Palaeomagnetic Data from the Gondwanic Continents

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The considerable palaeomagnetic data from the Gondwanic continents, Africa, Antarctica, Australia, India and South America, are critically examined and shown to support the hypothesis of continental drift.

Palaeomagnetic latitudes for Australia, traced by Irving and his colleagues from the late Precambrian to Recent times, indicate that Australia was near the equator in the Devonian and close to the Pole during the Permo-Carboniferous. During the Mesozoic and Tertiary it drifted northwards to its present position. Gough and his colleagues in Southern Rhodesia have recently concluded that since the middle of the Mesozoic the palaeomagnetic latitude of Africa has remained appreciably unchanged, but they find evidence of a marked drift northwards to its present latitudes from polar latitudes during the Permian and early Mesozoic. From my own studies of South American rocks I have deduced that there has been little movement of South America relative to the pole since the Triassic-Jurassic, but that a sharp change in magnetic latitude took place during the Lower and Middle Permian. Results from Devonian and Silurian rocks indicate that in those times northeast Brazil was closer to the pole than Tierra del Fuego. The movement of South America relative to the pole during the Permian was thus a continuation of an Upper Palaeozoic polar shift.

In the Triassic-Jurassic, basaltic lavas and diabase dykes were extruded and intruded into parts of all the Gondwanic continents. Palaeomagnetic studies have been made on these rocks from all five continents. The palaeolatitudes and palaeoazimuths so deduced are consistent neither with the present positions of these continents, nor with the suggestion that they were then adjacent to one another. A possible reconstruction satisfying the restrictions imposed by the palaeomagnetic data shows these continents occupying positions between those suggested by geologists for the Permo-Carboniferous and their present positions, and it is inferred that the continents as we know them today had separated and had started moving towards their present positions when this igneous activity occurred.

For the Palaeozoic era reliable palaeomagnetic data have, as yet, been obtained only for the Devonian, Silurian and Cambrian of Australia and South America. There is one not very well established Silurian result for South Africa. The consistency of these data with reconstructions of Gondwanaland based on geology is examined. Both du Toit's and J. T. Wilson's reconstructions are considered.

1. THE PALAEOMAGNETIC METHOD

Palaeomagnetic studies of many suites of Quaternary and Tertiary Igneous rocks have indicated that secular variations of the geomagnetic field from a postulated axial and dipolar main field average zero during 'palaeomagnetic instants' of 10^4 to 10^5 y (Creer 1962*a*). These experimental results prove that the geomagnetic field was axial and dipolar, on the average, throughout the Tertiary and Quaternary, and as a working hypothesis the geomagnetic field is supposed to have maintained this character during Phanerozoic time. This hypothesis is fundamental to the application of rock magnetism to geology. It is reasonably well founded theoretically. A palaeomagnetic survey of a suite of rocks representing at least 10^4 y thus provides information from which may be determined: (1) the palaeomagnetic latitude, L, of the site, and (2) the palaeomeridian direction. The former is related to the average value of the inclination of the fossil remanent magnetization to the ancient horizontal by the formula $\tan L = \frac{1}{2} \tan I$ and the latter used to lie parallel to

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the component of the fossil remanent magnetization in the ancient horizontal plane (e.g. bedding plane). Care must, of course, be taken to ensure that the magnetic vector measured was acquired during one 'palaeomagnetic instant' of geological time, that it is not composite and that it has been stable. The position of the geographical pole corresponding to a particular 'palaeomagnetic instant' may be calculated using the axial dipole field hypothesis (Creer, Irving & Runcorn 1957). Pole positions have usually been plotted on the present latitude-longitude grid system, and curves connecting poles corresponding to successive intervals of geological time are referred to as polar wandering curves. The supposed axial symmetry of the palaeomagnetic field prohibits the determination of the difference in palaeolongitude of any two continents at a particular geological time. However, if we have data for any two continents for a sequence of geological times, their polar wandering curves can be compared. If the continents have not moved relative to each other, their polar wandering curves will have the same shape, and by fitting them together an unambiguous reconstruction can be made, using palaeomagnetic data alone (see Creer 1964*a*, *b* and Graham, Helsley & Hales 1964).

2. Palaeomagnetic studies of South American rocks

Palaeomagnetic surveys were made in 1956, 1958 and 1963 and the results of the earlier two have been previously reported (Creer 1958, 1962*b*, *c*). In the last of these publications data computed from first measurements on several rock formations were listed and it was pointed out that many of these had been remagnetized by the recent palaeomagnetic field. Since then thermal and a.c. field experiments have been carried out on some of these rocks and the secondary magnetization has been destroyed. The data so obtained are contained in table 1, and for certain formations the changes produced by thermal demagnetization are indicated. Data from Peru, reported in Creer (1962*c*) are now not thought to represent the palaeomagnetic field because it has not yet been possible to correct for the complex geological structure, and so they are not included here.

Table 1. Summary of South American palaeomagnetic data

		locality		direction of magnetization				palaeo-latitude of Brasilia	pole position				
ref. no.	rock unit and age	lat. (° S)	long. (° W)	D (°)	I (°)	α (°)	number of sites* or samples N	L (° S)	lat.	long.	α (°)	polarity	treatment
1	Cambrian red beds	23	66	24	+18	47	17	—	—	—	—	R	natural
				17	+56	14		44	27° N	50° W	10	R	thermal
2	Urucum formation (Silurian)	19	58	60	+39	19	23	—	—	—	—	R	natural
				37	+41	9		31	34° N	16° W	9	R	thermal
3	Devonian red beds	23	66	27	+47	18	22	—	—	—	—	R	natural
				56	+51	8	10	52	9° N	22° W	10	R	thermal
4	Taiguati formation (Pennsylvanian)	17	65	294	−72·5	5	38	75	28° S	34° W	9	N & R	thermal
5	Piaui formation (Pennsylvanian)	5	43	143	+60	8	42	—	—	—	—	R	natural
				165	+44	9	20	34	65° S	13° W	10	R	thermal
6	Permian red beds	30	68	160	+66	4	53	35	65° S	13° W	6	R	thermal
7	Serra Geral (140 My)	22 32	46 56	347	−38	5	30*	10	78° S	54° E	4	N & R	a.c.
8	Kimeridgian red beds	38	71	4	−57	23	7	16	86° S	172° E	25	N	natural
9	Quaternary basalts	39	71	1	−61	5	58	16	83° S	126° E	6, 7	N & R	a.c.

