PALEOMAGNETIC STUDY OF THE CENTRAL ANDES: COUNTERCLOCKWISE ROTATION OF THE PERUVIAN BLOCK

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ABSTRACT

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Paleomagnetic study was performed on Mesozoic and Tertiary rocks from Peru and northernmost Chile. Comparisons of these results as well as other data from the Central Andes with paleomagnetic poles from South American craton strongly support the orocline hypothesis of Carey for the formation of the Arica (Santa Cruz) deflection. Paleomagnetic declinations of Jurassic and Cretaeous rocks are quite similar to the direction of the present-day structural trend in the Central Andes, which suggests that the mountain belt has rotated in a coherent fashion (i.e., rigid body rotation) in sections of the Central Andes. The occurence of this deformation is certainly post-Cretaceous, with some suggestion that rotation still continued as recently as Neogene. The mechanism of this deformation is not well known, but a differential stretching of the Amazon Basin behind the Peruvian Andes is a possibility.

INTRODUCTION

Paleomagnetic data from South America are not numerous, but the polar wander path for Phanerozoic time is well defined (e.g., McElhinny, 1973; Vilas, 1981). For Cretaceous and Jurassic time, a number of paleomagnetic results are available from the stable part of the continent, mostly from Argentina and Brazil (Table I). All these paleomagnetic poles lie quite close to the present geographic pole. In fact, paleomagnetic data reported from the stable platform suggest that there has been little appreciable polar wandering relative to the South American continent since Mesozoic time.

Paleomagnetic results from the Andean orogenic belt are relatively few, but some results for Cretaceous or Jurassic rocks have been reported from

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TABLE I

Jurassic and Cretaceous age Poles from the South American Platform.

Rock Unit (Reference)	Site Lat. °S	Site Long. °W	Age Ma	Number of Unit	Number of Sample	Pole Lat. °S	Pole Long. °W	α_{95} °
		Cretaceous						
Pocos de Caldas Complex (1)	22	47	75	7	42	82	268	14
Cabo de Sto. Agostinho (2)	8	35	85 − 99	9	100	88	315	5
Maranhâo Basalt Intrusion (3)	7	42	118	21	190	84	81	2
Serra Geral Formation (4,5)	20–30	46–56	115 ± 15	67	230	83	76	3
Mean of Cretaceous Poles				4		89	43	8
		Middle Jurassic						
Maranhâo Volcanics (3)	6	47	158 ± 12	15	121	85	263	7
Chon Aike Formation (6,7,8)	44–48	65–69	166 ± 5	54	165	85	197	6
Mean of Middle Jurassic Poles				2		86	230	12

References: (1) Opdyke and MacDonald (1973);
(2) Schult and Guerreiro (1980);
(3) Schult and Guerreiro (1979);
(4) Pacca and Hiodo (1976);
(5) Creer (1962);
(6) Valencio and Vilas (1970);
(7) Vilas (1972);
(8) Creer *et al.* (1972).

areas such as Colombia and Venezuela (MacDonald and Opdyke, 1972; Skerlec and Hargraves, 1980), northern Chile (Palmer *et al.*, 1980a, b) and Patagonia (Dalziel *et al.*, 1973). Most of the results from the Andean region show that magnetic declinations are quite different from the cratonic area, and that they tend to align along the trend of the orogenic belt. To explain the declination shift in the Caribbean region, Skerlec and Hargraves (1980) suggested a clockwise rotation as a consequence of the relative motion between the Caribbean and South American plates. For the southern Chile data, Dalziel *et al.* (1973) concluded that a counterclockwise tectonic rotation occurred in forming the Magellanes orocline.

An orocline is "an orogenic belt with a change in trend which is interpreted as an impressed strain" according to the original definition by Carey (1955). Carey suggested several examples which may be explained by the orocline hypothesis. One of these is the Arica deflection (also called Santa Cruz deflection) which he called the Bolivian orocline, which is indicated by the abrupt change in the coastline trend at the Peru-Chile border. It is an interesting problem whether or not the Arica deflection is an orocline, i.e., if it is a feature caused by bending in relatively recent times or is merely a change in the trend of the original sedimentary trough which later formed the Andean mountain belt.

Palmer *et al.* (1980a) attempted to compare paleomagnetic declinations in Mesozoic rocks on both sides of the deflection. Though they could not obtain reliable directions from Peruvian side, they showed that the Jurassic Camaraca Formation near Arica had a natural remanent magnetization rotated westward by about 25 degrees. This result suggests that Arica may not be exactly at a hinge as is inferred from the coastline trend, but that the deformation may have taken place over a wider area.

In order to test the orocline hypothesis in more detail, we carried out field work in the northern part of the Central Andes in cooperation with Instituto Geofisico del Peru (Lima) and Universidad de Chile (Santiago), and collected more than 600 paleomagnetic samples both from sediments and volcanic rocks. Their ages ranged through the whole Phanerozoic, but Cretaceous and Jurassic rocks were the most abundant. In this paper, we summarize paleomagnetic results of Mesozoic and Cenozoic rocks and evaluate them in terms of large scale tectonic movements. Details of individual paleomagnetic studies are being published separately by Heki *et al.* (1984, 1985).

GEOLOGY AND SAMPLING

The Central Andes extend from 47°S, where the Chile Rise (a mid-oceanic ridge) approaches the South American continent, to 3°S, where the Carnegie Ridge (an aseismic ridge) approaches the continent. There are numerous earthquakes of depths up to 700 km and trenches more than 5 km deep related to the Central Andes, but active volcanism is taking place only in the middle part of this segment (27°–15°S). The middle part is a typical continental margin active zone. The Andes in this region are composed of three mountain belts running roughly parallel to the coastline trend; the Eastern, Central and Western Cordillera. The Eastern and Central Cordillera in this area are made up of a Paleozoic miogeosyncline (continental shelf and continental slope deposits), which was compressed eastward and folded in Cenozoic time. The Western Cordillera is formed from volcanic and plutonic rocks and associated sediments of Mesozoic and Cenozoic age (Miyashiro *et al.*, 1982).

