PALEOMAGNETIC RESULTS FROM CRETACEOUS ROCKS IN THE LLAILLAY - SAN FELIPE - PUTAENDO REGION: IMPLICATIONS FOR BLOCK ROTATIONS IN THE ANDEAN FOREARC

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ABSTRACT

Block rotations in the Andean forearc are well documented by paleomagnetic studies, but the processes causing these rotations are not well understood. Lower Cretaceous volcanic and volcanogenic rocks in the San Felipe - Llaillay region retain strong and stable remanent magnetizations. Twelve sites north of Putaendo have distinct high-temperature and low-temperature magnetizations; these indicate that the area has been rotated clockwise by about 15° and possibly translated northward (relative to the stable interior of South America) as well. A similar amount of rotation (but no northward translation) is implied by the mean direction for ten other sites scattered between Llaillay and San Felipe. However, the mean direction for six tuffaceous beds in the Las Chilcas Formation located some 10 km farther south is not rotated (but may not represent a valid paleomagnetic dipole field direction). In general, the directions in these rocks support models for local block rotation not accompanied by large-scale transport. Polarities are entirely normal, suggesting that the rocks were magnetized after about 125 Ma.

Key words: Block rotation, Remanent magnetization, Andean forearc, Lower Cretaceous, Las Chilcas Formation, Chile.

RESUMEN

En el antearco andino se conocen rotaciones de bloques bien documentadas paleomagnéticamente; sin embargo, el proceso causante todavía no ha sido bien comprendido. Las rocas volcánicas y volcanogénicas,del Cretácico Inferior, en seis localidades del sector de San Felipe y Llaillay, retienen magnetizaciones remanentes fuertes y estables. Doce sitios ('sites'), al norte de Putaendo, tienen claras magnetizaciones de alta y baja temperatura; ellas señalan que el área ha sido rotada en sentido horario, alrededor de unos 15° y, posiblemente, también transladada hacia el norte (en sentido relativo al cratón estable interior de Sudamérica). Un ángulo de rotación similar, sin translación hacia el norte, está implícito en la dirección promedio para otros diez sitios dispersos entre Llaillay y San Felipe. Sin embargo, la dirección media para seis capas tobáceas de la Formación Las Chilcas, ubicadas unos 10 km más hacia el sur, no está rotada (aun cuando podría no representar una dirección válida del campo magnético dipolar). En general, la dirección en estas rocas está de acuerdo con modelos relacionados con la rotación local de bloques sin acompañamiento de transporte en gran escala. Las polaridades son totalmente normales, sugiriendo que las rocas fueron magnetizadas después de alrededor de 125 Ma.

Palabras claves: Rotación de bloque, Magnetización remanente, Antearco andino, Cretácico Inferior, Formación Las Chilcas, Chile.

INTRODUCTION

In this paper the paleomagnetism of Early Cretaceous Las Chilcas Formation and related rocks is discussed, and results obtained by the authors are interpreted in terms of various models for rotation of continental lithosphere within the leading edge of the South American plate.

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PLATE TECTONICS, MICROPLATE TECTONICS, AND BLOCK ROTATIONS

The Andean Cordillera provides the name for an appealingly simple (but hypothetical) type of orogeny (Dickinson, 1976) in which long-continued subduction of oceanic lithosphere beneath continental lithosphere leads to evolution of a forearc/magmatic arc/backarc system characterized by crustal thickening, deformation, and continental growth. However, it has been shown recently that at least one superficially 'Andean' orogen, the North American Cordillera, actually owes most of its growth to accretion of 'prefabricated' crustal blocks, termed tectonostratigraphic terranes, and their subsequent dispersal along the continental margin by strike-slip faulting (summaries in Beck, 1980, 1989; Jones *et al.*, 1983). This so-called 'microplate' model has been so successful in the North American Cordillera that there has been a tendency to apply it wherever orogens with puzzling tectonic elements are encountered (Nur and Ben-Avraham, 1982), not excepting the original 'Andean' orogen itself.

Tectonic models for the North American Cordillera published prior to the mid 1970's contain hardly a hint of the existence of far-travelled terranes (Burchfiel and Davis, 1971, 1975; Hamilton and Myers, 1966). Clearly this was because the paleomagnetic data base needed to detect large-scale displacements of terranes was lacking. By the late 1970's this had been rectified (summaries in Beck, 1976; Irving, 1979) and, with important input from stratigraphic studies, the 'terrane concept' emerged (Jones *et al.*, 1983). Interest in terranes, in turn, sparked considerable activity in Andean paleomagnetism, as shown by the fact that eleven investigations, in about 20 separate areas, have been completed in Chile alone since 1980. Twenty studies in an orogen that exceeds 3000 km in length is a good beginning, but is certainly inadequate. Nevertheless, based on what data are available, the following interim interpretation is offered:

1. Post-Jurassic accretion seems to be uncommon or absent, at least north of the Nazca-Antarctica-South America triple junction. By contrast, Paleozoic accretion has been established or suggested by several investigators (Mpodozis and Forsythe, 1983; Rapalini *et al.*, 1985; Ramos *et al.*, 1986). Also, accretion seems to have been more active in the Andes north of the Arica deflection (Feininger, 1987; Aspden and McCourt, 1986; Mourier *et al.*, 1988).
2. Despite the existence of long, range-paralleling faults within the Chilean Andes and Coast Range (Liquiñe-Ofqui and Atacama faults, among others) very little paleomagnetic evidence of large-scale transverse displacements has been uncovered. (Such evidence is a striking feature of the North American paleomagnetic data set). A possible exception is magnetization B in the Triassic Pichidangui Formation, sampled by Forsythe *et al.* (1987) between Los Vilos and Los Molles, along the Chilean coast. This magnetization appears to be primary and suggests that the region has been transported roughly 10°-15° northward relative to stable South America.
3. Small rotations are found in many Chilean paleomagnetic data sets; all are clockwise. North of the Arica deflection, but south of Ecuador, rotations are large and consistently counterclockwise. Several explanations have been proposed:
   a. J. Vilas and the late D. Valencio (oral commun., 1986; manuscript in review, 1989) suggested that the rotations are an artifact of improper use of the South American reference path. This is shown for the Cretaceous in figure 1. As seen, Cretaceous reference poles for the craton are strongly streaked (have an elongate distribution) in a direction that is approximately normal to meridian lines, joining sampling sites in Chile and Perú with the South Pole. Jurassic reference poles form a similar pattern. Thus, if Peruvian rocks were magnetized at a time when the reference pole was offset toward Africa at the eastern end of the apparent streak, their declinations would appear to be rotated counterclockwise. (This follows because all methods used to *average* the reference poles give a reference direction roughly identical to the present-day axial dipole direction; Forsythe *et al.*, 1987; Beck, 1988a). Likewise, magnetization when the pole was in the Pacific (western) part of the streak would produce apparent clockwise rotations. This explanation requires that the South American craton oscillated back and forth several times during the opening of the South Atlantic in the late Mesozoic (and possibly into the Tertiary as well, judging from results by Heki *et al.*, 1985). As discussed in Beck (1988a), this raises serious questions