The changes in palaeolatitude and orientation of South America deduced from these results are illustrated in figure 1. This was constructed by drawing an outline of the

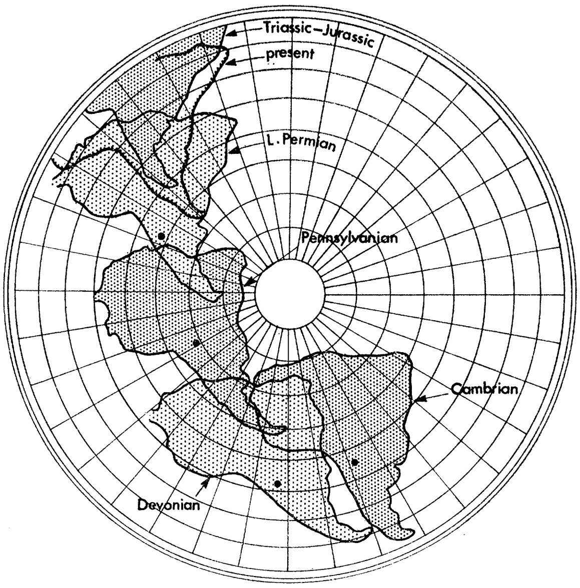

FIGURE 1. Palaeolatitudes and orientations of South America deduced from the magnetism of rocks.

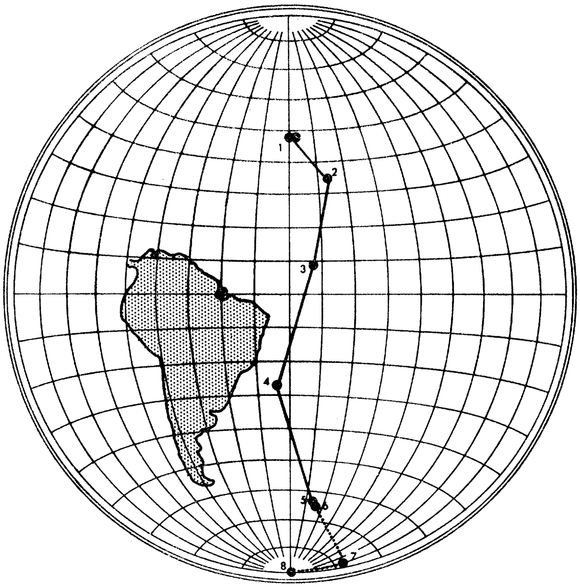

FIGURE 2. Movement of South Pole relative to South America deduced from magnetism of South American rocks.

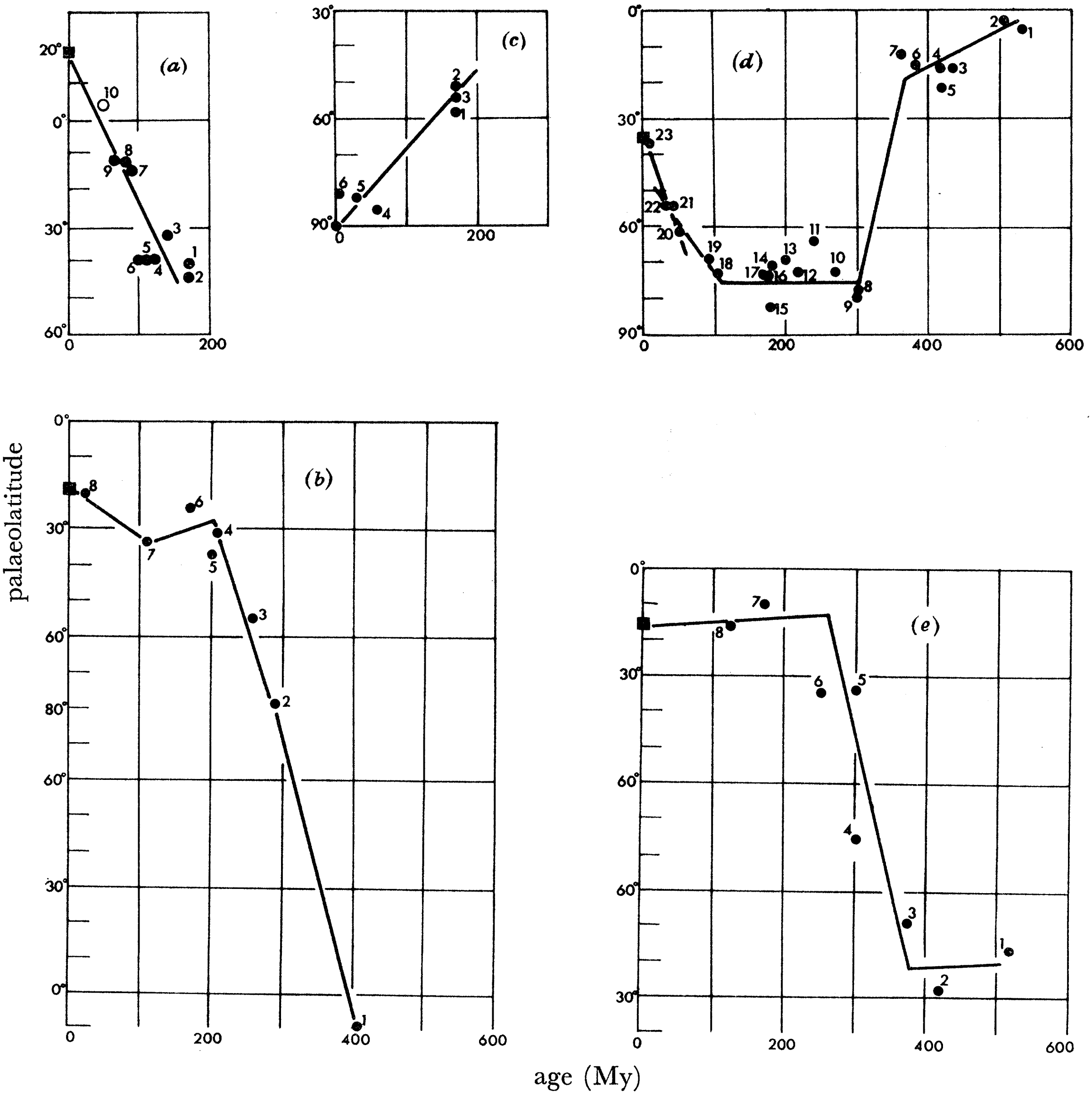

FIGURE 3. Palaeolatitudes of (a) Bombay, (b) Salisbury, (c) the present South Pole, (d) Canberra, and (e) Brasilia. See text for explanation.

continent on a transparent fibreglass hemispherical shell and placing it in the positions indicated by the palaeomagnetic results on a 50 cm globe marked with a latitude-longitude grid system. It is seen that a sequence of longitudes can be chosen such that the palaeomagnetic results can be explained by a movement of South America across the South Pole.

