

2. CONTINENTAL DRIFT AND PALEOCURRENT ANALYSIS (A comparison between Africa and South America)*

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ABSTRACT

The hypothesis of continental drift is approached from the point of view of paleocurrent analyses. A short revision of other approaches to the problem is made, including paleomagnetism, sea floor spreading and geologic similarities. The paleomagnetic evidences suggest that both continents were adjacent to each other until Upper Permian or Triassic times. In the Precambrian radiometric age determinations suggest also that both continents were adjacent to each other. The few paleomagnetic data available for the Lower Paleozoic rocks do not seem to be enough for a more precise determination of the pole position. There is no good agreement between the postulated pole and the paleoclimatic evidences for the Lower Paleozoic sequence.

The adjacent position of South America and Africa seems to be in agreement with the cross-bedding resultant vector obtained from sandstones, from Ordovician to Devonian age. When the two continents are fitted together, the paleocurrent pattern is peripheral to a large continental area located at the oriental part of South America eastward into Africa. The paleocurrents in both continents flow away from this common area. The Ordovician-Devonian formations used in this analyses are

- (1) in Africa the Cape System and the Paleozoic sequence of the Ahaggar in Central Sahara;
- (2) in South America the Caacupé, Furnas and Serra Grande formations.

The Ordovician and/or Silurian glaciations indicate also the provenance of the ice from the same continental area as is inferred from cross-bedding measurements. The ice movement in the Sahara was to the north, while the ice flow in the Cape Province was to the south.

The examination of the well-planed erosion surface which preceded the sedimentation of the Paleozoic sequences indicates a semi-arid or arid environment for its development. In the different areas studied, the well-planed erosion surfaces do not seem to be contemporaneous with each other. These surfaces were actually pediplanes and not peneplanes as usually stated.

The ice flow patterns deduced, for both Tubarão and Dwyka sequences, are suggestive of a former connection between Africa and South America. Nevertheless, complementary studies are still needed to solve many problems.

During the Permian, the Karroo and Paraná basins had a separate development as shown by paleocurrent analysis. In South America the data are still rather scarce. Good paleocurrent information is available for the Ecca and Beaufort sequences of South Africa.

Cross-bedding measurements of the eolian Mesozoic sandstones, both in South America and in Africa, indicate the presence of the South Atlantic Ocean between the two continents. This evidence is corroborated by paleomagnetic investigation.

INTRODUCTION

The hypothesis of continental drift and the problem of a former connection between Africa and South America has lately received careful attention. Many different approaches to the subject have been made. Everyone has contributed in some way to a better knowledge of the problem. For a long time, the geologic and paleontologic similarities between the two continents were used as arguments to prove the former connection between Africa and South America. More recently, one of the most important contributions was made by the paleomagnetic study of different rock formations. These studies have indicated that during the geological past the continents occupied different positions related to the equator and have also shifted in relation to each other (Creer, 1965 b, 1965 c).

The paleomagnetic conclusions re-opened general interest in the problem of continental drift, which before was based mostly on the parallelism of the coast lines of South America and Africa, and on the geologic and palaeontologic analogies between these continents. The superposition of the polar wandering curves, deduced from different continents, was a new approach, which provided good evidence for the determination of the relative movements and position of the continents during geological times (Creer, 1965 c).

The recent investigations of the ocean floor, including geophysics and sediment studies, provided new evidences for the concept of sea floor spreading (for references see Simpson and Needham, in print; Carey, 1955, 1958; Bullard, Everett & Smith, 1965; Ewing, Saito, Ewing & Burckle, 1966; Ewing, Ludwig and Ewing, 1963; Heezen & Tharp, 1961; Ewing and Ewing, 1967; Vine, 1966; Pitman & Heirtzler, 1966).

The Permo-Carboniferous deposits on both sides of the South Atlantic have been used as evidences of a former connection between South America and Africa. The direction of the ice flow has been determined mostly from striated floors and tillite fabric analysis. The general

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movement of the Gondwana ice sheets in Africa was referred to by du Toit (1927) and revised more recently by Stratton (Ph. D. thesis). For the Gondwana of Brazil, the first indication of the direction of the ice flow was given by Leinz (1937) and subsequently by Carvalho (1940), Barbosa (1940), Almeida (1948a) and Maack (1946).

Maack (1960, 1961 and 1966), based on du Toit's pattern of ice flow for south and south-western Africa, extrapolated the ice movement directions into southern Brazil, emphasizing that most of the drifted material came from Africa. Martin (1961, 1964) made a series of measurements of the attitude of Itararé folded strata which were interpreted as produced by the overriding ice sheets. Martin concluded also for a south-eastern provenance of the drifted material.

In the State of Paraná, the direction of ice movement and transportation during the Itararé time was determined by Bigarella, Salamuni and Fuck (1967) and Bigarella and Salamuni (1967 b) to be from south-southeast to north-northwest. This conclusion was based on

- (1) a sequence of striated floors produced by two glaciations;
- (2) tillite fabric analysis relative to three different glaciations; and
- (3) cross-bedding measurements of the periglacial sandstones corresponding to ice retreat episodes of three different deglaciation periods.

The average of the measurements made in the three different approaches is practically coincident.

In the present paper a different approach to the problem of the former connection between South America and Africa is tried, based mostly on the paleocurrent analysis of the various cross-bedded sandstone sequences. An analysis of the different basins was made in order to establish the possibility of former connections, as well as the time of separation. Cross-bedding measurements in South America were made by Bigarella and Comte (in press) for the Silurian rocks; Bigarella, Salamuni and Marques F^o (1966) and Bigarella, Mabesoone, Lins and Motta F^o (1965) for the Devonian sequences; Bigarella and Salamuni (1967a) for the periglacial, post-glacial and Permian sediments; Bigarella and Salamuni (1961), Bigarella & Oliveira (1966) and Bigarella (unpublished data) for the Mesozoic sandstones. In South Africa cross-bedding measurements were made by I. C. Rust (Ph. D. thesis, University of Stellenbosch) and Bigarella and Beukes (unpublished data) for the Ordovician-Silurian sequences; J. N. Theron (Ph. D. thesis, in preparation) for the Devonian rocks; P. Ryan (Ph. D. thesis) for the Permian sediments; J. N. Beukes (M. Sc. thesis, in preparation), Bigarella and Beukes, and Bigarella and van Eeden for the Mesozoic eolian sandstones. In South West Africa cross-bedding measurements were made by Heath (M. Sc. thesis) for the post-glacial deposits of the Dwyka sequence and by Hodgson (1970) and by Bigarella, van Eeden, Schalk and Hugo for the post-glacial Dwyka and for the Etjo eolian sandstone.

Cross-bedding measurements and paleocurrent analysis of Cambro-Ordovician and Devonian rocks in northern Africa (Ahaggar, Central Sahara) were made by geologists of the French and Algerian Petroleum Institutes.

The interpretation of the cross-bedding measurements provides a good indication of the relative position of South

America and Africa, and of the presence of a South Atlantic Ocean during Mesozoic time. For the Silurian and Devonian time the results are not so clear but they suggest that the sediments came from an area located over the present day ocean. This might be an indication of a former connection between the continents.

PALEOMAGNETIC EVIDENCES

The considerable amount of paleomagnetic data so far obtained from the Gondwanic continents, South America, Africa, Australia, Antarctica and India, supports the hypothesis of continental drift (Creer, 1965 b). The paleomagnetic evidence suggests that during the Paleozoic the pole drifted across Gondwanaland from North Africa to a position off the coast of south-east Africa, in Tasmania (Creer, 1965 b). The Gondwana glaciations, which seem to have started earlier in South America in Lower Carboniferous (Harrington, 1962) and persisted until the Upper Permian in Australia (Creer, 1965 b), constitute one of the strongest arguments in favour of the theory of continental drift. Polar wandering curves are suggestive of a former connection between Gondwana and Laurasia in Lower Paleozoic, forming a single super-continent, Pangaea (Creer, 1965c). The polar wandering curves for North America and Europe can be superimposed on the South American-African curve, suggesting that there were two continents (Gondwana and Laurasia) separated by a narrow sea, the Tethys sea (Creer, 1965 c). The curve of polar wandering diverges for North America and for Europe in Triassic-Jurassic time, and for Africa and South America in the Jurassic (Creer, 1970).

The shape and length of the South American and African polar wandering curves are similar in the Paleozoic parts (figs. 1 and 2). They suggest the absence of any

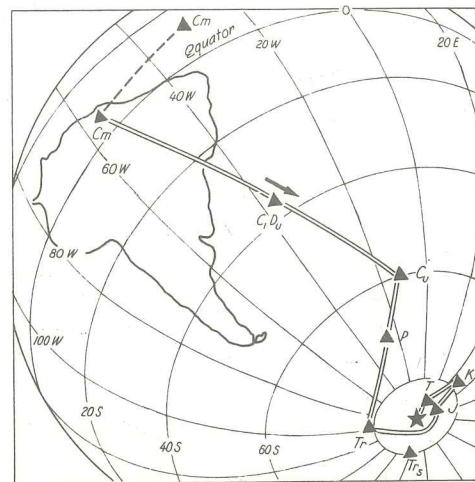


Fig. 1. Movement of the South Pole relative to South America deduced from magnetism of South American rocks (after Creer, 1970). Cm = Cambrian-Ordovician (Africa); Ordovician-Lower Devonian (South America); C₁Du = Upper Devonian-Lower Carboniferous; Cu = Upper Carboniferous; P = Permian; Tr = Permo-Triassic; J = Jurassic; K = Cretaceous; T = Tertiary.

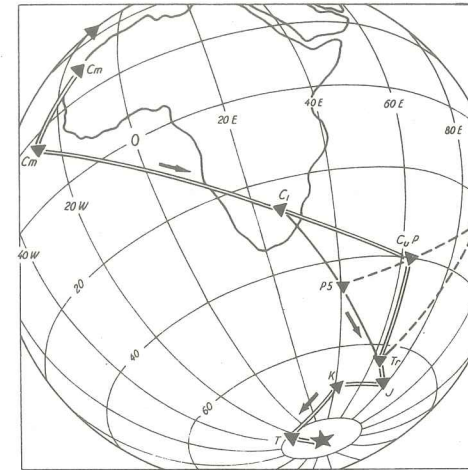


Fig. 2. Movement of the South Pole relative to Africa deduced from magnetism of African rocks (after Creer, 1970). Cm = Cambrian-Ordovician (Africa); C₁ = Lower Carboniferous; CuP = Permo-Carboniferous; P₄ = Permian?; P₅ = Upper Carboniferous?; Tr = Triassic; J = Jurassic; K = Cretaceous; T = Tertiary.

relative movement between the two continents in the Paleozoic before the end of the Triassic. When South America and Africa are fitted together, the two polar wandering curves are coincident (Creer, 1970; Valencio, 1970), suggesting the connection between the two continents. The two curves separate in the Jurassic. The divergence in Mesozoic indicates the break apart of Gondwanaland. South America and Africa drifted apart considerably during this Era.

The polar wandering curves indicate pronounced change in paleolatitude during the Paleozoic for South America and Africa (Creer, 1965 b). In these continents, paleomagnetic data from Cambrian and Ordovician formations are not yet available due to weaker magnetization of the rocks (Creer, 1964 c). References to Silurian poles were made for South America (Creer, 1964) and for Africa (Graham & Hales, 1961). The map of figure 3 presented by Creer (1964 c, p. 129) represents the paleolatitude and paleomeridian directions determined from paleomagnetic data from Silurian rocks. According to this map, large extensions of South America and Africa are located in low latitude (tropical and sub-tropical) areas. This is not in agreement with geologic evidences of the Lower Silurian glaciation in the Table Mountain Group (Rust, 1967) and with other Silurian glacial evidences or signs like the Zappla Tillite in Bolivia (Harrington, 1962) and striated pavements and "tillite" in the Serra Grande Formation (Malzahn, 1957).

The non-agreement verified between the paleomagnetic and paleoclimatologic data must be related to the uncertainty of the age of pre-Devonian formations. The Urucum Formation is ascribed to the base of the Silurian (Almeida, 1964, p. 76) and referred to by Creer (1964 c) as Silurian in his paleomagnetic work. However, this formation seems to be actually older than the known dated Silurian sequences

with graptolites, like the Caacupé Group of Paraguay. Due to lack of fossils and radiometric dating the age of the Urucum Formation is still an open question. The red siltstone studied by Graham & Hales (cited by Creer, 1964 d, pp 281 and 283) and referred to as Silurian belongs to the Table Mountain sequences which crop out near Cape Town, South Africa (possibly to the Peninsula Formation). At the time of the paleomagnetic study, the age of the red siltstone was considered either Silurian or Lower Devonian. More recent studies indicated an Ordovician age for this formation (Rust, 1967). Nevertheless, a revision of this problem is desirable for the explanation of the present discrepancies between paleomagnetic and paleoclimatic data. The paleolatitudes obtained from both formations are consistent with the adjacent position of South America and Africa. These formations appear to be closely equivalent in age, even if not Silurian.

