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An accreted continental terrane in northwestern Peru

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A paleomagnetic study of over 250 cores from 26 sites sampled in Early to Late Cretaceous and Paleogene volcanic, plutonic and sedimentary formations of the Lancones basin in the Piura province of northern Peru, indicates that most of these lithologies carry a stable primary remanent magnetization whose direction is significantly different from that of coeval formations of stable South America. A clockwise rotation ranging from 90° for the lowermost units to 35° for the uppermost ones has been documented, although the lack of precise chronology has not allowed a detailed temporal description. Four sites from Late Carboniferous (Pennsylvanian) formations in the Amotape-Tahuin Range also show a 110° clockwise rotation and yield evidence for a northward displacement. When considered together with previous geological studies, these data are consistent with the hypothesis of the accretion of an Amotape-Tahuin continental terrane to the Peruvian margin in Neocomian times. The accretion was followed by in situ rotation, suggesting a dextral shear regime. These results indicate that the geodynamical evolution of northern Peru is more closely related to the processes observed in Ecuador than to those classically assumed for the Central Andes of Peru.

1. Introduction

During the last decade a large number of paleomagnetic studies has shown that the western active margin of North America is a mosaic of allochthonous accreted terranes of widely differing sizes, some of which have undergone large latitudinal transport. The accretion and subsequent coastwise translation and rotation of these terranes are a major characteristic of the North American orogenic belt [1–6].

In contrast, the role and extent of microblock collisions in the building and shaping of the Andean Cordillera is still a wide open problem, and one which may have different answers in the three different major segments of the Cordillera documented by the geological observations (Fig. 1). North of 3°S latitude, the Andes of Colombia and Ecuador appear to be a cordilleran orogen related to the accretion of oceanic crust, as evidenced by ophiolitic sutures included in the belt and by recent paleomagnetic and structural studies [7–12]. Ophiolites are also present in the Magellan Andes of Chile and Argentina in the extreme south. The paleomagnetic data from this segment have been interpreted in terms of oroclinal bending [13], but it has been recently pointed out that block rotation in a distributed sinistral shear could account for the results as well [14].

The Central Andes, in which no ophiolitic suture has yet been recognized, have generally been considered as a genuine marginal orogen formed exclusively by subduction since the Early Jurassic [15–17]. Nevertheless, a number of potential suspect terranes have been identified by different authors. The paleomagnetic results from this zone indicate counterclockwise rotations in Peru and northernmost Chile and clockwise rotations farther south in Chile, and have generally been interpreted in terms of an oroclinal bending (the Arica deflection) [18–21]. More recently Beck [14] has proposed an alternative explanation in terms of in-situ block rotations in response to shear (sinistral to the north and dextral to the south of the Arica bend).

Clearly, although the existing paleomagnetic results already allow some tectonic speculations, many more are needed before a pattern can emerge

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with unambiguous tectonic implications, such as for the North American Cordillera.

In this article we report on a paleomagnetic study from formations located in the Huancabamba Andes of Northern Peru, which represent the connection between the Northern and Central Andes. This segment has generally been considered as part of the Central Andes, since no ophiolitic suture has been recognized in it. However, discrepancies in the stratigraphic and paleobiologic records briefly described in the next section suggest that the major coastal Paleozoic massif in this zone (the Amotape-Tahuin Range) has undergone a geological evolution different from that of the stable craton to the east [22]. Other very recent studies of the geology and of the gravity field in Ecuador and northern Peru also suggest the existence of several allochthonous terranes in this area [10,23]. Both these previous geological and geophysical observations and the paleomagnetic results reported here are consistent with the hypothesis of the accretion of an allochthonous continental terrane to the Peruvian margin in Neocomian times, suggesting that the geodynamical evolution of northern Peru is more closely related to the processes observed in Ecuador [7] than to those classically assumed for the Central Andes in Peru.

2. Geological setting and paleomagnetic sampling

The Huancabamba Andes extend between 3°S and 8°S over southern Ecuador and northern Peru, and represent the connection between the Northern and the Central Andes (Fig. 1). One of the major features of this segment is the change of the Andean trend, from N20°W in the northern part of the Central Andes to N20°E in the Northern Andes (Fig. 2). This bend is known as the Huancabamba deflection.