TABLE 2. SUMMARY OF AFRICAN PALAEOMAGNETIC DATA

		locality		direction of magnetization			palaeolatitude of Salisbury	pole position			
no.	formation	lat. (° S)	long. (° E)	*D* (°)	*I* (°)	α (°)	*L*	lat. (° S)	long.	α (°)	ref.
1	Silurian red beds	33	28	342	−3·5	6	10° N	50	11° W	4	*a*
2	Dwyka varved clays	18	29	360	−81	6	—				*b*
	(U. Carboniferous)			333	+76	7					
				(310	+86)	—	71° S	17	23° E	—	mean
3	Ecca red beds (L. Permian)	10	29	141	+65	11	55° S	38	65° E	16	*c*
4	Shawa Ijolite (209 My)	19	31·5	335	−52	11	31° S	64	85° E	14	*d*
5	Triassic red beds	16	28	350	−56	5	37° S	68	50° E	6	*e*
6	Karroo and Stormberg lavas	26–32		339	−55	6	24° S	67	98° E	4	*f*
	(140–190 My)		26–30								
7	Lupata volcanics (109 My)	16	34	336	−54	2	34° S	62	79° E	4	*g*
8	Miocene volcanics	1	37	8	−5	10	20° S	82	43° W	5, 10	*h*
9	Plio-Pleistocene	1–9	34–37	—	—	—	19° S	76	40° W	8	*h*

References: (*a*) Graham & Hales (1961); (*b*) Irving (1960); (*c*) Opdyke (1964*a*); (*d*) Gough & Brock (1964); (*e*) Opdyke (1964*b*); (*f*) van Zijl, Graham & Hales (1962); (*g*) Gough & Opdyke (1963); (*h*) Nairn (1964).

TABLE 3. SUMMARY OF AUSTRALIAN PALAEOMAGNETIC DATA

		locality		direction of magnetization			palaeo-latitude of Canberra	pole position			
no.	formation	lat. (° S)	long. (° E)	*D* (°)	*I* (°)	α (°)	*L* (°)	lat. (° S)	long.	α (°)	ref.
1	Antrim Plateau basalts (L. Cambrian)	16	128	53	− 2	12	5	36	26° E	6, 12	*a*
2	Elder Mt. sandstone (M. Cambrian)	16	128	231	−15	10	2	34	16° E	5, 10	*a*
3	Mugga porphyry (Silurian)	35	149	26	−30	22	16	60	23° E	14, 24	*a*
4	Ainslie volcanics (Silurian–Devonian)	35	149	17	−30	12	16	66	12° E	7, 13	*a*
5	Igneous rocks (A.C.T.) (Silurian–Devonian)	35	149	12	−37	6	21	71	8° E	14, 24	*b*
6	Murrumbidgee series (M. Devonian)	35	149	40	−29	10	15	58	29° E	5, 11	*b*
7	Nethercote basalts (U. Devonian)	37	150	5	−23	29	12	65	20° W	8, 15	*b*
8	Kuttung varvoids	33	151	270	−84	6	78	32	165° E	12	*a*
9	Kuttung lavas (U. Carboniferous)	33	151	5	−85	8	80	43	150° E	16	*a*
10	L. Marine latites (L. Permian)	32	151	230	+76	2	63	46	122° E	5	*c*
11	U. Marine latites (U. Permian)	32	151	232	+81	6	64	44	132° E	12	*c*
12	Chocolate shales (L. Triassic)	34	151	338	−82	7	73	49	160° E	14	*d*
13	Brisbane tuff (M. Triassic)	28	150	11	−74	6	69	57	143° E	11	*e*
14	Gingenbullen dolerite (Triassic–Jurassic)	34	150	190	+80	8	71	53	144° E	15	*f*
15	Gibraltar syenite (L-M. Jurassic)	34	151	27	−86	12	83	41	146° E	24	*f*
16	Prospect dolerite (168 My)	34	151	359	−81	7	73	51	151° E	13	*f*
17	Tasmanian dolerites (170 My)	42	146	318	−84	3	73	51	160° E	6	*d*
18	Cygnet complex (102 My)	43	147	314	−85	5	73	50	158° E	10	*e*
19	Mt. Dromedary complex (93 My)	36	151	19	−79	5	69	56	138° E	9	*e*
20	Older volcanics	38	145	17	−73	7	61	67	137° E	11, 12	*a*
21	Basalts of N.S.W.	42	147	190	+70	14	54	63	137° E	20	*g*
22	Tasmanian basalt (Tertiary)	—	—	12	−72	17	54	73	125° E	25, 29	*h*
23	Newer volcanics	38	143	3	−60	5	37	86	102° E	6, 7	*a*

References: (*a*) Irving (1960); (*b*) Irving (1961); (*c*) Irving & Parry (1963); (*d*) Irving (1963); (*e*) Robertson (1963); (*f*) Irving (1962*b*); (*g*) Irving (1962*a*); (*h*) Irving & Stott (1963).

This movement appears to have occurred during the Upper Palaeozoic. Not all the data contained in table 1 have been used in figure 1, because the outlines would have overlapped too much. However all the data are consistent with the movement illustrated. This can be seen in figure 3 (*e*) where the change in palaeolatitude of Brasilia with geological time is illustrated. Palaeolatitude is plotted along the ordinate in such a way that the single trend of movement indicated in figure 1 is revealed. Going back in time, the palaeolatitude of Brasilia increased from its present value of 16° S to about 70° S in the Pennsylvanian and then decreased during the Lower Palaeozoic. The representation of palaeomagnetic data by palaeolatitude curves is not entirely satisfactory because only part of the data are illustrated. That a particular palaeolatitude of, say, 30° S is associated with quite different orientations of the palaeomeridian in the Upper and Lower Palaeozoic is clear from figure 1. The ordinate of figure 3 is constructed so as to take this into account.

3. PALAEOLATITUDES OF THE GONDWANIC CONTINENTS

The palaeomagnetic data used to construct the palaeolatitude curves in figure 3 are summarized in tables 2 to 5.

