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PALEOMAGNETISM OF THE SUBANDEAN CARBONIFEROUS ("GONDWANA") SEQUENCE IN BOLIVIA: TECTONIC IMPLICATIONS

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ABSTRACT

The Carboniferous sequence cropping out along the Subandean belt of Bolivia comprises, from bottom to top, the Itácua, Tupambi, Tarija, Chorro and Taiguati Formations (Machareti Group) and the Escarpment and San Telmo Formations (Mandiyuti Group). These units make up an entirely clastic sequence of colored sandstones, mudstones, shales, argillites and diamictites of marine to glacial-marine origin. The ages of these strata are only approximately established, mostly on palynological and in part on invertebrate evidence, as belonging to the Early to Late Carboniferous. Sediments in the Subandean belt are tectonically deformed by parallel holomorphic folding. In the southern Subandean region a sequence of more than 1,000 meters, which includes the Tupambi, Itacuami, Tarija, Chorro, Taiguati, Escarpment and San Telmo Formations, was sampled for paleomagnetic analysis. In the central Subandean area, samples from the Itácua, Tarija and Taiguati Formations were also collected. The characteristic directions of magnetic remanence found in the sediments from the southern Subandean area are significantly different from those of coeval formations of stable South America indicating a 36° ± 20° clockwise rotation. No rotation was evident for the central Subandean area. It is proposed that the southern rotated block has its northern limit at about 20°S, where the axes of tectonic features like thrust or normal faults change abruptly from NNE in the south to NNW in the north.

INTRODUCTION

The Andes belt consists of linear chains (Cordilleras) trending parallel to the Pacific coast. The present morphology of the Andes has been associated with the orogeny which began in the Late Cretaceous as a consequence of the westward displacement of the South American platform, causing the subduction of the Pacific oceanic crust under the continental margin (James, 1971; Frutos, 1981; Coira et al., 1982).

At the Chile-Peru border the Cordilleras show an abrupt change in trend from near north-south to NW-SE,with the deflection axis extending from Arica (Chile) to Santa Cruz (Bolivia). The present shape of the Andes has been attributed to an orocline (Carey, 1955) and involves, in the Western Cordillera, counterclockwise rotations in Peru (e.g. Tsunakawa et al., 1987; Heki et al., 1984 and 1985) and clockwise rotations in Chile (Turner et al., 1984; Palmer et al., 1980), although other explanations for these rotations have been given by Beck (1988).

Paleomagnetic data from the Carboniferous Taiguati Formation (Creer, 1970), which crops out near Santa Cruz (at the "elbow" of that deflection) in the Central Subandean area, is in accordance with other Carboniferous poles of the stable part of South America and do not indicate any rotation of the area. However, this pole is based only on results of natural remanent magnetization (NRM), which are not acceptable, based on modern reliability criteria. In spite of this, the Taiguati pole is still being used as a reference pole due to the scarcity of Carboniferous paleomagnetic poles for South America.

We report in this paper some new data from the Carboniferous sedimentary sequence of the Subandean belt in Bolivia. Data come from both the Central and Southern Subandean areas.

THE CARBONIFEROUS SUBANDEAN SEQUENCE

The Paleozoic sequence crops out along the Subandean belt from the Peru border down to northern Argentina (Figure 1). Stratigraphic details are provided by Helwig (1972), Reyes (1972), Ayaviri (1972) and Castaños and Rodrigo (1980), among others.

The Carboniferous sequence comprises, from bottom to top, the Itácua, Tupambi, Tarija, Chorro and Taiguati formations (Machareti Group) and the Escarpment and San Telmo formations (Mandiyuti Group). These units make up an entirely clastic sequence of colored sandstones, mudstones, shales, argillites and diamictites of marine to glacial-marine origin. Its maximum thickness reaches 2,000m in the southern region, 1,600m in the Santa Cruz area and 600m in the northern region (Ayaviri, 1972).

The deposition of Carboniferous ("Gondwana") sediments was preceded by a period of erosion, as demonstrated by their disconformable contact with the underlying marine Devonian strata of various ages and facies (Ahlfeld and Branisa, 1960).

The ages of the Machareti and Mandiyuti sediments are only approximately established, mostly on palynological and in part on invertebrate evidence, as belonging to the Early to Late Carboniferous. Salinas et al. (1978) use palynological analysis to indicate a Visean age for the Itacua and Tupambi formations and a Namurian age for the Itacuami Formation. Based on the age review presented by Castaños and Rodrigo (1980) the Itácua and Tupambi formations are of Visean age, the Taiguati Formation is Westphalian and the San Telmo Formation can be attributed to the Carboniferous-Permian boundary.

EXPERIMENTAL PROCEDURES AND RESULTS

One hundred and twenty oriented block samples were collected mainly from exposures along the Pilcomayo River (Figure 1), in the Southern Subandean region. Near Villa Montes (63.46° W 21.26° S), a sequence of about 1000m was sampled which included, from bottom to top, the Tupambi (11 samples), Itacuami (5 samples), Chorro (21 samples), Taiguati(12 samples), Escarpment (23 samples; two were destroyed during transportation) and San Telmo (12 samples) formations. Near Bereti (63.59° W 21.25° S), two samples of the Taiguati Formation and 10 samples of the Tarija Formation were collected in the Tacuarandi homocline and 8 samples of the San Telmo Formation were collected in the Rio Salado anticline. In the central Subandean region, the Taiguati (3 samples), Tarija (5 samples) and Itácua formations (12 samples) were also sampled, along the Santa Cruz - Cochabamba (63.46°W 18.00°S) road. Whenever possible samples were oriented by both sun and magnetic compasses.

Samples were cored in the laboratory and prepared as small cylindrical specimens (one inch in diameter and height). Remanent magnetizations were measured in a Digico spinner and in a Molspin (Minispin) magnetometer. Samples were submitted to both alternating field and thermal demagnetizations, which were performed in steps of 5mT and 50°C respectively.

Almost all analysed samples possessed very stable magnetizations with no significant changes in both intensity and direction during the AF cleaning up to 80mT. The intensity of magnetization decayed to nearly zero at temperatures above 670°C while directions did not move considerably (Figure 2a). The Zijderveld (1967) diagrams revealed the presence of only one hard component of magnetization that probably is carried by haematite (red pigment or specularite) as deduced from the high coercivity and unblocking temperatures. It is well known that the natural remanent magnetization (NRM) of red sandstones may lie either in the red pigment, which gives the rocks their distinctive color, or in the black iron oxide particles which are also present, the majority of which are usually haematite (specularite). Collinson (1966) investigated the magnetic properties of the Taiguati Formation in samples collected near Santa Cruz and concluded that the natural remanence is originated in both the pigment and specularite, the red pigment being the dominant form of ferric oxide present in these samples although there was evidence that some of the pigment does not carry a permanent magnetization. In a later paper Collinson (1974) concluded that in the Taiguati samples, as in other red sandstones, the specularite possessed the hardest magnetization.

