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PALEOMAGNETIC STUDY OF CRETACEOUS ROCKS OF PERU, SOUTH AMERICA: EVIDENCE FOR ROTATION OF THE ANDES

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ABSTRACT

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Paleomagnetic data for the Cretaceous volcanic and sedimentary rocks in the Andean region of Peru are given. Reliable paleomagnetic field directions were obtained for three Cretaceous (Albian to Cenomanian) formations from calcareous sediments in northern Peru. Stable remanent magnetization directions were also derived from twelve Cretaceous lava flows and dikes in coastal Peru. Paleomagnetic data of the same age from the stable areas of South America such as Brazil demonstrate that the paleomagnetic poles are nearly coincident with the present pole, but Peruvian paleomagnetic directions studied here showed several tens of degrees of counterclockwise declination shifts. This suggests counterclockwise tectonic rotation of an extensive block which includes the whole of Andean Peru.

INTRODUCTION

Mesozoic paleomagnetic poles for the South American plate are well studied from the data based on the rocks of the cratonic area such as Precambrian shields or intracratonic basins (Creer, 1962; Vilas, 1974; Schult and Guerreiro, 1979 and 1980; and many others) while paleomagnetic poles are less well established in the Andean orogenic belts. Some investigators have reported anomalous paleomagnetic poles from such orogenic belts which are inconsistent with the standard pole determined from the stable region of South America. The Andean mountain belt has several deflection points where the structural trend abruptly changes its strike and anoma-

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lous paleomagnetic results are often attributed to the oroclinal bending around such deflections.

For example, from the northernmost Andes in Colombia and Venezuela, discordant Cretaceous and Tertiary paleomagnetic directions are reported. The observed field direction has an east–west trend, nearly 90 degrees different from the normal paleomagnetic directions (MacDonald and Opdyke, 1972; Skerlec and Hargraves, 1980; Stearns et al., 1982). Skerlec and Hargraves (1980) suggested that such paleomagnetic directions were rotated by some 90 degrees clockwise as a consequence of the relative motion of the eastward-moving Caribbean plate and the westward-moving South American plate. Dalziel et al. (1973) and Burns et al. (1980) reported systematic paleomagnetic declination change along the arcuate trend of the Patagonian Cordillera from Mesozoic rocks and concluded that an oroclinal bending gave rise to a counterclockwise tectonic rotation. Some investigators propose that this is the earlier phase of the same tectonic setting as in the northernmost Andes and that the relative motion of South America and the oceanic plate under Drake Passage bent the originally rectilinear trend of the Andes (Deuser, 1970; Dalziel and Elliot, 1973).

In the Central Andes, Palmer et al. (1980a) attempted to compare the paleomagnetic declinations between the northern and southern wings of the deflection at the Peru–Chile border and to test the Carey's (1955) hypothesis of the oroclinal bending (referred to as the Bolivian orocline). However, they failed to derive reliable paleomagnetic results from Peru due to the "instability" of the remanent magnetization of rock samples and only reported the post-Jurassic counterclockwise rotation of the Arica region in northernmost Chile, the very point of the deflection. Detailed paleomagnetic studies in the Peruvian region will thus clarify the rotation history of the region and enable us to verify the hypothesis of the oroclinal bending.

GEOLOGY

The distribution of Cretaceous rocks can be divided into three major belts: the western volcano-plutonic belt, the central marine sedimentary belt and the eastern marine–continental sedimentary belt (Fig. 1).

Along the coast of Peru, Cretaceous marine volcano-sedimentary rocks are exposed forming a relatively narrow belt. To the east of this belt, Cretaceous–early Tertiary granitic plutons are distributed forming the Andean batholith belt. To the east of this, Tertiary (partly Cretaceous) volcanics and volcanic sediments form the Western Cordillera. The western belt as a whole can be regarded as a Cretaceous–early Tertiary volcanic arc of the Andean orogenic belt. In the central belt, sedimentary sequences of Paleozoic–Cretaceous age compose a thrust-fold belt which shows a westward vergence. The Cretaceous system in this belt can be divided into two major lithologic units: a clastic dominated Neocomian–Aptian sequence and a carbonate dominated Albian–Turonian sequence. The eastern belt, which forms the sub-Andean thrust-fold belt, shows an intensive eastward vergent structural style. The lithofacies are dominated by more clastic materials than carbonates.

From the western belt, volcanic rocks such as lava flows or dikes were collected along the coast between 7°S and 14°S. Detailed descriptions are given in the following section as three groups, that is, the Huarmey area (HM), the Ancon area (AC) and other areas (NZ01, CM20).

From the central belt, carbonate-dominated Albian–Cenomanian formations from the Cajamarca region (CM10,13) and Bagua region (BG01) were sampled. These sampling sites are illustrated in Fig. 1.

