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The significance of the palaeomagnetism of Jurassic–Cretaceous rocks from South America: predrift movements, hairpins and magnetostratigraphy

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Summary. In this paper we show that: (1) The positions of the Cretaceous palaeomagnetic poles (PP) for South America and Africa exhibit elongated distributions that are due to rapid movement of these continents from the south pole.

(2) The positions of the Middle–late Jurassic virtual geomagnetic poles for South America exhibit an elongated distribution along the meridians 20–200°E; it is suggested that this is due to a rapid shift of South America in Middle–late Jurassic time.

(3) The late early–early late Cretaceous sections of the apparent polar wandering paths for South America and Africa are consistent with South Atlantic seafloor spreading data.

On the basis of the comparison of the reliable late Palaeozoic–late Cretaceous PPs for South America and Africa, taking into account the restrictions established by geological, palaeontological and seafloor spreading data, it is suggested that minor movements could have occurred within Western Gondwana in middle–late Jurassic time along a narrow zone which later became the South Atlantic divergent boundary.

Four 'hairpins' are defined in the late Palaeozoic–late Cretaceous section of the apparent polar wandering path for South America; the two youngest of these can be correlated with the origin of the South Atlantic Ocean basin and the onset of the Andean Orogeny, respectively.

The magnetostratigraphy for the Serra Geral lava flow sequence suggests that some of these flows were poured out rapidly without significant interruption.

1 Introduction

The apparent polar wandering path (APWP) describes the horizontal movements of a lithospheric block. Rapid changes in trend of these movements are defined by sharp turning points (hairpins, hooks or loops) in the APWP. These sharp turning points were correlated with plate tectonics and orogenic events (Irving & Park 1972; Van der Voo 1981). It is widely accepted that the episodes of fragmentation of Gondwana started in late Jurassic–early Cretaceous time and that the origin of the South Atlantic occurred in early Cretaceous time. The Andean orogeny started in late Cretaceous time. Therefore, we might expect sharp turning points in the late Mesozoic section of the Gondwana APWP and, particularly, in the late Jurassic–Cretaceous sections of the South American and African APWPs. Valencio & Vilas (1976) and Valencio *et al.* (1977a) have shown that the South American and African Cretaceous palaeomagnetic poles exhibit an elongated distribution and that they and the Jurassic poles define sharp turning points in the APWPs for these lithospheric blocks. More recently new Cretaceous and Jurassic palaeomagnetic poles (PP) for South America and Africa have been published. In this paper we show that, in gross outline, the new Cretaceous and Jurassic PPs for South America and the new Cretaceous PPs for Africa are essentially consistent with the former interpretation of those authors. In detail, however, some changes are noticeable and these mainly involve a more precise definition of the changes in direction of movements (hairpins) of those continents. The possible correlation of these sharp turning points with the plate tectonic events which affected Gondwana is also discussed.

The movements of lithospheric plates in late Mesozoic and Cenozoic times are recorded by the magnetic remanence of subaerial lavas from continents and suboceanic basalts formed at divergent boundaries during that period. In this paper we show that the relative movements of South America and Africa in the late early–early late Cretaceous recorded by subaerial lavas and sediments from these continents are consistent with the South Atlantic seafloor spreading data.

Finally, we discuss the geological implications of the magnetostratigraphy for sequences of South American Cretaceous rocks.

2 Geology

The best known exposures of Mesozoic igneous rocks from South America are those included in the Serra Geral Formation. From stratigraphic evidence the age of this Formation could lie in the range from the Upper Triassic to the Upper Cretaceous. Amaral *et al.* (1966) found a steady increase in igneous activity with time during the Serra Geral magmatic episode, starting at about 140 Ma ago, reaching a peak at 120 Ma and sharply declining after 115 Ma. Pacca & Hiodo (1976) reported ages of 103 ± 5 and 101 ± 7 Ma for the highest lava flows of a sequence of Serra Geral rocks exposed at Guatá-Bom Jardim. That is the radiometric age suggests that the Serra Geral magmatic episode lasted from the late Jurassic to at least the late–Lower Cretaceous (Van Eysinga 1972).

Large exposures of igneous rocks assigned to the Cretaceous are also present in Africa. In particular, the Kaoko basalts of the Etendeka plateau (South-West Africa) have been correlated with the Serra Geral basalts. The Kaoko basalts were poured out rapidly without significant interruption (Haughton 1969, quoted in Gidskehaug, Creer & Mitchell 1975). Radiometric studies yielded a major peak of K/Ar ages between 136 and 114 Ma for the Kaoko lavas (Siedner & Miller 1968, quoted in Gidskehaug *et al.* 1975; Siedner & Mitchell 1976). Palaeomagnetic data for South American and African rocks, the similarity of the Lower Cretaceous faunas (Hallam 1967; Reyment 1969; Reyment & Tait 1972) and the age assigned to the magnetic anomalies recorded in the South Atlantic (Larson & Ladd 1973) suggest that the separation of South America and Africa occurred in late early Cretaceous time. Therefore the correlation of the Serra Geral and Kaoko basalts is a key point in the geodynamic evolution of the South Atlantic: the sites of these two lava fields must have been adjacent or very close before the South Atlantic was opened; that is, they would have been parts of a single lava field formed either just before or during the first phases of the opening of the South Atlantic.

3 The available palaeomagnetic poles

3.1 SOUTH AMERICA

The reliable PPs (Valencio 1973) for South America assigned to the Jurassic and Cretaceous are given in Table 1. The late Jurassic–late Cretaceous pole positions given in Table 1 are plotted in Fig. 1; the position of the PP for the La Teta lava flows is not shown in this figure because it is affected by local tectonic movements (MacDonald & Opdyke 1972) and therefore is not useful for geodynamical interpretations of continental extent.