TABLE 4. SUMMARY OF INDIAN PALAEOMAGNETIC DATA

		locality		direction of magnetization			palaeo-latitude of Bombay	pole position			
no.	formation	lat.	long.	*D* (°)	*I* (°)	*α* (°)	*L*	lat. (° S)	long. (° E)	*α* (°)	ref.
1	Rajmahal traps	25° N	88° E	327	−62	8·5	40° S	15	112	12	*a*
2	Sylhet traps	25° N	91° E	332	−59	7	44° S				*b*
3	Deccan traps	Linga 22° N	79° E	164	+48	2	31° S	37	97	3, 2	*c*
4	,, ,,	Khandala 18·5° N	73·5° E	147	+58	3	39° S	25	101	5, 4	*c*
5	,, ,,	Nipani (L) 16·5° N	74° E	168	+60	4	39° S	35	85	6, 5	*c*
6	,, ,,	Amba (L) 17° N	73·5° E	144	+60	5	39° S	22	103	6, 5	*c*
7	,, ,,	Nipani (U)		338	−32	4	14° S	52	110	5, 3	*c*
8	,, ,,	Amba (U)		335	−26	7	12° S	52	116	8, 4	*c*
9	,, ,,	Pavagadh (L) 22·5° N	71·5° E	351	−16	7	12° S	58	89	8, 4	*c*
10	,, ,,	Pavagadh (U)		335	+17	7	5° N	75	91	8, 4	*c*

References: (*a*) Radhakrishnamurty (1963); (*b*) Athavale, Radhakrishnamurty & Sahasrabudhe (1963); (*c*) Deutsch, Radhakrishnamurty & Sahasrabudhe (1958).

TABLE 5. SUMMARY OF PALAEOMAGNETIC DATA FROM ANTARCTICA

		locality		direction of magnetization			pole position		
no.	formation	lat. (° S)	long.	*D* (°)	*I* (°)	*α* (°)	lat. (° S)	long.	*α* (°)
1	Jurassic dolerite intrusions, Ferrar glacier	78	161° E	256	−76	3	58	142° W	5, 5
2	Jurassic dolerite intrusions, Wright Valley	78	162° E	262	−70	7	51	132° W	10, 12
3	Jurassic dolerite intrusions, Theron Mountains and Whichaway Nunataks	80	30° W	64	−63	14	54	136° W	18, 18
4	Andean Intrusive Suite, Graham Land	65	64° W	351	−77	3	86	2° W	6, 6
5	Tertiary lavas, South Shetland Islands	63	61° W	15	−74	3	82	129° W	6, 6
6	Cenozoic volcanics, Cape Hallett	72	171° E	28	−80	4	81	94° E	8, 8

Reference: Blundell (1962).

The pronounced change in palaeolatitude during the Palaeozoic noted above in §2 for South America is also apparent when the curves for Africa and Australia are studied. It cannot yet be dated precisely since there are too few data especially for Africa. Later it should be possible to establish whether it occurred at exactly the same time in all three continents. There are no data for Antarctica and India for the Palaeozoic era.

A second pronounced change in palaeolatitude in the Tertiary and Quaternary is exhibited by the curve for Australia. This is also strongly shown by the curves for India and Antarctica. A smaller change occurs in the African curve for these times, while no such change is apparent in the South American curve.

The idea that the second feature might be associated with the drifting apart of these continents following the disintegration of Gondwanaland into separate parts and that the Palaeozoic feature might be associated with wandering of the pole across Gondwanaland is developed in the following paragraphs.

4. COMPARISON OF THE SOUTH AMERICAN AND AFRICAN POLAR WANDERING CURVES

The former is illustrated in figure 2 and the latter in figure 4. The shape and length of the Palaeozoic parts of these two curves are similar and this suggests that there was then no relative movement between the two continents. When the latter are fitted together so that their matching coastlines are adjacent, as in most palaeogeographical reconstructions, the two polar wandering curves coincide. This is illustrated in figure 5 which was drawn with the aid of the transparent hemispherical shells and the 50 cm globe.

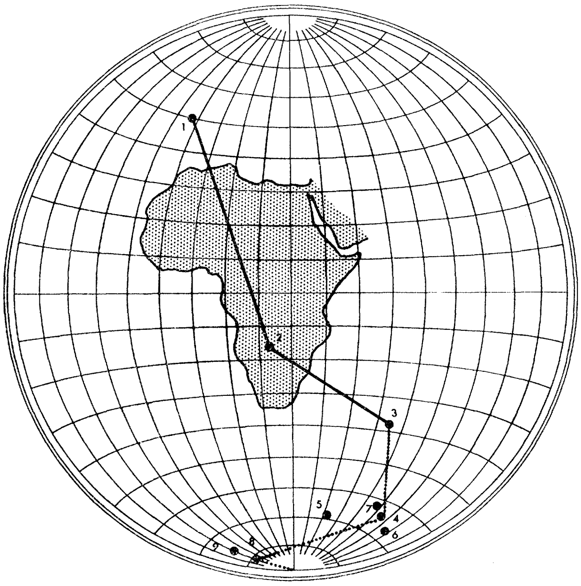

FIGURE 4. Movement of South Pole relative to Africa deduced from magnetism of African rocks.

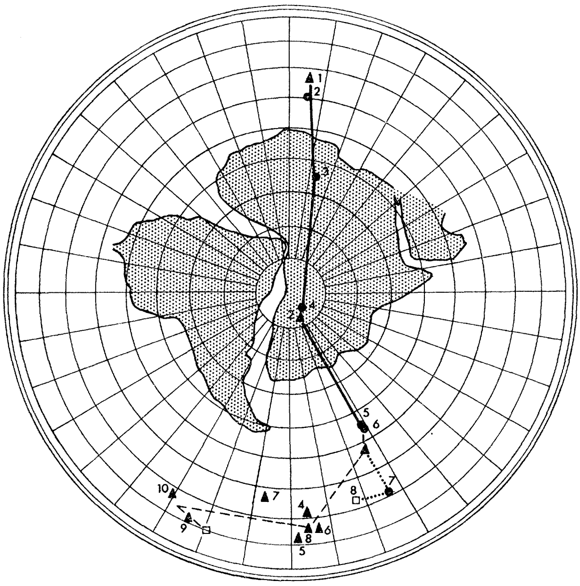

FIGURE 5. The polar wandering curves relative to South America and Africa superimposed when the two continents are placed adjacent to one another.

