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PALEOMAGNETIC RESULTS FROM THE LOS MONOS FORMATION, DEVONIAN OF BOLIVIA

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Paleomagnetic results from the early-late Devonian Los Monos Formation were obtained from eight hand samples collected near Villa Montes (63.52°W 21.21°S) along the Pilcomayo river canyon, southern Subandean Bolivia. Samples are of gray shales and sandstones collected from a single outcrop. The samples were submitted to AF and thermal cleaning. A characteristic magnetization was identified with mean direction corresponding to Dec = 229.4° and Inc = 62.7° (N = 8, α_{95} = 8.5° and K = 43.0). The remanence stability and the age of the characteristic magnetization are discussed.

Resultados paleomagnéticos da Formação Los Monos, Devoniano inferior-superior foram obtidos de oito amostras de mão, coletadas próximo a Villa Montes (63,52°W 21,21°S), na parte sul da região Subandina da Bolívia. As amostras são de folhelho cinza e de arenito coletadas num único afloramento. As amostras foram submetidas a tratamento térmico e por campos magnéticos alternados. Identificou-se uma magnetização característica cuja direção média corresponde e Dec = 229,4° e Inc = 62,7° (N = 8, α_{95} = 8,5° e K = 43,0). Discute-se a estabilidade da remanência e a idade da magnetização característica.

INTRODUCTION

Paleomagnetic poles for the Devonian of South America are very scarce and in general exhibit large errors and evidence of hard secondary magnetizations (Table 1). Hence the pole positions are not very useful for defining polar wander paths.

For Gondwana as a whole the Devonian APW path is known only approximately, but most of the information comes only from Australia. Devonian poles from Australia are derived from rocks belonging to the Tasman orogenic zone (southeast Australia), and some authors (e.g., McElhinny & Embleton, 1974; Van der Voo, 1982) argue that these poles are not useful for Gondwana because the Tasman belt has been displaced with respect to the rest of Australia. On the other hand, Morel & Irving (1978) accept the Australian Devonian poles as representative of all Gondwana based on the fact that: 'the Silurian and Devonian island arcs, which comprised the Tasman foldbelt, were never actually very far from the rest of Australia. . .', Schmidt & Morris (1977) also adopted these poles for the whole of Australia in the light of an alternative interpretation of the shape of the Australian pole path.

In 1979, as part of a project of revision of the Paleozoic polar wander path for South America, a paleomagnetic expedition was organized with the main purpose of sampling the Carboniferous glaciogenic sequences of Subandean Bolivia. On that occasion several samples from the Devonian Los Monos Formation, which underlies the Upper Paleozoic, were collected. Preliminary paleomagnetic results of these samples have been previously presented (Ernesto, 1981) at the Annual Meeting of the IGCP, Project Nº 42, Upper Palezoic of South America and its boundaries, in San Luis, Argentina.

The results have been refined since then, and in view of the conflicting opinions which presently involve the Devonian segment of the Gondwana polar path, it seemed appropriate to discuss more fully the results from the Los Monos Formation, which, though not definitive, may offer new insight into the problem.

SAMPLING AND GEOLOGICAL SETTING

Samples for paleomagnetic analysis come from a single outcrop (Fig. 1) of gray-black micaceous shale overlying fine to medium grained sandstone beds cropping out along the Pilcomayo river canyon, some 6 km west of Villa Montes, southern Bolivia (63.52°W, 21.21°S). Three samples (BL-93/95) are of sandstone and were collected from the lowermost exposed levels. The other six samples (BL-87/92) are of shale collected at higher levels. The total sampled thickness was ten meters. Sample orientation was performed using both sun and magnetic compasses.

Table 1 — Paleomagnetic poles for South American Devonian formations.

Stratigraphic unit	Age	N	Long. (°E)	Lat. (°S)	α_{95} (°)	Comments	Reference
Icla and Sica Sica Formations (Bolívia)	$D_E - D_M$	26	307	−7	20.5	sediments; magnetization probably acquired during chemical processes in the iron oxides	Creer, 1970
Picos and Passagem Formations (Northeastern Brazil)	$D_E - D_M$	12	313	30	31.1	sediments with moderate red to pale-reddish brown colour; great amount of secondary magnetization present in the rocks	Creer, 1970
Baritu Formation (Argentina)	D_E	29	339	75	6.0	silicified sandstone with a red to reddish-purple colour; magnetization acquired after folding	Thompson, 1973
Ñuñorco Formation (Argentina)	$S_L - D_E$	4 2	337 316	30 −36	14.0 17.0	10 sites sampled (37 samples representing various volcanic events)	Valencio et al., 1980

N is the number of samples; Long. and Lat. are the geographic coordinates of the paleomagnetic poles; α_{95} is the semi-angle of the cone of 95% confidence about the mean. Explanation: D_E: early Devonian; D_M: middle Devonian; S_L: late Silurian.