Fig. 1 shows that the South American Cretaceous PPs exhibit an elongated distribution; this had been noted before by Valencio & Vilas (1976) and Valencio *et al.* (1977a). In the latter it was shown that this distribution is not due to the effect of relative movements of the collecting sites and it was suggested that it is due instead to a rapid apparent polar wander. This can also be realized by observing the positions of the PPs for the stable areas of south-eastern Brazil (black and white symbols) and central Argentina (solid symbols) in Fig 1: the PPs for each of these areas exhibit an elongated distribution. We should also note that some of these PPs were computed on the basis of samples of different age collected at the same site, i.e. the elongated distribution of the Cretaceous PPs is not diagnostic of the relative movements of the collecting sites. On the other hand, in gross outline, the direction of the South American apparent polar movement in Cretaceous time is clearly different from that of the late Palaeozoic movement (Fig. 3). This suggests that the sharp changes in the direction of movement are related with the late Mesozoic plate tectonic events; if this is the case the different positions of the Cretaceous PPs should be due to the relative age of the rocks used to compute them and the movement of South America during this time interval.

Let us now discuss the Middle and late Jurassic PPs for South America (Table 1). The pole for the Middle Jurassic Chon Aike lavas (SAJ_1) reported by Vilas (1974) was computed on the basis of palaeomagnetic data for Chon Aike rocks from Puerto Deseado (Valencio & Vilas 1970), Camarones (Creer, Mitchell & Abou Deeb 1972) and Estancia La Reconquista, Argentina. All these authors noted that the Chon Aike VGPs exhibit an elongated distribution (Fig. 2a). Schult & Guerreiro (1979) reported a PP for Middle Jurassic volcanics from Maranhão, Brazil (SAJ_2). The position of this PP is close to SAJ_1 (Fig. 2b) and the authors also noted an elongated distribution of the Maranhão VGPs (Fig. 2a). Palmer, Hayatsu & MacDonald (1980b) reported a PP for Jurassic rocks (Camaraca Formation) from Arica, Chile (SAJ_3). This PP is not close to the PP for Chon Aike rocks (SAJ_1) (and also of the PP for Maranhão rocks, SAJ_2); this was interpreted by the authors as evidence of a counterclockwise rotation of Arica. We have another interpretation for this: it is the effect of a fast polar wandering shift of South America in Middle–late Jurassic time. This is based on the analysis of Figs 2 and 3. The first of these figures shows that the Chon Aike (□) and Maranhão (○) VGPs exhibit exhibit an elongated distribution roughly along meridians 20–200°E, practically coincident with the Middle Jurassic (SAP-J) – late Jurassic–early Cretaceous (SAKel) section of the apparent polar wandering path for South America (Fig. 3). Fig. 2(a) shows that most of the Camaraca VGPs (△) cluster around the youngest end of the elongated distribution of the Chon Aike and Maranhão VGPs; this explains why the position of SAJ_3 is close to that of the PP for the Rio Molino dykes (SAK_3) (Fig. 1). Fig. 2(a) also shows that the Camaraca VGPs, as a whole, also exhibit the elongated distribution. All this suggests that the relative positions of SAJ_1–SAJ_2 and SAJ_3 are an effect of a rapid polar wandering shift of South America in the Middle–late Jurassic.

Table 1. Summary of the reliable Cretaceous and Jurassic palaeomagnetic poles for South America.

Formation, Group, Subgroup or Complex	Age K/Ar Ma	Age Geology	Site Lat. (°)S	Site Long. (°)W	Palaeomagnetic poles Lat. (°)S	Palaeomagnetic poles Long. (°)E	A_{95} (°)	$d\psi$ (°)	$d\chi$ (°)	Name	References
Andacollo Series	69		37	70.6	74	65	–	6	9	SAK$_9$	Vilas & Valencio (1978a)
San Luis and Córdoba Vulcanitas	85–66		33	65	70	45	12.1	–	–	SAK$_{16}$	Valencio *et al.* (1983)
Viñita F.	65*	Early Coniacian–late Albian (?)	29.9	70.9	82	252	7	–	–	SAK$_{19}$	Palmer, Hayatsu & MacDonald (1980a)
Poços de Caldas Complex	>75, 75		21.9	46.6	81	233	–	8	13	SAK$_7$	Opdyke & MacDonald
Cabo de Sto. Agostinho	99–85		8.4	35.0	88	315	4.5	–	–	SAK$_{15}$	Schult & Guerreiro (1980)
Pirgua Subgroup	114–77		25.7	65.8	85	222	–	7	10	SAK$_6$	Valencio *et al.* (1977a)
Vulcanitas Cerro Rumipalla F.			32.2	64.1	88	146	9.0	–	–	SAK$_4$	Vilas (1976); Valencio & Vilas (1976)
Quebrada Marquesa F.	62–92	Late Neocomian	29.9	70.9	77	194	6	–	–	SAK$_{18}$	Palmer *et al.* (1980a)
Arqueros F.	–	Hauterivian–Barremian	29.9	70.9	81	165	11	–	–	SAK$_{17}$	Palmer *et al.* (1980a)
La Teta lavas	120–95		12 N	72	10	201	–	10	19	SAK$_{14}$	MacDonald & Opdyke (1972)
Maranhão basalt intrusions	118		6.5	42.0	84	81	1.9	–	–	SAK$_{13}$	Schult & Guerreiro (1979)
Serra Geral F. (RA)	–		28.8	49.9	86	107	6.1	–	–	SAK$_{12}$	Ernesto, Hiodo & Pacca (1976); Pacca *et al.* (1977)
Serra Geral F. (TA)	–		29.2	50.2	85	318	10.2	–	–	SAK$_{11}$	Pacca *et al.* (1977)
Secca Geral F. (BM)	–		29.3	50.3	80	88	7.6	–	–	SAK$_{10}$	Pacca & Hiodo (1976); Pacca *et al.* (1977)
Serra Geral F. (GB)	132–101		28.4	49.5	85	126	3.8	–	–	SAK$_8$	Pacca & Hiodo (1976); Pacca *et al.* (1977)
Serra Geral Formation	142–100		22–32	46–56	78	54	5.7	–	–	SAK$_1$	Creer (1962)
Vulcanitas Cerro Colorado F.	121		32.2	64.1	83	16	10.0	–	–	SAK$_2$	Valencio (1972); Valencio & Vilas (1976)
Almafuerte lava flows	130–120		32.2	64.3	72	25	6.0	–	–	SAK$_5$	Mendía (1978)
Río Los Molinos dykes	150–129 68–63†		31.6	64.5	78	13	8.0	–	–	SAK$_3$	Linares & Valencio (1975)
Camaraca F.	157 ± 4		18.6	70.3	71	10	6	–	–	SAJ$_3$	Palmer *et al.* (1980b)
Maranhão volcanics	158 ± 12		6.4	47.4	85	263	7	–	–	SAJ$_2$	Schult & Guerreiro (1979)
Chon Aike F.	166 ± 5		44–48	65–69	85	197	6	–	–	SAJ$_1$	Vilas (1974)

*It was suggested that this age is not a valid estimate of the time of formation.

