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Palaeomagnetism of the Cretaceous Pirgua Subgroup (Argentina) and the age of the opening of the South Atlantic

Daniel A. Valencio and José E. Mendía *Departamento de Ciencias Geológicas, Universidad de Buenos Aires, Ciudad Universitaria, Pabellón 2, Buenos Aires, Argentina*

Alfonso Giudici and Joaquín O. Gascon *Gerencia de Exploración, Yacimientos Petrolíferos Fiscales, Av. Roque Saenz Peña 777, Buenos Aires, Argentina.*

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Summary. Palaeomagnetic data for the Cretaceous Pirgua Subgroup from 14 different time units of basalts and red beds exposed in the north-western part of Argentina (25° 45′ S 65° 50′ W) are given.

After cleaning all the units show normally polarized magnetic remanence and yield a palaeomagnetic pole at 222° E 85° S ($d\psi$ = 7°, $d\chi$ = 10°).

The palaeomagnetic poles for the Pirgua Subgroup (Early to Late Cretaceous, 114–77 Myr), for the Vulcanitas Cerro Rumipalla Formation (Early Cretaceous, < 118 Myr, Valencio & Vilas) and for the Poços de Caldas Alkaline Complex (Late Cretaceous, 75 Myr, Opdyke & McDonald) form a 'time-group' reflecting a quasi-static interval (mean pole position, 220° E 85° S, α_{95} = 6°) and define a westward polar wander in Early Cretaceous time for South America.

Comparison of the positions of the Cretaceous palaeomagnetic poles for South America with those for Africa suggests that the separation of South America and Africa occurred in late Early Cretaceous time, after the effusion of the Serra Geral basalts.

The K–Ar ages of basalts of the Pirgua Subgroup (114 ± 5; 98 ± 1 and 77 ± 1 Myr) fix points of reference for three periods of normal polarity within the Cretaceous palaeomagnetic polarity column.

1 Introduction

The history of the formation of the South Atlantic has been recorded in the stable magnetic remanence and fossil assemblages of Cretaceous rocks from South America, Africa and the South Atlantic. The Departamento de Ciencias Geológicas of the Universidad de Buenos Aires started in 1971 a palaeomagnetic study of Cretaceous igneous rocks and red-beds exposured in Argentina. The results of some of these palaeomagnetic studies carried out with rocks from the central part of Argentina (about 32° S 64° W) have been recently reported (Valencio 1972; Linares & Valencio 1975; Valencio & Vilas 1975; Vilas 1976; Mendia 1976). In this paper results of a palaeomagnetic study of Cretaceous igneous and sedimentary rocks of the Pirgua Subgroup, exposed in the north-western part of Argentina at 25° 45′ S 65° 50′ W, are given.

A new interpretation of the Cretaceous palaeomagnetic poles for Africa is given; it is showed that they define a westward excursion in Early Cretaceous time similar to that suggested for South America for this time (Valencio & Vilas 1975).

2 Available data

2.1 GEOLOGICAL EVIDENCE

In the southern part of the Province of Salta, close to the border with the Province of Tucumán, continental deposits and igneous rocks included in the Pirgua Subgroup are exposed. These rocks were formed in Cretaceous time in the Andean Basin and have been classified from the base to the top into three formations: La Yesera Formation, Las Curtiembres Formation and Los Blanquitos Formation.

La Yesera Formation consists of conglomerates, sandstones and basaltic lava flows and is fairly well exposed at Abra Isonza and at the headwaters of the Río Cajón. In these areas La Yesera Formation rests with angular unconformity on the metamorphic basement of Early Palaeozoic and Proterozoic age; 10 m above this unconformity is exposed a sequence of basalts about 40 m thick. Along the Río Cajón the lowest exposures of La Yesera Formation consists of pink and red sandstones interbedded with mudstones and conglomerates.

