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NEW TEMPORAL CONSTRAINTS ON THE ROTATION OF THE PERUVIAN CENTRAL ANDES OBTAINED FROM PALEOMAGNETISM

O. Macedo-Sánchez^{1,2}, J. Surmont¹, C. Kissel¹ and C. Laj¹

Abstract. New paleomagnetic data from middle Eocene to middle Miocene volcanic and plutonic formations of the Western Cordillera of Central Peru document a counterclockwise rotation of $11 \pm 7.4^\circ$. This rotation, similar to previous results reported for the northern Peruvian margin, is post middle-Miocene in age. It is thus coeval with the acceleration of the Andean uplift and supports Isacks' model.

Introduction

Paleomagnetic results from Mesozoic formations have documented large counterclockwise rotations along the Central Peruvian Andes [Kono et al., 1985]. More recently, these results have been extended geographically from the Huancabamba deflection in the north to the Arica bend in the south and in time to Cenozoic formations [Mitouard et al., 1990; Macedo-Sánchez et al., 1992; Kissel et al., 1992]. These new results have established the remarkable coherence of the $15\text{--}20^\circ$ counterclockwise rotation of the Peruvian margin over a distance exceeding 1500 km. Because this rotation is post-Eocene the authors have suggested that it might be related to the main uplift of the Central Andes, following a mechanism recently proposed by Isacks [1988]. According to this author, the crustal thickness of more than 70 km observed in the region of the Arica bend and the bending of the Bolivian orocline, result from along-strike variations in the amount of late Cenozoic shortening. Maximum shortening exists at 20°S latitude and decreases both northward and southward from the Arica bend, leading to counterclockwise and clockwise rotations of the Peruvian and Chilean margins respectively [Isacks, 1988]. Any precise description of the time evolution of this rotational pattern is however hindered by the lack of paleomagnetic results from Cenozoic and in particular Neogene formations. The only reliable and significant Cenozoic results available so far are limited to those from the Paleocene-Eocene formations in the Cajamarca region [Mitouard et al., 1990] and to a few sparse results of Paleocene to late Miocene age recently obtained in the Lima region [Macedo-Sánchez et al., 1992] and in the Arequipa region [Kissel et al., 1992]. Also, uppermost Miocene data obtained by Tsunakawa et al. [1987] in the Pisco, Nazca and Puno areas do not show any significant rotation and suggest that the Peruvian margin at this time was probably close to its present day position. On the other hand, the results obtained by Heki et al. [1985] on the late Miocene Ocos dyke swarm

indicating a significant counterclockwise rotation ($14 \pm 5.5^\circ$), have been seriously questioned by Beck [1988] as a result of a critical statistical re-examination of the data.

In this letter we report on new, more complete results obtained in the western Central Peru region from volcanic and intrusive formations of lower Eocene to middle Miocene age. These new paleomagnetic data are interpreted using the available reference poles from Stable South America (SOAM) and yield new constraints on the timing of the geodynamical evolution of the Peruvian margin during the Neogene.

Geological setting and sampling

The studied area is shown schematically in Figure 1. It comprises, from west to east, the Coastal Zone, the Western Cordillera and the High Plateaus. The geological and structural features of these zones have been described by Mégard [1978], Cobbing et al. [1981] and Jaillard [1987]. In the western sector of the Cordillera, the Mesozoic sedimentary and volcano-sedimentary sequences were intruded during late Cretaceous and Paleogene by a complex system of granites and granodiorites (the Coastal Batholith). They were then covered by the lavas and tuffs of the Calipuy Group the age of which ranges from 53 to 15 Ma [references in Atherton et al., 1985]. East of the batholith, at least 5 episodes of plutonism,

Fig. 1. Schematic geological map of the Western Cordillera in Central Peru showing the locations of the sampling sites.

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generally granodioritic, have been documented. Their ages range from 41 to 3 Ma [Soler and Bonhomme, 1988]. South of 13°S, in the Western Cordillera, the Coastal Batholith cuts into late Jurassic to early Cretaceous schists and sandstones which are partially covered by the conglomerates and tuffs of the Nazca formation dated from 22 to 19 Ma [Noble et al., 1979a].

The sampling has been conducted in 1988 and 1990 and the locations of the sites are shown on Figure 1. Six sites (PE204 to 209) were drilled in the siliceous tuffs of the Nazca formation. Three sites were sampled in the Surco (PE104 and 106) and the Catahuasi granites (PE122) dated at 21 Ma and 24 Ma respectively [Mukasa, 1984; Beckinsale et al., 1985]. Site PE140 was sampled in the West Churin tonalitic stock dated at 30 Ma [Cobbing et al., 1981; Soler & Bonhomme, 1988], four sites (PE210 to 213) in the Acos small granitic intrusion considered as upper Eocene in age (~37 Ma [Soler, 1987]), two sites (PE217-218) in the dioritic post-metamorphic dykes dated between 39 and 31 Ma [Vidal, 1987] and which cut the Mesozoic series. However, these last seven sites (PE140, PE210 to 213, PE217-218) may be older than their assumed ages as a consequence of a general reset of the K/Ar ages in this area [Soler, 1987]. Finally, we sampled five sites in the Eocene to Miocene lavas and volcanoclastic series of the Calipuy Group (PE107, PE142 and PE214 to 216). Sites PE214 and PE216 were sampled in the undeformed tuffs at the very base of the formation, close to the place dated at 40-41 Ma by Noble et al. [1979b].

