	89.0	−79.9	50.6
S7	GM	C	1	7	306.7	−41.8	156/73	15.2	−32.9	12.8	23.0	−70.7	163.9
Mean A component*													
	In situ			3/8	127.5	30.7				22.0	18.4		
	Corrected			3/8				174.8	52.8	8.8	195.6	−85.2	358.6
Mean C component*													
	In situ			3/8	309.2	−35.4				12.3	101.6	−43.0	26.1
	Corrected			3/8				358.3	−37.8	21.2	34.7	−74.4	159.2

Interpreted as modern remagnetization, see text.
See Table 1 for explanations.
Li: lithology; MRS: medium red sandstone; FGS: fine gray sandstone; GM: grey mudstone.

Table 3. Palaeomagnetic data from Cerro Colorado-Caminiaga (Córdoba Province, lat. 30.0°S, long. 64.0°W).

Site	Li	Co	Cl	N	*In situ*		Strike/Dip	Palaeohorizontal		α_{95}	K	VGP	
					Dec.	Inc.		Dec.	Inc.			Lat.	Long.
Caminiaga (Medium red sandstones)													
S1	MRS	B	1	11	6.4	−45.7	Subhoriz.	6.4	−45.7	6.5	49.7	−83.6	181.0
S2	MRS	B	1	6	354.4	−41.6	Subhoriz.	354.4	−41.6	14.5	22.2	−82.2	75.7
S3	MRS	B	1	8	13.7	−32.5	Subhoriz.	13.7	−32.5	11.0	26.1	−72.4	164.8
S4	MRS	B	1	11	9.3	−39.5	Subhoriz.	9.3	−39.5	6.4	51.4	−78.7	166.1
S5	MRS	B	1	4	5.3	−40.1	Subhoriz.	5.3	−40.1	18.2	26.3	−81.4	151.3
Mean B component				5/5				6.1	−40.1	6.9	123.7	−81.2	154.6
Caminiaga (Red mudstones)													
S6	BM	A	1	4	156.4	61.1	Subhoriz.	156.4	61.1	7.8	137.9	−67.5	346.5
S7	FRS	A	1	6	173.0	50.3	Subhoriz.	173.0	50.3	12.9	27.8	−83.9	13.8
Cerro Colorado (Quartz-cemented pink sandstones)													
S8	FPS	A	1	5	180.8	64.1	147/12	196.5	56.0	15.5	25.2	−74.7	236.1
S9	FPS	A	1	4	177.6	63.4	147/12	193.7	55.8	5.9	241.1	−76.9	238.8
S10	FPS	A	1	6	148.5	68.4	147/12	175.8	65.1	5.3	160.1	−72.5	305.3
S11	FPS	A	1	6	166.8	69.8	147/12	190.6	63.3	4.0	279.0	−72.9	269.5
Mean A component				6/6				181.4	59.4	8.0	70.9	−79.3	290.6

See Table 1 for explanations.
Li: lithology; MRS: medium red sandstone; FRS: fine red sandstone; FPS: fine pink sandstone; BM: brown mudstone.

through the sequence and, for that reason, calculated two different poles, named *estratos inferiores* (lower strata) and *estratos superiores* (upper strata). Thompson (1972) continued the sampling upwards, through the unconformity which separates La Colina from the overlying Amaná Formation (Triassic), and recalculated the Upper Los Colorados pole adding the new sites from the top of La Colina Formation (UC in Fig. 10).

However, the precise position of the unconformity has not been established (see table 2 in Thompson 1972). It is possible that the upper strata are, in fact, Triassic in age. Suggestively, the pole calculated for the upper strata is similar to that obtained in the uppermost Triassic section. Embleton (1970a) noted that the upper strata differ from the lower strata in having lower remanence intensity by one order of magnitude (3 vs. 40×10^{-3} A m^{-1}), which marks a lithological difference probably related to the unconformity and may have not been noticeable in the field.