Conversely, by matching the polar wandering curves, the relative positions of these two continents could have been deduced. When more palaeomagnetic work has been done it should be possible to use this method to make reconstructions of the positions of continents for intervals of geological time when large polar wandering but no relative continental movement occurred. One important source of error is that the magnetic age of sedimentary rocks may differ from their true age, so that there may be some doubt concerning correlation of palaeomagnetic poles from different continents. Thus, poles 4 and 5 for South America were derived from red beds of Pennsylvanian age. The magnetization from which pole 5 was derived must, however, date from the Permian since it agrees with pole 6 which is derived from Permian rocks (see table 1) and also with pole 3 for Africa which was computed from the magnetization of red beds from Tanganyika of Lower Permian age (see table 2). In spite of these difficulties a purely palaeomagnetic reconstruction would be very similar to that obtained by matching the coastlines or continental shelves, possibly because the polar movement was large and fairly rapid and because both curves have a 'knee', so that they can be more easily matched.

The two polar wandering curves diverge in the Mesozoic indicating that during this era Africa and South America were drifting apart. The poles corresponding to the Stormberg lavas and the Serra Geral formation of Triassic-Jurassic age are about 20° apart whereas the present poles relative to the adjacent Palaeozoic positions of these continents are 35 to 40° apart. Thus if these lavas are of the same age, Africa and South America cannot have been adjacent to one another when they were erupted. Separation appears to have begun during the Permian. The relative positions of the continents when the Mesozoic basalts and dolerites were erupted is discussed in §7.

5. Comparison of South American and Australian palaeomagnetic data with palaeogeographic reconstructions of Gondwanaland

The first comparison is made for the Devonian period. The reconstructions of (i) du Toit (1937) and (ii) Wilson (1963) were carefully drawn on transparent hemispherical shells. The former was placed on the 50 cm globe in the position indicated by the Devonian palaeomagnetic data for South America, i.e. the site in the province of Salta, Argentina, was placed at the appropriate palaeolatitude and with the palaeomeridian along a longitude line on the globe, as shown in figure 6 (*a*). The position of the shell corresponding to Wilson's reconstruction is shown in figure 6 (*b*). The data can be compared in two ways.

For each reconstruction, the latitude and longitude of the site in Australia where Devonian rocks were collected (the Ainslie volcanics and the Elder Mountain sandstone) were noted and the pole positions on the illustrated latitude-longitude grid were calculated from the Australian palaeomagnetic data. If the South American and Australian rocks are of the same magnetic age and for the correct reconstruction, the poles derived from the latter rocks should not differ significantly from the pole of the projection in figure 6. For both du Toit's and Wilson's reconstructions, the difference is significant, the 95% errors of each Australian pole and that of the projection being about 15°.

To inquire in another way how closely the palaeomagnetic data agree with the palaeographic reconstructions, Australia has been drawn in figure 6 at the palaeolatitude and with the orientation deduced from the palaeomagnetism of the Ainslie volcanic series, the longitude having been chosen so as to bring this position of Australia as close as possible to that given by the palaeogeographic reconstruction positioned on the grid in accordance with the South American palaeomagnetic data.

In figure 6 (*b*) the Australian Devonian poles computed from Wilson's reconstruction are about 60° from the South American pole, the pole of the projection. By comparing the two outlines of Australia, it is seen that the discrepancy in the positions of the poles is mainly due to rotation. The palaeolatitudes deduced from the Australian palaeomagnetic data differ by about 20° from those obtained by combining Wilson's reconstruction with the South American palaeomagnetic data. Local tectonic movement at one of the sites could possibly account for the discrepancy in pole position. On the other hand, the Australian poles computed from du Toit's reconstruction are closer to the South American poles (figure 6 (*a*)) the angular separation being about 40° than are those computed from Wilson's. Here the disagreement is mainly due to a difference in palaeolatitude. However, the main difficulty in deciding which reconstruction agrees better with the palaeomagnetic data is that of correlation of geological and magnetic age.

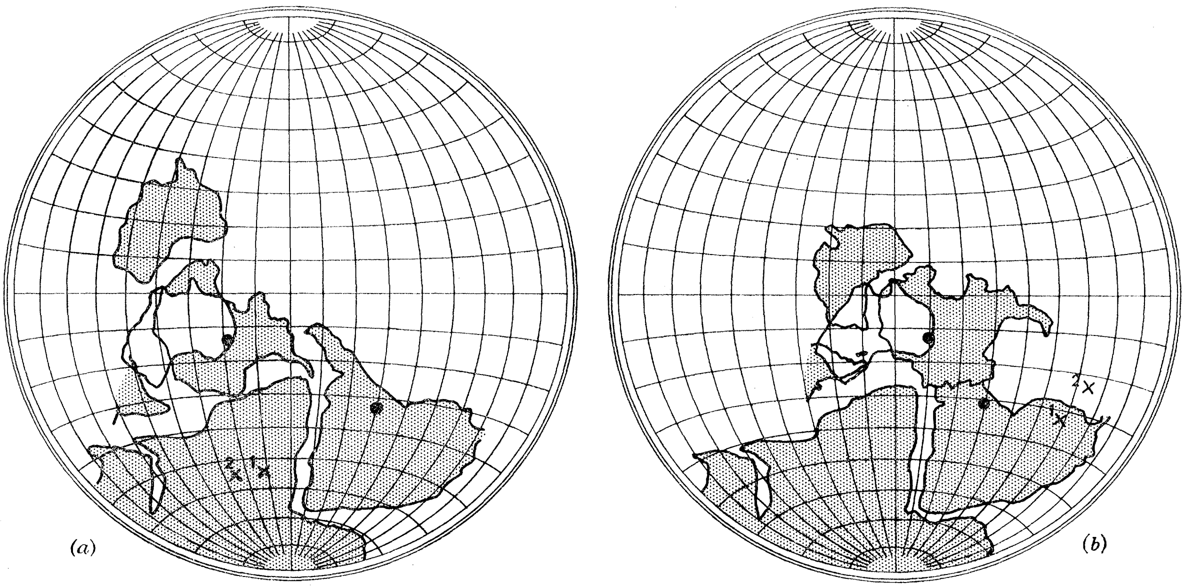

FIGURE 6. South American and Australian palaeomagnetic data for the Devonian compared with the palaeogeographic reconstructions of (*a*) du Toit and (*b*) Wilson. The pole of the grid is the Devonian palaeomagnetic pole for South America. The Devonian palaeomagnetic poles for Australia are marked × and would not differ significantly from the pole of the grid if the reconstructions were in agreement with the palaeomagnetic data. The 95 % circles of confidence have radii of approximately 15 to 20°. The unshaded outline of Australia illustrates a possible position deduced from the Australian palaeomagnetic results and should be compared with the other position deduced by combining the South American palaeomagnetic results, with palaeogeography.

