The late Palaeozoic Gondwana glaciation

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With 4 figures

Zusammenfassung

Die glazialen Ablagerungen von Gondwana sind heute über eine ganze Hemisphäre verteilt. Auch auf dem rekonstruierten Gondwana nehmen sie noch ein Gebiet ein, welches das der pleistozänen Vereisung übertrifft. Die frühesten, unter- und mittelkarbonen Vereisungsspuren finden sich im Anden-Gürtel und im Tasman-Belt in Ostaustralien, wo zu dieser Zeit hohe Gebirgsketten existiert haben können. Während des Stephan und Sakmar, als der Pol sich auf der Antarktis befand, erreichten große Inlandeis-Decken den Seespiegel in allen größeren Ablagerungsbecken. Paläotopographische Rekonstruktionen erlauben die Schlußfolgerung, daß einige der Eiszentren sich auf Hochländern mit Höhen von bis zu 1500 m befanden. Die glazialen Sedimente zeigen, abhängig von ihrer paläotopographischen Position, alle zu erwartenden Faziestypen. Es gibt Hinweise, daß Eis von Afrika in das Paraná-Becken und von Antarktika in das Große Karoo-Becken und nach Australien geflossen sein könnte. Wenigstens 12 Vorstöße und Rückzüge sind im Paraná-Becken erkannt worden. In der Nähe der Eiszentren ist die Zahl geringer. Die Rückzüge hatten wahrscheinlich mehr die Natur von Interstadialen als von Interglazialen. Es gibt Hinweise, daß das finale Abschmelzen im unteren Perm in mehreren Phasen von Südamerika über Afrika nach Antarktika fortgeschritten sein könnte. Die Eiszentren wurden durch feuchte Luftmassen vom Pazifischen Ozean und der Tethys genährt.

Abstract

The glacial deposits of Gondwana are today spread over one whole hemisphere. On the re-assembled Gondwana continents they still occupy an area exceeding that of the Pleistocene glaciation. The onset of the glaciation in the different areas has not yet been dated satisfactorily. The earliest lower and middle Carboniferous glacial beds occur in the Andean belt and in eastern Australia, where high mountains may have existed at that time. During Stephanian-Sakmarian time, when the pole wandered over Antarctica, large ice sheets reached sealevel in all the major depositories. Palaeotopographical reconstructions allow the conclusion that some of the ice centres were supported by uplands which reached altitudes of up to 1,500 m above sealevel. Depending on their palaeotopographical positions the glacigenic sediments exhibit the full facies range to be expected between glaciated uplands and glaciomarine environments. There are indications that ice may have flowed from Africa into the Paraná Basin, and from Antarctica into the Great Karoo-Basin and into Australia. At least 12 advances and retreats have been recognized in the Paraná Basin. Closer to the ice centres the record is less complete. The retreats were probably more of an interstadial than an interglacial nature. There is some evidence that the final deglaciation proceeded in stages from South America over Africa to Antarctica. The ice centres were fed by moist air from the Pacific Ocean and the Tethys.

Résumé

Les dépôts glaciaires de Gondwana sont répartis actuellement sur une hémisphère entière. Même sur le Gondwana reconstitué, ils occupent encore une surface qui dépasse

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celle de la glaciation pleistocène. Les traces de glaciation les plus précoces, èo- et méso-carbonifères se trouvent dans la ceinture andine et dans la ceinture tasmanienne d'Australie orientale, où des chaînes de montagnes élevées ont pu exister à cette époque. Pendant le Stéphanien et le Sakmarien, lorsque le pôle s'est trouvé dans l'Antarctique, de grandes nappes continentales de glace ont atteint le niveau de la mer dans tous les grands bassins sédimentaires. Des reconstitutions paléotopographiques permettent de conclure que quelques-uns des centres de glaciation se trouvaient dans des zones de montagnes ayant des altitudes atteignant 1500 m. Les sédiments glaciaires montrent, en fonction de leur position paléotopographique, tous les types de faciès que l'on peut attendre. D'après certaines indications, la glace aurait pu couler d'Afrique dans le bassin du Paraná et de l'Antarctique dans le grand bassin du Karoo et vers l'Australie. Au moins douze avancées et retraits ont été reconnus dans le bassins du Paraná. A proximité des centres de glaciation leur nombre est moindre. Les retraits avaient sans doute un caractère plus interstadiaire qu'interglaciaire. Certaines indications permettent de penser que la fusion finale pouvrait avoir progressé, au cours du Permien inférieur, d'Amérique du Sud vers l'Afrique puis vers l'Antarctique, en plusieurs phases. Les centres de glaciation ont été nourris par des masses d'air humides venant de l'Ocean Pacifique et de la Téthys.

