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New Early Cretaceous palaeomagnetic pole from Córdoba Province (Argentina): revision of previous studies and implications for the South American database

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SUMMARY

A continental sequence of red beds and interbedded basaltic layers crops out in the Sierra Chica of Cordoba Province, Argentina (31.5°S, 64.4°W). This succession was deposited in a half-graben basin during the Early Cretaceous. We have carried out a palaeomagnetic survey on outcrops of this basin (147 sites in seven localities). From an analysis of IRM acquisition curves and detailed demagnetization behaviour, three different magnetic components are identified in the volcanic rocks: components A, B and X are carried by single- or pseudo-single-domain (titano) magnetite, haematite and multidomain magnetite, respectively. Component A is interpreted as a primary component of magnetization because it passes conglomerate, contact, tilt and reversal tests. The carrier of the primary magnetization, fine-grained (titano)magnetite, is present in basalts with a high degree of deuteric oxidation. This kind of oxidation is interpreted to have occurred during cooling. Components B and X are discarded because they are interpreted as recent magnetizations. In the sedimentary rocks, haematite and magnetite are identified as the carriers of remanence. Both minerals carry the same component, which passes a reversal test. The calculated palaeomagnetic pole, based on 55 sites, is Lat. 86.0°S, Long. 75.9°E ($A_{95}=3.3$, $K=35$). This palaeomagnetic pole supersedes four with anomalous positions reported in previous papers.

Key words: Argentina, Early Cretaceous, palaeomagnetism, South America.

INTRODUCTION

The importance of apparent polar wander (APW) paths for palaeogeographic reconstructions and global tectonics is well known. The poorly defined APW path for cratonic South America, in particular for the Cretaceous, has been a troublesome problem, particularly with regard to evaluating models for the tectonic evolution of the Andean Cordillera (Beck et al. 1986; Beck 1988; Cembrano et al. 1992; Somoza 1994). Palaeomagnetic poles (PPs) for the stable part of the continent show an elongated distribution that has been interpreted in different ways. Some authors have suggested that this distribution reflects a complex movement of the plate during the opening of the South Atlantic (Valencio et al. 1983). Others have suggested that the streaked distribution is due to an inadequate procedure of PP selection, and therefore they inferred that South America has had no great latitudinal movement since the Cretaceous (Beck 1988; Castillo et al. 1991; Cembrano et al. 1992). Of importance in solving this problem is a discussion of the reliability of the PPs.

Four of the reference PPs for stable South America are derived from volcanic rocks of the Early Cretaceous rift of Sierra Chica, Córdoba, Argentina. The PPs are called Vulcanitas Cerro Colorado (Valencio 1972), Vulcanitas Rumipalla (Vilas 1976; both of these recalculated in Valencio & Vilas 1976), El Salto–Almafuerte volcanics (Mendía 1978) and Río Los Molinos dykes (Linares & Valencio 1975). The four poles show the same kind of inconsistency as is observed more generally for South American Cretaceous poles. These previous publications did not include significant tests of reliability.

A re-examination of the four previous studies has revealed that although the isolation of a characteristic magnetization was essentially correct, the small number of sites and the

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uncertainty in the structural correction could be responsible for an incomplete averaging of palaeosecular variation (PSV) or inaccurate restoration to the palaeohorizontal.

In this paper we present a new palaeomagnetic pole from Early Cretaceous localities of Sierra Chica, based on a sufficient number of sampling sites and more stringent reliability criteria. This new PP was calculated from 55 sites at seven localities in Sierra Chica, Córdoba, and is supported by positive conglomerate, baked contact, reversal and fold tests. This new PP coincides with other Early Cretaceous palaeopoles from South America.

GEOLOGICAL SETTING

Sierra Chica of Córdoba is a north-trending, westward-verging, fault-bounded basement uplift in Central Argentina. Cretaceous outcrops are small relicts (Fig. 1) of a basin that possibly covered all of the Sierra Chica, and are composed of mainly coarse red beds, intercalated with basaltic flows (Gordillo & Lencinas 1980).
Normal faulting controlling the basin was related to widespread extensional processes that culminated with the opening of the South Atlantic Ocean (Uliana et al. 1990); the faults followed pre-existing zones of weakness, related to a Proterozoic suture zone in the metamorphic basement (Kraemer et al. 1995). The same zones of weakness were reactivated later in the Neogene due to Andean compression, causing the elevation of the ranges and the erosion of the Cretaceous deposits (Schmidt et al. 1995). Remnants of the Cretaceous basin therefore appear as gently tilted outcrops of faulted blocks, with maximum dips of about 20°. Apatite fission-track ages on basement rocks are not younger than Mesozoic (Jordan et al. 1989), indicating that no important thermal events occurred after the deposition of the Cretaceous rocks.

Cretaceous deposits are only extensive at the northern and southern edges of the whole Sierra Chica: Sierra de Pajarillo–Copacabana–Masa and Sierra de Los Condores, respectively (Fig. 1). The other Cretaceous outcrops are small and are located along the eastern flank of Sierra Chica. The only exception is the outcrop of El Pungo, situated on the upper part of the western flank, preserved as a relict due to local structure (Gordillo & Lencinas 1967a). Shallow basaltic dykes related to Cretaceous volcanism have been reported intruding the basement rocks in Río Los Molinos (Gordillo & Lencinas 1969). These rocks have been included in the Sierra de Los Condores Group (Gordillo & Lencinas 1980).

Red beds of the Sierra de Los Condores Group lie discordantly on plutonic–metamorphic Precambrian basement. They are mainly composed of immature sediments that are derived from the basement. Diagenetic processes are represented by the precipitation of carbonate cement, the recrystallization of clay minerals and incipient secondary growths on quartz and feldspar. Haematite pigment is present in the cement (R. Andreis, personal communication, 1995).

Volcanic layers are potassium-rich, moderately alkaline basalts and subordinate andesites. There is a variety of colours in the volcanic rocks because of a high variation in the degree of oxidation. Oxidation affects mainly olivine, which appears completely iddingsitized in brown basalts but fresher in black basalts. These processes have been related to deuteric alteration

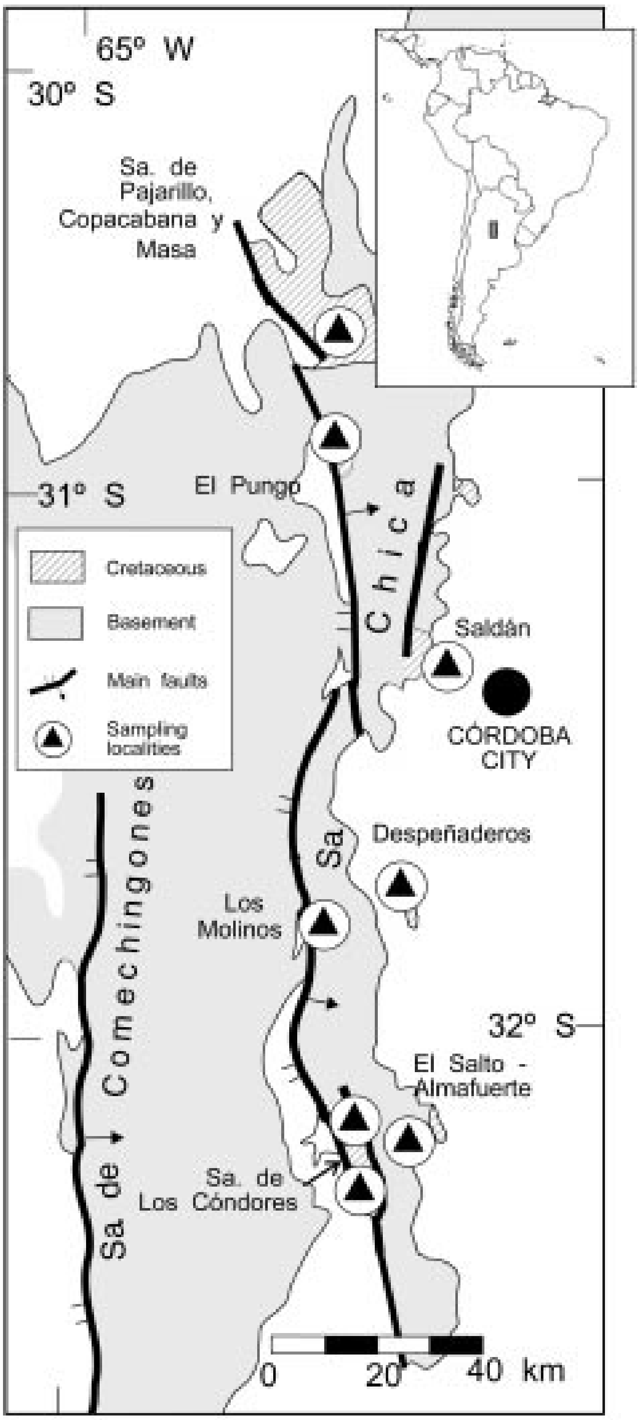

Figure 1. Geological map of the Sierra Chica de Córdoba showing Early Cretaceous outcrops and sampling localities.

simultaneous with cooling in an oxidizing, water-rich chemical environment (Gordillo & Lencinas 1967b).

From the earlier studies of Bodenbender (1929) it was established that all of the small outcrops of volcano-sedimentary deposits from Sierra Chica belong to the same basin-forming event. K/Ar ages on basaltic flows and dykes in Sierra de Los Condores, El Salto-Almafuerte and El Pungo range from 133 to 115 Ma, with a peak value of 123 Ma (Linares & Gonzalez 1990). Río Los Molinos dykes are a little older, with an average age of 141 Ma (Linares & Valencio 1975).

SAMPLING PROCEDURES AND ANALYTICAL WORK

Oriented samples were collected at eight localities in the Sierra Chica (two of them in the Sierra de Los Condores, Fig. 1, Table 1). We sampled 147 sites from 17 stratigraphic sections. At least three hand-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. Where no sandstone units were interbedded, the original attitude of the volcanic rocks could be established because different flows were generally separated by volcanic breccias and reddened zones at their bases.

For palaeomagnetic measurements the samples were sliced into specimens of 2.5 cm diameter and 1.5–2.5 cm length. 84 non-processed complementary specimens from the original collection of D. A. Valencio (property of the Laboratorio de Paleomagnetismo, University of Buenos Aires) were added. Usually five specimens per site were analysed.