A similar comparison for the Cambrian is illustrated in figure 7. The palaeomagnetic data are here seen to agree better with Wilson's reconstruction than with du Toit's, but this conclusion must be viewed with caution because it is by no means certain that the rocks are of the same magnetic age.

The inconsistencies revealed may in future be resolved when more precise and well dated palaeomagnetic data are obtained, and it may be possible to show whether either or neither of the reconstructions is to be preferred. At present, however, there is no doubt that the palaeomagnetic data agree much better with these palaeogeographic reconstructions than with the present positions of these continents.

Both of the palaeogeographic reconstructions of Gondwanaland considered above separate South America from Australia by a greater distance than is required by either

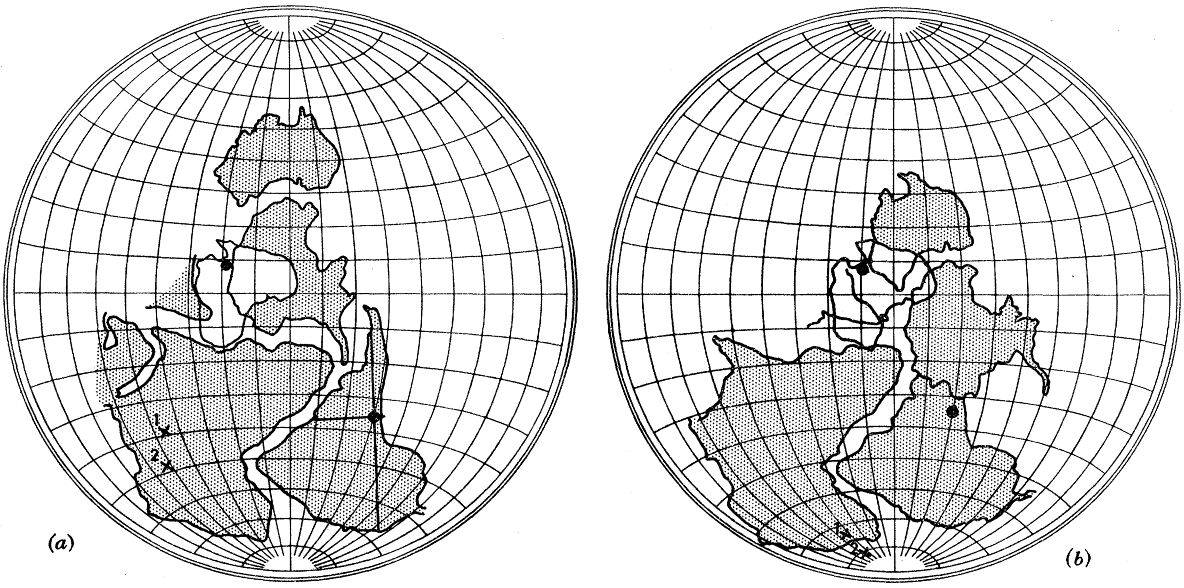

FIGURE 7. South American and Australian palaeomagnetic data for the Cambrian compared with the palaeogeographic reconstructions of (*a*) du Toit and (*b*) Wilson. The pole of the grid is the Cambrian palaeomagnetic pole for South America. The Cambrian palaeomagnetic poles for Australia are marked × and would not differ significantly from the pole of the grid if the reconstructions were in agreement with the palaeomagnetic data. The 95% circles of confidence have radii of approximately 15 to 20°. The unshaded outline of Australia illustrates a possible position deduced from the Australian palaeomagnetic results and should be compared with the other position deduced by combining the South American palaeomagnetic results, with palaeogeography.

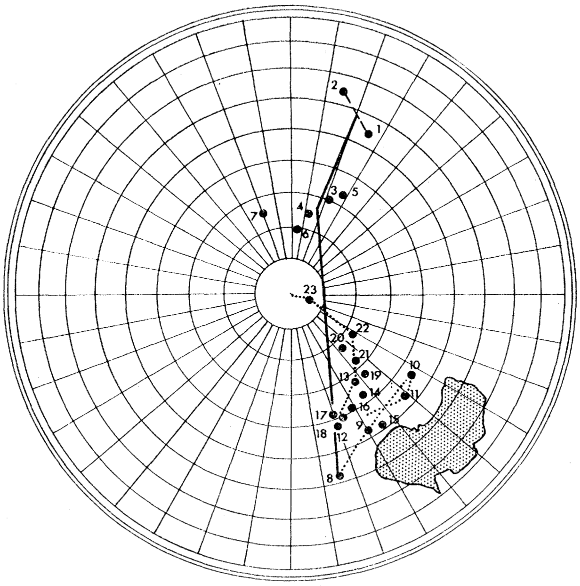

FIGURE 8. Movement of South Pole relative to Australia.

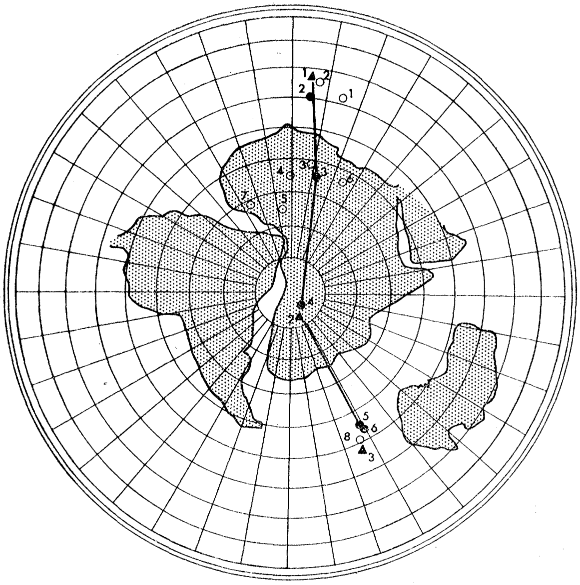

FIGURE 9. The relative positions of South America, Africa and Australia for the Palaeozoic obtained by bringing their polar wandering curves together.

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the Devonian or the Cambrian palaeomagnetic data. In this connexion it is interesting to note that the polar wandering curve for Australia, illustrated in figure 8, has a similar shape to those for Africa and South America. When the three curves for the Palaeozoic are superimposed, the three continents occupy the relative positions shown in figure 9 in which the Cambrian and Devonian Australian poles were used to fix the straight portion of the Australian curve to the South American–African curve. There may be something wrong with this reconstruction, however, because the Australian Pennsylvanian pole 8 lies closer to the South American and African Permian poles 6 and 3 than to their Pennsylvanian poles. Possible reasons for this have been considered by Creer (1964*a*) since the presentation of this paper. The three polar wandering curves diverge in the Mesozoic and Tertiary as illustrated in figure 10.