FIG. 1. Equal area projection of south paleomagnetic poles from Cretaceous rocks of South America (solid circles) and Serra Geral pole (square).

about the motion of the South American plate.

b. Japanese investigators have detected a pattern of counterclockwise rotation north of the Arica deflection and have proposed a model based on the orocline hypothesis of Carey (1955). Kono *et al.* (1985) summarized arguments for this point of view. There are formidable space problems and questions about driving mechanism associated with this hypothesis (Beck, 1988a); Isacks (1988) presented a possible model. Note that, even if the Peruvian (counterclockwise) rotations are due to oroclinal bending, clockwise rotations in Chile can hardly be oroclinal, because rotated and unrotated blocks are interspersed with one another all along the Chilean coast (Beck, 1988a).

c. Hartley *et al.* (1988) sought to account for the systematic difference between the sense of rotation in the forearcs of Perú and Chile, using a model that hinges on oblique extension. As the sense of obliquity changes at the Arica deflection (because of the abrupt change in the trend of the shoreline; Fig. 2), so does the sense of rotation. This suggestion bears considerable resemblance to the model of Geist *et al.* (1988) for rotation of blocks in the forearc of the Aleutian subduction zone.

d. Irwin *et al.* (1987) obtained an apparently concordant paleomagnetic direction for Jurassic intrusions in the Cordillera de la Costa near Valparaíso. They contrasted this with a clockwise-rotated direction (Beck *et al.*, 1986) of mid-Cretaceous ashflow tuffs near San Fernando. To explain this difference they noted that topographic and structural trends bend abruptly between the two sampling areas (near Santiago), and suggested that the rotation observed paleomagnetically might be related to this bending (Fig. 3). Irwin *et al.* (1987) also speculated that the clockwise rotation of the southern limb (south of Santiago) may be caused by a greater volume of plutonic rock having been intruded there. This model involves rotation of a several-hundred-kilometer long segment of the leading edge of South America about a pivot at its northern end, and hence is essentially an oroclinal model, on a smaller scale. The geologic map of Chile shows

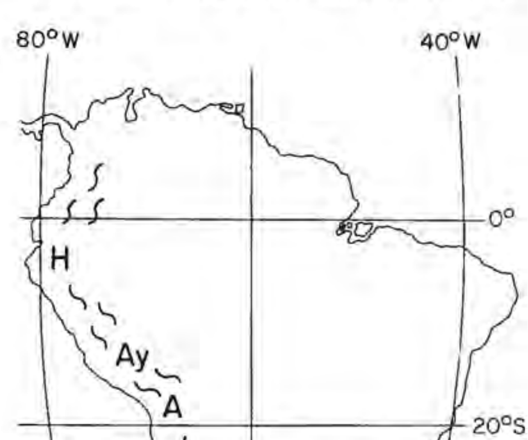


FIG. 2. Modified orthographic projection of South America showing changes in trend of the coastline and Cordillera (elongate Ss), especially pronounced near Arica (A).

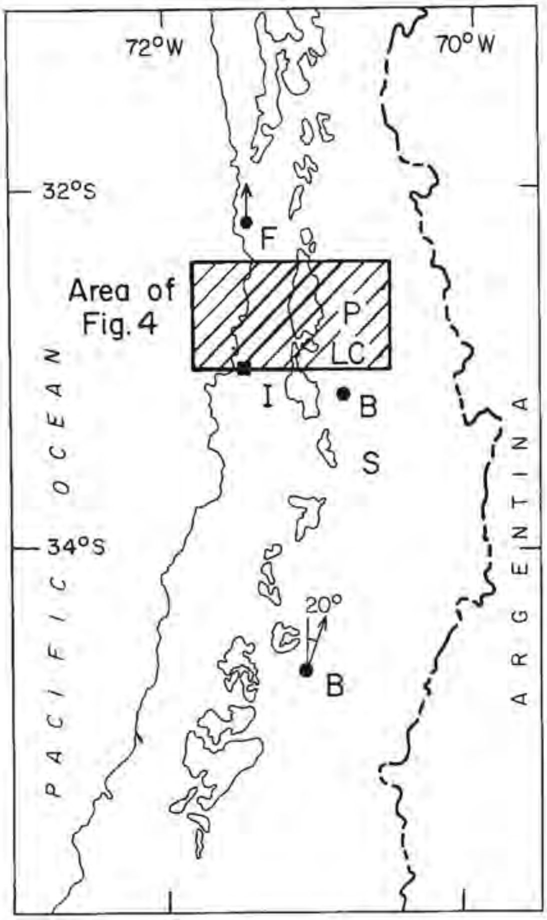


FIG. 3. Map of central Chile showing 25° change in the trend of Lower Cretaceous rocks (outlined) near Santiago (S). Previous paleomagnetic results document 20° clockwise rotation to the south (southern B: Beck *et al.*, 1986) but no rotation to the north (northern B: Beck, unpublished data; F: Forsythe *et al.*, 1988; I: Irwin *et al.*, 1987). Locations sampled for this study are near Putaendo (P) and Las Chilcas (LC).

several such piecewise 'oroclinal' bends between Arica and the Strait of Magellan. It is important to determine whether these bends are indeed small oroclines, or primary features.

e. Beck (1988a) proposed that block rotations in the leading edge of South America are a response to the shearing (margin-parallel) component of oblique subduction. If the Arica deflection is a primary feature, then the sense of obliquity for virtually any configuration of plate convergence will have opposite sense in Chile and Perú (Fig. 2). For example, normal convergence (no rotation) in Chile entails sinistral oblique convergence (counterclockwise rotation) in Perú, and *vice versa*. Only if the pole of rotation were nearby (which it apparently was not: Pilger, 1983; Pardo-Casas and Molnar, 1987), or convergence were extremely oblique, could this generalization fail. Beck (1988b) discussed the mechanics of block rotation driven by oblique convergence, and Geist *et al.* (1988) showed oblique-subduction-related rotation actually occurring in the forearc of the Aleutian arc. England (1989), using a simplified rheological model for deformation of continental lithosphere, showed that deformation can extend inland for up to several hundred kilometers for a long plate boundary; thus, rotations throughout Chile and into Argentina are possible with this model. Note that there would appear to be no conflict between this model and the oblique-extension model of Hartley *et al.* (1988) because, as shown in diagrams by Geist *et al.* (1988), rotation of forearc blocks inevitably entails extension.

PURPOSE OF THIS RESEARCH

If the summary given in the previous section is substantially correct, then it appears that the North American 'microplate tectonics' model does not apply to central and northern Chile, and probably not to Perú either. However, there seems to be strong evidence that some tectonic process or processes have caused systematic rotations. The authors undertook this study to see if they could answer some of the questions about how rotations are driven and accommodated in the Andean orogen.