Huarmey area (HM series)

In this region, paleomagnetic samples were taken at five sites (HM01-05) from outcrops along the Panamerican Highway. Detailed geological information is available in Myers (1974). Sampled rocks belong to the Punta Gramadal Formation and the La Zorra Formation of the Casma Group, which consists of widespread Cretaceous volcanics and sediments in coastal Peru. The Punta Gramadal Formation is comprised of a 600 m sequence of pillow lava interbedded with tuff, tuffaceous graywacke and both tuffaceous and bituminous limestone. One pillow lava (HM03), one basaltic dike (HM04) and one basalt lava flow (HM05) were sampled (78°01′W, 10°21′S). The age is suggested to be late Middle Albian from fossils in the sediment layer and the unit is considered to correspond to the Pariatambo Formation in the

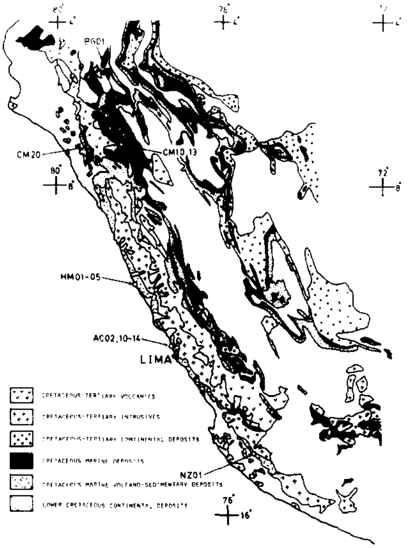


Fig. 1. Distribution of Cretaceous rocks in Peru. Circles indicate the paleomagnetic sampling sites.

central sedimentary belt (Myers, 1974). The La Zorra Formation conformably overlies the Punta Gramadal Formation and is composed of a 1800 m sequence of andesite lava flows, andesitic and dacitic ignimbrite, tuff, submarine pyroclastic flow, etc. One andesite lava (HM01) and one andesite dike (HM02) were sampled from the border between the Punta Gramadal Formation and the La Zorra Formation (78°03′W, 10°19′S). The fossil age is also known to be late Middle Albian from thin bedded bituminous and tuffaceous limestones in this formation (Myers, 1974).

Ancon area (AC series)

Five andesite dikes (AC10-14) and one andesite lava flow (AC02) were sampled near the lighthouse of Ancon Peninsula some 30 km north of Lima (77°11′W, 11°46′S). These dikes vertically cut an alternation of tuff, volcanic sandstone and autobrecciated lava flow and are overlain by massive lava flow. The dikes trend approximately north–south and range in width from 50 cm to 1 m. These rocks have been assigned also to the Casma Group (Bellido, 1979).

Other Cretaceous volcanics (CM20 and NZ01)

Rocks were sampled from one porphyry dike (CM20) which cuts Cretaceous limestone strata near Tembradera (79°61′W, 7°15′S), northern Peru. One pyroxene andesite dike (NZ01) was sampled near Nazca at the outcrop along the Panamerican Highway (75°14′W, 14°31′S). The dike cuts thin bedded fine tuff of Cretaceous age. The ages of these dikes themselves are not known but we tentatively classified them into Cretaceous age.

Cretaceous limestone of northern Peru (CM10, 13, BG01)

In the Andean region of Peru, Cretaceous marine and continental sediments are widely distributed. Late Early to early Late Cretaceous marine sediments are especially abundant in the region of northern Peru near Cajamarca (Reyes, 1980). Paleomagnetic samples were taken at road cut exposures along the route between Encañada and Celendin (CM10,13) and at a stream cut valley near Bagua (BG01). The Lower Albian Chulec Formation conformably covers fluvial deposits of the Neocomian–Aptian Goyllarisquizga Group. This formation is made of white-grey psammitic limestone-marl, grey limestone and is considered to be cyclic shelf carbonates. Oriented rock samples were taken from a bedded micritic limestone layer exposed some 10 km northeast of Encañada (CM13; 78°16′W, 7°03′S). The Upper Albian Pariatambo Formation conformably overlies the Chulec Formation and is composed of dark bituminous limestone–dolomitic limestone. This formation is characterized by a reducing depositional environment suggesting the maximum transgression in this time. Samples were taken from marl and bituminous shale layers near Encañada (CM10; 78°20′W, 7°05′S). The Pariatambo Formation is overlain by the Cenomanian Yumagual Formation, which consists of limestone and dolomite. Paleomagnetic samples were collected in a marl layer exposed along the Rio Utcubamba, some 40 km east-southeast of Bagua Grande (BG01; 78°09′W, 5°54′S).