Краткое содержание

Ледниковые отложения Гондваны распределены сегодня по всему полушарию. На реконструированной Гондване они занимают область, превышающую плейстоценовое олединение. Следы оледенения в раннем, нижнем и среднем каменноугольном периоде находят в поясе Анд и в тасманском поясе восточной Австралии, где в те времяна могли иметься высокие горные хребты. В течение стефанского и сакмарского веков, когда полюс находился в районе Антарктики, большой покров материкового льда достигал уровня воды всех больших бассейнов осадконакопления. Палеотопографические реконструкции разрешают сделать вывод, что некоторые центры оделенения находились на плоскогорьях на высоте до 1,500 м. Ледниковые осадочные отложения проявляют, в зависимости от их палеотопографического положения, все известные типы фация. Имеются указания на то, что ладник Африки мог перемещаться в бассейн Parana', а Антарктики — в большой бассейн Karoo и в Австралию. В бассейне Parana' отмечают, по крайней мере, 12 наступлений и отступлений ледника. Вблизи центра оледенения количество таких явлений меньше. Отступление ледников носили, по-видимому, межстадиевый, а не межледниковый характер. Имеются указания на то, что окончательное таяние в нижней перми протекало по нескольким фазам от Южной Америки через Африку до Атлантики. Центры оледенения питались богатыми влагой воздушными массами, идущими от Тихого океана и Тетиса.

Introduction

ALFRED WEGENER has already in the first, 1915 edition of his book "Die Entstehung der Kontinente und Ozeane" regarded the evidence for a Permo-Carboniferous glaciation on the widely separated Gondwana continents as a strong argument for his Continental Drift Hypothesis. During the last six decades much has been learned concerning this great glacial period. It is still the strongest single, purely geological argument for the dispersion of Gondwana and for polar wandering (Fig. 1). The knowledge of the extent and the palaeogeography of the glaciated areas justifies attempts to construct palaeoclimatic models for the glacial history of Gondwana, but several unresolved questions remain.