In the coastal area of the Huancabamba Andes, the pre-Mesozoic basement outcrops in the large Amotape-Tahuin Range, in the Paita and Illescas massifs and in the Lobos de Tierra island. In the Amotape-Tahuin Range it consists of polyphase metamorphic rocks of Precambrian and early Paleozoic age, unconformably overlain by conformable to disconformable Devonian to Permian marine and continental sedimentary series. On the other hand, no pre-Devonian deformational and

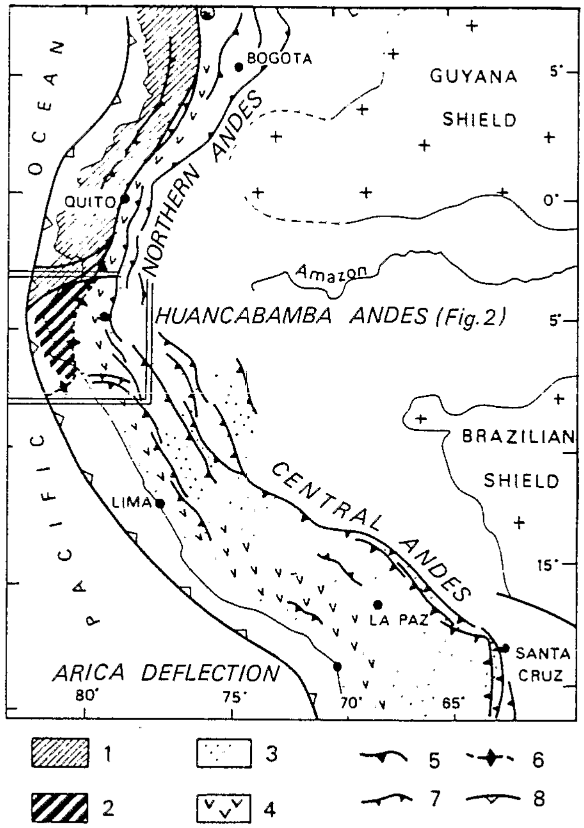

Fig. 1. The Huancabamba Andes and their position within the Andean orogen (modified from Mégard [11]). *1* = accreted oceanic terranes (Northern Andes); *2* = coastal area of the Huancabamba Andes; *3* = integral Peruvian Andes (Central Andes); *4* = volcanic and plutonic Cenozoic belt; *5* = sutures; *6* = presumed suture; *7* = main intracontinental overthrusts; *8* = actual trench.

metamorphic event is observed in the Paleozoic massifs situated farther east, e.g. the Olmos massif of northern Peru, the Cordillera Real of Ecuador or the Maranon geanticline. Rather, the Paleozoic evolution of central and eastern Peru is characterised by Late Devonian/early Carboniferous Eohercynian folding not observed in the Amotape-Tahuin massif [22].

The Mesozoic record of the coastal area shows a complete hiatus of post-Permian and pre-Albian deposits. Albian carbonates unconformably overlie the Amotape-Tahuin pre-Mesozoic basement and are in turn overlain by flysch series of late Cretaceous age. Both these and the Albian carbonates grade eastward into mixed volcanic and partly volcanoclastic sedimentary rocks which fill the Lancones synclinorium. A different evolution is observed in the Olmos massif, where the basement is unconformably overlain by a conformable to disconformable platform sequence, similar to that observed in the remainder of northern Peru, consisting of carbonates of Triassic to Liassic age, volcanic and/or clastic rocks of middle to late Jurassic age, deltaic siliciclastic rocks of Neocomian age and carbonates of Albian to Santonian age [22].

Paleogeographic reconstructions [22] of the Huancabamba Andes show that two different volcanic arcs were successively active during the Mesozoic. A middle to late Jurassic and earliest Cretaceous volcanic arc trended NNE. It was situated east of the Olmos massif and can be traced from the coastal area of southern and central Peru to the Subandean hills of Ecuador. This arc was suddenly replaced in the early Cretaceous by a younger arc situated about 150 km to the west of the Olmos massif, much closer to the present trench. Paleontological and radiometric data [7,24] indicate that the arc jump occurred between the Valanginian and the Aptian about 130 Ma [22].

The Cretaceous volcanics are mainly located in the Lancones synclinorium, between the Amotape-Tahuin Range and the Olmos massif (Figs. 2 and 3). They consist of a basal pre-Albian undated basic complex represented by pillow-lava flows intercalated with hyaloclastic breccias and scarce volcanoclastic strata, intruded by dykes and sills of basaltic to andesitic composition. This basal complex is unconformably overlain by the Albian to Senonian volcanic arc and volcanoclastic series of the Lancones synclinorium [25]. These in turn are intruded by granodioritic plutons not precisely dated but certainly of post-Senonian and pre-Oligocene age [25].

One of the initial aims of the paleomagnetic study was to sample the three Paleozoic massifs to obtain a direct comparison of their stable paleomagnetic directions. No suitable site, however, could be located in either the Olmos massif or the Maranon geanticline, so that the sampling has been conducted only in the Amotape-Tahuin massif and in the different units of the Lancones synclinorium. The location of the sites sampled for the paleomagnetic study is shown schematically in Fig. 3.