A chemical demagnetization (Figure 2c) was performed in the Tupambi samples in order to destroy the red pigment and try to isolate the remanence carried by specularite only, the less soluble haematite form. The chemical treatment consisted of immersing the samples in a 8N hydrochloric acid solution for a given time, washing in distilled water, drying in free air, measuring the remanence and reimmersing in clean acid. To accelerate the leaching rate the acid was kept at 75°C and samples were prepared in the way described by Henry (1979), with two horizontal slots, to facilitate acid penetration. Runs were at intervals of 3, 5, 12, 24 hours, with up to 145 hours of immersion (Figure 3). After 10 or 15 hours the magnetization intensity was reduced to about 10% of the NRM value. Directions changed slightly but after 75 hours of immersion a high between-sample scatter was produced. Thus the chemical demagnetization did not reveal any other characteristic remanent magnetization for the Tupambi samples.

The gray diamictites of the Tarija Formation collected near Bereti were magnetically unstable and gave no consistent results. The Taiguati, Tarija and Itacua samples from the Santa Cruz-Cochabamba road were severely weathered. The AF cleaning did not produce a significant intensity decay but temperatures between 300° C and 400° C were sufficient to reduce the intensities considerably. This behaviour may be an indication of the presence of goethite as a consequence of weathering. However, a stable remanence persisted up to 670°C (Figure 2b).

The paleomagnetic data are given in Tables 1 to 3. Results correspond to the average of three or four specimens of each block after thermal cleaning at temperatures not less than 400°C. The majority of the samples had very stable remanence and low initial between-specimen scatter, so that after the thermal cleaning the direction grouping did not change meaningfully. Another group of samples, however, showed "cleaned" directions better grouped than the NRM directions, whereas a third group of samples with very scattered NRM directions did not improve considerably after thermal cleaning. In this case the most discrepant specimens were rejected for sample mean calculations.

Results from the San Telmo and Taiguati formations allowed the application of the fold test (McElhinny, 1964) since their samples came from more than one sampling area. After the structural tilt correction (Figure 3) the two groups of San Telmo samples came closer and 95% confidence circles of the mean magnetizations superposed. The Taiguati directions are also better grouped after tilt correction, thus leading to the conclusion that the characteristic magnetization of these samples was acquired before folding. This statement is also valid for the other samples since their magnetic properties are essentially the same.

All samples from the southern Subandean section are reversely magnetized, with the exceptions of three samples from the Escarpment Formation, both red (BL-22 and BL-31) and gray (BL-27 to BL-30) sandstones, and one red diamictite block from the Tupambi Formation. On the contrary, all samples collected in the central Subandean section are normally magnetized. However, these samples are more weathered than the ones from the southern Subandean region. Creer (1970) reported both normal and reversed polarity remanences for his collection of samples from the central Subandean area.

ANALYSIS OF PALEOMAGNETIC RESULTS

The directional data for the Villa Montes sequence is displayed graphically in Figure 4. Declination and inclination angles are plotted according to the relative stratigraphic position of the blocks. The declination curve describes large loops, some of which may be related to excursions or reversals, as indicated by the negative inclinations, although these angles are too shallow to correspond to complete reversals; they are more compatible with transitional fields. Large variations in declination are also produced when the inclination angle is steep, as in the Taiguati and Tupambi formations. However, these shortwave variations differ from the large amplitude longwave variations that can be noticed, for example, in the Tupambi to Taiguati data. The declination changes are followed by a systematic lowering in inclination to the Itacuami level, and then increasing again to the initial values in the upper Chorro and Taiguati formations. Considering the long time interval involved, this cyclic variation cannot be simply associated with the secular variation of the geomagnetic field and should actually reflect the plate displacement. However, the Itacuami samples are mostly friable brown sandstones which seem considerably weathered and may have had their original magnetization replaced by a younger remanence.

Mean magnetization directions and paleomagnetic poles for each formation (Table 4) were calculated giving unit weight to each block sample. Samples with circles of confidence greater than 30° and those far (>40°) from the main distribution were rejected. Due to the continuous magnetic record throughout the Villa Montes sequence, data were grouped according to magnetic limits rather than stratigraphic limits only, in order to calculate the means. In this way the Taiguati mean direction in Table 4 incorporates also the data from the base of the Escarpment Formation and the top of Chorro Formation (samples BL-34 to BL-60). The Itacuami samples were grouped with the remaining Chorro samples. Both the Villa Montes and Bereti samples of the San Telmo and Taiguati Formations were included in the means.

The average of the three Taiguati PGVs (not defining a true paleomagnetic pole) is included in Table 4 but will not be considered for further interpretation due to the high dispersion (α_{95}>50).

The obtained paleomagnetic poles (open symbols) are plotted in Figure 5 along with other existing Carboniferous poles for South America (full symbols) including the two Taiguati poles (TG1 and TG2) obtained by Creer (1970) from samples collected along the Santa Cruz-Cochabamba road. These last poles refer to the NRM only but can be compared with the new poles because the "cleaned" remanences obtained in this paper do not differ too much from the NRMs.

Creer´s TG1 and TG2 poles refer respectively to reversed and normal polarities only. Samples TG2 come from an outcrop which is about 950m stratigraphycally lower than TG1. Geologic descriptions of the Carboniferous sequence in the area (e.g. Helwig, 1972) indicate a 220m thickness for the Taiguati Formation, and 960m for the whole Carboniferous sequence (in Samaipata). Thus it is possible that the low latitude paleomagnetic pole TG2 refers actually to an older (Devonian ?) formation.

The new Carboniferous poles obtained in this paper (cf. Fig. 5) do not agree with the distribution of the Carboniferous poles from stable areas of South America. They are more consistent with data of younger ages taking into account the apparent polar wander path (APWP) proposed by Irving and Irving (1982). In fact it is difficult to ascertain the age of the remanent magnetization in red beds although, in this case, the red pigmentation was probably acquired soon after deposition, as evidenced by the Taiguati pole (TG1), which coincides with other poles of the same age. The poles TG and TU obtained in this paper, however, are significantly different from pole TG1 and do not fit the younger portion of the APWP. They seem completely anomalous.

TECTONIC IMPLICATIONS

In order to interpret these anomalous results we have used the 300Ma La Colina Formation paleomagnetic pole (C4 in Fig. 5) given by Sinito et al. (1979) as a reference. Pole C4 is derived from characteristic remanent magnetizations which seem best identified by means of AF, thermal and chemical demagnetizations. As a consequence C4 differs slightly from the other upper Carboniferous poles.

Pole C4 would produce in the Villa Montes region a declination and inclination of D=131.4° and I=65.7° . The observed direction differs from the expected one by a (R=36° ± 20°) clockwise rotation and a negligible (F=1°±6°) flattening, where the parameters R and F were calculated by the equations given by Beck (1980) and the confidence limits according to McWilliams (1984). This result implies that the observed and the expected directions will be statistically indistinguishable after the observed group is rotated counterclockwise at least 16°, but less than 56°. In fact, the tectonic features in the Subandean belt (Figure 1) change direction abruptly around latitude 20° S. The mean angle they form is about 20° , suggesting a clockwise rotation of the southern Subandean region. A 25° counterclockwise correction of the southern Subandean paleomagnetic poles will bring them closer to the other Carboniferous poles for South America, reinforcing the idea of an "in situ" rotation of the southern block.