As shown in figure 3, there is an abrupt bend in geological (and topographic) trends at about the latitude of Santiago; the amount of this bend is roughly 25°. Immediately south of the bend there is a single paleomagnetic result (Beck *et al.*, 1986), which shows a clockwise rotation of 20° ± 8°. This rotation found from paleomagnetism thus closely matches the apparent rotation of geological and topographic

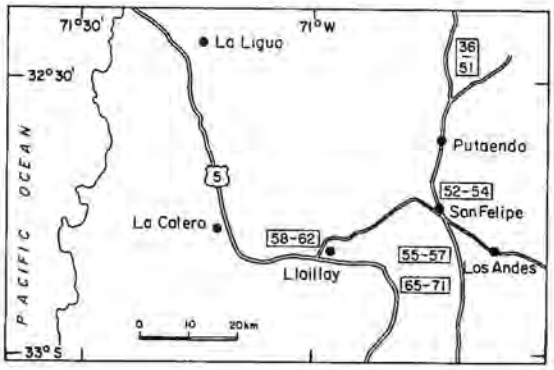


FIG. 4. Location of sites. Putaendo sites (36-51) are north of Putaendo; Las Chilcas sites (65-71) are farthest south; San Felipe sites (52-62) are scattered from west of Llaillay to north of San Felipe.

trends south of Santiago, relative to trends farther north. Immediately north of the bend there are three paleomagnetic results (Fig. 3). Jurassic intrusives near Valparaíso appear to show no rotation or north-south motion relative to the interior of South America (Irwin *et al.*, 1987). Triassic volcanic rocks near Los Vilos (Forsythe *et al.*, 1988) are interpreted to indicate perhaps 15° of northward relative transport, but no rotation. Finally, an inadequate collection of Late Cretaceous ashflow tuffs (Lo Valle Formation) near Colina, a short distance north of Santiago, also points toward no rotation (secular variation almost certainly has not been averaged in this study).

The studied area (Fig. 4) lies immediately north of the deflection in trends, and inboard of the apparently unrotated Triassic and Jurassic exposures on the coast described earlier. The rocks in the area are dated as post-Neocomian-pre-Senonian. Thus there is the potential for a useful test of rotation models. Both the piecewise oroclinal bending model of Irwin *et al.* (1987) and the oblique extension model of Hartley *et al.* (1988) predict that the area is unrotated. Thus if a rotation is found, these models must not apply and distributed shear (Beck, 1988a) or some other mechanism is indicated.

GEOLOGY OF THE SAMPLING AREA

In this study the authors sampled Cretaceous volcanic and sedimentary rocks that have been assigned to various mapping units by several investigators over the past few decades. The stratigraphy and correlation of rocks in the area recently have been revised after field work by Rivano *et al.* (1986).

Lo Prado Formation (Thomas, 1958). This is the oldest unit sampled. It consists of three members: sandstones, shales and fossiliferous limestones of Hauterivian age; andesitic lava flows and volcanic breccias; lava flows and breccia with calcareous pelitic rocks. The Lo Prado Formation is largely Neocomian, on the basis of fossils. The authors sampled the volcanic units of the middle and upper members. The geology and stratigraphy of the Lo Prado Formation are described in detail by Piracés (1976) and Piracés and Maksaev [1]. The thickness of the unit is estimated at between 2.3 and 2.9 km.

Veta Negra Formation (Thomas, 1958). This unit overlies the Lo Prado Formation concordantly. It formed by two members, the lower Purehue Member, consisting of lava flows and breccias with intercalated red sandstone units, and the overlying Ocoa Member, which is exclusively volcanic and contains the well-known, coarsely porphyritic 'ocoite' flows (Thomas, 1958). In the area of the present study, the Veta Negra Formation has a maximum thickness of perhaps 6 km. This unit is considered to be Early Cretaceous in age.

Las Chilcas Formation (Thomas, 1958; Piracés and Maksaev [1]. The bulk of our samples are from this unit. In the area sampled, Las Chilcas rocks are mainly andesitic lava flows, reddish tuffs, breccias, and accompanying volcaniclastic sedimentary rocks. The sequence is estimated to be about 3.0 - 3.2 km thick. As revised by Godoy (1982) and Rivano *et al.* (1986), Las Chilcas Formation includes the Lo Valle Formation, which is a predominantly ashflow tuff sequence that crops out to the south. As mentioned above, there are some paleomagnetic data available for the Lo Valle Formation (Beck *et al.*, 1986), which are interpreted as insufficient to average the geomagnetic secular variation. K/Ar dates for the Lo Valle Formation by R.F. Drake reported in Beck *et al.* (1986) are Late Cretaceous.

The combined stratigraphy of the Lo Prado, Veta Negra, and Las Chilcas formations appears to suggest a continental arc environment. Volcaniclastic

[1] 1977. Geología de la Hoja Quillota, IV y V Región, Chile. Instituto de Investigaciones Geológicas (Unpublished), 140 p. Obtainable from Biblioteca del Servicio Nacional de Geología y Minería, Santiago.

rocks associated with the flows and pyroclastic units probably accumulated in local basins within the arc. Plutons of various ages (mainly Aptian to Cenomanian; Rivano *et al.*, 1986) intrude the Cretaceous arc. In selecting sampling sites for paleomagnetic study we were careful to stay as far away from these plutons as possible, in order to minimize the risk of collecting rocks that had been remagnetized by reheating or chemical changes. Nevertheless, some of the remagnetization discussed below may be attributable to this plutonic activity.

PALEOMAGNETISM

In 1988 (January), 272 oriented samples were collected at 36 sites near Putaendo, San Felipe, and Quebrada Las Chilcas (Fig. 4). All samples were drilled and oriented *in situ*, using both sun and magnetic compass. In the laboratory, at least one specimen from each core was subjected to stepwise thermal demagnetization to just below the Curie temperature of hematite. Companion specimens for samples with low unblocking temperature also were demagnetized by alternating field. Thermal demagnetization was the method of choice for all but six sites as hematite apparently carries the dominant magnetization in most of these red volcanics and tuffaceous sedimentary beds. All specimens used in the statistical analysis were stepwise-demagnetized. Examples of the demagnetization process are shown in figure 5. Magnetic components were extracted from the demagnetization data using a line-fitting technique. Samples were excluded if their maximum angular deviation (Kirschvink, 1980) exceeded 15°. In a few sites a single sample direction fell far outside an otherwise well-defined group, but was well-determined in all other respects. These probably result from undetected block rotations, orientation errors, or possibly lightning strikes; whatever the cause, they were excluded before calculation of mean directions.