Paganzo village and Las Mellizas mine

These two sections belong to the La Colina Formation and occur within the same district, although separated by 25 km (Fig. 13). Azcuy & Morelli (1970) correlated them because they are bounded by the same units (Upper Carboniferous Lagares Formation at the base and Triassic Amaná Formation above) and contain similar basaltic intercalations. The 5 m-thick basaltic flows from both localities were used by Thompson & Mitchell (1972) to calculate a palaeomagnetic pole. Radiometric K/Ar ages on the basalts were not the same (295 Ma in Las Mellizas and 266 Ma in Paganzo,

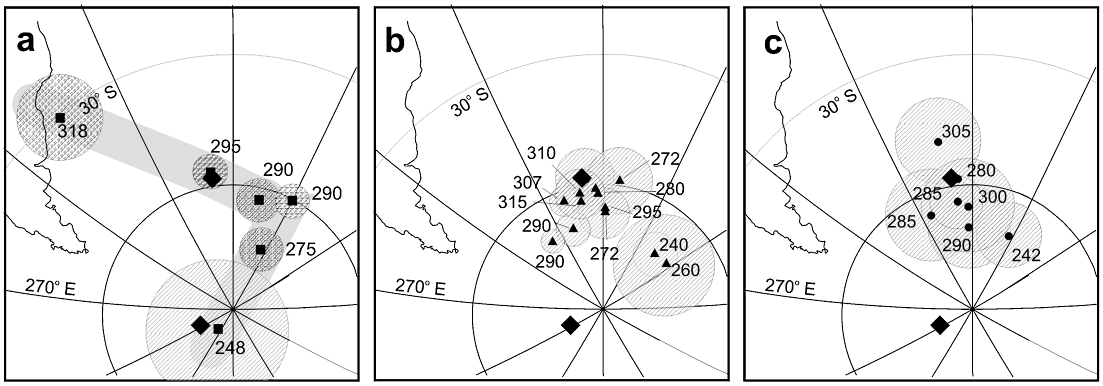

Figure 12. (a) Apparent polar-wander path for South America, adapted from Tomezzoli (2001). Poles from Paganzo basin have been excluded. (b) Late Palaeozoic poles from Africa, transferred to South American coordinates using Lottes & Rowley (1990) reconstruction parameters. (c) Late Palaeozoic poles from Australia, transferred to South American coordinates using Ricou *et al.* (1990) reconstruction parameters. Numbers are ages in Myr.

Table 4. Carboniferous–Permian reverse superchron poles from the Paganzo basin.

*	Code	Locality	MS	Geological unit	Stratigraphical age	Radiometric age	Pol.	Palaeomagnetic pole					References
								Lat.	Long.	N	α_{95}	K	
1	RC	Río Chaschuil	UP	De la Cuesta Fm.	251–274 (1)		M	−85.0	64.0	21	7.6		Thompson (1972)
2	UC	Upper Los Colorados	LP	La Colina Fm.	274–293 (1)		R	−74.0	313.0	27	4.5		Thompson (1972)
2	LC	Lower Los Colorados	LP	La Colina Fm.	274–293 (1)		R	−59.5	357.5	26	3.5	72.7	Embleton (1970a)
3	HU	Huaco	LP	Patquía Fm.	274–293 (1)		R	−63.0	356.0	9	9.5	29.2	Embleton (1970a)
4	PG	Paganzo	LP	La Colina Fm.	274–293 (1)	259–273 (2)	R	−80.6	268.8	162	2.8	16.2	Recalculated after Embleton (1970b); Thompson (1972) and Valencio *et al.* (1977)#
5	ME	Las Mellizas	LP	La Colina Fm.	274–293 (1)	290–300 (3)	R	−52.4	341.6	63	4.9	14.5	Recalculated after Thompson & Mitchell (1972a) and Sinito *et al.* (1979)#
6	SL	Km 114	LP-TU	Del Salto Fm.	274–310 (1)		R	−26.8	357.0	8	5.4		Rapalini & Mena (2001)
7	RB	Rincón Blanco	TU	Punta del Agua-Río del Peñón Fms.	274–310 (1)	287–295 (4)	R	−75.0	291.5	19	6.7	25.9	This paper
8	CC	Cerro Colorado	?	Cerro Colorado-Caminiaga Fm.	251–320		R	−79.3	290.6	6	11.0	37.8	This paper
9	CH	Chancaní	?	Chancaní Fm.	251–320		R	−85.2	358.6	3	10.3		This paper
10	UR	Río Uruguay	?	Guandacol-Tupe-Patquía Fms.	251–320		R	−76.3	346.1	9	7.6	33.8	Buggisch *et al.* (1993)
11	FR	Río Francia	?	Guandacol-Tupe-Patquía Fms.	251–320		M	−32.4	359.1	13	6.4	32.9	Buggisch *et al.* (1993)
2	BB	Bum Bum	TU	Lagares Fm.	293–320 (1)		M	−85.0	335.0	25	6.6	20.0	Thompson (1972)