EXPERIMENTAL PROCEDURE AND PALEOMAGNETIC RESULTS

Sedimentary rocks

Each sample was taken from an outcrop as an oriented block and was cored in the laboratory. A cryogenic magnetometer at the University of California, Santa Barbara was used in the measurements of the remanences of sedimentary rocks. A number of the samples had natural remanent magnetization (NRM) of the order of 10^{-7} Am^2/kg, but the typical NRM intensity was of the order of 10^{-8} Am^2/kg. Stepwise alternating field (AF) demagnetization was performed up to 80 mT in peak intensity on each specimen and any soft secondary components were removed.

The rock magnetic study of marine limestones has been very difficult owing to the low concentration of magnetic minerals. Lowrie and Heller (1982) compiled current knowledge about the magnetic properties of marine limestones and suggested that both magnetite and hematite are the most abundant carriers of NRM. The magnetite is generally of depositional origin while the hematite has been suggested to have grown during the diagenesis (see also Channel et al., 1982). The importance of these two magnetic components is controlled by their relative contributions to the total NRM. Generally speaking, limestones whose NRM is carried mainly by hematite are characterized by a pinkish color and show higher coercivity and blocking temperatures than those whose NRM is carried by magnetite.

The Peruvian limestones studied here range in color from grey to pinkish grey. Purely grey specimens are easily demagnetized during stepwise AF demagnetization up to 80 mT while those with pinkish color hardly change in direction or intensity. This suggests that the carriers of the remanences of these rocks are mainly magnetite and hematite, respectively. In this study, we preferred the magnetization component carried by magnetite because the acquisition of remanence of diagenetic hematite might post-date the formation of the rock. From these viewpoints, only those samples with their vector diagrams (Zijderveld, 1967) converging towards the origin were used for the determination of paleomagnetic field directions. Several specimens were discarded due to the hematite contribution to the NRM. Thermal demagnetization was also performed on these specimens and no blocking temperatures exceeding the Curie temperature of magnetite were found. Their AF and thermal demagnetization diagrams (Fig. 2) suggest little contribution of hematite to the remanence.

The "field" directions obtained were then structurally corrected using the bedding planes of the rocks. These directions are plotted on Fig. 3 by Lambert equal area projection. The observed "field" directions were of normal polarity and counter-clockwise declination shifts of 20°–50° from north were found. Statistical parameters and mean field directions (Fisher, 1953) are given in Table 1.

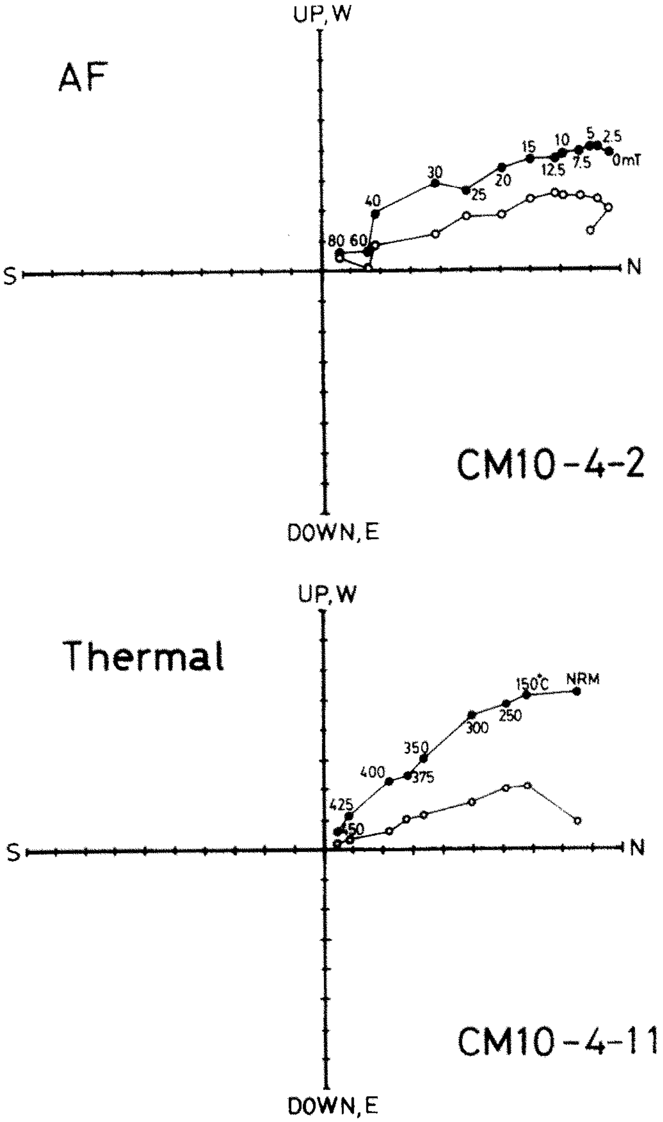


Fig. 2. Zijderveld diagrams of progressive thermal and AF demagnetization of a Peruvian limestone (CM10). Open and solid symbols correspond to the projections onto vertical and horizontal planes respectively. Demagnetizing temperature and AF strength (in peak intensity) are also given. Scales are arbitrarily taken.