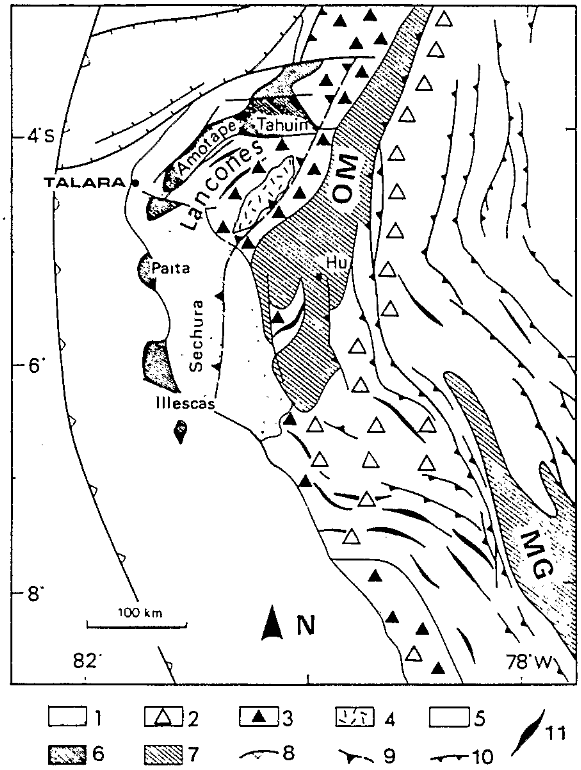

Fig. 2. Main geologic features of the Huancabamba Andes. *1* = Tertiary basins; *2* = Jurassic volcanic arc; *3* = Cretaceous volcanic arc; *4* = Pre-Albian basic complex; *5* = Meso-Cenozoic undifferenciated series; *6* = Paleozoic units of the Amotape-Tahuin coastal range; *7* = Precambrian/Paleozoic basement (*OM*: Olmos massif; *MG*: Maranon geanticline); *8* = Peru Trench; *9* = hypothetical suture; *10* = main thrusts; *11* = axes of major folds. *Hu* = Huancabamba.

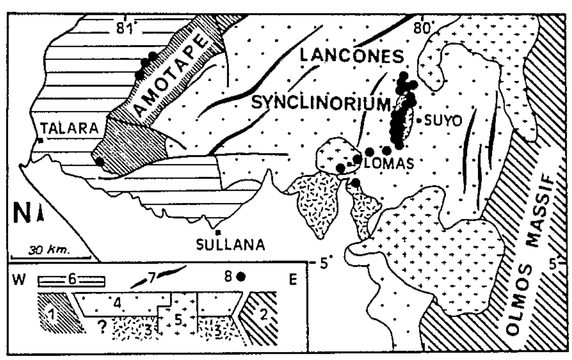

Fig. 3. Map showing the location of the paleomagnetic sites. *1* = Paleozoic series of the Amotape Range; *2* = Paleozoic series of the Olmos massif (Occidental cordillera); *3* = Pre-Albian basic complex; *4* = Cretaceous volcanic and sedimentary series of the Lancones synclinorium; *5* = post-Cretaceous intrusives; *6* = Cenozoic marine sediments of the Talara basin; *7* = major folds; *8* = sites of sampling.

Careful attention was paid in the field to the tectonic setting of the sampled sites since it is necessary to restore the formations to their original horizontal position for the correct interpretation of the paleomagnetic results. Some volcanic formations contained interbedded sediments that yielded precise bedding corrections. In others, less reliable criteria were used, such as the attitude of pillow-lava paleoslopes or columnar jointing in massive flows and sills. For all these sites typical tilts were of the order of 15–20°. Only the sites sampled in the granodioritic plutons were devoid of bedding plane indications, and we have assumed that these post-tectonic intrusions have not been significantly tilted.

The cores were obtained with a portable drilling equipment. The corer is a 25-mm barrel with a sintered diamond cutting edge and water was used as a coolant. At each site a minimum of ten cores were drilled and each core was independently oriented with a special device using both a magnetic and a sun compass.

A total of 300 cores were obtained from 26 sites in the different units of the synclinorium. These include: 15 sites from the pillow lava basalts and associated basic to andesitic flows, fine grained breccias, sills and dykes of the basic pre-Albian complex in the Suyo area; 5 sites from Albian sediments, sills, and associated flows at the base of the volcanic and volcanoclastic series, north of Suyo; 4 sites from Albian to Senonian andesitic agglomerates, sills and dykes interbedded in the Lancones series; 2 sites situated in the post-Senonian to Upper Eocene granodiorites near the village of Las Lomas. Four sites also were obtained in the tilted but undeformed Carboniferous siltstones of the Amotape range.