Remanent magnetization was measured using either a Schonstedt or a Digico spinner magnetometer. Sedimentary samples with a low intensity of magnetization were measured using a 2G DC squid cryogenic magnetometer. Alternating-field demagnetization (AF) was carried out to a maximum of 110 mT (peak) using a static 2G demagnetizer. Step-wise thermal demagnetization was performed using a Schonstedt TSD-1 thermal demagnetizer.

Two pilot specimens per site were subjected to both demagnetization methods in order to examine the coercivity and blocking-temperature spectra of the natural remanent magnetization (NRM). AF cleaning was performed on one pilot specimen from fields of 3 up to 110 mT in steps of 3 (up to 12 mT), 5 (up to 50 mT) and 10 mT (up to 110 mT). The other specimen was thermally demagnetized from 150 °C up to 680–700 °C in steps of 50 °C up to 550 °C and in steps of 20 or 30 °C up to 680–700 °C, if necessary. Possible changes in susceptibility values were monitored using a RMSH-III TATA Institute susceptibilimeter.

The pilot specimens were used to decide which of the methods was the most effective for each site. At least three more specimens were then treated; at least five steps of demagnetization were applied for all specimens.

Magnetic directions were plotted on vector endpoint diagrams and were analysed using principal component analysis (Kirschvink 1980). A magnetic component was accepted only if the maximum angular deviation (MAD) was less than 10°; it was usually less than 5°. Statistical analysis was carried out using standard Fisher (1953) statistics, by means of the MAG88 computer program (Oviedo 1989). McFadden & McElhinny's (1988) method was used for sites with samples that showed remagnetization circles.

Analysis of the palaeomagnetic directions

To analyse the palaeomagnetic directions, we first divided the results according to lithology. In other words, we analysed separately the directions recorded by volcanic and sedimentary rocks, considering that the acquisition of the remanence could be different in the two lithologies.

Volcanic rocks

The behaviour of the magnetic system was intimately related to the degree of oxidation of the volcanic rocks: black basalts had systematically higher values of magnetic susceptibility and NRM intensity, and lower values of remanent coercive force (H_{cr}) than brown basalts, which are more oxidized (Fig. 2).

Three magnetic components with different magnetic coercivities were detected in volcanic samples, possibly correlating with the degree of oxidation.

Component X (Fig. 2a). This component is present in samples with NRM intensities above 10^{-1} A m^{-1}; it is a soft component, removed at no more than 30 mT (usually less than 10 mT). The low stability of this component suggests that it is carried by a magnetic mineral with a low relaxation time, probably multidomain (titano)magnetite. Thermal demagnetization confirms this (Fig. 3a), because it reveals a broad distribution of blocking temperatures, typical of multidomain grains (McClelland-Brown 1982). Samples with a dominant X component (usually black basalts) showed efficient acquisition of IRM and low values of H_{cr} (determined using backfield or AF demagnetization methods), around 10–20 mT (Fig. 4a).

Component A (Fig. 2b). This component was generally removed beyond 70 mT; its blocking temperature was between 550 and 615 °C (Fig. 3c). H_{cr} values of samples with a dominant A component (usually brown basalts) were about 40 mT (Fig. 4b), which suggests that fine (titano)magnetite (possibly single or pseudo-single domain) is the main carrier. Lowrie's (1990) method confirms that (titano)magnetite is the carrier of this component (Fig. 4c).

Component B (Fig. 2c). In some specimens AF demagnetization up to 130 mT failed to remove another component of low intensity (of the order of 10^{-2} A m^{-1}). This type of component is present in reddened samples and is carried by haematite. Samples dominated by the B component (usually volcanic clasts in red conglomerates) had complex IRM acquisition curves, some of them composed of two segments (Fig. 4d, sample EM76)—the first showing efficient acquisition (titanomagnetite) and the second a sigmoid shape, without saturation at fields under 2 T (haematite). Lowrie's (1990) method confirms the presence of both magnetic minerals (Fig. 4e).

The three types of components are present in most samples in different proportions, mainly related to the different types of basalts. For example, only black basalts record exclusively component X, and only brown basalts record exclusively the more stable component A (Fig. 2g). In a single site, component X sometimes coincides with the direction of the present geomagnetic field, but in other cases shows random directions (Fig. 5a). We interpret this component as being a viscous remanent magnetization carried by multidomain magnetite. Component A (Fig. 5b) is mainly present in basalts with deuteric alteration, and is virtually absent in fresh basalts, so it is interpreted as a chemical or thermochemical remanent magnetization (CRM, TCRM). Component B (Fig. 5c) is present in reddened basalts containing haematite, so it appears to be related to some kind of oxidation process.

To evaluate when components A and B were acquired, conglomerate and contact tests were performed.

Conglomerate test. Basaltic clasts contained in conglomerates

Table 1. Palaeomagnetic data for the Early Cretaceous volcano-sedimentary rocks from Sierra Chica, Córdoba.

Site		Lith	N/N_0	In situ Dec.	Inc.	Strike/dip	Tilt corrected Dec.	Inc.	a_{95}	k	VGP °S	°E
Sierra de Los Cóndores (Lat. 32.22°S, Long. 64.44°W)												
PAR5+4	(2)	B+S	9/10	343.4	−59.4	140/11	357.8	−53.7	7.7	45.9		
PAR3		BAS	0/3	–	–	140/11	–	–	–	–		
PAR2		SED	8/8	151.8	53.3	140/11	165.0	49.8	7.7	53.2	77.1	28.9
PAR1		SED	10/10	173.4	61.7	140/11	187.0	54.6	4.5	117.3	83.5	234.0
RU1–7		BAS	0/7	–	–	107/6	–	–	–	–		
RU1–4		SED	0/7	–	–	107/6	–	–	–	–		
RU1–1	(5)	BAS	3/5	352.7	−50.6	107/6	355.3	−45.1	9.0	189.7		
RU1B-1	(3)	BAS	9/10	149.8	54.6	107/10	158.3	47.2	6.3	67.9		
RU2–5+4	(4)	B+S	13/13	342.4	−34.8	206/20	356.5	−46.9	3.7	127.8		
RU2–3		BAS	4/4	333.6	−31.0	206/20	344.5	−45.7	5.8	249.0	75.6	42.3
RU2–2		BAS	0/5	–	–	206/20	–	–	–	–		
RU2–1	(3)	BAS	3/6	142.8	22.6	206/20	149.0	40.4	21.5	33.9		
RU3–2	(5)	BAS	9/9	4.5	−24.1	272/10	4.8	−34.2	6.9	56.6		
RU3–1	(4)	BAS	4/4	356.3	−45.3	272/10	354.9	−55.4	4.2	484.9		
RU4–2		BAS	0/7	–	–	224/17	–	–	–	–		
RU4–1	(3)	BAS	5/5	167.6	37.7	224/17	178.1	51.0	8.4	82.9		
TBNS	†	BAS	14/35	202.6	67.1	116/11	203.9	56.0	9.6	17.9	69.9	224.6
TBP	†	BAS	31/41	163.9	62.2	116/11	174.4	53.1	4.2	38.0	85.1	6.5
RB	†	SED	6/6	171.9	53.1	116/11	178.3	43.5	4.6	217.4	83.0	103.1
TCAS	†	BAS	33/51	131.0	65.2	116/11	150.5	60.3	5.9	18.9	64.8	356.1
TBNI+TCAI	†	BAS	46/60	153.5	62.2	116/11	166.4	55.3	2.9	52.6	78.2	3.9
CC1		BAS	6/6	186.6	65.8	138/17	202.2	51.5	10.4	42.5	71.2	211.4
CC2–2+1	(1)	B+S	9/9	4.9	−41.4	158/5	8.3	−39.3	6.6	61.9		
CC2–1	*	SED	3/4	131.6	4.2	158/5	132.0	6.2	8.6	204.3		
CC3–1	(1)	BAS	5/5	358.2	−55.3	147/10	8.7	−49.4	5.1	229.1		
GAR3	(2)	BAS	5/5	343.3	−53.3	158/5	349.2	−52.6	4.3	315.9		
GAR2	(1)	B+S	17/29	11.8	−56.1	158/5	16.9	−53.4	5.7	39.5		
GAR1	*	SED	23/23	136.3	24.4	158/5	138.3	26.0	4.3	54.0		
EST7+6+5	‡ (2)	B+S	31/36	8.5	−46.8	358/14	353.3	−47.5	3.6	52.6		
EST4+3+2	‡ (1)	B+S	70/76	2.2	−47.2	358/14	347.3	−46.4	2.4	49.0		
EST2	*	SED	11/11	188.7	33.4	358/14	179.2	34.9	5.6	93.9		
EST1	*	SED	8/8	190.7	20.9	55/10	188.5	13.8	9.8	57.1		
LIB4	‡	BAS	43/81	4.7	−52.1	150/11	14.4	−45.0	3.1	51.2	76.3	185.0
LIB3	‡	BAS	33/55	355.4	−50.4	150/11	5.9	−44.8	3.9	42.8	82.3	158.3
LIB2	‡	BAS	24/34	4.4	−38.6	150/11	10.6	−31.9	4.8	39.0	72.2	150.8
LIB1		SED	4/4	10.0	−62.5	150/11	22.5	−54.5	21.1	19.9	71.1	220.4
A6+7+8		BAS	13/13	357.8	−52.1	203/6	5.3	−54.3	4.2	97.4	84.9	236.9
A5		BAS	5/5	350.7	−42.4	203/6	355.8	−45.4	4.0	374.2	83.5	80.2
A4		BAS	4/4	358.0	−53.3	203/6	5.8	−55.4	3.6	646.2	84.0	244.7
A2+3		BAS	7/9	354.9	−37.7	203/6	359.3	−40.4	5.8	69.2	80.7	111.7
A1		BAS	5/5	352.4	−33.7	203/6	356.1	−36.6	8.4	83.1	77.6	98.5
B4		BAS	0/5	–	–	90/7	–	–	–	–		
B3		BAS	0/5	–	–	90/7	–	–	–	–		
B2		BAS	4/5	19.1	−78.2	90/7	12.1	−71.5	7.8	141.0	64.7	279.8
B1		SED	7/7	357.4	−46.3	90/7	357.8	−49.3	4.0	224.7	87.1	74.1
C3		BAS	5/5	171.3	47.3	45/5	168.5	43.2	12.0	41.3	77.6	58.0
C2		BAS	6/6	2.0	−58.0	45/4	356.8	−54.4	4.7	200.9	86.2	340.7
C1		BAS	5/5	337.4	−62.8	45/4	334.3	−58.2	8.8	75.7	68.2	0.9
D3		BAS	5/5	345.7	−57.8	100/14	352.0	−44.7	6.6	134.5	80.9	64.2
D1+2		BAS	6/6	350.5	−45.7	100/14	354.0	−32.3	4.4	228.0	74.3	93.9
E4		BAS	4/4	20.1	−58.5	90/5	17.7	−53.8	9.9	86.7	75.1	218.2
E3		BAS	2/2	357.8	−47.4	90/5	358.0	−42.4	13.8	331.4	82.0	102.0
E2		BAS	0/1	–	–	90/5	–	–	–	–		
E1		BAS	2/2	14.4	−62.4	90/5	12.4	−57.6	43.3	35.4	78.3	239.5
(5) CNOR			12			–	2.7	−36.9	6.1	52.1	78.1	127.8
(4) TNOR			17			–	356.2	−48.9	3.3	120.1	85.9	61.4
(3) UREV			17			–	161.8	47.6	5.6	41.0	74.0	33.5
(2) SNOR			45			–	353.0	−49.4	3.0	50.9	83.7	42.1
(1) PNOR			101			–	354.6	−47.7	2.4	33.1	84.2	60.6
Mean			33	353.2	−51.8		359.2	−49.6				
				$a_{95}=4.1$; $k=30.2$			$a_{95}=3.6$; $k=48.7$					
		McFadden SCOS = 13.23						2.61 (95 per cent critical value: 7.54)				

Table 1. (Continued).