† It was suggested that this age may be affected by argon loss.

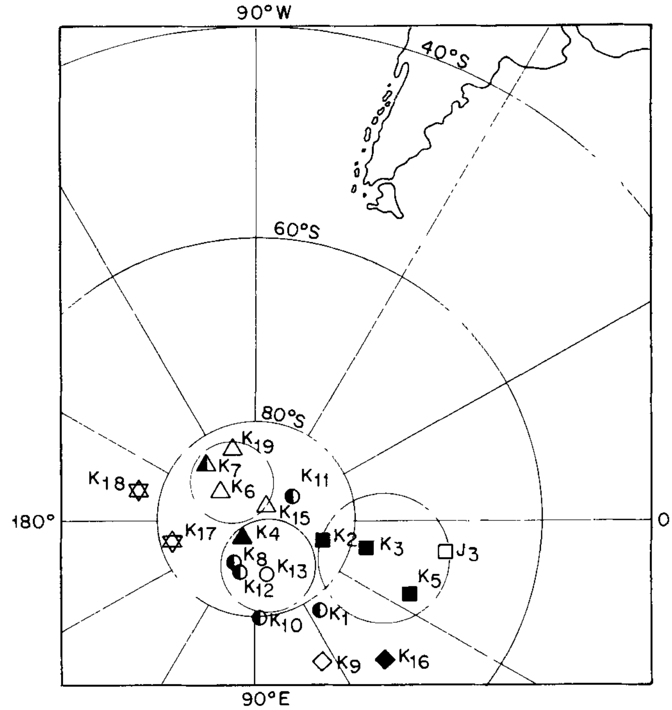

Figure 1. Late Jurassic–late Cretaceous palaeomagnetic poles for South America (Table 1). Different symbols (△, ○, □, ◇) have been used for poles forming different groups. Solid symbols: PPs from the stable area from Central Argentina; black and white symbols: PPs from the stable area of south-eastern Brazil. The A_{95} circles (Table 2) defined for the different groups are also shown (see Section 3).

The mean positions (and the statistics) of the groups formed by the Jurassic and Cretaceous PPs for South America are given in Table 2 and shown in Fig. 3. The ages assigned to these mean positions and the eldest and youngest radiometric ages obtained for igneous units of each group are also given in the table. Fig. 3 also shows the late Palaeozoic–Mesozoic section of the APWP for South America. This section defines three hairpins, namely (in chronological order): SAP–J (late early Permian–Middle Jurassic), SAKel (late Jurassic–early Cretaceous) and SAK$_{18}$ (late Neocomian). However, we should appreciate that only two of these hairpins (SAKel and SAK$_{18}$) are associated with rapid changes in the direction of the movement. The other hairpin (SAP-J) defines a sharp change in trend of the movement but this change was not necessarily rapid because SAP–J defines a quasi-static period. The positions of PPs SAK$_{16}$ and SAK$_9$ suggest a fourth hairpin; this is well defined when the Cenozoic PPs (83°S 126°E, $d\psi = 6°$ $d\chi = 7°$, 0.1–20.0 Ma, Valencio 1970; and 86°S 5°E, $\alpha_{95} = 4°$, 2.4–2.8 Ma (Valencio & Mendía 1974) are considered.

3.2 AFRICA

The PPs for Africa assigned to the Cretaceous are given in Table 3 and plotted in Fig. 4. The figure shows that these Cretaceous PPs also exhibit an elongated distribution. This had been noted before by Valencio *et al.* (1977a); the Cretaceous PPs for Africa reported in the last couple of years (AfK$_{11}$ and AfK$_{12}$, Table 3) are consistent with this. On the basis of similar reasons to those given for the South American Cretaceous PPs, we interpret this elongated

