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PALEOMAGNETIC EVIDENCE OF VERTICAL AXIS BLOCK ROTATIONS FROM THE MESOZOIC OF NORTHERN CHILE

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Abstract. We present paleomagnetic results for three Mesozoic formations from northern Chile: La Ternera Formation (Upper Triassic), Quebrada Monardes Formation (Upper Jurassic); Cerrillos Formation (Upper Cretaceous). Results from the Cerrillos are divided into eastern (Cuesta El Gao (CEG)) and western (Elisa De Bordo (EBD)) localities. Most specimens from La Ternera volcanic and sedimentary rocks are magnetically stable, as shown by alternating field and thermal demagnetization. More complicated but still reliable results were obtained from Quebrada Monardes red beds. Normal and reverse polarities are present in both units; means of both populations are antiparallel at 95% confidence. The Quebrada Monardes Formation also yields positive conglomerate and fold tests. Paleomagnetic poles for La Ternera and Quebrada Monardes are 60.9S, 218.3E (A95, 7.8°), and 66.9S, 191.6E (A95, 12.7°), respectively. Comparison with appropriate reference poles shows that this region of Chile has undergone about 25° of clockwise rotation, with negligible latitudinal transport. Cerrillos CEG results are less reliable and possibly complicated by remagnetization during emplacement of early Tertiary intrusives. Most Cerrillos EDB specimens are stable, but marked increase in scatter upon unfolding suggests remagnetization. Results for the Cerrillos CEG locality, which is contiguous to the sampling area of the La Ternera and Quebrada Monardes formations, show only about half the rotation of those two units, suggesting that rotation commenced after deposition of the Quebrada Monardes rocks in the Late Jurassic and was approximately half complete by the time Cerrillos CEG rocks acquired their magnetization. Cerrillos EDB results come from an area approximately 40 km to the west; these show roughly 45° of clockwise rotation. Dispersion is very low between EDB sites, suggesting that secular variation may not be completely averaged. Nevertheless, the great difference in direction between the two Cerrillos localities suggests that they lie in different structural blocks.

Introduction

Paleomagnetic studies provide an additional dimension to the tectonic analysis of mountain belts. To cite a well-known example, paleomagnetic evidence from the North American Cordillera shows that crustal blocks located on the western edge of the continent have experienced variable amounts of vertical axis rotation, in most cases accompanied by displacement parallel to the continental margin [Beck, 1976; Irving et al., 1980; Stone et al., 1982]. For the South America Cordillera the pattern is quite different; data show little or no evidence of terrane accretion or large-scale block displacement since the Paleozoic [Ramos et al., 1986; Beck, 1988]. However, there is an interesting pattern of rotation; paleomagnetic studies demonstrate that rocks north of the Peru/Chile border are rotated counterclockwise, whereas in nearly all studies the rocks from Chile show clockwise rotation. Broadly speaking, two models have been advanced to explain these discordant paleomagnetic declinations, both of which involve interaction between the subducted Nazca and the overriding South American plates.

The orocline. Carey [1954] proposed that the abrupt deflection in Andean tectonic and topographic trends near Arica (northern Chile) represents oroclinal bending (Figure 1a). Although originally dismissed by many scientists as unlikely, this idea has been shown to fit paleomagnetic results from Peru [e.g., Kono et al., 1989] and Isacks [1988] has proposed a highly plausible model to account for oroclinal bending in the context of Andean subduction.

Small-block rotation models. Margin-parallel shear caused by oblique subduction also can explain the different sense of rotation [Beck, 1987, 1988]. In models of this sort (Figure 1b), crustal blocks rotate in a shear zone caused by oblique convergence between the Nazca and South American plates; the sense of rotation is controlled by the sense of obliquity which reverses at the Arica deflection where the trend of the plate margin changes abruptly. This mechanism might be expected to drive rotations that decrease with increasing distance from the trench [Beck et al., 1986; England and Wells, 1991], although rotations could be located far inland of the trench along major strike slip faults. Local geological conditions should control the size of the individual blocks and also might influence the timing and amount of rotation.

Other kinematic models relate in situ block rotations to crustal extension within the Andean forearc. For instance, Hartley et al. [1988] suggest that rotations occur during roll-back of the subducted slab (Figure 1c). A related model is described by Irwin et al. [1987]. These models also predict that the amount of rotation should decrease with distance from the trench. If models of this sort are correct, then the amount of rotation might vary from block to block but ought to be related in some fairly obvious way to plutons or extensional structures. A weakness of this class of model is the inability to account for a consistent sense of rotation and its relationship to the Arica deflection. Presumably, the sense of obliquity in convergence must be involved.

The paleomagnetic study described in this report includes results from Upper Triassic, Upper Jurassic, and Upper Cretaceous rock units, distributed over a wide geographic area (Figure 2). We originally hoped that results from these rocks could be used to constrain the age and duration of rotation, if any was found. We deliberately sampled over a large geographical area in order to detect and isolate independ-

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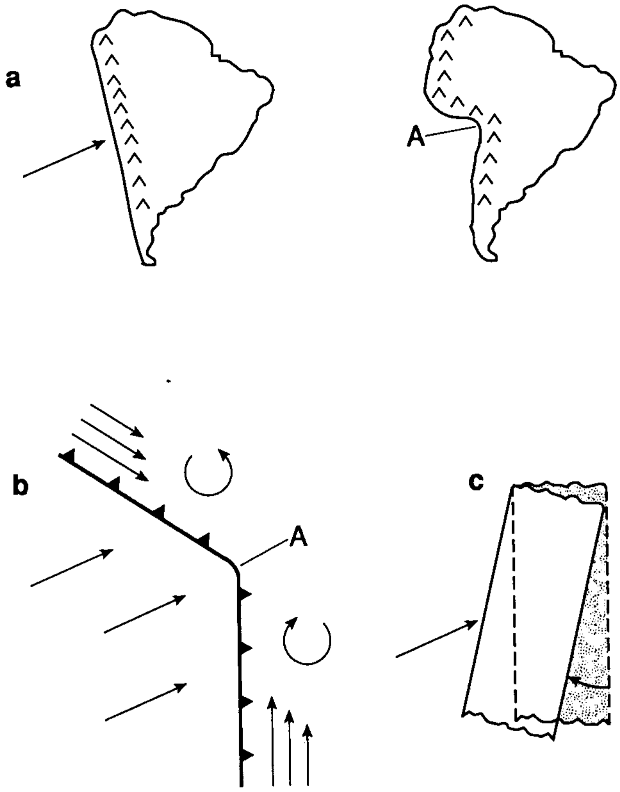

Fig. 1. Several tectonic models proposed to account for vertical axis rotations of crustal blocks in western South America. (a) Orocline. Interaction of South America with the Nazca plate causes differential crustal thickening and indentation of the continental margin; oroclinal bending is one result. A is Arica. (b) Small block rotation driven by oblique convergence. Subduction of the Nazca plate beneath an inherited bend in the South American coastline causes margin-parallel shear and block rotations. Sense of shear and rotation changes at Arica (A). (c) Rotation by differential extension. Greater extension in the South than in the North produces vertical axis block rotation. Area of extension is shown.

ently rotated blocks, and perhaps shed some light on the rotation mechanism.

Geology of the Sampling Area

The study area is located on the southern Altiplano plateau just west of the Andean divide (Figure 2). Uplift along north-south oriented faults exposes Paleozoic basement, overlain by a thick sequence of Mesozoic volcanic and sedimentary rocks. Structure in the area is relatively simple; most layered rocks are subhorizontal, except locally where bedding is affected by faults. Paleocene and Eocene plutonic rocks locally intrude the Mesozoic section.

Our sampling included Triassic volcanic and sedimentary rocks (La Ternera Formation), Upper Jurassic terrigenous red beds (Quebrada Monardes Formation), and Cretaceous volcaniclastic and volcanic rocks (Cerrillos Formation).