The paleomagnetic data from the central Subandean area do not show evidence of tectonic rotations. If the Bolivian orocline hypothesis still holds, then the major amount of rotation might have occurred to the north of the Arica-Santa Cruz deflection. However, available paleomagnetic data indicate that a considerable amount of rotation (counterclockwise to the north and clockwise to the south of the Arica-Santa Cruz deflection) has taken place along the active margin of South America. Although this pattern is consistent with the oroclinal model it can also be explained by small-block "in situ" rotations (Beck, 1988) due to shear arising from the convergent plate interactions. Allenby (1987) proposed a mechanism to explain the Bolivian Orocline which involves the compression of the former Pacific coast region against the resistant Brazilian Shield causing the present bending of the Andes. Even if the oroclinal hypothesis is viewed with doubt, the above mechanism could be applied to explain the "in situ" rotation of blocks, like the one proposed here for the southern Subandean block.

PALEOMAGNETIC AGES AND THE SOUTH AMERICAN APWP

Although there is some uncertainty in the calculated amount of tectonic rotation affecting the southern Subandean poles, some inferences about the relative ages of these poles can be made by comparing them with poles from stable South America. Figure 6 shows that poles TG (combinig Taiguati and Chorro Formations) and TU (Tupambi Formation) are statistically coincident leading to the conclusion that these formations are of the same age (Westphalian, based on the age of pole C4 from La Colina Formation, Argentina); consequently, the deposition rates of these sediments were high. Alternatively, the older Tupambi Formation could have acquired its magnetization during the deposition of the Taiguati sediments. The overlying Itacuami Formation (pole TM), a transition between the Tupambi and Chorro formations, seems to have its original magnetization superimposed by a Permo-Carboniferous secondary component.

The San Telmo and Escarpment poles corresponding to the upper part of the Carboniferous sequence are consistent with other Permo-Carboniferous data. These poles, however, tend to be placed to the eastern side of the Permo-Carboniferous group of poles, their circles of confidence interlacing the circle of confidence of pole C8 from the Itararé Subgroup, Paraná Basin. Pascholati (1983) claims that this pole might have been affected by a Cretaceous component of magnetization, but it is also possible that the pole refers to the upper part of the Subgroup (Pascholati, 1980) while poles C6 (Valencio et al., 1975) and C7 (Pascholati and Pacca, 1976), from the same formation could be older. This possibility, along with the new data presented in this paper, suggests that the Permo-Carboniferous pole path for South America could actually be different from previously proposed paths, based on the limited data available till now.

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References cited

Ahlfeld, F. and Branisa, L., 1960. Geologia de Bolivia. Inst. Bol. Petr., La Paz, Bolivia.

Allenby, R.J., 1987. Origin of the Bolivian Andean orocline: a geologic study utilizing Landsat and Shuttle Imagin Radar. Tectonophysics, 142: 137-154.

Ayaviri, A., 1972. El Sitema Carbónico en el Sureste Boliviano. An Acad. Brasil. Ciênc., 44 (supl.): 51-60.

Beck Jr, M.E., 1980. Paleomagnetic record of plate margin tectonic processes along the western edge of North America. J. Geophys. Res., 85: 7115-7131.

Beck Jr, M.E., 1988. Analysis of Late Jurassic-Recent paleomagnetic data from active plate margins of South America. J. South American Earth Sci., 1: 39-52.

Carey, S.W., 1955. The orocline concept in geotectonics. Proc. R. Soc. Tasmania, 89: 255-288.

Castaños, A. and Rodrigo, L.A., 1980. Paleozoico superior de Bolivia. An. Acad. Brasil. Cienc., 52 (4): 851-866.

Coira, B., Davidson, J., Mpodozis, C. and Ramos, R., 1982. Tectonic and magmatic evolution of the Andes of Northern Argentina and Chile. Earth-Sci. Rev., 18: 303-332.

Collinson, D.W., 1966. Magnetic properties of the Taiguati Formation, Bolivia. Geophys. J.R. Astr. Soc., 11: 337-347.

Collinson, D. W., 1974. The role of pigment and specularite in the remanent magnetism of red sandstones. Geophys. J. R. Astr. Soc., 38: 253-264.

Creer, K.M., 1970. A palaeomagnetic survey of South American rock formations. Phil. Trans.Roy Soc. London, A267:457-558.

Embleton, B.J.J., 1970. Nuevos estudios paleomagnéticos del Neopaleozoico (Paganzo II) de la Republica Argentina. Rev. Asoc. Geol. Argentina, XXV: 103-110.

Fisher, R.A., 1953. Dispersion on a sphere. Proc. R. Soc. London, ser. A, 217: 295-305.

Frutos, J., 1981. Andean tectonics as a consequence of sea-floor spreading. Tectonophysics, 72: T21.

Heki, K., Hamano, Y., Kinoshita, H., Taira, A. and Kono, M., 1984. Paleomagnetic study of Cretaceous rocks of Peru, South America: evidence for rotation of the Andes. Tectonophysics, 108: 267-281.

Heki, K., Hamano, Y., Kono, M. and Ui, T., 1985. Palaeomagnetism of Neogene Ocros dyke swarm, the Peruvian Andes: implications for the Bolivian orocline. Geophys. J. R. Astr. Soc., 80: 527-534.

Helwig, J., 1972. Stratigraphy, sedimentation, paleogeography and paleoclimates of Carboniferous ("Gondwana") and Permian of Bolivia. Am. Assoc. Petroleum Geologists Bull., 56: 1008-1033.

Henry, S., 1979. Chemical demagnetization: methods, procedures and applications through vector analysis. Can. J. Earth Sci., 16: 1832-1841.

Irving, E. and Irving, G. A., 1982. Apparent polar wander paths, Carboniferous through Cenozoic and the assembly of Gondwana. Geophys. Surv., 5: 141-188.

James, D. E., 1971. Plate tectonic model for the evolution of the Central Andes. Geol. Soc. Am. Bull., 82: 3325-3346.

McElhinny, M.W., 1964. Statistical significance of the fold test in palaeomagnetism. Geophys. J. R. Astr. Soc., 8: 338-340.

McWilliams, M., 1984. Confidence limits on net tectonic rotation. Geophys. Res. Sett., 1: 825-827.

Mégard, F., Dalmayrac, B., Laubacher, G., Marocco, R., Martinez, C., Paredes, J. and Tomasi, P., 1971. La chaîne Hercynienne au Pérou et en Bolivie. Premiers résultats. Cah. ORSTOM, sér. Géol. III: 5-44.

Palmer, H.C., Hayatsu, A. and MacDonald, W.D., 1980. The Middle Jurassic Camaraca Formation, Arica, Chile: palaeomagnetism, K-Ar age dating and tectonic implications. Geophys. J. R. astr. Soc., 62: 155-172.

Pascholati, E.M., 1980. Estudo paleomagnético do Grupo Itararé na porção sudeste da Bacia do Paraná. M.Sc. thesis, University of Sào Paulo, 121 pp.

Pascholati, E.M., 1983. Possibilidade de interferências termais do magmatismo Juro-Cretácico na análise paleomagnética do Grupo Itararé. An. IV Simpósio Regional de Geologia, São Paulo: 211-222.

Pascholati, E.M. and Pacca, I.G., 1976. Estudo paleomagnético de secções do Sub-Grupo Itararé. An. XXIX Congr. Brasil. Geol., 2: 275-281.

Reyes, F.C., 1972. On the Carboniferous and Permian of Bolivia and Northwestern Argentina. An. Acad. Brasil. Cienc., 44: 261-277.

Roperch, P., Megard, F., Laj, C., Mourier, T., Clube, T.M. and Noblet, C., 1987. Rotated oceanic blocks in Western Ecuador. Geophys. Res. Lett., 14: 558-661.