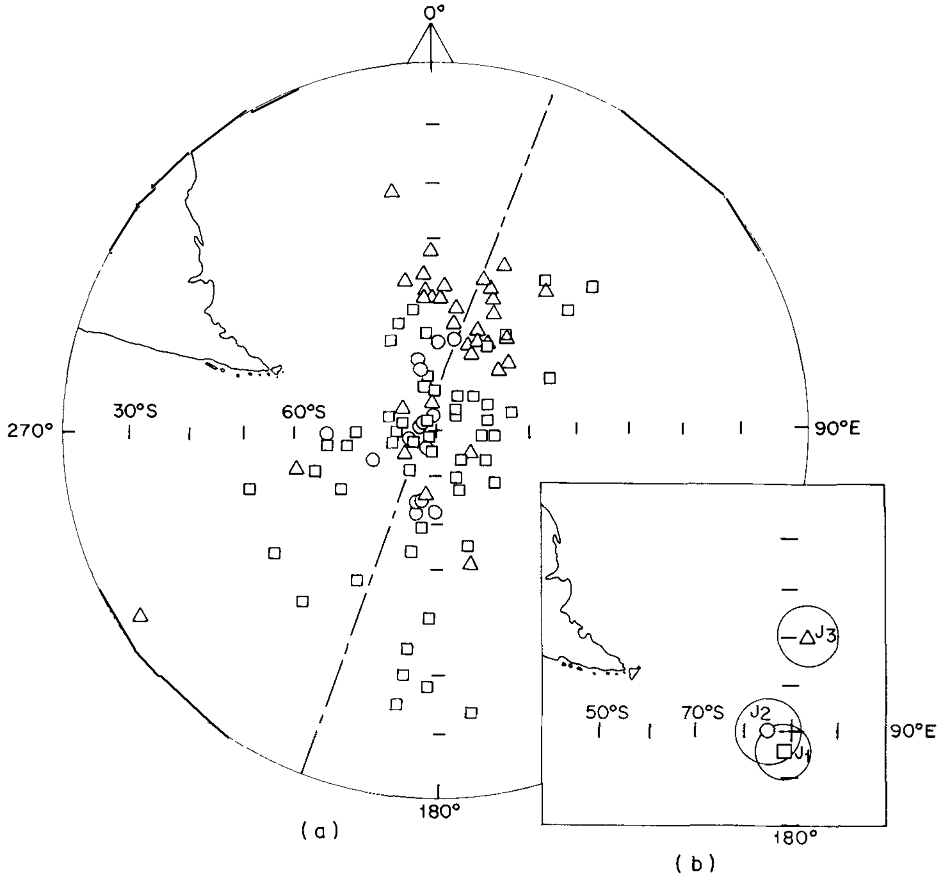

Figure 2. (a) Virtual geomagnetic poles for the middle Jurassic Chon Aike (□) and Maranhão (○) igneous rocks and the Middle–late Jurassic Camaraca rocks (△); these VGPs exhibit an elongated distribution roughly along meridians 20–200°E. (b) Jurassic palaeomagnetic poles for the Chon Aike (SAJ_1), Maranhão (SAJ_2) and Camaraca rocks (SAJ_3); note that they are roughly distributed along meridian 20–200°E.

distribution as due to apparent polar wander. The mean positions of the groups formed by the late Jurassic (?) to late Cretaceous PPs for Africa are given in Table 2 and shown in Fig. 5. Fig. 4 shows the A_{95} circles of confidence of these mean positions. In Fig. 5 the late Palaeozoic–early Mesozoic section of the APWP for Africa is also shown. The figure shows that the late Palaeozoic–Cretaceous section of the APWP for Africa defines three hairpins, namely (in chronological order): AfP-J (Permian to Middle–late Jurassic), AfK_4 (older than Aptian, younger than Middle Jurassic) and AfK (early late Cretaceous). Two of these (AfK_4 and AfK) are associated with rapid changes in the direction of movement. The other hairpin is associated with a quasi-static period (AfP-J) and therefore the change in trend of the movement was not necessarily rapid.

4 Discussion

4.1 EVIDENCE FOR PRE-DRIFT MOVEMENTS WITHIN WESTERN GONDWANA?

It is widely accepted that South America and Africa were jointed by their Atlantic litorals (to form Western Gondwana) in late Palaeozoic–early Mesozoic times and that the opening

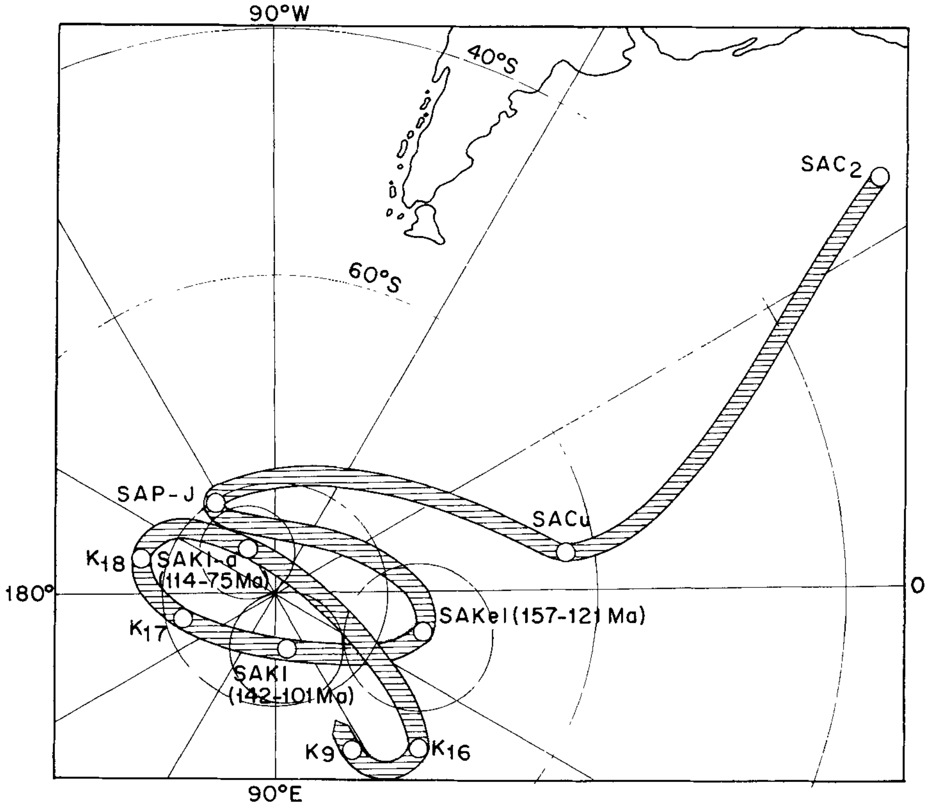

Figure 3. Late Palaeozoic to late Cretaceous PPs (Tables 1 and 2) and apparent polar wandering path for South America. SAC_2 is the PP for the Moscovian Taiguati Formation; SACu is the mean position for the group formed by the late Carboniferous (Stephanian) PPs; and SAP-J is the mean position for the time group (reflecting a quasi-static period) formed by the late early Permian to Middle Jurassic PPs (includes SAJ_1 and SAJ_2) (Valencio, Vilas & Mendía 1977b and Vilas 1981).

of the South Atlantic occurred in early Cretaceous time. With these premises in mind we shall discuss the geodynamic significance of the late Palaeozoic to late Cretaceous PPs for South America and Africa.

Fig. 6 shows the PPS and APWPs for South America and Africa plotted on the reconstructions of Western Gondwana suggested by Vilas & Valencio (1977) (Fig. 6a, based on the fitting of palaeomagnetic data) and Smith & Hallam (1970) (Fig. 6b, based on the fitting of the 500 fathom line). The figure shows that the fitting of the late Palaeozoic and early Mesozoic PPs (SACu with AfPC, and, SAP-J with AfP-J, respectively) on reconstruction (a) is much better than that on reconstruction (b). The fitting is consistent with the existence of Western Gondwana in late Carboniferous–early Mesozoic times. However, on reconstruction (a) the overlapping of the mean polar positions SAKl-u (114–75 Ma) and AfKl (122–109 Ma) (about 100 per cent at the 95 per cent confidence limit) suggests that the South Atlantic was not yet open in late early Cretaceous time; this is not consistent with seafloor spreading and palaeontological data (see Section 2).