Upper Triassic La Ternera Formation in the sampling area consists of intermediate to felsic lava flows and pyroclastic rocks. According to Sepulveda and Naranjo [1982], La Ternera Formation in nearby areas contains a sedimentary member from which Triassic plant fossils have been collected. The La Ternera Formation unconformably overlies Paleozoic granitic rocks and is overlain conformably by the abundantly fossiliferous marine Lower Jurassic Lautaro Limestone, which we did not sample.

Upper Jurassic red beds of the Quebrada Monardes Formation conformably overlie the Lautaro Limestone. The Quebrada Monardes Formation is a sequence of terrigenous sedimentary rocks deposited in an arid to semi-arid environment [Bell, 1982]. Sedimentary facies reflect deposition of aeolian dunes, alluvial fans, braided streams, playa mudflats, saline lakes, and coastal lagoons. Andesitic sills and some flows also are present within this unit. The Upper Jurassic age is constrained by its stratigraphic position and by relatively scarce paleobotanical material [Sepulveda and Naranjo, 1982].

Cretaceous volcanic and volcaniclastic rocks of the Cerrillos Formation conformably overlie the Quebrada Monardes Formation. These consist of conglomerates, andesitic lavas and breccias, pyroclastic rocks, and scarce limestones. These Cretaceous rocks have been attributed to an "aborted marginal basin" (Mpodozis and Ramos, 1990). The age of the Cerrillos Formation is poorly known. West of Copiapo (western margin of Figure 2), the Cerrillos Formation discordantly overlies rocks of Barremian age. Whole rock and hornblende K/Ar ages on Cerrillos volcanics are Paleocene-Eocene (Zentilli, 1974), but in view of the number of early Tertiary intrusions known in the area these ages may be partially reset.

Paleomagnetic Sampling, Measurements, and Statistical Techniques

In two field seasons we collected oriented samples (usually 6-8) from 127 sites, disproportionately from the well-exposed Quebrada Monardes Formation. In this paper we present all our results for the La Ternera and Cerrillos formations, together with preliminary results for the Quebrada Monardes Formation. As discussed below, Quebrada Monardes red beds tend to have complicated magnetizations that are difficult to resolve.

Most samples were drilled and oriented in the field, using a combination solar-magnetic compass. At some sites we collected oriented hand samples, owing to the remote location of the outcrop or to equipment failure. Specimens were measured on a Schonstedt spinner magnetometer and progressively demagnetized within magnetic shields using either a Schonstedt alternating field (AF) tumbling specimen demagnetizer or a home-built open-air furnace. Pilot specimens from nearly all sites have been analyzed to help us choose the most efficient demagnetization techniques. Here we report final results for all acceptable sites completed to date.

Magnetic component analysis was performed by least squares fitting of free lines to straight-line segments selected from orthogonal diagrams (Kirschvink, 1980). Site mean directions were computed by combining sample directions using Fisher [1953] statistics. Sites with mean directions that were poorly determined (radius of circle of 95% confidence > 20°) were eliminated. Virtual geomagnetic poles (VGP) were calculated by averaging site mean VGPs. Relevant site statistics are given in Tables 1-3; details of lithology, location, and demagnetization procedure are summarized in Table 4.

Paleomagnetic Results

Behavior of representative samples during demagnetization is shown in Figure 3, and the cluster of site mean directions for each formation is illustrated in Figures 4-7. "Expected directions," also shown in Figures 4-7, are geomagnetic field directions calculated from the appropriate reference poles for the South Ameri-

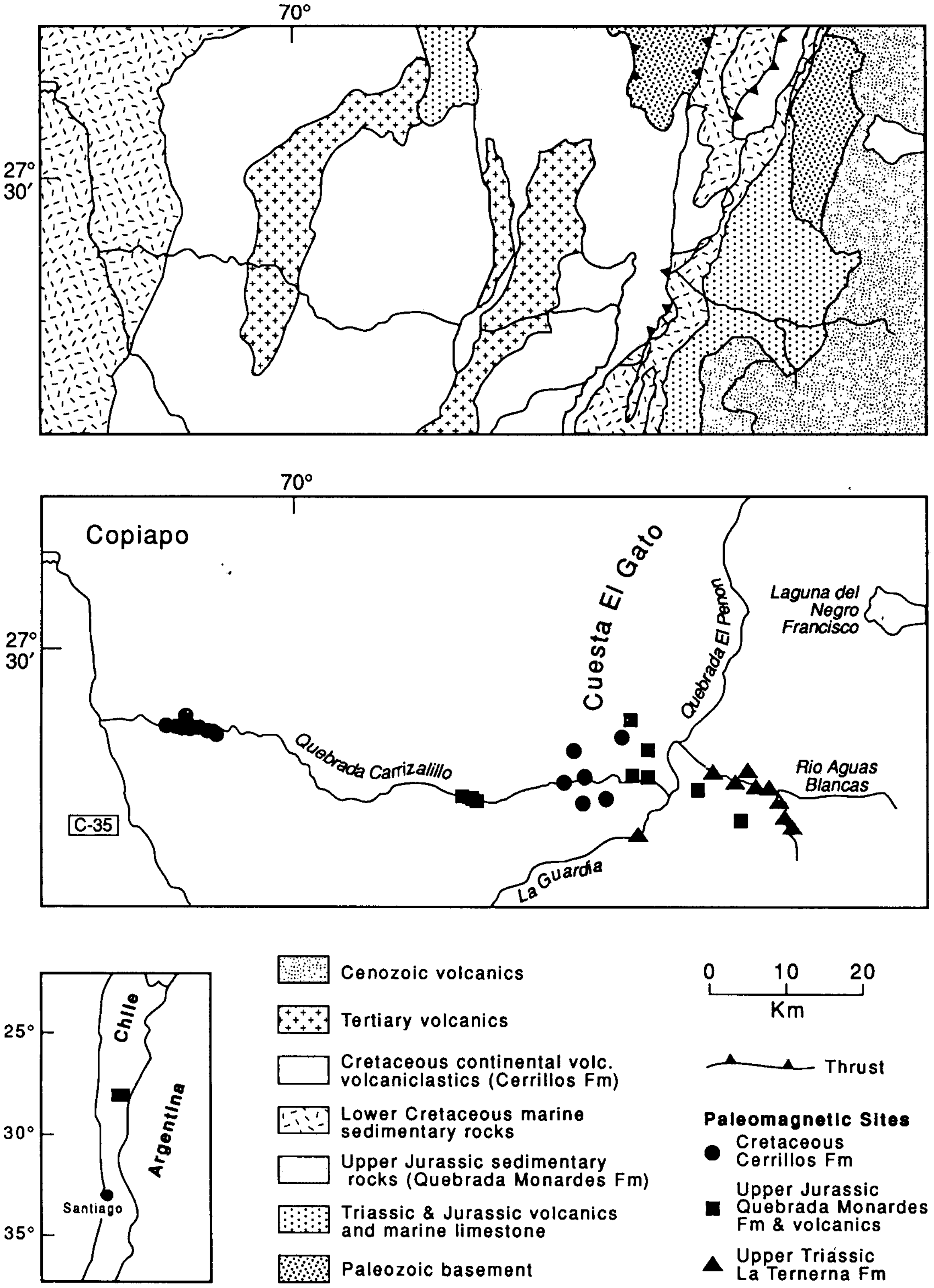

Fig. 2. Geological sketch map and sample location map.

can craton (Table 5). The Cerrillos Formation was sampled in two distinct localities, one (Cuesta el Gato [CEG]) near the sampling areas of the La Ternera and Quebrada Monardes formations and the other [EDB] about 40km to the west. As the magnetic behavior and mean directions of rocks from the two areas are distinct, we report results separately in Table 3.