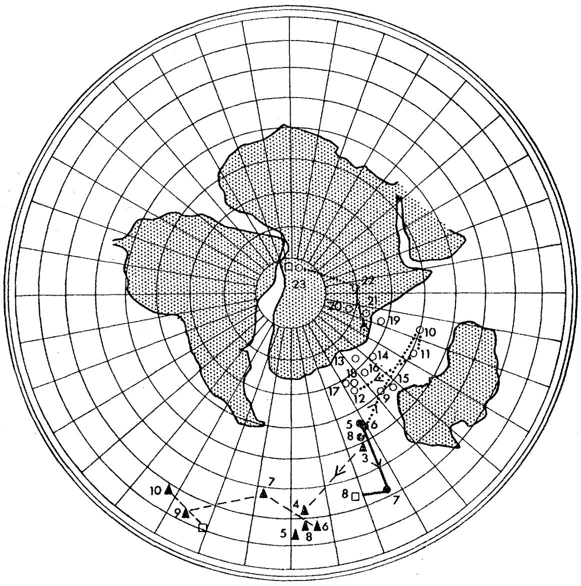

FIGURE 10. To illustrate the divergence of the polar wandering curves for the Mesozoic. The relative positions of the three continents is that deduced for the Palaeozoic.

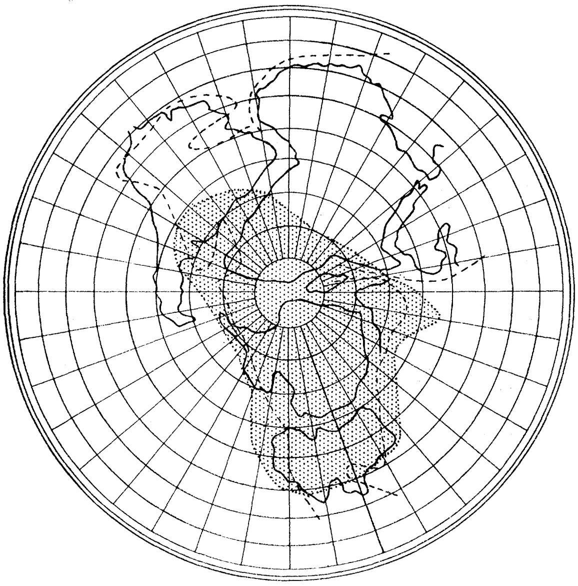

FIGURE 11. The extent of the Permo-Carboniferous glaciation (after du Toit). The probable position of the coastline of Gondwanaland is indicated thus – – –, and the maximum extension of the ice-sheet . . . .

6. PALAEOMAGNETISM AND THE PERMO-CARBONIFEROUS GLACIATION

One of the strongest arguments in favour of the theory of continental drift is that it becomes easier to understand the Permo-Carboniferous glaciations of the continents of the southern hemisphere and of India if they were then grouped together and formed one single supercontinent, Gondwanaland.

The palaeomagnetic evidence (§ 3 and figure 9) suggests that, during the Upper Palaeozoic, the pole drifted across Gondwanaland from North Africa to Tasmania. The area glaciated is shown in figure 11. Permo-Carboniferous glacial beds are not usually very rich in magnetic minerals and have been found to be non-magnetic as a rule particularly those in South Brazil. However, the Kuttung varvoids from Australia and the Dwyka tillites from Africa possess measurable remanent magnetization. In both cases the palaeomagnetic latitude is extremely steep (see figures 12 (*a*) and 12 (*b*)), and this suggests that the centre of glaciation followed the pole. Thus random polar shifts of the order of 30° must have been necessary to account for the successive glaciations in the different parts of Gondwanaland, supposing the du Toit or Wilson reconstructions to be correct. These polar shifts must have been superimposed on the gradual drift of the pole across Gondwanaland. There is some geological support for this general pattern of events because there are indications (see, for example, the U.S.G.S. *Handbook of South American geology*, David's *Geology of the Commonwealth of Australia*, Furon's *Geology of Africa*) that the glaciations started earliest in South America (in the Mississippian) while they persisted latest in Australia (until the Upper Permian).

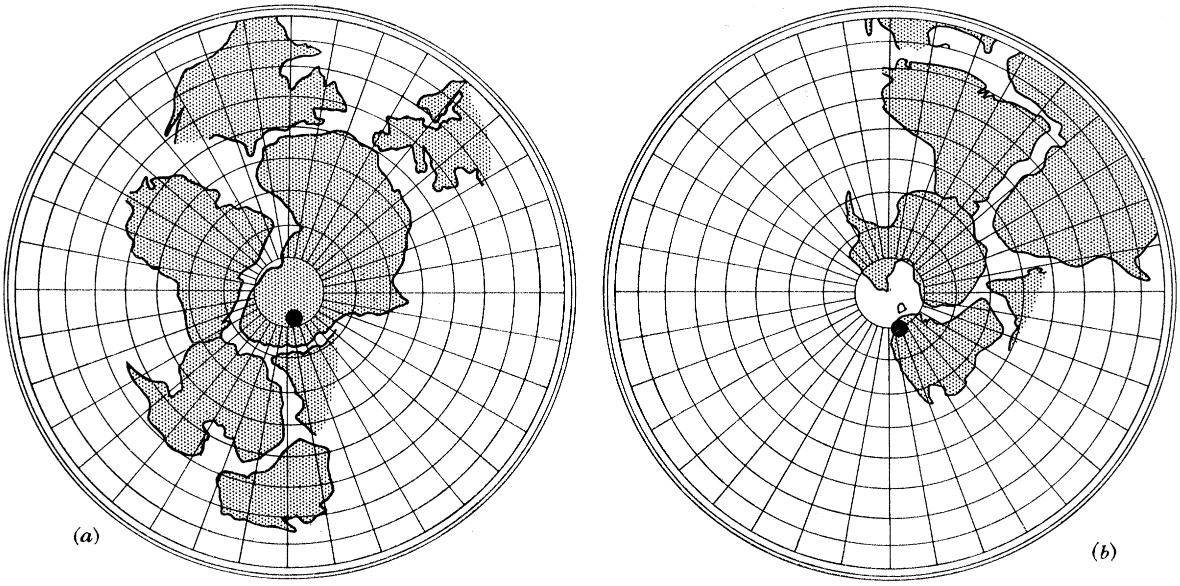

Figure 12. Gondwanaland, as reconstructed by Wilson, drawn on a latitude-longitude grid based on the magnetism of (*a*) the Dwyka tillites of Africa and (*b*) the Kuttung varvoids of Australia.