Site		Lith	N/N_0	In situ Dec.	Inc.	Strike/dip	Tilt corrected Dec.	Inc.	a_{95}	k	VGP °S	°E	
El Salto-Almafuerte (Lat. 32.17°S; Long. 64.25°W)													
29–30		BAS	5/5	177.5	45.4	346/16	160.9	46.3	7.9	94.2	72.9	36.2	#
31–33		BAS	27/27	165.6	45.8	346/16	149.9	43.4	5.7	23.8	62.8	32.6	#
27–28		BAS	6/15	184.8	29.7	346/16	175.2	33.6	10.2	50.8	75.5	97.2	#
26		BAS	2/7	–	–	346/16	–	–	–	–			
25–32		BAS	20/32	178.9	48.6	346/16	160.3	49.6	6.4	27.4	73.1	26.5	#
24		BAS	1/3	189.5	29.2	346/16	180.0	34.4	–	–	76.7	115.9	#
	(9)	BAS	3/5	346.6	−44.7	346/16	331.3	−42.7	16.9	54.0			
23		BAS	6/9	4.9	−55.5	346/16	340.6	−57.5	6.6	105.1	73.1	9.0	#
Dyke	(9)	BAS	10/10	6.5	−43.6	346/16	350.5	−47.1	8.0	37.4			
20–21–22	(8)	BAS	2/10	125.3	38.1	330/16	115.8	30.2	9.7	6918.0			
19		BAS	0/9	–	–	330/16	–	–	–	–			
18–16	(7)	BAS	11/15	177.0	48.7	330/16	157.8	53.5	5.6	80.5			
	(9)	BAS	2/3	15.3	−32.7	330/16	5.8	−43.2	23.3	116.6			
17		BAS	0/3	–	–	330/16	–	–	–	–			
11	(9)	BAS	5/10	354.5	−44.5	330/16	337.9	−49.1	8.1	90.8			
10	(6)	BAS	6/7	177.3	32.7	330/16	166.6	38.8	13.1	29.3			
9		BAS	3/7	–	–	320/24	–	–	–	–			
	(9)	BAS	4/9	356.8	−48.1	320/24	326.7	−57.4	13.8	45.4			
8		BAS	0/8	–	–	320/24	–	–	–	–			
7		BAS	5/10	190.8	13.1	320/24	184.1	31.0	15.2	27.9	74.1	130.2	#
6		BAS	2/15	–	–	320/24	–	–	–	–			
5		BAS	0/2	–	–	320/24	–	–	–	–			
15		BAS	0/13	–	–	320/24	–	–	–	–			
14	(8)	BAS	12/20	104.6	49.3	343/35	94.0	17.6	12.5	13.0			
3		BAS	0/3	–	–	343/35	–	–	–	–			
13–4	(6)	BAS	7/22	209.2	23.2	343/35	189.6	44.7	10.9	34.6			
12	(7)	BAS	10/13	207.7	45.7	343/35	162.1	60.2	10.2	24.6			
2		BAS	0/10	–	–	320/35	–	–	–	–			
1		BAS	4/5	356.3	−38.9	320/35	321.5	−51.2	15.3	37.1	57.5	15.8	#
(9)Dyke+Con.			24			–	343.0	−49.3	5.3	33.3	75.4	29.0	#
(8)			14			–	96.2	18.5	11.3	13.5	10.2	20.9	#
(7)			21			–	159.9	56.2	5.4	38.6	72.8	4.7	#
(6)			13			–	177.3	47.5	12.1	12.8	85.8	82.2	#
Mean			11	184.2	40.1		165.9	47.0					
				$a_{95}=6.5$; $k=31.4$			$a_{95}=5.8$; $k=38.7$						
		McFadden SCOS=2.65						2.38 (95 per cent critical value: 4.80)					
Despeñaderos (Lat. 31.81°S; Long. 64.31°W)													
12		BAS	5/5	343.6	−54.7	111/12	351.5	−44.7	4.6	281.0	−80.7	59.8	#
11		BAS	5/5	326.5	−62.1	111/12	340.7	−53.9	8.9	75.4	−73.7	11.1	#
10		BAS	5/5	321.7	−60.1	111/12	336.1	−52.7	4.3	310.1	−69.8	15.1	#
9		BAS	5/5	321.4	−62.7	111/12	337.1	−55.2	7.1	118.0	−70.6	7.8	#
8		BAS	5/5	324.7	−66.2	111/12	341.6	−58.0	4.7	267.0	−73.5	356.0	#
7		BAS	5/5	329.9	−63.2	111/12	343.8	−54.5	5.0	237.7	−76.1	7.9	#
6		BAS	5/5	332.0	−70.1	111/12	349.1	−60.8	2.6	871.6	−76.7	333.4	#
5		BAS	3/4	345.7	−61.2	111/12	354.9	−50.9	10.7	134.3	−85.6	27.5	#
4		BAS	5/5	322.8	−61.2	111/12	337.5	−53.6	6.4	143.5	−71.0	12.7	#
3		BAS	5/5	330.3	−61.4	111/12	343.3	−52.7	6.4	145.7	−75.8	15.1	#
2		BAS	5/5	334.6	−58.9	111/12	345.6	−49.8	4.9	246.6	−77.6	27.5	#
1		BAS	5/5	326.0	−62.6	111/12	340.6	−54.5	5.2	221.0	−73.5	9.3	#
1 a 11	**		53/54	328.4	−62.8	111/12	342.5	−54.3	1.7	135.0	−75.1	9.3	#
Mean 1 a 12			12	330.2	−62.3		343.6	−53.6	2.9	227.9	−76.0	11.0	#
Mean 12+	**		2	336.9	−59.0		347.4	−49.6	24.7	104.6	−79.0	28.3	#
Saldán (Lat. 31.35°S; Long. 64.34°W) (Geuna 1997)													
8		SED	6/6	345.1	−41.9	220/3	346.7	−44.4	10.2	44.3	77.2	46.8	
7		SED	4/5	156.0	29.6	220/3	156.8	32.3	10.7	74.7	64.9	53.6	
6		SED	5/5	174.3	29.1	220/3	175.6	31.2	15.1	30.5	74.9	99.0	
5		SED	8/8	10.8	−33.2	270/16	13.8	−48.9	8.3	44.9	78.0	202.1	
4		SED	7/7	0.9	−40.8	311/4	358.5	−43.8	6.7	82.9	84.1	102.7	
3		SED	7/7	343.3	−32.9	311/4	340.9	−35.0	7.5	65.9	69.0	56.2	
2		SED	7/7	358.8	−47.0	311/4	355.6	−49.9	12.2	25.3	86.2	33.9	
1		SED	7/7	358.6	−31.2	311/4	356.8	−34.2	6.8	78.9	77.1	102.1	
Mean			8	353.3	−36.2	–	352.4	−40.5	8.0	49.2			

Table 1. (Continued).