Figure 1 shows the routes and sampling sites of the 1980–1981 field trips in Peru and northernmost Chile. Geologically, this area can be devided into five separate zones (e.g., Cobbing and Pitcher, 1972; Reyes, 1980). From the Pacific coast inland they are (a) Precambrian and paleozoic rocks along the coast of southern Peru (Arequipa massif), (b) Mesozoic volcanic and

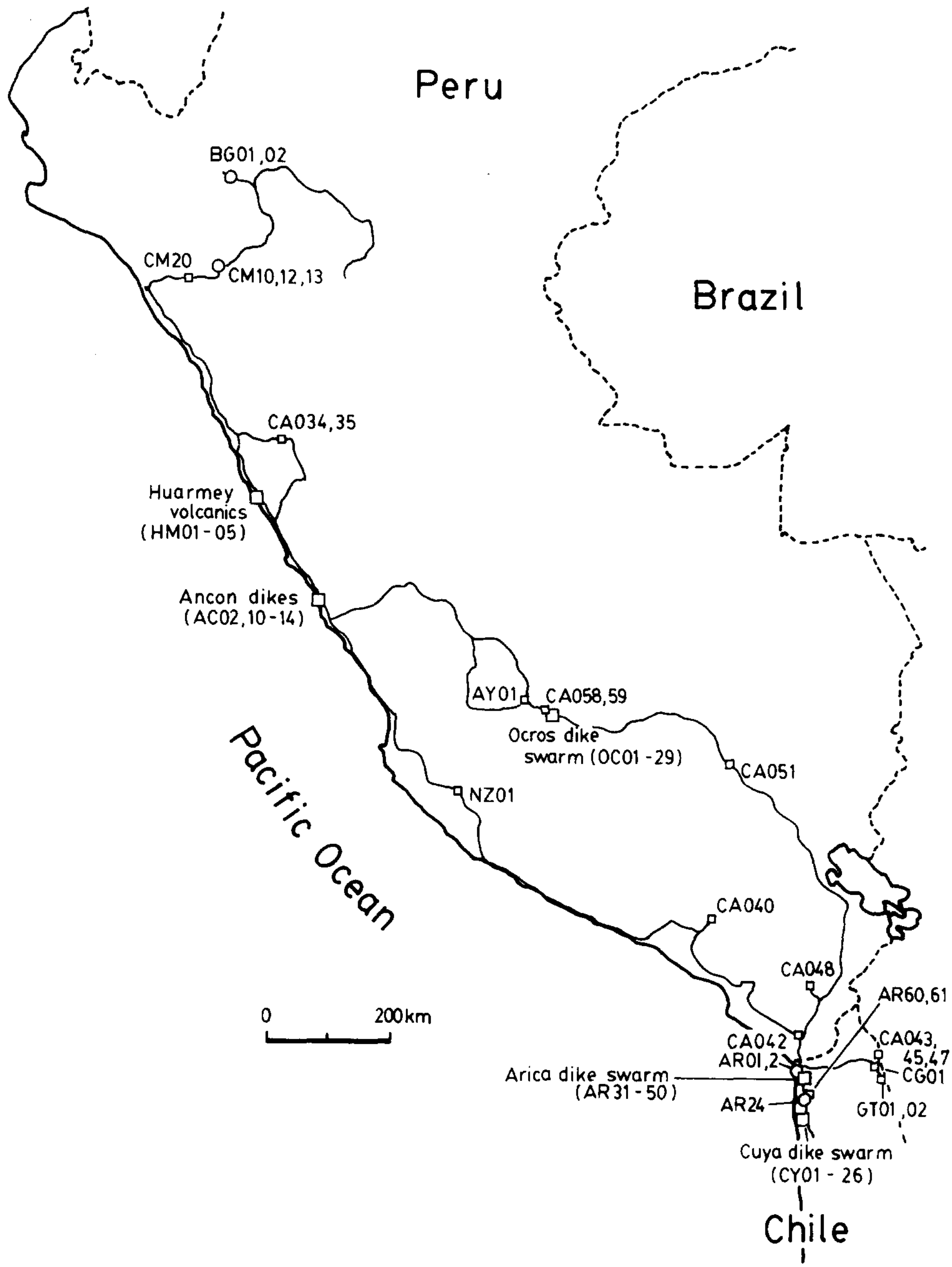

Fig. 1. Routes and sampling sites of the 1980–1981 field trip in Peru and Chile. Squares and Circles indicate volcanic and sedimentary rocks. Sites include those which are not treated in this paper.

clastic rocks of the coast range, (c) Mesozoic to Cenozoic batholiths and marine sediments in the Western Cordillera, (d) Paleozoic metamorphic and sedimentary rocks of the Eastern Cordillera, and (e) Mesozoic and Cenozoic continental sediments of the subandean thrust-fold belt.

From the coastal area, upper Cretaceous volcanic rocks (lava flows and dikes) were sampled at several places between 7°S and 14°S. These rocks belong to the upper part of the Mesozoic marine sedimentary-volcanic complex which form a relatively narrow belt along the Peruvian Pacific coast. Near Lima, the strata are composed of (from bottom to top) late Jurassic to early Cretaceous submarine volcanic and clastic rocks, lower Cretaceous sandstones, limestones and mudstones, and thick submarine volcanics as well as volcaniclastic rocks of Albian and later age (A. Taira, personal communication, 1983). Pillow lavas are abundant, but samples were mostly collected from dikes because the former appeared usually more weathered. Five cooling units were sampled near Huarmey (HM), and five units were obtained near Ancon (AC). Some isolated volcanic units were also sampled near Nazca (NZ) and near Cajamarca (CM20).