A total of 226 cores has been obtained from these 21 sites dated as an average between 53 and 15 Ma. Clear bedding attitudes were observed for the tuffs and the ignimbrites, with tilts never exceeding 10°. No correction was used for the intrusives. Each core yielded 2-3 specimens allowing laboratory studies of the magnetic mineralogy and of the remanent magnetization.

Magnetic Mineralogy and Paleomagnetic Results

The magnetic mineralogy was investigated for at least one sample per site. Stepwise acquisition of isothermal remanent magnetization (IRM) indicates that saturation is virtually attained in all samples at fields lower than 0.3 T. Thermomagnetic analyses, done on powder samples with an horizontal Curie balance, yield reversible heating and cooling curves with a Curie temperature close to 580°C. This indicates that magnetite is the main magnetic mineral in the samples.

Small pellets made from powdered samples were analyzed with a Micromag alternating gradient force magnetometer. A typical hysteresis loop is shown in Figure 2a. There is a small paramagnetic contribution, shown by the slightly positive slope at high fields. After subtraction of this component the saturation magnetization (M_s), the saturation remanence (M_r), the coercive field (H_c), and the coercivity of the remanence (H_{cr}) were calculated. The coercivities are all smaller than 80 mT, which is consistent with the presence of magnetite. The ratios of the parameters (Figure 2b) indicate that the main fraction of the magnetization is carried by PSD-magnetite [Day et al., 1977].

Measurements were made with a three axis cryogenic magnetometer in a shielded room. Thermal demagnetization with a minimum of 12 steps from room temperature to the limit of reproducible results (600°C usually) was used throughout.

Fig. 2. A: Typical magnetic hysteresis loop; B: Magnetization and coercivity ratios from 11 representative volcanic and intrusive samples. All the values are grouped in pseudosingle domain area.

No significant changes of the low field susceptibility were observed during the thermal treatment, suggesting that the magnetic minerals are not seriously affected by the heating.

The natural remanent magnetizations (NRM) are typically of the order of 0.3 A/m. Generally the samples from the volcanic Nazca and Calipuy formation are characterized by a single stable component of magnetization isolated after 200-300°C (Figure 3a). Stable directions were determined from orthogonal demagnetization diagrams and the mean direction was calculated using Fisher's statistic [1953]. However, samples from the intrusive formations sometimes show two components of magnetization with overlapping blocking temperature spectra. In these cases, stable final directions and demagnetization circles were combined (Figure 3b) using the method of McFadden and McElhinny [1988].

The results are shown in Table I. There is a general good agreement between the data except for the sites from the Acos intrusive. In all the Acos sites (PE210 to 213) the presence of two antiparallel components close to the present day field gives evidence of a remagnetization (data from sites PE210 and 211 have been combined together for a better definition of the characteristic direction). This remagnetization could be related to the episode of metamorphism which has affected this region more recently than the lower Miocene [Soler, 1987]. Samples from site PE 209, drilled in the subhorizontal beds of the Miocene tuffs of the Nazca Formation are all characterized by two unexplained sub-vertical antiparallel components of magnetization. Therefore, sites PE209 to 213 were not considered in the final statistics. Because our sites are distributed in two separated areas (Lima and Nazca), two

Fig. 3. Orthogonal projection diagrams (A) and equal area plot (B) of typical thermal behaviours. A: volcanic samples with a single stable component of magnetization. B: intrusive site showing both remagnetization circles and stable directions.

mean paleomagnetic directions were calculated ($D=339.4^\circ$; $I=-26.6^\circ$; $\alpha_{95}=8.8^\circ$ and $D=343.1^\circ$; $I=-25.1^\circ$; $\alpha_{95}=7^\circ$, respectively). The good agreement between these two directions and the absence of any documented shear zone between Lima and Nazca areas, led us to conclude that these two areas have been affected by the same rotation and have not rotated as independent crustal blocks. Accordingly, if all the data are combined together, the mean Eocene to middle Miocene paleomagnetic direction for the area studied here is: $N=16$; $D=340.5^\circ$; $I=-26.1^\circ$; $\alpha_{95}=6.1^\circ$. When the two mean directions which are clearly outside the main group are rejected, we obtain a virtually identical mean regional direction with a smaller scatter: $N=14$; $D=341.4^\circ$; $I=-27.3^\circ$; $\alpha_{95}=4.7^\circ$.