Salinas, C., Oblitas, J. and Vargas, C., 1978. Exploración del Sistema Carbonífero en la cuenca oriental de Bolivia. Rev. Téc. YPFB, VIII: 5-51.

Sinito, A.M., Valencio, D.A. and Vilas. J.F., 1979. Palaeomagnetism of a sequence of Upper Palaeozoic-Lower Mesozoic red beds from Argentina. Geophys. J.R. Astr. Soc., 58: 237-247.

Thompson, R., 1972. Palaeomagnetic results from the Paganzo Basin of north-west Argentina. Earth Planet. Sci. Lett., 15: 145-156.

Tsunakawa, H., Tanaka, H., Amano, K. and Kono, M., 1987. Paleomagnetic study of late Miocene and early Pliocene rocks from southern Peru, Central Andes. J. Geomag. Geoelectr., 39: 477-486.

Turner, P ., Clemmey, H. and Flint, S., 1984. Palaeomagnetic studies of a Cretaceous molasse sequence in the Central Andes (Coloso Formation, Northern Chile). J. Geol. Soc. London, 141: 869-876.

Valencio, D.A., Rocha-Campos, A.C. and Pacca, I.G., 1975. Paleomagnetism of some sedimentary rocks of the Late Paleozoic Tubarão and Passa Dois Group, from the Paraná Basin, Brazil. Rev. Brasil. Geocienc., 5: 186-197.

Zijderveld, J.D.A., 1967. A.C. demagnetization of rocks: analysis of results. In: D. W. Collinson, K.M. Creer and S.K. Runcorn (eds.), Methods in Palaeomagnetism. Elsevier, Amsterdam: 254-286.

TABLE 1 - Paleomagnetic results for the Villa Montes section (Southern Subandean area)

Formation	Sample Number	n	Directions of Magnetization before and after tilt correction: Dec. (°)	Inc. (°)	Dec. (°)	Inc. (°)	α_{95} (°)	K	Virtual Geomag. Poles: Long. (°E)	Lat. (°N)	dp	dm
San Telmo	BL- 1	4	190.0	52.0	180.1	24.4	2.3	1581	47.4	-69.2	2.5	4.4
	BL- 2	4	211.7	41.4	179.9	28.8	0.8	13905	115.6	-94.1	0.9	4.4
	BL- 3	4	209.4	58.5	161.9	37.1	3.8	579	25.1	-73.1	4.5	6.9
	BL- 4	4	232.5	65.2	157.9	49.4	1.3	4648	356.5	-68.1	1.7	2.1
	BL- 5	4	199.8	37.4	176.6	19.3	7.7	142	99.9	-78.2	8.0	15.1
	BL- 6	4	258.0	70.9	145.7	57.8	1.4	4150	348.5	-55.9	2.1	2.0
	BL- 7	4	206.6	50.1	169.4	31.2	12.0	59	48.5	-79.1	13.4	22.5
	BL- 8	4	227.8	37.9	191.8	36.9	6.1	226	205.1	-79.0	7.1	11.1
	BL- 9	4	225.2	53.4	172.9	42.8	11.9	61	356.4	-82.4	14.7	20.6
	BL-10	4	251.5	71.4	146.5	55.7	6.5	198	351.9	-57.3	9.3	9.6
	BL-11	3	87.3	69.1	108.1	27.8	9.8	159	18.6	-21.9	10.7	18.6
	BL-12	4	209.0	66.2	153.0	40.4	8.1	129	17.3	-65.0	9.8	14.3
Escarpment	BL-13	3	212.7	59.1	163.0	43.6	2.4	2626	8.3	-73.9	3.0	4.1
	BL-14	4	206.8	48.9	171.4	35.0	3.3	780	38.9	-81.7	3.8	6.1
	BL-15	3	210.6	58.6	162.8	42.4	2.0	3957	11.7	-73.8	2.5	3.4
	BL-16	4	196.8	61.8	154.3	38.5	8.6	115	20.8	-66.1	10.2	15.4
	BL-18	3	196.7	53.2	162.4	33.0	4.7	695	34.7	-73.1	5.3	8.7
	BL-19	1	195.5	48.1	166.1	28.9	---	---	48.2	-75.6	---	---
	BL-20	4	186.2	47.6	161.4	24.3	7.3	159	49.3	-70.3	7.8	14.1
	BL-21	3	213.8	66.4	153.9	47.2	3.5	1272	4.6	-65.3	4.5	5.8
	BL-22	2	349.4	-46.8	332.0	-17.0	2.9	7463	47.3	-60.2	3.0	5.7
	BL-23	4	238.5	54.0	178.8	54.5	20.7	21	300.6	-76.2	29.2	31.1
	BL-25	3	220.3	61.1	162.8	47.8	3.5	1208	356.8	-72.7	4.5	5.7
	BL-26	4	197.7	68.6	147.2	42.7	5.5	279	13.6	-59.7	6.8	9.6
	BL-27	2	305.4	-56.3	302.3	-17.1	46.2	31	29.9	-33.2	47.8	90.8
	BL-28	2	334.5	-45.2	323.3	-10.9	31.1	67	45.1	-51.1	31.5	61.8
	BL-29	2	304.5	39.2	322.4	77.7	17.3	210	282.4	- 2.2	32.5	12.8
	BL-31	2	214.8	57.1	166.1	43.6	52.8	25	5.8	-76.6	65.8	90.0
	BL-32	4	229.0	53.2	176.5	49.0	5.0	333	315.9	-80.8	6.6	8.1
	BL-33	4	217.0	63.6	158.5	47.4	6.0	234	1.8	-69.2	7.8	10.0
	BL-34	2	315.1	55.0	57.7	78.8	18.6	183	314.9	- 8.9	35.3	13.1
	BL-35	3	328.5	54.1	50.6	71.2	6.1	411	322.3	1.9	10.7	6.0
	BL-36	4	61.7	81.2	107.6	45.2	4.1	495	5.8	-24.5	5.2	7.0
Taiguati	BL-37	1	239.4	53.3	188.1	54.5	---	---	271.0	-74.5	---	---
	BL-38	3	240.3	51.3	192.9	54.4	16.5	57	259.6	-72.2	23.2	24.9
	BL-39	4	251.3	39.5	215.4	53.3	6.4	206	236.2	-56.2	8.9	9.8
	BL-40	4	245.9	47.8	200.0	55.3	18.3	26	250.7	-67.3	26.1	27.2
	BL-42	4	279.8	58.9	185.0	77.3	5.8	251	293.6	-45.4	10.8	4.4
	BL-43	4	306.7	67.1	113.4	77.7	2.8	1090	321.3	-28.7	5.3	4.4
	BL-44	4	296.0	60.0	152.3	84.1	5.7	261	302.9	-31.5	11.2	3.2
	BL-45	3	147.2	86.9	124.2	52.2	8.2	226	0.9	-39.5	11.2	12.8
	BL-46	4	267.9	80.5	133.5	62.4	6.8	181	345.0	-45.6	10.6	8.7
	BL-47	4	231.9	81.2	137.3	57.1	4.7	390	352.8	-49.8	6.8	6.8
	BL-48	4	245.8	78.4	141.6	60.1	4.4	440	346.3	-52.1	6.7	6.0
	BL-49	4	285.3	64.5	156.5	77.4	6.9	178	309.4	-42.8	12.9	5.2
Chorro	BL-50	4	229.6	69.8	167.4	61.0	2.6	1296	320.7	-66.7	4.0	3.5
	BL-51	4	217.2	74.2	156.2	59.3	3.0	951	338.2	-62.4	4.5	4.1
	BL-52	4	245.8	58.3	195.6	61.9	11.6	63	269.3	-64.6	18.0	15.1
	BL-53	4	260.5	47.2	225.7	61.4	10.8	73	246.5	-46.5	16.6	14.2
	BL-54	4	240.3	49.6	204.4	53.8	4.4	443	243.0	-64.9	6.2	6.7
	BL-55	3	240.7	64.5	181.4	62.8	4.8	668	293.9	-67.1	7.5	6.1
	BL-56	4	238.2	69.2	170.9	63.6	5.9	243	311.8	-65.0	9.3	7.3
	BL-57	3	229.7	72.7	161.7	62.0	3.9	989	327.1	-63.3	6.0	5.1
	BL-58	4	265.8	71.6	165.7	72.9	4.5	416	308.5	-51.5	8.0	4.1
	BL-59	4	222.9	69.0	166.8	58.5	4.2	471	325.8	-68.8	6.2	5.9
	BL-60	4	38.3	61.0	76.2	49.3	3.8	576	353.6	0.5	5.0	6.2
	BL-61	4	231.2	83.5	138.2	63.6	6.4	205	341.5	-48.3	10.1	8.0
	BL-62	4	218.6	59.6	178.3	51.5	7.3	158	304.1	-79.0	9.9	11.5
	BL-63	4	225.8	59.4	182.4	54.2	7.0	171	288.1	-76.4	9.8	10.5
	BL-64	4	195.6	70.1	155.4	51.6	28.3	12	354.8	-65.5	38.5	44.5
	BL-65	4	257.4	12.0	249.1	29.7	6.8	186	214.8	-24.8	7.5	12.8