Site		Lith	N/N_0	In situ Dec.	Inc.	Strike/dip	Tilt corrected Dec.	Inc.	a_{95}	k	VGP °S	°E	
El Pungo (Lat. 31.0°S; Long. 64.46°W)													
A4	(10)	BAS	2/6	113.7	73.3	94/35	160.7	46.8	20.5	150.1			
A2+3	(11)	BAS	8/15	349.5	−70.1	94/35	358.0	−35.5	6.3	78.4			
A1		BAS	0/15	–	–	94/35	–		–	–			
B2	(12)	BAS	2/6	102.1	−78.5	108/12	59.5	−72.6	65.7	16.6			
B1	(10)	BAS	7/12	142.6	40.3	108/12	149.7	32.8	12.8	23.2			
C1		BAS	0/9	–	–	108/12	–		–	–			
D4	(12)	BAS	3/3	192.0	−57.2	108/12	188.9	−69.1	12.0	106.3			
D3	(10)	BAS	2/2	143.6	43.7	108/12	151.4	36.1	0.9	75054.6			
D2		BAS	0/6	–	–	108/12	–	–	–	–			
D1	(11)	BAS	6/6	341.9	−37.9	108/12	346.2	−27.9	9.3	52.8			
(12)			5			–	156.1	−79.9	21.4	13.8	−12.8	287.5	#
(11)			14			–	352.7	−32.4	5.7	49.1	−75.1	87.6	
(10)			11			–	151.7	36.1	8.4	30.6	−62.3	42.1	
Mean			2	328.5	−54.0		341.2	−36.3					
				(a_{95} = 19.3; k = 16.7)			(a_{95} = 11.2; k = 48.0)						
			McFadden SCOS = 4.1					1.7 (95 per cent Critical value: 2.6)					
Sierra de Pajarillo-Copacabana y Masa (Lat. 30.72°S; Long. 64.38°W) (Geuna 1996)													
1A		SED	2/2	196.4	29.1	268/5	197.3	33.4	21.4	138.8	−70.0	171.1	
1B	*	SED	7/7	172.9	43.5	268/5	172.4	48.1	11.7	33.2			
2	*	SED	8/8	173.5	24.5	268/5	173.3	29.0	11.1	26.8			
3	*	SED	6/6	162.0	15.2	268/5	161.6	19.6	9.3	53.8			
4		SED	4/4	350.4	−16.4	268/5	350.2	−20.9	8.7	113.4	−68.2	88.8	
5	*	SED	4/4	352.3	−32.1	268/5	351.9	−36.6	8.4	443.6			
6		SED	4/4	348.5	−39.6	242/6	350.2	−45.5	10.9	71.8	−80.6	46.4	
A	*	SED	3/3	345.7	59.3	242/6	343.6	53.2	1.9	4181.0			
B	*	SED	4/4	29.2	−4.8	242/6	29.8	−8.2	10.7	100.9			
7		SED	4/4	173.9	57.6	242/6	178.4	63.3	11.9	60.5	−75.8	300.2	
7	*	SED	1	155.4	61.7	242/6	156.2	67.8	–	–			
8	*	SED	9/9	178.2	3.7	242/6	178.4	9.2	8.5	40.8			
CA		SED	3/3	172.5	39.1	242/6	174.6	44.9	5.8	449.6	−83.7	65.5	
CB	*	SED	2/2	191.3	33.1	242/6	194.2	37.8	1.4	2154.0			
D		SED	5/5	168.9	52.2	242/6	171.8	58.1	8.4	82.9	−79.4	333.0	
E		SED	9/9	188.7	40.7	242/6	192.3	45.6	3.5	219.3	−78.6	189.8	
9A		SED	2/2	169.6	34.7	242/6	171.2	40.6	5.2	2301.1	−79.2	66.9	
9B	*	SED	4/4	177.7	55.0	242/6	182.3	60.5	27.7	41.7			
10		SED	2/2	152.3	39.8	242/6	152.3	46.0	18.7	180.5	−65.6	26.3	
F	*	SED	3/3	171.6	34.3	232/5	173.3	40.1	21.1	95.0			
G		SED	6/6	357.6	−42.5	232/5	0.4	−46.3	4.6	213.7	−86.9	122.8	
H		SED	5/5	0.4	−34.0	232/5	2.6	−37.6	5.4	204.9	−80.1	129.6	
I		SED	5/5	2.1	−35.6	232/5	4.5	−39.1	2.9	678.1	−80.6	141.7	
J	*	SED	4/4	29.2	−25.2	232/5	33.1	−24.4	9.3	111.5			
K	*	SED	2/2	156.1	28.4	232/5	156.2	33.0	22.9	120.6			
L	*	SED	4/4	164.0	24.1	232/5	159.3	20.7	28.0	15.4			
M	*	SED	3/3	92.5	11.1	232/5	143.9	38.1	26.0	63.0			
Mean			12				175.2	38.2	6.8	41.3			

Lith: site lithology (BAS, basalt; SED, sedimentary rock; B+S, basalt directions combined with that of the underlying heated sediment).
N/N_0: number of specimens used in statistics/number of demagnetized specimens.
Dec., Inc.: declination and inclination. a_{95} and K are Fisher's (1953) statistical parameters. Blank entries indicate no consistent results. (1) indicates that the site has been grouped with other correlative sites with the same number in brackets, after tilt correction. A+B indicates successive sites grouped because of statistical coincidence.
† Recalculated from Valencio (1972) in Geuna & Somoza (1996);
‡ Recalculated from Vilas (1976).
* Bicomponent red beds; final component was discarded because undetected mixture not resolved.
# VGPs discarded for PP calculation, for reasons discussed in text.

belonging to the Lower Cretaceous Sierra de Los Cóndores Group were sampled from three localities. The clasts ranged in size from about 5 to 20 cm. One to three specimens per clast were subjected to AF demagnetization. The three magnetic components (A, B and X) were detected in variable proportions, as in the lava flows. The clasts were classified according to the relative importance of the components A and B:

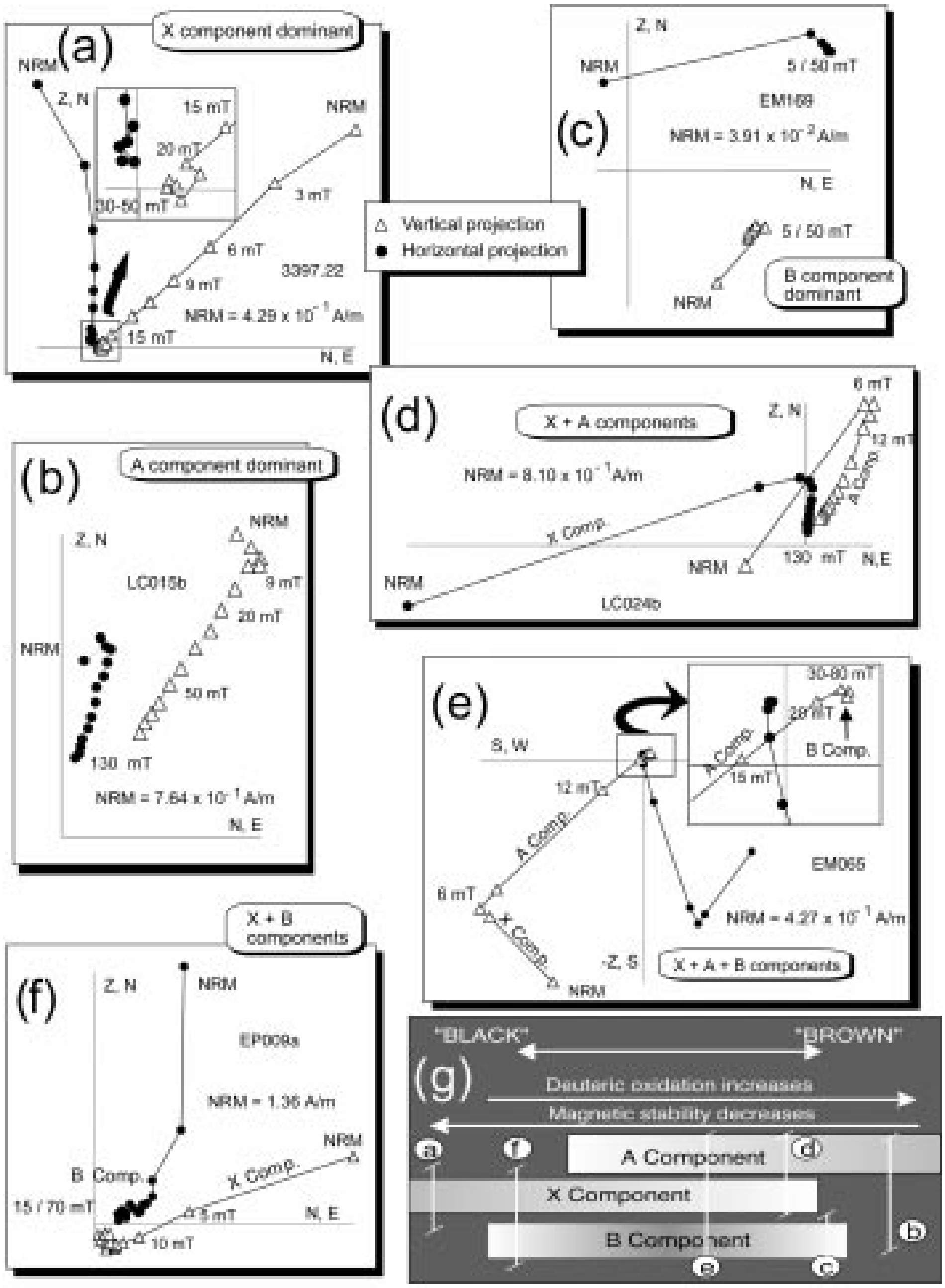

Figure 2. (a)–(f) Zijderveld diagrams showing typical behaviour for the volcanic samples during AF demagnetization (explanations given in text). (g) Schematic explanation of the distribution of magnetic components according to the degree of oxidation of the basalts. Letters in this box represent the proposed situation of the examples illustrated (a to f). Most commonly samples are in the oxidized field, examples (b) and (d).

clast type 1—recorded only component A;
clast type 2—recorded both component A and component B;
clast type 3—recorded only component B.

Component A in clast types 1 and 2 has a random distribution according to the value of X2 obtained for the population of their directions (Fig. 6a); the directions of this component in lava flows are, additionally, very well grouped (see k values in Table 1). On the other hand, the directions that belong to component B isolated in clast types 2 and 3 were well grouped about the present geomagnetic dipolar field direction (Fig. 6b).

A positive conglomerate test for the directions of component A implies that this component could have been acquired by the basalts during deuteric alteration, which, according to Gordillo & Lencinas (1967b), was simultaneous with the cooling of the flows. This result means that only component A can be considered as a primary component of magnetization, whilst component B is related to later reddening due to weathering.

Igneous contact test. The igneous contact test was performed on a basaltic dyke intruding andesitic flows in the El Salto–Almafuerte locality. Both the dyke and the host rock belong to the same volcanic cycle (Gordillo 1971) and have similar K/Ar ages (Gonzalez & Kawashita 1971; Mendıa 1978). The dyke is northwest trending, subvertical and 1.5–2 m wide; there is no visible evidence of baking in the andesitic rock.

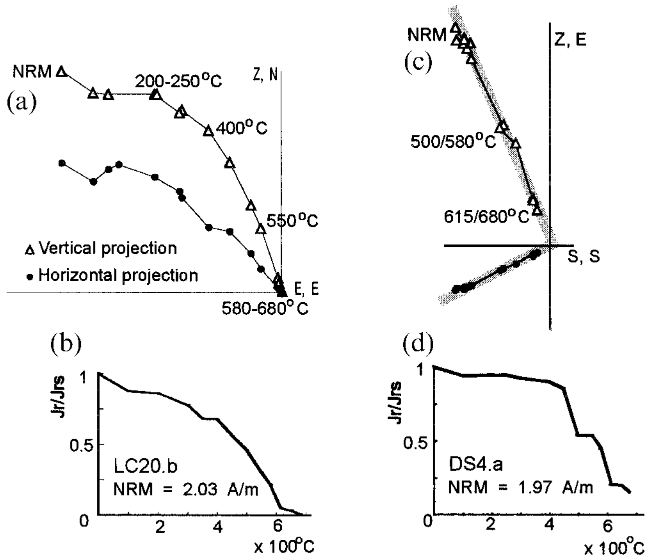

Figure 3. Typical behaviour of the volcanic samples during thermal demagnetization. (a) and (b) Zijderveld and demagnetization diagram for samples with dominant X component. (c) and (d) Zijderveld and demagnetization diagram for samples with dominant A component (explanations given in text).