3. Results

3.1. General magnetic properties

In order to identify the magnetic carriers the isothermal remanent magnetisation (IRM) acquisition in fields up to 1.6 T and subsequent AF demagnetization of the saturation IRM (SIRM) were studied for at least one sample per site. In addition, Curie balance experiments were performed on samples from the different sites drilled in the pillow lava units. The results show that the IRM saturates in fields of 0.15–0.2 T and that the median AF destructive field of the SIRM is always lower than 3 mT. The Curie balance experiments (Fig. 4) indicate the presence of a single magnetic phase with a Curie temperature of 580°. Thus all the results are consistent with a magnetic mineralogy dominated by magnetite.

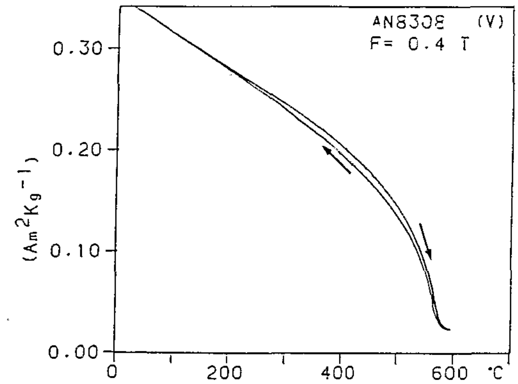

Fig. 4. Thermomagnetic behaviour of pillow-lavas from the Lancones substratum indicating that the magnetization is carried by magnetite. Arrows indicate heating and cooling curves.

Measurements of remanent magnetization were made using either a spinner magnetometer or a LETI 3-axis cryogenic magnetometer, depending on the intensity of the samples. The highest magnetization intensities are those of the pillow basalts of the lowermost units, which range from 0.5 to 15 A/m, somewhat lower than those usually associated with submarine basalts dredged on oceanic sea floor. Much lower NRM, of the order of 2×10^{-4} A/m are observed in the sedimentary paleozoic units from the Amotape-Tahuin Range. In this case we have used the double precision measuring procedure of Vandenberg [26], which involves four independent measurements of each sample in connection with the cryogenic magnetometer.

Both thermal and AF stepwise demagnetizations were used. Although both methods isolated the same stable component of magnetization for samples of the same core, the AF method sometimes failed to decrease RM intensity to values lower than 10–15% of the NRM. The thermal method, on the contrary, always yielded very consistent results and was used routinely.

All samples were stepwise demagnetized with 12–15 steps between room temperature and the limit of reproducible results, which ranges be-

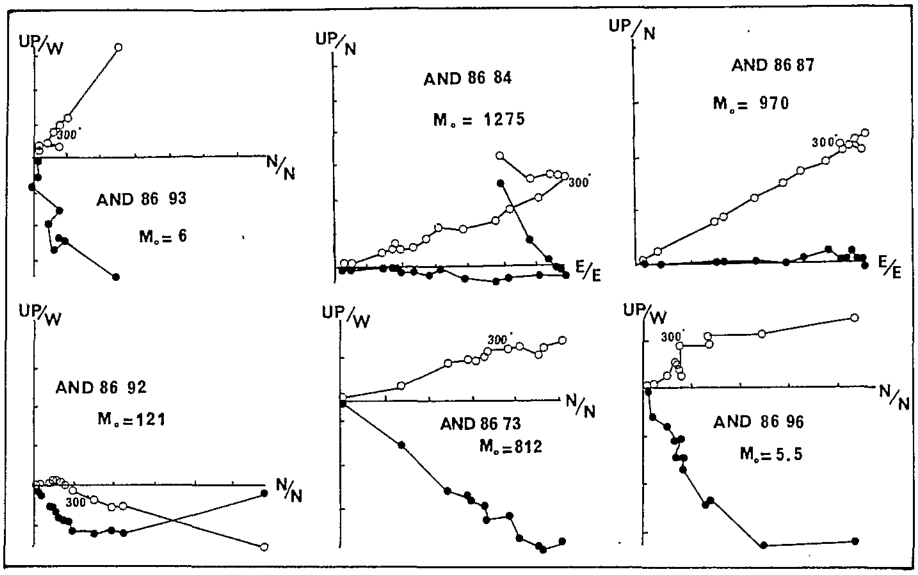

Fig. 5. Typical thermal demagnetization diagrams from the sampled formations. The 300 ° C step is indicated on each diagram.

tween 450 ° and 580 °. At each step the low field magnetic susceptibility was measured for volcanic and sedimentary samples. The maximum changes observed over the entire temperature interval were of the order of a factor of two. This indicates that the magnetic carriers have not changed drastically during the thermal treatment.