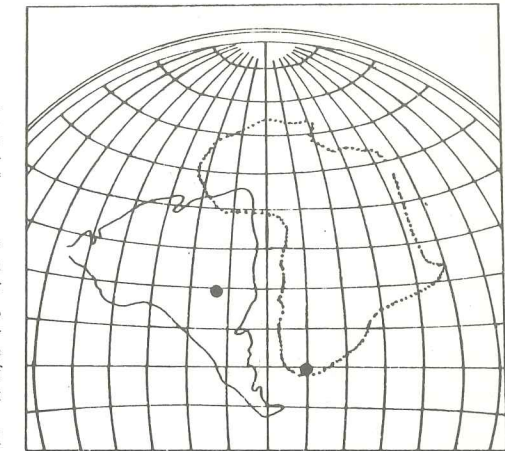


Fig. 3. Paleolatitudes and paleomeridian directions of South America and Africa determined from paleomagnetic data from Silurian rocks (after Creer, 1964 c).

In Cambrian to Lower Devonian times, north-eastern Brazil was closer to the pole than Tierra del Fuego as indicated by paleomagnetic data (Creer, 1965 b; 1964 c, p. 128). In Middle and Upper Devonian the pole was near Rio de Janeiro in the Atlantic (Creer, 1970). The adjacent position of South America and Africa in Devonian is shown in figure 4. A middle latitude area is suggested for the deposition of the Bokkeveld and Campos Gerais groups. Paleomagnetic data for the Carboniferous sequences of South America are still insufficient. Nevertheless, the polar wandering curves suggest that during the Gondwana glaciation South America and Africa were closer to the south pole.

At the end of the Triassic the polar wandering curves for South America and Africa diverge indicating that in Mesozoic and later times the two continents no longer occupied the same relative positions. From this time on, both continents started to drift apart into their present positions.

The paleolatitude and paleozimuths deduced from the South American and African lava flows and diabase dykes

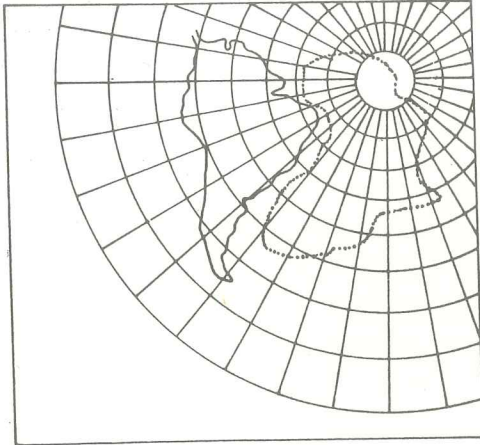


Fig. 4. Devonian paleogeography of South America and Africa (after Creer, 1964 c).

do not correspond either to the present position of both continents nor to the suggestion that they were then adjacent to one another (Creer, 1965 b). When the Mesozoic igneous activity started, both continents had already started moving towards their present settings. Paleomagnetic studies show that there has been little movement of South America relative to the pole since Triassic-Jurassic times (Creer, 1965 b). In the same way, there is no appreciable change of the paleomagnetic latitude of Africa since Middle Mesozoic as shown by Gough and collaborators (cited by Creer, 1965 b, p. 27).

The age of the intrusive dolerites from the Karroo basin ranges between 152 m.y. and 190 m.y. (McDougall, 1963 b) and one of the lava flows about 200 m.y. (Manton, 1968). Based on these data, the age of the effusive volcanism in south-east Africa has been stated to be apparently some 80 m.y. younger than that of South West Africa (Siedner & Miller, 1968). The ages of 154 m.y. to 190 m.y. referred for the Drakensberg basalts (Martin, 1968; Maack, 1969) are actually those of the intrusive dolerites. An age of 197 m.y. for the basaltic flow in Lesotho above the Cave Sandstone (lower sequence) was determined by Miller & Fisk (Prof. Attridge personal communication). Ages of about 200 m.y. were referred by Manton (1968) from the acid volcanics and granophyre of the southern part of the Lebombo Mountain and of the Nuanetsi area in the south-eastern corner of Rhodesia. The age of the Serra Geral magmatic cycle, with intrusive volcanism, ranges between 119 m.y. and 147 m.y., being in average about 125 m.y. (Cordani & Vandomos, 1967). The age of the Kaoko lava flows (South West Africa) ranges between 114 m.y. and 136 m.y. with a maximum at 125 m.y.; while the intrusive dykes are considerably older, at 164 m.y. and 196 m.y. (Siedner & Miller, 1968).

The Serra Geral and Kaoko lava flows have the same average age. The upper age limit for the Botucatu and Etjo sandstones is roughly related to the age of the overlying lava flows.

The interpretation of the Mesozoic paleomagnetic data from South America and Africa was made by Creer

(1965b). At the time of Creer's studies age determinations for the Serra Geral flows were not available. He concluded that the poles corresponding to the Karroo and Serra Geral lava flows were 20° apart. He mentioned also that, if the lavas were of a same age, both continents could not have been adjacent to one another at the time of the eruptions. The lava flows being not contemporaneous, it is possible that polar wandering occurred between the eruptions. In this case, polar wandering could entirely account for the difference between the position of the ancient and present poles (Creer, 1958). More studies are still needed. A comparison between the paleomagnetic data from the basalts of South West Africa and those of the Serra Geral is desirable to demonstrate whether the non-coincidence of ancient poles is due entirely to relative movements of continents. The Mesozoic paleowind pattern suggests the presence of an ocean between South America and Africa.

PRECAMBRIAN BASEMENT

Several attempts to correlate the Precambrian structures of Africa and South America have been made (Ebert, 1957; Beurlen, 1961; Pflug, 1963; Maack, 1969). However, the assumed continuation of the structures in both continents is not yet a definite proof for the connection between Africa and South America (Martin, 1968, p. 29). Nevertheless, the general pattern indicated by the structures is suggestive of a former link between the two continents (Martin, 1968, p. 30). The best evidences for a Precambrian connection between South America and Africa were provided by the radiometric age determinations (fig. 5), which make it possible to delimitate isochronous areas matching on both sides of the Atlantic (Cordani, 1968).

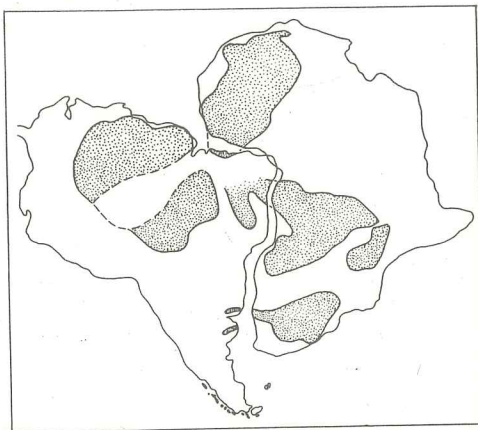


Fig. 5. Correlation between the Precambrian geochronologic provinces of South America and Africa. The dotted areas represent old cratons with about 2 000 m.y. (after Hurley, 1968; Cordani, 1968).

South America

The majority of the South American Precambrian rocks belongs to the Brazilian Craton or Platform which comprises three main areas separated by the Amazon, Parnaiba and Paraná intercratonic basins. The craton at

both sides of the Amazon Basin, the São Luiz area, the São Francisco craton and the Uruguay-Argentina area, underwent a well defined geologic event at about 2 000 m.y. ago (Cordani *et al.*, 1968; Snelling & McConnell, 1966). "These old cratonic areas are separated from each other by metamorphic belts that underwent orogenies or were reactivated in Late Precambrian or Early Cambrian times, 650 to 450 m.y. ago" (Cordani *et al.*, 1968). In this way, the areas of the shields facing the intercratonic or pericratonic basins were mostly formed by younger Precambrian metamorphic rocks (Harrington, 1962) aged between 500-700 m.y.

Africa

The oldest part of the Sahara Platform is located to the west of the Ahaggar. In the western Ahaggar, the Tanezrouft-Adrar zone constitutes the eastern end of the West-African stable craton aged about 2 850 m.y. (Beuf *et al.*, 1968). The central and eastern Ahaggar represents a mobile zone surrounding the old craton. This zone underwent intense orogenic activity at the end of the Precambrian between 500-650 m.y. (Beuf *et al.*, 1968).

The cratonic areas of Ghana, Ivory Coast and Liberia show ages of about 2 000 m.y. The adjacent areas of Nigeria and Camerun were reactivated at about 500 m.y. ago (Cordani, 1968).

An attempt to compare Early & Middle Precambrian and Late Precambrian provinces on both sides of the Southern Atlantic was made by Martin (1961). From Nigeria to the Cape of Good Hope and from Recife to Argentina predominate Precambrian structures subparallel to the coast and rocks rejuvenated at around 500-600 m.y. (Martin, 1968, p. 30).

The radiometric data obtained in both continents confirm the existence of two distinct geochronologic provinces, one with an age about 2 000 m.y. and the other with about 500 m.y. When the two continents are fitted together, the limits of the two provinces agree on both sides of the Atlantic (fig. 5). So there is an agreement between the Precambrian geochronology of the northern and north-eastern coast of South America in relationship with the coast of Equatorial Africa. The same is true for the eastern coast of South America and the western coast of Africa (Cordani, 1968).

PALEOZOIC SEDIMENTARY BASINS

Tectonics

The Paleozoic basins here discussed were formed as intercratonic basins by the subsidence of the Precambrian basement. With the exception of the Cape folded belt, the cratonic sedimentary sequences of Central Sahara, South Africa and South America were not submitted to any extensive folding movement, other than local deformations caused either by faulting or by igneous intrusions.

Warping movements occurred at several times in the Brazilian shield during the deposition of the Paleozoic and Mesozoic sequences. According to Freitas (1951 a, 1951 b) the climax of the warping was in Cenozoic times. The Irati Formation in the Paraná Basin constitutes a good key horizon for study of the tectonic movements inside the basin. Numerous faults can be detected, the best examples being those which brought the Irati down from the plateau

level to sea level in Southern Santa Catarina, in front of the Serra Geral Escarpment.

In the Paraná Basin, tectonic movements were operating concomitant with the deposition, as shown either by different dip values presented by successive formations (Gutmans, 1949) or by reversals in the paleocurrent directions (Bigarella & Salamuni, 1967).

Faulting movements occurred at several times mostly as a rejuvenation of Precambrian tectonic lines. In the coal measures of Santa Catarina, the fault pattern is represented by four different directions (Putzer, 1953 a, 1953 b). In some cases, as in the north-eastern part of the State of Paraná, a block fault system resulted with the development of horst and graben (Mempel, 1957; Bischoff, 1957).

Geologic maps of the northern part of the Paraná Basin in the States of Mato Grosso and Goiás show clearly the fault tectonics of the basin with uplifted and depressed blocks (Petrobrás S. A., unpublished data). This tectonism was the main responsible factor for the preservation of sedimentary units in that area. These tectonic movements were mostly pre-Cretaceous (Mendes, 1967, p. 124). This seems to be true for the northern part of the basin. It is also possible that a post-Cretaceous reactivation took place, faulting the Bauru Formation of Upper Cretaceous age. A problem still to be solved is the more precise age determination of the faulting reactivation. It is admitted that most faults occurred at the time when the oriental part of south-eastern and southern Brazil was warped to the east with the progressive and complex formation of the Serra do Mar escarpment and block system mountain, which was mostly controlled by fault lines and paleoclimatic conditions (Bigarella & Ab'Saber, 1964; Bigarella, Mousinho, & Silva, 1965).

The intrusion of a great number of diabase sills developed, in some areas, domelike structures showing periclinal dipping of the formations (Bigarella & Salamuni, 1967, p. 239). The dome of Lajes (S.C.) originated from a 66 m.y. old phonolitic stock intrusion which disturbed, tilted and faulted the surrounding Gondwanic sequences.

In the Paraná Basin, the sedimentary sequences are intruded by a dominant NW-SE system of diabase dykes which are specially numerous in the region of the so-called Ponta Grossa Arch warping (Maack, 1947; Bigarella & Salamuni, 1967). The density of the number of dykes decreases on both sides of this gentle warping (Marini, Fick & Trein, 1967). In the very wide flat syncline of the deep-seated fold the dykes are far less frequent. The intrusion of the diabase dykes did not cause any great disturbance. In some instances it followed fault lines and in others it disturbed the adjacent rocks causing tilting and local faulting (Bigarella & Salamuni, 1967, p. 240).