Four samples were taken from the dyke, four from the host rock near the dyke and five from the host about 10 m from the contact. All samples recorded component A. The andesitic flow at 10 m from the dyke recorded a direction with positive inclination (A_R), whereas the dyke and the flow near the dyke carried a common negative-inclination component (A_N, Fig. 7). Our interpretation is that the heating of the dyke remagnetized the host rock close to the contact, but did not affect it at a distance of 10 m.

Sedimentary rocks

Sedimentary rocks were sampled in localities with only red beds (Saldan, Sierra de Pajarillo–Copacabana–Masa) or in localities that have red beds interbedded with basaltic flows (Sierra de Los Condores). Results obtained from the sedimentary rocks were discussed in detail by Geuna (1996, 1997).

The NRM intensity ranged from 1×10^{-2} to 5×10^{-2} A m^{-1}. Thermal demagnetization was effective up to 550 °C; large increases in magnetic susceptibility were observed above 550 °C in some cases. The growth of a new magnetic phase sometimes prevented the determination of the final demagnetization.

However, most of the specimens showed residual directions with a straightforward decay to the origin after several steps of thermal demagnetization; a single component of magnetization with a high unblocking temperature and high coercivity was isolated (Figs 8a, b and c). IRM acquisition and backfield and thermal demagnetization of triaxial IRM curves suggest that the carriers of the remanence are magnetite and haematite in varying proportions (Figs 8b, c, e and f), both usually carrying the same component. Directions of this component are compared with component A isolated in volcanics in Fig. 9.

Some red bed samples covered by basaltic flows showed two distinct components of medium and high unblocking temperatures, carried, respectively, by magnetite and haematite (Figs 8d, e and f). The medium-unblocking-temperature component recorded a direction coincident with that of the overlying basaltic flow and was removed at about 580 °C. The samples with this component have higher magnetic intensities and higher values of susceptibility. We interpret magnetite carrying this component as a secondary mineral related to the extrusion of the lava flows. On the other hand, the component carried by haematite recorded a different direction not reset by the heating of the flows. The high-temperature component of these specimens was usually determined by a combination of demagnetization circles and characteristic remanence directions using the method of McFadden & McElhinny (1988). The resulting component is included in Table 1, but it was not considered in later procedures because some overlap might not be resolved using this method.

Revision of previous studies

Four Cretaceous PPs from volcanic localities of Sierra Chica were obtained from samples collected in 1969 by D. Valencio and colleagues. We re-examined the data in two ways: first, we checked that the demagnetization procedure had been thorough enough to isolate a characteristic remanent magnetization (ChRM), or otherwise what type of component (X or B) had been isolated. We also processed in detail 84 new specimens of samples remaining from the original collection, and the new results were compared with the previous palaeomagnetic data obtained by Valencio and/or colleagues, whose original files were inspected with the kind help of Dr J. Vilas.

We also tested the statistical/geological independence of the sampling sites to prove that the N-values of the directions of previous PPs had not been overestimated. In the following we compare the new and old results for each locality.

Vulcanitas Cerro Colorado (Valencio 1972). This study was performed on the lower volcanic member of the Sierra de Los Condores Group, in the area of Sierra de Los Condores (Fig. 1). Samples of basalts from Cerro Colorado recorded both component X and component A. Component X was eliminated between 15 and 30 mT, but the demagnetization applied by Valencio (1972), up to 30 mT, was sometimes not enough to detect a final component. Our new analysis combined demagnetization circles and directions, using the method of McFadden & McElhinny (1988), to determine new site mean directions. This methodology was previously used by Geuna & Somoza (1996) with the previous palaeomagnetic data of the original files of Valencio. After applying the McFadden & Lowes (1981) test for directions of successive flows, five independent spot-readings of the Earth's magnetic field were obtained (see Table 1).

Rio Los Molinos Dykes (Linares & Valencio 1975). Mean directions from dykes of the previous study included six of reversed polarity and two of normal polarity for the locality shown in Fig. 1. Linares & Valencio (1975) suggested, from the presence of both polarities, that the PSV had been averaged, despite the small number of sites involved.

K/Ar ages of the eight dykes fell in two age groups, Early Cretaceous (141 Ma) and Late Cretaceous–Tertiary (65 Ma). Linares & Valencio (1975) suggested that these two ages could belong to different intrusive events, separated by 75 Myr. However, dykes of apparently different ages have strong similarities. All intrude the same basement rocks with roughly the same trend, all have similar chemical compositions (Gordillo

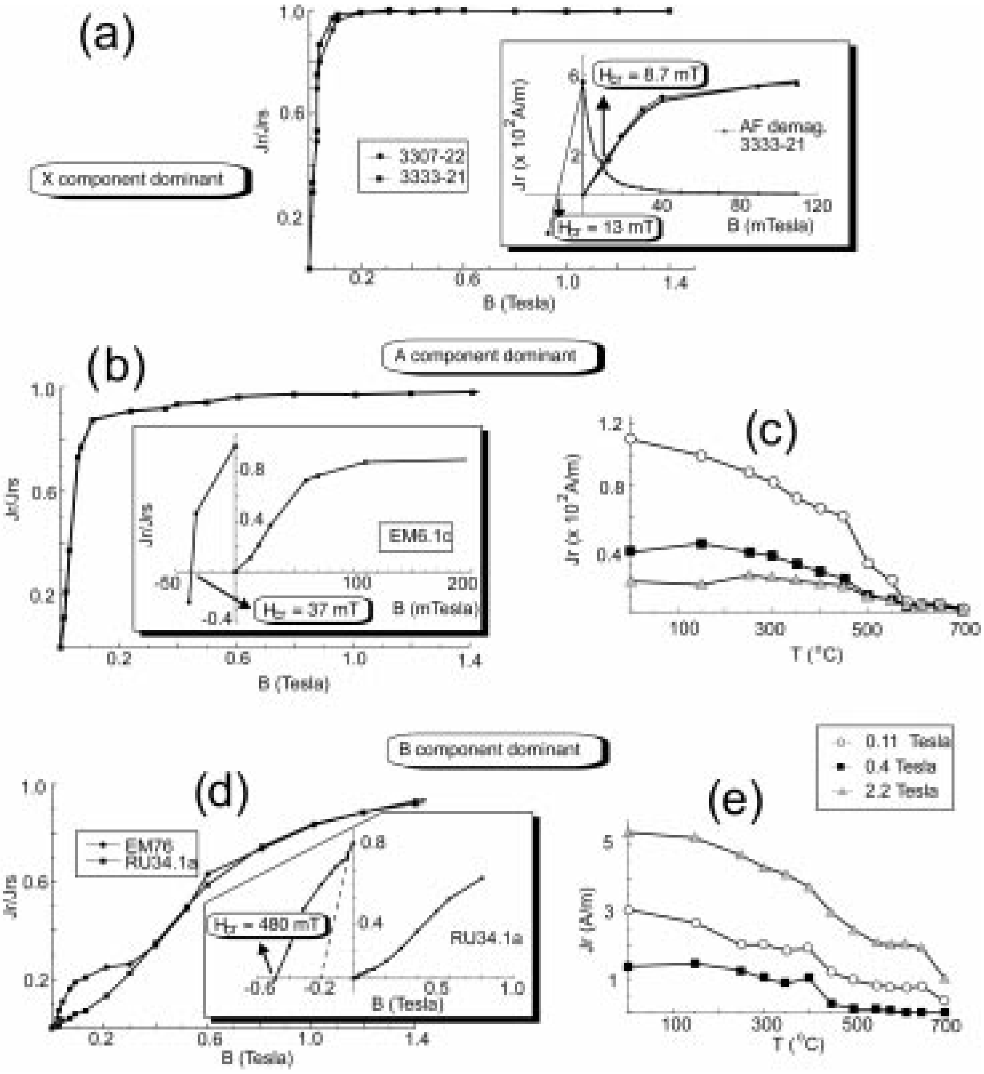

Figure 4. Rock magnetism in volcanic samples. (a), (b) and (d) are IRM acquisition curves, including determinations of H_{cr} (in the frame). (a) Note the similarity of the H_{cr} values determined using AF demagnetization of IRM (Cisowski 1981) and backfield methods. (d) Rough value of H_{cr}. (c) and (e) Thermal demagnetization of IRM on three axes (Lowrie 1990), showing (c) magnetite as main carrier (oxidized basalt) and (e) haematite as main carrier, with subordinate magnetite (reddened clasts of basalt).

& Lencinas 1969), and closed directions of positive inclinations are recorded by almost all of these dykes (Linares & Valencio 1975). These positive directions are similar to that of component A in the volcanics.

Low- and medium-coercivity components isolated in specimens analysed in this study were similar to components X and A identified in the Sierra de Los Condores volcanics. Two palaeomagnetic sites interpreted by Linares & Valencio (1975) as recording normal polarity are composed predominantly of the unstable X component. Our interpretation is thus that the directions of normal polarity belong to the present geomagnetic field.

The well-grouped component A recorded by the dykes (Table 2) shows that they could belong to just one Early Cretaceous geological event; the younger ages could be related to some sort of later alteration. In fact, there is a petrographical difference between the two age groups: the groundmass of the dykes with older ages is formed of analcime or sanidine, while the groundmass of dykes with younger ages is formed of volcanic glass (Gordillo & Lencinas 1969) that could have undergone alteration, leading to younger K/Ar ages.

Vulcanitas Rumipalla (Vilas 1976). Vulcanitas Rumipalla is the upper member of the Sierra de Los Condores Group in the Sierra de Los Condores (Fig. 1); samples of this section recorded mainly component A, and the new results were broadly coincident with those of Vilas (1976). However, several successive flows were probably not independent spot-readings of the Earth's magnetic field. After applying McFadden & Lowes' (1981) statistics, the directions were grouped into only five records, as considered previously by Geuna & Somoza (1996) using the original files employed by Vilas (1976).

El Salto-Almafuerte (Mendía 1978). This paper included a palaeomagnetic study of a volcanic sequence cropping out just a few kilometres to the northeast of Sierra de Los Condores (Fig. 1). Mendía (1978) reported seven reversals of the Earth's magnetic field, based on 15 sites with both 'stable remanent magnetization' and discarded 'unstable NRM' (sic). The latter actually belongs to component X of this study.