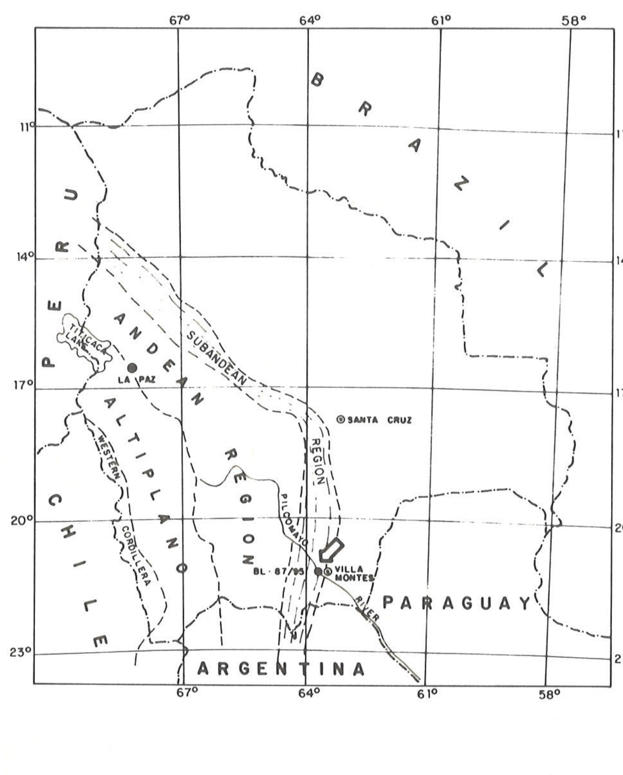

Figure 1 — Sketch map showing the sampling site (arrow).

The analysed beds have been mapped by Yacimientos Petroliferos Fiscales Bolivianos as representing the Los Monos Formation (Padula & Reyes, 1960), locally exposed near the core of a broad, N-S trending anticline transversely cut by the canyon; the contact with overlying Carboniferous sediments is unconformable (Salinas, 1979, personal communication). Interpretation of the precise age within the Bolivian Devonian for the Los Monos Formation near Villa Montes, as well as in the Subandean area in general, is still problematic and to a large extent depends on the accepted correlation of these sediments with other paleontologically dated units. Suárez Riglos (1975), for instance, places the Los Monos conformably above the Huamampampa and below the Iquiri Formations and on brachiopod evidence considers it as ranging in age from late Emsian to Eifelian-Givetian (early-middle Devonian). Isaacson (1977), on the other hand, interprets the Los Monos as a fine-grained facies and lateral equivalent of the Huamampampa and Sica Sica Formations, which contain brachiopods of mid-Emsian to Eifelian age (early-middle Devonian). More recently, Suárez Riglos (in Hünicken et al., 1980) has modified his view on the age of the Huamampampa Formation, mostly on the basis of the discovery of the goniatite *Tornoceras (Tornoceras)* bolivianum Kullmann in the lower part of the unit. Accordingly, he assigned a late Givetian-early Frasnian age to the Huamampampa Formation, this age range being extended to the Los Monos Formation. This chronological interpretation, however, is not in accordance with palynological data obtained by McGregor (1984) who reports the occurrence only of forms indicative of pre-Givetian age in the Huamampampa and Los Monos Formations. The above chronological controversy is difficult to assess at the moment, and it seems that the age of the Los Monos can at best be brackted as early-late Devonian (Emsian-early Frasnian).

PALEOMAGNETIC ANALYSIS

Fifty-four specimens, 2.5 cm in diameter and length, were prepared from eight hand samples (sample BL-91 broke during transportation). A Digico Spinner magnetometer was used for remanent magnetization measurements. The specimens were subsequently submitted to thermal and/or AF cleaning. In most cases the AF demagnetization was more suitable because some samples showed significant susceptibility variation when heated above 250°C (Fig. 2). It was found preferable to avoid thermal cleaning whenever possible, although no directional variation could be directly associated with changes of susceptibility.