Deep-Seated Folding

During the geological history of the Paraná Sedimentary Basin, the basement was submitted to differential movements caused by deep-seated warping (Bigarella & Salamuni, 1967, p. 242). These movements seem to have had a somewhat undulatory character for their propagation, producing differential uplift and subsidence inside the basin. These movements were very subtle and only recognised after accurate measurements of the attitude and thickness of the different formations, and after basin analysis through paleocurrent investigations.

In Devonian time the Paraná Basin was opened to the north in an apparent connection with the Amazon and Parnaíba basins (Bigarella & Oliveira, 1966). Cross-bedding measurements in the Furnas Formation in the northern part of the Paraná Basin indicated that the marine current flowed to north-west, i.e. to the outside of the present edge of the basin, into the Amazon Basin. Micropaleontological evidences indicated that in Middle Devonian the Amazon, Parnaíba and Paraná basins were interconnected (Lange, 1967 b). The Amazon and Paraná basins became definitively separated in post-Devonian time by a large cratonic belt. Furthermore, still according to micropaleontologic interpretation, in Lower Devonian both basins were separated showing independent fossil assemblages (Lange, 1967 b).

In the State of Paraná, the Gondwana glacial and periglacial sediments of the Itararé Subgroup present transport to NNW (Bigarella, Salamuni & Fuck, 1967) indicating a subsident area around the Paranapanema Valley in south-western São Paulo. A reverse condition occurred for the post-glacial deposition of the Rio Bonito Formation of the Guatá Subgroup. Cross-bedding measurements indicate for the latter paleocurrents flowing south-south-eastward, just in an opposite direction to that of the Itararé time. This would mean that the former area of accumulation in south-western São Paulo and northern Paraná underwent an opposite movement, i.e. the area became uplifted (Bigarella & Salamuni, 1967, p. 242).

In Permian time, during the deposition of the Irati and Estrada Nova formations, the area of greater subsidence was located in central Paraná and in south-western Rio Grande do Sul. However, in the upper part of the Permian sequence (Rio do Rasto Formation) cross-bedding measurements indicate paleocurrents flowing away from the previously subsident area.

Pre-Paleozoic Erosion Surface

After the last pre-Paleozoic orogeny, the basement was eroded to a very well-developed and flat paleosurface, which has been usually interpreted as a peneplane by most authors, while others prefer to consider it a pediplane (Bigarella, 1964; Bigarella, Mabesoone, Lins & Mota F^o, 1965; Bigarella, Salamuni & Marques F^o, 1966; J. Dresh, personal communication; L. C. King, cited by Haughton, 1969, p. 26).

In the studied areas both in South America (Paraná and Parnaíba basins) and Africa (Karoo and Central Sahara basins) the Paleozoic sediments rest on these extensive and well planed erosion surfaces (pediplane). The erosion surfaces in the different basins do not seem to be contemporaneous. In Central Sahara the Paleozoic starts with Cambro-Ordovician sequences. In South Africa the Table Mountain Group is possibly Upper Ordovician and even older (Rust, 1967). The lower part of the Paleozoic (Furnas and Serra Grande formations) in Brazil was attributed to Lower Devonian. However, the Serra Grande Formation may be Silurian or even older.

In the Paraná Basin the pre-Furnas Formation erosion surface, known as pre-Devonian erosion surface, constitutes a well-planed surface which was developed under semiarid conditions as a pediplane. Subsequent humid climatic conditions produced a chemically weathered mantle (Bigarella, Salamuni & Marques F^o, 1966). The upper part of the

Furnas Formation is considered as upper Lower Devonian (Emsian) based on micropaleontological evidence (Lange, 1967 b). However, the exact age of the lower part of the sequence is still unknown.

In North-eastern Brazil the pre-Serra Grande erosion surface is also a flat and well-planed surface, which was interpreted by Bigarella, Mabesoone, Lins & Mota F^o (1965, p. 264) as being possibly a pediplane. The apparent relief presented by this surface is due to deep-seated folding or warping which was pene-contemporaneous with the sedimentation. Prior to the marine transgression, the erosion surface was subjected to chemical weathering possibly under humid climatic conditions which favoured the development of a regolith mantle.

In the Ahaggar (Central Sahara) the Cambro-Ordovician sequence (Unit II) rests on a well-planed surface (pediplane) developed under semiarid conditions. Similar features are presented by the pre-Table Mountain erosion surface, which also represents a pediplane developed under rough climatic conditions.

LOWER PALEOZOIC

The age of several of the geological formations considered as Devonian is now in a process of revision due to the discovery of new fossiliferous horizons. According to Rust (1967) the Silurian-Lower Devonian age of the Table Mountain Group has been shifted down to Lower Ordovician (Graafwater Formation) and Lower Silurian (Cedarberg Formation). The same has been verified with the Serra Grande and Pimenteiras formations of North-eastern Brazil, previously considered as Devonian. The discovery of microfossil assemblages in the lower part of the Pimenteiras Formation (Itaim Member) furnished the evidence of a Silurian age (Lange & Petri, 1967, p. 46). This implies an older age for the Serra Grande Formation, whose lower limit in age, in the Paleozoic, is still undetermined.

A possible Silurian age for the Furnas Formation has been mentioned (Barbosa, Ramos, Gomes & Helmbold, 1966). However, other geologists disagreed with this assumption (Lange & Petri, 1967, p. 46). Nevertheless, the unfossiliferous part of the Furnas Formation has not yet been convincingly dated.

In this paper the sequences from the Cambro-Ordovician to Devonian are discussed together in view of the general persistence of the paleocurrent trend throughout these geological periods. Both in South Africa and in Central Sahara, it has been verified, after a great number of cross-bedding measurements, that the paleocurrent direction was maintained almost constant from Ordovician to Devonian times. In South America the same is true from the Serra Grande Formation to the Cabeças Formation (Silurian and/or Ordovician? to Middle Devonian).

In the following paragraphs is given a general description of the formations where paleocurrents were measured.

Ahaggar (Central Sahara)

The pre-Devonian stratigraphic succession of the Ahaggar, in Central Sahara, is represented by the Cambro-Ordovician and Silurian sequences. Besides some pioneer studies, basic work in the area was mostly performed by the French and Algerian Petroleum Institutes in co-operation with the Universities of Algiers, Nancy and Strasbourg. The

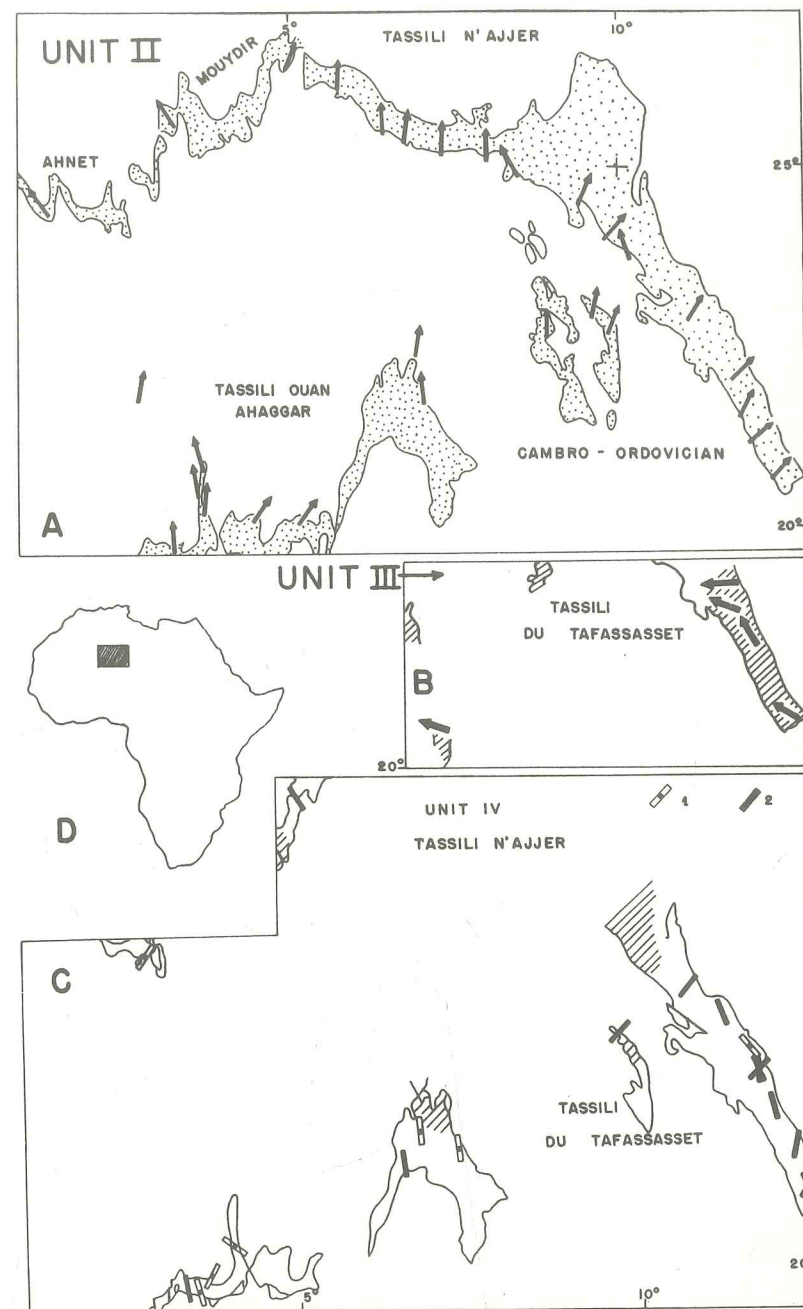


Fig. 6. Paleocurrents and striated surfaces from the Cambro-Ordovician sequences of Central Sahara. A—Direction of transport based on cross-bedding measurements from the sandstones of Unit II; B—Directions of transport from the sandstones of Unit III; C—Orientation of the striations and glacial relief (1—at the base of Unit IV; 2—inside Unit IV); D—Geographic setting of the area studied by the French Petroleum Institute and by the Algerian Petroleum Institute.

Cambro-Ordovician sequence is divided into four formations, which are not yet named, but designated by Roman algarisms (Gariel, de Charpal & Bennacef, 1968; Beuf *et al.*, 1968). The lowermost formation (Unit I) has a limited distribution in the region of Amguid. This formation is made up of arkoses and conglomerates. The Unit II has a widespread distribution and rests with a major angular discordance over the Precambrian basement. Locally it rests unconformably on Unit I. The nature of the paleosurface has been described elsewhere in this paper.

The Unit II is composed of cross-bedded sandstones which were interpreted as deposited by a braided stream system (Gariel, de Charpal & Bennacef, 1968). Cross-bedding measurements have indicated paleocurrents flowing northwards (fig. 6). Interbedded, there are marine beds with frequent organic structures and traces.

The physical nature of the Unit II with its characteristic cross-bedding pattern is very similar to those of the Table Mountain, Serra Grande, Caacupé and Furnas sandstones. Similar structures in the Serra Grande and Furnas formations of South America have been interpreted as marine (Bigarella, 1964; Bigarella, Salamuni & Marques F^o, 1966; Bigarella, Mabesoone, Lins & Mota F^o, 1965). For the Table Mountain sandstones a similar interpretation was advanced (Swart, 1950; de Villiers, 1956; Rust, 1967). During a field trip in the Tassilis of the Ahaggar region, Prof. Seilacher has found trilobite fossil tracks inside the cross-bedded units. These findings support a marine environment for the development of the cross-bedding pattern. Although the type of cross-stratification suggests fluvial structures, the organic structures (trails and tracks) are indicative of marine environment.

Unit III is mostly composed of well-stratified micaceous fine-grained sandstones with frequent organic structures. The environment of deposition is undoubtedly marine. The age was attributed to Middle Ordovician (Bennacef, Biju-Duval, Beuf, de Charpal, Gariel & Rognon, 1970).

The Unit IV is referred to elsewhere in this paper (Evidences of Ordovician and/or Silurian Glaciation). Above the Unit IV occurs a sequence of Silurian shales with graptolites. A transitional zone is found below the Devonian sequence of crossbedded sandstones. These sandstones have also been interpreted as fluvial. However, they may well be marine. The cross-bedding pattern indicates a transport from south-east to north-west (fig. 6).

Cape Province (South Africa)

The Table Mountain, Bokkeveld and Witteberg Groups are included in the so-called Cape System which consists of a considerable but variable thickness of sandstones, shales and quartzites which rest unconformably upon older formations and are overlain by the basal beds of the Karroo System (Du Toit, 1954; Haughton, 1969). The Table Mountain Group is characterized by a great thickness of predominantly coarse sediments, occasional layers of pebbles, and the general absence of fine-grained sediments. The nature of these sediments resembles very much the Cambro-Ordovician sequences of Central Sahara, as well as the Serra Grande Formation of north-eastern Brazil and the Caacupé and Furnas formations respectively from Paraguay and Southern Brazil.