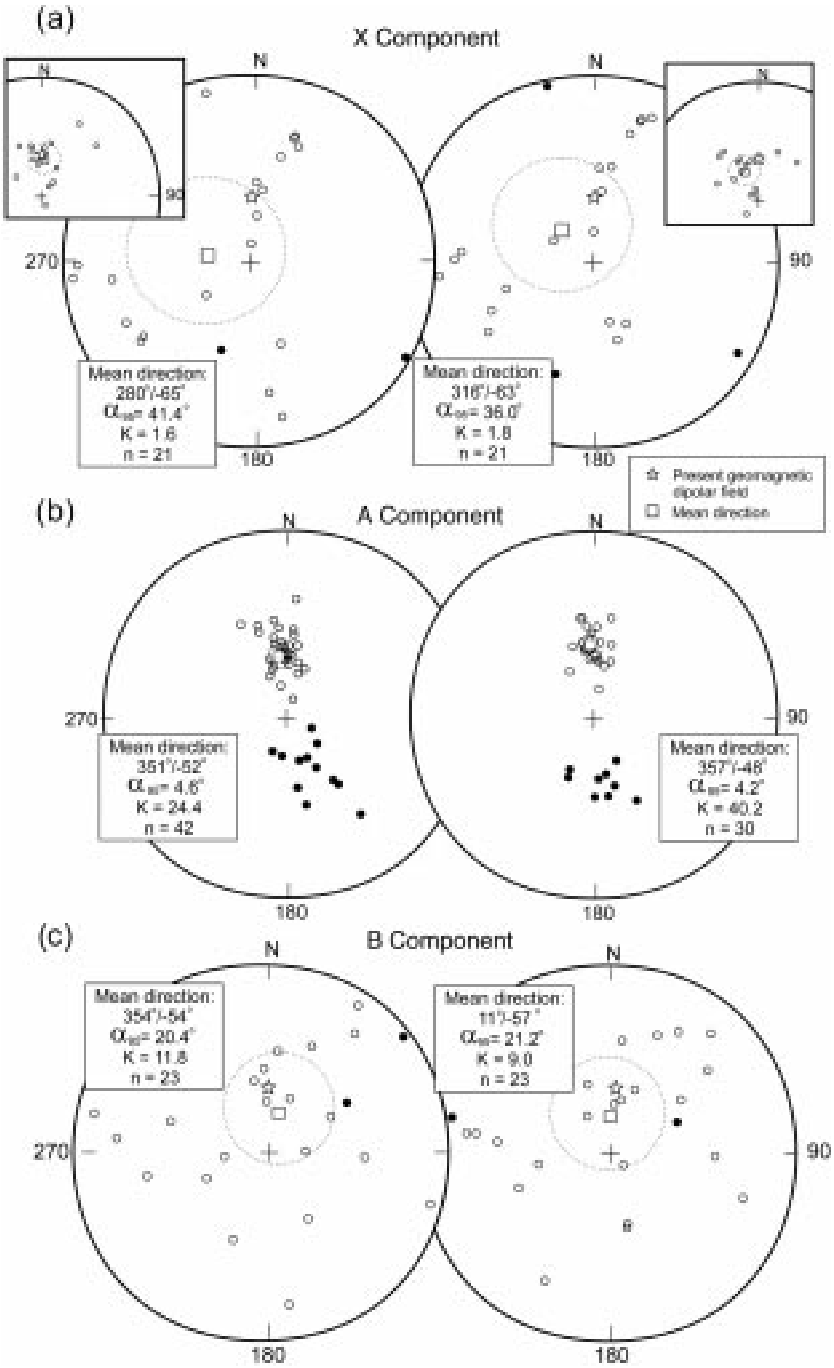

Figure 5. Site mean directions of magnetic components in volcanic rocks, in situ (left) and tilt corrected (right). (a) X component; in box: soft component isolated at El Salto–Almafuerte, broadly coincident with the dipole field direction. (b) A component; (c) B component.

The outcrops of this locality are extensively covered by recent sediments, but it is possible to detect the same volcanic sequence in five similar inclined blocks separated by normal faults (Schroeder 1967). The whole volcanic sequence is intruded by dykes (Schroeder 1967; Gordillo 1971); one of these was used in this study to perform the igneous contact test (see previous section).

After isolating component A from samples of all sites, it was observed that four individual lava flows recorded both polarities in different samples from the same site, just as in the andesitic flow that was the 'host rock' to a basaltic dyke where the baked contact test was performed (see above). It is possible that dykes (not observed during sampling) could be responsible for local heating, causing local thermal magnetizations with opposite inclinations to those previously recorded. Considering what is observed in the section where the baked contact test was carried out, we interpret the normal polarity of these four volcanic flows to belong to the same intrusive event as the observed dyke, and we group them into only one mean direction. The reversed polarity directions are interpreted as the original remanence.

Two lava flows recorded directions with only normal

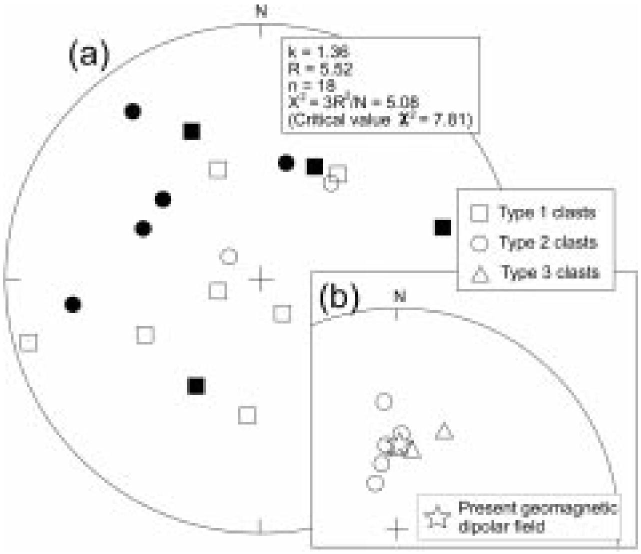

Figure 6. Conglomerate test performed on basaltic clasts of conglomerates of the Sierra de Los Condores Group; directions of the isolated magnetic components are shown on equal-area projections. Open/solid symbols: negative/positive inclination. (a) Directions of the component A, with results of statistical test of uniformity. (b) Well-grouped directions of component B.

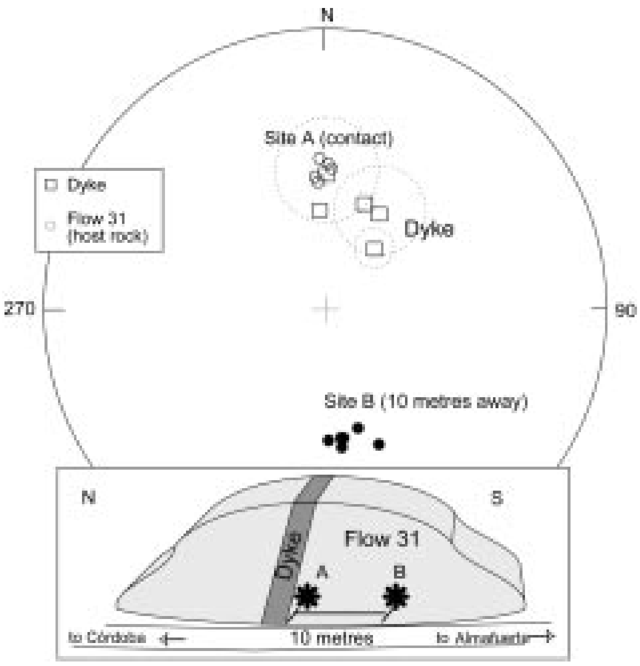

Figure 7. Baked contact test performed on an andesitic flow intruded by a basaltic dyke. Directions of the component A are shown in equal-angle projection. Open/solid symbols: negative/positive inclination. In box: position of the samples used in the test.

polarity, assumed to be a primary magnetization; however, it is impossible to rule out the option that they were remagnetized during the intrusion of dykes.

After applying structural corrections, it was observed that the directions recorded in flows from different blocks were coincident. This suggests that this volcanic sequence is probably repeated by faults, so we averaged the directions of different blocks (see Table 1).

We obtained 11 mean directions, of which only two were of normal polarity. Instead of the seven reversals suggested by Mendía (1978), in our interpretation we have only three periods of different polarities: the first, of normal polarity, at the base of the sequence (the two flows mentioned above); the second, of reverse polarity, at the top; and the third possibly related to the intrusion of dykes.

MEAN 125 MA PALAEOMAGNETIC POLE POSITION FOR SIERRA CHICA DE CORDOBA

Before obtaining the virtual geomagnetic poles (VGPs), all the directions of stratigraphically adjacent volcanic flows were compared, using the method of McFadden & Lowes (1981), to define cooling units, as was done by Butler et al. (1991). In other words, if the directions were not statistically distinguishable, they were averaged to obtain a unique mean direction, thus avoiding biasing the palaeomagnetic data towards the directions recorded during fast volcanic extrusions.

In general, no more than two adjacent flows were averaged after applying this method, except in the locality of Despenaderos (Fig. 1), where almost all volcanic flows recorded quite similar directions (see Table 1). In each locality, the site mean directions or cooling units passed the tilt test (Table 1); they were then used to calculate VGPs (Fig. 10a).

The palaeopoles of each locality are illustrated in Fig. 10(b). They are grouped close to the geographical pole; it is noteworthy that the smaller intervals of confidence (A_{95}) belong to the localities with the greatest numbers of sites, such as Sierra de Los Condores and Sierra de Pajarillo–Copacabana–Masa. Palaeopoles of El Salto–Almafuerte and Río Los Molinos are discordant.

Although the population of VGPs from each locality is 'clustered' according to the method of Woodcock & Naylor (1983; shape parameter > 1, see Table 3), those from El Salto–Almafuerte and Saldan are particularly elongated. In fact, after applying the statistics of Engebretson & Beck (1978), we observed that the ratio between the maximum and minimum axes (a/b) is greater than 2 (Table 3).

The elongation of the El Salto–Almafuerte VGP population reported by Mendía (1978) was commented on by Castillo et al. (1991), who suggested that it could be due to incomplete demagnetization. We obtained new directions after applying accurate and detailed demagnetization processes supported by field tests. However, the new population of VGPs is also elongated. We suggest that this elongation is due to an improper structural correction of some beds (the tilt test is not statistically significant, Table 1) or to an incomplete average of the PSV ($n=11$). For these reasons, the VGPs from El Salto–Almafuerte are not considered in further analyses.

In the locality of Saldan there are also few palaeomagnetic sites ($n=6$); however, the palaeopole from this locality overlaps the more reliable ones of Sierra de Los Condores and Sierra de Pajarillo–Copacabana–Masa. The process of magnetization of the Saldan red beds may have averaged the PSV.

