Paleomagnetic Study of Late Miocene and Early Pliocene Rocks from Southern Peru, Central Andes

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We carried out a paleomagnetic study on rocks from southern Peru to reveal more precise timing of the post-Cretaceous tectonic rotation of Peruvian block in Central Andes as suggested by the previous studies. The samples were taken from Late Miocene to Early Pliocene sedimentary rocks, the Changuillo, Pisco and Paracas formations, and from Latest Miocene volcanic rocks. The paleomagnetic pole obtained from these rocks is close to Miocene to Quaternary poles of the stable part in South America, indicating that the post-Cretaceous tectonic rotation of the Peruvian block ceased in or prior to the Late Miocene.

1. Introduction

The Andean region is a subduction zone characterized by the Peru-Chile trench and the Andean orogenic belt. This subduction zone is a continental arc with no apparent marginal seas at present. Paleomagnetic studies of the Andean belt have been performed to clarify tectonic deformation. In the southernmost part of Andes in Chile the structural trend changes from north-south to northwest-southeast. This change is ascribed to a post Cretaceous deformation by the paleomagnetic method (DALZIEL *et al.*, 1973; BURNS *et al.*, 1980). In the northernmost part, the trend of the Andean belt changes from northeast-southwest to east-west. MACDONALD and OPDYKE (1972) reported a shift in magnetic declination for the Cretaceous rocks which infers tectonic rotation of northernmost part of the Andean belt. From paleomagnetic and K–Ar geochronological studies PALMER *et al.* (1980) suggested post-Jurassic counterclockwise rotation of the Arica region in Central Andes. Further HEKI *et al.* (1983) carried out intensive sampling and measurement of Cretaceous rocks in Peru and in northernmost Chile. They concluded that the Peruvian block rotated counterclockwise by about 30° after the Cretaceous and that this rotation is a cause of the abrupt change of trend from north-south trend in the Chilean Andes to northwest-southeast of the Peruvian. HEKI *et al.* (1985) also showed a slight declination shift of Neogene dike swarm in Peru. This deformation is quite interesting on account of its characteristics as an intraplate one, whereas the others in the southernmost and northernmost parts have occurred at edges of the continental

plate. The possible time of counterclockwise rotation of Peruvian block is, therefore, between the early Tertiary and the recent. In order to obtain constraints to determine timing of tectonic rotation of the Peruvian block we further studied paleomagnetism of Late Miocene to Early Pliocene sedimentary rocks and Latest Miocene volcanic rocks in southern Peru.

2. Samples and Method of Measurement

We collected the samples in 1984 as a part of the Geophysical Studies of the Central Andes (Second Phase). Sedimentary rocks were sampled from the Tertiary system in southern Peru (Fig. 1). It consists of the Changuillo Formation (upper part of this system), the Pisco Formation (middle part), and the Paracas Formation (lower part), which are nearly horizontal layers. These formations are covered by the Quaternary conglomerate of the Cañete Formation, and underlied by conglomerate of the Caballas Formation, which is thought to be of Tertiary age. The lithology of the sampled formations are mainly siltstone (Paracas Formation), diatomite (Pisco Formation) and fine sandstone (Changuillo Formation). Columnar sections and the sampled horizons are summarized in Fig. 2. PS03 of the Changuillo Formation and PS02 of the Pisco Formation were sampled from a flexure zone at Pisco with 30–60° dips. AMANO *et al.* (1987) performed paleontological study of these formations by using diatom fossils, which indicates ages of the Pisco and Changuillo formations as the Latest Miocene to Early Pliocene because the Mio-Pliocene boundary is found at the upper part of the Pisco Formation. The Paracas Formation yields no reliable paleontological ages but can be assigned an age of Late Miocene because we observed that it conformably underlies the Pisco Formation. These sedimentary rocks are distributed in the region where no igneous activity and metamorphism occurred after the Cretaceous. Accordingly, possibilities of thermal disturbances to remanent magnetization can be excluded. Volcanic rocks composed of andesite and shoshonite were collected mainly from the sites near the Lake Titicaca. KANEOKA and GUEVARA (1984) reported K–Ar ages of 5–6 Ma for rocks of the same sites.