On reconstruction (b) the different positions of SAKl-u and AfKl (about 4 per cent of overlapping at the 95 per cent confidence limit) indicates that the South Atlantic was open in late early Cretaceous time (about 122 Ma) and this is consistent with seafloor spreading and palaeontological data. On the other hand the position of the PP for the Kaoko lavas

Table 2. Mean position of the groups formed by the Jurassic–late Cretaceous palaeomagnetic poles for South America and Africa.

Name	Group	Age	Lat. (°)S	Long. (°)E	N	A_{95} (°)	k	Palaeomagnetic poles which form the group	References
SAKl-u	Time	Late early to early late Cretaceous (114–75 Ma)	86	238	5	4.3	317	$K_4, K_6, K_7, K_{15}, K_{19}$	
SAKl	Age	Early Cretaceous (142–101 Ma)	85	75	6	5.0	179	$K_1, K_8, K_{10}, K_{11}, K_{12}, K_{13}$	
SAKel	Age	Late Jurassic–early early Cretaceous (157–121 Ma)	76	16	4	6.6	190	K_2, K_3, K_5, J_3	
SAP-J	Time	Late early Permian–Middle Jurassic	82	252	18	4.0	74		Vilas (1981)
AfKu	Age	Late Cretaceous	61	47	3	8.3	211	K_8, K_9, K_{10}	Vilas & Valencio (1978b) and this paper
AfK	Time	Late early Cretaceous – late Cretaceous	77	32	4	5.1	328	K_3, K_6, K_7, K_{11}	
AfKl	Age	Early Cretaceous (122–109 Ma)	61	81	2	4.8	2147	K_1, K_2	Vilas & Valencio (1978b)

An age group is formed by PPs of the same age; a time group is formed by PPs whose ages are different but cover a period of time, reflecting a quasi-static period (Valencio & Vilas 1972).

Table 3. Summary of the Cretaceous palaeomagnetic poles for Africa.

Formation, Group, Series or site	Age	Site		Pole position					Name	References
		Lat. (°)	Long. (°)	Lat. (°)S	Long. (°)E	A_{95} (°)	$d\psi$ (°)	$d\chi$ (°)		
Kimberlite pipes	Late Cretaceous	29 S	25 E	58	57	–	–	–	AfK_{10}	McElhinny & Brock (1975)
Sicily, volcanics	Late Cretaceous	36.7 N	15.1 E	62	44	–	3	6	AfK_9	Barberi *et al.* (1974)
Nubian sandstone, Wadi Natash	Late Cretaceous	24.5 N	34.2 E	63	38	–	3	6	AfK_8	Shazly & Krs (1973)
Nubian sandstone Aswan	Late Cretaceous	25 N	33 E	80	47	–	4	6	AfK_{11}	Schult, Soffel & Gouda Hussein (1978)
Nubian iron ores	Late Cretaceous	24 N	33 E	75	23	–	6	11	AfK_7	Shazly & Krs (1973)
Tororo Ring Complex	Cretaceous (?) pre-Miocene	0.8 N	34.2 E	76	15	9	–	–	AfK_3	Raja & Vise (1973)
High Atlas red sandstone	Older than Cenomanian	31.7 N	6.9 W	75	47	8	–	–	AfK_6	Hailwood (1975)
Lupata Alkaline Volcanics	Early Cretaceous 109 Ma	16.5 S	34 E	62	80	4	–	–	AfK_2	Gough & Opdyke (1963)
Mlanje Sienite	Early Cretaceous 122 Ma	16 S	35.5 E	60	82	12	–	–	AfK_1	Briden (1967)
Kaoko Lavas	Early Cretaceous 136–114 Ma	20 S	14 E	48	87	3	–	–	AfK_5	Gidskehaug *et al.* (1975)
Atlas Beni Mellal Volcanics	Older than Aptian, younger than Middle Jurassic	32.2 N	66 W	44	71	10	–	–	AfK_4	Bardon *et al.* (1973)

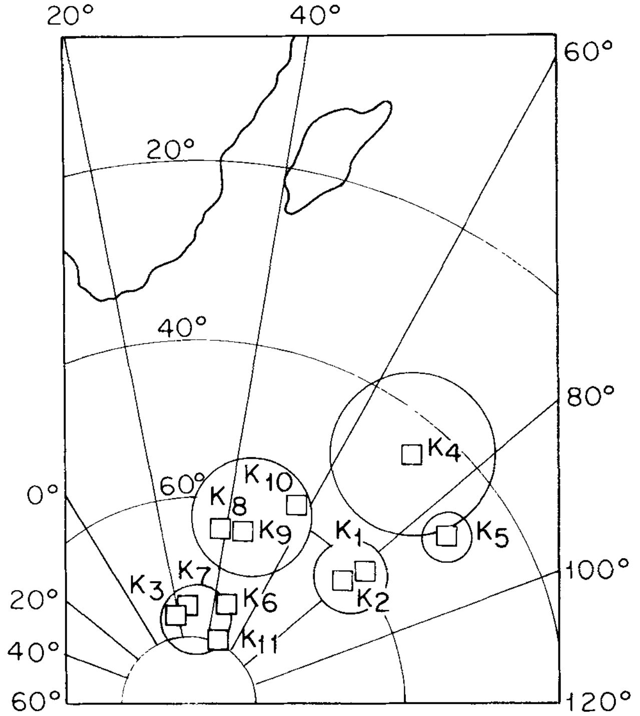

Figure 4. Cretaceous palaeomagnetic poles for Africa (Table 3). A_{95} circles (Table 2) defined for the different groups of PPs are also shown.

(AfK$_5$) fits very well with the mean position of the PPs for Serra Geral lavas (SAKl) (much better than in reconstruction (a)); this is consistent with the interpretation that these igneous rocks formed part of the same lava field in Western Gondwana. Briefly, reconstruction (b) is not consistent with the late Palaeozoic–early Mesozoic palaeomagnetic data for South America and Africa, but is consistent with the Cretaceous geological, seafloor spreading and palaeontological data.