La Ternera Formation. Eighteen (of 25) sites displayed very stable remanant magnetization. Rocks sampled include basaltic and andesitic flows, red lithic volcaniclastic sandstones and breccias, green pyroclastic tuffs, and welded lithic tuffs. Results are divided into three categories:

Category A (site 28) is characterized by the presence of two opposing magnetic directions. Results of alternating field (AF) and thermal demagnetization suggest that both components reside in magnetite. A component of relatively

TABLE 1. Paleomagnetic Data for the Upper Triassic La Ternera Formation of Northern Chile

Site	Uncorrected		Corrected		α 95	R	N/No	VGP	
	D	I	D	I				Lat	Long
90tr02	198.5	+41.7	187.8	+34.9	3.9	7.965	8/8	78.9	152.3
90tr03	35.2	-47.8	24.6	-46.1	8.3	6.888	7/7	68.2	205.8
90tr06	27.6	-43.4	11.6	-40.0	11.4	5.859	6/6	78.4	178.1
90tr10	19.7	-41.6	19.7	-41.6	7.7	7.866	8/8	71.9	193.2
90tr13	232.6	+49.8	232.6	+49.8	5.7	7.926	8/8	44.4	217.5
90tr16	220.6	+47.9	227.7	+40.9	4.3	7.959	8/8	47.0	206.1
90tr20	235.3	+56.8	246.1	+38.8	6.6	7.901	8/8	30.4	211.1
90tr22	32.5	-51.2	24.5	-58.8	7.6	7.871	8/8	66.5	237.3
90tr23	26.1	-59.5	6.8	-62.6	5.5	4.979	5/7	72.8	273.8
90tr24	49.7	-49.5	39.0	-57.2	6.9	3.983	4/4	55.8	228.0
90tr25	219.9	+54.4	219.9	+54.4	10.3	5.884	6/7	55.4	222.9
90tr26	30.4	-45.5	19.3	-50.1	9.6	5.899	6/9	72.9	216.1
90tr27	9.5	-48.6	9.5	-48.6	8.7	4.949	5/5	81.4	215.7
90tr28	208.7	+79.8	247.2	+66.4	10.6	4.924	5/6	35.1	242.7
90tr99	37.0	-36.7	40.9	-40.9	5.8	4.977	5/5	54.3	213.9
90tr100	28.9	-43.1	31.5	-56.0	.5	4.983	5/5	62.1	226.8
90tr101	49.6	-34.7	55.5	-45.7	18.4	3.884	4/4	41.2	213.4
90tr103	29.0	-48.5	40.4	-51.1	3.7	7.968	8/8	54.9	217.1
GMU	33.9	-49.5			5.5	17.57	18		
GMC			33.1	-51.1	6.5	17.42	18		
MVGP					7.8	17.15	18	60.9	218.3

D, and I are site-mean declination and inclination; α 95 is radius of circle of 95% confidence; R is length of vector sum; N/No is number of samples used in calculations/number of samples collected; Lat and Long are south latitude and east longitude of virtual geomagnetic pole (VGP); GMU and GMC are group means uncorrected for tilt and corrected for tilt; MVGP is mean VGP for tilt-corrected directions.

TABLE 2. Paleomagnetic Data for the Lower Jurassic Quebrada Monardes Formation and Associated Volcanic Rocks

Site	Uncorrected		Corrected		α 95	R	N/No	VGP	
	D	I	D	I				Lat	Long
90qm14	81.4	-38.0	35.7	-41.5	6.4	5.969	6/6	57.7	202.0
90qm18	18.8	-52.4	18.1	-29.2	4.9	9.903	10/10	69.4	168.6
90qm19	5.6	-48.6	21.4	-47.7	14.1	4.869	5/7	71.1	209.1
90qm47	354.8	-36.5	19.4	-40.8	10.36	4.928	5/5	72.0	191.0
90qm48	20.8	-26.1	33.5	-19.7	17.2	3.898	4/4	54.0	177.9
90qm51	185.8	+ 1.3	187.0	+ 6.0	6.0	4.976	5/6	64.6	126.8
90qm54*	159.3	+59.4	197.4	+67.2	29.6	2.891	4/6	64.0	264.3
90qm55	222.7	+66.2	238.8	+60.5	18.5	3.883	4/4	40.6	232.9
90qm85	164.2	+28.9	192.5	+41.1	20.0	3.863	4/4	78.1	184.0
GMU	15.5	-40.9			14.1	7.55	8		
GMC			23.7	-40.9	20.5	7.04	8		
MVGP					12.7	6.63	8	66.9	191.6

Column headings are as in Table 1. VGP is calculated for tilt-corrected directions.
*Omitted from final average.

TABLE 3. Paleomagnetic Data for the Cretaceous Cerrillos Formation

Site	Uncorrected		Corrected		α 95	R	N/No	VGP	
	D	I	D	I				Lat	Long
90cs33	214.6	+54.2	161.0	+71.2	10.2	5.886	6/6	59.7	222.6
90cs34	192.2	+41.5	202.3	+48.1	6.6	4.970	5/7	78.4	184.0
90cs41	210.6	+54.1	206.8	+24.3	7.7	6.904	7/10	63.0	223.0
90cs42	203.7	+25.8	202.5	+11.2	8.1	4.955	5/7	63.8	172.7
90cs44	162.1	+63.2	208.3	+72.4	4.9	14.77	15/16	67.8	325.6
90cs45	184.1	+64.6	208.8	+57.8	5.5	3.989	4/4	70.9	281.7
GMU	191.7	51.8			15.4	5.75	6		
GMC			201.6	+48.5	22.9	5.47	6		
MVGP					16.2	5.70	6	74.8	229.8
Elisa De Bordo									
90eb65	41.6	-52.4	29.8	-58.3	8.7	5.917	6/6	53.9	218.9
90eb66	38.4	-48.1	35.5	-57.9	7.1	6.917	7/7	56.3	211.8

TABLE 3. (continued)

Elisa De Bordo

Site	Uncorrected		Corrected		α 95	R	N/No	VGP	
	D	I	D	I				Lat	Long
90eb69	43.4	-46.3	358.0	-46.9	5.9	7.921	8/8	51.7	210.3
90eb70	71.0	-24.0	46.2	-50.2	27.4	3.754	4/5	22.5	202.6
90eb71	48.2	-44.3	351.4	-44.1	15.4	4.843	5/6	47.2	209.2
90eb72	59.2	-43.2	67.7	-67.6	9.9	5.893	6/6	37.4	211.6
90eb73	50.7	-36.9	51.2	-61.9	14.3	3.929	4/5	43.5	202.7
90eb74	43.8	-42.2	46.0	-62.2	10.7	3.959	4/7	50.7	205.4
GMU	46.8	-45.0			5.2	6.96	7		
GMC			26.1	-59.7	13.0	6.73	7		
MVGP					5.8	6.94	7	48.8	211.0

Column headings are as in Table 1. VGP is calculated for uncorrected directions.