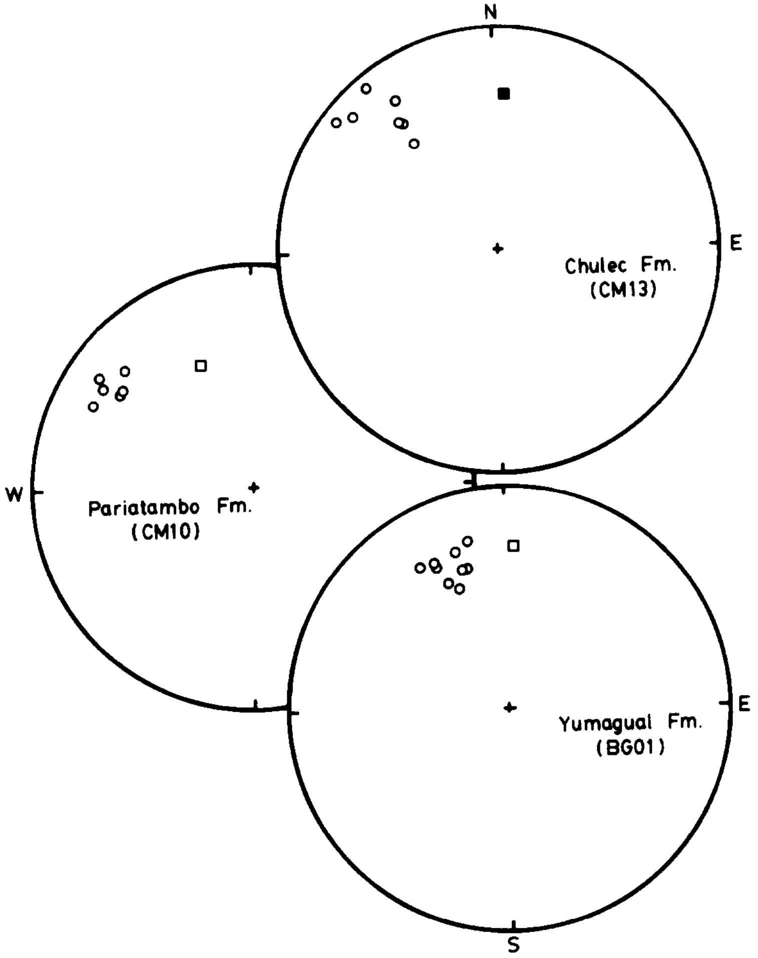


Fig. 3. Lambert equal area projection of the remanent magnetization directions of the Cretaceous sedimentary rocks in northern Peru. Squares indicate present axial dipole field directions viewed from the individual paleohorizons. Open and solid symbols indicate negative and positive inclinations respectively.

Volcanic rocks

The NRM of the volcanic rocks was measured using a Schonstedt spinner magnetometer at the University of Tokyo, and stepwise AF demagnetization was also performed. The NRM intensity of these samples was relatively weak (10^{-5}–10^{-6} Am^2/kg). However, they showed sufficient stability against AF demagnetization and median destructive fields (MDF's) usually exceeded 30 mT (Fig. 4). A paleomagnetic field direction was obtained from the gradient of the linear portion of the diagram or at a certain optimum step determined by the minimum dispersion criterion. HM05 data were discarded because of their large directional scatter and instability against the demagnetization. The paleomagnetic results are illustrated in Fig. 5 and are also summarized in Table 1.

In this report, no bedding corrections are made to the paleomagnetic field directions of volcanic rocks from the Huarmey and Ancon areas. The shape of the pillow structures (HM03) and the verticality of the dike contacts (AC series) demonstrate that structural corrections are unnecessary for these sites. For NZ01 and CM20, bedding corrections were made using the structures of the host rocks.

The paleomagnetic field directions were mostly of normal polarity but reversed polarity directions were obtained from two sites, that is, AC13 and CM20. They showed 20°-30° counterclockwise declination shifts from the axial dipole field, which is consistent with the results from the sedimentary rocks of northern Peru (Fig. 5).

DISCUSSION

The Phanerozoic apparent polar wander path of South America established by Creer (1970) demonstrates that the paleomagnetic pole during Mesozoic time should