Las Curtiembres Formation consists basically of reddish mudstones, silstones and claystones; the higher exposures also include fine sandstones. In Quebrada de los Harneros this formation includes a sequence of basalts about 405 m thick. Las Curtiembres Formation rests conformably on La Yesera Formation. Reyes & Salfity (1972) have found an unconformity in the upper section of Las Curtiembres Formation relating it with intra-Senonian movements.

Los Blanquitos Formation consists of reddish coarse to medium grained sandstones interbedded with conglomerates.

The lithologic characteristics of the rocks of the Pirgua Subgroup and more details about the geology of the areas involved in this study are described in Valencio *et al.* (1975a).

Bossi & Wampler (1969) have suggested that the depositation of the Pirgua Subgroup started in Early Cretaceous time. Radiometric studies (K–Ar; $\lambda_e = 0.585 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.715 \times 10^{-10}$ yr^{-1}; $K^{40}/K = 0.0119$ per cent) carried out on the oldest basalt of La Yesera Formation exposed in the Abra Isonza yield an age of 114 ± 5 Myr supporting this interpretation (Valencio *et al.* 1975a). Three samples of a lava flow situated 23 m above this basalt were also dated by the last-quoted authors giving a mean age of 98 ± 1 Myr.

Samples of the basalts of Las Curtiembres Formation exposed in Quebrada de los Harneros were dated by the K–Ar method giving a mean age of 77 ± 1 Myr (Valencio *et al.* 1975a); that supports that these lava flows are related with intra-Senonian movements as suggested by Reyes & Salfity (1972).

La Yesera Formation and the lower part of Las Curtiembres Formation were affected by the intra-Senonian movements; these formations were later on deformed during the Andean orogeny. Samples were collected from sites with different attitudes of bedding planes. Azimuths and dips of bedding planes for La Yesera Formation vary between 90° and 98° and 41° and 50° respectively; for Las Curtiembres Formation they vary between 70° and 277° and 14° and 51°.

Table 1. Summary of the palaeomagnetic data referred to palaeohorizontal and K–Ar ages (Valencio *et al.* 1975a) for the basalts and red beds from the Pirgua Subgroup, Province of Salta, Argentina.

Subgroup	Formation	Area	Rock	Unit	K–Ar Age (My)	Number of cylinders	NRM D (degree)	NRM I (degree)	NRM α_{95} (degree)	NRM k	Cleaned RM D (degree)	Cleaned RM I (degree)	Cleaned RM α_{95} (degree)	Cleaned RM k	Jr/Jo
PIRGUA	Las Curtiembres	Rio Tonco	Sandstone	16		3	23	−33	18	197	25	−49	13	374	0.62
			Sandstone	15		3	14	−39	35	54	11	−49	24	110	0.46
		Quebrada de los Harneros	Basalt	14		3	11	−17	32	63	8	−21	21	143	0.47
			Basalt	13	77 ± 1	3	340	−39	33	59	337	−43	5	2138	0.80
			Basalt	12		3	342	−32	7	1350	351	−32	16	257	0.56
			Basalt	11		3	–	–	–	–	–	–	–	–	–
		A º Las Chilcas	Sandstone	10		9	360	−57	16	33	6	−62	29	11	0.40
		Río Cajón	Sandstone	9		3	358	−29	14	336	356	−35	11	516	0.84
			Sandstone	8		3	6	−30	24	108	4	−35	15	266	0.75
			Sandstone	7		3	355	−48	14	317	2	−45	18	192	0.69
	La Yesera	Río Cajón	Sandstone	6		6	262	−51	83	3	351	−44	28	15	0.86
			Sandstone	5		3	16	−39	36	50	25	−49	8	1096	0.87
			Sandstone	4		1	31	−68	–	–	28	−46	–	–	0.56
			Sandstone	3		6	17	−61	19	25	34	−60	9	113	0.72
		Abra Isonza	Basalt	2	98 ± 1	15	7	−57	22	13	19	−50	15	26	0.55
		h. Río Cajón	Basalt	1	114 ± 5	18	4	−63	23	12	7	−58	14	32	0.48

Table 2. Mean directions of the natural and cleaned remanent magnetization and south palaeomagnetic poles for the Cretaceous lava flows and red beds from Province of Salta, Argentina.