In the Western Cordillera, carbonate-dominated Albian to Turonian formations attain a thickness of more then 200 m. They are, from bottom to top, Chulec, Pariatambo, Yumagual, Mujarrun, and Cajamarca Formations (Reyes, 1980). The Albian Chulec Formation was sampled near Cajamarca (CM13), where it is composed of bedded micrite and marl, each with a thickness of about 10 m. The Pariatambo Formation (Albian) is about 200 m thick and mostly consists of bituminous limestones and interbedded shales. They represent an oxygen-poor environment at the time of maximum transgression (A. Taira, personal communication, 1983). At the south of Bagua Grande, a 80 m section of the Yumagual Formation (Cenomanian) was sampled (BG01, 02). This sequence is composed of an upper limestone unit and a lower marl unit (massive and laminated gray marl with intercalations of minor shell beds). Molluscan fossils are abundant, and such genus as *Homomya*, *Exogyra*, *Phoradomya*, and *Protocardia* were identified in the collected specimens. An age of Cenomanian was assigned to this formation based on these fossils (A. Taira, personal communication, 1984).

Some Mesozoic samples were also obtained near Arica at the Peru-Chile border. They are red sandstones of the Atajaña Formation (AR24) and the Arica dike swarm (AR31–50) of Cretaceous age, shales of the Camaraca Formation (AR01) and the Cuya dike swarm (CY) of Jurassic age. The Atajaña Formation is composed of alternating coarse-grained sandstone and granitic conglomerate at the top and reddish massive silty sand at the bottom. The Camaraca Formation is made of coarse sandstones and shales. The Arica dike swarm is situated just south of Arica where it intrudes into Cretaceous tuff breccia and red sandstones, and is overlain by Tertiary ignimbrites. The Cuya dike swarm is located further south in the valley of the River Chiza, about 100 km south of Arica. The dikes intrude Jurassic sandstones and limestones, and also are overlain by Tertiary ignimbrites.

One Neogene dike swarm was sampled at Ocros (OC). This site is along the highway between Ayacucho and Cuzco, on the upstream gorge of the River Pampas. Continental margin type volcanism started in upper Paleogene period, mostly in subaqueous environment, covering basement rocks of Paleozoic sediments and Cretaceous to lower Tertiary granites. Neogene volcanic rocks including the Ocros dike swarm overlaid these formations. These volcanic formations are heavily glaciated and deeply dissected (T. Ui, personal communication, 1983). Samples were collected along a road cut.

The formation ages are well constrained by marine fossils and by stratigraphic correlation for the sedimentary strata of northern Peru, but not well defined for others.

EXPERIMENTAL PROCEDURES

Oriented hand samples were collected in the field and core specimens were cut in the laboratory. Magnetic remanences of sediments (mostly limestones) were measured using a cryogenic magnetometer. Natural remanent magnetization (NRM) of typical sediment samples was of the order of 10^{-7}–10^{-8} Am^2/kg. Stepwise alternating field (AF) demagnetization was applied to all of the specimens at least to 80 mT peak field. For specimens from selected pilot samples, stepwise thermal demagnetization was carried out up to the Curie temperature of hematite. AF and thermal demagnetization results were in most cases in good agreement. The primary component of magnetization was determined by least squares fitting of a straight line to points on a Zijderveld diagram.

The NRM in the majority of the sedimentary rocks is carried by magnetite or Ti-poor titanomagnetite. This can be ascertained by thermomagnetic analysis as well as by the results of AF and thermal demagnetization; remanences are reduced to less than 10% by 80 mT or 550°C demagnetization levels. In some rocks, remanence carriers are bimodal; both magnetite and hematite components were recognized by AF and thermal demagnetization. Although we did not perform a detailed study of the origins of the NRM components, we prefered the remanences carried by magnetite because they give results consistent with volcanic rocks. Hematite may be a secondary mineral in these rocks formed in the course of weathering and alteration. In cases where only hematite remanence is available (e.g., BG02), the results were discarded for the present analysis to keep the data consistency.

The NRMs of the volcanic rocks were measured using a spinner magnetometer. Volcanic samples in this study have relatively weak NRM intensity (10^{-5}–10^{-6} Am^2/kg), but are relatively stable against AF demagnetization. The median destructive field (MDF) was generally in excess of 30 mT. Thee mean NRM directions were determined either by least squares fitting in Zijderveld diagrams as was done for the sedimentary samples, or by selecting an optimum step in the AF demagnetization, as determined by minimum dispersion criterion.

Most of the results were corrected for the bedding of strata. For the dike swarms, the bedding of the host rock was used for this correction, assuming that the ages of dikes are not much different from those of the host rocks. However, no corrections were applied for Peruvian coastal volcanics (Ancon and Huarmey series), because field evidence such as the flat-lying pillow structure (HM) and the vertical contact of dike intrusions (AC) demonstrate that such corrections are not necessary.

PALEOMAGNETIC RESULTS

Table II summarizes the paleomagnetic directions for Mesozoic and Tertiary rocks obtained in this study. Although the amount varies, all the data consistently show magnetic declinations deflected westwards. Mesozoic paleomagnetic poles from the Central Andes are plotted in Figure 2. Data are grouped into three regions; Peru, northernmost Chile, and central Chile and Argentina. Data sources other than the present study are listed in

TABLE II

Paleomagnetic Results of Mesozoic and Tertiary Rocks.