(1) Ages after Azcuy *et al.* (1999), referred to the modified Permian scale of Menning (1995) and the International Stratigraphic Chart (Remane 2000).
(2) K/Ar age on basaltic flow, Thompson & Mitchell (1972) (probably rejuvenated age).
(3) K/Ar age on basaltic flow, Thompson & Mitchell (1972)
(4) 2 K/Ar ages on andesites from Punta del Agua Fm., Fauqué *et al.* (1999).
*Location in Fig. 2.
Combined using McFadden & McElhinny's (1995) method.
MS: megasequence; UP: Upper Patquía-De la Cuesta; LP: Lower Patquía-De la Cuesta; TU: Tupe; GU: Guandacol.
Pol.: polarity; R: reverse; M: mixed (reverse and normal polarity zones).

Thompson & Mitchell 1972), which was attributed by the authors to argon loss in Paganzo village sample.

The 600 m-thick sedimentary sequence from Paganzo village was studied by Thompson (1972) and Valencio *et al.* (1977). The former used 35 samples of the La Colina Formation, from both limbs of a steep anticline. They carried a pre-tectonic reversed characteristic magnetization, determined after the elimination of a post-tectonic secondary component. Valencio *et al.* (1977) performed a more detailed and numerically larger collection of samples, however, only in the eastern limb of the anticline. They obtained more scattered final directions, probably as a result of incomplete elimination of secondary components, however, the final result was essentially the same as obtained by Thompson (1972) (PG in Fig. 10).

Sinito *et al.* (1979) sampled the same sequence in the homoclinal exposure in Las Mellizas mine and obtained all-reversed characteristic magnetization. However, the Las Mellizas pole position (ME in