Formation or subgroup	NRM referred to the palaeohorizontal					Cleaned RM referred to present horizontal					Cleaned RM referred to palaeohorizontal					Palaeomagnetic pole			
	N	D (degree)	I (degree)	α_{95} (degree)	k	N	D (degree)	I (degree)	α_{95} (degree)	k	N	D (degree)	I (degree)	α_{95} (degree)	k	Lat (° S)	Long (° E)	$d\psi$ (degree)	$d\chi$ (degree)
Las Curtiembres F.	9	1	−37	11	24	9	359	−42	24	5	9	2	−42	10	28	88	154	8	12
La Yesera F.	5	355	−62	28	9	5	38	−47	16	18	5	14	−53	12	44	76	240	12	17
Pirgua Subgroup	14	0	−45	12	12	–	–	–	–	–	14	5	−46	8	27	85	222	7	10

2.2 THE PALAEOMAGNETIC STUDY

Sampling was carried out by geologists of Yacimientos Petrolíferos Fiscales (YPF). More than 85 cylinders of basalts and sedimentary rocks from La Yesera Formation and Las Curtiembres Formation were cut from 16 time units distributed among six different sampling areas (Table 1). Orientation was carried out with both sun and magnetic compasses and in most cases the magnetic and sun-compass azimuths agreed to within 3°. In these cases, when the differences were not systematic, the mean of magnetic and sun-compass azimuths was used. Where the disagreement was more than 3° the sun-compass azimuths were used. A spinner magnetometer was used to measure the natural remanent magnetization (NRM) of the cylinders. Detailed thermal and alternating field (AF) cleaning were used to determine the stability of the remanent magnetization (RM). One cylinder from each igneous unit was demagnetized in increasing steps of 50 Oe (5mT) to at least 300 Oe peak field. In this way the best AF for isolating the stable remanence of each pilot cylinder was determined. The criterion adopted for the choice of the best AF strength was that the direction of the RM of the pilot cylinder exhibited no further change in response to higher AF strengths. The other cylinders of the same igneous unit were submitted to that optimum AF for a better definition of the stable remanence. The stability of the RM of sedimentary rocks was verified by a similar thermal cleaning. The statistical method of Fisher (1953) was used to compute the mean direction of the NRM and stable RM of each unit on the basis of the direction of the natural and cleaned remanence of its cylinders.

2.2.1 La Yesera Formation

The mean directions, referred to the palaeohorizontal, of the NRM of each time unit of La Yesera Formation are given in Table 1. The mean direction, referred to the palaeohorizontal, of NRM of the five units of La Yesera Formation is given in Table 2. The best demagnetizing field strength for units 1 and 2 is 200 Oe; the cylinders of these igneous units retain more than 0.48 of their NRM after the treatment in that AF ($Jr/Jo > 0.48$, Table 1). The best demagnetizing temperature for units 3, 4, 5, and 6 is 400° C; the cylinders of these sedimentary units retain more than 0.3 of their NRM after cleaning at 550° C. The mean directions, after bedding plane correction, of cleaned RM for each time unit are given in Table 1. Directions of the remanence of units are substantially better grouped after AF and thermal demagnetization than before. All the units yield normally polarized mean directions. The mean direction, referred to the palaeohorizontal, of stable remanence of the five time units from La Yesera Formation is given in Table 2. It can be seen that directions of the remanence of each unit are better grouped after cleaning ($k = 44$) than before ($k = 9$). The occurrence of grouped directions, divergent from the present field, indicate that substantial secondary remanences are absent after cleaning. Unit 4 is a friable sandstone and it was possible to cut only one cylinder from it (Table 1); therefore the directions of the NRM and the stable remanence of this unit were not used to compute the mean directions for the formation (Table 2).