Rock Unit	Site		Age	Number of		NRM Direction			Pole	
	Lat. °S	Long. °W		Unit	Sample	Incl. °	Decl. °	α_{95} °	Lat. °S	Long. °E
Ocros Dike Swarm	13.4	73.9	Tm-p	32	192	−31.8	−14.2	5.3	75.8	358.8
Coastal Volcanics	5–15	75–80	K(Ce)	12	68	−26.7	−22.1	5.1	68.0	359.5
Yumagual Fm.	5.9	78.2	K(Ce)	3	52	−32.2	−20.6	5.1	66.7	339.7
Pariatambo Fm.	7.1	78.3	K(Al)	1	6	−21.1	−52.5	5.4	38.1	3.4
Chulec Fm.	7.1	78.3	K(Al)	1	7	−22.6	−38.3	10.2	52.0	1.6
Atajaña Fm.	18.8	70.3	K	1	28	−25.6	−14.9	4.1	74.7	37.9
Arica Dike Swarm	18.6	70.3	K	19	103	−41.7	−12.4	3.3	77.2	352.4
Camaraca Fm.	18.5	70.3	J	1	22	−37.6	− 7.9	2.8	82.1	359.4
Cuya Dike Swarm	19.2	70.2	J	25	110	−21.1	−14.1	7.8	74.1	49.1

Tm-p, Miocene to Pliocene; K, Cretaceous; Ce, Cenomanian; Al, Albian; J, Jurassic.

TABLE III

Mesozoic and Tertiary Paleomagnetic Data of the Central Andes.

Rock Unit (Reference)	Site Lat. °S	Site Long. °W	Age Ma	Pole Lat. °S	Pole Long. °E	Angular Deviation Rotation °	Angular Deviation Flattening °
			Peruvian Andes				
Ocros Dike Swarm	13	74	Tm-p	76	359	−14 ± 6	−6 ± 8
Coastal Volcanics			K	68	0	−21 ± 10	−9 ± 17
Yumagual Fm.	6	78	K	67	340	−20 ± 10	−22 ± 16
Pariatambo Fm.	7	78	K	38	3	−51 ± 10	−9 ± 16
Chulec Fm.	7	78	K	52	2	−37 ± 14	−10 ± 19
			Northernmost Chile and Bolivia				
Salla Group (2)	17	68	50–55	64	0	−27 ± 17	−12 ± 12
Atajaña Fm.	19	70	K	75	38	−14 ± 9	8 ± 13
Arica Dike Swarm	19	70	K	77	352	−11 ± 9	−9 ± 13
Camaraca Fm.(Lava) (1)	19	70	157 ± 4	71	10	−24 ± 14	0 ± 19
Camaraca Fm. (Shale)	19	70	J	82	359	−12 ± 13	−1 ± 18
Cuya Dike Swarm	19	70	J	74	49	−18 ± 15	17 ± 22
			Chilean and Argentinian Andes				
Pirgua Subgroup (3)	26	66	77–114	85	222	7 ± 14	−2 ± 13
Central Chile (4)	30	71	85–125	81	209	12 ± 11	−2 ± 11
Vulcanistas Cerro Rumpipalla Fm. (5)	32	64	< 121	83	95	−1 ± 11	7 ± 12
Vulcanistas Cerro Colorado Fm. and Almafuerte Lavas (5,6,7)	32	64	119–127	76	23	−15 ± 11	0 ± 11

For definition of rotation and flattening, see text.
References: (1) Palmer *et al.* (1980a); (2) Hayashida *et al.* (1984);
(3) Valencio *et al.* (1977); (4) Palmer *et al.* (1980b);
(5) Vilas (1976); (6) Valencio (1972); (7) Mendia (1978).

Table III. It is clear from Figure 2 that the deviation from the paleomagnetic poles of the stable platform is largest for Peru, smaller for northernmost Chile and almost non-existent for the southern part. Apparently, the Peruvian block underwent a counterclockwise rotation since late Mesozoic time.

It is interesting that the rotation of the declination is not confined to the north of Peru-Chile border. This fact was first made clear by the paleomagnetic study of the Camaraca Formation by Palmer *et al.* (1980a). The present data are in good accord with their results. Although the amount is smaller than those for the Peruvian Cretaceous samples,