The NRM intensities were very low (0.056 – 0.286 x 10^{-6} emu/cm^3) and after a few demagnetization steps the intensities fell down to the magnetometer noise level (about 0.02 x 10^{-6} emu/cm^3). Due to the low intensities, remanences were easily influenced by spurious magnetizations acquired during successive steps of cleaning, and the magnetization vectors did not reach a stable end-point, although they clearly showed a characteristic direction (Fig. 3a). Therefore, it was necessary to define criteria for selecting the appropriate magnetic field or temperature for each specimen, for which the major amount of secondary magnetization was eliminated and remagnetizations and/or susceptibility variations avoided.

Three conditions were then imposed: a) the magnetization intensity should be at least twice the instrumental noise level; b) in cases where thermal cleaning was used, the characteristic diretions were selected only for temperature

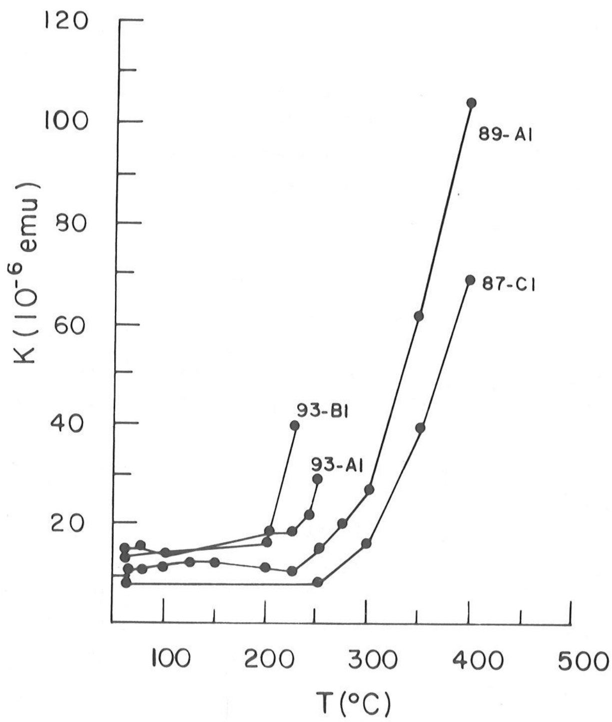

Figure 2 — Susceptibility variation with temperature for several specimens.