Table 2 also gives the mean direction of cleaned remanence referred both to the present and palaeohorizontal. These mean directions are not significantly different but since the dispersion is decreased when bedding plane correction is applied it would seem that the stable remanence of units preceded their structural deformation.

2.2.2 Las Curtiembres Formation

The mean directions, referred to the palaeohorizontal, of the NRM of each time unit of Las Curtiembres Formation are given in Table. 1. The mean direction of NRM of these units is given in Table 2. The optimum AF strength for units 12, 13 and 14 varies between 150 and

200 Oe. It was not possible to isolate stable RM in cylinders from unit 11. The optimum demagnetizing temperature for all the sedimentary units is 400° C. The normalized remanence after demagnetization at 550° C is 0.3. The within-unit precision of the NRM of units 7, 10 and 12 is larger than that of the cleaned RM (Table 1) and we attributed the increased scatter to instrumental errors in measuring the weak RM remaining after demagnetization. However, the precisions for the populations of cleaned RM are acceptable. The mean directions, referred to the palaeohorizontal, of stable RM for each unit of Las Curtiembres Formation are given in Table 1. All the units yield normally polarized mean directions and the mean direction, referred to the palaeohorizontal, is given in Table 2. The precision with which the direction of RM of each unit is defined is improved after cleaning. As for La Yesera Formation the grouping of RM directions is improved when referred to the palaeo rather than the present horizontal (Table 2) indicating that the acquisition of stable RM preceded the deformation of the rock units.

In Table 2 the mean direction of the cleaned RM of the 14 units of the Pirgua Subgroup is also given.

3 Interpretation of results

McElhinny & Burek (1971) proposed a geomagnetic field polarity timescale for the Mesozoic and Creer (1971) introduced the Mesozoic palaeomagnetic column defined by USSR scientists. The available palaeomagnetic polarity and radiometric information is not sufficient to define the changes of polarity within the Cretaceous. Particularly, the ages of some of the USSR defined Cretaceous reversed zones are fixed without the support of radiometric information. Valencio (1972, Fig. 6) summarized our knowledge of the Cretaceous palaeomagnetic polarity column. Normal stable remanence has been isolated in igneous units from La Yesera and Las Curtiembres Formation which have been dated at 114 ± 5, 98 ± 1 Myr and 77 ± 1 Myr (Table 1). These palaeomagnetic and radiometric data provide new reference points in the Cretaceous palaeomagnetic polarity column. Data derived from the basalt exposure at the headwaters of Río Cajón (114 ± 5 Myr) support the period of normal polarity defined between the Sierra de Los Cóndores and Gatanskaja events of reversed polarity and data derived from the basalt from Abra de Isonza (98 ± 1 Myr) support the long period of normal polarity defined between the Gatanskaja and Kuldginskaja events of reversed polarity of the geomagnetic field. Palaeomagnetic and radiometric data derived from the basaltic exposures of Las Curtiembres Formation from Quebrada de los Harneros (77 ± 1 Myr) support the period of normal polarity defined between the Akoh and Beringsuskaja events of reversed polarity.

Poles were computed for La Yesera Formation and Las Curtiembres Formation from the mean directions referred to the palaeohorizontal of their cleaned remanences (Table 2). In this table is also given the position of the combined palaeomagnetic pole computed for the Pirgua Subgroup (SAK_6); the position of this pole may be also computed as the mean of the virtual geomagnetic poles for each rock unit of Table 1 (85° S 220° E, α_{95} = 6°). Fig. 1 shows the position of SAK_6; it is reasonable close to the position of the Late Cretaceous Poços de Caldas Alkaline Complex palaeomagnetic pole (SAK_7, 75 Myr, Opdyke & MacDonald 1973). The mean distance between the sampling area of the Pirgua Subgroup and that of the Poços de Caldas Alkaline Complex is about 2000 km; the difference between the positions of the palaeomagnetic poles for these two areas is not significant at the level p = 0.05 (Fig. 1); this suggests that no relative movements have occurred between these areas and that, on average, the geomagnetic field was similar to that of a geocentric dipole in Late Cretaceous times in southern South America. Fig. 1 also shows the positions of the Early Cretaceous palaeomagnetic poles available for South America: SAK_1 (120 Myr, Creer 1964);

