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Rotation of the Peruvian Block from palaeomagnetic studies of the Central Andes

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Palaeomagnetic studies were performed on the rocks of the Central Andes to test the hypothesis of oroclinal bending of the Andes around the Peru–Chile border. Natural remanent magnetization of Mesozoic volcanic and sedimentary rocks of Peru shows a counterclockwise shift of declination by several tens of degrees relative to the field directions of the same ages in the stable South American craton. Two Mesozoic dyke swarms from Arica region (northernmost Chile) also indicate about 20° of declination shift in a counterclockwise sense. These results suggest a considerable amount of counterclockwise rotation of large area north of Arica, that is, oroclinal bending of the Andes around some hinge near the Peru–Chile border. One Neogene dyke swarm sampled in central Peru also gave declination which deviates counterclockwisely by ~15°. If this declination shift is a result of the wide-area tectonic rotation as suggested by the Mesozoic rocks, oroclinal bending appears to have continued until relatively recent times.

An abrupt change in the structural trend is observed in the Central Andes at the Peru–Chile border as shown by the sudden break of the coastline trend. This is generally referred to as Santa Cruz deflection or Arica deflection and is interpreted as an oroclinal bend by Carey[1]. Palaeomagnetism has the potential of providing information about tectonic rotation and should reveal whether this deflection is the result of oroclinal bending or no more than the change in trend of the original sedimentary trough. Palmer *et al.*[2] first tried to test the oroclinal bending hypothesis by comparing the palaeomagnetic directions of the supposedly preoroclinal rocks from northern (Peruvian) and southern (Chilean) wings of the deflection. Unfortunately, they failed to derive any reliable palaeomagnetic results from the Peruvian side and only reported the results from Jurassic rocks collected in Arica region, the very point of deflection. Their results suggest about 25° counterclockwise rotation of Arica region with respect to the cratonic area of South America after Jurassic time. However, much more data with wider spatial and temporal coverage are necessary to verify the orocline hypothesis.

In 1980 and 1981, we collected over 600 oriented rock samples in Peru and Northern Chile in collaboration with Instituto Geofisico del Peru (Lima) and Universidad de Chile (Santiago). They are composed of Mesozoic sedimentary rocks and volcanic rocks, Cenozoic volcanic rocks and a small amount of Palaeozoic and Precambrian sedimentary and metamorphic rocks. Mesozoic sedimentary rocks were most extensively sampled in the northern part of the Peruvian Andes in the area usually described as miogeosyncline[3]. Rocks having ages of Lower to the lower part of Upper Cretaceous were most abundant because the sedimentation rate was the greatest in that period. Mesozoic igneous rocks were sampled from the coastal region of Peru and northern Chile in the area of eugeosyncline[3]. Mesozoic volcanic samples include two dyke swarms near Arica, northern Chile (Cretaceous Arica dyke swarm and Jurassic Cuya dyke swarm). Cenozoic volcanics were collected in the high Andes region of Peru and Chile. One Neogene dyke swarm was also sampled near Ayacucho, Central Peru (Ocros dyke swarm).

Magnetic remanences of sedimentary rocks (mostly limestones) were measured by a cryogenic magnetometer, and those of igneous rocks were measured by using a spinner magnetometer. Every specimen was subjected to stepwise alternating field (a.f.) demagnetization at least to 80 mT and stable remanences were isolated by using a Zijderveld vector diagram[4]. Results were excluded from the subsequent analyses if directional scatters were too large. Experimental details and complete palaeomagnetic results are given in ref. 5.

Table 1 summarizes palaeomagnetic poles derived from Tertiary Ocros dyke swarm, coastal volcanic rocks of Peru, Arica dyke swarm and Cuya dyke swarm. Each was obtained by averaging several virtual geomagnetic poles (VGPs) determined from independent volcanic units such as lava flows or dykes. Palaeosecular variation can be regarded to be averaged out in these palaeomagnetic poles. Results from Peruvian Cretaceous sedimentary rocks are summarized in Table 2. A few other Jurassic and Cretaceous palaeomagnetic poles reported in the Central Andes are included in Table 1. These poles are plotted in Fig. 1 and are compared with the standard apparent polar wonder path (APWP) of stable South America since late Carboniferous[6]. Most palaeomagnetic poles from Peru (circles in

Table 1 Palaeomagnetic poles derived from igneous rocks and palaeomagnetic poles reported by other workers.