Therefore, the comparison of the reliable PPs for South America and Africa assigned to the late Palaeozoic and Mesozoic, taking into account the restrictions established by geological, palaeontological and seafloor spreading data, suggests that minor movements could have occurred within Western Gondwana before its fragmentation. Such movements would have occurred along the narrow zone which later became the South Atlantic divergent boundary. These movements would have occurred within the period Middle–late Jurassic and as a consequence of them the configuration of Western Gondwana would have changed from one similar to that in Fig. 6(a) (Vilas & Valencio 1977) to another similar to that in Fig. 6(b) (Smith & Hallam 1970). Roughly, such minor movements would have implied a compression in the south and a shearing in the north. As these movements would have occurred early in the development of the South Atlantic Ocean basin, they could be related with the early phases of the process of thinning of the Western Gondwana crust along the narrow zone which became the initial South Atlantic rift valley and, later, the rifting edges of South America and Africa. McConnell (1974) indicated that the rift faults of an incipient divergent boundary commonly follow and reactivate old structures. It is then tempting to correlate the structures produced by the predrift movements within Western

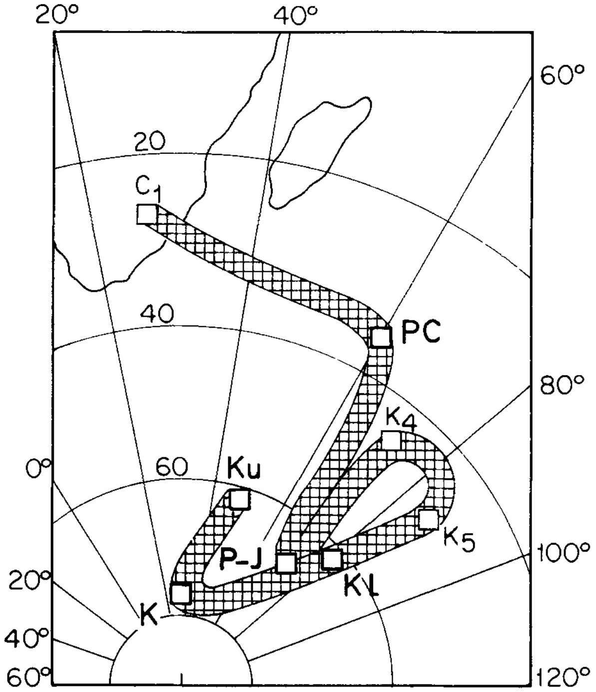

Figure 5. Late Palaeozoic to late Cretaceous PPs (Tables 2 and 3) and apparent polar wandering path for Africa. AfC$_1$ is the PP for the Carboniferous Dwyka Formation; AfPC is the mean position for the group formed by the Permocarboniferous PPs; and AfP-J is the mean position for the time group (reflecting a quasi-static period) formed by the late Permian to Jurassic PPs (Vilas & Valencio 1978b).

Gondwana with those which were reactiviated during the grabening phase of the South Atlantic divergent boundary.

4.2 THE CONSISTENCY OF PALAEOMAGNETIC AND SEAFLOOR SPREADING DATA

The South Atlantic seafloor spreading data can be used to check the APWPs for South America and Africa in late early–early late Cretaceous time: the movements indicated for these continents by the PPs should be consistent with the movements indicated for the South American and African plates by seafloor spreading data. The different positions of SAKl-u (114–75 Ma) and AfKl (122–109 Ma) (Fig. 6b) indicate that the relative movements of South America and Africa had started in late early Cretaceous time. South America had a quasi-static period in late early–early late Cretaceous time (SAKl-u); during the same period, or part of it, Africa moved following the path AfKl-AfK (Fig. 7). This should be consistent with the movements indicated for the South American and African plates, in the same period (roughly 120–80 Ma), by the seafloor spreading data. To check this, let us reproduce the movements of the South American and African plates in that period and assume that we observe them from Africa. If there is consistency, an observer situated on Africa will see SAKl-u (attached to South America) following a path similar to AfKl-AfK when South America follows a movement similar to that suggested by seafloor spreading data. Based on South Atlantic floor spreading data Le Pichon & Hayes (1971) and Larson & Ladd (1973) have shown that the relative movements of South America and Africa in the