In western Cape Province the Table Mountain Group

was divided into the following lithological units, which are from below upwards,

- (1) Basal Shale
- (2) Main Sandstone
- (3) Upper Shale with glacial beds at the base, and
- (4) Upper Sandstone (Haughton, 1969, p. 331).

The following litho-stratigraphic subdivision (formations) was proposed by Rust (1967), from below upwards,

- (1) Piekenier Fm.
- (2) Graafwater Fm.
- (3) Peninsula Fm.
- (4) Pakhuis Fm.
- (5) Cedarberg Fm., and
- (6) Nardouw Fm.

The environment of deposition, both of the Table Mountain Sandstone (South Africa), and the Furnas Sandstone (Southern Brazil), was in the past considered as marine, deltaic, lacustrine, eolian and fluvial (Rust, 1967; Bigarella, Salamuni & Marques F^o, 1966).

Fossil evidences and organic structures (burrows, tracks, trails and tubes) are on the whole suggestive of a marine environment for the deposition of great part of the Table Mountain Group (Rust, 1967). Some formations are without any doubt marine (Cedarberg Formation with Brachiopod zone) while in others, like the upper part of the Peninsula Formation, the marine environment is deduced with reasonable certainty. Trilobite tracks in these rocks are relatively scarce (Rust, 1967). The apparent lack of fossils or organic marine traces in the normally unfossiliferous formations is not a proof of a non-marine environment. It has been already mentioned that Prof. Seilacher has found a reasonable amount of tracks in the Unit II (Ahaggar) which was considered before as having been deposited in a non-marine environment. The lower part of the Table Mountain Group, according to Rust (1967), is believed to have been deposited respectively in deltaic (Piekenier Fm.) and tidal flat (Graafwater Fm.) environments.

The following data on paleocurrent trends for the Table Mountain Group were taken from Rust (1967). The cross-bedding pattern of the Piekenier Formation indicates strong currents flowing consistently from the NW (fig. 7). For the Graafwater Formation the cross-bedding indicates inconsistent directions for the transport of the sediments. Sometimes, a reversal of the flow direction occurs. The paleocurrents determined in the Peninsula Formation (fig. 7) show a major change in the direction of the flow in the basin, when compared with the flow pattern of the Piekenier Formation. The paleoflow pattern of the Nardouw Formation closely parallels that of the Peninsula Formation.

Current-bedding measurements of the uppermost Table Mountain Sandstone in western and eastern Cape Province were made by J. N. Theron (Table I). North of Durban (Natal), in the Victoria County area, the current bedding dips of the Table Mountain Sandstone are concentrated to the southwest (Kent, 1938). Cross-bedding measurements of the Table Mountain Sandstone, in the Province of Natal, were made by J. J. Bigarella and by N. J. Beukes, along the Durban-Pietermaritzburg highway and in the vicinity of Port Edward (Table I).

The results obtained from the Table Mountain Sandstone cross-bedding measurements made by Rust (1967), Theron (personal communication), and Bigarella & Beukes

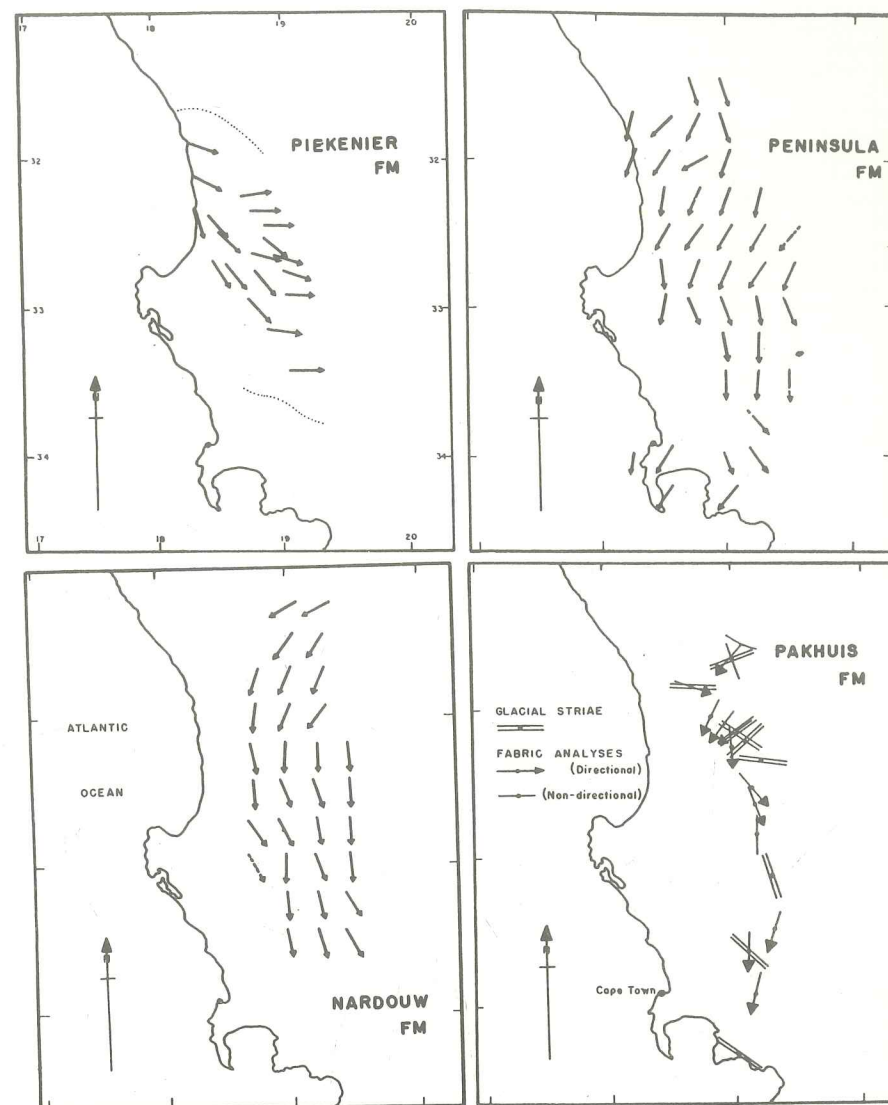


Fig. 7. Paleocurrent trends deduced from the cross-bedded sandstones of the Table Mountain Group (Western Cape Province, South Africa). Orientation of striated pavements and fabric analyses. (Diagrams after Rust, 1967).

are indicative of a slightly radial-like pattern for the transportation trend (fig. 9). Going east-northeastward from Cape Town to Durban, there is a slight south-eastward shift of the vector direction. This indicates a peripheral provenance of the sediments, from an area situated to the north and north-northwest, respectively, from Cape Town and Durban.

The directions of transportation determined from the Lower Devonian Sandstones of the Bokkeveld Group are very near to those of the Table Mountain Group (Theron,

personal communication). Table II presents the vector mean of the Bokkeveld sandstones, both for the western and eastern Cape Province (fig. 10). Cross-bedding measurements in the basal part of the Witteberg Group were made by Theron in western and eastern Cape Province. There is an appreciable difference between the two areas (Table II) which could be due to an insufficient number of measurements. However, the results so far obtained indicate a transport to SSW (S 22° W) in the eastern area and to SE (S 51° E) in the western area.

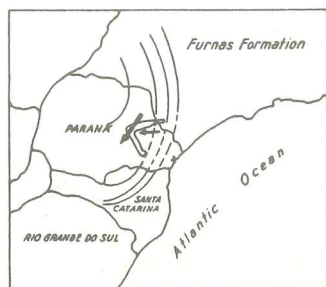


Fig. 8. Paleocurrent trends and isopach lines from the Furnas Formation (Paraná Basin).

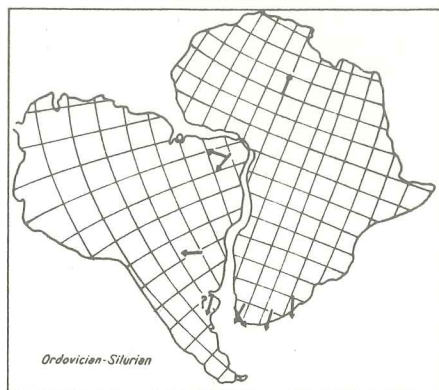


Fig. 9. Paleocurrent mean direction deduced from Ordovician and Silurian rocks in Africa and South America. A roughly radial pattern indicates a provenance from a common continental area located in eastern South America and western Africa. The paleocurrent trends agree with the adjacent position of both continents.

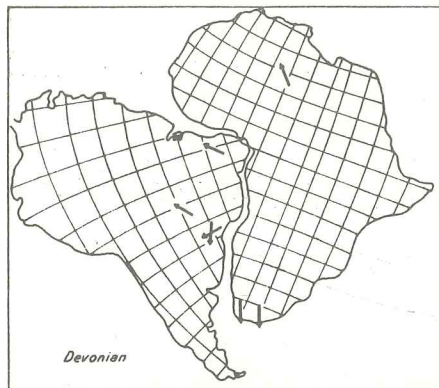


Fig. 10. Paleocurrent mean direction deduced from Devonian rocks in Africa and South America. A roughly radial pattern is found indicating a common continental source area, which agrees with the adjacent position of the continents. There is an astonishing permanence of the transportation pattern from Ordovician to Devonian time.

Caacupé Group (Paraguay)

The Caacupé Group crops out in the western side of the Paraná Basin, in Paraguay. It is also found in subsurface in the pericratonic Grand Chaco Basin (Eckel, 1959). In the central part of the Paraná Basin, there has not yet been found any evidence of the Caacupé sediments in the deep boring made by Petrobrás S.A. The Itacurubi beds described by Harrington (1950) as Devonian were included in the Caacupé Group by Wolfart (1961, p. 37). The age of the group is considered generally as Silurian. The upper part of the sequence contains a marine fauna of Lower Llandovery age (Wolfart, 1961). The lower part of the sequence (basal conglomerate and Caacupé sandstone) may be Lower Silurian or even older (Upper Ordovician?).

Cross-bedding measurements from the Caacupé Sandstone were made by Bigarella & Comte (in press). The average dip direction indicates a transport to WNW (N 63° W), which is outwards from the present day edge of the Paraná Basin (fig. 9).

In the Paraná Basin, cross-bedding measurements from the Furnas Formation were made both in the southern and northern outcrops (Bigarella, Salamuni & Marques F°, 1966; Bigarella & Salamuni, 1967). The average transportation trend for the southern part of the basin was to SW (S 55° W), while for the northern outcrops in Goiás and Mato Grosso the average current direction was to north-west (N 35° W). In Paraná and Sao Paulo the lower section of the Furnas Formation shows a direction of transportation from east to west. The preferred orientation of included pebbles also provides evidence of currents moving westward, away from the emerged eastern land (fig. 10). The middle and upper part of the formation has an average trend of S 31° W for the current movement, indicating currents moving parallel to the shoreline coming from the north-northeast. The resultant vector roughly coincides with the orientation of the Furnas Formation isopach lines (fig. 8). Repeated alternations of westward and south-southwestward transportation trends were a characteristic feature of the lower part of the Furnas Formation. The westward trend represents the transport of material into the basin, in a direction normal to the former coastline. The south-southwestward trend indicates a reworking of the material by currents flowing parallel to the former coast. This alternation of paleocurrents in a stratigraphic section was one of the main arguments used for interpreting the environment of deposition as marine (Bigarella & Salamuni, 1967 a). Two different paleocurrents were also identified from the Table Mountain Group (Piekenier Fm. and Peninsula Fm.). They indicate also transport from an emerged area and a possible reworking sub-parallel (?) to the coastline (fig. 7). However, repeated alternations of both directions were not observed. In other formations (like the Cambro-Ordovician of Central Sahara, the Caacupé and Bokkeveld groups) there is only one paleocurrent trend. In this case, the paleocurrent has been interpreted as at right angles to the coast, i.e. flowing down the paleoslope dip.

In the northern part of the Paraná Basin, the paleocurrent flowed away from the present-day edge of the basin, suggesting that there was a connection with other basins, perhaps the Amazon or possibly the Parnaíba, to the north (fig. 10).

In the Parnaíba Basin, the Serra Grande Formation has

an average cross-strata dip direction of N 55° W, the paleocurrent flowing northward possibly being parallel to the coastline. The lower beds at the Serra Capivara indicate paleocurrents flowing to the south-west (S 59° W). These currents, which are at right angles to the north-western ones, represent transportation from the land toward the basin. Alternations of both current trends were not observed to occur in the Parnaíba Basin (Bigarella, Mabesone, Lins & Mota F°, 1965).