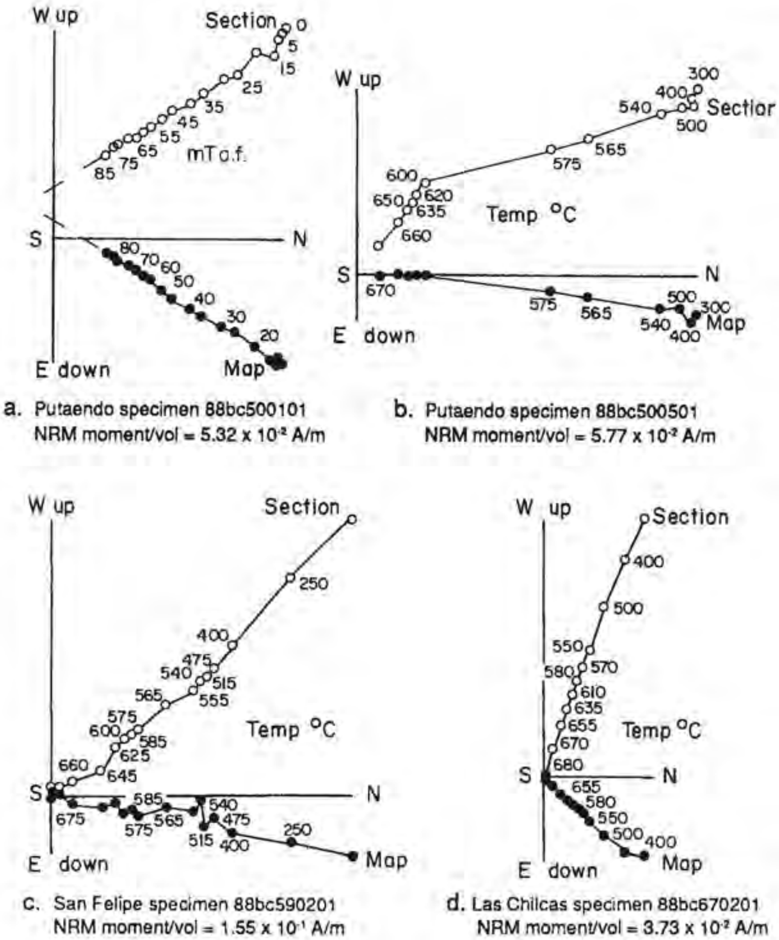
Mean directions for each site were determined using the method of Fisher (1953) and Onstott (1980). As site-mean directions calculated with the same data by the two methods differ by less than a small fraction of one degree, only the more conventional Fisher means are reported.

The data will be discussed in three groups. The northernmost sites are from a gently dipping stack of volcanics north of Putaendo (Fig. 4). These will be referred to as the Putendo sites. All Putaendo sites had two clearly distinct components of magnetization a high-temperature (above 580°C) component revealed only after a low-temperature component was completely demagnetized (Fig. 5a,b). Directions for both components are presented in tables 1 and 2 and in figure 6. In the southern part of the area results were obtained from a sequence of six tuffaceous beds in Quebrada Las Chilcas (Las Chilcas sites). These sites have only a single component of magnetization (Fig. 5d); results are shown in table 3 and figure 7. Finally, results for miscellaneous rock units are presented, mostly intrusive bodies, widely scattered over the area between Llaillay and the town of Los Andes; these will be referred to as the San Felipe sites. Results for these units, which also have only a single component of magnetization (Fig. 5c), are given in table 4 and figure 8.

Reference direction

Paleomagnetism can be a powerful tool for detecting relative displacements of crustal blocks. In the present study, the authors are investigating whether all or part of their sampling area has rotated about a vertical axis, moved north or south, or both. (As is well known, paleomagnetism cannot detect purely east-west motions). To detect relative motion it is necessary to compare the present mean directions (Tables 1-4) with a reference direction. In continental-drift studies the practice is to use the earth's present geomagnetic field as a reference; this method yields displacements (rotations and north-south translations) relative to the earth's latitude-longitude grid. In tectonic studies it usually makes more sense to map displacements relative to some nearby crustal block that can be assumed to have remained undeformed. In principle, directions for any crustal block can be used, but the common practice is to calculate reference directions from the curve of apparent polar wander (APW) for the stable interior of the continent to which the orogen is attached. Thus, the South American APW path must be looked to for reference directions. Techniques for calculating and comparing APW paths are explained in Beck (1989).

The APW path for South America contains some



a. Putaendo specimen 88bc500101
NRM moment/vol = 5.32 x 10⁻² A/m

b. Putaendo specimen 88bc500501
NRM moment/vol = 5.77 x 10⁻² A/m

c. San Felipe specimen 88bc590201
NRM moment/vol = 1.55 x 10⁻¹ A/m

d. Las Chilcas specimen 88bc670201
NRM moment/vol = 3.73 x 10⁻² A/m

Fig. 5. Orthogonal diagrams showing demagnetization paths typical of each locality. Samples from Putaendo sites contain two components; the shallower one erased by alternating field **(a)** and by heating to 580°C **(b)** likely resides exclusively in magnetite while the steeper one, untouched by a.f. and persistant to 670°C, survives in hematite. Samples from San Felipe **(c)** and Las Chilcas

unconvincing segments, but for Early Cretaceous time the excellent Serra Geral (SG) Formation pole of Bellieni *et al.* (1983) can be used. As recalculated in Beck (1988a), this is located at 83.8°S, 94.6°E, with a circle of 95% confidence of 3.4° and a precision parameter of 32.7 (N=54). Using the SG pole the (normal polarity) direction that can be expected in Lower Cretaceous rocks in the field area (32.88°S, 70.75°W) is: D. 358.2°; I. -45.4°. Alternatively, it is possible to follow Forsythe *et al.* (1987) and assume that the paleomagnetic pole for stable South America since mid-Mesozoic time is indistinguishable from the present dipole (PD). On this assumption the rocks in the sampling area ought to be magnetized in the direction: D. 0.0°; I. -52.3°. Both of these reference directions were used in the analysis, below:

Putaendo sites. Tables 1 and 2 and figure 6, the following can be concluded:

a. Both high-temperature and low-temperature components were acquired before folding. This is suggested by the fact that dispersion decreases when the tilt correction is made. It is also suggested by the fact that the distribution is conspicuously more circular for both components after tilt correction than before.
b. The high temperature component has a significantly steeper inclination than the low-temperature component. If: 1. non-axial elements of the geomagnetic field have been averaged to zero by our sampling scheme, and 2. the high-temperature component was acquired first (as by simple cooling), then it follows that there has been significant northward motion of the sampling site ***during*** the time that magnetization was being acquired. This scenario is discussed further below.
c. Declinations point east of the expected declination, no matter which reference direction is used.