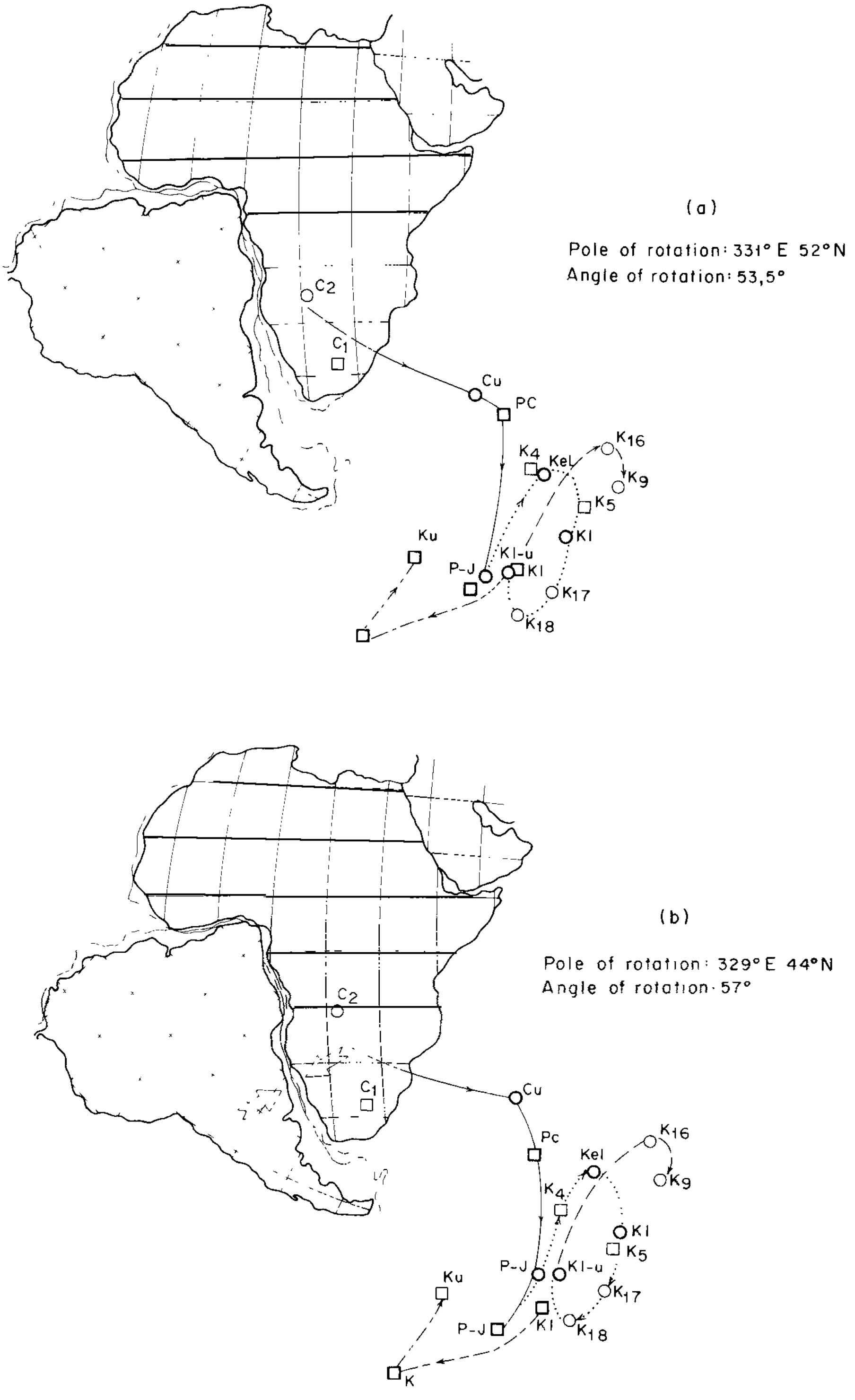

Figure 6. Comparison of the late Palaeozoic and Mesozoic PPs and apparent polar wandering curves for South America (○) and Africa (□) on the reconstructions of Western Gondwana presented by Vilas & Valencio (1977) (a) and Smith & Hallam (1970) (b). References as in Figs 3 and 5.

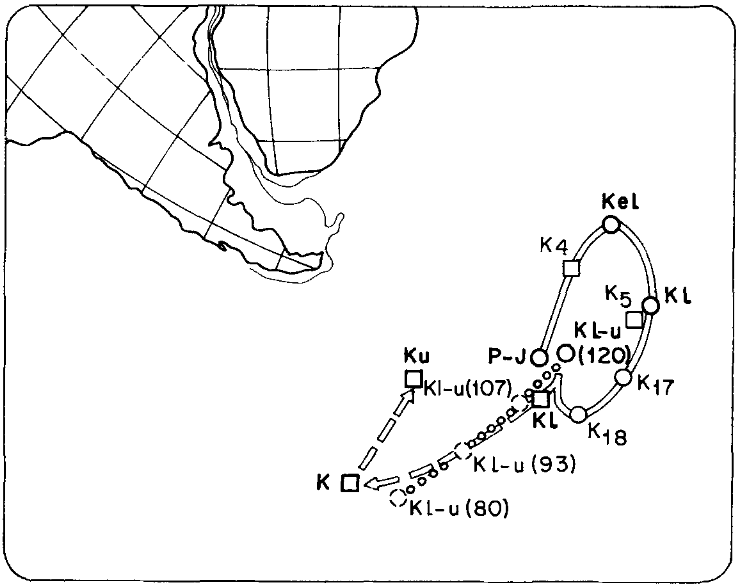

Figure 7. Consistency of the late early–early late Cretaceous palaeomagnetic poles for South America (○, Kl-u) and Africa (□, Kl→K) and the South Atlantic floor spreading data. It is shown by the similarity of the observed (dashes) and theoretical (dots) apparent polar wandering paths for Africa (see Section 4.2).

period 127–80 Ma are defined by a pole of rotation situated at 21.5°N 346°E and an angle of rotation of 29.9°. That is, if we give this rotation to South America and its pole SAKl-u, the theoretical APWP defined by this pole (SAKl-u/120 Ma→107 Ma→93 Ma→80 Ma, Fig. 7) should be similar to the African APWP AfKl→AfK, if the South Atlantic floor spreading data and the palaeomagnetic poles are consistent. Fig. 7 shows that the theoretical and the observed APWPs for Africa are similar; therefore we conclude that the mean PPs for South America and Africa within the period 120–80 Ma are consistent with seafloor spreading data.

4.3 HAIRPINS AND GEODYNAMICS

Fig. 6 shows that the late Palaeozoic–early Cretaceous section of the APWP for Western Gondwana defines three hairpins, namely in chronological order: SAP-J, SAKel and SAK_{18}. The Cimerian orogeny, particularly the Nevadic phase, might correspond to the first of these hairpins. The minor movements which would have affected Western Gondwana and changed its configuration from that of Fig. 6(a) to that of Fig. 6(b), might also be correlated with this hairpin. The second hairpin (SAKel, late Jurassic–early Cretaceous) may be correlated with the first fragmentation of Gondwana (separation of South America–Africa–India from Australia–Antarctica, Vilas & Valencio 1977). However, we should appreciate that there are no early Cretaceous PPs for Australia and Antarctica and therefore we cannot know whether that separation occurred in late Jurassic or early Cretaceous times. The third hairpin (SAK_{18}, late Neocomian) can be correlated with the fragmentation of Western Gondwana: the different positions of the younger PPs SAKl-u and AfKl indicate that the South Atlantic was formed shortly after this hairpin.

Another hairpin (SAK_{16}) (see Section 3) is defined in the late Cretaceous section of the APWP for South America; this hairpin may be correlated with the origin of the Andean orogeny.

4.4 THE SIGNIFICANCE OF THE MAGNETOSTRATIGRAPHY

The geological evidence suggests that Serra Geral lava flows formed in different phases of the major magnetic episode and that in some of these phases the lava flows could pour out so rapidly that intercalated sediments are not present. This is also valid for the sequences of Cretaceous igneous rocks from Córdoba (Argentina).