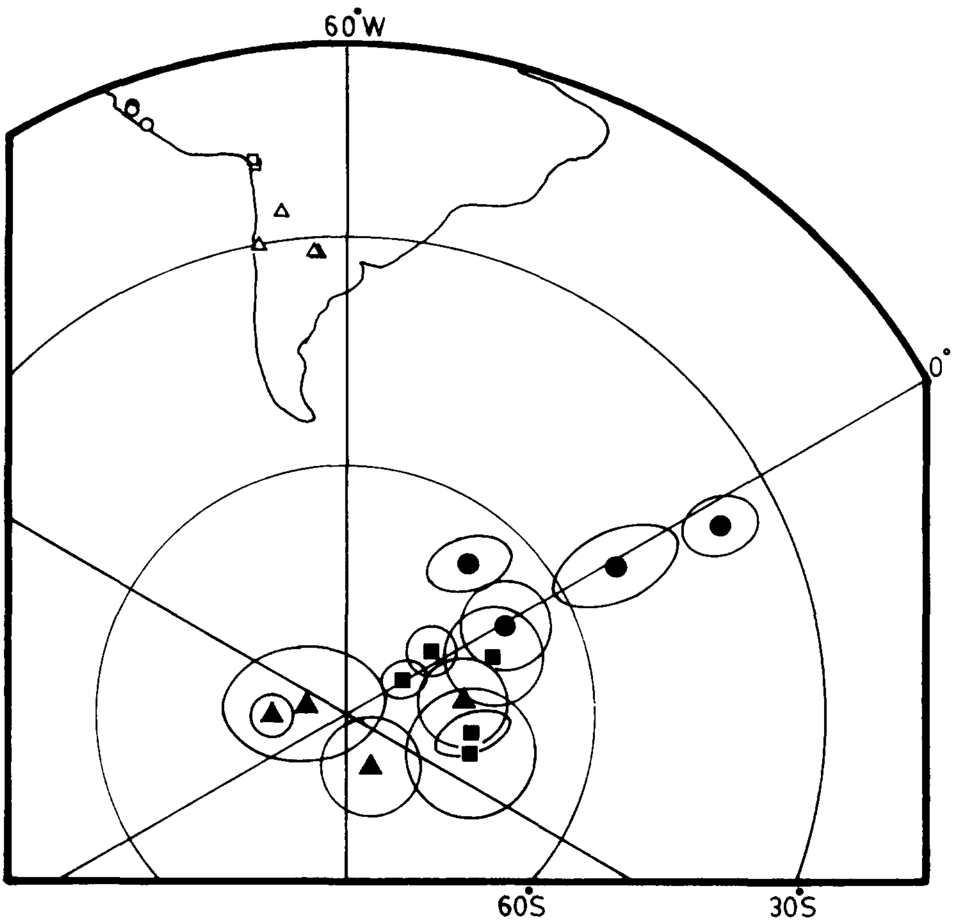

Fig. 2. Mesozoic paleomagnetic poles of the Central Andes. Circles, squares and triangles denote poles of the Peruvian Andes, northernmost Chile and Chilean/Argentinian Andes, respectively. Ovals indicate 95% confidence limits. Corresponding sampling sites are shown as small open symbols in the map.

paleomagnetic results from Cretaceous and Jurassic rocks of northernmost Chile clearly indicate that they also underwent some counterclockwise rotation since the Cretaceous. Therefore the extent of the rotated block is not confined to the north of Peru-Chile border.

To express the anomaly of NRM directions, the following two quantities were calculated following the definitions of Beck (1980). First the expected field direction was obtained at each sampling site in the orogenic belt using the pole position of the stable part of South America (Table I). Rotation R is calculated as the difference between the observed and expected declinations, while flattening F is the difference between the two inclinations. Likewise, 95% confidence limits are also calculated for R and

F by the method of Beck (1980). Table III lists R and F for Mesozoic and Tertiary data in the Central Andes area. As can be expected from the foregoing discussion, R takes large negative values in Peru, much reduced but still significant in northernmost Chile, and is small and below the noise level in central Chile and the Argentine Andes. It is also clear that the flattening F is very small and not significant in every part of the Central Andes. Figure 3 summarizes rotation R with its 95% confidence limits for the paleomagnetic data in Table III.

DISCUSSION

Figure 3 shows that the magnetic meridian in Jurassic and Cretaceous time was very nearly parallel to the present day structural trend in the Central Andes. This can be seen more clearly if we omit two Tertiary data (Ocros and Salla) from the figure. The close correlation of the rotations with the strike of the orogenic belt can be statistically tested as follows. Figure 4a is the structural trend read from the map of Hayes (1974). Paleomagnetic data are rotated counterclockwise so as the strike of the orogenic belt becomes straight. Figure 5b shows poles before and after such "unbending". Clearly, the dispersion of poles becomes significantly smaller and the mean pole coincides with those of the South American craton (Table II). The difference in the angular standard deviations of these two groups of poles (17.1° and 11.8°) is significant at 95% confidence level.

It may be concluded that a large scale counterclockwise rotation occurred in the northern part of the Central Andes. From the coherence of Jurassic and Cretaceous data and from the close correlation of the amount of rotation with the structural trend, it is certain that tectonic deformation is post-Cretaceous and is more or less a rigid body rotation. However, as the data are scarce for the Tertiary in both Peru and northernmost Chile, it is difficult to assign a precise time for this rotation. The only available Tertiary paleomagnetic pole is from the Ocros dike swarm in central Peru, which clearly indicate that the rotation R, though smaller than that for the Mesozoic data, cannot be neglected for Neogene.

If the Ocros result reflects not local but regional tectonic movement as is the case with Mesozoic data, the rigid body rotation was still going on after the emplacement of the volcanic rocks there. In that case, the age of volcanic activity is crucial in defining the timing of tectonic rotation. The Peruvian geologic map classifies the Ocros dikes and volcanics as Plio-Pleistocene. Preliminary K-Ar dating gave a somewhat older age of 6–8 Ma. These ages are only tentative and we are hoping to have a reliable age in a short time. To be sure of the continuation of tectonic rotation of the Peruvian block as late as Neogene, more Tertiary data are needed.