3.2. *Paleomagnetic results*

In general the rocks yielded reliable paleomagnetic results. Stable and consistent primary paleomagnetic directions were isolated after heating at 200–250 ° C, sometimes less, and were precisely determined for most of sites using orthogonal diagrams, some of which are shown in Fig. 5. As an exception three sites sampled in the dykes and sills of the Suyo area are characterized by an unreasonably high within-site scatter, although single samples present perfectly linear demagnetization diagrams. This was also observed in a site sampled in volcanic breccia, in spite of the fact that these formations have clearly been deposited at high temperature, and in one of the two sites sampled in the granitic intrusion. We have chosen to reject these highly scattered sites (K < 10). On this basis 5 sites were rejected.

The results obtained from the sites of Cretaceous or post-Cretaceous age from the Lancones

TABLE 1

Paleomagnetic results from the Pennsylvanian formations of the Amotape-Tahuin Range

Site	n	Before bedding correction		After bedding correction		k	α_{95} (°)
		D (°)	I (°)	D (°)	I (°)		
AND8676A	14	277.0	80.0	237.0	58.7	32	6.6
AND8676B	9	284.0	70.0	273.5	41.0	18	10.8
AND8612B	10	332.0	72.0	249.5	66.6	21	9.7
AND8619	8	273.0	63.6	259.0	32.2	50	7.0

Mean value (after bedding correction):

$N = 4/4$; $D = 257°$, $I = 50.3°$; $K = 19.2$ $\alpha_{95} = 15.9°$

Concordance/discordance statistics (from [4 and 28])

Substratum: $R \pm \Delta R = 108 \pm 21°$ $F \pm \Delta F = 26 \pm 19°$

TABLE 2

Paleomagnetic results from the substratum and the volcanic formations of the Lancones Basin

Site	n	Before bedding correction		After bedding correction		k	α_{95} (°)
		D (°)	I (°)	D (°)	I (°)		
Substratum							
AND8678	10	97.4	0.8	98.8	−11.3	28	8.4
AND8679	10	98.4	1.7	99.7	−11.5	13	13.7
AND8680	7	89.7	5.2	90.2	−9.0	12	15.3
AND8681	9	93.6	−23.0	89.7	−44.3	25	10.4
AND8682	9	100.0	−36.2	100.0	−36.2	37	7.5
AND8683	10	79.3	−12.0	78.0	−23.0	43	6.8
AND8684	13	85.5	−4.7	86.5	−3.2	51	5.0
AND8685	10	78.0	0.8	79.0	5.2	115	4.0
AND8686	10	91.3	−0.2	91.3	−0.2	20	9.8
AND8687	9	91.3	−2.6	91.3	−2.6	48	6.7
AND8688	5	81.6	5.8	81.6	5.8	216	5.2
AND8689	5	99.2	−17.5	99.2	−17.5	76	8.8
				Mean value (after bedding correction):			
				$N=12/12$; $D=90.3°$, $I=-12.3°$; $K=21.8$; $\alpha_{95}=8.6°$			
Volcanic formations							
AND8690	13	49.7	−18.9	51.0	−10.2	268	2.4
AND8691	7	49.5	−26.5	24.8	−35.5	43	8.0
AND8692	11	52.0	−11.0	52.0	−11.0	19	9.0
AND8693	9	50.4	−29.3	62.9	−24.1	28	8.0
AND8694A	7	70.7	7.2	69.5	9.9	10.1	16.5
AND8694B	7	62.2	−24.4	69.2	−19.5	27	10.2
AND8695	11	56.0	−22.5	61.0	−10.1	143	3.0
AND8696	7	71.6	−16.0	67.9	−21.0	108	5.1
AND8697	10	66.0	−25.0	66.0	−25.0	98	4.5
				Mean value (after bedding correction):			
				$N=8/9$; $D=58.9°$, $I=-16.7°$; $K=36.3$, $\alpha_{95}=8.2°$			
Intrusive formation							
AND8673	12	37.7	−19.1	37.7	−19.1	526	1.0

Concordance/discordance statistics (from [4,28]):
Substratum: $R \pm \Delta R = 93.4 \pm 7.3°$ $F \pm \Delta F = -7.0 \pm 9.6°$
Volcanic formations: $R \pm \Delta R = 62.0 \pm 7.2°$ $F \pm \Delta F = -11.4 \pm 9.6°$

synclinorium and those from the sites of Paleozoic age in the Amotape range are described separately below:

