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Palaeomagnetism of Neogene Ocros dyke swarm, the Peruvian Andes: implication for the Bolivian orocline

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Summary. Remanent magnetization directions of 32 dykes and lava flows sampled near Ayacucho, the Peruvian Andes revealed 14.2° ± 5.5° counter-clockwise rotation after the Neogene intrusion of this dyke swarm. Palaeomagnetic results of these rocks and other palaeomagnetic evidences from the Central Andean Mesozoic rocks suggest relatively recent occurrence of the Andean oroclinal bending around the axis at the Peru–Chile border.

Introduction

Palaeomagnetic studies on the Mesozoic rocks of the Peruvian Andes and northernmost Chile (Heki, Hamano & Kono 1983; Heki 1983; Heki *et al.* 1984) have revealed post-Cretaceous counter-clockwise rotation of the Peruvian block and oroclinal bending of the Central Andes around an axis at the Peru–Chile border (referred to as the Bolivian orocline; Carey 1955). Hayashida *et al.* (1984) also showed the counter-clockwise deviated declination of the Eocene red sediments of the Salla Group in the Bolivian Altiplano and suggested that the oroclinal bending is post-Eocene. Palaeomagnetic studies for much younger rock formations will provide important information on the age of the bending of the Central Andes. Here we report the result of a palaeomagnetic investigation on a Neogene dyke swarm near Ayacucho, in the Peruvian Andes.

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Geology

Upper Cretaceous to Quaternary volcanic formations are widely distributed in the Peruvian Andes over the highland of the Western Cordillera. These formations are composed of lava flows, volcanic breccias, agglomerates and tuffs and their compositions are predominantly andesitic. These volcanics can be divided into several stratigraphical groups according to the degree of influence of the compressive deformations in the Andean orogeny. The youngest volcanic formations which were formed after the most recent compressive pulse (Quechuan orogeny; Bellido 1979) are generically called the Sillapica Group or the Barosso Group. Farrar & Noble (1976) bracketed the onset of the Quechuan deformation between 21 and 14 Ma and suggested the age of the termination to be about 10 Ma. From this point of view, Plio–Quaternary ages have been assigned to these youngest volcanic formations. However, radiometric age determination studies reveal that even the volcanic rocks whose ages were

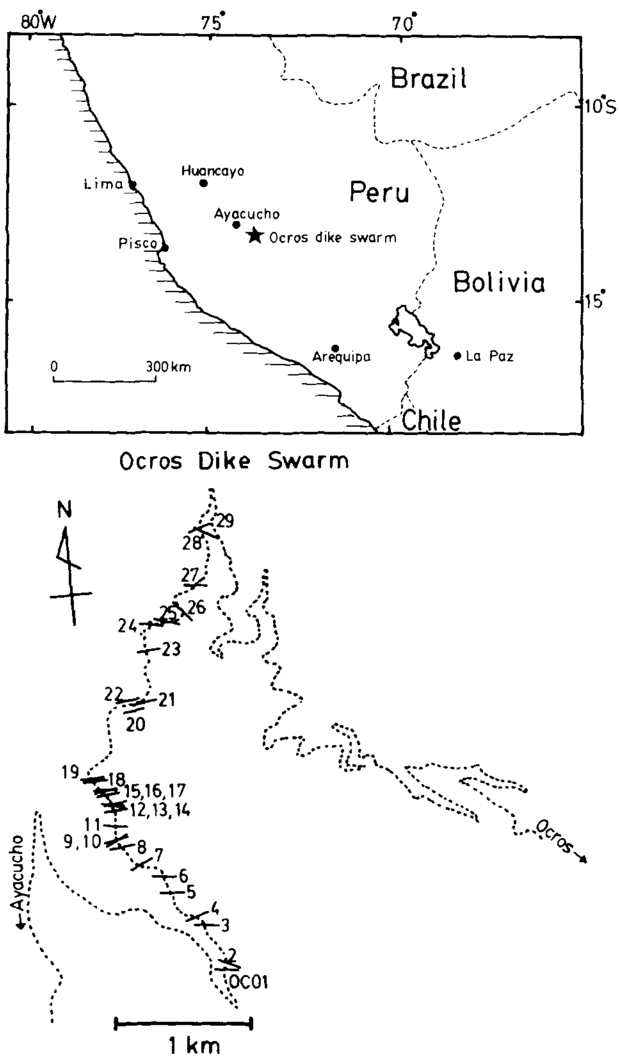

Figure 1. The location of the Ocros dyke swarm in the Peruvian Andes. Dykes are illustrated as short bars (OC01-29). Directions of the bars indicate the strikes of the dyke contacts. The dotted line shows the route between Ayacucho and Ocros. Magnetic north is also illustrated on the lower map.

assumed to be Quaternary show ages representative of the Upper Miocene, say 5–7 Ma (Bellon & Lefèvre 1976; Kaneoka & Guevara 1984). Thus it is reasonable to consider that these rocks are post-Miocene.