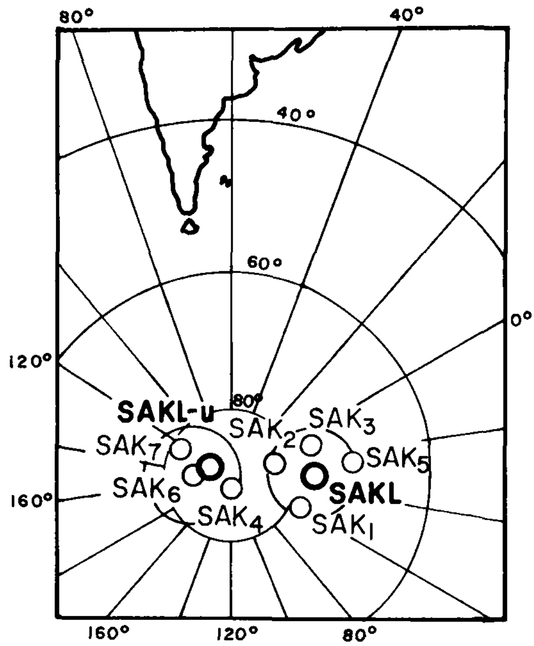

Figure 1. Cretaceous palaeomagnetic poles for South America. SAK_6 is the pole for the basalts and red beds from the Pirgua Subgroup. Key to other labels are given in Section 3 of the text.

SAK_2 (118 Myr, Valencio & Vilas 1975); SAK_3 (138 Myr, Linares & Valencio 1975), SAK_5 (123 Myr, Mendía 1976), and SAK_4 (< 118 Myr, Valencio & Vilas 1975). The South American Cretaceous palaeomagnetic poles exhibit an elongated distribution; this distribution involves poles both from Argentina and southern Brazil and may be attributed either to tectonic movements or polar wander. The discrepancy between the Argentinian Early Cretaceous pole positions SAK_2 (Vulcanitas Cerro Colorado Formation, 118 Myr) and SAK_4 (Vulcanitas Cerro Rumipalla Formation, < 118 Myr) needs explanation since both of these poles were derived from rocks located within the same area of the Province of Córdoba; the Vulcanitas Cerro Rumipalla Formation rests on the Vulcanitas Cerro Colorado Formation and therefore the discrepancy may represent a rapid westward excursion of the pole. On the other hand, the remarkably good agreement between (i) Early Cretaceous poles for Argentina (SAK_2, SAK_3, SAK_5) and Brazil (SAK_1) and (ii) Late Cretaceous poles for Argentina (SAK_6) and Brazil (SAK_7) indicates that the observed distribution is not due to the effects of relative tectonic movements and suggests that it is due to apparent polar wander.

Fig. 1 shows that the positions of palaeomagnetic poles SAK_1, SAK_2, SAK_3 and SAK_5 form an 'age-group' of early Early Cretaceous age and poles SAK_4, SAK_6 and SAK_7 define a 'time-group' (reflecting a quasi-static interval, Valencio & Vilas 1972) of late Early Cretaceous to Late Cretaceous age. The mean pole position of the early Early Cretaceous 'age-group' is: 78° S 27° E (SAKl, α_{95} = 7°) and that of the late Early Cretaceous to Late Cretaceous 'time-group' is: 85° S 220° E (SAKl-u, α_{95} = 6°) (Valencio & Vilas 1975). Fig. 1 shows the positions of these mean poles.