TABLE 4. Additional Data for Mesozoic Formations in North Central Chile

Site	Lat	Long	Attitude	Demag Range	Lithology
Upper Triassic La Ternera Formation					
90tr02	27°42'33"	69°21'54"	N40°E/15°SE	410-590	welded tuff
90tr03	27°41'39"	69°22'12"	N40°E/10°SE	26-100	hornblende andesite
90tr06	27°40'36"	69°22'42"	N30°E/18°SE	18-100	andesite breccia
90tr10	27°39'51"	69°24'00"	----------	28-100	fine grained andesite
90tr13	27°39'51"	69°24'15"	----------	40-100	red volcanic breccia
90tr16	27°38'42"	69°28'03"	N00°E/10°W	25-100	welded red tuff
90tr20	27°38'42"	69°28'03"	N00°E/20°W	30-100	fine grained basalt
90tr22	27°40'00"	69°23'40"	N50°W/10°E	30-100	fine grained basalt
90tr23	27°40'00"	69°23'41"	N00°E/11°E	420-590	fine grained basalt
90tr24	27°40'00"	69°23'00"	69°23'41"	30-60	fine grained andesite
90tr25	27°40'00"	69°23'41"	----------	30-100	red welded tuff
90tr26	27°40'00"	69°23'41"	N00°E/11°E	20-50	green tuff
90tr27	27°39'15"	69°25'10"	----------	30-100	fine grained basalt
90tr28	27°39'30"	69°26'00"	N00°E/17°W	26-85	fine grained basalt
90tr99	27°43'45"	69°37'15"	N70°W/13°N	340-660	red porphyritic basalt
90tr100	27°43'45"	69°37'15"	N70°W/13°N	410-660	red porphyritic basalt
90tr101	27°43'45"	69°37'15"	N70°W/13°N	3-65	fine grained basalt
90tr103	27°43'45"	69°37'15"	N70°W/13°N	30-100	fine grained basalt
Lower Jurassic Quebrada Monardes Formation					
90qm14	27°39'24"	69°26'50"	N55°E/50°SE	420-630	red sandstone
90qm18	27°39'12"	69°26'30"	N70°W/23°S	350-580	red sandstone
90qm19	27°38'09"	69°28'39"	N10°E/14°N	350-610	red sandstone
90qm47	27°38'30"	69°35'30"	N15°E/30°N	20-100	red sandstone
90qm48	27°38'30"	69°35'30"	N15°E/30°N	20-90	volcaniclastic sandstone
90qm51	27°38'30"	69°35'30"	N20°E/20°N	40-100, 530-630*	hornblende andesite
90qm54	27°38'28"	69°35'29"	N20°E/20°N	20-70	volcaniclastic sandstone
90qm55	27°38'28"	69°35'29"	N05°E/10°N	20-100, 630-675*	red sandstone
90qm85	27°30'39"	69°34'40"	N15°E/40°N	550-650*	red sandstone
Cretaceous Cerrillos Formation: Cordon El Gato					
90cs33	27°39'25"	69°39'45"	N12°W/30°N	500-580,* 40-85	fine grained andesite
90cs34	27°39'10"	69°39'20"	N50°E/12°N	20-90	fine grained andesite

TABLE 4. (continued)

Cretaceous Cerrillos Formation: Cordon El Gato

90cs41	27°38'35"	69°37'43"	N70°W/30°S	540-610*	porphyritic andesite
90cs42	27°37'43"	69°37'43"	N85°W/15°S	40-100	porphyritic andesite
90cs44	27°39'30"	69°36'30"	N30°E/20°N	550-640,* 40-90	prophyritic andesite
90cs45	27°39'30"	69°36'30"	N10°W/15°S	500-580,* 20-100	fine grained andesite

Upper Cretaceous Cerrillos Formation: Eliza de Bordo

90eb65	27°34'40"	70°07'00"	N00°E/10°E	40-100	andesite flow
90eb66	27°34'40"	70°08'00"	N45°W/12°NE	350-580,* 25-65	mafic flow
90eb60	27°34'30"	70°12'00"	N20°E/40°SE	340-580,* 30-100	andesite
90eb70	27°33'10"	70°11'55"	N20°E/40°SE	20-75	volcanoclastic
90eb71	27°34'20"	70°12'30"	N20°E/52°SE	20-80	limestone
90eb72	27°34'40"	70°11'30"	N40°W/25°NE	30-90, 400-500*	prophyritic andesite
90eb73	27°34'35"	70°11'50"	N40°W/25°NE	350-570*	andesite breccia
90eb74	27°34'15"	70°09'25"	N50°W/20°NE	340-560*	porphyritic andesite

Lat and Long are south latitude and west longitude of site. Attitude is given in standard geological notation (strike/dip). Demag range indicates range of demagnetization steps used in line fitting to determined sample directions. Thermal demagnetization is shown by asterisk; other numbers are alternating field demagnetization range, in milliteslas. Note that some sites contain samples whose directions were determined by both alternating field demagnetization and thermal demagnetization or by a combination of the two (see text).

low stability, directed NE and up, is removed by 20mT and 410°C. A more stable SW and down component then is removed between 20 and 80 mT and between 410° and 580°C. Table 1 gives the directions of the higher-stability component; the less stable component probably represents a VRM acquired in the present geomagnetic field.

Category B sites (2, 3, 6, 10, 13, 16, 20, 22, and 24-27) have a single, well-defined component of magnetization residing mostly in magnetite but also present in hematite. Both polarities are present. The direction of the hematite component (isolated between 580° and 650°C) is indistinguishable at 95% confidence from the component isolated by AF (presumably carried by magnetite). AF results are reported in Table 1.

Category C (sites 99 and 100) has normal polarity residing in hematite. Site 99 displays a single component removed between 350° and 640°C. Site 100 showed a linear thermal demagnetization trend which diverged from the origin, suggesting that a small component of magnetization may remain after demagnetization to 670°C.

Seven sites from the La Ternera Formation are not included in Table 1. Four of these are coarse grained sandstones or obviously altered andesites that displayed erratic demagnetization paths. Three other sites, in unaltered volcanics, have stable single-component magnetizations but high within site scatter, possibly indicating lightning strikes, postmagnetization rheomorphic flow, orientation errors, or other unknown effects.

Quebrada Monardes red beds. Site mean directions for the nine reasonably well behaved sites that we have completed from this unit are listed in Table 2. These directions were obtained from red fluvial and aeolian sandstones and from one andesitic flow. Results are divided into four categories:

Category A (sites 14, 18, and 19) have a single-component normal polarity magnetization carried by hematite, isolated from 350° to 650°C.

Category B (site 85) has a NW and up component removed by 425°C and a stable SW and down component isolated between 425° and 670°C. Alternating field demagnetization up to 100mT had little effect on this site, suggesting that both components reside in hematite. Table 2 includes only results from the component with high unblocking temperature.

Category C (sites 47 and 48) is characterized by a NE and up component of magnetization carried by magnetite. Samples responded well to AF demagnetization.