Paleomagnetic results from the Amotape-Tahuin Range. The results obtained from the Pennsylvanian formations in the Amotape-Tahuin Range are reported in Table 1. Despite the very weak magnetization of all the samples, the four studied sites are characterized by reasonably grouped paleomagnetic directions ($N=4/4$, $D=257°$, $I=50.3°$, $k=19.2$, $\alpha_{95}=15.9°$, after bedding correction). Because the sites have similar bedding plane attitudes it was unfortunately not possible to perform a fold test. However, the very high value of the inclination observed before bedding correction ($\sim 75°$) can hardly be related to an overprint of the remanent magnetization since the deposition of the sediments. For this reason we interpret the result as a primary, rotated reverse paleomagnetic direction.

Paleomagnetic results from the Lancones synclinorium. The results obtained from 21 reliable

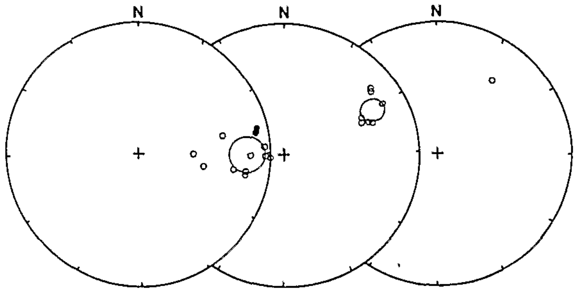

Fig. 6. Stereographic projection of the mean directions of paleomagnetic vectors for the Lancones synclinorium formations. Open circles correspond to upper-hemisphere projections. Full circles correspond to lower-hemisphere projections. Big circles correspond to the 95% confidence area about the mean. A. Basic substratum of the Lancones synclinorium. B. Post-Cretaceous granodioritic pluton of the Lomas area.

sites in the Lancones synclinorium are reported in Table 2, and also represented on the stereograms of Fig. 6. It can be seen from the table that the mean paleomagnetic direction obtained, after bedding correction, from the sites sampled in the pre-Albian basement ($N = 12/12$, $D = 90.3°$, $I = -12.3°$, $K = 21.8$, $\alpha_{95} = 8.6°$) is significantly different from that obtained for Albian to Senonian volcanics above the unconformity ($N = 8/9$, $D = 58.9°$, $I = -16.7°$, $K = 36.3$, $\alpha_{95} = 8.2°$ after bedding correction).

Unfortunately, because some of the sites are virtually horizontal and all the others never tilted more than 15–20°, no fold test could be performed, for either the pre-Albian basement or the Albian to Senonian volcanics. As an exception, at site AND86 91, which is a sill, a bedding plane tilting 30° was measured on sedimentary beds all around. Using this value, and thus assuming that the sill was emplaced before the tilt, the paleomagnetic direction from this site significantly deviates from the other results while a good consistency is observed if no bedding correction is applied (Table 2). This suggests that tilting has occurred before the emplacement of the sill, which seems unreasonable from a geologic point of view, because no large post-tectonic hypovolcanic episodes have been documented to date. The result from this site is thus not fully understood at present and has been rejected from the final statistics.

Finally a trustworthy paleomagnetic direction ($D = 37.7°$, $I = -19.1°$) was obtained from one of the two sites sampled in the granitic intrusion.

4. Discussion

For the interpretation of the paleomagnetic data, the paleomagnetic directions recovered from the sampled lithologies must be compared with those from coeval formations of stable South America (SOAM). Unfortunately, the apparent polar wandering (APW) path for SOAM is still somewhat ill defined, both for the upper Carboniferous and the Cretaceous, so that some uncertainties might exist for a very precise geodynamical interpretation of our results.

4.1. Upper Carboniferous results

To interpret the Late Carboniferous results we have used the APW curve for South America given by Irving and Irving [27]. The sampled sediments have been assigned biostratigraphically [28] to the Pennsylvanian period, about 315–290 Ma. We have used the 300 Ma reference pole obtained after smoothing with a 30 Ma window as our Pennsylvanian reference pole.

In Table 1 the results are analyzed in terms of concordance/discordance, where the rotation R and the flattening F parameters were calculated by the equations given by Beck [4] and modified by Demarest [29].

The observed direction differs from the expected one by a very significant $(108 \pm 21)°$ clockwise rotation and by a significant $(25.8 \pm 19)°$ flattening, implying a northward transport of some 17° in latitude of the Amotape Tahuin Range with respect to stable South America.