Fig. 2 shows the Late Carboniferous–Late Cretaceous part of the polar wander curve for South America (Valencio & Vilas 1975). SAC_2 is the palaeomagnetic pole for the Moscovian Taiguati Formation; SACu, SAPC and SAKl are the mean pole positions of the 'age-groups' formed by the Upper Carboniferous, Permocarboniferous and early Early

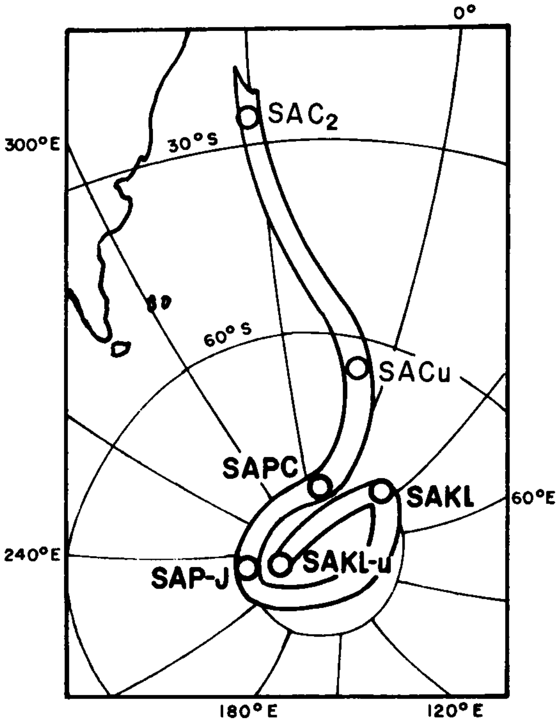

Figure 2. Late Palaeozoic–Late Cretaceous section of the polar wandering curve of South America. SACu, SAPC, and SAKl are the mean polar positions for the 'age-groups' of Late Carboniferous, Permo-Carboniferous and Early Cretaceous age. SAP-J and SAKl-u are the mean of the Permo-Jurassic and Early–Late Cretaceous 'time-groups' (see Section 3).

Cretaceous palaeomagnetic poles, respectively (Valencio *et al.* 1975b), and SAP-J (*Op. cit.*) and SAKl-u are the mean pole positions of the Middle Permian to Middle Jurassic and the late Early Cretaceous to Late Cretaceous 'time-groups', respectively. Note the rapid polar shift relative to South America which spanned the time from the Jurassic (SAP-J) to the Late Cretaceous (SAKl-u). It started after the Middle Permian-Middle Jurassic (263–161 Ma) quasi-static interval defined by the Middle and Late Permian, Early, Middle and Late Triassic and Middle Jurassic palaeomagnetic poles for South America.

Fig. 3 shows the positions of the Cretaceous palaeomagnetic poles available for Africa: AfK_1 (Early Cretaceous, 116 ± 6 Ma, Briden 1967); AfK_2 (Early Cretaceous, 110–107 Myr, Gough & Opdyke, 1963); AfK_3 (pre-Miocene, probably Cretaceous, Raja & Vise 1973); AfK_4 (Early Cretaceous, older than Aptian, Bardon *et al.* 1973); AfK_5 (Early Cretaceous, 110–128 Myr, Gidskehaug, Creer & Mitchell 1975); AfK_6 (Early Cretaceous, older than Cenomanian, Hailwood 1975); AfK_7 (Cretaceous, Shazly & Krs 1973); AfK_8 (Late Cretaceous, Hailwood 1975); AfK_9 (Late Cretaceous, Schult 1973) and AfK_{10} (Late Cretaceous, McElhinny & Brock 1975). The African Cretaceous palaeomagnetic poles also exhibit an elongated distribution. On the basis of similar reasons to those given for the South American palaeomagnetic poles we accept that this distribution is not due to the effects of relative tectonic movements and is due to polar wander. Fig. 3 suggests that the positions of palaeomagnetic poles AfK_4 and AfK_5 and AfK_1 and AfK_2 form two 'age-groups' of Early Cretaceous age; poles AfK_3, AfK_6 and AfK_7 define an 'age-group' of Cretaceous or late Early Cretaceous age and poles AfK_8, AfK_9 and AfK_{10} form an 'age-group' of Late Cretaceous age. The mean pole positions of the Early Cretaceous 'age-