A dyke swarm was found within a volcanic formation which is described as the Barosso Group (Bellido 1979) and was named the 'Ocros dyke swarm' (Fig. 1). The sampling route spans about 4 km extending approximately north to south and we collected about 200 oriented block samples from 29 dykes intruding into an alternation of lavas and pyroclastics

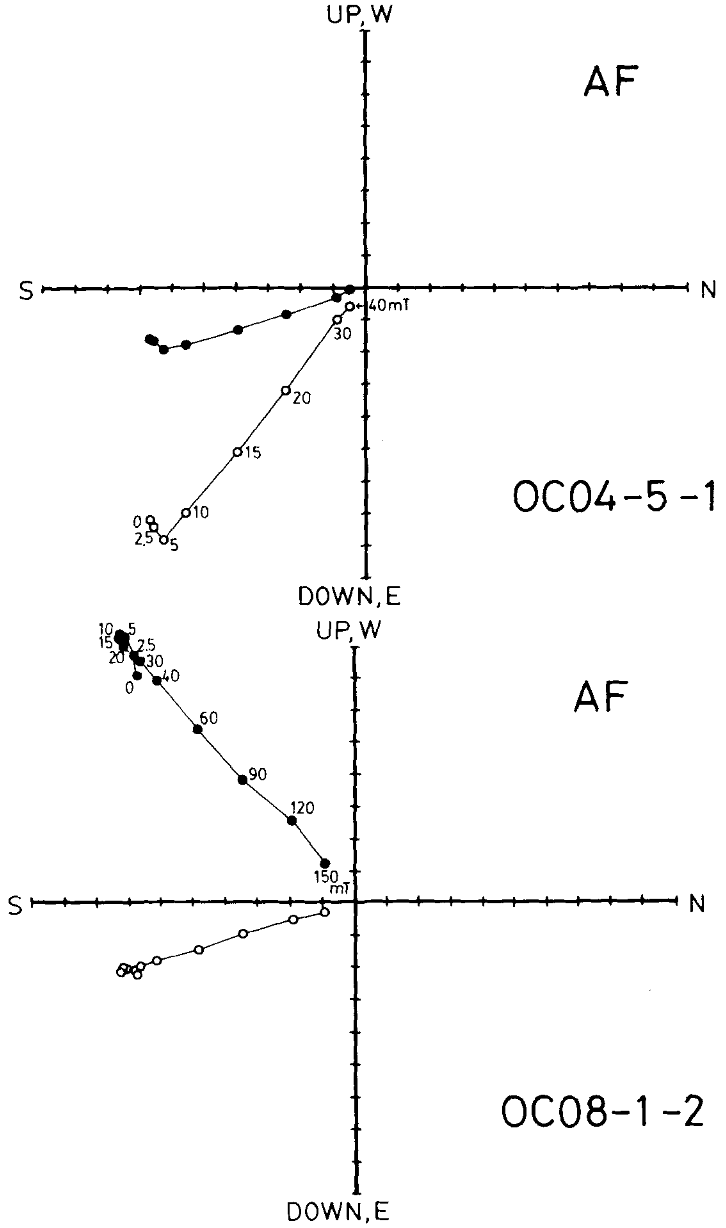

Figure 2. Zijderveld diagrams in the progressive AF demagnetization of the specimens of Ocros dyke swarm. Open and solid symbols indicate the projections on to vertical and horizontal planes respectively. Scales are arbitrary.

(Fig. 1, OC01-29). At several dykes (OC03, 05, 06) adjacent lava flows were also sampled. The general trend of the dykes is N80°E (Fig. 1), which is roughly parallel with the present direction of plate convergence at the trench. From the facts that this volcanic formation post-dates the last compressive pulse and that each dyke contact is vertical, structural tilting is considered to have been almost absent since the time of the intrusion of this dyke swarm. Detailed geologic and petrologic information on these dykes is given in Ui *et al.* (1985).