The reconstruction implied by the palaeomagnetic data (figure 9) renders the postulation of such large random polar shifts unnecessary, for it brings Australia much closer to Africa and South America, and the glaciated area would have been correspondingly smaller.

It will be interesting to see whether additional palaeomagnetic data agree with the reconstruction in figure 9, or whether errors in the present palaeomagnetic data account for the discrepancy with the palaeogeographic reconstructions.

7. Palaeomagnetic data from the Mesozoic dolerites

These are summarized in table 6 in which palaeolatitudes and the rotations of the meridian are also listed. In figure 13 it is shown that these data are consistent with the suggestion that Gondwanaland was breaking up when these lavas and dykes were formed.

Of all the Gondwanic continents, South America seems to have moved least relative to the pole since the early Mesozoic. On the basis of Wilson's reconstruction, Gondwanaland is illustrated in a position corresponding to the palaeomagnetic data from the Serra Geral formation from southeast Brazil and Uruguay in figure 13 (*a*). In figure 13 (*b*) the Gondwanic continents have palaeolatitudes and orientations as listed in table 6. It is seen

Table 6. Triassic-Jurassic lava flows, dykes and sills

continent and lat. and long. of site	formation	direction of remanent magnetization			palaeo-latitude		azimuth		pole position on present grid.			no. of samples		Reference
		D (°)	I (°)	α (°)	L (°)	ΔL (°)	ϕ (°)	$\Delta\phi$ (°)	lat. (° S)	long.	α (°)	sites	samples	
Africa, 29–30° S, 28–29° E	Stormberg Lavas and Karroo Dolerites	339	−55	6	36 ±	6	−21 ±	10	67	98° E	4	—	74	van Zijl *et al.* (1962)
Antarctica, 78° S, 162° E	Dolerite Intrusions, Wright Valley	262	−70	7	54 ±	10	−98 ±	20	51	132° W	11	11	8	Blundell (1962)
Antarctica, 80° S, 30° W	Theron Mountains	244	−68	14	51 ±	20	−116 ±	38	54	136° W	18	8	7	do.
Australia, 42° S, 147° E	Tasmanian Dolerites	319	−84	3	80 ±	6	−41 ±	29	51	160° E	6	51	132	Irving (1963)
India, 25° N, 88° E	Rajmahal Traps	323	−64	4	46 ±	8	−37 ±	9	11	113° E	—	17	108	Radhakrishnamurty (1963)
S. America, 21–31° S, 47–57° W	Serra Geral	347	−38	5·7	26·5 ±	4	−13 ±	5	78	54° E	4	30	74	Creer (1962*b*)

that longitudes can be chosen consistent with the suggestion that these continents were drifting apart. According to this picture, India and Australia had farthest to drift and this suggestion is reinforced by the palaeomagnetic data from these two continents, their palaeolatitude curves in figure 2 showing the greatest changes.

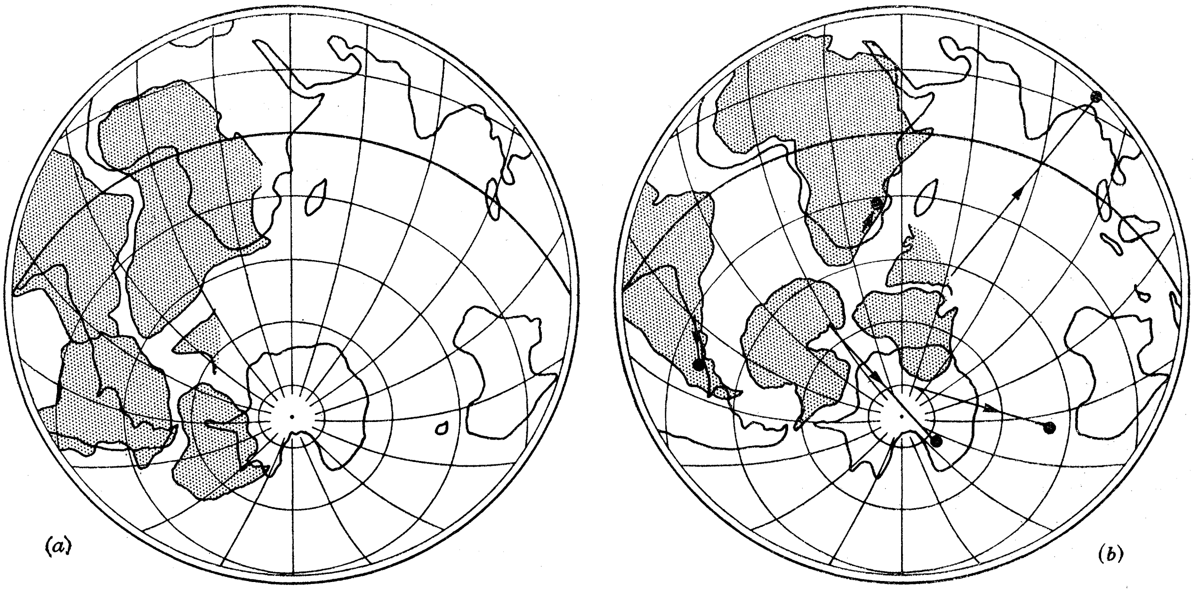

FIGURE 13. The Palaeolatitudes and orientations deduced from the magnetism of the Mesozoic dolerites can be interpreted by supposing that Gondwanaland was breaking up when these rocks cooled. In (*a*) Gondwanaland (after Wilson) is positioned using the South American data from the Serra Geral formation. In (*b*) positions consistent with the palaeomagnetic results lie between those of (*a*) and the present positions marked ●.

8. CONCLUSIONS

The palaeomagnetic data available at present lead me tentatively to draw the following conclusions:

(i) Gonwanaland, in one form or another existed during the Palaeozoic era.

(ii) During the Palaeozoic, the South Pole wandered across Gondwanaland from North Africa to South Australia.

(iii) There are significant differences between the palaeomagnetic data from the Cambrian and Devonian from Australia and South America and the reconstructions of du Toit and Wilson. These may be resolved when the magnetic ages of rocks can be correlated better.

(iv) Gondwanaland started to break up in the Permo-Triassic.

(v) During the Mesozoic, Australia and India drifted further relative to the pole than Africa. The position of South America relative to the pole has not changed appreciably since the early Mesozoic.

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