	Locality				Pole				
Rock unit (ref.)	Lat. (°S)	Long. (°W)	Age	No. of samples (sites)	Lat. (°S)	Long. (°E)	dp	dm	A_{95}
1. Ocros dyke swarm	13.4	73.9	Tm-p	192 (32)	75.8	358.8			5.3°
2. Coastal volcanics	5–15	75–80	K	68 (12)	68.0	359.5			5.3°
3. Arica dyke swarm	18.6	70.3	K	103 (19)	77.2	352.4			3.3°
4. Cuya dyke swarm	19.2	70.2	J	110 (25)	75.1	65.7			6.3°
5. Herradura, Vinchos, Moracoche (7)	11	76	K	—	63	30			8°
6. Camaraca Formation (2)	18.6	70.3	Jm	—	71	10			6°
7. Central Chile (8)	29.8	70.9	Ku	—	81	209			4.4°
8. Pirgua Subgroup (9)	25.8	65.8	Kl-u	—	85	222	7°	10°	
9. Las Cabras Formation (10,11)	32	69	Jl	—	74	94	11°	18°	

Tm-p, Miocene to Pliocene; K(l or u), Cretaceous (Lower or Upper); J(l or m), Jurassic (Lower or Middle); Kl-u, upper part of Lower Cretaceous to Upper Cretaceous. dp, Radius of confidence oval measured in the direction from site to pole; dm, radius of confidence oval measured perpendicular to dp.

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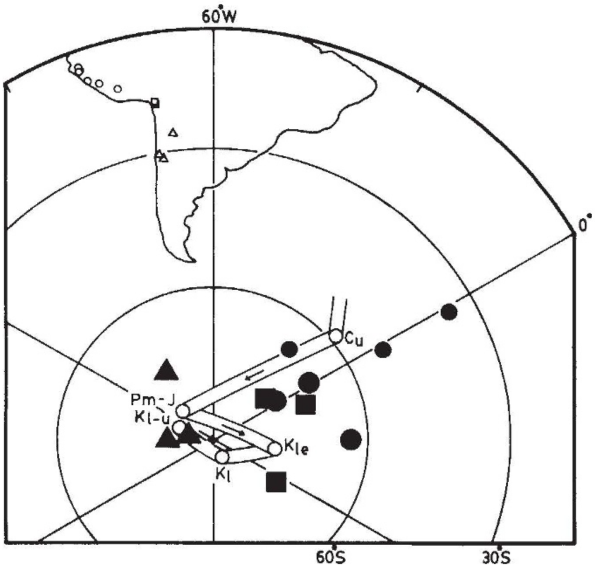

Fig. 1 Palaeomagnetic poles of Peru (solid circles), Arica region, northern Chile (solid squares) and central Chile and northwestern Argentina (solid triangles) listed in Table 1 (large symbols) and Table 2 (small symbols). Corresponding sampling localities are also shown as small open symbols. Standard APWP[6] from South American craton since late Carboniferous is also illustrated. The ages of the standard poles are as follows: Cu, late Carboniferous; Pm-J, Permian to Jurassic; Kle, early early Cretaceous; K1, early Cretaceous; Kl-u, late early Cretaceous to late Cretaceous.