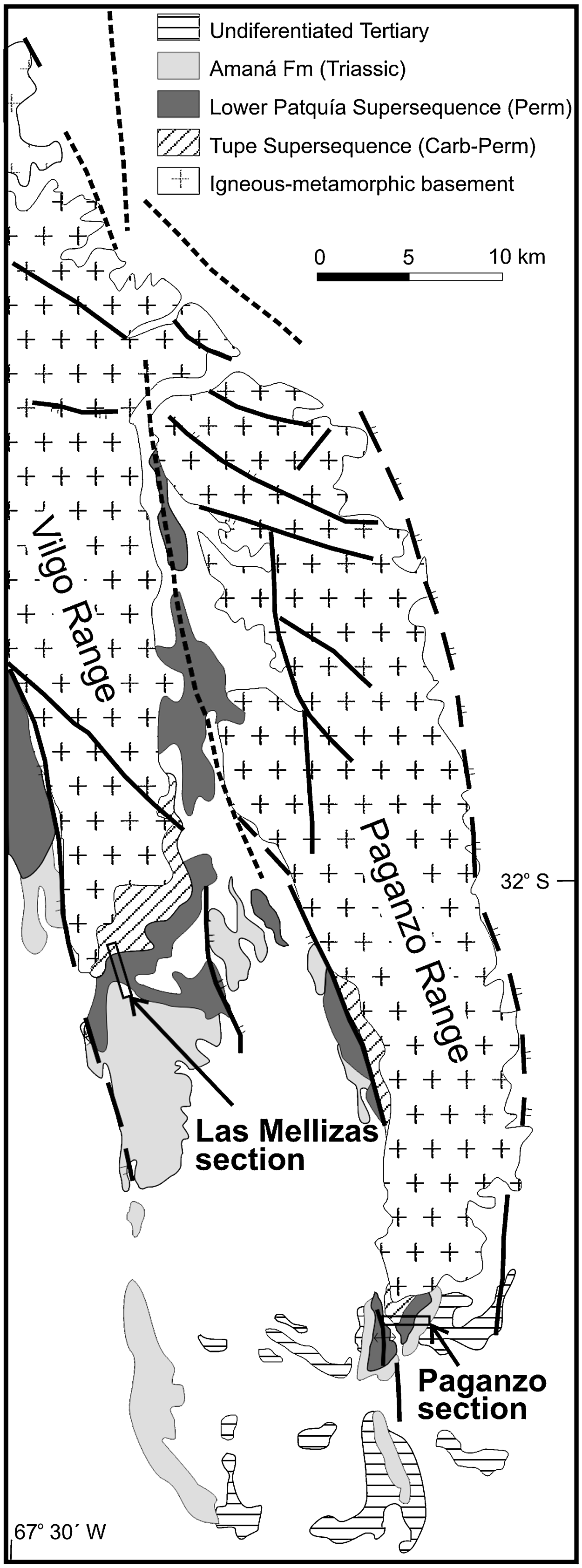

Figure 13. Geological sketch of Paganzo-Las Mellizas area, adapted from Limarino *et al.* (1999) and Cravero *et al.* (1999). Note the vicinity of both localities showing very different palaeomagnetic results. Paganzo section has suffered complex folding and possibly rotation around a vertical axis.

Fig. 10) was different from Paganzo village, which they interpreted as evidence of the two sequences not having the same age, supported by the rejuvenated K/Ar age obtained by Thompson & Mitchell (1972).

The difference in age used to explain the incongruency between both poles is not fully convincing because it is based on only one K/Ar date that may be unreliable, as was pointed out by Thompson & Mitchell (1972). Both sections represent the basal sequence of the Lower Patquía-De la Cuesta supersequence, clearly characterized by the presence of scarce basaltic flows.

The difference between the two poles could be produced by a rotation of the Paganzo section about a vertical axis. Paganzo section outcrops as a southern extension of a basement block uplifted during Andean orogeny and it has suffered complex folding resulting in a plunging, asymmetric fold (Fig. 13).

As for the remaining PCRS Paganzo poles: the Chaschuil pole (Thompson 1972) includes normal and reversed directions; most of the samples were unstable and the selected samples still form a scattered population, which could indicate a secondary component not completely erased. Bum Bum mine (Thompson 1972) is the only PCRS pole not determined from Permian Lower Patquía-de la Cuesta supersequence but within the basal Carboniferous–Permian Tupe supersequence. Four normal polarity intervals were identified and seven samples provided specimens with both polarities. Although this could be the record of the last reversals prior to the PCRS, we prefer to attribute this behaviour to the incomplete elimination of a secondary component, given that secondary hematitization has been reported massively affecting some sandstone and mudstone levels at Bum Bum (Net 2002). Therefore, the Chaschuil and Bum Bum poles could be typical examples of biasing towards the present axis caused by remagnetizations.

As pointed out above, the Lower Los Colorados and Huaco poles (Embleton 1970a) are based on a highly stable remanence, which constitutes the entire NRM. These poles are approximately coincident and they are in good agreement with African coeval poles (Figs 10 and 12).

Discrepancies between the new poles presented here and previous results from the Paganzo basin can be examined from a variety of perspectives, as discussed below.

(i) Apparent polar wander (APW) for South America.
(ii) Intracontinental tectonic rotations.
(iii) Remagnetization.
(iv) Inclination error and method-related errors.