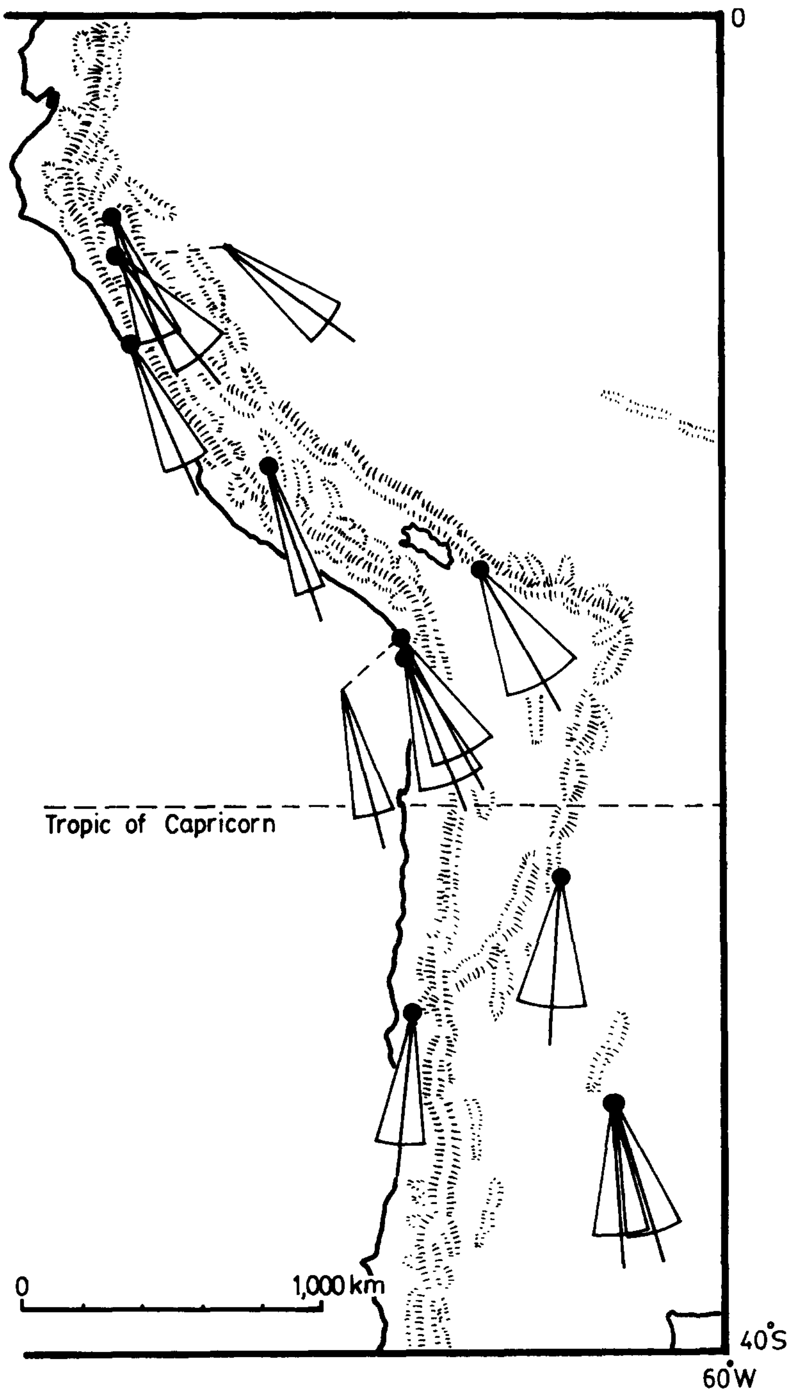

Fig. 3. Rotations and their 95% confidence limits for Jurassic, Cretaceous and Tertiary data. The points northwest of Lake Titicaca (Ocros) and southeast of the lake (Salla) are for Tertiary rocks, while two other points south of the lake (Camaraca, Cuya) are for samples of Jurassic age. All the other data are for Cretaceous age sites.

It is difficult to postulate a mechanism leading to a regional declination anomaly in Mesozoic and early Tertiary rocks of the Central Andes. Except possibly the Arequipa massif, no allochtonous terranes have been recognized in Peru or northern Chile which may have accreted from the oceanic side; i.e., continental fragments, oceanic swells suh as seamounts, or an uplifted trench prism, as are commonly seen in the western coastal areas of North America or southwestern Japan. Moreover, our data consistently show that the rotation of declination is coherent over a wide area, which practically negates the existence of independent blocks in this region. Therefore, declination anomalies cannot be ascribed to the rotation of accreted terranes.

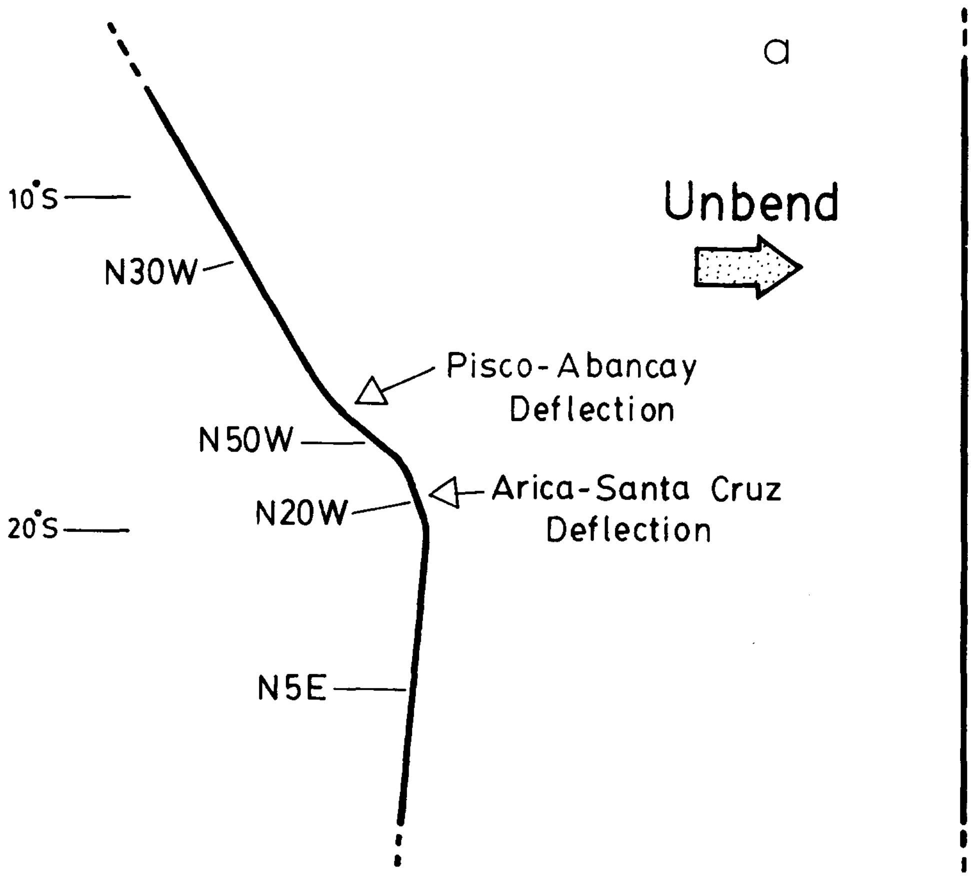

Fig. 4. a. The Andean structural trend in Peru and northern Chile. Locations of deflections are indicated by arrows. b. Paleomagnetic poles from the Central Andes before (top) and after (bottom) unbending of structural trend indicated in a. After unbending, angular standard deviation (ASD) becomes significantly smaller and the mean pole (star) coincides with the platform data.