It must be stressed that the evidence for the northward drift does not result from the particular choice of the 300 Ma pole; 290 or even 280 poles give the same result. However, about half of the relatively large errors on R and F arise from the accuracy of the pole and half from the observed α_{95}. Thus, refinements of the South American APW path, and not only additional sampling of the region, would certainly contribute to a more accurate description of the geodynamical evolution of the Amotape-Tahuin block

4.2. Cretaceous results

A peculiar characteristic of the Cretaceous poles from SOAM is that they are not distributed uniformly but rather along a highly elongate pattern, which, if real, would imply that the pole swung back and forth several times during the Cretaceous. The total spread of the "streak" covers over 30°, making the choice of a particular Cretaceous pole quite difficult.

Part of this streak has, however, been questioned by Ernesto [30] on the basis of paleomagnetic results from the Mesozoic volcanic rocks from the Serra Geral Formation in Brasil. Beck [14] also recently analyzed possible explanations for the streak (genuine apparent polar wander, intra-cratonal deformation or a geomagnetic explanation) and concluded that they do not readily account for the elongated pattern. Consequently, he has assumed a single Cretaceous pole for SOAM, not significantly different from the Early Cretaceous pole of Ernesto.

The assumption of a unique pole for the entire Cretaceous might appear to be a rather crude approximation, especially when, as in the Lancones basin, results from Cretaceous formations of different ages have to be compared. Indeed, a difference between the Early and Late Cretaceous pole positions, essentially affecting the expected inclinations in northern Peru, is documented by Ernesto's results [30]. However, we have used the pole given by Beck [14], because no precise radiometric dates are available for the studied formations, only their relative stratigraphic position is precisely known. Thus a choice of a particular pole for each formation would be somewhat arbitrary.

As for the Paleozoic, the Cretaceous data have been analyzed in Table 2 in terms of concordance/discordance using the rotation R and flattening F parameters [4,29]. For both the pre-Albian basement and the volcanic units the flattening parameters are not significantly different from zero, showing that no significant latitudinal movement of these units has occurred since their formation. The rotation parameters are on the contrary different from zero and from each other: the pre-Albian basement of the Lancones synclinorium has undergone a large, 94°, clockwise rotation significantly different from the 63° clockwise rotation of the volcanic formations situated above the unconformity. Again, essentially identical results would have been obtained using the 110–120 Ma and 90 Ma poles given by Irving and Irving [27], which would be our best choice for the pre-Albian substratum and the volcanic formations respectively. Therefore our interpretation is not seriously biased by a particular choice of the reference curve.

Finally, the 35° clockwise rotation of the post-Cretaceous intrusion (with no northward displacement) needs confirmation from other coeval sites, before any conclusion can be derived from it.

The paleomagnetic results from the Paleozoic and Cretaceous units of northwestern Peru indicate a geodynamical history different from that of stable South America. When considered together with the previous geological observations, they are consistent with the hypothesis of the accretion of an Amotape-Tahuin allochthonous continental terrane to the active Peruvian margin in the Early Cretaceous, after a moderate northward displacement of this block with respect to the stable craton. As a direct consequence of this collision, we assume that the late Jurassic/Early Cretaceous subduction zone died out and was replaced by a late Cretaceous subduction zone situated ~150 km more to the west, to which the Albian to late Cretaceous Lancones arc is associated (Fig. 7).

The results of a recent gravity survey [23] in this area also support this hypothesis. A strong (100 mgal) positive Bouger anomaly over the entire Amotape range and the Lancones synclinorium has been interpreted as evidence for

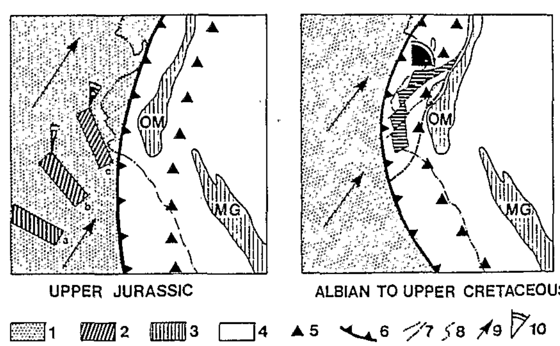

Fig. 7. Hypothetical model for the geodynamic evolution of the north Peruvian margin during Upper Jurassic and Cretaceous times. *1* = oceanic type crust; *2* = Amotape-Tahuin continental block; *3* = actual outcrops of Paleozoic rocks (*OM*: Olmos massif; *MG*: Maranon geanticline); *4* = continental South-America; *5* = Volcanic arc; *6* = Trench, *7* = faults and suture; *8* = actual coastline; *9* = hypothetical convergence direction; *10* = values of clockwise rotations. *a*, *b*, *c*: Successive hypothetical positions of the Amotape-Tahuin continental block before accretion.

dense oceanic basement underlying the entire area. In our interpretation the lowermost basic units of the Lancones synclinorium are considered to be part of an island arc caught in the suture zone between the Amoptape-Tahuin block and continental SOAM.