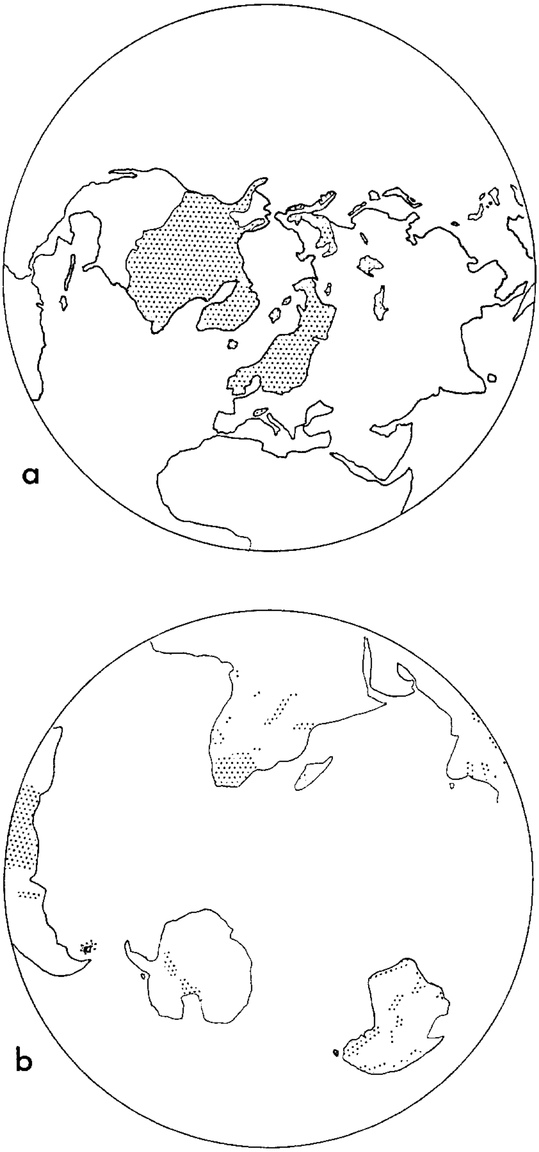

Fig. 1. Comparison of the regions affected by the Pleistocene and by the Permo-Carboniferous glaciations. (a) The extent of the Pleistocene glaciation after FLINT (1957). The glaciated part of the Himalayas has been omitted as it seems certain that no mountain ranges of comparable elevation existed in the regions of Permo-Carboniferous glaciation. (b) The regions containing Permo-Carboniferous glacial deposits.

The configuration of Gondwana

The discussion of the palaeogeography of the glaciated regions must be based on a reconstruction of Gondwana. WEGENER's original method of roughly fitting the continental shelves together was a very successful approximation which has been improved by the SMITH-HALLAM (1970) computer fit of the 1000 m isobath (Fig. 2). Uncertainties have remained with respect to the fit between West Gondwana (South America and Africa) and East Gondwana (EMBLETON et al., 1980). An improvement of the SMITH-HALLAM fit was achieved by NORTON & SCLATER (1979) who reversed the spreading vectors and distances deduced from the magnetic anomaly lineations of the Indian Ocean. This reconstruction brings Antarctica into a slightly more southerly position with respect to Africa (Fig. 3). Thereby room is created to accommodate the Falkland Plateau. Its probable former position at the southeastern margin of southern Africa (LABRECQUE & HAYES, 1979) is strongly supported by the result of DSDP site 330. There, on the eastern spur of the plateau, the drill encountered in 2600 m water, at a depth of 3200 m gneissic-granitic basement overlain by 9 m of subaerial clayey sandstone and lignite of probably Liassic age. This evidence, showing that continental basement can subside to a depth of 3,000 m at continental margins, is a strong argument for using the 3,000 m isobath for continental reconstructions, if magnetic lineations do not indicate a more precise continent/ocean boundary (RABINOWITZ & LABRECQUE, 1979).

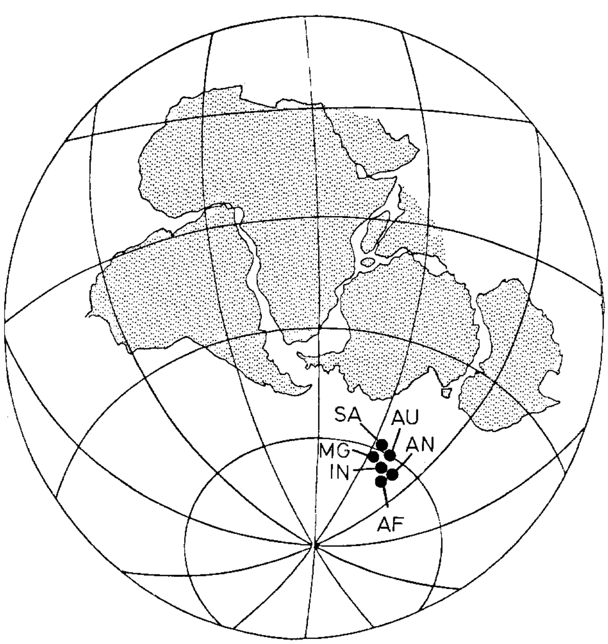

Fig. 2. The lower Jurassic pole positions (after SCHMIDT, 1976) superimposed on the SMITH-HALLAM (1970) fit of the southern continents. Pole positions: SA = South America, An = Antarctica, MG = Madagascar, IN = India, Au = Australia, AF = Africa.

The palaeomagnetic data for the lower Jurassic support these reassemblies (Fig. 2) for the time just before the break-up. For the Permian and the Carboniferous, however, the palaeopole positions show a considerable dispersion (ANDERSON & SCHWYZER, 1977). This dispersion results partly from the poor age control of the palaeomagnetically investigated formations, partly from the distortion suffered by Gondwana during the Triassic Gondwanide folding (DU TOIT, 1937).