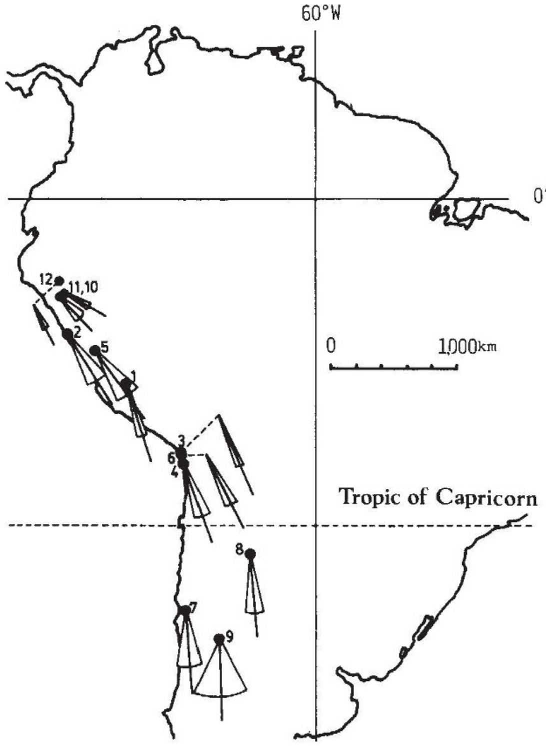

Fig. 2 Palaeomagnetic declinations and their 95% confidence limits for rock units in Tables 1 and 2. These directions are adjusted so that the expected declination deduced from the standard palaeomagnetic pole[6], point due south. The declination deviations from south therefore directly indicate the rotation that occurred after the formation of the rock units.

Fig. 1) and northern Chile (squares, Fig. 1) deviate significantly from the standard APWP; they tend to lie approximately along the Greenwich meridian. These deviations correspond to the systematic shift of palaeomagnetic declinations and imply a counterclockwise tectonic rotation of the sampling area with respect to the stable part of South America.

The declination anomalies are defined as the difference between the observed palaeomagnetic declination and the normal declination expected from the standard APWP. They are illustrated in Fig. 2 together with their 95% confidence intervals. The amount of declination shift is about 30° for the Cretaceous volcanic rocks of Peruvian coastal area while those for Peruvian Cretaceous sedimentary rocks are more divergent and have values between 25° and 60°. Early palaeomagnetic data reported by Creer[7] on Peruvian Cretaceous rocks are based on natural remanent magnetism measurements and are not subjected to any stability tests. His results, however, also show a declination shift of about 30° and are therefore consistent with our data. Palaeomagnetic results derived in Arica region (Cretaceous Arica dyke swarm and Jurassic Cuya dyke swarm) also show 15–20° counterclockwise declination shifts. These results are quite similar to palaeomagnetic data on Jurassic volcanic rocks of Arica region reported by Palmer *et al.*[2].

On the other hand, palaeomagnetic poles are fairly consistent with the standard APWP for the region south of the deflection (Fig. 1, triangles). Mesozoic palaeomagnetic data in central Chile[8] and northwestern Argentina[9–11] do not show any counterclockwise declination shift and corresponding pole positions are concordant with the APWP from the stable part of South America. Tertiary palaeomagnetic pole of the Central Andes is available only from the Neogene Ocros dyke swarm in Peru. A counterclockwise rotation of 15° is also suggested. However, it might be premature to conclude a tectonic rotation of large area because more data covering a wider area, are lacking.

The results may be summarized as follows: (1) Mesozoic palaeomagnetic data from Peru and northernmost Chile are generally discordant with those from the stable part of South America and show a considerable amount of counterclockwise declination shift. (2) The region of anomalous declination does not extend to central Chile and northwestern Argentina, that is, the southern part of the Central Andes. (3) Definite conclusions for Tertiary palaeomagnetic poles cannot be made at

Table 2 Poles derived from sedimentary rocks.

	Locality				Pole			
Rock unit	Lat. (°S)	Long. (°W)	Age	No. of samples	Lat. (°S)	Long. (°E)	dp	dm
10. Chulec Formation	7.1	78.3	Kl (Albian)	7	52.0	1.6	4.7°	8.8°
11. Pariatambo Formation	7.1	78.3	Kl (Albian)	6	35.9	0.8	3.1°	5.8°
12. Yumagual Formation	5.9	78.2	Ku (Cenomanian)	9	66.7	339.7	3.2°	5.7°

K(l or u), Cretaceous (Lower or Upper).

present. However, the only available data from the Neogene dykes (Ocros dyke swarm) suggest that a certain amount of counterclockwise rotation still occurred as late as Miocene time.

In the western edge of North America, many palaeomagnetic data show anomalous directions characterized by various amounts of clockwise declination shift and/or flattening of inclination[12]. Intensive works in this area clarified an existence of extensive allochthonous terranes which were originally carried by oceanic plate and were accreted to the western margin of the North American continent. Rotation of such terranes appears to have occurred at or after the time of accretion due to dextral shear motion at the plate boundary[13].