The Itaim Member of the Pimenteira Formation has the same average cross-bedding dip direction (N 55° W) as the underlying Serra Grande Formation. The average cross-bedding dip direction of the Cabeças Formation is also close to the average of the subjacent formations. This shows that in the Parnaíba Basin, at least off-shore, there was no appreciable change in the circulation pattern from Silurian and/or Ordovician (?) to Devonian times.

The Ordovician-Silurian and the Devonian paleocirculation trends are represented in figures 9 and 10 showing Africa and South America fitted together. In both illustrations the arrows indicate a peripheral transportation trend from a former common land mass comprising parts of South America and Africa. These features can be considered as good evidence for a former connection between both continents in Lower Paleozoic times.

EVIDENCES OF ORDOVICIAN AND/OR SILURIAN GLACIATIONS

Many times, deposits resembling tillites have been interpreted as evidences of glaciation. However, in several instances, they can be interpreted as having been originated by turbidity currents, mud-flows, slumps, etc. There is still an urgent need for definition of genetic terms used in describing deposits made up by ice advance or retreat. In this paper, the use of the term tillite is restricted to ground moraine deposits formed by the ice advance. Any other deposit resembling tillite formed in the periglacial environment is referred to here as diamictite. As periglacial sediments we consider all the deposits formed during the retreat of the ice cap.

Evidences of an Upper Ordovician widespread continental glaciation have been recently recognized and proved for the stratigraphic sequence of Unit IV in Central Sahara region (Beuf & Biju-Duval, 1966; Rognon, de Charpal, Biju-Duval & Gariel, 1968; Arbey, 1968). Other evidences can be traced according to Fairbridge (1969) from the borders of Morocco (Eglab Massif), Mauretania (Taoudenni Basin), Algeria and Tunisia (Ougarta, Grand Erg), Niger (Talak Basin), to Tchad (Tibesti, Borkou, and Ennedi).

During the Upper Ordovician, the Sahara platform was uplifted and dissected by erosion. A glacial period followed filling the paleovalleys with glacial and periglacial sediments. The general movement of the ice sheet was from the south to the north, in the same general trend of the older paleocurrents (fig. 6). The evidences of this glaciation are represented by glacio-tectonic foldings, striated and grooved surfaces, by the sediments of the Unit IV, and by remnants of arctic-like types of morphology (Rognon, de Charpal, Biju-Duval and Gariel, 1968).

Inside the Table Mountain Group (South Africa), the Glacial Zone or Pakhuis Formation (Rust, 1967) is a

well-established glacial sequence which was recognized a long time ago (Rogers & du Toit, 1909). Glacial-tectonic foldings were described in detail by Haughton, Krige & Krige (1925). From the folding pattern Haughton (1929) concluded that the ice sheet moved from the west to the east.

The glacio-tectonic foldings in unconsolidated sediments were first interpreted as transverse structures formed below the moving ice sheet. According to Visser (1962), the intraformational foldings are not transverse features but actually they develop parallel to the ice flow. The point of view of Visser is supported by the orientation of the glacial striations and grooves, by tillite fabric analysis, and by the progressive decrease of the proportion of mechanically unstable heavy minerals (Visser, 1962; Rust, 1967). The southward movement of the ice flow deduced by Visser (1962) was confirmed by Rust (1967). Both the orientation of the striations and the fabric analysis vectors (fig. 7) are roughly parallel to the axial plane trend of the fold zone (Rust, 1967).

The glacial deposits of the Table Mountain sequence are located stratigraphically below the Brachiopod zone of the Cedarberg Formation. The whole fauna of this zone indicates a definite Lower Silurian, probably Lower Llandovery age (Rust, 1967). The Graafwater Formation is possibly Lower Ordovician in age (Rust, 1967). The glaciation is in this way limited in time between Ordovician and Silurian. According to paleontologic evidences, the Ordovician pole was interpreted as located somewhere in north central Africa (Spjeldnaes, personal communication).

Both glaciations, the one in Sahara and the other in the Cape Province, might or not have been contemporaneous. Nevertheless, the ice sheets actually moved in opposite directions from an elevated, not yet exactly determined, region located somewhere in between.

To the South American Ordovician (Middle Tremadocian time) Harrington (1962, p. 1782) refers the activity of local and short-term glaciers along the northern plunge of the Pampean Ranges massif in Argentina. In northern Argentina and Bolivia, the Silurian so-called "Zappla tillite" represents a glacial marine conglomerate at the base of the Wenlockian sequence (Schlangintweit, 1943).

The Iapó Formation, in the State of Paraná, has been considered as formed by tillite and glacial drift deposits (Maack, 1947, 1969; Caster, 1952; Rich, 1953; Beurlen, 1955; Martin, 1961). This interpretation has been discussed by Bigarella, Salamuni & Marques F° (1966). The Iapó Formation at the Serra S. Joaquim (type locality) is about 15 m thick. It is composed of a succession of rudaceous layers, whose matrix is sandy-silty-clayey. These deposits (diamictite) are of polymictic character, and the phenoclasts are generally angular to sub-angular. Pebbles of granite and gneiss are the most frequent ones, followed by those of rhyolite and quartzite. Other phenoclasts, such as those of sedimentary rocks, quartz, chert and phyllite, occur in a smaller percentage (Bigarella & Salamuni, 1967 c).

Some striated pebbles in the Iapó deposits have been mentioned by Maack (1947). There is a strong tendency to consider all striated pebbles as developed in the glaciers. However, striations may be produced under other circumstances, like mudflows, as shown by Winterer & von der Borch (1968). More work is desirable for a better

understanding of the development of striations on the pebble surface.

The polymictic nature of the pebbles could be developed either in glacial or in semiarid environments. The Iapó Formation seems to have originated through successive mudflows which were heavily charged with rudaceous material. Such succession indicates the superposition of many subaerial mudflows, lacking any graded bedding, due to concentrated rainfall in the source area. These features are related to an environment where semiarid conditions prevailed (Bigarella & Salamuni, 1967 c). The Iapó Formation was considered to be the correlative deposit of the pediplanation processes responsible for the development of the pre-Furnas erosion surface.

The unfossiliferous Iapó Formation was dated as Silurian (Gotlandian) by Maack (1947). Anyway, its age is limited between the known age of the rhyolites (450 m.y.) and the Lower Devonian beds (Ponta Grossa Shales). Even if not glacial, the deposition of the Iapó Formation could be contemporaneous with the Ordovician or Silurian glaciation. It has been shown by Bigarella, Mousinho & Silva (1965) that, during the Quaternary ice ages, semi-arid climatic conditions predominated outside the glaciated areas. Under such circumstances, the Iapó Formation could have been deposited as a succession of mudflow layers during a glacial period.

For the Parnaíba Basin, Malzahn (1957) reported having found surfaces striated by the ice in the upper part of the Serra Grande Formation sandstones, as well as tillites and varved sediments at the base of the Pimenteira Formation. These signs of glaciation occur only in restricted localities and not on a regional scale. The glaciation was attributed to the Devonian. The evidences were discussed by Bigarella, Mabessone, Lins & Mota F^o (1965). The age, both of the Serra Grande Formation and of the Itaim Member of the Pimenteira Formation, is possibly no longer Devonian as considered before. Micro-paleontological studies indicated a Silurian age for the Itaim Member (Lange & Petri, 1967, p. 46). The tillite and the striated pavement are at the base of the Pimenteira Formation (Itaim Member) as referred by Malzahn (1957, p. 8). The Silurian age was established for the marine microfossils of the Itaim Member, which rests above the postulated glacial deposits. The age of the Serra Grande Formation is still unknown. If the evidences of glaciation pointed out by Malzahn can be completely proved, it is possible that the Serra Grande/Pimenteira glacial deposits can be correlated with those of the Unit IV of Central Sahara. Further studies are urgently needed in order to confirm or discredit the hypothesis of a glacial episode in the upper part of the Serra Grande Formation and in the lower portion of the Pimenteira Formation.

UPPER PALEOZOIC

The comparison of the Upper Carboniferous and Permian sequences of South America and Africa has been considered as the most convincing evidence of the former existence of Gondwanaland. Due to the great enthusiasm of some former investigators of the problem of continental drift, many geological features have been over-emphasized to fit a connection between South America and Africa, and were sometimes misinterpreted. In the present stage of

knowledge, an accurate mapping project is needed on both sides of the South Atlantic. Before further comparisons can be made a review of the stratigraphic problems is also desirable.

The Dwyka paleo-ice movements were determined long ago by du Toit (1927). More recent studies in South West and South Africa were made by Martin (1953, 1961, 1964) and by Stratten (Ph. D. thesis). Maack (1946, 1960) extrapolated the ice flow directions from South West and South Africa into southern Brazil. In the Brazilian lower Gondwana, many attempts were made to determine the directions of ice movement and water currents. For such purposes either tillite fabric or directional structures, together with other vectorial features imparted by ice flow or water currents, have been searched for, and lately been used rather extensively.

The reliability of the results so far obtained is still a matter of dispute, since many discordant data have been presented by different geologists. However, despite this fact, the results so far obtained are helpful for the understanding of the environment of deposition and the paleogeographic problems. Probably, the first consideration about the ice movement in the Gondwana of South America was made by du Toit (1927) from striated floors in northern Uruguay. He recognized a northwestward movement for the ice flow. Also in Uruguay Walter (1931) described a set of striations indicating a westward movement. Glacial striations in the Gondwana of Brazil were first mentioned by Carvalho (1940, p. 271) in an outcrop between Mafra and São Bento (S.C.). Barbosa (1940, p. 272) deduced the direction of flow as northwestward (N 32° W). A similar direction for the ice movement was recognized at Salto (S.P.) by Almeida (1948 a, p. 115).

Tillite fabric analyses made by different authors are not conclusive for indicating the ice movement direction. These studies indicated for the paleo-ice flow

- a southwestward movement (Leinz, 1937);
- a south-southwestward trend (Maack, 1946, p. 195);
- a westward to northwestward direction (Mau, 1958, p. 22);
- a north-northwestward movement (Bigarella, Salamuni & Fuck, 1967).

Only the north-northwestward or northwestward directions are in agreement with other vectorial features like those presented by orientation of striations or periglacial cross-bedding trends.

According to Beurlen (1957) the centre of glaciation was in the south in the latitude of the Rio Grande do Sul shield. The ice moved mainly from a south-western direction reaching areas as far as Minas Gerais, Mato Grosso and Goiás. The same direction of flow has been mentioned by Mempel (1957). Mendes (1962) believes that the centre of the glaciation was placed nearer to the northern part of the Paraná Basin. This assumption was also advanced by De Loczy (1964), and agreed with the general results presented by Leinz (1937) and Maack (1946), but is not supported by recent work.

Deformational structures apparently caused by glaciotectionics have been sometimes employed to determine the direction of ice flow. Possibly the first reference made in South America to such structures was that of Washburne (1930, p. 32) who concluded a westward or

northwestward movement of the ice flow. According to Almeida (1953), the orientation of the folds indicated an ice flow to the north-west. The most extensive and detailed study of the folding and imbrications developed during the Gondwana glaciation was made by Martin (1961, 1964). He described several outcrops mainly along the eastern border of the Paraná Basin, reaching the conclusion that the ice-sheets came from the east and the south-east. Martin made his interpretation on the belief that the folding pattern was developed transverse to the ice flow. The vector obtained by him in the State of Paraná is at a high angle to the mean striation direction and to both the tillite fabric and cross-bedding vectors determined by Bigarella, Salamuni & Fuck (1967). As mentioned before for the glacial zone of the Table Mountain Group, it seems also possible that the folding axis originated inside the Itararé beds by the overriding ice-sheet which developed roughly parallel or diagonal to the ice flow.

Recent paleocurrent studies in the Tubarão Group were made by Bigarella & Salamuni (1967 b & c), Rocha-Campos (1967) and Frakes & Crowell (1969). Striated floors are rather widespread in some areas of the Second Plateau of the State of Paraná (Bigarella, Salamuni & Fuck, 1967). Within this area, 22 localities were mapped and studied, and the results compared with petrofabric analysis and cross-bedding average dip directions. The striations are not restricted to pre-Itararé surfaces, but they occur also on periglacial deposits of the Itararé Subgroup. Some striated floors are overlain by typical tillites, while in others the former till was eroded and replaced by periglacial deposits. In the outcrops where the striated floors are overlain by tillite, a comparison was made between the direction of the striation and the mean vector deduced from pebble long-axis orientation.

The direction of the linear structures is quite persistent in the different outcrops. The striae have an average direction of N 02° W. Whenever possible, concomitant studies of tillite fabric were made, measuring both the pebble long-axis direction and the pebble long-axis dip direction. The average pebble long-axis direction, as determined from 889 measurements in typical tillite, was S 37° E - N 37° W, while the average long-axis dip direction was S 20° E. This indicates that the ice-sheet moved to NNW (N 20° W).