In my opinion some doubt still remains with regard to the former position of Madagascar.

Extent of the glaciated areas

Since WEGENER's time the extent of the regions with known glacigenic sediments has been greatly expanded by the addition of the Andean belt in South America, central Africa, western Australia and Antarctica. Today these areas have a spread of about 180 degrees, whereas on a re-assembled Gondwana their maximum spread, from the Paganzo Basin to eastern Australia, extends over about 110 degrees (Fig. 4). A simultaneous glaciation of this whole area seems rather improbable, but the palaeontological evidence indicates, nevertheless, a similar age for the majority of the glacial deposits.

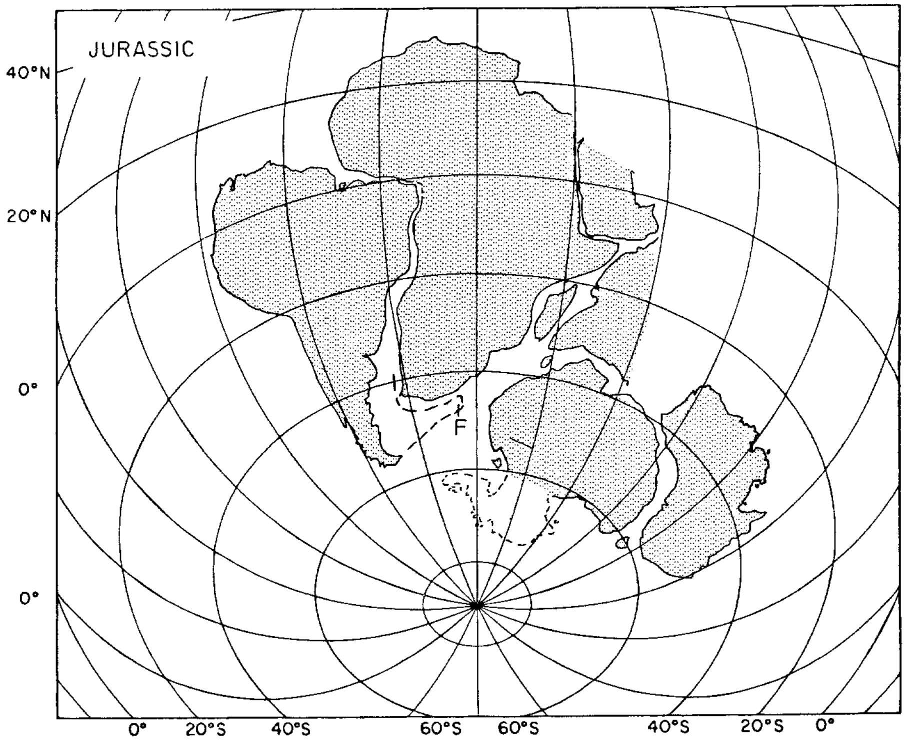

Fig. 3. Jurassic Gondwana re-assembly after NORTON & SCLATER (1979) and LABRECQUE & HAYES (1979). F = eastern spur of Falkland Plateau on which DSDP site 330 is situated.

The age limits of the Permo-Carboniferous glaciation

The ages of the glacial deposits of the different parts of Gondwana have not yet been securely correlated with the international time scale, because the usually sparse marine invertebrate faunas consist of mostly endemic forms of not well defined time ranges (RUNNEGAR & MCCLUNG 1975; MCCLUNG, 1975) and because the macro- and microfloras allow only relative correlations inside Gondwana (ANDERSON, 1973; 1977; KEMP, 1975). Furthermore, where the glacial beds overlie older rocks unconformably, the onset of the glaciation may predate the age of the glacigenic sediments by an unknown time span, because a vigorously eroding ice sheet may deposit practically no englacial material (see below), and may have destroyed older glacial sediments. With these reservations the following age ranges have been proposed.