(Table 1 - Continued)

Formation	Sample Number	n	Directions of Magnetization before and after tilt correction: Dec. (°)	Inc. (°)	Dec. (°)	Inc. (°)	α_{95} (°)	K	Virtual Geomag. Poles: Long. (°E)	Lat. (°N)	dp	dm
	BL-66	4	205.6	46.7	181.9	36.7	6.3	217	181.1	-88.0	7.4	11.4
	BL-67	4	205.4	58.8	171.8	46.2	2.7	1123	345.0	-80.3	3.5	4.5
	BL-68	4	214.1	53.3	182.2	45.3	2.9	982	276.9	-84.1	3.7	4.9
	BL-69	4	187.5	56.9	163.0	39.0	3.4	713	20.7	-74.2	4.1	6.1
	BL-70	4	217.3	25.3	204.5	23.7	7.7	142	189.6	-65.0	8.2	14.9
Itacuami	BL-71	3	215.1	55.2	183.7	49.4	5.5	503	276.9	-80.4	7.3	8.9
	BL-72	3	209.8	36.9	193.2	32.2	4.1	914	191.7	-77.0	4.6	7.6
	BL-73	3	191.5	55.4	167.9	41.9	7.6	265	9.8	-78.5	9.3	13.6
	BL-74	3	190.9	59.8	164.3	45.4	9.6	167	2.1	-74.6	12.2	16.3
	BL-75	3	210.6	65.8	169.2	55.7	12.7	96	326.4	-72.3	18.2	18.7
Tupambi	BL-76	3	234.6	64.8	182.8	63.0	7.4	281	291.4	-66.7	11.6	9.4
	BL-77	3	109.1	66.0	115.2	42.1	5.6	490	10.1	-30.7	6.9	9.8
	BL-78	2	246.6	69.8	176.4	69.3	28.6	79	300.6	-58.3	48.8	29.9
	BL-79	2	1.8	-49.5	344.8	-33.9	59.7	20	34.6	-75.5	68.2	110.3
	BL-80	3	226.4	79.2	149.2	66.1	14.3	75	331.2	-53.4	23.4	16.6
	BL-81	2	277.7	78.6	141.7	75.4	20.9	145	318.9	-41.3	38.3	17.1
	BL-82	3	220.0	70.4	166.9	61.3	8.3	221	321.9	-66.0	12.7	10.9
	BL-83	3	273.1	73.1	164.0	77.6	8.0	237	305.4	-43.9	15.0	5.9
	BL-84	2	293.3	45.7	283.3	69.1	60.3	19	245.6	- 5.4	88.4	85.9
	BL-65	2	272.1	57.7	227.8	73.7	31.6	65	267.7	-39.0	56.4	27.9
	BL-86	3	226.0	67.7	173.5	61.7	3.0	1649	309.2	-67.7	4.6	3.9

n = number of samples; Dec. = declination; Inc. = inclination; α_{95} and K = Fisher's statistical parameters; Long. = longitude; Lat. = latitude; dp and dm = oval of confidence.

TABLE 2 - Paleomagnetic results for the Bereti section (Southern Subandean area)

Formation	Sample Number	n	Directions of Magnetization before and after tilt correction: Dec. (°)	Inc. (°)	Dec. (°)	Inc. (°)	α_{95} (°)	K	Virtual Geomag. Poles: Long. (°E)	Lat. (°N)	dp	dm
Taiguati	BL-106	3	132.1	- 9.2	157.9	52.5	8.2	224	350.6	-67.1	11.3	12.7
	BL-107	3	126.8	-11.5	149.4	55.2	17.3	52	351.3	-59.6	24.6	25.8
San Telmo	BL-108	4	232.5	42.4	152.1	42.9	14.9	39	12.4	-64.1	18.4	25.8
	BL-109	4	251.1	23.5	188.2	53.3	26.1	13	267.8	-75.5	36.3	40.1
	BL-110	4	223.0	16.5	185.2	34.1	8.3	124	179.4	-84.5	9.5	15.3
	BL-111	4	224.8	16.5	185.7	35.8	10.2	82	192.1	-84.5	11.8	18.6
	BL-112	4	230.7	27.2	173.0	42.8	11.0	71	355.5	-82.6	13.6	19.1
	BL-113	4	229.5	29.2	170.2	41.8.	8.7	114	6.7	-80.5	10.7	15.2
	BL-114	4	221.1	24.7	175.1	33.9	11.6	63	55.3	-84.7	13.2	21.4
	BL-115	4	219.8	19.7	180.7	31.9	8.5	119	125.6	-86.0	9.6	15.9

n = number of samples; Dec. = declination; Inc. = inclination; α_{95} and K = Fisher's statistical parameters; Long. = longitude; Lat. = latitude, dp and dm = oval of confidence.