Category D (sites 51, 54, and 55) has a NE

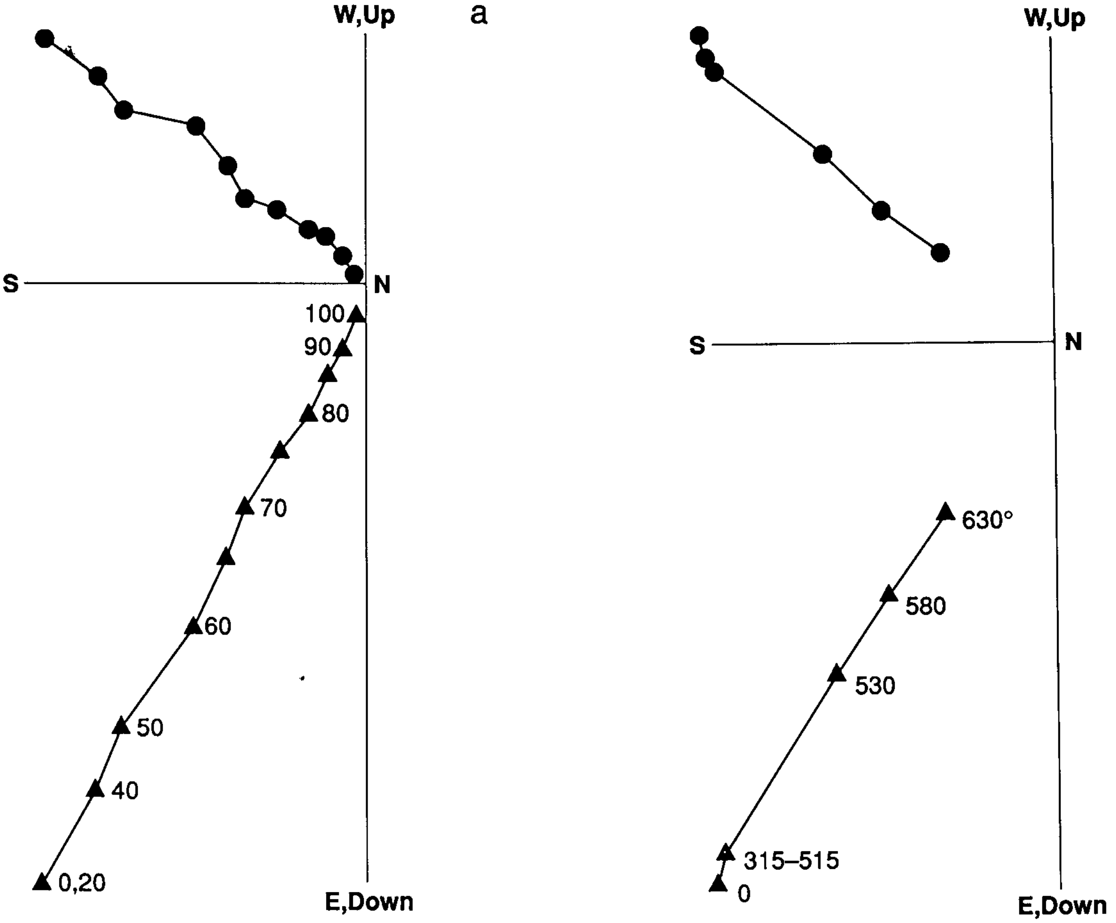

Fig. 3. Orthogonal diagrams illustrating response to laboratory demagnetization. (a) Alternating field (AF) demagnetization of reverse-polarity red welded tuff from La Ternera Formation. Peak demagnetizing field (in milliteslas) indicated. Dots represent map view; triangles represent vertical section. (b) Thermal (Th) demagnetization of same rock unit. Temperatures (in degrees Celsius) are indicated. (c) Th demagnetization of normal-polarity red sandstone from Quebrada Monardes Formation. (d) Th and AF demagnetization of andesite from Cerrillos Formation, Cuesta el Gato locality. Sample was first demagnetized to 80mT, then from 500° to 630°C. (e) AF demagnetization of mafic flow from Cerrillos Formations, Eliza de Bordo locality.

and up component of magnetization, removed by 60mT and 340°C, and a SW and down component isolated between 60 and 100 mT or between 20 and 70 mT. Site 90qm54 has a circle of 95% confidence that exceeds 20° and has not been used in group mean calculations.

The remaining Quebrada Monardes sites studied to date display very complicated results. For instance, four sites located stratigraphically below site 90qm54 were resistant (failed to change direction) to AF (to 100mT) and thermal (to 680°C) demagnetization. Two other sites, located near site 85 in thinly bedded mudstone and limestone, had linear demagnetization paths but highly discordant directions. Work is still in progress on our remaining Quebrada Monardes collection which, owing to the enthusiasm of the second author during the first field season, is still quite substantial.

Cerrillos Formation. Results from the Cerrillos Formation are discussed by locality. The western locality, Elisa de Bordo (EDB), consists of volcanic and sedimentary rocks that dip 30°-45° to the NE and SW. The eastern locality, Cuesta el Gato (CEG), located in the same general area as the La Ternera and Quebrada Monardes sites, includes andesite flows, breccias, and volcaniclastic rocks.

EDB. Site mean directions for eight (of 10) sites and the expected direction are given in Table 3. All sites have normal polarity. Results are divided into two categories.

Category A (sites 65, 66, 68 and 69) has a single component of magnetization, carried mostly by magnetite but also present in hematite. Pilot samples demagnetized thermally had fairly uniform unblocking temperatures of 550°-620°C; AF pilots were magnetically cleaned (reached stable end-points) between 20 and 100 mT.

Category B (sites 70, 71, 73, and 74) is similar to category A but with the addition of one or both of the following: (1) a streaked distribution of sample directions and (2) multiple components of magnetization. Site 90eb70 had a large circle of confidence and highly divergent mean direction (Table 1); hence it was not used to calculate the group mean.

CEG. Site mean directions for the six stable sites collected at this locality are

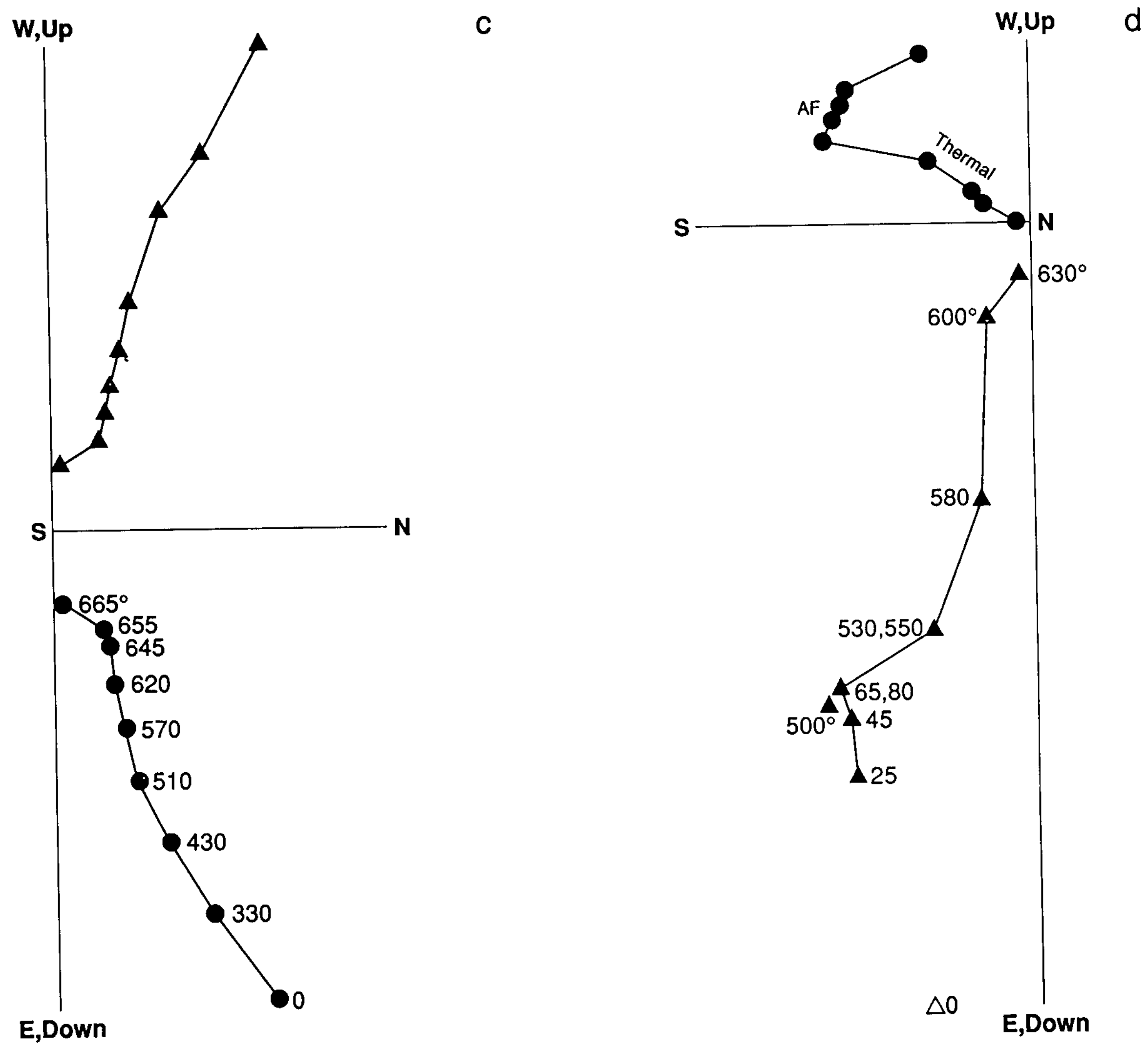

Fig. 3. (continued)

given in Table 3; several other sites yielded unstable or ambiguous magnetizations. Many problematic sites in this locality are situated near an Eocene granodiorite and probably have been affected by local thermal or hydrothermal events of unknown magnitude or duration. The complicated magnetic behavior of these rocks makes their directions suspect. All samples are reversely magnetized. Acceptable results are divided into two categories.