The oldest, somewhat scanty indications of glacial activity are found in South America, in the Andean belt of Argentina, in lower Carboniferous beds of the Paganzo Basin (Rio Blanco Basin of FRAKES & CROWELL, 1969), Fig. 4.

For the middle and upper Carboniferous of the Andean belt the glacial imprint in several marine sequences is better documented (FRAKES & CROWELL, 1969).

In the Paraná Basin the time of onset of glacial conditions has not been established. In the São Paulo region the marine Capivari Formation, in the middle of the glacial sequences has probably a lowermost Permian age (ROCHA-CAMPOS, 1967, p. 93). This would speak for a lower Permian age of the greater part of the glacial sequence but in the southern part of the basin the glacial beds may be upper Carboniferous (op. cit., p. 94; KEMP, 1976). Thus the probable age range seems to be upper Carboniferous-lower Permian.

In the southern, deepest part of the Great Karoo Basin (Fig. 4) the lower part of the glacial Dwyka Group may be of Carboniferous age, and is, on palynological evidence, separated by a hiatus from the greater, upper lower Permian part. The glacial beds in the northern part of the basin have a lower Permian age (ANDERSON, 1977).

The South Kalahari and the small Karasburg basins (Fig. 4) were originally connected with the Great Karoo Basin. Their glaciomarine boulder mudstones contain a fauna of probably lower Permian age (DICKINS, 1961; MARTIN & WILCZEWSKI, 1970; MCLACHLAN & ANDERSON, 1975). However, the deposition of the glacial sequence was preceded by a period of considerable glacial erosion. Therefore the onset of the glaciation may have occurred in the Carboniferous.

In Zaire and Gabon (Fig. 4) the glacial and periglacial formations contain microfloral assemblages indicating a lower Permian age (CAHEN & LEPERSONNE, 1978; KEMP, 1975).

In Antarctica the glacial deposits seem to have a lower Permian age (KEMP, 1975), but the glaciation may well have begun in the Carboniferous (ADIE, 1975).

In Australia the oldest glacial sediments of Westphalian, or perhaps upper Namurian age are confined to the Sydney Basin (Fig. 4). In the other basins the glaciation seems to have begun in the Stephanian and to have ended in the Sakmarian. In the Sydney Basin and in Tasmania rafting by icebergs continued into the middle Permian (MCCLUNG, 1975; KEMP, 1975; RUNNEGAR & MCCLUNG, 1975).

In India and in the Salt Range of Pakistan the microfloral assemblages and invertebrate faunas speak for a Stephanian-Sakmarian age of the glacial sediments (FRAKES et al., 1975).

In summarizing the following conclusions seem justified:

1. The oldest, lower and middle Carboniferous glacial deposits are confined to the Pacific margin of Gondwana which was affected by middle Devonian and lower Carboniferous orogenic phases in the Andean and Tasman belts, where alpine-type mountain ranges may have existed (CROWELL & FRAKES, 1975), Fig. 4.
2. During the Stephanian-Sakmarian glacial conditions seem to have prevailed right across the wide extent of Gondwana.
3. Within the probably rather broad limits afforded by palynological dating there is no evidence that the glaciation ceased earlier in South America and Africa than in Australia (KEMP, 1975).
   There is, however, some geological evidence for a systematic, probably fairly rapid shift of the deglaciation (see p. 493).

Palaeopole positions during the Gondwana glaciation

The palaeomagnetically determined Permian and Carboniferous pole positions show considerable dispersion (SMITH et al., 1973; ANDERSON & SCHWYZER, 1977; SCOTESE et al., 1979). This may be partly due to the difficulties of dating the sampled formations accurately, partly to the deformation suffered by Gondwana during the Triassic orogeny.

The available data indicate that during the lower Carboniferous the pole was situated somewhere in the region of southern Africa, close enough to the Andean belt to have caused a glaciation there, even under a comparatively mild global climate. During the late Carboniferous the pole seems to have been situated on the part of Antarctica which faced Africa, and during the lower Permian the pole wandered off Antarctica into the Pacific. Thus, the available data indicate that during the time of the widest spread of glacial conditions the pole was situated on Antarctica, and that Antarctic ice sheet could have moved far into the adjoining continents, because there was no confining ocean.