The comparison of the magnetic stratigraphy for some of the sequences of the Cretaceous rocks and the time-scale for the reversals of the geomagnetic field (Fig. 8) can be useful to

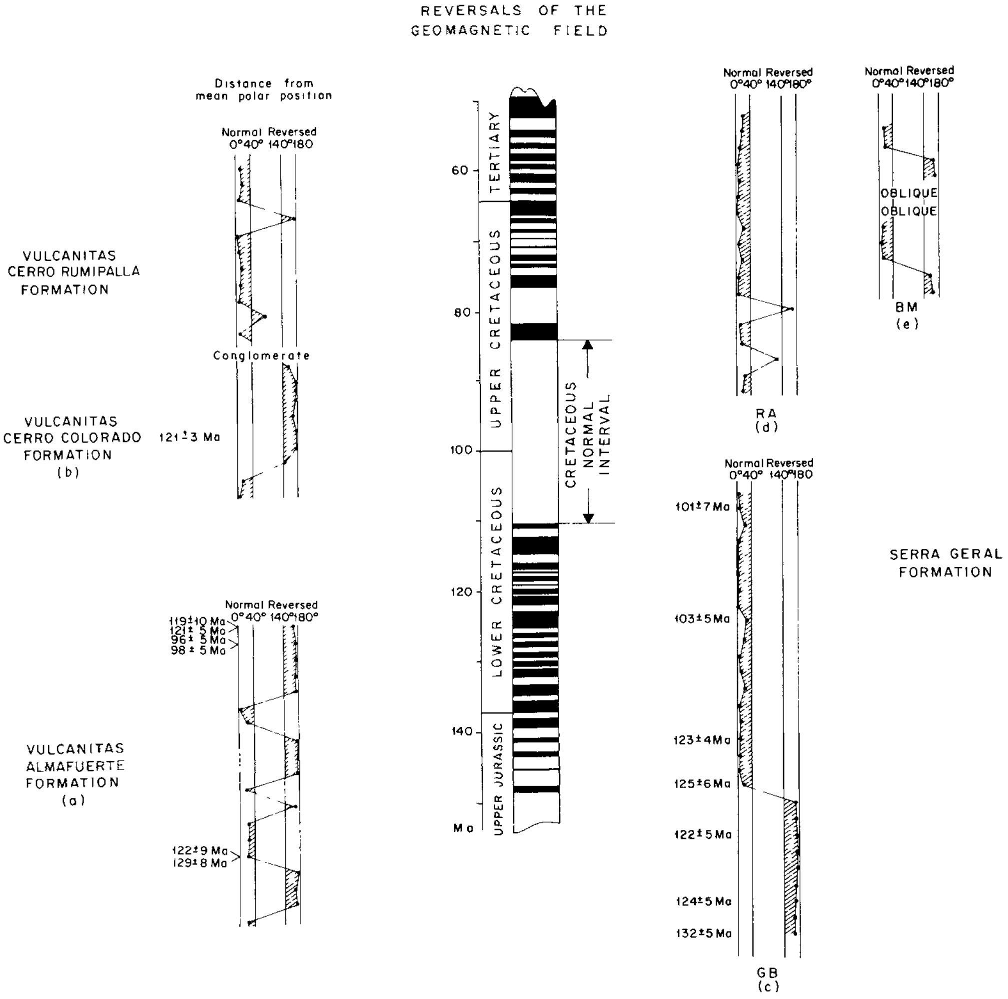

Figure 8. Comparison of the magnetostratigraphy for sequences of Cretaceous rocks from South America and the reversals of the geomagnetic field. ▭,normal polarity; ■,reversed polarity. The vertical scale is schematic: the same vertical equidistance was given for the different lave flows. The reversals time-scale is that of McElhinny (1977). GB: Guatá-Bom Jardim; RA: Turvo Encruzilhada das Antas, and BM: Barra do Ouro–Morrinhos.

know more about the magmatic episode which affected South America in late Jurassic–Cretaceous time. Fig. 8 shows the magnetic stratigraphy for six of these sequences (the magnetic stratigraphies for the Vulcanitas Cerro Colorado and Vulcanitas Cerro Rumipalla Formations are presented in the same profile; a polymict orthoconglomerate, about 60–80 m thick, lies in between these formations). We should note that the continuity in the drawings does not imply stratigraphic continuity.

Radiometric data suggests that the Almafuerte lava flows were formed within the period 129 ± 8–121 ± 5 Ma. Seven reversals of the geomagnetic field are recorded within the sequence of these lava flows (Fig. 8a). We should note that the number of reversals could even be larger, as sediments are intercalated in between the Almafuerte lava flows. This is consistent with the number of reversals of the geomagnetic field that occurred within that period (Fig. 8). This is also the case for the composite sequence of Vulcanitas Cerro Colorado and Vulcanitas Cerro Rumipalla rocks (Fig. 8b).

One reversal of the geomagnetic field is recorded within the sequence of Serra Geral lava flows exposed at Guatá-Bom Jardin, which is the thickest of all the sequences of rocks of this formation included in this report (Fig. 8c). The radiometric ages suggest that these lava flows were formed in at least two magmatic phases around 132 ± 5–123 ± 4 Ma and 103 ± 5 Ma. The normal stable remanence of the youngest lava flows of the sequence (103 ± 5 Ma) should be correlated with the Cretaceous quiet interval of normal polarity. On the other hand the number of reversals recorded in the oldest lava flows is not consistent with the number of reversals of the geomagnetic field that occurred in the same period of time. This is also valid for the number of reversals of the geomagnetic field recorded within the other sequences of Serra Geral rocks (Turvo Encruzilhada das Antas and Barra do Ouro-Morrinhos, Figs 8d and 8e, respectively) if we accept that they formed during the main phase of the Serra Geral magmatic episode (Amaral *et al.* 1966). However, we cannot rule out the possibility that the normal stable remanence recorded in the highest Serra Geral lava flows at Turvo Encruzilhada das Antas can be correlated with the Cretaceous Normal Interval. That is, the lava flows of the lowest part of the sequences of Serra Geral rocks at Guatá-Bom Jardim and Turvo Encruzilhada das Antas and the sequence of laval flows at Barra do Ouro-Morrinhos did not record all the reversals of the geomagnetic field that occurred in early Cretaceous time. This points out a difference with the Argentinian sequences of lavas and suggests that the Serra Geral lava flows included in this study poured out rapidly, without significant interruption, during the main magmatic episode (the absence of oblique directions recorded in these sequences supports his interpretation).

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