(i) APW for South America is suggested by the grouping of all-reverse poles around an approximate direction Long. 300°E, Lat. 80°S (Oviedo & Vilas 1984). This group clearly differs from the Cu group (around Long. 350°E, Lat. 60°S). Rapalini & Vilas (1991) and Rapalini & Vilas (1996) suggested a relationship among this period of fast APW, oblique convergence in the western margin of South America, tectonic rotations and the San Rafael orogenic phase. This section of APW, however, is not in agreement with paths of the rest of Pangaea at that time. Therefore, it is necessary to consider South America (or at least its western part) moving relative to the rest of Pangaea in order to account for the fast APW in these South American poles. No geological evidence has been given for that at continental scale, however, locally SROP is an important deformation event, followed by Choiyoi volcanism that covered more than 200,000 km^2. However, there is no apparent sequential order in the age of the pole groups and, instead, poles of supposed similar ages fall indistinctly in both groups. Thus, the APW hypothesis needs, with the present state of knowledge, some ad hoc hypotheses involving error in age assignment for the sedimentary sequences and/or for the remanence acquisition.

(ii) Tectonic rotations related to intracontinental movements. This is clear for the Precordilleran poles, as discussed earlier, and vertical-axis rotations were also registered in Late Palaeozoic units from the Calingasta-Uspallata subbasin (Fig. 2) by Valencio & Vilas (1985) and Rapalini & Vilas (1991). Interestingly, Rapalini & Vilas (1991) found that the amount of rotation decreased significatively for rock units deposited after SROP, which led them to interpret the SROP as an event related to oblique convergence.

The Rincón Blanco direction calculated in this study shows a clockwise declination anomaly when compared with Cu group directions, which is consistent with the presence of a tectonic rotation of approximately 40°. This is consistent with the situation of this locality near the more mobile western end of the basin.

This explanation could also be applied to intracratonic poles, such as Paganzo village; in fact, lateral displacement has been documented in main regional lineaments, such as Valle Fértil fault (Fig. 2), since the Late Carboniferous (Fernández Seveso *et al.* 1990) and its reactivation in the Tertiary and recent times has been described by Introcaso & Ruiz (2001). However, there is no regional pattern of rotations emerging from the known data, with adjacent localities belonging to either the Cu or anomalous group. Should vertical-axis rotations be responsible for the discrepancies in the poles, they would respond to very local deformation phenomena.

(iii) Remagnetization. An extensive remagnetization of Kiaman age was documented by Rapalini & Tarling (1993) and Rapalini *et al.* (2000), affecting Lower Palaeozoic limestones of the Precordillera, as well as Ordovician ophiolites of the Alcaparrosa Formation. However, the remagnetization front would not have reached beyond Cerro Totora (Fig. 2), where Rapalini & Astini (1998) obtained a Cambrian palaeomagnetic pole from red siliciclastics and carbonate rocks.

A remagnetization event during the PCRS would not be unlikely because it is the age of the main SROP. However, it would not explain why the poles fall in characteristic positions of younger times. Basin-forming processes were active in the foreland region in the Triassic and Early Cretaceous (Ramos 1999), and mineralizing events related to Permo-Triassic and Tertiary volcanism are evidenced by the presence of porphyry systems in the Andean cordillera (Williams *et al.* 1999; Zappettini 1999). A widespread remagnetization as young as Tertiary can be discarded because Lower Cretaceous and Tertiary deposits have given reliable results with confident magnetic-polarity stratigraphy established (e.g. Butler *et al.* 1984; Reynolds 1987). A remagnetization in Triassic times, related to basin-forming processes, could not be discarded, however, the all-reverse polarity (indicating a single polarity chron.?), affecting such wide areas and thick deposits, would not be explained.

(iv) Inclination error, as suggested by Rochette & Vandamme (2001). Inclination shallowing of depositional or post-depositional remanence in sedimentary rocks would produce systematically lower apparent palaeolatitudes, however, it would not explain the observed difference in declinations that separates the Cu group from the remaining poles. Incorrect estimation of the palaeohorizontal can be discarded because the poles come from sedimentary sequences in which the bedding plane can be easily determined. Incomplete averaging of the palaeosecular variation is not likely because sedimentary rocks usually average the field within-sites, and because of the wide distribution of sites and the thickness of the sequences from which the palaeomagnetic results come, particularly, for Rincón Blanco pole.