Experimental procedures

Oriented block samples were cored in the laboratory and were measured using a Schonstedt spinner magnetometer at the University of Tokyo. Stepwise alternating field (AF) demagnetization was carried out on each specimen until the most part of the original remanence was destroyed. The natural remanent magnetization (NRM) intensities ranged from 10^{-4} to 10^{-2} Am^2 kg^{-1}. The remanent magnetization directions were fairly stable against AF demagnetization and median destructive fields (MDFs) usually exceeded 20 mT. Fig 2 shows vector diagrams (Zijderveld 1967) of the progressive AF demagnetization. A palaeomagnetic field direction was determined from the angle between the linear portion of the data points and the axes of the diagram.

Results and discussion

All the palaeomagnetic results are listed in Table 1. The site-mean remanent magnetization directions are illustrated with 95 per cent confidence circles (Fisher 1953) in Fig. 3 by

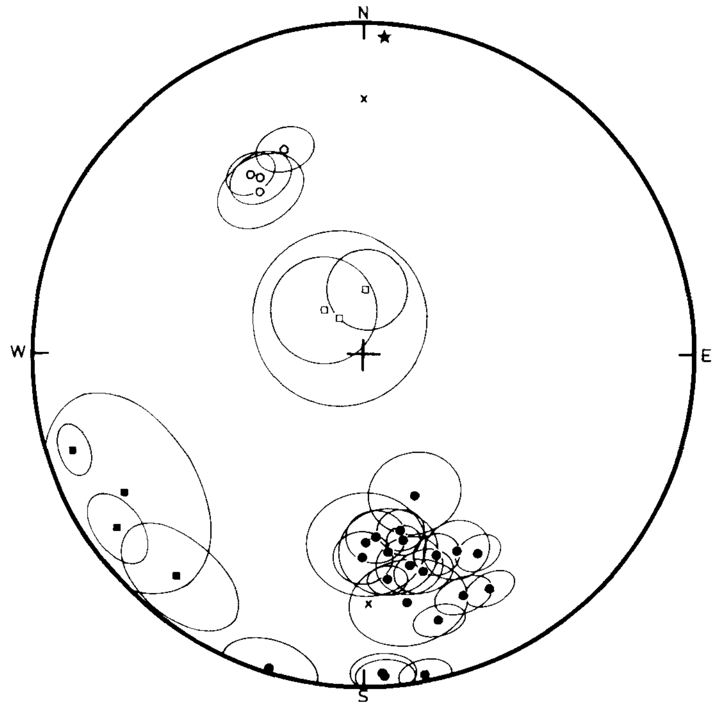

Figure 3. Lambert equal-area projection of the site-mean remanent magnetization directions of Ocros dyke swarm. The 95 per cent confidence circles are also illustrated. The open and solid symbols denote negative (upward) and positive (downward) inclinations respectively. The star indicates the present field direction in this area and the X indicates the present axial dipole field. Squares denote intermediate polarity directions.

Lambert equal-area projection. About two-thirds of the site-mean directions cluster near the present axial dipole field (ADF, denoted as Xs in Fig. 3) of reversed polarity and it is noticed that they deviate counter-clockwise from the ADF by 10°–20°. There are also four dyke-mean directions which are nearly antipodal to those of reversed polarity. These two groups can be interpreted to represent reversed and normal polarities respectively. Thus, four dykes (OC12, 15, 16, 17) are classified as normal polarity and 21 dykes and lavas (OC01-07, 13, 14, 18, 22-29) are classified as reversed polarity. Seven dykes (OC08-11, 19-21; shown as squares in Fig. 3) have their virtual geomagnetic poles (VGPs) more than 40° apart from the mean position of the other 25 VGPs and are considered to be of intermediate polarity. These intermediate polarity (or possibly transitional) directions were excluded from the subsequent discussion.

If we assume that the times of intrusion of the dykes are randomly distributed over the whole activity duration of the dyke swarm, the scatter of VGPs may be considered to represent a measure of the ancient secular variation of the geomagnetic field. The angular standard deviation (ASD) of the VGPs for the 21 reversed polarity dykes is 13.7° with a 95 per cent confidence interval between 11.3° and 17.4°. When normal polarity VGPs are inverted to those of reversed polarity, the ASD of the 25 VGPs is 14.2° with 95 per cent confidence limits of 11.9° and 17.7°. These ASDs show good agreement with the global trend of the Plio–Pleistocene palaeosecular variation presented in McElhinny & Merrill (1975).

The axial geocentric dipole hypothesis predicts that the geomagnetic field almost coincides

Table 1. Palaeomagnetic directional data of Ocros dyke swarm.