TABLE 3 - Paleomagnetic results for the Santa Cruz-Cochabamba Section (Central Subandean area)

Formation	Sample Number	n	Directions of Magnetization before and after tilt correction: Dec. (°)	Inc. (°)	Dec. (°)	Inc. (°)	α_{95} (°)	K	Virtual Geomag. Poles: Long. (°E)	Lat. (°N)	dp	dm
Taiguati	BL-154	3	309.4	-71.2	310.5	-56.6	18.9	44	172.1	42.8	27.4	27.5
	BL-155	3	293.5	-81.7	305.3	-67.0	15.1	67	157.5	36.2	25.0	17.0
	BL-156	3	159.4	-69.3	201.4	-80.0	27.6	21	123.5	- 0.2	52.9	18.4
Tarija	BL-137	3	306.4	-21.5	0.3	-56.6	7.6	263	115.8	70.9	11.0	11.0
	BL-138	1	314.4	-12.2	350.4	-46.1	---	---	157.9	77.1	----	----
	BL-139	3	311.3	-18.7	357.8	-51.3	10.4	311	124.2	75.9	14.1	16.4
	BL-140	3	312.8	- 5.6	341.0	-44.4	4.0	947	178.5	70.7	5.0	6.8
	BL-141	3	295.5	- 6.0	325.0	-59.5	4.6	723	162.4	52.5	6.9	6.3
Itácua	BL-142	2	63.5	-53.7	84.6	-44.7	21.9	132	50.4	-12.5	27.6	37.3
	BL-143	3	354.5	-35.3	7.2	-50.1	10.6	137	271.5	-76.0	14.1	17.1
	BL-144	3	132.5	10.4	131.7	30.3	9.0	188	21.5	-44.0	10.0	17.0
	BL-145	3	26.9	-40.8	45.4	-45.0	11.0	126	138.7	-52.2	12.4	20.6
	BL-146	3	352.4	-24.6	0.4	-40.4	4.6	714	295.4	-85.2	5.5	8.2
	BL-147	3	349.4	-29.8	358.7	-46.1	5.0	602	305.4	-80.8	6.4	8.4
	BL-148	3	337.7	-34.9	345.6	-53.3	0.7	30715	334.3	-69.8	1.0	1.1
	BL-149	3	348.8	-44.0	5.0	-59.8	3.1	1593	287.5	-67.5	4.7	4.3
	BL-150	3	13.8	-43.7	34.3	-52.0	11.0	126	238.5	-56.6	15.0	17.3
	BL-151	3	352.1	-33.4	3.4	-48.9	8.9	192	283.2	-78.2	11.7	14.6
	BL-152	3	115.9	-25.6	118.0	- 6.9	55.9	22	39.7	-25.2	56.3	111.4
	BL-153	2	13.1	-22.6	22.3	-32.8	9.9	156	209.0	-61.1	11.2	18.4

n = number of samples; Dec. = declination; Inc. = inclination; α_{95} and K = Fisher's statistical parameters; Long. = longitude; Lat. = latitude, dp and dm = oval of confidence.

TABLE 4 - MEAN MAGNETIZATION DIRECTIONS AND PALEOMAGNETIC POLES

Code	Formation	Mean Magnetization Directions: N	Dm	Im	α_{95}	K	South Paleomagnetic Poles: Long (°E)	Lat (°S)	α_{95}	K	Rotated Poles: Long (°E)	Lat (°S)
a) Southern Subandean area												
ST	San Telmo	19	170.7	39.7	6.1	31	11.9	80.7	6.3	30	16.4	57.7
ES	Escarpment	12	162.4	42.4	5.7	59	10.0	73.6	5.5	63	12.9	50.9
TG	Taiguati/Chorro	25	166.6	67.7	6.5	21	312.7	57.0	10.3	22	331.3	46.5
TM	Chorro/Itacuami	12	174.8	46.3	5.7	59	331.8	81.7	6.1	52	7.0	61.5
TU	Tupambi	7	166.8	68.3	6.3	92	312.2	57.4	9.9	38	331.3	47.0
b) Central Subandean area												
TG	Taiguati	3	255.0	-84.7	30.1	17	328.4	28.1	52.9	6		
TJ	Tarija	4	346.5	-53.7	13.1	50	329.9	69.4	16.9	31		
TC	Itácua	9	11.8	-49.0	9.5	30	248.9	79.3	14.1	14		

Figure 1 - Simplified geological map (modified from Mégard et al. 1971), showing sampling sites (stars).

(Fig. 2, next page)

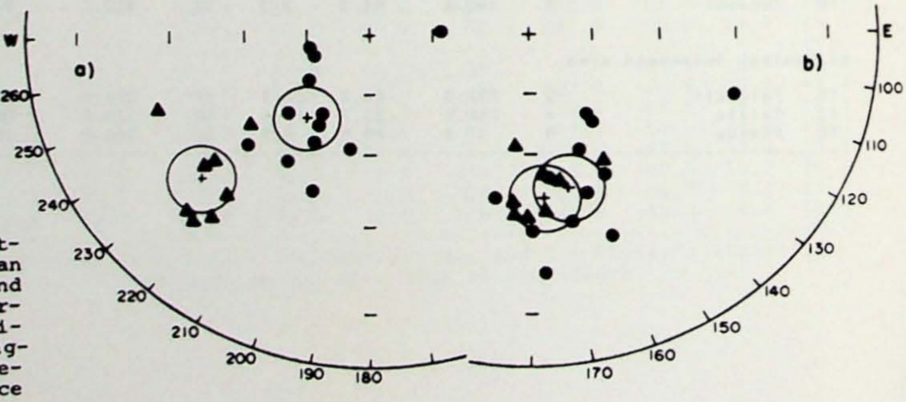

Figure 3 - Sample mean magnetization directions for the San Telmo Formation before (a) and after (b) tilt correction. Circles: Villa Montes samples; triangles: Bereti samples. Mean magnetization (crosses) and corresponding circle of confidence are also shown.