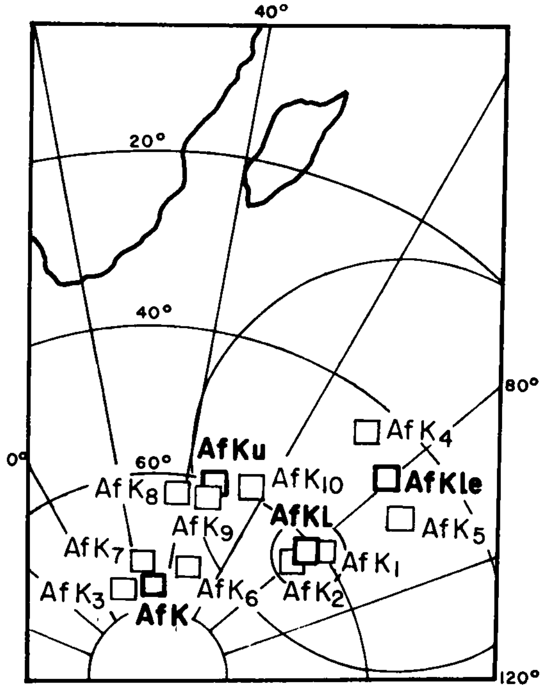

Figure 3. Cretaceous palaeomagnetic poles for Africa. Key to other labels are given in Section 3 of the text.

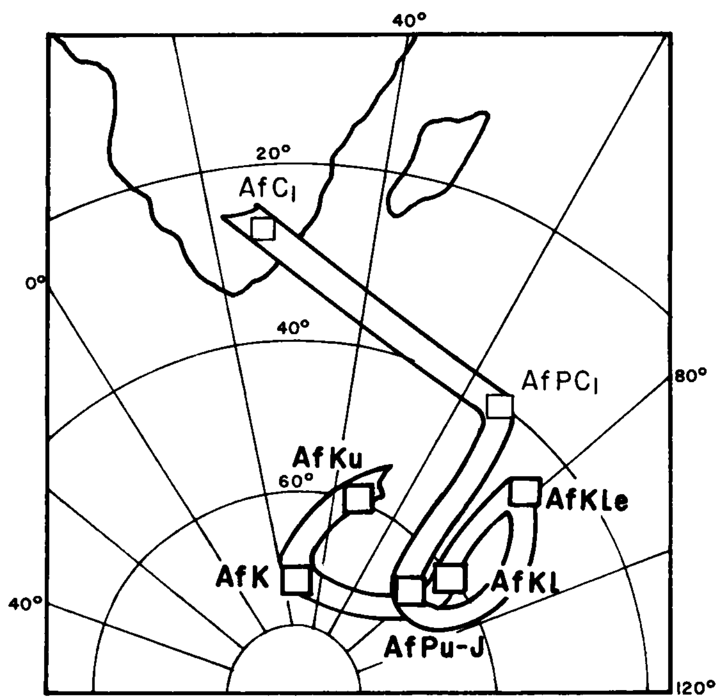

Figure 4. Late Palaeozoic – Late Cretaceous section of the polar wandering curve of Africa. AfKle, AfKl, AfK and AfKu are the mean polar positions of the 'age-groups' of early Early Cretaceous, Early Cretaceous, Cretaceous and Late Cretaceous age. AfPu-J is the mean of the Permo-Jurassic 'time-group'. Key to other labels are given in Section 3.