The difference in the rotation parameters between the basic complex and the overlying volcanic units indicates that about 25–30° of the total rotation of the Lancones area are related to pre- or syn-accretion processes (Fig. 7), as has also been documented in other studies elsewhere [4,51,32]. As no northward drift has been documented for the Cretaceous units, the 60° rotation of these units has occured in situ. Coherent block rotations about a vertical axis have been documented by paleomagnetic studies in many areas of tectonic activity [2,5,32–36] and appear to be a widespread characteristic of lithospheric deformation in response to shear.

The results obtained here thus suggest that some distributed dextral shear must also exist in this zone between the Nazca plate, the Amotape-Tahuin block and stable South America. The minimum amount of shear necessary to account for the clockwise rotation of the Amotape Tahuin Range can be roughly estimated from the amount of the rotation itself using a block model of distributed deformation by faulting [33]. Assuming for the shear zone a width of 150 km, i.e. the amplitude of the Jurassic to Cretaceous arc jump, a 60° rotation implies a minimum northward displacement along the Amotape block since the Cretaceous of the order of 250 km. Such a displacement is undetectable with paleomagnetic methods and thus not inconsistent with the observed results. However, one would expect such a shear to be associated with strike-slip faulting, but none has yet been documented in the field. So far, the geological evidences of Cretaceous and post-Cretaceous active faulting along the Amotape range have been considered as purely extensional features. Further structural studies are thus needed in this area and special attention should be paid to the faulted edges of the Amotape-Tahuin Paleozoic range where strongly dipping fold axes could be related to strike-slip faulting. The significance of the long NE-SW trending parallel lineaments crossing southern Ecuador and northwestern Peru [37] should also be checked in the field.

5. Conclusions

The absence of notable Mesozoic northward displacement is a common feature of the paleomagnetic data available for the Central and Southern Andes which all document significant rotations without any compelling evidence for large latitudinal displacement or accretion processes during the Mesozoic and the Tertiary. Oroclinal bending has thus been inferred to explain the observed deviated paleomagnetic directions [19,20,21]. Recently, however, Beck [4] has questioned the oroclinal interpretation, pointing out that shear regimes due to oblique convergence could act as major factors in the Andean building processes. For instance, dextral and sinistral shear respectively south and north of the Arica bend (Fig. 1) could arise as a result of the angular relation between the convergence and the trend of the margin. If this hypothesis is confirmed by future work, the lithospheric processes in the Central Andes would appear to a certain extent similar to those observed in North America [4,32]. Nevertheless, the absence of large latitudinal displacements and accretion processes is a striking difference between the Central Andes and the North American Cordilleras.

On the other hand, the general pattern of the Northern Andes is comparable to the one observed in western North America, with accretion and coastwise transport of allochthonous terranes and/or of forearc slivers. This is evidenced by paleomagnetic results on the Bonaire block of Venezuela and northern Colombia [14,37–40], by structural studies in the Central Cordillera of Colombia [8.9], and by geological, gravimetric and paleomagnetic data on the Western Cordillera and the coastal part of Ecuador [7–12].

The different tectonic regimes observed along the Andean margin are certainly a consequence of the changes in the direction of convergence between the South American and Nazca plates [14]. According to recent plate tectonic models [41,42] the convergence has been much more oblique in the Northern Andes than in the Central ones, during the Late Cretaceous and the Paleocene. This is due to the different trends of the margin in these two segments of the Cordillera. In the Northern Andes the strongly oblique subduction has provided the dextral shear regime responsible for terrane transport and accretion. Parts of these terranes have certainly been truncated along longitudinal wrench faults with consequent clockwise rotations.

The paleomagnetic results from northern Peru yield new evidence for a possible pre-Albian (Mesozoic) northward transport, for an Early Cretaceous terrane accretion and for in situ post-accretion clockwise rotations (Fig. 7), suggesting that the geodynamical evolution of Northern Peru is more closely related to the processes observed in the Northern Andes than to those classically assumed for the Peruvian Andes. As discussed above, they also infer the existence of strike-slip faulting in the Huancabamba Andes which is presently poorly documented. Finally, they show that careful additional structural and paleomagnetic studies are still needed to investigate the precise lithospheric processes ocurring along the Northern Andes.

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