TABLE 1

Paleomagnetic directional data *

Site	N	Incl. (°)	Decl. (°)	R	k	α_{95} (°)	ODF (mT)	Remarks
Volcanic rocks								
HM01	5	−26.2	−20.0	4.9892	371	4.0	LSF	lava flow
HM02	4	−34.2	−16.7	3.9886	262	5.7	LSF	dike
HM03	10	−20.5	−14.7	9.9014	115	4.5	LSF	pillow lava
HM04	5	−8.9	−9.8	4.8854	35	13.1	LSF	dike
AC02	6	−38.8	−26.8	5.8504	33	11.8	5	lava flow
AC10	5	−28.4	−20.4	4.9729	147	6.3	10	dike
AC11	7	−33.1	−23.8	6.8011	30	11.2	LSF	dike
AC12	6	−24.4	−19.2	5.9867	376	3.5	LSF	dike
AC13	6	21.9	140.0	5.6136	13	19.3	LSF	dike
AC14	5	−31.1	−14.4	4.9715	140	6.5	40	dike
CM20	4	34.6	145.0	3.9776	134	8.0	80	dike
NZ01	5	−33.0	−26.4	4.9600	100	7.7	LSF	dike
Sedimentary rocks								
CM10	6	−21.1	−52.5	5.9676	154	5.4	40	limestone
CM13	7	−22.6	−38.3	6.8328	36	10.2	40	limestone
BG01	9	−32.2	−20.6	8.9220	103	5.1	LSF	limestone

* N = number of samples studied, Incl. = mean inclination, Decl. = mean declination, R = length of resultant vector, k = precision parameter, α_{95} = radius of 95% confidence circle, ODF = optimum demagnetizing field (LSF means that the field direction was determined by least square fit to the linear portion of the demagnetization diagram.).

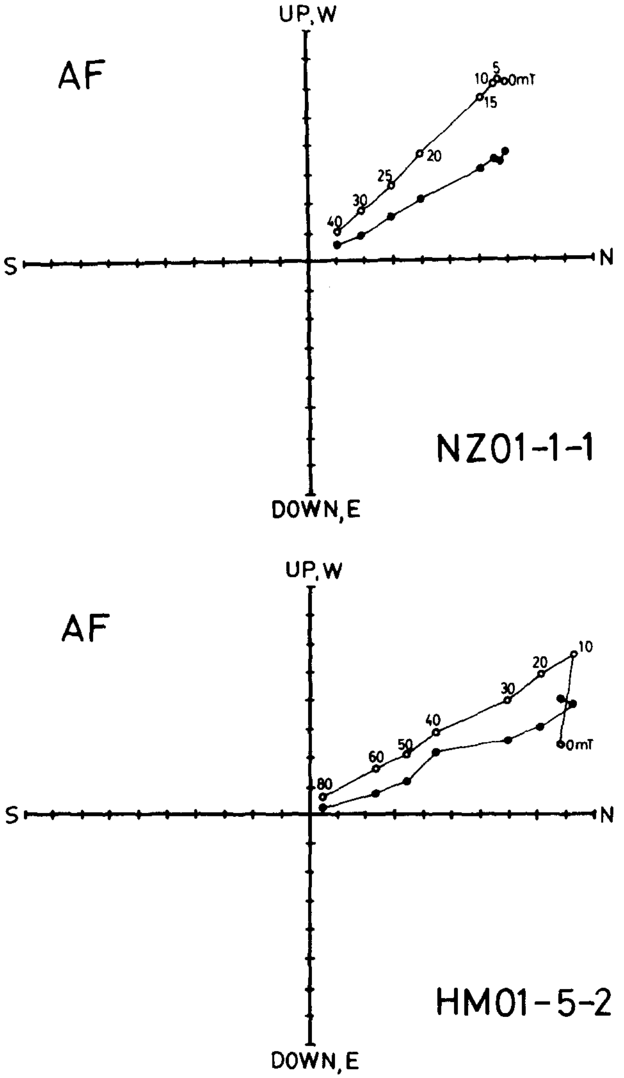
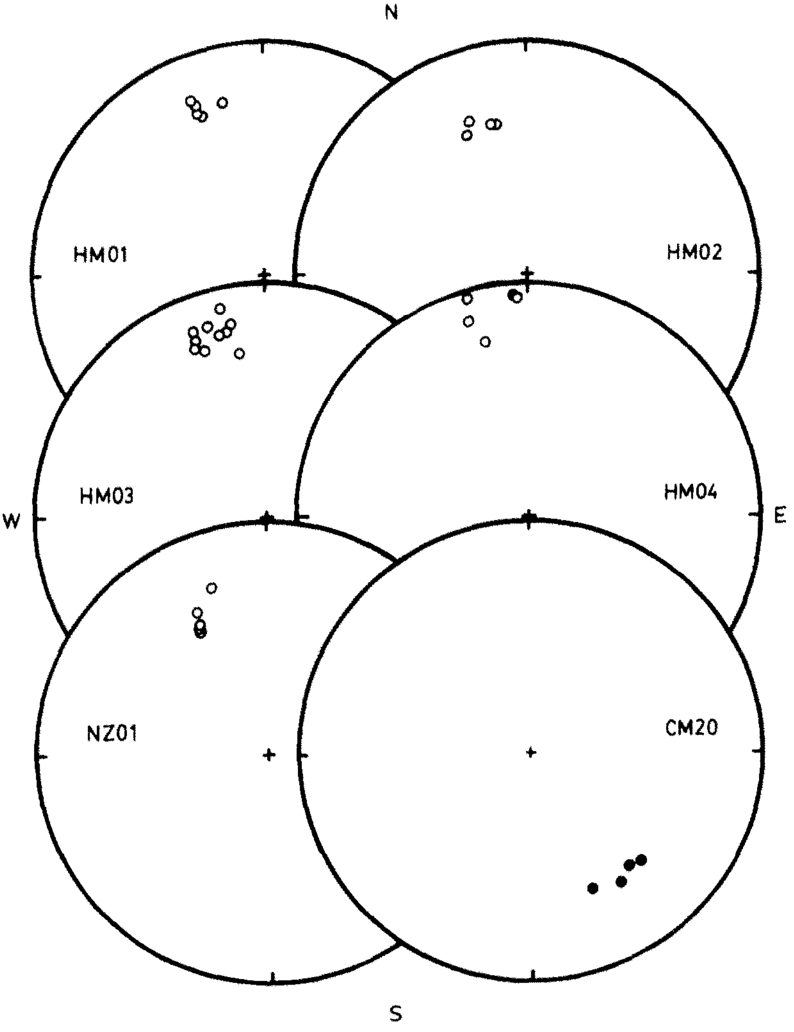