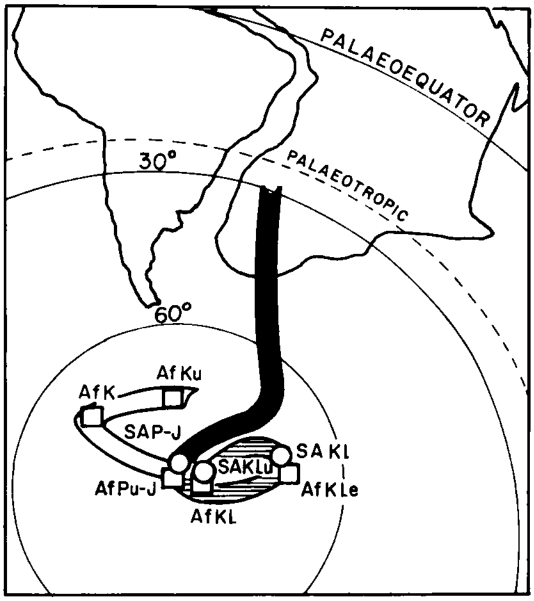

Figure 5. Palaeomagnetic reconstruction of the positions of South America and Africa for the Late Palaeozoic and Early Mesozoic. These continents have been placed so that the Late Palaeozoic and early Early Cretaceous sections of their polar wandering curves coincide. ○, South American poles; □, African poles.

groups' are: 46° S 79° E (AfKle, α_{95} = 26, Valencio & Vilas 1975) and 61° S 81° E (AfKl, α_{95} = 5°, Valencio & Vilas 1969) and those of the Cretaceous and Late Cretaceous 'age-groups' are: 76° S 27° E (AfK, α_{95} = 5°) and 61° S 47° E (AfKu, α_{95} = 8°), respectively. Fig. 3 shows the positions of these mean poles. If we accept that AfKle is older than AfKl and this one is older than AfK, the African Early Cretaceous and Cretaceous palaeomagnetic poles also define a rapid westward excursion of the pole. Fig. 4 shows the Late Palaeozoic-Late Cretaceous section of the polar wandering curve for Africa. AfC_1 is the palaeomagnetic pole for the Carboniferous Dwyka Formation; $AfPC_1$ is the palaeomagnetic pole for the Permocarboniferous Ecca Red beds and AfPu-J is the mean pole position of the 'time-group' formed by the Late Permian, Triassic and Jurassic palaeomagnetic poles (Rocha Campos, Valencio & Pacca, 1977). Note the rapid polar shift relative to Africa which spanned the time from Jurassic (AfPu-J) to the Late Cretaceous (AfKu); this polar shift started after the Late Permian–Jurassic quasi-static interval defined by AfPu–J.

Fig. 5 reconstructs the positions of South America and Africa such that the Late Palaeozoic and Early Cretaceous sections of their polar wandering curves overlap. Note the coincidence of the positions of the 'age-groups' SAKl and AfKle and of the 'time-group' SAKl-u and the 'age group' AfKl. It suggests that South America and Africa, joined by their Atlantic margins, moved as a single continental block during most of the Lower Cretaceous and that the opening of the South Atlantic took place after the effusion of the Serra Geral Basalts (Gidskehaug, Creer & Mitchell 1975; Valencio & Vilas 1975 and Pacca & Iodo 1975). Fig. 5 also shows that the Late Cretaceous poles of South America (SAKl-u) differ from those of Africa (AfKu) and this suggests that they were already drifting apart by that time. Therefore, we infer that these Gondwanic continents began to drift apart so forming the South Atlantic in late Early Cretaceous. This interpretation supersedes those given previously about the age of the South Atlantic on basis of palaeomagnetic data and agrees fairly well with the age assigned to the magnetic lineations recorded in the South Atlantic (Larson & Ladd 1973) and the similarity of the Early Cretaceous faunas from South America and Africa (Hallam 1967; Reyment 1969 and 1974).

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