Finally, the new version of the Río Los Molinos palaeopole is strongly discordant with respect to the remaining poles. As it is based on only six reversed directions recorded by dykes, we assume that the PSV is not averaged. Furthermore, K/Ar ages reported for these dykes are a little older than ages

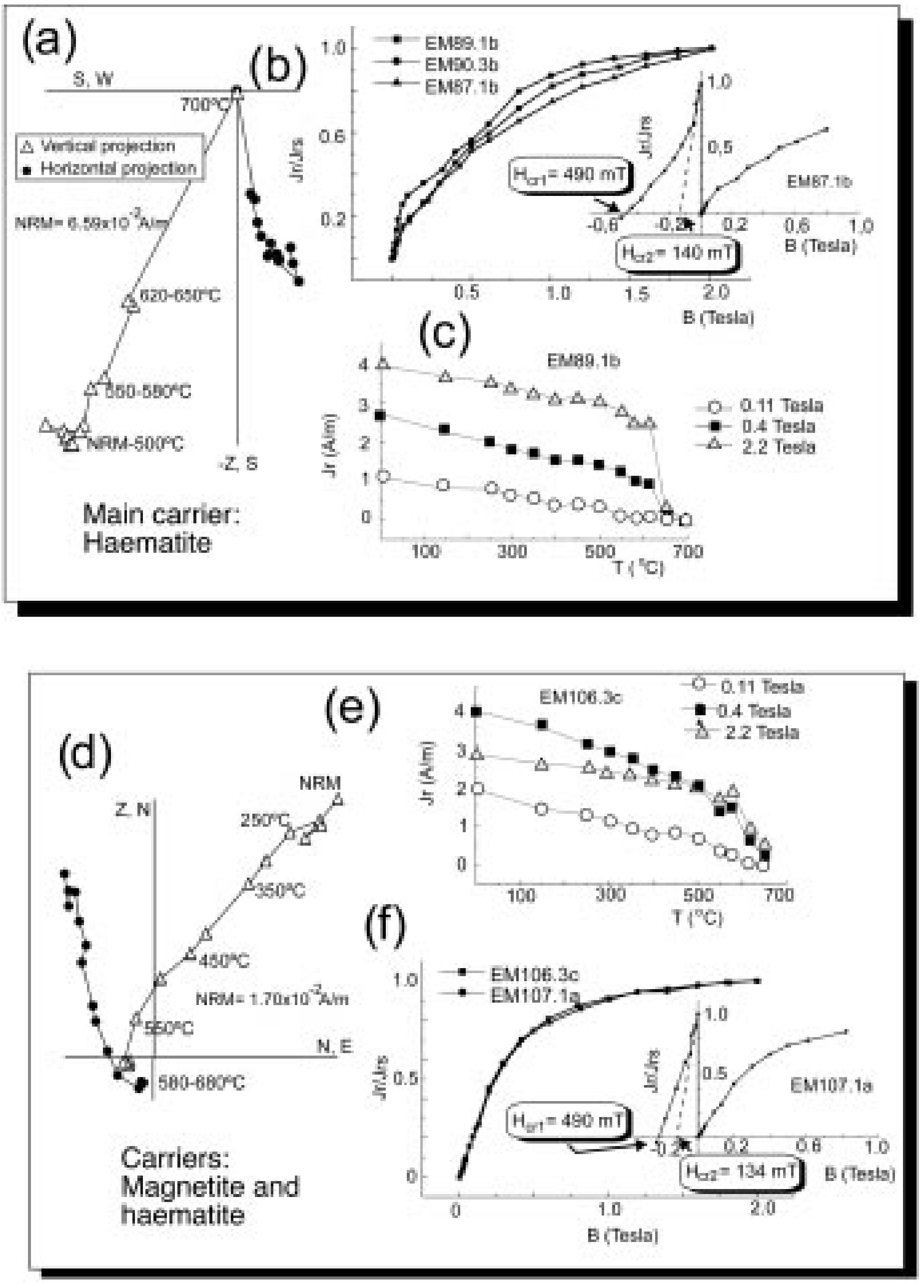

Figure 8. Magnetic behaviour of sedimentary samples. (a) and (d) Zijderveld diagrams showing typical behaviour during thermal demagnetization. (b), (c), (e) and (f) Rock magnetism in red bed samples. (b) and (f) are IRM acquisition curves, including rough estimations of H_{cr}. (c) and (e) Thermal demagnetization of IRM in three axes, showing (c) haematite as main carrier, with subordinate magnetite, and (e) stable magnetite and haematite as main carriers.

Table 2. Palaeomagnetic data for the Río Los Molinos Dykes (Lat. 31.8°S, Long. 64.52°W). References as in Table 1.

Site	Lith	N/N_0	In situ		Strike/dip	Tilt corrected		a_{95}	k	VGP	
			Dec.	Inc.		Dec.	Inc.			°S	°E
Dyke 4	BAS	13/17	165.9	51.6	0/5	160.0	50.1	6.5	43.1	72.9	23.3
Dykes 8 & 9	BAS	8/28	166.4	60.1	0/5	158.4	58.6	5.8	93.2	70.9	356.3
Dyke 10	BAS	3/8	184.9	57.8	0/5	176.9	57.9	20.8	36.0	82.8	315
Dyke 11	BAS	4/4	166.1	74.7	0/5	150.1	72.8	5.4	292.2	56.7	324.0
Dyke 13	BAS	2/8	151.6	57.1	0/5	145.3	54.5	6.1	1657.1	61.0	9.6
Dyke 14	BAS	8/22	167.6	44.2	0/5	163.0	42.9	10.5	29.2	73.6	45.8
Mean		6	167.1	57.9		159.6	56.5	9.7	48.9		

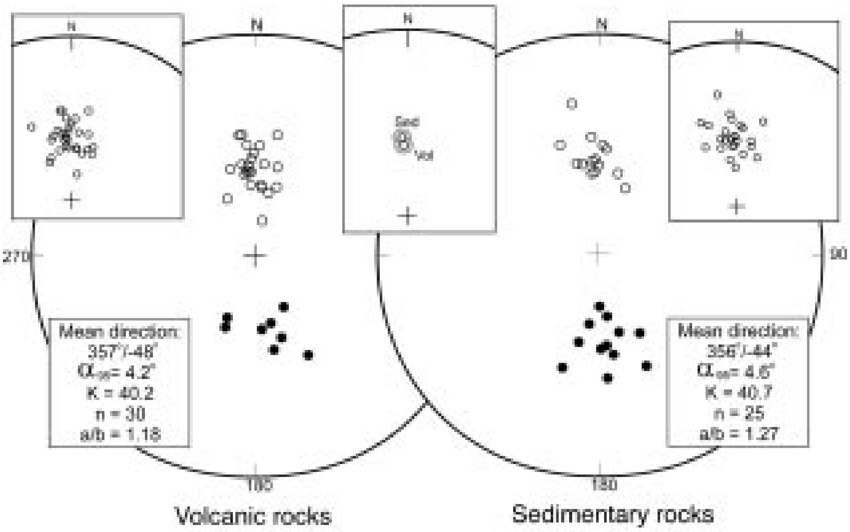

Figure 9. (a) Site mean directions of volcanic rocks of the Sierra de Los Cóndores Group. (b) Site mean directions of sedimentary rocks. Note the coincidence in mean directions, scatter and shape distributions.

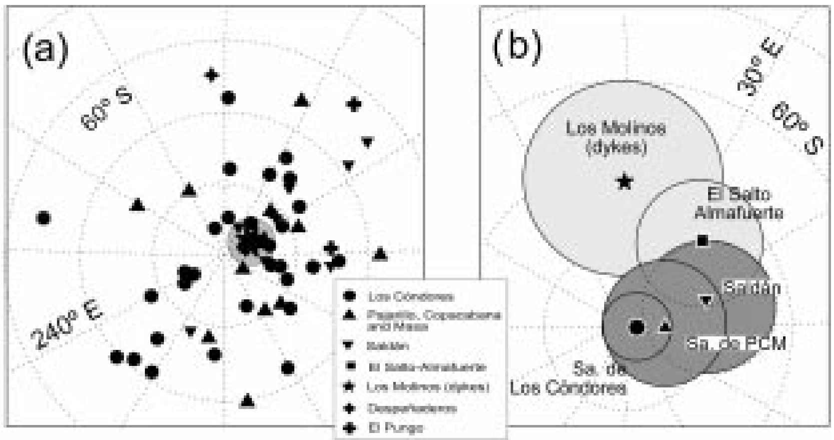

Figure 10. Palaeomagnetic data of the Sierra de Los Cóndores Group in Sierra Chica de Córdoba, in the southern hemisphere, represented on equal-area projections. (a) VGPs and mean palaeomagnetic pole, with 95 per cent confidence circle. (b) Palaeopole of each locality; note the discrepancy between El Salto–Almafuerte, Río Los Molinos Dykes and the other poles.

Table 3. Statistical parameters for VGP populations by localities from Sierra Chica, Córdoba.

	Locality	N	S	S_u	S_l	a/b	w	c	f	Class (*)
1	Sa. de Los Cóndores	33	13.4	16.1	11.5	1.35	−97	5.5	4.0	Str. Cl.
2	Sa. de Pajarillo, Cop. y Masa	12	13.7	18.8	10.8	1.27	−71	7.5	3.9	Str. Cl.
3	El Salto–Almafuerte	11	13.5	18.8	10.5	2.94	−66	1.4	5.2	Cl. to G.
4	Saldan	8	11.9	17.6	9.0	2.48	−111	1.9	5.2	Cl. to G.
5	Los Molinos dykes	6	14.1	22.2	10.3	1.45	−18	4.8	4.1	Str. Cl.
6	Despenaderos	2	–	–	–	–	–	–	–	–
7	El Pungo	2	–	–	–	–	–	–	–	–
	Total (1+2+4+7)	55	13.6	15.6	12.0	1.40	–104	4.8	3.9	Str. Cl.

N: number of sites; S: angular dispersion $(81^\circ/k^{1/2})$; S_u, S_l: confidence limits for S after Cox (1969); a/b: ratio between distribution axes (Engebretson & Beck 1978) w: angle between elongation in the VGP and palaeomeridian; c and f: shape and strength parameters (Woodcock & Naylor 1983). (*): Classification after Woodcock & Naylor (1983): Str. Cl. strong cluster; Cl. to G. cluster transitional to girdle.

assigned to the Sierra de Los Cóndores Group (Early Cretaceous, Gordillo & Lencinas 1980).