TABLE 1. SITE-MEAN DIRECTIONS, PUTAENDO, HIGH-T COMPONENTS

Site	Dmg	N	Uncorrected		Corrected		α_{95}	k	Location	
			Dec°	Inc°	Dec°	Inc°			Lat.	Long.
88bc50	t	5	1.8	-61.4	24.9	-66.1	14.9	27	32.53°S	70.68°W
88bc49	t	8	353.9	-45.0	4.9	-52.2	6.3	80	"	"
88bc48	t	7	359.7	-40.0	9.3	-46.3	7.6	65	"	"
88bc47	t	7	343.9	-43.4	352.9	-52.3	7.5	67	"	"
88bc51	t	8	7.3	-41.4	24.9	-66.1	3.1	333	"	"
88bc37	t	8	356.0	-49.0	344.5	-63.1	4.3	167	30.54°S	70.70°W
88bc40*	t	6	2.9	-45.9	12.6	-60.3	10.1	45	"	"
88bc39	t	7	6.5	-42.6	16.1	-56.5	5.1	140	"	"
88bc36	t	7	356.1	-58.2	354.9	-66.2	5.7	113	30.55°S	70.70°W
88bc41	t	6	25.1	-57.1	28.9	-61.6	3.8	313	"	"
88bc42*	t	7	30.1	-59.6	35.2	-63.8	8.2	55	"	"
88bc44	t	5	23.5	-55.5	23.5	-55.5	7.0	118	30.56°S	70.70°W
Group means										
All sites		12	4.4	-50.6			6.3	48.5		
					11.9	-58.3	5.7	59.0		
Without		10	2.6	-50.0			6.8	51.0		
40,42					10.0	-57.3	6.5	56.5		
Expected direction at Putaendo, using										
Serra Geral pole:			358.2;	-45.4						
Present dipole:			0.0;	-52.3						

Note: Dmg is type demagnetization t. thermal; a. alternating field; N. number of samples/sites; Dec., Inc. are mean declination and inclination of sites/group; α_{95}, radius of circle of 95% confidence; k. precision parameter; * indicates conspicuous within-site streaking.

TABLE 2. SITE-MEAN DIRECTIONS, PUTAENDO, LOW-T COMPONENTS

Site	Dmg	N	Uncorrected		Corrected		α_{95}	k	Location
			Dec°	Inc°	Dec°	Inc°			
88bc50	t	4	21.4°	-38.6	31.2	-40.6	27.5	12	For
88bc48	a	7	357.5	-28.3	3.6	-35.2	7.3	70	locations,
88bc47	t	6	355.0	-30.3	359.5	-39.4	6.9	69	see
88bc51	t	7	8.5	-29.8	15.5	-34.7	3.4	316	Table 1
88bc37	t	3	1.2	-37.4	355.5	-52.4	19.8	40	
88bc40*	t	6	352.6	-39.9	356.8	-55.4	17.2	16	
88bc39	t	5	4.1	-32.8	10.7	-44.6	5.0	150	
88bc36	t	6	4.2	-42.5	4.9	-50.4	6.1	122	
88bc41	t	5	23.2	-45.8	25.5	-50.4	7.3	111	
88bc42*	t	7	24.9	-41.3	27.0	-45.8	9.4	42	
88bc44	a	6	34.2	-51.3	34.2	-51.3	4.6	217	
Group means									
All sites		11	8.7	-38.7			7.3	40.3	
					13.2	-46.3	6.9	45.1	
Without:		7	8.1	-37.9		10.6	33.3		
37,40,42,50				12.6	-44.3	9.0	46.2		

Note: Explanation same as for Table 1. Notice high scatter for sites 88bc50 and 88bc37.

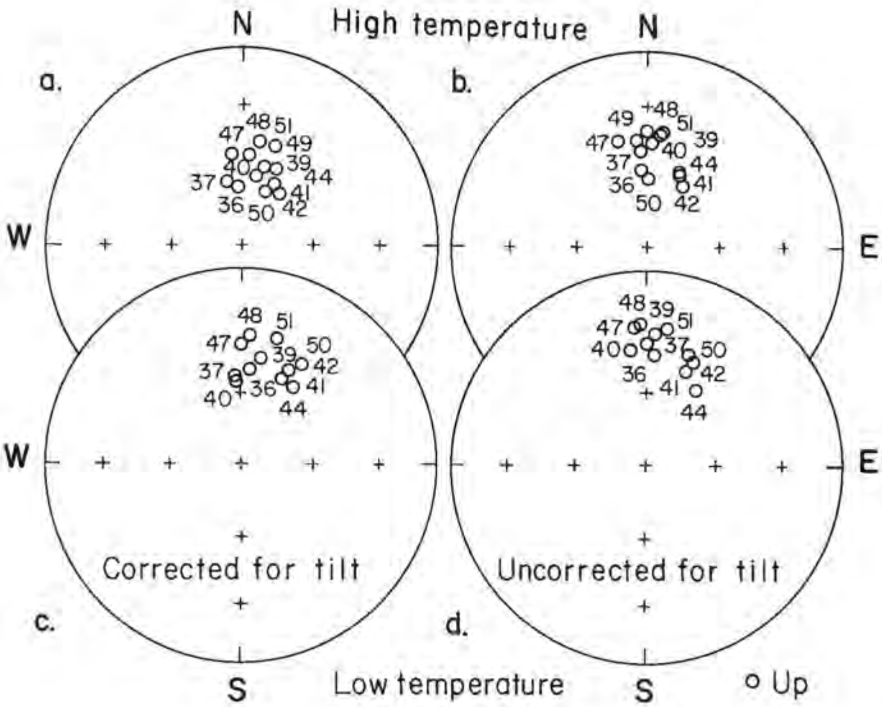


FIG. 6. Equal area projections of mean directions for Putaendo sites. The high-temperature component **(a,b)** is consistently steeper than is the low- **(c,d)**. Corrected directions **(a,c)** have smaller and more circular distributions than do uncorrected ones **(b,d)** suggesting that both components predate at least the last deformation.

TABLE 3. SITE-MEAN DIRECTIONS, QUEBRADA LAS CHILCAS

Site	Dmg	N	Uncorrected Dec°	Uncorrected Inc°	Corrected Dec°	Corrected Inc°	a_{95}	k	Location
88bc65	t	8	17.1	-50.6	358.0	-40.3	4.3	200	
88bc66	t	8	19.5	-63.2	348.0	-49.7	9.5	35	All sites at
88bc67	t	8	1.0	-54.1	348.7	-32.4	10.8	27	Lat 32.85°S,
88bc68	t	7	10.3	-53.3	353.4	-43.1	5.9	103	Long 70.85°W
88bc70	t	3	22.3	-32.1	2.8	-41.9	9.3	182	
88bc69	t	7	18.7	-43.9	355.5	-52.1	6.3	94	
Group means									
		6	15.3	-49.8			9.6	48.2	
					354.4	-43.3	6.7	98.5	

Note: For explanation and expected directions, see Table 1.