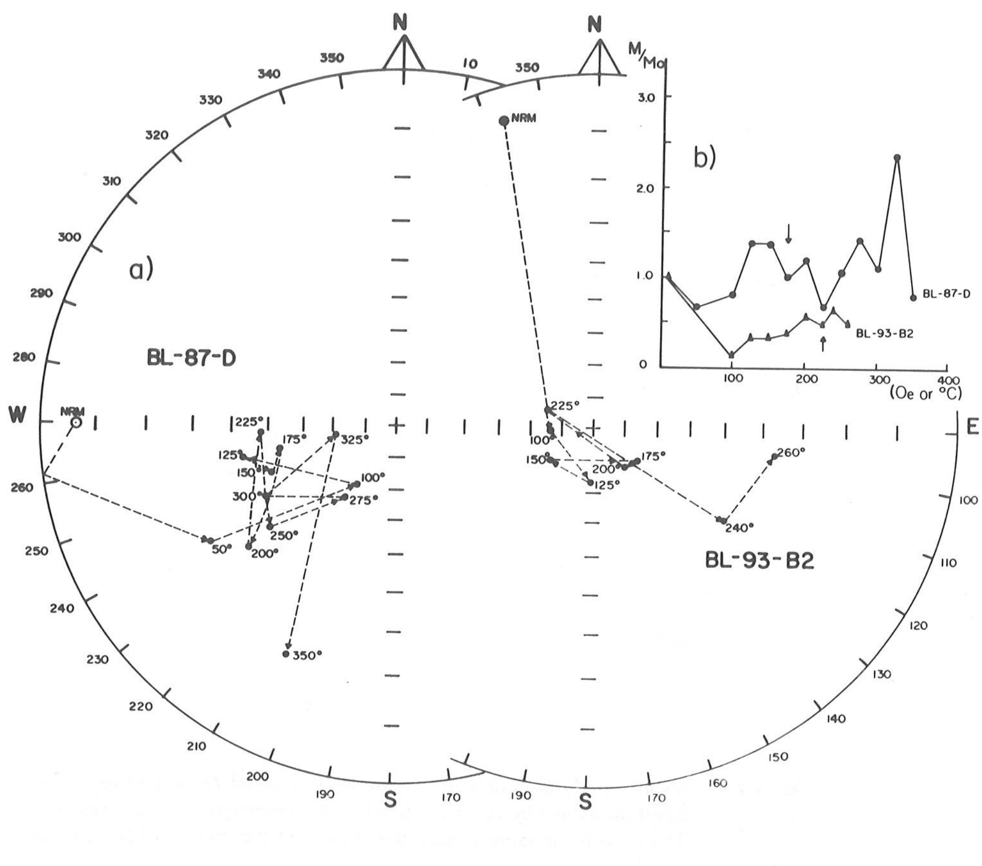

Figura 3 — a) Examples of sample behavior during stepwise demagnetization. Solid symbols indicate reverse magnetization, open symbols indicate normal magnetization. b) Demagnetization curves for the specimes shown in a). Circles indicate magnetic field, triangles indicate temperatures. The arrows indicate the points above which the specimens were significantly remagnetized.

below those values which eventually showed significant susceptibility changes; c) the remanence should exhibit small remagnetization based on the demagnetization curve (Fig. 3b) and the vector displacement. As the direction of magnetization changed from normal (NRM) to reversed polarity, there was an intensity increase, which, however, could not be considered as a remagnetization.

Following application on the above criteria, characteristic directions were defined for 42 specimens. The directions were found for temperatures between 100° and 325°C and for AF intensities between 100 and 350 Oe. Results for each sample are displayed in Table 2. The directions of magnetization before and after cleaning are shown in Fig. 4. All directions are referred to the paleohorizontal after

Table 2 – Paleomagnetic results for the Los Monos samples.

Sample Number	n	Int. (10^{-6} emu/cm^3)	Dec. (°)	Inc. (°)	α_{95} (°)	K	VIRTUAL GEOMAGNETIC POLES		SECONDARY MAGNET.	
							Long. (°E)	Lat. (°S)	Dec. (°)	Inc. (°)
BL-87	6	0.098	231.4	59.5	14.2	22.9	242.3	42.6	315.3	–46.3
BL-88	5	0.104	224.4	60.8	21.0	14.1	246.0	47.8	355.5	–53.8
BL-89	5	0.070	229.3	52.3	18.0	18.9	224.8	47.3	340.1	–47.6
BL-90	6	0.088	226.6	46.4	13.2	26.5	232.3	44.9	319.5	–30.3
BL-92	4	0.121	231.7	57.0	14.3	42.0	238.6	42.7	340.9	–46.3
BL-93	6	0.042	213.1	69.7	18.7	13.7	266.7	49.0	354.5	–36.7
BL-94	3	0.061	224.6	75.9	41.8	9.7	272.7	38.4	348.3	–37.6
BL-95	7	0.044	272.4	76.2	13.1	21.9	268.9	17.9	5.0	–26.3
Mean	N=8	–	229.4	62.7	8.5	43.0	250.0	42.6	342.7	–41.8
							$\alpha_{95} = 11.7°$	K = 23.2	$\alpha_{95} = 11.3°$	K = 24.7

n is the number of specimens; N is the number of samples; α_{95} is thesemi-angle of the cone of 95% confidence about the mean; K is the Fisher (1953) precision parameter.