Dyke (lava)	N	Incl.[1] (°)	Decl.[1] (°)	R	k	α_{95} (°)	VGP Lat. (°N)	VGP Long. (°E)
OC01	4	3.9	176.5	3.9786	242	5.9	-78.0	88.9
OC02	6	0.8	-163.1	5.9209	63	8.5	-68.8	159.6
OC03	6	52.5	160.3	5.8739	40	10.8	-63.4	-34.9
(OC03)	6	44.8	168.5	5.9649	142	5.6	-73.1	-36.0
OC04	5	42.4	179.3	4.8687	31	14.1	-78.8	-70.7
OC05	6	32.4	164.7	5.9578	118	6.2	-74.7	-1.8
(OC05)	13	32.0	174.0	12.8808	101	4.2	-83.0	-13.6
OC06	6	24.7	170.2	5.8422	32	12.1	-80.5	17.6
(OC06)	5	39.4	172.9	4.9244	53	10.6	-78.8	-37.9
OC07	6	17.5	164.4	5.9724	181	5.0	-74.1	30.6
OC08	5	17.2	-120.6	4.7201	14	20.9	-31.7	-161.8
OC09	6	13.1	-140.2	5.8151	27	13.1	-50.3	-159.7
OC10	6	9.5	-125.5	5.9375	80	7.5	-35.6	-167.7
OC11	6	8.8	-108.6	5.9755	204	4.7	-19.1	-163.9
OC12	6	-36.4	-32.5	5.9611	129	5.9	58.2	179.2
OC13	6	34.4	154.9	5.9335	75	7.8	-65.3	-0.1
OC14	6	34.6	167.7	5.9420	86	7.3	-76.9	-11.1
OC15	7	-34.6	-21.6	6.9315	88	6.5	68.5	178.0
OC16	6	-38.6	-30.7	5.9482	97	6.9	59.6	175.7
OC17	6	-41.6	-32.9	5.9043	52	9.4	57.2	172.5
OC18	7	38.4	-179.6	6.9192	74	7.1	-81.8	-76.6
OC19	4	-79.5	-37.0	3.8513	20	21.0	29.2	119.9
OC20	5	-75.4	-43.0	4.8872	36	13.0	32.3	127.9
OC21	6	-74.2	2.1	5.8976	49	9.7	42.9	104.6
OC22	6	31.2	150.5	5.9762	210	4.6	-61.3	5.4
OC23	6	43.8	176.1	5.9440	89	7.1	-77.2	-57.8
OC24	6	2.9	176.3	5.9655	145	5.6	-77.5	88.7
OC25	6	1.3	169.3	5.9709	172	5.1	-73.4	65.5
OC26	3	35.4	160.3	2.9963	545	5.3	-70.2	-4.7
OC27	5	41.9	168.1	4.9908	434	3.7	-74.4	-29.4
OC28	7	22.1	157.9	6.9487	117	5.6	-68.3	18.7
OC29	8	20.7	152.0	7.9520	146	4.6	-62.5	18.6
mean[2]	21	-	-	20.4057	34	5.6	-78.7	0.0
mean[3]	25	-	-	24.2329	31	5.3	-75.2	-1.2

N: number of samples studied, *R*: length of resultant vector, *k*: precision parameter (Fisher 1953), α_{95}: radius of 95 per cent confidence circle.

[1] All directions are determined by least squares fitting to the linear portions of the demagnetization diagrams.

[2] Only reversed polarity VGPs are averaged.

[3] Normal polarity VGPs are converted to those of reversed polarity and are averaged together with reversed polarity VGPs.

with that of an axial and almost geocentric dipole (in other words, the mean VGP almost coincides with the geographic pole) when averaged over a certain time range covering the whole secular variation periods (McElhinny 1973). The normal and reversed remanent magnetization directions obtained from the Ocros dyke swarm show significant counter-clockwise declination shifts (the mean VGP is different from the geographic pole at the 95 per cent confidence level; Table 1) although the ASD seems sufficient to include the whole period of the palaeosecular variation. Therefore there should be some important reasons for this declination shift.