Fig. 4 Zijderveld diagrams of AF demagnetization of the Peruvian coastal volcanic rocks (HM01 and NZ01).

approximately coincide with the present geographic pole. Newly reported Cretaceous paleomagnetic poles from cratonic areas of South America are also nearly coincident with the present pole (Opdyke and MacDonald, 1973; Pacca and Hiodo, 1976; Schult and Guerreiro, 1979, 1980). It is therefore inferred that the Mesozoic paleomagnetic field direction should not deviate significantly from today's axial dipole field. However, paleomagnetic results of the Cretaceous sediments and volcanics in the Peruvian Andes show several tens of degrees of counterclockwise declination shift, which should be interpreted in terms of declination anomaly, namely, tectonic rotation. The Peruvian paleomagnetic declinations obtained in this study are illustrated with their 95% confidence intervals on the map (Fig. 6). In Fig. 6, it is noticed that these declinations are roughly parallel with the coastline trend in Peru, suggesting that the Peruvian coastal trend was nearly north–south in Cretaceous time.

In order to determine the Peruvian paleomagnetic pole, virtual geomagnetic poles (VGPs) of the twelve Peruvian Cretaceous volcanics have been averaged. The poles were also derived from the Pariatambo (CM10), Chulec (CM13) and Yumagual (BG01) Formations. Table 2 summarizes the positions and the 95% confidence limits of these poles.