Palaeogeography, directions of ice flow, glacial-interglacial facies realms

A comprehensive synthesis of these aspects of the glaciation based, to a considerable extent on personal studies, was published by CROWELL & FRAKES (1975) and FRAKES et al. (1975). This chapter makes extensive use of these reviews and adds a few more recent results.

Palaeogeography

With respect to the physiographic environments of the glacigenic deposits of Gondwana it has to be asked, which depositories were situated close to alpine, type mountains, which were close to or below sealevel and which were bordered by uplands of moderate altitudes.

On Gondwana alpine-type mountain ranges seem to have existed only along the Pacific margin (Fig. 4) which had been affected by middle Devonian and lower Carboniferous orogenic phases. The first glaciers may have formed in the Andean belt of Argentina during the lower Carboniferous and in eastern Australia in the Westphalian or uppermost Namurian. Already during this initial stage the climate was so cold that the glacigenic material is found in close association with marine beds. It is, of course, also probable that alpine-type mountains existed along the Pacific margin of Antarctica, but there is at present no observational evidence for Carboniferous glacial sediments.

During the main, Stephanian-Sakmarian part of the glaciation all the major, more extensive glacial sequences were deposited close to or below sealevel, as proved by close stratigraphic association or interfingering with marine sediments (Fig. 4), and by the sediment petrographic and geochemical characteristics of the glacigenic sediments (FRAKES & CROWELL, 1975). It is therefore certain that ice sheets reached sealevel in practically all the far-flung regions which show glacial features. The Gondwana glaciation cannot be explained by the assumption of moderately sized upland ice caps.

Palaeotopography of the uplands

With respect to the altitudes of some upland regions which supported ice centers rough estimates can be made. This is possible where pre-glacial valleys have been preserved, because the relative depth of such valleys gives a minimum figure for the altitude of the adjoining uplands.

The greatest still preserved relief exists in northwestern Namibia. There, in the Kunene Valley the difference in elevation between the valley floor with its beautifully striated *roches moutonnées* and glacial sediments and the highest basement ridges in the vicinity is about 1500 m (MARTIN, 1961). Originally the difference has probably exceeded this figure, because a Triassic-Jurassic bevel forms the summit level of the basement ridges (MARTIN, 1975). The other, shorter valleys of the Kaokoveld (south of the Kunene River) are less deeply incised, but contain also glacially striated walls and remnants of glacial sediments. The ice movement was towards the west. At the height of the glaciation the ice must have overflowed the basement interfluves, because erratics have been carried across some of the high ridges. The Kaokoveld ice sheet was centred farther east, possibly over the watershed region between the Kunene and the Zambezi rivers and over the Etosha-Amboland Basin in which drilling has revealed the presence of tillite with interbedded varved shales.

Along the southern margin of the central highlands of Namibia a remnant of a re-exhumed pre-glacial valley is incised to a depth of 400 m into the Naukluft plateau which is spanned by a Mesozoic surface, and the difference in altitude between the glaciomarine transgression in the South Kalahari Basin and the highest hilltops of the central highland, the source area of the Namaland ice sheet (DU TOIT, 1922), is approximately 1000 m.

These palaeotopographyic features allow the conclusion that the higher Gondwanic uplands had altitudes of about 1000 to 1500 m above sealevel.

Paleovalleys have also been recognized at the southern margin of the Transvaal upland against the Great Karroo Basin (Fig. 4). The larger ones of these paleovalleys radiate from the supposed ice centre on central and northern Transvaal (DU TOIT, 1922). To the north of Kimberley the Vaal and Harts rivers have re-

Fig. 4. Gondwana re-assembly (slightly modified after NORTON & SCLATER, 1979) with glacigenic deposits and palaeotopographical features. Pag = Paganzo Basin, Pa = Paraná Basin, GK = Great Karoo Basin, K = Karasburg Basin, SK = South Kalahari Basin, Ka = Kaokoveld, Tv = Transvaal uplands, Za = Zaire, De = Dekese, G = Gabon, WA = West Antarctica, Sy = Sydney Basin, SR = Salt Range.

exhumed such SSW and SW trending, glacially shaped, pre-glacial valleys containing remnants of glacigenic sediments and numerous exposures of striated floors. The palaeotopography has a relief of up to 380 m (VISSER et al. 1978) which was only little altered by post-Karoo erosion. During the Transvaal glacial phase the whole relief was deeply burried under the ice sheet. This is conclusively shown by the fact that the ice moved obliquely across these valleys (DU TOIT, 1922, p. 197).