Currently available Neogene palaeomagnetic data for the South American plate are not sufficient to establish the palaeomagnetic pole position for this period. However, the South American pole can be estimated indirectly by rotating the North American palaeomagnetic pole (e.g. Iriving 1977) around the pole of the recent relative movement between North American and South American plates obtained from the Atlantic magnetic anomaly linea-

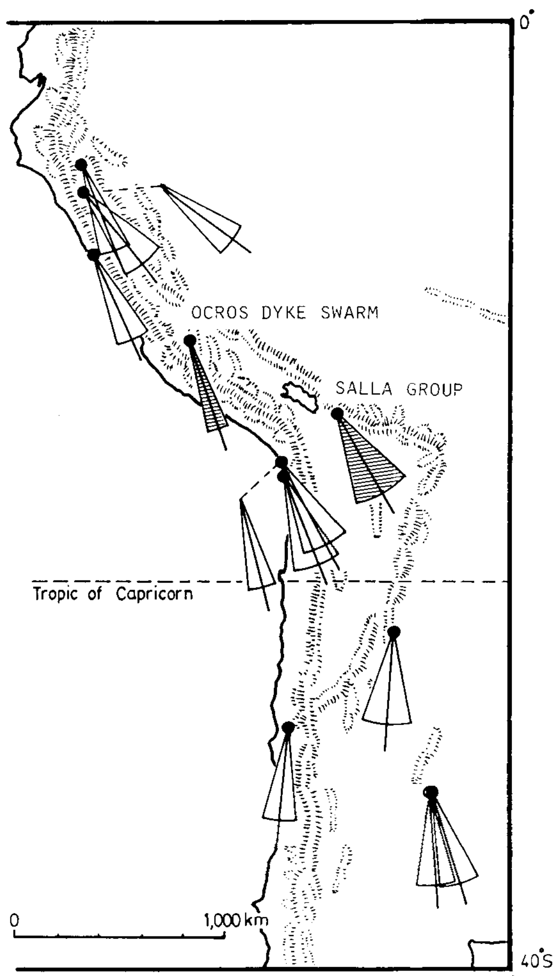

Figure 4. Rotation angles and their 95 per cent confidence limits obtained from the palaeomagnetic studies of the Central Andes (after Heki *et al.* 1983; Kono *et al.* 1985). Rotation angles are shown as the angles between the south and the central lines of the fans. Hatched data are Tertiary (Neogene Ocros dyke swarm and the Eocene Salla Group).

tion data (Ladd 1976). The position of the South American palaeomagnetic pole for the last 10 Myr estimated in this way is not significantly different from the present pole. Several palaeomagnetic studies of late Cenozoic rocks in the Argentine Andes also indicate that the palaeomagnetic pole in this period is nearly coincident with the present-day geographic pole (e.g. Creer & Valencio 1969; Valencio, Vilas & Mendia 1975). Hence, the declination shift of the remanent magnetization of the Ocros dykes is considered to be due to tectonic movements of this region rather than an apparent polar shift of the entire South American plate.

One possibility to explain this declination shift is a tilting of the whole part of the Ocros dyke swarm. In order to convert the ADF direction to the average of the observed remanent magnetization directions of Ocros dyke swarm, the palaeohorizontal plane should have a dip of about 30° with a nearly north–south strike. However, as mentioned already, the observed dyke contacts are almost vertical and Plio–Pleistocene tilting up to 30° is quite unlikely.

It is more plausible to suppose that the declination shift is due to the counter-clockwise rotation of the block involving the dyke swarm with respect to the other regions of South America. By assuming the coincidence of the present pole and the Neogene palaeomagnetic pole for the South American plate, we can estimate the rotation angle and its 95 per cent confidence interval after the method of Beck (1980). The obtained value ($14.2° \pm 5.5°$) is illustrated in Fig. 4 as an angle from the present south. (This confidence interval includes neither uncertainty in the cratonal pole, nor the uncertainty of undetected tilt, and so the actual error limits might be somewhat larger.) Fig. 4 also shows the rotation angles obtained from palaeomagnetic studies of Mesozoic rocks in the Central Andes as the white fans (Heki *et al.* 1983; Kono, Heki & Hamano 1985). Tertiary data (the Eocene Salla Group, Hayashida *et al.* 1984; Ocros dyke swarm, this study) are shown as hatched fans.

In Fig. 4, although the rotation angles for the Mesozoic and Eocene rocks are concordant with the structural trend of the Andes, that of the Ocros dyke swarm appears to be significantly smaller. This suggests that the counter-clockwise rotation of the Peruvian Andes, i.e. the occurrence of the Bolivian orocline, is rather recent and the Ocros dyke swarm possibly recorded an intermediate point of the rotation of the Peruvian Andes. In summary, palaeomagnetic results from the Ocros dyke swarm provide a strong constraint in considering the age of the Bolivian orocline, that is, about half of the rotation occurred after the intrusion of the Ocros dyke swarm in the Neogene.

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