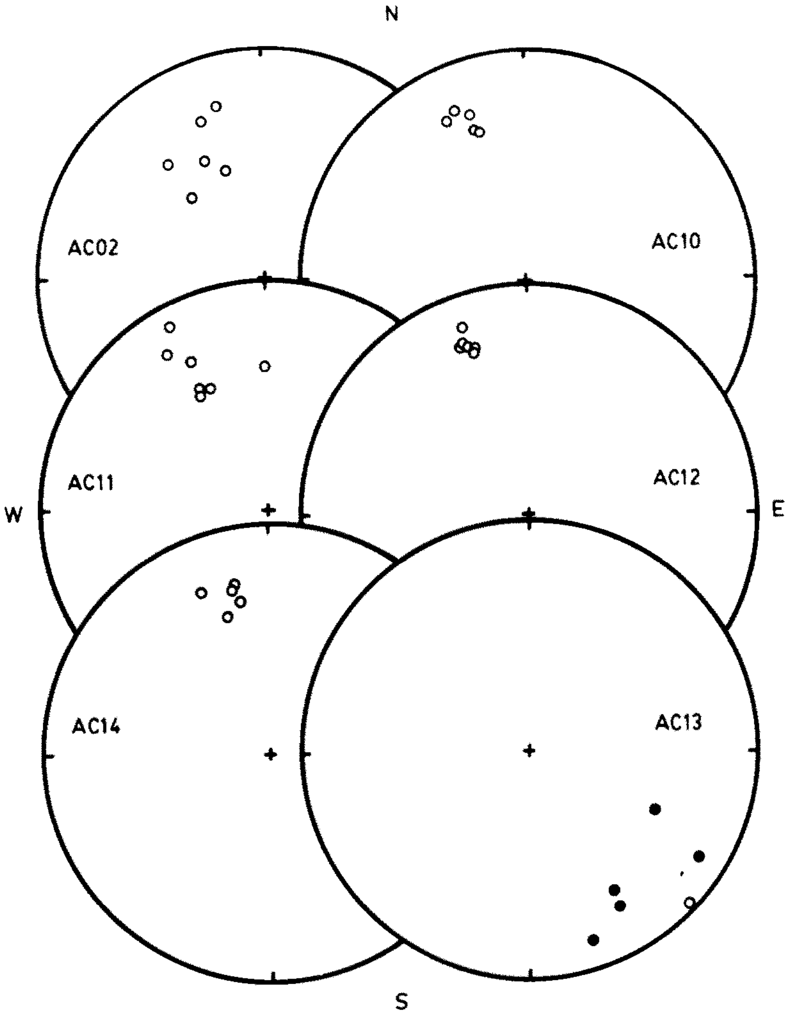


Fig. 5 Lambert equal area projection of the directions of the remanent magnetization of twelve Cretaceous volcanics of Peruvian coast. Open symbols denote negative (upward) inclinations and solid symbols denote positive (downward) inclinations.

In order to obtain a reference Cretaceous South American pole, we made a careful selection from presently available poles considering the following three points; (1) the number of independent volcanic units should be large enough to average out paleosecular variations, (2) the sampling site should not belong to the area of the Andean orogenic belt, (3) stability tests should have been performed on NRMs. Four paleomagnetic poles fulfilled these criteria: the Serra Geral Formation (83°S, 76°E, $A_{95} = 3.4°$: recalculated combining Creer (1962) and Pacca and Hiodo (1976)), the Maranhâo basalt intrusions (84°S, 81°E, $A_{95} = 1.9°$: Schult and Guerreiro, 1979), Cabo de Sto. Agostinho (88°S, 315°E, $A_{95} = 4.5°$: Schult and Guer-

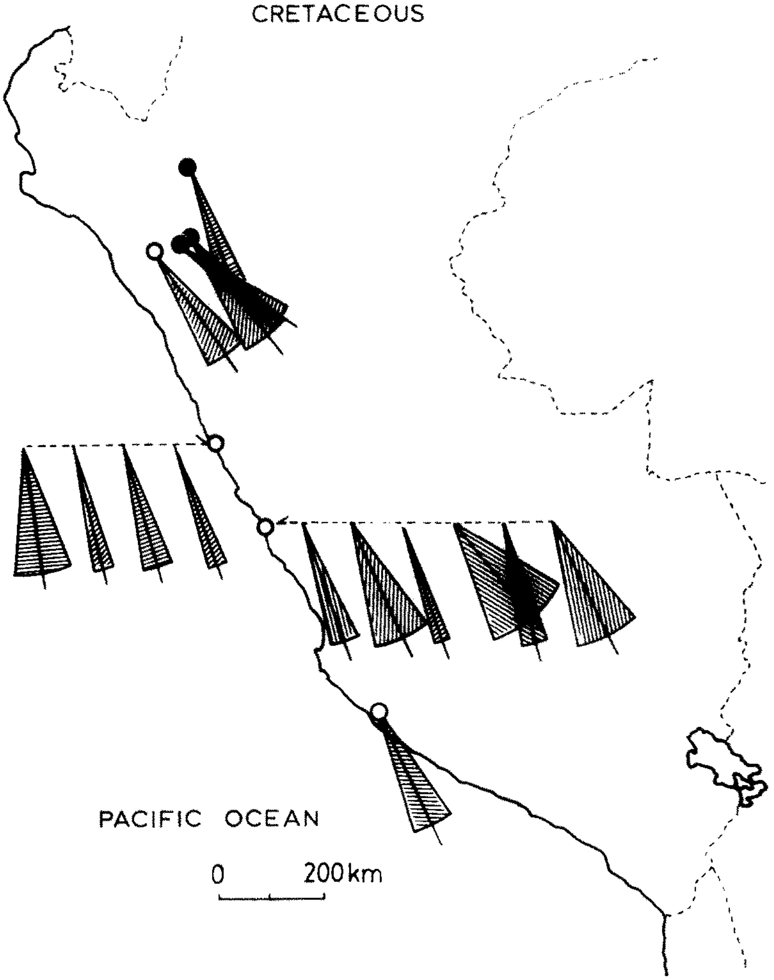


Fig. 6 Site mean declinations and their 95% confidence intervals of Cretaceous rock samples in Peru. Open circles indicate volcanic rocks and solid circles indicate sedimentary rocks. For the sake of visual simplicity, all directions are drawn as those of reversed polarity.

reiro, 1980), the Poços de Caldas Complex (82°S, 268°E, $A_{95} = 14.3°$: Opdyke and MacDonald, 1973). The ages of these poles range from 130–100 Ma (Serra Geral Formation) to 75 Ma (Poços de Caldas Complex). However, they are coincident within 95% confidence limits and we do not need to consider the apparent polar wandering for the stable area of South America in this period. We use the mean position of these paleomagnetic poles (88.7°S, 42.6°E, $A_{95} = 8.0°$) as the reference Cretaceous pole in discussing the tectonic rotation of Peru. All these poles are illustrated in Fig. 7 together with the Peruvian poles.