Cross-bedding measurements (491 readings) were made from the periglacial sandstones, either associated with tillites or with other periglacial deposits. All the measured structures are of subaqueous origin (Bigarella & Salamuni, 1967 b & c, p. 254). One locality supposed to be of eolian origin was mentioned by Martin, Bigarella & Salamuni (1960). However, this locality may have been misinterpreted. The beds assigned to the Itararé sequence probably belong to the Rio Bonito Formation.

Besides the above-mentioned criteria, other directional structures have been occasionally measured in the Itararé subgroup. Some of these have been ascribed to turbidity currents (Salamuni, Marques F^o & Sobanski, 1966). Such lineations measured in the Rio Negro-Mafra area have shown an average direction of N 32° W. In the Lapa area (State of Paraná), similar lineations are in average N 21° W. The average transport direction obtained from the cross-bedding measurement was N 10° W.

In the State of Paraná, the comparison between the

results obtained from the several linear structures, tillite fabric, as well as from cross-bedding measurements, indicates coincident paleocurrent trends for the Itararé Subgroup sediments, corresponding to a general north-northwestward transport direction. The paleocurrent analysis of the Itararé Subgroup sequences confirms the presence of a subsistent area around the Paranapanema Valley in south-western São Paulo and northern Paraná during the deposition time.

Due to the lack of both detailed geologic maps and good stratigraphic correlation it is very difficult to compare different areas of the Paraná Basin. It is also difficult for paleogeographic interpretation to use a mixed set of data, sometimes statistically insufficient. It is preferable to analyse paleocurrent trends using at each time a single set of observations, avoiding, for instance, the mixing in the same map of the orientation of the striated floors, cross-bedding mean vectors, folding structures, and so on. In this way a clearer pattern is obtained.

The Gondwana glacial sequence paleocurrent trends are illustrated in figure 11 showing the available data (South America) and speculative interpretation (Africa). In the Paraná Basin the different data on paleocurrents may not correspond to isochronous sequences.

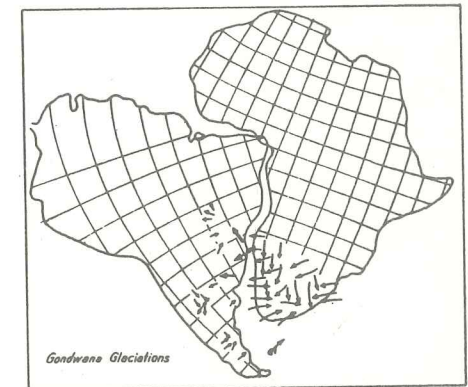


Fig. 11. Paleocurrent trends and ice flow directions for the glacial and periglacial deposits of the Gondwana glaciations. (Based on du Toit, Stratten, Martin, Rocha-Campos, Frakes & Crowell, and Bigarella & Salamuni).

The former attempt at interpreting the provenance of the ice-sheet and glaciation centres made by Maack (1958) is not in agreement with more recent data. It seems also very improbable that the Itararé sequences, in the Second Plateau of Paraná, were derived in part directly from South West Africa when both continents were adjacent to each other. To prove this, there are still needed more data for a better statistical analysis. Figure 11 shows that the source area for the Itararé sequences in Paraná was to the SSE. This still indicates a South African provenance of sediments if both continents are fitted together. However, in the possible source area in South Africa there is no indication of a transport towards the same direction, i.e. northwards (fig. 11).

Based on paleocurrent analysis, Frakes & Crowell (1969, p. 1033) mention for the Paraná Basin three centres

from where the ground moraine and fluvial deposits were derived:

- (1) State of São Paulo
- (2) Paraná south of the Ponta Grossa arch and northern Santa Catarina, and
- (3) around the Uruguayan shield.

In the western part of the Paraná Basin, the Asunción arch is considered the principal source for glacial sediments between 26° and 20° of latitude (Frakes & Crowell, 1969, p. 1034).

Along the western edge of South America "an ancient Andean range probably held a chain of alpine glaciers which here and there coalesced upon reaching lowland into broad piedmont glaciers" (Crowell & Frakes, 1968, p. 300). The Gondwana glacial deposits from the Falkland Islands indicate a western provenance, which could be related to the former Andean range glaciers (Crowell & Frakes, 1968). Another centre of glaciation probably was located in the Southern Hills of Buenos Aires indicating an ice-flow to the NE (Crowell & Frakes, 1968).

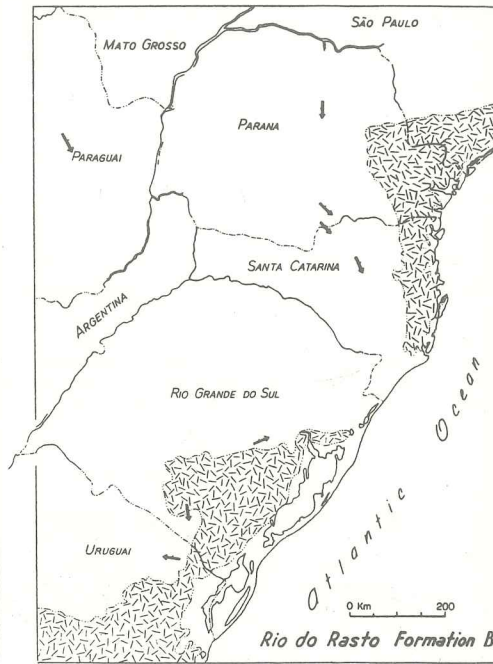
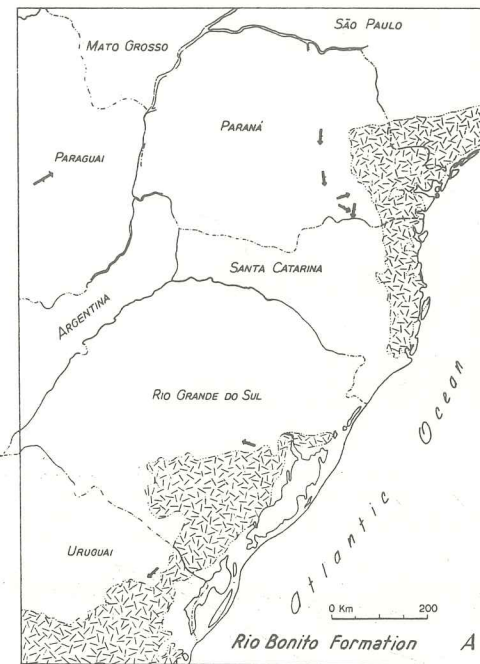


Fig. 12. A—Paleocirculation trend deduced from cross-bedding measurements for the Rio Bonito Formation, Paraná Basin.
B—Cross-bedding measurements resultant vector showing the transportation trend for the Permian Rio do Rasto Formation of the Passa Dois Group, Paraná Basin.

In the northern part of the Karoo Basin, the movement of the ice was directed mainly from the N and NE. The greater development of the tillite in the southern part of the basin must indicate the presence of a deep trough, oriented east-west. Recent studies in the Cape fold belt suggested the existence of another glaciated land-mass south of the trough from which the debris were carried northwards into the southern belt of the basin (Haughton,

1969, p. 400). A source in the west is also suggested (Stratten, Ph. D. thesis). The western to the south-western provenance of the ice-sheets is in good agreement with the data presented by Crowell & Frakes (1968) for South America (fig. 11).

A large ice mass was centred over South West Africa, from where the ice flowed southwards and westwards following the valleys of a subdued mountain range (Martin, 1961, 1968). The westward direction of the ice-flow was used as an argument to prove the adjacent position of Africa and South America (Maack, 1958, 1969; Martin, 1961, 1964). However, these directions do not agree well with the ones obtained in Paraná, but fit better with some of the striated pavements and alignments of pre-glacial valleys and hills which have been found in São Paulo, southern Santa Catarina, Rio Grande do Sul and Uruguay.

The postglacial deposits of the Tubarão Group are represented by the Rio Bonito and Palermo Formations. Between the Rio Bonito beds and the underlying Itararé sequences there is a slight angular unconformity which

becomes apparent only on the scale of geological mapping. The cross-bedding measurements were restricted to the subaqueous Rio Bonito sandstones. Measurements were made in Paraná (5 localities, 264 readings), Rio Grande do Sul (64 measurements), Uruguay (89 readings) and Paraguay (55 readings).

In the State of Paraná, the average dip direction from the Rio Bonito Formation is S 22° E. This vector indicates

a transport to SSE, i.e. in an opposite direction to the one from the Itararé interglacial sandstones. The source area of the Rio Bonito in Paraná was located to the north in the region which was previously subsident in Itararé time (figure 12-A). This area became uplifted and a reversal of the drainage pattern took place. The movement of the basement was interpreted as caused by deep-seated folding. An undulatory and differential movement of subsidence and uplift was originated.

In the western part of the Paraná Basin, in Paraguay, the sediments of the upper part of the Tubarão Group may be equivalent to the post-glacial sediments of the Rio Bonito Formation. The arkosic cross-bedded sandstones at about 20 km NW of Cel. Oviedo have an average dip direction of N 60° E (consistency ratio 0.58) indicating a transport to ENE (fig. 12-A) into a subsident area located in the western part of the State of Paraná and southern Mato Grosso (Bigarella & Comte, unpublished data).

The directions of transport indicated by Frakes & Crowell (1969, p. 1033, fig. 12) for the western part of the Paraná Basin correspond probably to "postglacial" deposits of the Aquidauana sequence (fig. 11). The southern outcrops indicate currents flowing eastward into the Paraná Basin, while the outcrops located more to the north reveal a transport to the outside of the present-day edge of the basin. This paleocurrent trend may be also due to differential movements, the sandstones of both areas being not necessarily contemporaneous.

In Rio Grande do Sul, the direction of transport for the Rio Bonito beds was towards WNW (N 72° W) away from the shield area (fig. 12-A). In Uruguay the transport was to SW (S 48° W) in direction towards the shield area (fig. 12-A).

Cross-bedding measurements from the upper beds of the Dwyka sequence (postglacial) in South West Africa were made by Heath (M. Sc. thesis) and by Bigarella, van Eeden, Schalk & Hugo (unpublished data).

Although the Gondwana glacial sediments are considered the best evidences of the former connection between Africa and South America, as well as the best proof of continental drift, the above data on striated floors and paleocurrents are suggestive but not definite proofs of the former adjacent position of the continents. Furthermore, a revision of the stratigraphic correlation between the different areas where measurements were made is desirable, as well as a revision of some data which apparently are discrepant with the general trends.

The Permian formations in both continents seem to have had a completely independent development. No direct connections between the Paraná and the Karoo basins are suggested from cross-bedding measurements. During the time of deposition of the non-marine Irati Formation (Paraná Basin), and the lithologically similar White Band (Karoo Basin), the two basins must have been separated possibly by an elevated area (Martin, 1968).

However, cross-bedding measurements from the Ecça and lowermost Beaufort sequences in the Karoo Basin indicate the provenance of the sediments from areas located off the western and southern coast of Cape Province, as well as off the coast of Natal.

In the Paraná Basin, cross-bedding measurements were made from the very fine-grained and silty sandstones of the Rio do Rasto Formation, corresponding to the upper part

of the Permian Passa Dois Group (fig. 12-B). During a great part of the deposition of the Passa Dois Group, great subsidences were verified in the central part of Paraná and in southwestern Rio Grande do Sul. In these areas the thickest sequences of the Passa Dois Group were accumulated. However, the measurements of cross-bedding in the upper part of the group, in the Rio Bonito Formation, show again a reversed condition of transport. These subsident areas for most part of the Passa Dois deposition became uplifted during the sedimentation of the Rio do Rasto Formation.

In Rio Grande do Sul, the area which was subsident during the deposition of the Guata Subgroup, Irati and Estrada Nova formations became uplifted during Rio do Rasto time originating a reverse trend for the sediment transportation. The new direction, towards east-northeast, was maintained also during Santa Maria Formation time (Bigarella & Salamuni, 1967 b, p. 242). In Uruguay, near Melo, the upper part of the Permian sequence shows a westward transportation (Bigarella & Salamuni, 1967 b, p. 262). In Paraguay, about 10 km south of San Estanislau, the Rio do Rasto beds indicate a transport to the south-southeast (S 27° E; number of measurements: 57; c. r. = 0.87; Bigarella & Comte, unpublished data).