Category A (sites 33, 42, 44, and 45) has linear AF and thermal demagnetization trajectories, with the remanent magnetization (RM) carried by magnetite. Most magnetizations were demagnetized by 100 mT and 580°C, although persistence of some remanence above these levels shows that hematite is present.

Category B (sites 34 and 41) contains sites with multiple components of magnetization residing in both magnetite and hematite. AF (up to 100 mT) followed by thermal 580° to 640°C) demagnetization isolated different components of magnetization in some specimens. Generally, thermal demagnetization between 500° and 630°C isolated a component which trended toward the origin. For other samples, AF demagnetization (to 100 mT) identified a similar trend. The results given in Table 3 were obtained from selected, relatively uncomplicated demagnetization trajectories that trended toward the origin.

Field stability tests. Field stability tests were used to help determine whether components of magnetization were primary or secondary. Tests used in this study include the fold test, consistency of reversal, and a conglomerate test.

Tilt corrections for the La Ternera Formation are too small to allow a meaningful fold test. There is a slight increase in scatter upon tilt correction seen in Table 1 and Figures 4a and 4b, although the increase is not significant at 95% confidence according to Cox [1969]. The increase probably is the result of our inability to measure the dip with high accuracy and of incorrectly applying tilt corrections for what was actually an original dip. Mean normal (N) and reverse (R) directions are antipodal at 95% confidence. RM of specimens from the N and R subgroups displayed similar stability during laboratory demagnetization. No correlation was found between polarity and lithology, color, location, or magnetic mineralogy. As there is no geological reason to suspect remagnetization we use the tilt-corrected mean direction for further analysis.

The Quebrada Monardes Formation also has N and R sites with nearly antipodal mean direc-

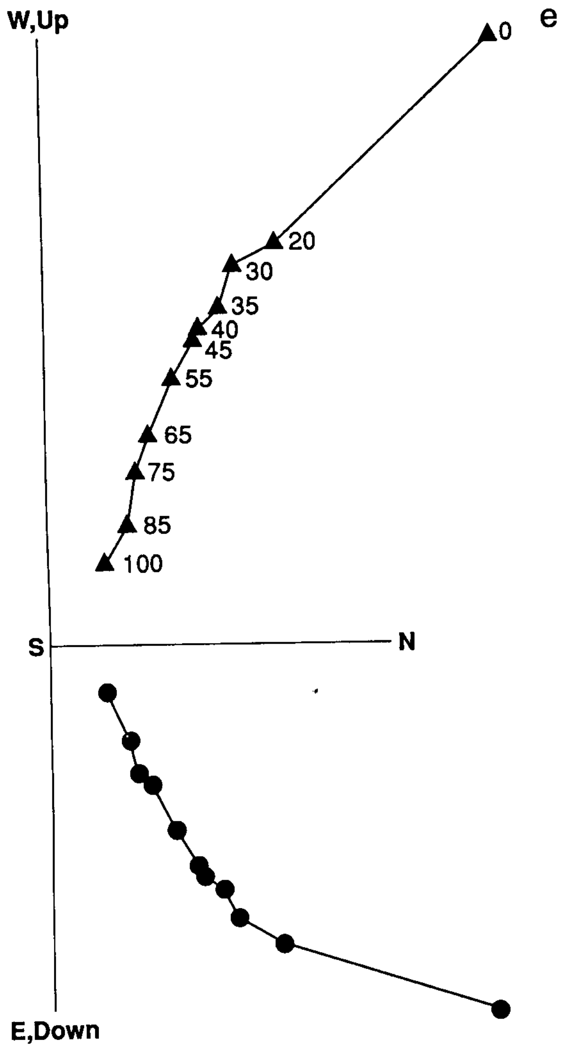

Fig. 3. (continued)

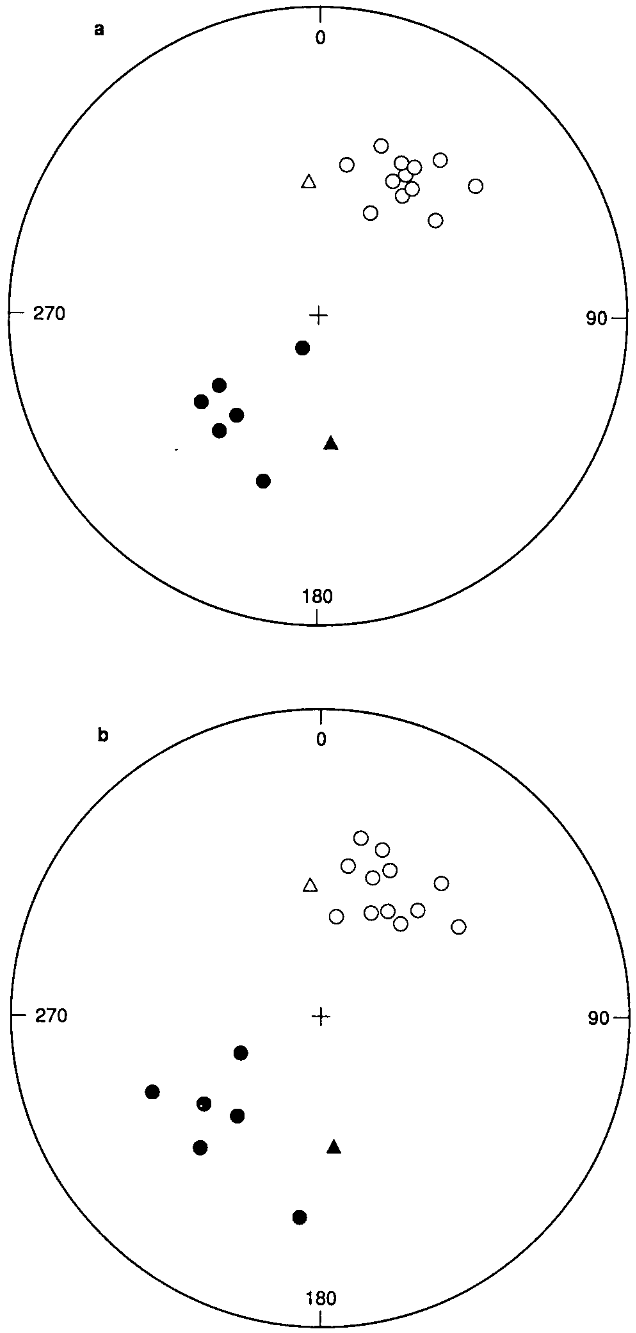

Fig. 4. Equal-area plot of site mean directions of remanent magnetization from La Ternera Formation: (a) in situ and (b) corrected for tilt. Solid/open symbols indicate lower/upper hemisphere. Triangles show expected direction.

tions, plus positive conglomerate and fold tests. For the conglomerate test, clasts were collected from three conglomerate beds (near sites 47, 51, and 54). Most are volcanic andesites and probably are Triassic and/or Jurassic in age. Magnetization was stable during AF and thermal demagnetization; the directions recovered were random. As with the La Ternera Formation, a formal fold test for the Quebrada Monardes Formation is infeasible. However, the increase in precision parameter that results when the tilt correction is made (7.3 to 14.1) is significant at 95% confidence, according to Cox [1969]. The weight of evidence thus supports a primary origin for the Quebrada Monardes remanence. Note that in both the La Terera and Quebrada Monardes sections, dips are so gentle that mean directions with and without tilt correction are indistinguishable at 95% confidence.