All the samples were collected as blocks with orientation by magnetic compasses and core specimens were cut from these samples in laboratory. Remanent magnetization of specimens of the Pisco and Paracas formations were measured with a cryogenic magnetometer and those of the Changuillo Formation and of volcanic rocks were measured with a Schonstedt spinner magnetometer and a ring-core type spinner magnetometer, respectively. All specimens were subjected to stepwise alternating field (AF) demagnetization up to peak fields of 80–100 mT with 2.5–40 mT steps. Using the orthogonal vector diagram (ZIJDERVELD, 1967), we isolated stable components of remanent magnetization.

3. Results of Measurements of Remanent Magnetization

Typical results of AF demagnetization for the present samples are shown in Fig. 3. The Changuillo (CH) samples have natural remanent magnetization (NRM) of

Fig. 1. Sampling localities of Late Miocene to Early Pliocene rocks from southern Peru. Tertiary and Quaternary sequence is also schematically shown.

Fig. 2. Columnar sections of sedimentary rocks in southern Peru. The horizons where the paleomagnetic samples were collected are also shown. Refer to Fig. 1.

about 10^{-2} A/m which yields a stable component in alternating field over about 10 mT. CH01 is an uppermost part of sampled sections and shows both normal and reversed polarities. The samples yielding normal polarity were situated at the upper horizons of CH01 site. Samples of CH02–06 were collected from stratigraphically lower layers and all of them show reversed polarity. The Pisco (PS) and Paracas (PR) samples have NRM of about 10^{-4} A/m. PS01–02, PR01 and PR03 have only normal polarity while PR02 shows both normal and reversed polarities. The PR02 sample with reversed polarity was collected from the lower horizons of PR02 site. Data for the stable remanences of CH, PS and PR samples are summarized in Table 1 and their

Fig. 3. Typical results of stepwise demagnetization in alternating field up to 80 mT. CH011 is a sample from the CH01 site of the Changuillo Formation and AC0351 from the AC03 of the Latest Miocene volcanic rocks. Intensity units correspond to natural remanent magnetizations of 7.10×10^{-3} A/m (CH011) and 1.41 A/m (AC0351). Solid squares are projected on vertical plane and solid circles on horizontal plane.

directions are shown in Fig. 4. When both of normal and reversed polarities were yielded within a site, we calculated an antipodal direction for a reversed one and used it for the paleomagnetic analysis. Most of the volcanic rock samples have natural remanences of about 1–10 A/m and show monotonic decrease in AF demagnetization over 10 mT. PU06 samples exhibit relatively large secondary components with coercivity up to 20–40 mT. However an effect of viscous components on NRM is not significant in the present study since the remanence directions in Fig. 4 show an antipodal grouping. As the sedimentary rocks appear to have been formed with relatively high sedimentation rate (AMANO *et al.*, 1987), the mean direction of each site may not average out the geomagnetic secular variation. Therefore we treat the paleomagnetic results from sedimentary rocks in the same way as those from volcanic rocks in the present study.

4. Paleomagnetic Poles of the Peruvian Block and Their Implication

Virtual geomagnetic poles (VGPs) listed in Table 2 are calculated from stable remanent magnetizations of the sedimentary and volcanic rocks. The mean of paleomagnetic poles from all sites is at (84.1° S, 41.3° E) with a 95% confidence radius (a_{95}) of 6.7° . A paleomagnetic pole of (87° S, 48° W) with a_{95} of 8° was obtained from Miocene to Pleistocene basaltic lavas in Argentina by CREER and VALENCIO (1970). Their result probably represents a paleomagnetic pole of the stable part in South America because HEKI *et al.* (1983) suggests that the Chilean region, except its

Table 1. Directions of stable remanent magnetization of the Late Miocene to Early Pliocene sedimentary rocks and the Latest Miocene volcanic rocks from southern Peru in the present study. *N*: number of samples collected independently and used in the analysis, *I*: inclination, *D*: declination, *a*₉₅: 95% confidence radius (FISHER, 1953), *k*: precision parameter (FISHER, 1953), *B*: bedding plane, *P*: normal polarity (N) and reversed one (R) with number of samples. (*) The remanence directions were corrected for observed bedding plane.