In the Karoo Basin, about 80 to 90 percent by volume of the Ecça and lowermost Beaufort sediments has an extra-continental origin (Ryan, 1967, p. 157). According to Ryan the sediments were derived

- (a) from three mainly granitic source areas lying respectively to the east and north-east of the present Natal coast, to a considerable distance south of the east-west trend of the Cape folded belt, and to the west of the north-south trending Cape Orogenic belt;
- (b) from the pre-Karoo formations along the northern margin of the basin (fig. 13; Table V).

These data are suggestive of former continental connections.

MESOZOIC

Recent sea-floor spreading investigations have suggested a period of 150 to 200 m.y. for the entire development of the South Atlantic Ocean (Heirtzler, 1968). The beginning of the separation is referred to Late Jurassic time, about 150 m.y. ago (Heirtzler, 1968; Dietz, 1967). The paleowind pattern on both sides of the South Atlantic suggests that, at the time of deposition of the Etjo Sandstone in South West Africa, and of the upper part of the Cave Sandstone sequence in Northern Transvaal, during Upper Jurassic and Lower Cretaceous time, the former Atlantic Ocean was already in existence. During the deposition of the lower part of the Cave Sandstone (below the Drakensberg lava flows) both continents were adjacent to each other according to paleomagnetic evidences (Creer, 1970; Valencio, 1970).

The opening of the Atlantic, according to the sea-floor spreading hypothesis, was intermittent and the spreading process cyclic. An earlier cycle (or cycles) of spreading occurred possibly during the break apart of Gondwana and Laurasia (Ewing & Ewing, 1967). The earlier period of spreading terminated in Late Mesozoic time or Early Cenozoic (Ewing & Ewing, 1967; Le Pichon, 1968). The beginning of the drift movements was probably much older.

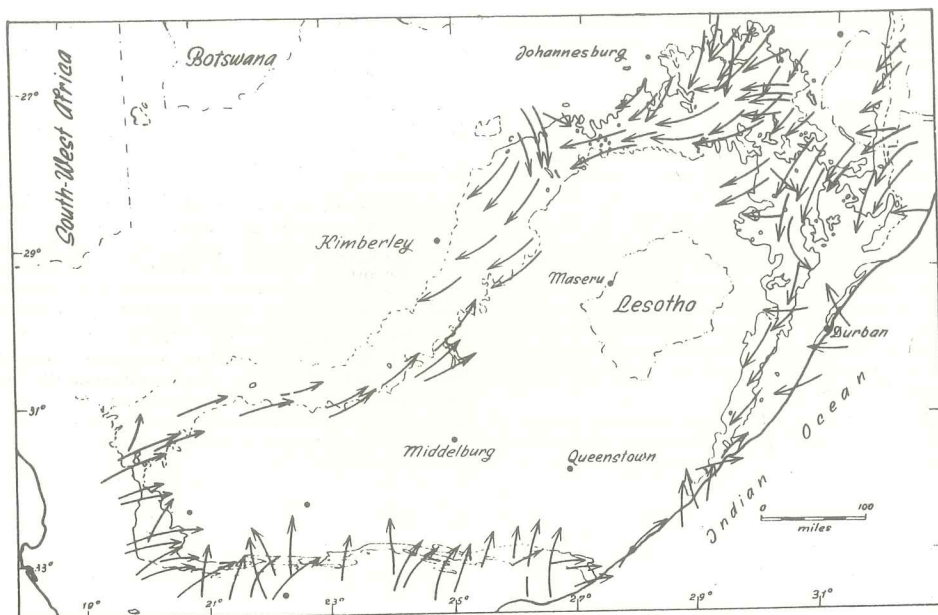


Fig. 13. Sketch of paleocurrent directions during the deposition of the Ecca Group (after Ryan, 1967).

Earlier paleomagnetic data have suggested the presence of a primitive South Atlantic Ocean since the Permian or Triassic time (Creer, 1958; McElhinny, 1968). More recent evidence indicates the beginning of drifting in Triassic-Jurassic time (Creer, 1970; Valencio, 1970). At the time of the Etjo and correlatable sandstones, in Upper Jurassic and Lower Cretaceous, the opening of the ocean was sufficiently large to maintain a permanent high-pressure cell blowing the westerly winds recorded from the eolian sandstones in South West Africa and Northern Transvaal.

The earlier period of spreading must have brought South America and Africa to a setting in which the relative position to the Equator and to the meridians was not much different from nowadays, with the exception of the shorter longitudinal distance between them.

Micropaleontological studies based on the similarities of the ostracod faunas known from the Northeastern Brazilian and Gabon basins were used to suggest that the disjunction between Africa and South America took place from a time interval between Lower and Middle Cretaceous (Belmont, Hirtz & Wenger, 1965).

The pre-Albian continental sediments (lacustrine, lagoon and estuarine environments) of the Bahia "Supergroup" and Cocobeach Formation, from both sides of the South Atlantic, have shown the simultaneous occurrence of similar species in equivalent stratigraphic successions (Grekoff & Krömmelbein, 1967). About a third of the Brazilian species of non-marine ("Wealden") ostracods occurs in Gabon forming the same assemblages (Krömmelbein, 1966a). An Upper Jurassic (?)–Lower Aptian age is preferred for the sequence (Krömmelbein, 1966a).

From the Middle Permian to the end of the Jurassic, no marine beds have been found on either side of the South

Atlantic (Beurlen, 1961; Martin, 1968; Maack, 1969). Lower to Middle Cretaceous salt deposits in the northeastern Brazil and Gabon basins are related to the first marine incursion (Belmont, Hirtz & Wenger, 1965). The salt deposits are overlapped by a sequence of carbonate rocks found along the opposed seaboards of South America and Africa, which confirms undoubtedly the establishment of the South Atlantic Ocean.

Marine benthonic Cretaceous ostracods of Aptian-Albian age and Early Turonian age occur also in both regions (Krömmelbein, 1966b). The distribution of non-marine and marine benthonic ostracods "is certainly best explained by the assumption of a direct continental connection between Africa and South America during Early Cretaceous time" (Krömmelbein, 1966b). According to Krömmelbein (1966b), during late Early Cretaceous and Late Cretaceous time the South Atlantic Ocean was relatively shallow to allow the migration of benthonic ostracods between west Africa and northeastern Brazil.

The abovementioned paleontological evidences have been used to demonstrate the opening of the South Atlantic Ocean in Cretaceous time. However, other evidence like paleomagnetic data suggests an earlier opening of the South Atlantic in Jurassic time (Creer, 1970; Valencio, 1970). Moreover paleowind analysis (Bigarella & Salamuni, 1967b; Bigarella & van Eeden, unpublished data) are suggestive of the presence of an ocean between Africa and South America during the time of the deposition of the Upper Cave, Etjo, Botucatu and Sambaiba sandstones. Furthermore, Krömmelbein (1966a and b) as well as other investigators admit the possibility of transport by birds and relocation of ostracod egg cases carried on the mud clinging to the feet of waterfowl. They consider also the possibility

(not yet fully demonstrated) of the dispersal of marine benthonic organisms either by larval transportation or by means of a passive transport of encysted eggs in air or ocean currents.

Krömmelbein (1966c) calls attention to the need of an investigation on the possibility of migration of marine benthonic ostracods by larval transport in present-day ocean currents in order to solve some of the paleogeographic problems. It is probable that at the time of the deposition of the Etjo, Botucatu and Sambaiba sandstones, the Gabon and northeastern Brazilian basins were not contiguous, but that a separation between the continents was already in existence. In this way, the above considerations on the dispersal of non-marine and marine ostracods could account for a similar, but not totally identical, distribution of the faunistic assemblages on both sides of the Atlantic, at a time when both continents were closer to each other.

The usefulness of the Mesozoic paleodesert distribution as a criterion to prove the former connection between South America and Africa has received different interpretations. It was considered as a proof by Maack (1969, p. 92) and as a non-valid argument by Martin (1961, p. 40). However, the paleodesert distribution and the paleowind pattern became actually good evidence to prove the existence of the sea between the continents at the time of the deposition of the eolian sandstones.

Paleowind directions were determined from the eolian sandstones in South America and Africa. The first attempt to determine paleowind trends in South America was made by Almeida (1954) in the State of São Paulo, who made 260 measurements concluding that the paleowind blew from the north. Later on, an extensive and detailed survey was made by Bigarella & Salamuni (1961) on the eastern outcrops of the Botucatu sandstone in the States of Minas Gerais, São Paulo, Paraná, Santa Catarina, Rio Grande do Sul and in the Republic of Uruguay. These authors made 2892 cross-bedding measurements from which two paleowind trends were recognized. The southern outcrops of the Botucatu paleodesert indicated deposition by westerly and south-southwesterly winds, while the northern outcrops indicate deposition by northerly and north-northeasterly winds (return trade-winds).

Further cross-bedding measurements were made in the northern outcrops of the Botucatu Sandstone in Mato Grosso and Goiás (Bigarella & Oliviera, 1966), and in the western outcrops in Paraguay (Bigarella and Comte, unpublished data). The northern and western part of the Paraná Basin shows the same general paleowind trend as that from the eastern part. In the Parnaiba Basin of northern Brazil, the Sambaiba Sandstone (equivalent to the Botucatu Sandstone) indicates paleowinds blowing from the southeast (south-easterly trade-winds).

In Africa, cross-bedding measurements of the Cave Sandstone (Stormberg Group) were made in the Orange Free State, Natal and Transkei (Beukes, M. Sc. thesis in preparation) and northern Transvaal (Bigarella & van Eeden, unpublished data). The Etjo Sandstone was surveyed in South West Africa (Huab River) by Bigarella, van Eeden, Schalk & Hugo (Table IV). The cross-bedding measurements from the Cave and Etjo eolian sandstones indicate deposition by westerly and south-southwesterly paleowinds. A reference to south-southwesterly paleowinds

is also made by Houghton (1969, p. 408) and by Ryan (1967, p. 159).

These results are similar to those obtained for the southern region of the Botucatu paleodesert. The comparison between the paleowind trends of Africa and South America is used in this paper to demonstrate the presence of the South Atlantic at the time of deposition of the Mesozoic eolian sandstones.

Unfortunately, there is no precise age determination for the Mesozoic eolian sandstones. The upper age limit is the radiometric age of the basalts, which for the Cave Sandstones (lower sequence, below the lava) is about 200 m.y. (Manton, 1968) and for the Botucatu and Etjo sandstones is 120 m.y. (Lower Cretaceous). The lower age limit for these sandstones are the fossiliferous Red Beds and the Santa Maria Formation of Triassic age. During the Mesozoic in Africa, there is a longer period (80 m.y.) of desert conditions with the development of dune fields, from the Cave Sandstone sequence (Orange Free State, Natal and Transkei) to the Etjo Sandstone of South West Africa (Kaokoveld).

The Cave Sandstone of southern Africa (below the Drakensberg lava flow) was deposited under climatic conditions which were not as severe as thereafter. The dune fields (cross-bedded sandstones) are not continuous in the sequence. There are signs of semiaridity and a great amount of rainfall which accounted probably for the dissipation of most of the former dune structures. The Cave Sandstone of Northern Transvaal (west of Messina) is younger than the sequences in the south (Drakensberg Escarpment) and in the east (Kruger National Park). In a general way, the climatic condition seems to have deteriorated upwards in the stratigraphic record from the Triassic to the Lower Cretaceous. For the Botucatu Sandstone, in the southern part of the paleodesert, the climatic conditions were extremely severe with the development of a continuous erg of cross-bedded dune sands. In the northern part of the paleodesert, rainfall was more frequent as shown by intercalated alluvial and playa lake deposits.

The cross-bedding resultant vectors from the Mesozoic eolian sandstone, both for Africa and South America, are statistically significant and are used in this paper to interpret the paleogeographic conditions at the time of deposition, with special reference to the age problem of the opening of the South Atlantic Ocean.