Discussion and Conclusions

The interpretation of paleomagnetic results from the Andes is somewhat delicate, because of the lack of a continuous and precise Apparent Polar Wander Path (APWP) for SOAM. Taking into account the ages of the studied formations (Eocene to middle Miocene), we have referred all our results to the 40 Ma mean pole calculated by Mitouard et al. [1990]. This pole does not differ significantly from the younger one (15 Ma) given by Valencio and Creer [1968]. The results are summarized in Table I and Figure 4 where the corresponding values of the rotation (R) and flattening (F) parameters calculated after Demarest [1983] are also reported.

TABLE I. Paleomagnetic results from Eocene to Miocene volcanic and intrusive formations of Central Peru.

Site	n/N	D(°)	I(°)	Dc(°)	Ic(°)	K	α_{95} (°)	Age
PE104	10/10	156.1	43.5			56	5.3	21
PE106	12/12	174.5	2.0			12	11.4	21
PE107	10/15	155.8	32.6			47	6.4	15-53
PE122	11/11	349.9	-24.8			54	5.7	24
PE140	6/8	341.3	-26.2			164	4.4	30?
PE142	6/6	146.0	29.2			356	3.0	15-53
PE204*	12/12	166.8	26.9	166.8	26.9	225	2.9	19-22
PE205*	9/9	158.3	14.9	158.3	14.9	352	2.8	19-22
PE206	11/11	161.0	25.9	162.6	24.2	327	2.5	19-22
PE207*	11/11	167.3	26.4	167.3	26.4	164	3.7	19-22
PE208	6/6	168.0	21.8	160.5	32.6	330	3.7	19-22
PE209**	12/13	18.9	-78.9	18.9	-78.9	291	2.8	19-22
PE210/211*	16/23	356.3	-17.7			120	3.5	~37?
PE212*	11/11	0.0	-32.2			180	3.5	~37?
PE213*	8/8	357.0	-35.8			146	4.9	~37?
PE214	12/12	316.4	-38.6			40	6.4	15-53
PE215	11/11	344.6	-31.1	343.2	-13.4	176	3.5	15-53
PE216	12/12	350.2	-16.6			51	6.4	15-53
PE217	12/14	152.3	33.8			53	5.9	31-39?
PE218	9/10	159.2	27.0			166	4.0	31-39?

n/N = 16/20 D = 340.5° I = -26.1° K = 37.6 $\alpha_{95} = 6.1^\circ$
 R = -11.8° ± 8.1° F = -3.9° ± 10.6°

n/N = 14/20 (sites PE106 and PE214 rejected; see text)
 D = 341.4° I = -27.3° K = 73 $\alpha_{95} = 4.7^\circ$
 R = -11° ± 7.4° F = -2.7° ± 10.2°

Mean directions are reported for each site before (D, I) and after bedding correction (Dc, Ic) (°: sites with horizontal observed bedding attitude); K, α_{95} : Fisher's statistic parameters; the age of the rocks are given in Ma (? : sites which may be older than their assumed age); R, F: rotation and flattening parameters. *: sites rejected (see text).

Fig. 4. Equal area projection of the reliable mean directions of the sites with their 95% angle of confidence.

There is a large uncertainty on the F parameter. Within these limits it does not indicate any significant latitudinal drift of the investigated area with respect to SOAM, in agreement with the autochthonous character of the studied formations.

The R parameter documents a significant post middle Miocene counterclockwise rotation of $11^\circ \pm 7.4^\circ$. The amplitude of this rotation is poorly defined largely because of the low accuracy on the position of the 40 Ma reference pole ($A_{95} = 7.5^\circ$). This hinders a precise quantitative interpretation of the data. However, the mean amplitude of the rotation obtained for the Lima and Nazca areas is only 4° less than the one of the rotation obtained from the Cretaceous data in the same area [Macedo-Sánchez et al., 1992]. It is also similar to the Paleogene paleomagnetic results reported from Northern Peru [Mitouard et al., 1990]. The new results thus confirm the remarkable consistency of the post-Eocene rotation of the Peruvian margin from Northern to Central Peru over a distance exceeding 700 km, and support Isacks' model for the uplift of the Central Andes.

In addition, according to the timespan covered by the new formations studied here, the rotation documented for Central Peru is much younger than previously supposed in Macedo-Sánchez et al. [1992]. The rotation is thus coeval with the acceleration of the Andean uplift documented by Sébrier et al. [1988]. It ended probably during middle-late Miocene, as the paleomagnetic data reported by Tsunakawa et al. [1987] seem to indicate. However, a better quantitative description of the rotation of the South American continental margin requires a significant improvement in the accuracy of the APWP for SOAM.

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