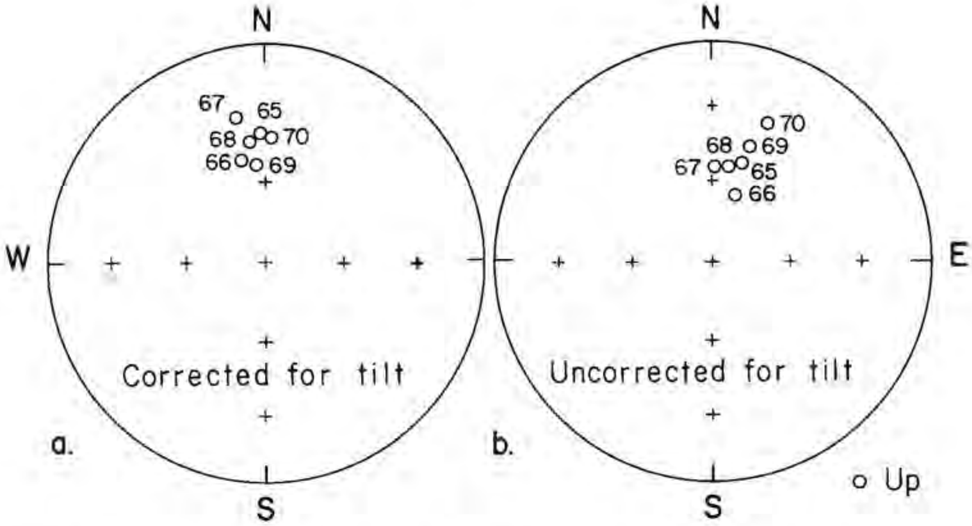


FIG. 7. Equal area projections of mean directions for Las Chilcas sites show tighter and more circular distribution after correction for tilt **(a)** than before **(b)**, which is consistent with magnetization before folding.

This strongly implies clockwise rotation, probably about 10-15°.

Las Chilcas sites. As table 3 and figure 7 demonstrate, the results obtained from Quebrada Las Chilcas (involving only six sites) are little more than a progress report. Further field work is planned, and a primary aim will be to determine whether the magnetization (which is well-behaved and consists of only a single component) is primary and contemporaneous with the age of the rock, or secondary and acquired after the rocks formed. At present there are two conflicting lines of evidence. From Table 3, tilt-correction conspicuously improves grouping of the sites, implying that the magnetization is pre-folding. Tilt-corrected data also are more circular than are the directions before tilt-correction (Fig. 7). However, a conglomerate sampled a short distance from the Las

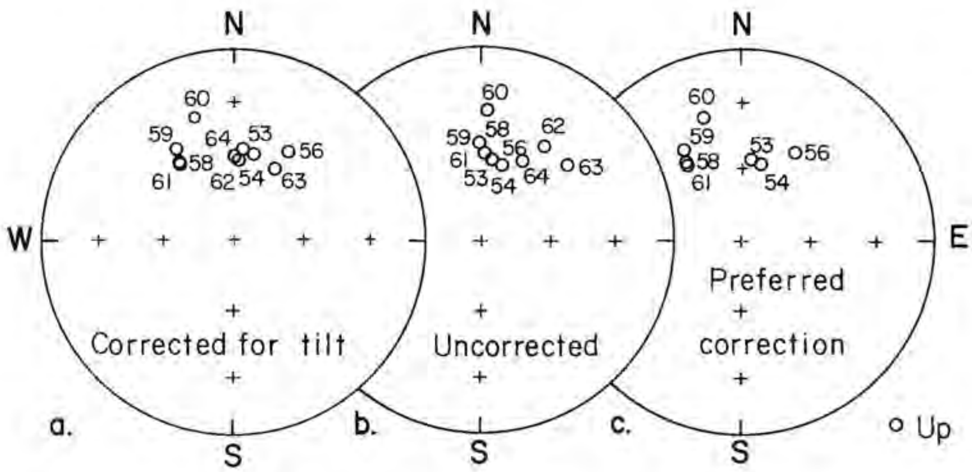


FIG. 8. Equal area projections of mean directions for miscellaneous sites near San Felipe. Correction for tilt **(a)** scatters many of the directions, which, consistent with failure of a within-site fold test, indicates they were remagnetized after deformation. Nevertheless a conglomerate test near two sites suggest they were not remagnetized. Corrected directions for these two are combined with uncorrected directions **(b)** from clearly remagnetized sites in **(c)**.

TABLE 4. PALEOMAGNETIC DATA FOR MISCELLANEOUS SITES, SAN FELIPE AREA, CHILE

Site	Dmg	N	Uncorrected Dec°	Uncorrected Inc°	Corrected Dec°	Corrected Inc°	α_{95}	k	Comments and location
88bc53	a	7	7.7	-55.4	7.0	-51.4	4.4	188	Fine sandstone, near site of conglomerate test. Loc: 32.76°S, 70.74°W
88bc54	t	7	14.7	-56.4	13.4	-52.5	3.43	316	Lithology like 88bc53; same location
88bc56	t	7	8.5	-54.8			4.0	231	'Super-site'; 7 samples spread over about 120 m of section, through which attitude varies. Loc: 32.83°S, 70.72°W
					31.9	-45.5	7.9	58	
88bc58	a	8	2.7	-52.8	324.8	-48.7	4.2	175	Bottom 'flow', in Ocoa Member, Lo Prado Formation. Loc: 32.84°S, 71.11°W
88bc59	a	8	359.5	-47.9	327.8	-43.8	6.5	74	Second 'flow', immediately above 88bc58. Same location
88bc60	t	8	2.7	-32.9	342.5	-33.8	6.5	73	Third 'flow', above 88bc59. Same location
88bc61	a	8	3.8	-53.8	324.3	-49.8	4.1	184	Most easterly site in Ocoa Member, Lo Prado Formation. Same location
88bc62	t	7	34.5	-40.6	4.0	-55.6	5.0	146	Intrusion into Las Chilcas Formation. Attitude of surrounding sedimentary rocks very poorly known. Loc: 32.82°S, 71.0°W
88bc63	t	8	49.6	-40.1	28.8	-53.0	4.6	146	Probably a thick sill; near base. Loc: 32.71°S, 70.91°W
88bc64	t	8	28.2	-51.8	2.4	-51.6	6.0	86	Same as 88bc63 near top. Same location
Group means									
			330.0	-51.6			9.5	26.2	
					15.5	-49.1	8.2	35.1	
Preferred			5.1	-49.6			6.1	98.8	

Note: For explation and expected directions, see Table 1.