The difference between the Peruvian poles and the South American reference poles strongly suggests counterclockwise rotation of the Peruvian Andes with respect

TABLE 2

Peruvian Cretaceous poles *

Rock unit	Locality		Age	Pole				
	lat. (°S)	long. (°W)		lat. (°S)	long. (°E)	dp (°)	dm (°)	A_{95} (°)
Coastal volcanics	5–15	75–80	K	58.0	0.5			5.1
Chulec Fm. (CM13)	7.1	78.3	Al.	52.0	1.6	4.7	8.8	
Pariatambo Fm. (CM10)	7.1	78.3	Al.	38.1	3.4	3.1	5.8	
Yumagual Fm. (BG01)	5.9	78.2	Cen.	66.7	339.7	3.2	5.7	

* Poles are southern hemisphere poles, dp = radius of 95% confidence oval measured in the direction from site toward pole, dm = radius of 95% confidence oval measured perpendicular to dp, A_{95} = radius of 95% confidence circle, lat. = latitude, long. = longitude, K = Cretaceous, Al. = Albian, Cen. = Cenomanian.

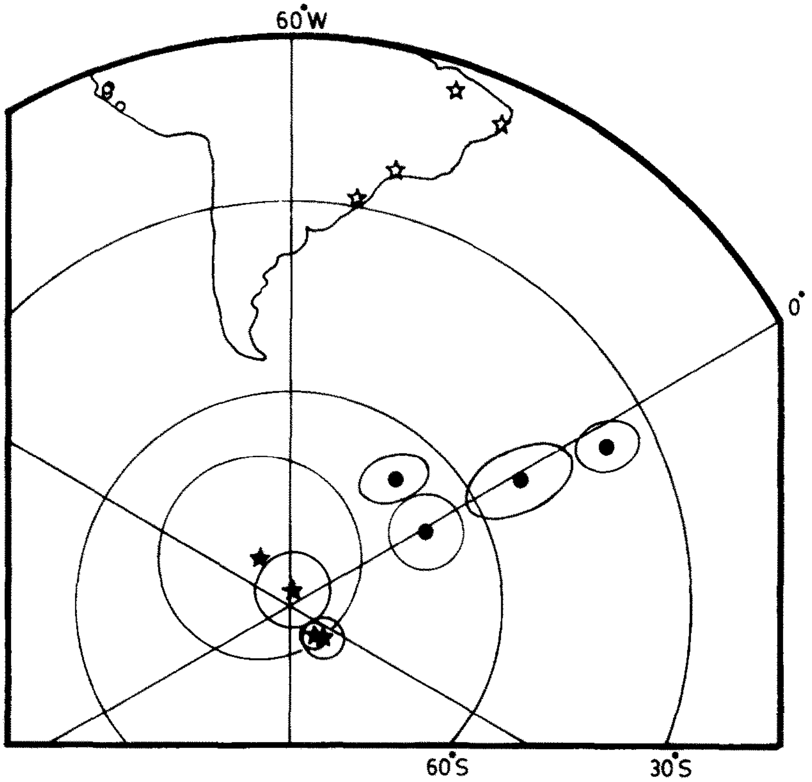


Fig. 7. Cretaceous paleomagnetic poles from the stable region of South America (stars) and the Peruvian Andes (circles). 95% confidence limits are also indicated. Small open symbols within South America indicate the locations of the sampling sites.

to the cratonic region. The rotation angles and their 95% confidence limits were estimated using the formula of Beck (1980) and we obtained the following values, that is, 21.0 ± 9.8 (Peruvian Cretaceous coastal volcanics), 51.4 ± 10.0 (CM10), 37.2 ± 13.7 (CM13) and 19.5 ± 10.0 (BG01). Although these values are a little divergent, these are, on an average, consistent with the general structural trend of the Peruvian Andes suggesting a rotation as a nearly rigid block rather than independent rotations of small terranes. Some disturbances due to quite local tectonic movements such as those listed in MacDonald (1980) might be responsible for the diversity of the rotation values.

We draw attention to the fact that the area of post-Mesozoic counterclockwise rotation extends as far as northernmost Chile (Palmer et al., 1980a) but does not extend farther to the south (Argentine and Chilean Andes, Valencio et al., 1977; Palmer et al., 1980b), where the Andean trend is almost north–south. Therefore, this rotation is considered to be a consequence of the oroclinal bending of the Central Andes as suggested by Carey (1955). Paleomagnetic studies in the Central Andes are still in progress by us (Heki et al., 1983), for example, Peruvian Neogene volcanic rocks (Heki et al., 1984a), Northern Chilean Jurassic and Cretaceous rocks (Heki et al., 1984b,c), etc. detailed discussions about the timing of the bending and its geodynamic implication will be given in Kono et al. (1984).

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