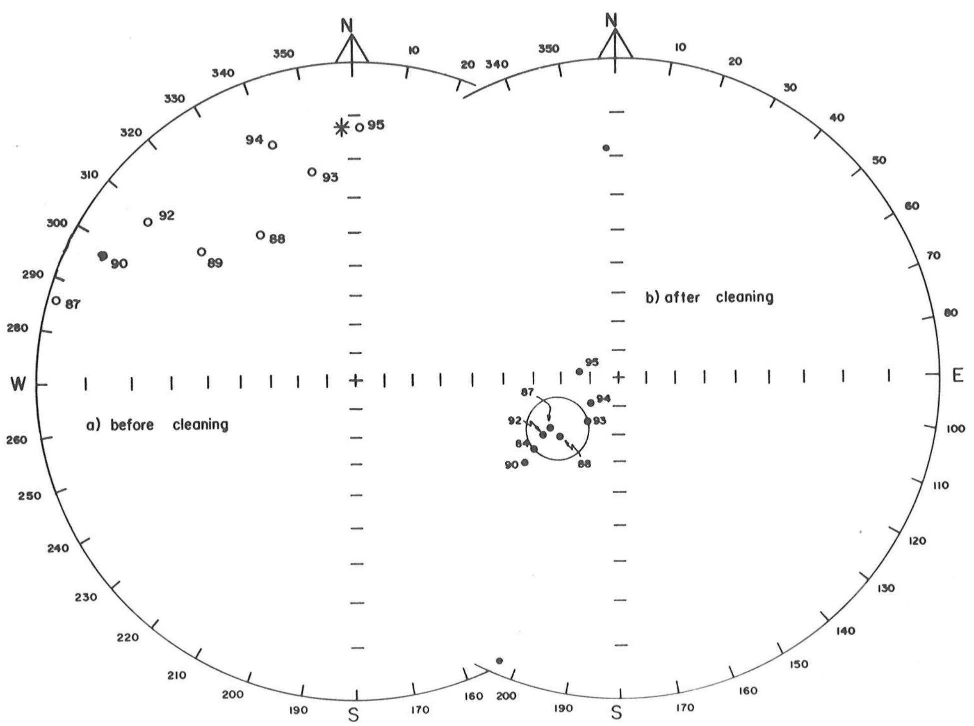

Figura 4 – Mean sample directions of magnetization. a) NRM, and b) after cleaning magnetizations. Symbols as in Fig. 3. The asterisk is the geomagnetic field direction at the sampling site. The cross is the sample mean direction with the 95% confidence circle.

correcting for the structural attitude of the beds at the sampling site (strike = 358º, dip = 10º).

DISCUSSION AND CONCLUSIONS

The characteristic magnetization for the Los Monos beds shows reverse polarity if the sampling site is considered as having been in the southern hemisphere at the time of the magnetization acquisition, and is quite different from the present local geomagnetic direction. Even the NRM directions do not cluster around the present local field, thereby revealing good remanence stability, since no hard viscous magnetization seems to be present. Therefore, the unstable behaviour of the remanence, when submitted to relatively low AC fields or temperatures, may be attributed to the effect of spurious magnetizations during treatment, an effect which becomes more intense as the remanence intensity decays.

The direction of the eliminated secondary magnetization is another evidence for remanence stability. The secondary component was calculated by subtracting the characteristic direction from the NRM direction for each sample. The results are shown in Table 2. The mean direction for all samples is Dec = 342.7º and Inc = -41.8º (normal polarity) and the corresponding pole is at **12.8ºE, 73.8ºS** (dp = 8.5; dm = 13.8).

This pole (δLM) adjusts reasonably well with the distribution of selected South American Cretaceous paleomagnetic poles (Valencio et al., 1983) displayed in Fig. 5, although it can only be considered as a rough determination. Different symbols in Fig. 5 denote different pole groups. The K-Ar ages attributed to the poles represented by squares among which δLM may be included, range from 157± 4 to 68-63 Ma.

The possibility of explaining the secondary magnetization as having been imprinted during one of the tectonic events which affected the eastern foldbelt of Bolivia is hampered by our present lack of adequate information on the structural evolution of the Central Andes.

Within the Paleozoic the generalized angular unconformity that separates the Devonian from younger rocks indicates that terminal Devonian/pre-Carboniferous tectonism ("eo-Hercynian") was widespread in Bolivia (Lohman, 1970; Helwig, 1972; Martinez & Tomasi, 1978). Post-Devonian movements (Carboniferous-Permian) are less clearly evidenced by the influence of tectonic elements (such as the Pampean Massif) on the sedimentation pattern, or by the local occurrence elsewhere in Bolivia of tuff beds and acidic lava flows in strata of these ages (Helwig, 1972).

During the Mesozoic, granitic intrusions, which may have caused low grade metamorphism, occurred during the late Triassic-early Jurassic in the Cordillera Real of Bolivia