In contrast, both areas of Cerrillos rocks appear to be remagnetized. Directions from the CEG locality become more dispersed and less circular when the tilt correction is applied (Figures 6a and 6b and Table 3). Rocks at the EDB locality appear completely unaltered in the field, but Figures 7a and 7b and Table 3 strongly indicate that they also have been remagnetized after tilting. No field stability tests were possible at either Cerrillos locality.

South American Reference Poles

Since our ultimate objective is to determine whether or not our sampling area has moved with respect to stable South America, we must next compare the mean poles of Tables 1-3 with appropriate reference poles for the South American craton. Table 5 summarizes the reference poles used in this study. For the Triassic we calculated the mean of five separate formation poles (listed in Table 5), and for the Jurassic we used results of a similar combination, from Beck [1988]. Although the Cerrillos is assigned a Cretaceous age, its magnetization is clearly

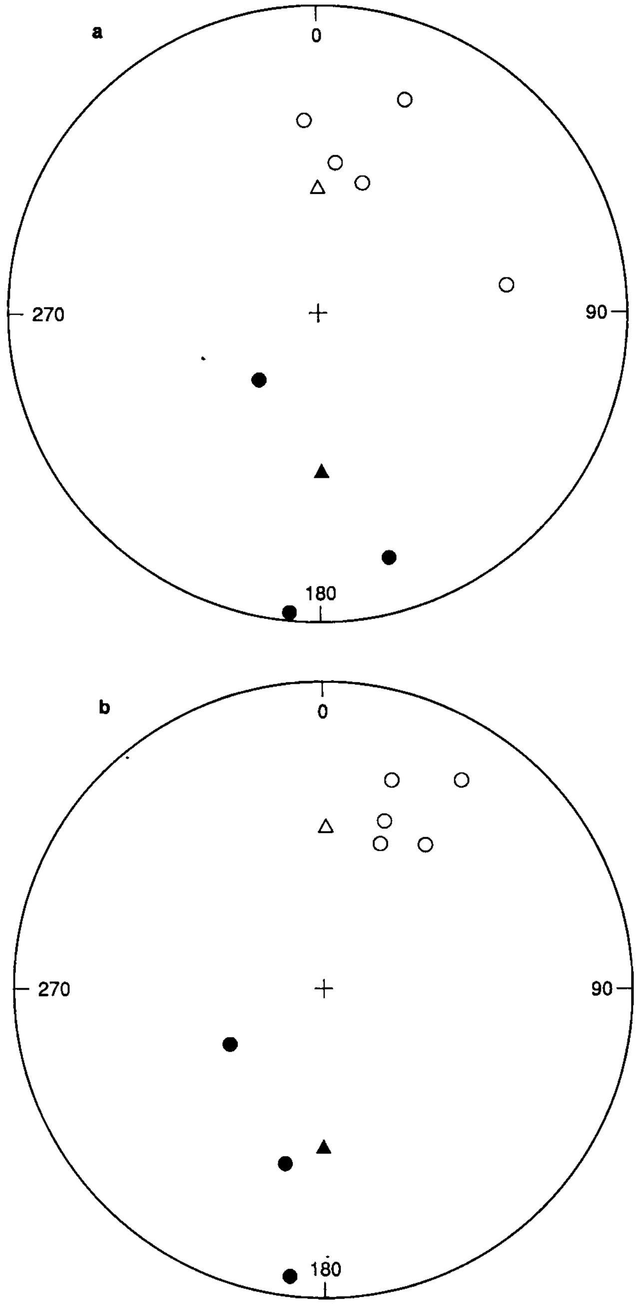

Fig. 5. Quebrada Monardes Formation. See caption for Figure 4.

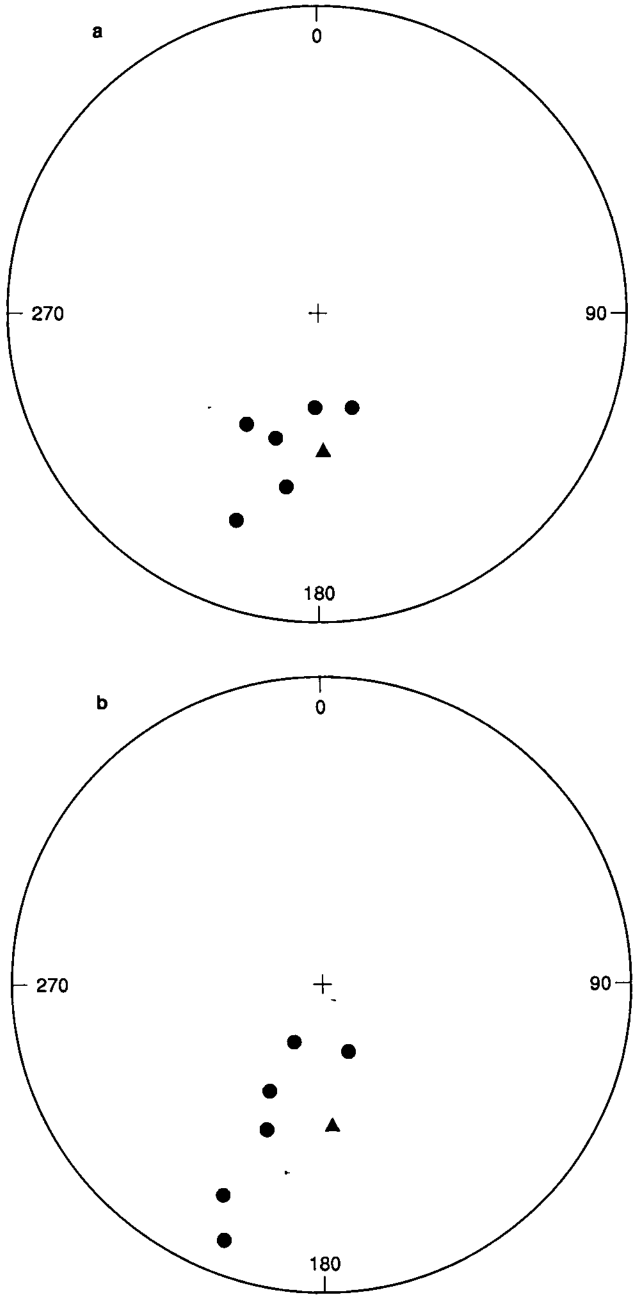

Fig. 6. Cerrillos Formation, Cuesta el Gato locality. See caption for Figure 4.

younger; presumably early Tertiary. Unfortunately, there are no reliable early Tertiary reference poles for stable South America (see compilation by Irving and Irving, 1982). For that reason we used the early Tertiary (44-54 Ma) North American (NA) pole of Diehl et al. [1983], rotated into South America (SA) coordinates using the reconstruction parameters of Engebretson et al. [1985]. To perform the rotation, we used the 37 Ma SA/NA stage pole, then prorated the rotation on the 66 Ma stage pole to 44 Ma. We have arbitrarily assigned an "error circle" of 10° to this rotated pole. The nominal error circle on the Diehl et al. [1983] pole is only 3.0°, but this clearly understates the probable error on our ultimate objective, that is, to establish a "reference pole" for a poorly specified time in the early Tertiary for South America, by using a reference pole from another continent.

Note that none of the reference poles listed in Table 5 is significantly different from the present spin axis at 95% confidence, and in fact the maximum angular difference between the Triassic and Jurassic poles of Table 5, commonly used South American Cretaceous reference poles [Bellieni et al., 1983; Butler et al., 1991], and the rotated Tertiary pole of Diehl et al. [1983] is only 13.4°. It seems clear that apparent polar wander (APW) relative to South America during the past 230 m.y. has been remarkably slight and thus that any motion of South America relative to the spin axis has been almost completely along lines of latitude.