For the interpretation of the cross-bedding mean vectors of the Botucatu Sandstone, Bigarella & Salamuni (1961) suggested that the paleowinds were derived from two distinct high-pressure cells. One was located to the west in the former Pacific Ocean (westerly winds) and the other over a former Atlantic Ocean (north-northeasterly return trade-winds). This interpretation was also in agreement with paleomagnetic data referred to by Creer (1958). To explain a possible paleocirculation fitting the adjacent position of South America and Africa, Maack (1969, p. 91) advanced another interpretation for the paleowind trends recorded by Bigarella & Salamuni (1961) and Bigarella & Oliveira (1966) for the Botucatu Sandstone and by Bigarella, Coutinho & Montenegro (unpublished data) for the Sambaiba Sandstone. Maack (1969, p. 92) referred cross-bedded measurements made by Reuning from the eolian sandstones in the Kaokoveld as indicating easterly winds. This direction is just the opposite to the vector mean

deduced for the Etjo Sandstones (see Table IV). In the map published by Maack (1969, p. 91) there are indications of paleowind directions for regions without Mesozoic eolian sandstones, for instance Northeastern Brazil, Chile, Argentina and southern Central Africa. The paleowind directions postulated by Maack were actually not obtained from field measurements, but were drawn hypothetically to fit an adjacent position of the continents (see figure 14). We will take advantage of this hypothetical paleocirculation map of Maack by comparing it with another map of the adjacent position of the continents (fig. 15) showing the actually determined mean vectors (paleowind directions) obtained from field measurements of the Mesozoic eolian cross-bedded sandstones. The map presented by Maack (fig. 14) indicates how the paleowind circulation pattern would have looked if both continents were adjacent to each other at the time of deposition. Actually, the circulation pattern for the Southern Hemisphere is counter-clockwise. However, based on cross-bedding measurements we have to analyse the paleowind circulation pattern according to figure 15. This figure shows that the westerly paleowinds in South America have a tendency to shift to the right in Africa, i.e. in a clockwise way, which is in complete disagreement with the general counter-clockwise trend of the Southern Hemisphere wind circulation pattern. This constitutes the best evidence for the opening of the South Atlantic Ocean

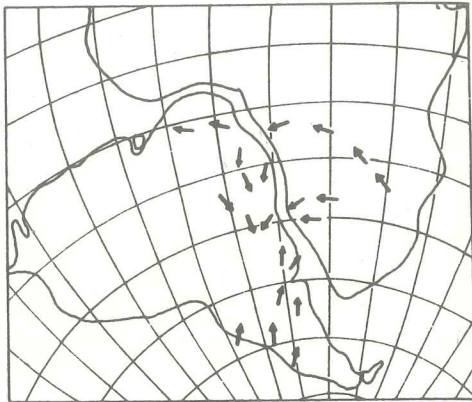


Fig. 14. Hypothetical paleowind circulation pattern suggested by Maack (1969) to fit an adjacent position of the continents. Some of the arrows representing paleowinds were based on Bigarella & Salamuni (1961), the others were not based on field measurements. This figure shows, however, how the wind pattern would have been if the continents were contiguous at the time of deposition. The true measurements are indicated in figures 15 and 16.

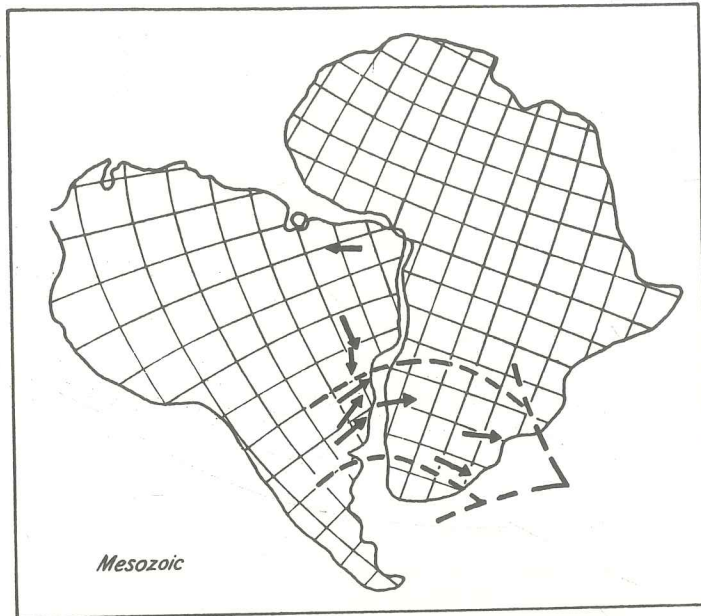


Fig. 15. Mesozoic eolian sandstones. The arrows indicate the paleowind trend deduced from cross-bedding measurements. This figure demonstrates the impossibility of the adjacent position of both continents at the time of deposition of the eolian sandstones. In this figure, the westerlies have a tendency to shift clockwise which is in opposition to the counter-clockwise trend of the wind circulation in the Southern Hemisphere. Continental fit around the Atlantic at the 500-fathom contour (after Bullard *et al.* 1965).

before the deposition of the Botucatu, Etjo and correlatable sandstones in Upper Jurassic-Lower Cretaceous time. Furthermore, the map of figure 15 demonstrates that the westerly paleowinds of South America and Africa came from different high-pressure cells. In South America they

longitudinal paleodistance between the two continents is not known. The paleolatitude for Africa seems also not to be very far from the present one as indicated by the westerly paleowinds. However, there is an indication that the African continent migrated slightly northwards.

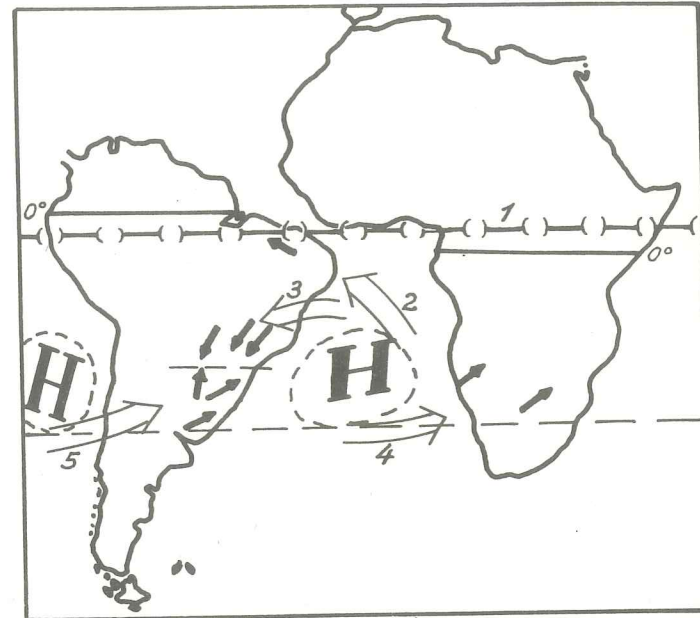


Fig. 16. In Africa and South America the paleowind circulation pattern of the Mesozoic eolian sandstones is better understood with the South Atlantic Ocean between the continents. The exact paleodistance between the continents at the time of deposition is unknown. The paleowinds were derived from two different high-pressure cells.

came from a high-pressure cell located over the South Pacific Ocean. These paleowinds reached the Paraná Basin due to the non-existence of the Andean Range barrier. In Africa, the westerly paleowinds for the Etjo and Upper Cave Sandstones must have developed from a high-pressure cell located over the former South Atlantic Ocean. These paleowinds penetrated deeply into Africa due to the non-existence of mountain barriers. Moreover, the same high-pressure cell over the Atlantic would be responsible for the southeasterly paleotrade-winds of Sambaiba Sandstone time and for the north-northeasterly return paleotrade-winds of the northern part of the Botucatu Paleodesert.

The paleowind pattern deduced for the Cave Sandstone below the lava flow is interpreted by Bigarella and van Eeden (unpublished data) as originating from a high pressure cell located over the former Gondwana continent.

The paleowind pattern of the Botucatu paleodesert allows the determination of the paleolatitude for South America, which agrees with the former position of the continent in relation to the Equator as deduced by paleomagnetism (Creer, 1958). The paleowinds are also in good agreement with the paleomeridians. For Africa, however, the paleolatitude could not be determined due to the lack of paleowinds other than westerlies. The African westerly paleowinds are in better agreement with paleomeridians oriented like the present-day meridians. The

Another argument supporting the presence of the South Atlantic Ocean during the deposition of the Mesozoic eolian sandstones is the similarity between the paleowind circulation pattern and the orientation of the present-day coastal dunes in Brazil, western Cape Province and South West Africa. In both cases (Mesozoic and Recent dunes) the vectorial properties were derived from a similar high pressure cell, which originated westerlies, trade-winds and return tradewinds.

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TABLE I

Cross-bedding measurements from the Table Mountain Group

FORMATION	No. of measurements	Average dip direction	Consistency ratio	Average dip	Maximum dip	
Western Cape (1)	207	S 11° W	—	—	—	
Eastern Cape (1)	133	S 5° E	—	—	—	
Durban (2)	I	92	S 75° E	0.62	17.6°	26°
		92	S 36° E	0.41	13.6	26°
	III	161	S 15° E	0.61	16.9°	33°
General	345	S 36° E	0.50	16.2°	33°	
Port Edward (2)	121	S 14° W	0.60	15.9°	30°	
Durban and Port Edward. General	466	S 22° E	0.48	16.1°	33°	

(1) Measurements made by J. N. Theron

(2) Measurements made by Bigarella and Beukes

TABLE II

Cross-bedding measurements from the Bokkeveld and Witteberg (Cape Province), according to J. N. Theron

		No. of meas.	Vector mean
Witteberg Group	Western	80	S 51° E
	Eastern	61	S 22° W
Bokkeveld Group	Western	666	S 17° E
	Eastern	423	S 16° E

TABLE III

Post-glacial sandstone cross-bedding measurements from the Rio Bonito Formation (Paraguay), and Upper Dwyka beds (Southwest Africa).
Data from: 1) Bigarella & Comte; 2) D. C. Heath; 3) Bigarella, van Eeden, Schalk and Hugo

FORMATION	No. of measurements	Average dip direction	Consistency ratio	Maximum dip	Average dip	
1) Rio Bonito (Paraguay)	55	N 60° E	0.58	27°	18.0°	
2) Dwyka (Southwest Africa) (1) Nossob Ss	a	S 22° W				
	b	S 23° W				
	Middelste Tilloiedlaag	S 01° W				
	Onderste Tilloiedlaag	S 23° W				
	Boonste Tilloiedlaag	S 26° W				
	Aub Ss	a	S 26° W			
		b	S 16° E			
		c	S 43° E			
d		S 08° W				
3) Dwyka (Huab River region)	I	S 16° E	0.92	31°	20.7°	
	II	S 20° W	0.81	26°	16.0°	
	III	S 11° E	0.71	31°	18.2°	
	IV	S 39° W	0.43	30°	18.3°	
	General (I-IV)	226	S 02° W	0.60	31°	18.3°

TABLE IV

Cross-bedding measurements from the Cave and Etjo Sandstones (Africa), and from the Sambaiba Sandstone (Brazil)

FORMATION	No. of measurements	Average dip direction	Consistency ratio	Maximum dip	Average dip	Reference
1	331	S 80° E	0.81	—	—	N. J. Beukes N. J. Beukes Beukes & Bigarella
2	112	N 78° E	0.82	—	—	
3	75	S 79° E	0.67	24°	16.1°	
1-3 General	518	S 85° E	0.78	—	—	
4	92	N 56° E	0.68	40°	21.2°	Bigarella & Van Eeden
	321	N 78° E	0.74	40°	22.1°	
4-5 General	413	N 74° E	0.60	40°	21.9°	
6	272	N 63° E	0.80	36°	21.8°	Bigarella, Van Eeden, Schalk & Hugo
7	41	N 82° W	0.66	33°	18.3°	Bigarella, Coutinho & Montenegro (unpublished data)
	19	N 62° W	0.98	26°	20.9°	
	54	N 52° W	0.67	29°	18.5°	
	73	N 70° W	0.81	30°	20.5°	
7-10 General	187	N 67° W	0.74	33°	19.5°	

1, 2 and 3. Mr Beukes' thesis area (Orange Free State, Natal & Transkei); 1—North of Parallel 30°; 2—South of Parallel 30°; 3—same as 1; 4—north of Louis Trichardt; 5—Northern Transvaal near the Limpopo River; 6—Huab Valley; 1-5 Cave Sandstone in South Africa; 6—Etjo Sandstone in South West Africa; 7—Regeneração, Natal and Burro Duro area; 8—Between Regeneração and Amarante; 9—Amarante; 10—South of Amarante; 7 to 10—Sambaiba Sandstone (Piauí, Brazil).

TABLE V

Cross-bedding measurements from the Ecça and Beaufort group. Data recalculated from those compiled by Ryan (1967) for the Eastern, Northeastern, Northern, Northwestern, Cape Province and southernmost Orange Free State. Recalculation made by R. D. Becker.

GROUP OR FORMATION	KARROO BASIN				
	E	NE	N	NW	Cape
Middle Beaufort	n. θ c.r.	39 N 23° W 0.78			
Lowermost Beaufort	n. θ c.r.	105 N 42° W 0.31	168 S 15° W 0.54	150 S 74° W 0.45	49 N 25° E 0.70
Upper Ecça	n. θ c.r.				70 N 15° E 0.62
Middle Ecça	n. θ c.r.	179 S 52° W 0.50		152 S 13° W 0.53	
Above coal zone	n. θ c.r.		437 S 44° W 0.47	526 S 59° W 0.64	
Coal zone	n. θ c.r.		806 S 35° W 0.61	479 S 32° W 0.64	
Below Coal zone	n. θ c.r.		1400 S 14° W 0.55		