When all site mean directions of the Lower Cretaceous outcrops of Sierra Chica de Córdoba are considered together, excluding the somewhat older Río Los Molinos dykes and the doubtful El Salto–Almafuerte volcanics, they pass the tilt test (Table 4 and Fig. 11) and the reversal test (class B, McFadden & McElhinny 1990).

The population obtained with these directions is practically circular, with a slight elongation (a/b = 1.4, Engebretson &

Table 4. Statistical parameters of positive tilt test (after McFadden 1990).

Mean direction	Dec.	Inc.	a_{95}	K	j (McFadden 1990)
In situ	352.1	−47.9	3.5	24.8	30.49
Palaeohorizontal	356.0	−46.4	2.8	39.0	0.49

SCOS critical values: 95% 9.52
99% 13.46

Beck 1978) along a great circle roughly perpendicular to the meridian of the sampling localities. The angular dispersion of this VGP population is 13.6, similar to others reported for Lower Cretaceous palaeomagnetic data of South America at similar latitudes, for example the Parana Basin Basalts (Ernesto et al. 1990) and the Ponta Grossa Dykes (Raposo & Ernesto 1995).

A palaeomagnetic pole, based on all site mean VGPs of Sierra de Los Condores, Sierra de Pajarillo–Copacabana–Masa, Saldan, El Pungo and Despenaderos was calculated. Its geographical coordinates and statistical parameters are Lat. 86.0°S, Long. 75.9°E ($A_{95}=3.3$, $K=35.2$, $N=55$). This PP agrees with other South American PPs of the same age: the Serra Geral PP (Raposo & Ernesto 1995), the Alkaline Province of Eastern Paraguay PP (Ernesto et al. 1996) and the Maranhao Dykes PP (Schult & Guerreiro 1979).

DISCUSSION

The first palaeomagnetic studies in South America were used for palaeogeographic reconstructions to support the theory of continental drift. For example, studies on Cretaceous rocks from Cordoba Province, which included the Cerro Colorado PP (Valencio 1972) and the Rıo Los Molinos Dykes PP (Linares & Valencio 1975), suggested that the Atlantic Ocean had already opened in the Early Cretaceous, because these PPs did not agree with Cretaceous poles from Africa after a reconstruction of West Gondwana.

Later, the agreement between the Serra Geral Basalts PP (Pacca & Hiodo 1975) and the Kaoko Basalts PP (Gidskehaug et al. 1975) revealed that the age of the opening of the Atlantic Ocean was younger than Early Cretaceous, in agreement with updated studies of seafloor-spreading anomalies. The Cretaceous PPs from Cordoba have remained controversial since then (see Beck 1988). The anomalous PP from El Salto–Almafuerte (Mendıa 1978) reinforced the controversy, and various suggestions were put forward to explain the peculiar distribution of the Cretaceous PPs from Cordoba Province.

Valencio et al. (1983) considered these PPs to define a sequence of rapid continental movements before the opening of the South Atlantic Ocean. The viability of this geodynamic suggestion was discussed by Beck (1988). He preferred to discard the extreme values of the elongated population of South America Cretaceous PPs (i.e. the El Salto–Almafuerte and Rıo Los Molinos Dykes PPs) and calculated only one mean Cretaceous PP for the continent. Castillo et al. (1991), after applying a similar procedure, obtained a mean PP that coincided with the present geographical pole, and suggested that South America did not experience any latitudinal movement during the Cretaceous, which contrasts with the absolute plate motion inferred from hotspot tracks (Morgan 1983). Other authors, such as Cembrano et al. (1992) and Somoza (1994), decided to select just two or three Cretaceous PPs, respectively, from South America as a reference for their tectonic models.

In this study, we suggest that both the previous and the new palaeomagnetic data from the Rıo Los Molinos Dykes and El Salto–Almafuerte are not useful for geodynamic or tectonic models. The palaeomagnetic data from the Rıo Los Molinos Dykes are not sufficient to average the PSV properly, and cannot be grouped with data from the other localities because of their age difference. An inadequate structural correction could account for the anomalous geographical position of the

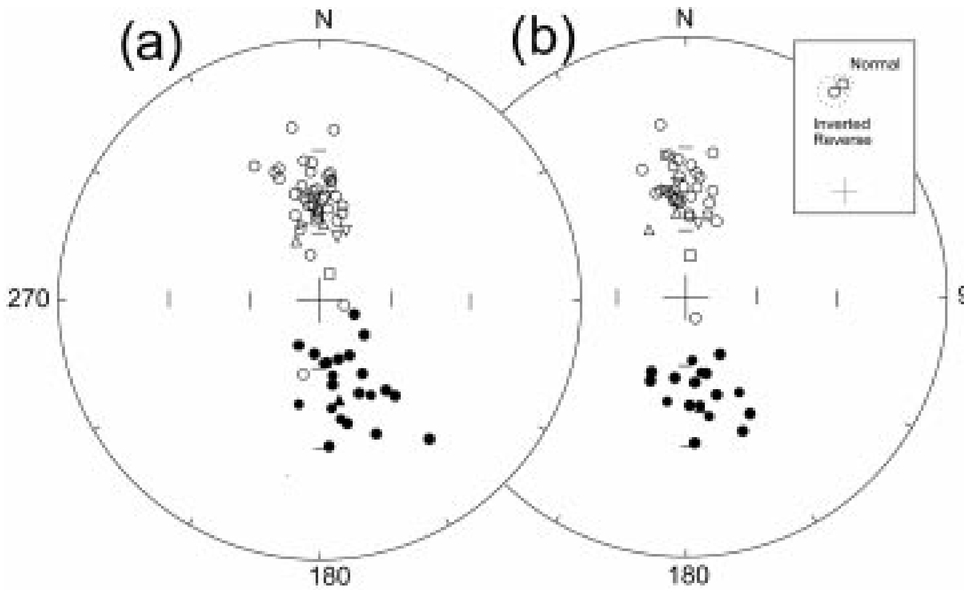

Figure 11. Site and cooling unit mean directions. Open/solid symbols: negative/positive inclination. (a) In situ. (b) After structural correction. In box: positive antipodal test (class B after McFadden & McElhinny 1990).

El Salto–Almafuerte PP and the elongated distribution of its VGPs.

On the other hand, we provide a fairly reliable Early Cretaceous palaeopole, here called the Sierra de Los Condores PP (Lat. 86.0°S, Long. 75.9°E, $A_{95}=3.3°$, $K=35$), whose palaeomagnetic directions pass reversal, conglomerate and tilt tests. This PP supersedes four previous conflicting PPs from the Cordoba Province (Fig. 12). Neither geodynamic explanations nor further recalculations are needed to explain the geographical position of this new PP. It agrees with other reliable Early Cretaceous South American PPs, such as those of Serra Geral (Raposo & Ernesto 1995), the Alkaline Province of Eastern Paraguay (Ernesto et al. 1996) and the Maranhao Dykes (Schult & Guerreiro 1979). These PPs define an Early Cretaceous pole position that can be clearly distinguished from the present geographical pole and from the mid-Cretaceous pole position defined earlier by Somoza (1994) and Raposo & Ernesto (1995).

CONCLUDING REMARKS

(1) A new palaeomagnetic study has been carried out in Sierra Chica de Cordoba (Argentina) on Early Cretaceous rocks. The ChRM isolated from the basalts studied, here called component A, passes field and reversal tests.

(2) A new Early Cretaceous PP has been obtained from the VGPs of the directions that belong to the ChRM. The geographical coordinates and statistical parameters of the Sierra de Los Condores PP are Lat. 86.0°S, Long. 75.9°E, $A_{95}=3.3°$, $K=35$.

(3) This new PP does not include any data from the El Salto–Almafuerte locality. The anomalous position of a PP from this area and the elongated distribution of its VGPs could be due to the small number of sites, which is not sufficient to average the PSV properly, or, more likely, to an inadequate structural correction of the palaeomagnetic directions.

(4) There are insufficient palaeomagnetic data from the Río Los Molinos Dykes to average the PSV. Considering that the age of the dykes is somewhat older than the age of the rest of the Sierra de Los Condores Group, we cannot group them with the other results from Sierra de Los Condores. A PP obtained from the dykes is not useful in any geodynamic or tectonic models.

(5) The new Sierra de Los Condores PP from Córdoba Province supersedes previous PPs based on too few spot-readings of the Earth's magnetic field. These PPs either overestimated the number of directions isolated in lava flows that belong to cooling units, or had insufficient data to completely average out the PSV.

(6) This new PP is in agreement with other reliable Early Cretaceous PPs from South America whose geographical positions are clearly distinguishable from the present geographical pole and from the mid-Cretaceous PP.

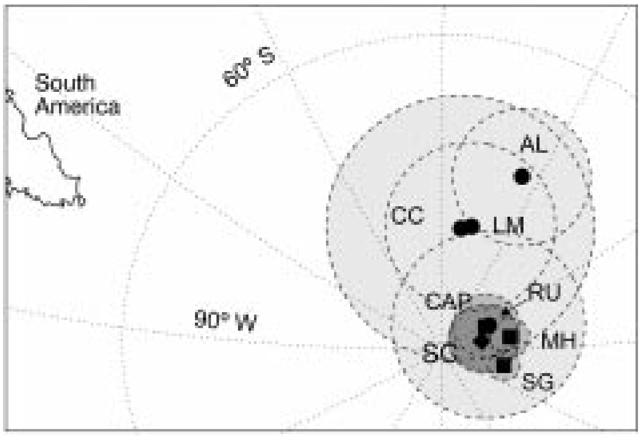

Figure 12. Palaeomagnetic pole for the Sierra Chica de Córdoba (125 Ma, Early Cretaceous) with 95 per cent confidence circle, compared with previous PPs. Southern hemisphere equal-area projection. SC (diamond): Sierra de Los Condores, this work. Squares are coincident Early Cretaceous South American PPs: SG, Serra Geral (Raposo & Ernesto 1995); CAP, Central Alkaline Province of Eastern Paraguay (Ernesto et al. 1996); MH, Maranhao Dykes (Schult & Guerreiro 1979). Circles with lighter 95 per cent confidence circle are previous PPs of Sierra Chica de Cordoba: CC, Vulcanitas Cerro Colorado (Valencio 1972); LM, Río Los Molinos Dykes (Linares & Valencio 1975); RU, Vulcanitas Rumipalla (Vilas 1976); AL, El Salto–Almafuerte (Mendía 1978).

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Dedicated to the memory of Daniel A. Valencio.

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