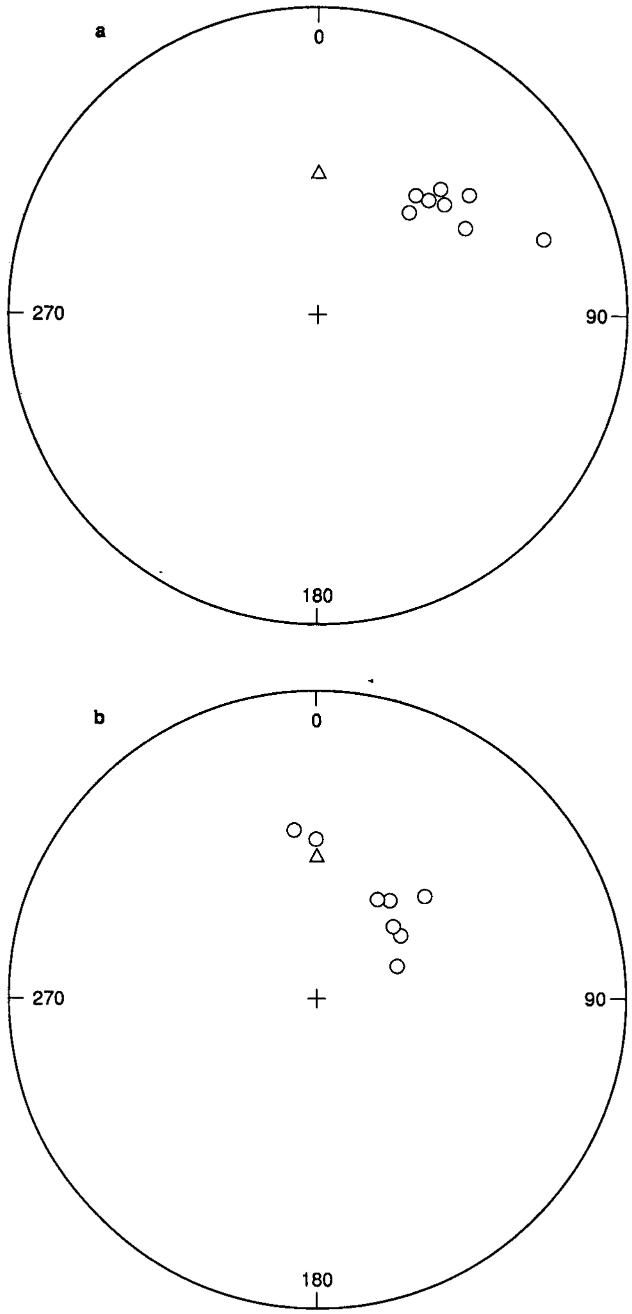

Fig. 7. Cerrillos Formations, Eliza del Bordo locality. See caption for Figure 4.

Discussion

This study presents paleomagnetic results from rocks ranging in magnetization age from early Triassic to (probably) early Tertiary, distributed over a relatively large region. Directions within the La Ternera and Quebrada Monardes formations are substantially uniform throughout the area (lateral dimensions of the order of 50 km), implying the absence of small, variably rotated crustal blocks. For this reason we have calculated poles for the La Ternera and Quebrada Monardes formations by combining all respective site mean VGP (bottom of Tables 1 and 2). Comparison of poles from the La Ternera and Quebrada Monardes formations (tilt corrected) with their respective references poles points to about 25° of clockwise rotation, with no significant latitudinal transport (Table 6).

Within the Cerrillos CEG Formation only R polarity is present, and the observed increase in dispersion when the tilt correction is made suggests remagnetization. Furthermore, magnetizations within the Cerrillos CEG sites are complicated and difficult to isolate. Another complication in interpreting the Cerrillos CEG results is that we are unsure of the correct reference pole, as explained earlier. These uncertainties inevitably make any tectonic conclusions tentative. The rotation listed in Table 6 for Cerrillos CEG (17.3°) is only slightly more than half that of the older formations in the same area.

Cerrillos EDB exposures have only N polarity. (Thus the two Cerrillos localities do not have the same age of magnetization.) After site 90eb70 is dropped, scatter is improbably low (Table 3), possibly because remagnetization occurred so rapidly that the secular variation was not fully sampled. Thus the Cerrillos EDB direction is doubly suspect. However, for what it is worth, it shows an unusually large clockwise rotation (48.1°), with insignificant latitudinal displacement.

The essentially identical rotation found in Upper Triassic and Upper Jurassic rocks from the eastern sampling area suggests that rotation did not begin until sometime after the Late Jurassic. The fact that the Cerrillos CEG locality has a (poorly defined) rotation of about 15° may mean that rotation was roughly half complete when these rocks were remagnetized, presumably in the early Tertiary.

Results from the Cerrillos EDB locality are interesting, although unfortunately not particularly reliable. Cerrillos EDB rocks apparently were thoroughly remagnetized, at some time when the geomagnetic field had normal polarity; time of remagnetization is otherwise poorly constrained but probably was early Tertiary. The tight cluster of site mean directions for the EDB locality suggests that the secular variation has not been completely averaged, and the fact

TABLE 5. Reference Poles

Time Interval	South Latitude	East Longitude	A_{95}	Reference
Triassic	82.7°	285.5°	7.4	TC1-5
Jurassic	89.1°	217.1°	4.6	Beck [1988]
Early Tertiary	85.1°	303.2°	10.0	D and E

References are TC1, Veldcamp et al. [1971]; TC2, sum of Thompson [1972], Valencio et al. [1977], and Creer et al. [1970]; TC3, Valencio [1970]; TC4, Valencio et al. [1975]; and TC5, sum of Valencio et al. [1975], Creer et al. [1970]. D and E reference indicates early Tertiary North American reference pole of Diehl et al. [1983] rotated into South American reference frame using reconstruction parameters of Engebretson et al. [1985]. A_{95} is radius of circle of 95% confidence. Circle of confidence for early Tertiary pole is assigned arbitrarily. See text.

TABLE 6. Displacements of the Various Sampling Areas Relative to Stable South American, Calculated From Paleomagnetic Poles

Formation	Observed Pole	Observed α 95	Reference Pole	Reference α 95	Rotation	Poleward Transport
La Ternera	60.9S; 218.3E	7.8	82.7S; 285.5E	7.4	28.1 ± 9.0°	-4.5 ± 8.6°
Quebrada Monardes	66.9S; 191.6E	12.7°	89.1S; 217.1E	4.6°	23.7 ± 11.7°	-6.9 ± 10.8°
Cerrillos						
CEG sites	74.8S; 229.8E	16.2°	85.1S; 303.2E	10°	17.3 ± 18.4°	+1.7 ± 15.2°
EDB sites	48.8S; 211.0E	5.8°	85.1S, 303.2E	10°	48.1 ± 10.8°	-4.8 ± 9.2°

Observed poles are mean virtual geomagnetic poles, from Tables 1-3. Reference poles are summarized in Table 5 and discussed in text. Rotation and poleward transport were calculated using poles from Beck [1989]. Positive rotations are clockwise; positive poleward transport is northward.

that the rocks are remagnetized opens the possibility of post magnetization tilting. If neither of these problems is substantial, then the Cerrillos EDB locality has a large rotation, perhaps as much as 45°. This would indicate that the EDB and CEG localities have different rotational histories and therefore are located in different structural blocks. This tentative interpretation obviously needs to be tested by further work.

Finally, with respect to the ultimate cause of rotation, it is worth noting that our results do not match the predictions of the orocline model (Figure 1a) of Isacks [1988] particularly well. Isacks' model calls for about 10°-15° of clockwise rotation on the southern limb of the orocline, far less than we encountered. Furthermore, Isacks envisaged most of the rotation as occurring in a single episode, during the Miocene. Our results (excluding the Cerrillos EDB locality) are more compatible with mechanisms that produce time-dependent rotation, with some of the rotation having been acquired during the Mesozoic. However, results from north of Arica match the predictions of the Isacks [1988] model (P. D. Riley, unpublished compilation, 1992). It seems very likely that results south of the Arica deflection reflect both mechanisms: rotations of small blocks in response to oblique subduction added to the effects of oroclinal bending.

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