TABLE 5. ROTATION AND POLEWARD DISPLACEMENT FOR PUTAENDO AND SAN FELIPE SITES

Data Set	SG Reference		PD Reference	
	R ± ΔR	P ± ΔP	R ± ΔR	P ± ΔP
Ph	14.2° ± 8.5°	14.6° ± 6.5°	12.4° ± 9.3°	8.6° ± 7.1°
Pl	15.0° ± 7.8°	1.1° ± 6.9°	13.2° ± 8.6°	-4.9° ± 7.4°
SF	7.0° ± 5.9°	4.0° ± 5.1°	5.2° ± 7.0°	-2.0° ± 5.9°
Ph + Pl	14.6° ± 6.3°	8.2° ± 5.3°	12.9° ± 7.4°	2.2° ± 6.1°
Ph + Pl + SF	13.3° ± 5.6°	7.2° ± 4.6°	11.1° ± 6.5°	1.2° ± 5.4°

Note: **R** (clockwise rotation) and **P** (poleward transport; positive northward) calculated using poles, after Beck (1989). **Ph, Pl, SF** are Putaendo sites, high-temperature, Putaendo sites, low-temperature, and San Fernando 'Preferred' sites, respectively. **SG** (Serra Geral) and **PD** (present dipole) are reference poles discussed in text. Confidence limits are 95 percent. A 95 percent confidence circle of 5 degrees has been assigned to **PD**.

Chilcas field area gave well-grouped directions from lithic clasts, implying that it had been magnetized *after* deposition. This may mean that the other Las Chilcas magnetizations also are secondary (perhaps due to reheating), but were acquired before the final stage of folding (but not necessarily when the rocks were horizontal and undisturbed; Bazard *et al.*, 1990). The suspiciously low scatter (k=98.5) of the tilt-corrected direction may indicate that non-axial elements of the ancient geomagnetic field have not been fully averaged to zero (if the magnetization is primary), or that they have been averaged within sample during remagnetization. There are too many problems with this data set to permit us to make any confident interpretations; nevertheless, it is interesting that the tilt-corrected mean direction for the Las Chilcas Formation in Quebrada Las Chilcas agrees very well with the expected direction calculated from the Serra Geral Formation, implying that the rocks have not moved.

San Felipe Sites. These sites extend from several kilometers west of Llaillay to near the town of Los Andes, (Fig. 4) and consist of intrusive bodies, questionable lava flows, and sedimentary units. They are lumped together in this section for convenience in reporting the results (Table 4, Fig. 8). Some San Felipe sites clearly carry primary magnetizations, whereas others are remagnetized. Sites belonging to the Lo Prado, Veta Negra and Las Chilcas formations are included in this category.

Two sites for which we are sure of the time of remagnetization are sedimentary units 88bc53 and 54, which immediately overlie a conglomerate that gave a positive conglomerate test; that is, clasts from the conglomerate had random magnetic directions, indicating that the conglomerate had not been remagnetized after deposition. Equally certain is the way that site 88bc56 should be handled; this site unmistakably failed a within-site fold test, indicating that it had been remagnetized *in situ*. Thus in calculating a mean direction for these sites we must use sites 53 and 54 with tilt correction and site 56 without.

The remaining San Felipe sites are problematical. Sites 88bc58-61 are from units in the Ocoa Member of the Lo Prado Formation (Thomas, 1958), sampled near the Pan American Highway. Four conspicuous layers were sampled; these dip steeply to the east. However, figure 8 shows that correcting for

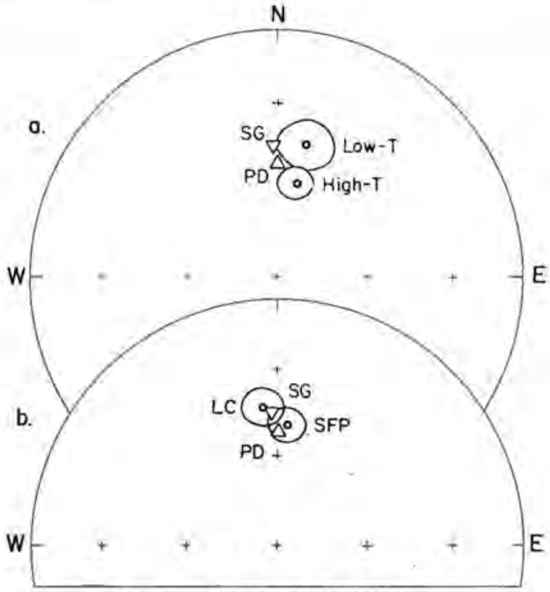


FIG. 9. Equal area projections of mean directions and their confidence limits for both high- and low-temperature components from Putaendo sites **(a)**, and from Las Chilcas and San Felipe sites **(b)**. The Putaendo components differ significantly in inclinations. They and the San Felipe mean are suggestively clockwise of both reference directions whereas the direction from Las Chilcas sites is not. Local block rotation is a plausible explanation.

'tilt' gives these units anomalously westerly declinations. Thus we suspect that the Ocoa units are either sills that were intruded in approximately their present position, or, if lava flows, have been remagnetized after tilting. The remaining San Felipe sites are intrusive rocks for which there is little or nothing to guide us in making a tectonic correction.

In table 4 the mean for the San Felipe sites in three has been calculated in three different ways: all sites corrected for tilt, all sites uncorrected, and a combination based on field tests of paleomagnetic stability. The first two are clearly wrong. Note that the mean of the corrected directions is distinctly westerly (owing to the peculiar Ocoa directions), whereas the mean of the uncorrected directions is very similar to the means calculated for Putaendo and Quebrada Las Chilcas rocks. The calculation designated 'Preferred' consists of tilt corrected directions for 88bc53 and 54 and *in situ* directions for 56 and 58-61. Clearly this is the 'best' mean direction for the San Felipe sites. As with the Quebrada Las Chilcas sites, scatter is suspiciously small (k=98.8). For what it is worth, the 'Preferred' mean direction is rotated slightly clockwise of the SG and PD expected directions.

INTERPRETATION

Paleomagnetic data for these lower Cretaceous rocks seem to be telling several things -but, unfortunately, nothing very clearly! One thing is unmistakable, however; the entire region has normal magnetic polarity. An obvious explanation for this observation is that the rocks were magnetized during the Cretaceous long normal interval (118-83 Ma, or Aptian through Santonian). This agrees fairly well with the age span suggested by Rivano *et al.* (1986), which is Lower Cretaceous (roughly 145-97,5 Ma, using the time scale of Harland *et al.*, 1982). Because reverse anomalies M0 and M1 are very brief (each less than 1 m.y.; Harland *et al.*, 1982), the period of nearly constant normal geomagnetic polarity could be pushed back to about 125 Ma. However, this still leaves the first 20 Ma of the Early Cretaceous unrepresented. There are three possible explanations:

1. The rocks are younger than previously supposed; no older than Barremian, instead of spanning most of the Early Cretaceous.
2. The rocks are Neocomian, but have been extensively remagnetized during the Cretaceous normal interval.
3. The bulk of the samples (which are from Las Chilcas Formation) are less than about 124 Ma. The remainder, from Lo Prado and Veta Negra formations, have normal polarity because 1. they were remagnetized later, or 2. they acquired a primary magnetization during one of several short normal-polarity intervals that occurred during Neocomian time (Harland *et al.*, 1982). We prefer this explanation, but more work obviously is needed.