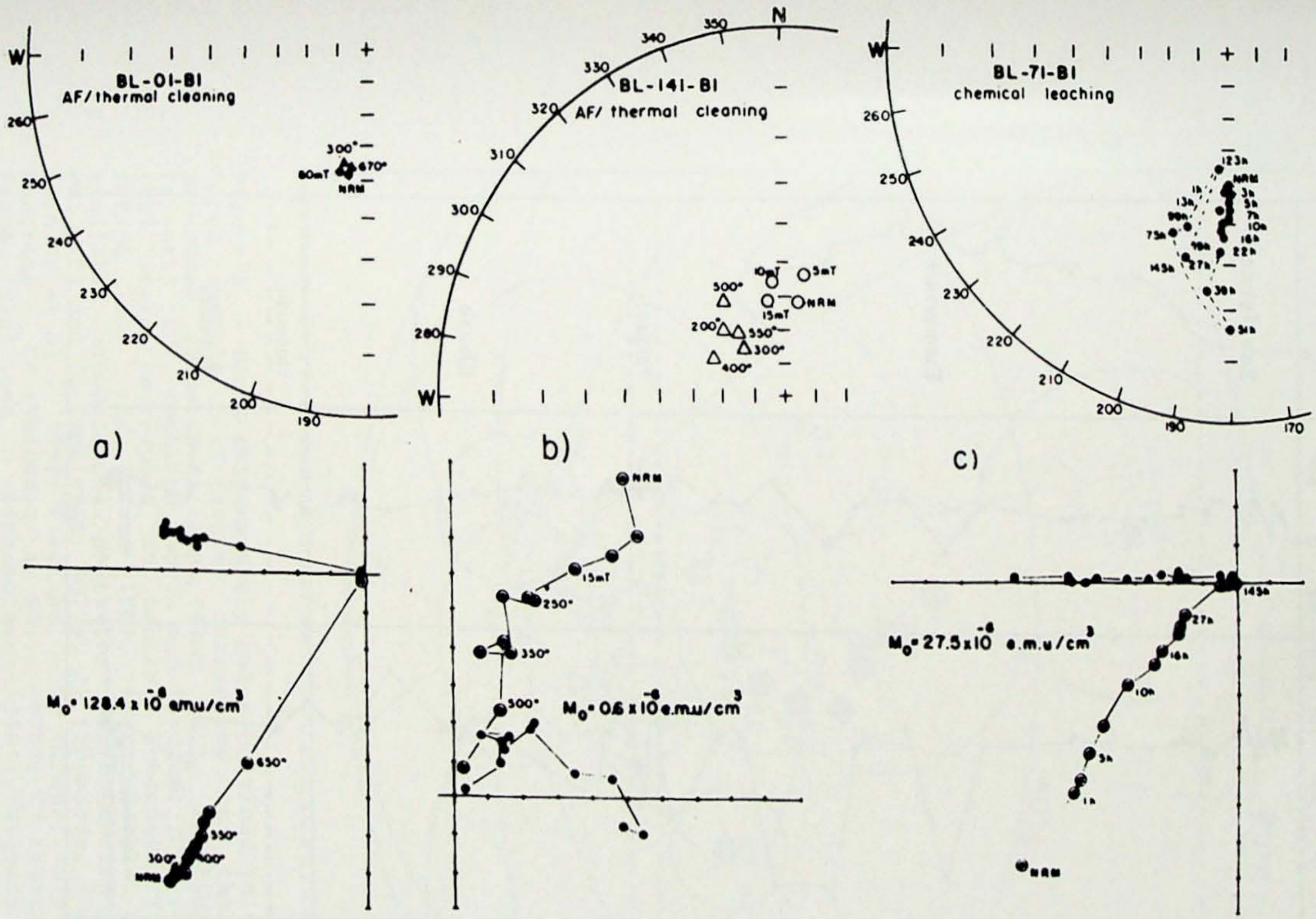

Figure 2 - Examples of demagnetization in samples from a) southern Subandean and b) central Subandean regions. c) Example of chemical demagnetization, with up to 145 hours of immersion in hydrochloric acid. The bottom part of the figures shows the vectorial projections (Zijderveld diagrams) in the horizontal (full circles) and vertical (open circles) planes. M_o is the intensity of the NRM.

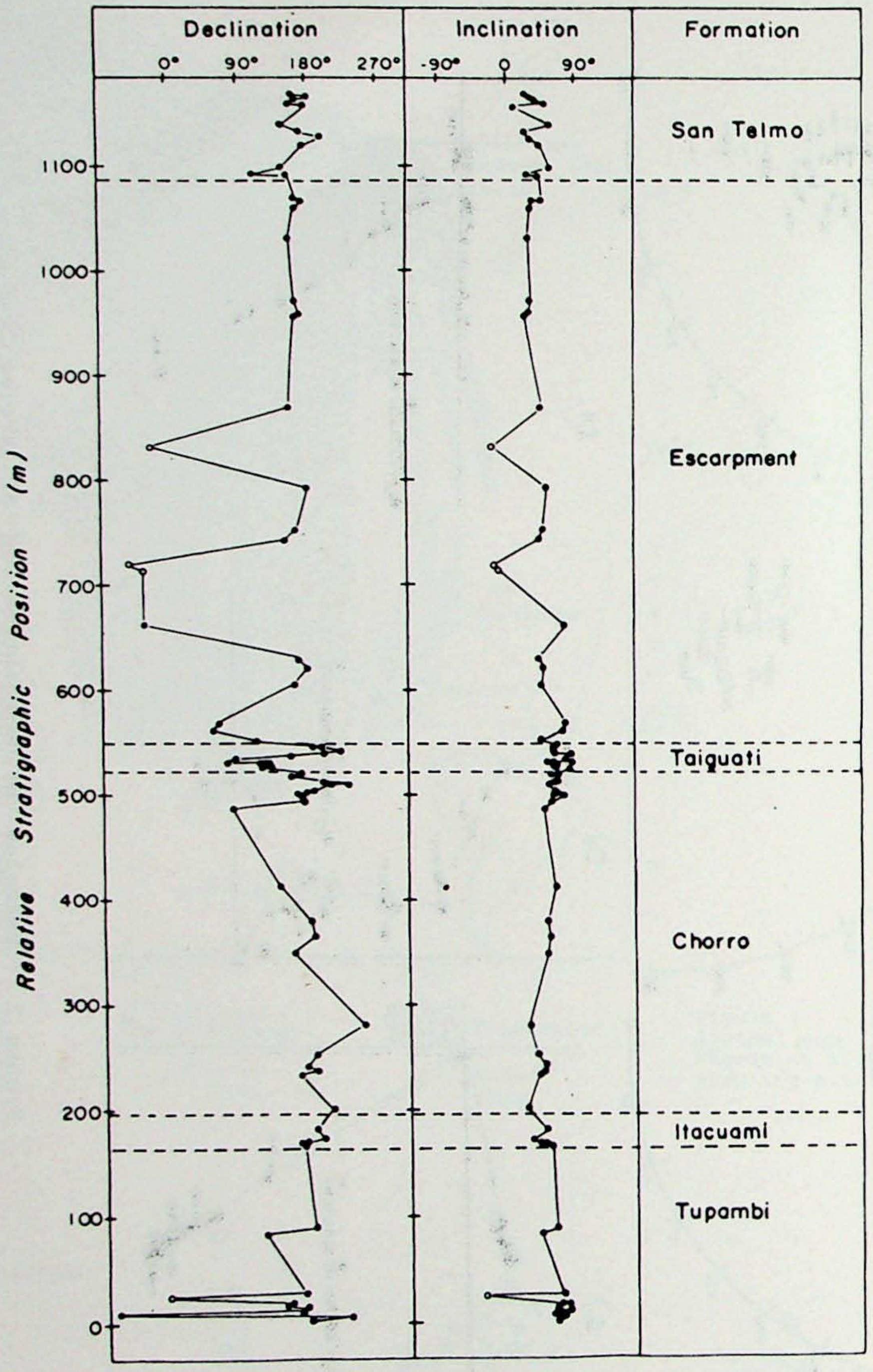

Figure 4 - Variations of magnetic declination and inclination through the Villa Montes sequence. Open circles indicate negative inclinations (normal polarity) and full circles positive inclinations (reversed polarity).