In southern Chile, it is suggested that an ancient island arc and intervening fossil marginal basin collided with South America[14]. As for the Central Andes, it is thought that no large exotic terranes exist in the coastal area. We cannot prove the inexistence of similar collided terranes in this area, but the uniformity of the declination shift for Jurassic and Cretaceous rocks in a large area north of the deflection (Fig. 2) suggests a coherent rotation of the Central Andes block. From palaeomagnetic evidences mentioned above, we conclude that the Santa Cruz deflection (Arica deflection) is not an original feature but one that arose later due to an oroclinal bending around some hinge near Arica region, at least after the Cretaceous and possibly even after the time of intrusion of Ocros dyke swarm.

There may be several interpretations of this bending, among which one possibility is to assume a collision of a continental sliver with the Peru–Chile border whose remnant is presently observable as the Arequipa massif on the coast of southern Peru. Accretion of unsubductable mass from oceanic side will stop the receding oceanic trench at that place, and so form the axis of bending. Whatever the mechanism is, there will be some significant consequences caused by the oroclinal bending. If the bending is really recent as suggested from our data, it would have not only influenced tectonic evolution of the Andes itself but also given rise to various tectonic phenomena in surrounding areas which ought to be observable today. For example, because the Central Andes is a continental arc, there should be considerable stretching (behind northern Peru portion) and/or shortening (behind Peru–Chile border) of the continental lithosphere which accompany oroclinal bending. It is tempting to speculate that the late Cenozoic uplift of the Altiplano is a consequence of shortening caused by the Bolivian orocline.

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Palaeomagnetism of Lower Cretaceous tuffs from Yukon-Kuskokwim delta region, western Alaska

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During the past decade, the prescient arguments[1–3] for the allochthoneity of large portions of southern Alaska have been corroborated by detailed geological and palaeomagnetic studies in south-central Alaska[4–9] the Alaska Peninsula[10], Kodiak Island[11,12] and the Prince William Sound area[13] (Fig. 1). These investigations have demonstrated sizeable northward displacements for rocks of late Palaeozoic, Mesozoic, and early Tertiary age in those regions, with northward motion at times culminating in collision of the allochthonous terranes against the backstop of 'nuclear' Alaska[14,15]. A fundamental question is which parts of Alaska underwent significantly less latitudinal translation relative to the 'stable' North American continent, thereby serving as the 'accretionary nucleus' into which the displaced 'microplates'[16] were eventually incorporated[17,18]? Here we present new palaeomagnetic results from tuffs and associated volcaniclastic rocks of early Cretaceous age from the Yukon–Kuskokwin delta region in western Alaska. These rocks were probably overprinted during the Cretaceous long normal polarity interval, although a remagnetization event as recent as Palaeocene cannot be ruled out. This overprint direction is not appreciably discordant from the expected late Cretaceous direction for cratonal North America. The implied absence of appreciable northward displacement for this region is consistent with the general late Mesozoic–early Tertiary tectonic pattern for Alaska, based on more definitive studies: little to no poleward displacement for central Alaska, though substantially more northward drift for the 'southern Alaska terranes' (comprising Alaska Peninsula, Kodiak Island, Prince William Sound area, and Matunuska Valley) since late Cretaceous to Palaeocene time.

The study area is located at the Devils Elbow bend in the Lower Yukon River near the village of Ohogamiut (61.6° N lat., 162.0° W long.), about 80 km north-west of Bethel (Fig. 1). The suite we sampled[19,20] comprises thin- to massive-bedded, aphanitic grey and green ash-fall tuff, coarse-grained crystal lithic tuff, and tuffaceous sandstone and siltstone (Fig. 2). Hoare[19] estimated the thickness of this assemblage at a minimum of 3 km; we believe that our sampling interval spans at least one-third of the total section. Dips are gentle and fairly uniform throughout the section, generally to the north and north-east (Fig. 2).

Granitic stocks locally cut the volcanic sequence. Radiometric dates are unavailable for these intrusive igneous rocks, but their inferred age, based on geological relations, is late Cretaceous to early Tertiary. Similarly, the age of the volcaniclastic rocks in the study area is equivocal. Four small fossil collections were obtained from these strata near Ohoganiut. The fossils consist of belemnites, ammonite fragments and pelecypods (*Buchia* sp.)[19]. R. W. Imlay reported that the belemnites are almost certainly Jurassic and the ammonites probably Jurassic or early Cretaceous in age, while D.L. Jones assigned the pelecypods an early Cretaceous age (cited in ref. 19).

§ Deceased.