Paleomagnetic directions in these rocks also are hard to interpret. Figure 9 shows our best guess as to the characteristic directions for the three groups of sites, plotted with reference directions. The directions from all three groups are almost concordant. This means that the San Felipe-Putaendo-Quebrada Las Chilcas area has not moved much, relative to the South American craton, since post-Neocomian-pre-Senonian time. This contrasts starkly with the situation in the North American Cordillera, where virtually every Cretaceous rock unit has undergone significant displacement.

From figure 9 there appears to be some evidence of clockwise rotation of the Putaendo and San Felipe sites. If one assumes that the corrected high- and low-temperature Putaendo directions and the San Felipe directions belong to the same population, then the mean of the population (D. 10.8°; I. -51.9°; K. 46.8; α_{95}. 3.9°) is rotated about 10-15° clockwise. Furthermore, if the SG reference direction is correct, then the area has an inclination that is significantly too steep, suggesting transport from the south. Table 5 gives the statistics. The total rotation between the Putaendo-San Felipe sites (apparently rotated) and the Quebrada Las Chilcas sites (apparently undisturbed) is 16.4° ± 9.1°.

Perhaps the most puzzling aspect of this study is the behavior of the Putaendo sites, all of which have two distinct magnetic components. Both components have declinations that point significantly clockwise, but the high-temperature (HT) component has an inclination that is significantly steeper than the low-temperature (LT) and SG-reference directions. Alternating-field and thermal demagnetization indicate that HT magnetization in the Putaendo sites is carried by hematite whereas the LT component resides in magnetite, hence the following scenarios are possible:

1. The HT component may be a primary thermore-

manent magnetization carried by large, high-blocking-temperature hematite grains, whereas the LT component was acquired later - perhaps during late cooling or deuteric alteration of magnetite. The LT component also might be significantly younger than the HT component, perhaps acquired during re-heating or regional alteration but before folding. (Decrease in scatter accompanying tilt-correction suggests that both components are pre-folding.) If both HT and LT components record a valid dipole field direction, then this interpretation calls for roughly 1,000 km of relative northward transport between the times that the HT and LT components were acquired!

2. Alternatively, the HT and LT components could both be primary and essentially contemporaneous, but one (or both) could have been deflected away from the ambient field direction by some rock-magnetic peculiarity, most probably magnetic anisotropy. (This is unlikely in view of the fact that the rock units are not strongly magnetized, are unfoliated, and have low magnetic susceptibility.)
3. Slightly more likely is the scenario which interprets HT and LT as primary and essentially contemporaneous, but acquired during separate intervals, each too short to have averaged the ancient geomagnetic secular variation. In this case, neither HT nor LT is a dipole direction (although their mean may be), and the difference in inclination between the two data sets has no tectonic significance. This appears to be possible because the scatter in the two data sets (k is approximately 50, equivalent to an angular dispersion of roughly 11.5°) is slightly less than expected in a set of directions that averages the non-axial terms in the geomagnetic field (Merrill and McElhinny, 1983). If this alternative is correct then we are not forced to regard the difference in inclination between HT and LT components as evidence of northward transport. However, the mean of HT and LT directions (D. 12.6°; I. -52.6°; α_{95}. 4.8°) is still significantly clockwise of and steeper than the Serra Geral (SG) reference direction, suggesting northward transport at some later time, together with significant clockwise rotation. If this direction is compared to the present-dipole (PD) reference direction the clockwise rotation remains but the northward transport is eliminated.

SUMMARY AND CONCLUSIONS

What began as a simple paleomagnetic study of possible block displacement developed severe complications that leave the authors with a set of tentative conclusions and several new questions. Based on present data, the following conclusions can be offered, in decreasing order or probability:

1. The rocks in the San Felipe - Putaendo - Llaillay area all have normal magnetic polarity. This includes some rocks from the Lo Prado and Veta Negra formations, although the bulk of the present samples are from Las Chilcas Formation. This may mean that the age of these rocks falls within the Cretaceous long normal interval (118-83 Ma; Harland *et al.*, 1982). Because reverse chrons M0 and M1 are short, the range of time of magnetization probably can be extended to 124-83 Ma. This agrees fairly well with age assignments (Thomas, 1958; Rivano *et al.*, 1986) which place these rocks in the Early Cretaceous. As discussed above, perhaps some of the rocks have been remagnetized after 124 Ma, while a few others may owe their normal polarity to primary magnetizations acquired during various normal intervals during Neocomian time. More work needs to be done to resolve this important question.
2. Some of the rocks studied have been remagnetized after tilting, but others clearly have not. Because of the uniform magnetic polarity, the remagnetization probably took place within the Cretaceous long normal interval, as discussed above. Because remagnetization was spotty -affecting some regions but not others- it probably resulted from local effects such as reheating from small intrusions or local hydrothermal processes.
3. Magnetic directions from all parts of the field area approximately match reference directions for the South American craton. This shows that the area is not grossly allochthonous; *i.e.*, that it is neither an accreted exotic terrane nor a far-traveled piece of the South American continental margin. Nevertheless, the mean direction for rocks from the northern part of the field area (Putaendo and San Felipe sites) suggests that the area has been rotated clockwise, and perhaps translated northward. The total amount of translation could be of the order of 1,000 km -which does not appear to agree particularly well with the geological evidence.

4. Directions from the southern part of the area (Quebrada Las Chilcas) are concordant, indicating neither rotation nor north-south translation. This may be an accidental result of under-sampling; the present data set contains only six sites, which is unlikely to average secular variation if the magnetization is primary. A combined conglomerate and fold test indicates that the rocks have been remagnetized, but before at least the last stage of folding. These observations make interpretation of the Quebrada las Chilcas results risky. If the present mean direction accurately reflects a Cretaceous dipole direction, then Quebrada Las Chilcas rocks have had a different history than related rocks only sightly farther north. Since the latter rocks show rotation, and perhaps some northward translation, then either these displacements were complete when the Quebrada Las Chilcas rocks were magnetized, or Quebrada Las Chilcas and the rocks farther north lie in separate structural domains.
5. As shown in figure 3, apparently unrotated Jurassic rock units near Valparaíso and the present apparently rotated Cretaceous rocks near San Felipe lie in the same north-south trending segment of the Cordillera. The diagram also shows that probably unrotated, possibly younger rocks at Quebrada Las Chilcas and in the Chacabuco area lie close together, near the southern tip of the north-south segment. These observations suggest that rotation is a local phenomenon not related to structural trends, and that it can occur inboard of segments of unrotated crust. If true, this would tend to favor the shear-driven model for local rotation discussed earlier.

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