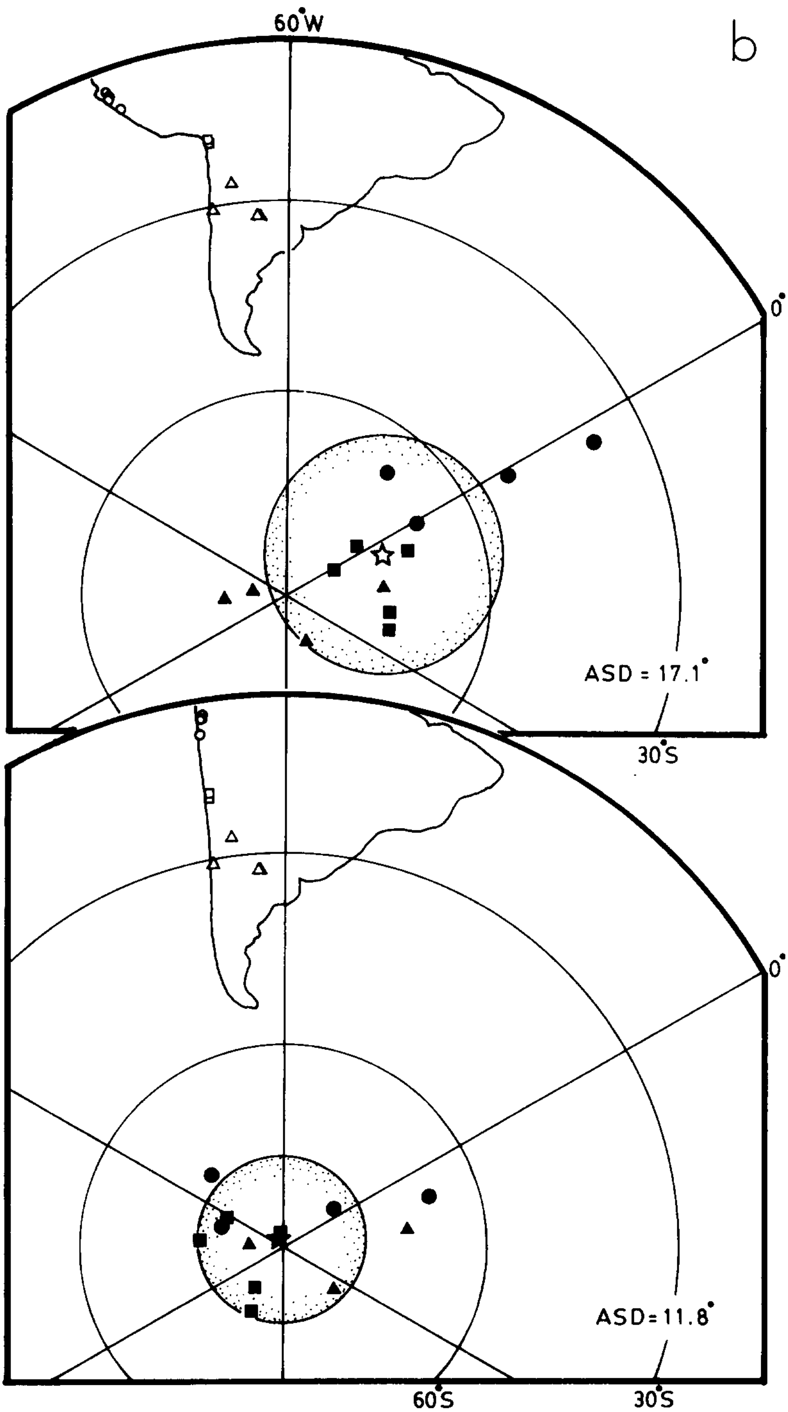

FIGURE 4 *(continued)*

In island arcs such as Japan, a possible mechanism for the bending of the arc is opening or closure of the back arc basins such as the Japan Sea. In the case of South America, only a shallow sea existed in Cretaceous time in the area of the Central Andes, and a severe contortion is absent in Mesozoic units. It is thus quite difficult to accomodate a basin behind the volcanic arc of the Western Cordillera, which was subsequently lost due to subduction or other reasons.

If we accept that the Central Andes was originally a straight feature in Mesozoic which underwent later bending (Figure 4a), the deformation must be accommodated in the continental lithosphere behind the orogenic belt. Two extreme cases can be considered for such intraplate deformation (Figure 5): (A) the region south of Bolivian orocline retreated eastward and Peruvian Andes rotated about a vertical axis at Peru-Ecuador border, or (B) Peruvian Andes rotated about a hinge at Peru-Chile border and proceeded oceanward.

If mechanism A dominated in the formation of Bolivian orocline, nearly 1000 km of continental crust should be disposed of behind Chilean Andes, for which there is no supporting evidence. Mechanism B involves a differential stretching behind Peruvian Andes, i.e., the westernmost part of Amazon basin. The amount needed is 1000 km at the northernmost part and zero at Peru-Chile border. Stretching would result in thinning of continental lithosphere (McKenzie, 1978) and would form a large depressed basin where rapid accumulation of sediment takes place. Such may be a cause of formation of the vast Amazon basin. Although not very convincing, we prefer mechanism B (Figure 5) for the mode of formation of Bolivian orocline, mainly because of the lack of decisive evidence *against* stretching.