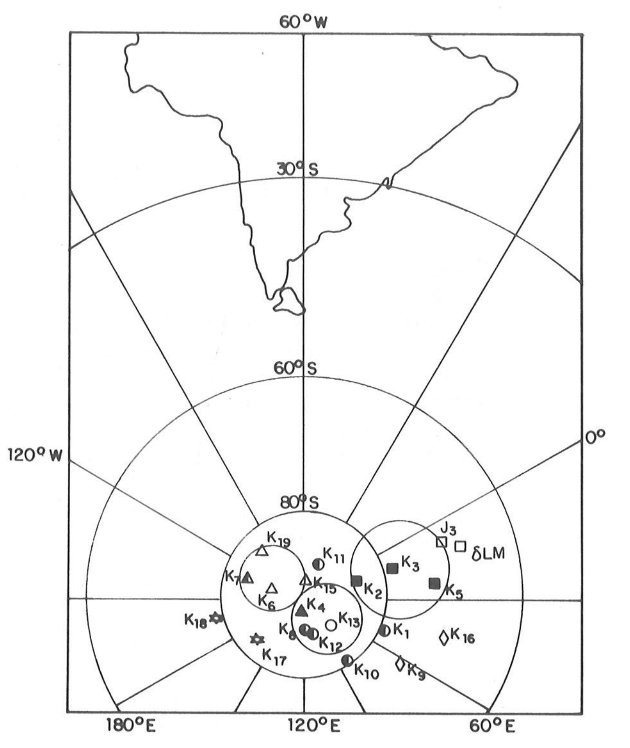

Figure 5 — Paleomagnetic poles for South American rocks assigned to the late Jurassic-Late Cretaceous, redrawn from Valencio et al. (1983, Fig. 1). δLM is the pole position corresponding to the calculated secondary magnetization of the Los Monos Formation. Other symbols are as in the original.

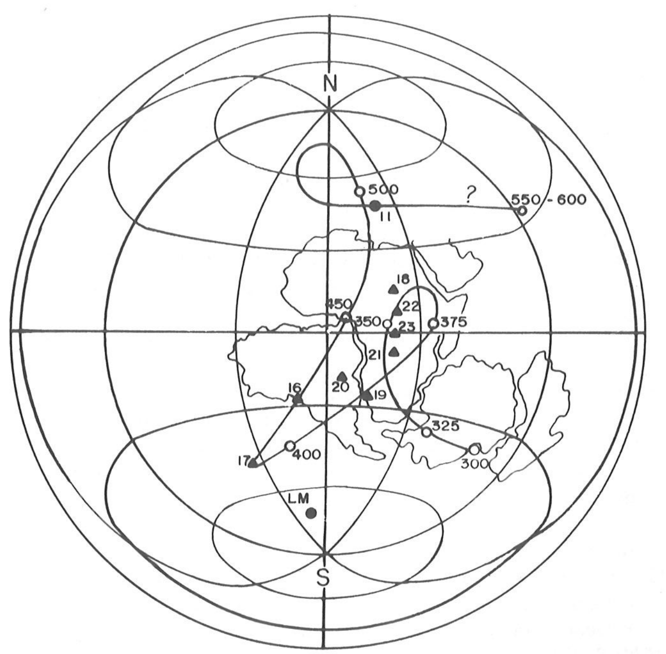

Figure 6 — Apparent polar wander path for Gondwana, redrawn from Morel & Irving (1978, Fig. 1). All poles from the Devonian, including the S-D and D-C boundaries, used to draw the curve are represented. Numbers are as in Morel & Irving (1978). Triangles denote poles from Australia and circles denote poles from South America. δLM is the Los Monos pole when South America is rotated into contact with Africa.

(James, 1971), along the eastern foldbelt (Lohman, 1970); however, the wide-spread angular unconformity at the base of the Bolivian Mesozoic sequences pointed out by Helwig (1972) is not recognized by other authors (Lohman, 1970; James, 1971).

Finally, a major cycle of orogeny in the Central Andes of Bolivia occurred in late Cretaceous through Tertiary times (Lohman, 1970; James, 1971; Helwig, 1972; Martinez & Tomasi, 1978). The secondary magnetization identified in the Los Monos beds is probably related to one of the above mentioned Mesozoic events.

The paleomagnetic south pole associated with the characteristic magnetization is located at 250.0°E, 42.6°S α_{95} = 11.7°), when referred to South America in its present geographic position. This pole is not very far from the Gondwana APW curve for the Silurian-Devonian interval presented by Morel & Irving (1978), which is based on data from the Tasman foldbelt (Fig. 6). The same could be said with reference to the Gondwana APW curve proposed by Schmidt & Morris (1977) using essentially the same data. However, as pointed out by Crowell et al. (1980) and Caputo (in press), the Morel & Irving curve seems more adequate to explain the geographic distribution of glacial sediments in South America, particularly with respect to the Silurian tillites of the Central Andes and the Devonian glacial beds in northern Brazil.

It is necessary to emphasize, however, that the data presented in this paper do not fulfill the modern reliability requirements for paleomagnetic poles, since only one outcrop was analysed with few samples. On the other hand, the remanence showed good stability and no hard secondary magnetization seems to be present. Therefore it is reasonable to admit that the characteristic direction may actually be a Devonian direction, even though it may be affected by some amount of secondary magnetization and perhaps also by secular variation.

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