CONCLUSIONS

Upper Palaeozoic Paganzo poles have been controversial in the definition of the APWP for South America. Some of them are coincident with poles from other continents and form a Cu group (350°E, 60°S), while other poles (grouping at 300°E, 80°S) have been previously interpreted as registering a period of rapid APW: however, this has not been observed in poles from other plates forming Pangaea in the Late Palaeozoic.

Ancient magnetizations were identified in samples from three localities belonging to the Paganzo basin. However, its isolation was more difficult for the easternmost localities (Chancaní and Cerro Colorado-Caminiaga) because the outcrops have poor quality and the samples are more affected by secondary components. Otherwise, the Rincón Blanco locality is very well exposed and shows the best magnetic behaviour. Although the results are of very different quality for the three localities, the final pole positions were roughly the same (Fig. 10).

The new poles, as well as some of the previously published Paganzo poles, were not coincident with the Cu group. All of them were reversely magnetized and their geological ages are Late Carboniferous–Early Permian. The reversed polarity is in agreement with a magnetization acquired during the PCRS, in agreement with the geological age of the strata. However, the position of some of the poles suggests a younger age when compared with APWPs from South America and another plates.

The characteristic reversed magnetization is pre-tectonic as deduced from localities where a fold test was performed. Deformation is mainly Andean (Tertiary), although folding in Rincón Blanco it could be attributed at least partially to the San Rafael orogeny phase (Permian). Irrespective of whether the magnetization is interpreted as primary or secondary (related to diagenetic processes), it was acquired during the PCRS, based on the persistent reverse polarity, even in the thickest sections (1500 m in Rincón Blanco).

Based on a careful revision of updated geological information, we conclude that Permian Paganzo poles are not internally consistent because sections belonging to similar stratigraphic sequences have provided different pole positions. This is attributed either to an incorrect age assignment (Los Colorados section) or to previously undetected tectonic rotations (Paganzo village section).

Intracontinental deformation is, also, probably affecting the Rincón Blanco pole, related to lateral movements along main faults controlling the development of the forearc basins.

Smith (1999) attributed the discrepancy between Permo-Triassic Laurasia and Gondwana poles to remagnetization processes, similar to those registered in Palaeozoic rocks from North America (McCabe & Elmore 1989). Although remagnetization has been proven in the Argentine Precordillera (e.g. Rapalini & Tarling 1993), we cannot extend its influence as a widespread phenomenon to the intracratonic basin. The geology of Gondwana, differing from Laurasia in being dominated by siliciclastics instead of limestones (França *et al.* 1995), is less susceptible to the widespread remagnetization reported by McCabe & Elmore (1989), which is found mainly as a thermoviscous remanence affecting limestones. However, local remagnetizations cannot be discarded and should be assessed by carefully evaluating the geological setting at each locality. The uncertainty in the age assignment of red beds, also, cannot be disregarded as a source of important palaeomagnetic noise.

Intracontinental deformation seems to be a common phenomena, even farther from the present orogenic belt. In this context, the tendency for Lower Permian (all-reversed) poles to group around Long. 300°E, Lat. 80°S could be merely coincidence, or it could reflect some structural pattern that dominated Late Palaeozoic–Cenozoic deformation events.

Further work has to be done to decide whether remagnetization, incorrect age assignment or tectonic rotations better explain the Late Palaeozoic palaeomagnetic poles of central-western Argentina. Whatever the case, it seems clear that San Rafael orogenic phase plays a major role in the geological evolution of southern South America and its signature, usually present in palaeomagnetic results from rock units older than Permian, must be carefully addressed. Furthermore, it cannot be discarded that the grouping of poles around 300°E, 80°S might be interpreted in terms of some peculiar movement of central-western Argentina related with SROP: the definition of such a movement is still prevented by the scarcity of reliable palaeomagnetic data and the inaccuracies in the age assignments of the rock units involved.

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