Site	<i>N</i>	<i>I</i>	<i>D</i>	<i>a</i> ₉₅	<i>k</i>	<i>B</i>	<i>P</i>
Changuillo Formation							
CH01	7	−18.8°	−12.5°	9.8°	39	horiz.	N(3), R(4)
CH02	5	32.8°	174.1°	5.8°	174	horiz.	R
CH04	7	23.8°	171.0°	3.9°	236	horiz.	R
CH05	5	26.9°	179.9°	7.1°	90	horiz.	R
CH06	4	18.9°	176.7°	11.1°	70	horiz.	R
PS03	6	−23.5°	−3.1°	15.1°	21	N15W30E*	N
Pisco Formation							
PS01	10	−26.3°	10.6°	8.3°	35	N25E12W*	N
PS02	11	−26.1°	−38.1°	5.5°	71	N25W60E*	N
Paracas Formation							
PR01	5	−28.5°	−0.7°	8.8°	77	N45E10W*	N
PR02	9	−9.4°	2.4°	7.5°	48	horiz.	N(8), R(1)
PR03	5	−13.7°	17.7°	10.3°	56	horiz.	N
Volcanic rocks							
AC03	6	29.2°	−177.2°	5.8°	135	—	R
AC04	6	33.4°	−176.9°	4.0°	274	—	R
PU01	5	17.5°	149.7°	6.9°	123	—	R
PU04	5	−26.0°	−21.4°	14.7°	28	—	N
PU06	5	7.9°	177.9°	14.9°	27	—	R

northern part, has shown no significant movements relative to the stable part since the Jurassic and this area is located between the central Chile and the stable cratons. VILAS (1981) reported a paleomagnetic pole of (86°S, 23°W) with *a*₉₅ of 6° for the stable part from 0.1–2.4 Ma volcanic rocks in Argentina and Brazil, although their ages are a little younger than those in the present study. Figure 5(a) shows these paleomagnetic poles in an equal area projection. The pole of Peruvian block obtained in the present study is not different from those of the stable part at the 95% confidence level.

HEKI *et al.* (1985) reported a paleomagnetic pole of (75.2°S, 1.2°W) with *a*₉₅ of 5.3° from a study on the Ocos dike swarm (8.5 Ma K–Ar age, I. Kaneoka, personal communication, 1986) in central Peru. Although HEKI *et al.* (1985) suggested that the declination shift still existed for the Ocos dikes, in Fig. 5(a) we find no significant difference among the paleomagnetic poles of the Ocos dike swarm, of the sedimentary and volcanic rocks in the present study and of the stable part, considering the 95% confidence limits. Cretaceous paleomagnetic poles of the Peruvian block and

Fig. 4. Equal area projection of stable remanences obtained in the present study. Solid and open circles indicate downward and upward inclinations, respectively. Each 95% confidence radius is also shown. Refer to Table 1.

Table 2. Virtual geomagnetic poles (VGPs) calculated for the Late Miocene to Early Pliocene sedimentary rocks and the Latest Miocene volcanic rocks from Peru in the present study (refer to Table 1).

Site	Locality	VGP	dp	dm
CH01	(14.7°S, 75.3°W)	(76.8°S, 35.8°E)	5.3°	10.2°
CH02	(14.7°S, 75.3°W)	(83.5°S, 15.8°W)	3.7°	6.6°
CH04	(14.7°S, 75.3°W)	(81.1°S, 28.1°E)	2.2°	4.2°
CH05	(14.7°S, 75.3°W)	(89.5°S, 95.6°E)	4.2°	7.7°
CH06	(14.7°S, 75.3°W)	(84.1°S, 71.0°E)	6.0°	11.5°
PS01	(14.8°S, 75.3°W)	(79.6°S, 179.0°W)	4.9°	9.0°
PS02	(13.7°S, 76.2°W)	(53.0°S, 9.1°E)	3.2°	5.9°
PS03	(13.7°S, 76.2°W)	(86.7°S, 38.9°E)	8.6°	16.1°
PR01	(13.9°S, 76.3°W)	(88.5°S, 49.6°W)	5.3°	9.7°
PR02	(13.9°S, 76.3°W)	(80.6°S, 118.3°E)	3.8°	7.6°
PR03	(13.9°S, 76.3°W)	(71.3°S, 173.9°E)	5.4°	10.5°
AC03	(15.9°S, 69.9°W)	(87.3°S, 165.4°W)	3.5°	6.4°
AC04	(15.9°S, 69.9°W)	(86.2°S, 121.1°W)	2.6°	4.6°
PU01	(15.8°S, 70.1°W)	(59.6°S, 29.2°E)	3.7°	7.1°
PU04	(15.8°S, 70.1°W)	(69.1°S, 22.8°E)	8.6°	15.9°
PU06	(15.8°S, 70.0°W)	(78.0°S, 99.4°E)	7.6°	15.0°
Mean ($N=16$)		(84.1°S, 41.3°E)	$a_{95}=6.7^\circ$