CONCLUSIONS

A number of paleomagnetic poles were obtained from sediments and volcanic rocks of Peru and northernmost Chile. The NRM of these rocks are quite stable to AF and thermal demagnetizations and their stability is attested by high MDF, small directional change in demagnetizations, and antipodal directions for sequences containing both normal and reversed polarities. For the case of volcanic rocks, secular variation is well represented by abundant independent units (lavas and dikes) and so we can conclude that true paleomagnetic poles were obtained by taking the averages.

Cretaceous samples from Peru consistently show a declination shift of 30°–50° in a counterclockwise sense. For Cretaceous and Jurassic rocks of Arica region and for the Neogene dike swarm at Oros, the amount of declination shift is smaller but still significant. These results indicate that the Peruvian block rotated as a rigid body in the Cenozoic, supporting the

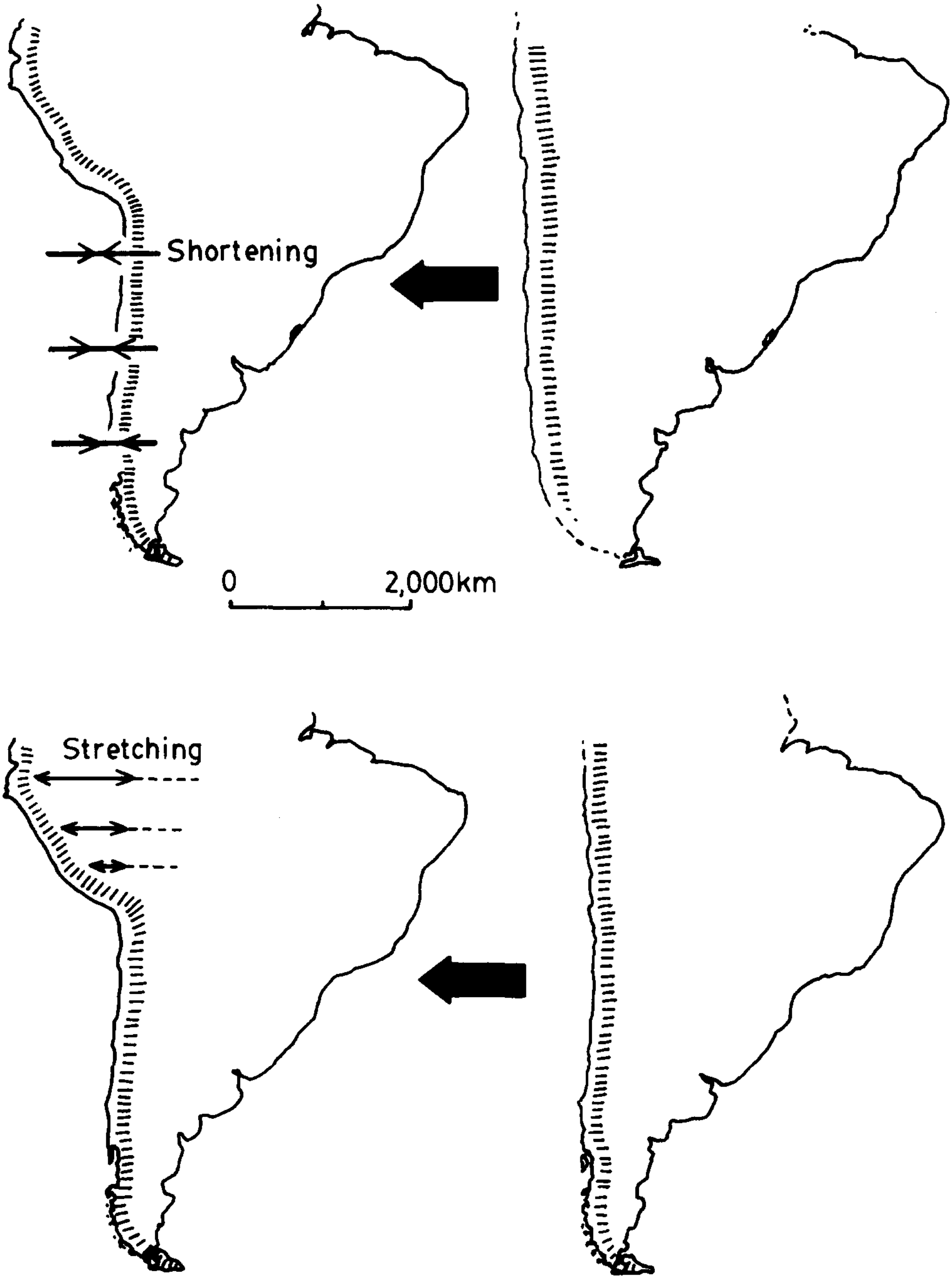

Fig. 5. Two mechanisms which can account for the deformation responsible for the formation of Bolivian orocline.

orocline hypothesis of Carey (1955). Results from the Ocros dike swarm suggest that the rotation may have continued up to the rather recent past. The mechanism of this tectonic rotation is not clear at this stage, but it may be concluded that continental blocks may not be so rigid as the oceanic plate and the large amount of deformation needed to form the Bolivian orocline may be accommodated in the Amazon Basin behind the Central Andes, as a stretching and thinning of continental lithosphere. Further paleomagnetic studies of the Amazon Basin as well as the Tertiary of the Central Andes are needed to clarify the nature of Bolivian orocline in more detail.

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