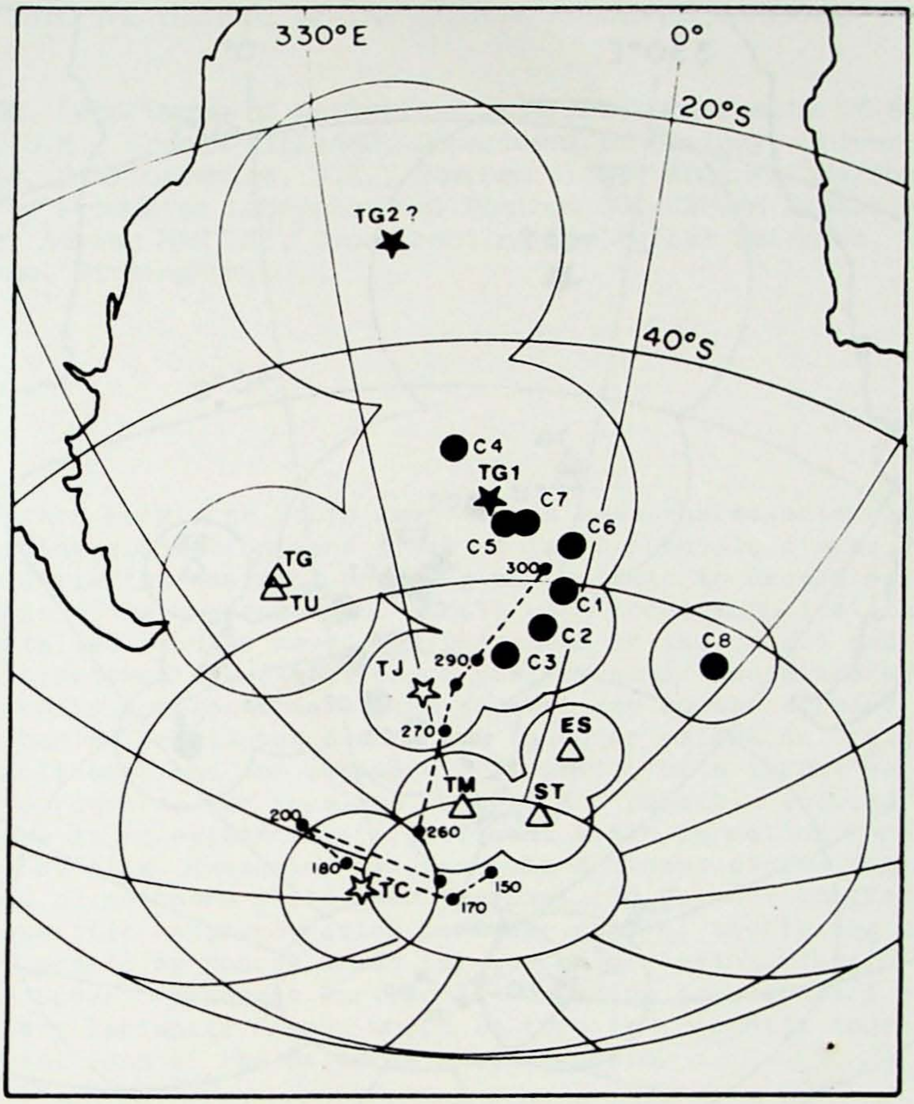

Figure 5 - South paleomagnetic poles obtained in this paper (open symbols). Triangles correspond to the Southern Subandean formations: San Telmo (ST), Escarpment (ES), Taiguati (TG), combined Chorro and Itacuami (TM) and Tupambi (TU). Stars correspond to central Subandean formations: Tarija (TJ) and Itácua (TC). Full symbols are other available Carboniferous poles for South America: La Colina Fm. - C1 and C2 (Embleton, 1970), C3 (Thompson, 1972) and C4 (Sinito et al., 1979); Piauí Fm. - C5 (Creer, 1970); Itararé Subgroup - C6 (Valencio et al., 1975), C7 (Pascholati and Pacca, 1976) and C8 (Pascholati, 1980); Taiguati Fm. - TG1 and TG2 (Creer, 1970), reversed and normal polarity respectively. Dashed line is the APWP of Irving and Irving (1982). Circles of confidence (Fisher 1953) are also plotted.

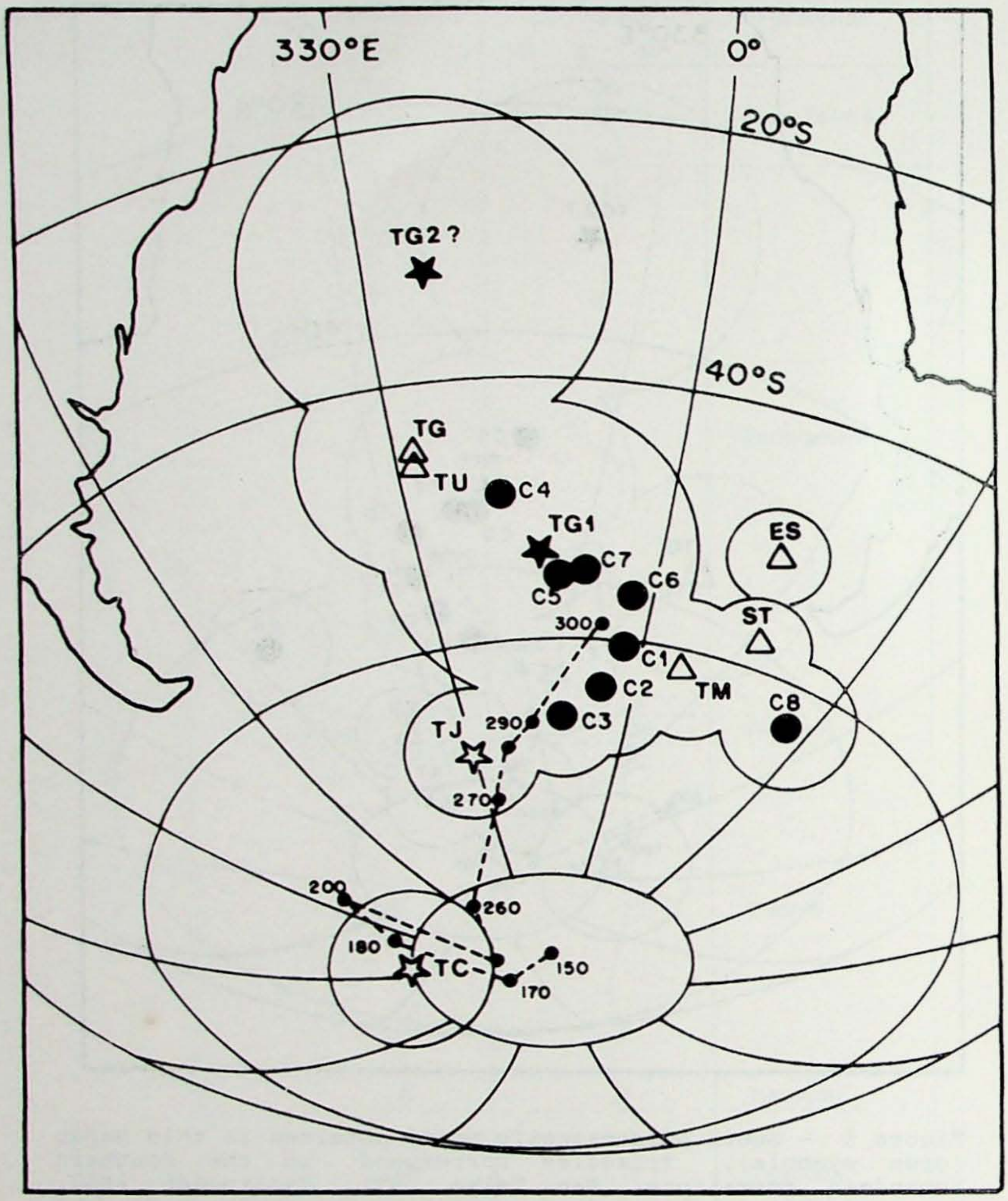

Figure 6 - Paleomagnetic poles from the southern Subandean region (open triangles) after a 25° counterclockwise rotation. Pole of rotation at 20.5°S 63.5°W. Other symbols as in Figure 4.