Fig. 5. (a) Equal area projection of the South American paleomagnetic poles in the Late Cenozoic. Solid squares: Peruvian block, southern Peru in this study (SP), Ocos dike swarm (OD) by HEKI *et al.* (1985) and open squares: stable part by CREER and VALENCIO (1970, SCA) and by VILAS (1981, SCB). Each 95% confidence circle is also shown. (b) Equal area projection of the South American paleomagnetic poles in the Cretaceous. Solid squares: Cretaceous Peruvian block, open squares: Cretaceous apparent polar wander of stable part, CV: coastal volcanics (HEKI *et al.*, 1983), AR: Arica dike swarm (HEKI *et al.*, 1983), HV: Herradura, Vinchos, Moracocha (CREER, 1970), CL: Chulec Formation (HEKI *et al.*, 1983), PT: Pariatambo Formation (HEKI *et al.*, 1983), YM: Yumagual Formation (HEKI *et al.*, 1983), PP: Puente Piedra Formation (MAY and BUTLER, 1985), SA1-3: apparent polar wander path of stable part of South America in the early Early Cretaceous (SA1), in the Early Cretaceous (SA2) and in the late Early to Late Cretaceous (SA3) after VILAS (1981).

the stable part are also plotted in Fig. 5(b) (HEKI *et al.*, 1983; MAY and BUTLER, 1985; CREER, 1970; VILAS, 1981), which clearly shows shifts of the Peruvian VGPs from those of the stable part. Hence we conclude that the post-Cretaceous counterclockwise rotation of Peruvian block has been completed in or prior to the Late Miocene.

HAYASHIDA *et al.* (1984) carried out paleomagnetic study of the Salla area in western Bolivia, which might have been a part of the Peruvian block. They also gave fission track (F.T.) ages of 52 and 54 Ma for the tuffaceous rocks studied for paleomagnetism. The paleomagnetic pole calculated for their result is located at (64.7°S , 7.9°W) with a_{95} of 8.9° , which is close to the Cretaceous ones of the Peruvian block and suggests a possibility of counterclockwise rotation after the formation of the Salla beds. MACFADDEN *et al.* (1985), however, reported 26 Ma K–Ar ages and 22 Ma F.T. ages of the Salla interbedded tuffs. HAYASHIDA and DANHARA (1985) performed re-examination of F.T. ages reported in HAYASHIDA *et al.* (1984), and presented the revised F.T. ages of 24–27 Ma. Hence the Salla beds are regarded to have been formed in the Oligocene to Early Miocene. Further MACFADDEN *et al.* (1985) also studied paleomagnetism at the Salla area. They show a mean direction of $I = -24.9^{\circ}$, $D = 357.2^{\circ}$, $a_{95} = 5.9^{\circ}$ from the samples with normal magnetizations and that of $I = 45.2^{\circ}$, $D = 169.5^{\circ}$, $a_{95} = 8.5^{\circ}$ for reversed ones. This result suggests no remarkable shifts of declination. However, two data subsets of normal and reversed ones do not pass a reversal test at the 95% confidence level (MACFADDEN *et al.*, 1985). They suggest that such inconsistency between normal and reversed subsets may be caused by incomplete removal of secondary components. Hence the paleomagnetism at the Salla area is still a matter of debate. More precise determination of the timing of rotation of the Peruvian block requires further paleomagnetic studies on Tertiary systems in both the Andean region and the stable part of South America.

5. Conclusions

The present study suggests that the paleomagnetic poles of the Late Cenozoic are not different between the Peruvian block and the stable part of South America. This result indicates that the post-Cretaceous counterclockwise rotation of Peruvian block has been complete in or prior to the Late Miocene.

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