Farther northeast, near Odendaalsrus the existence of a still burried, at least 50 km long, south trending valley with a basement relief of up to 800 m has been proved by drilling (COUSINS, 1951).

In northern Natal a similar palaeorelief has been re-exposed. There palaeovalleys of up to 50 km length and a palaeorelief of up to 300 m trend southeastwards (DU TOIT, 1922; MATTHEWS, 1970; BRUNN, V., in press).

These radiating pre-glacial valleys as well as striated floors and *roches moutonnées,* indicate an ice centre on central and northern Transvaal. DU TOIT (1922) has estimated the probable altitude above sealevel of this Permo-Carboniferous highland area. He concluded that the main upland surface may have stood at 600 to 800 m, and the Waterberg and Soutpansberg ranges perhaps at 1300 to 1500 m above sealevel. These estimates are of the same order as the differences of the palaeorelief which can be directly measured in the Kaokoveld (see p. 487).

The eastern rim of the Congo Basin in Zaire is another region, where the preglacial topography has been largely re-exhumed and allows the recognition of a broad, over 1,000 km long pre-glacial watershed into which a great number of valleys had been incised. In many parts of these paleovalleys glacial, periglacial and post-glacial sediments have been preserved. A number of striated floors indicate the directions of ice movement, Fig. 4 (CAHEN & LEPERSONNE, 1978). There is no evidence concerning the original heights of the palaeointerfluves between these valleys. But, as the region has suffered no orogeny since the end of the middle Proterozoic, it seems probably that the palaeointerfluves did not consist of high mountain ridges, but had a subdued topography comparable to that of the Transvaal upland. It seems likely that, at the height of the glaciation, this whole upland divide was covered by an ice cap which, in the waning stages, disintegrated into individual valley glaciers. From the divide the ice moved westwards into the Congo Basin, where a borehole at Dekese (Fig. 4) penetrated 960 m of glacial and periglacial sediments (HÜBNER, 1965), and eastwards probably into Tanzania.

On the other Gondwana continents major palaeotopographical features have been less well preserved. At the eastern margin of the Paraná Basin a palaeovalley has been identified near São Paulo, and valleys filled with post-glacial sediments on the Rio Grande do Sul shield (MARTIN, 1961).

In south Australia palaeovalleys with up to 300 m relief are recognizeable. The ice moved from an off-shore source area, presumably Antarctica, over this relief into the continent (CROWELL & FRAKES, 1971). In the subsurface of the Sydney Basin drilling has revealed two burried palaeovalleys filled with fluvioglacial sediments (HERBERT, 1971). In Peninsular India the glacial Talchir Formation has been preserved only in tectonic, partly fault-bounded depressions (FRAKES, et al., 1975). Therefore no estimates of the original palaeorelief are possible. But, because no part of the subcontinent was affected by a lower Palaeozoic orogeny, it seems unlikely that the ice centers stood any higher than the African ones.

The palaeotopographical features of Gondwana allow the following conclusions.

1. In most of the major basins glacigenic sediments were deposited close to, and in some basins even below sealevel.
2. Large ice sheets radiated from uplands which stood 800—1,000 m above sealevel. The upland surfaces had on the whole a subdued plateau-like topography, but ridges of very resistant rocks rose in some areas to 1,300 to 1,500 m.
   Into the margins of the uplands preglacial valleys had been incised to depths of 800 m and more. Glacial erosion gave a U-shape to these valleys and overdeepened them, on weaker lithologies, by as much as 200 m.
3. Large ice sheets covered low-lying areas, e.g. the Paraná Basin and Western Australia.
4. Alpine-type mountains seem only to have existed during the lower and middle Carboniferous in the Andean and the Tasman belt.

Directions of ice flow

For many areas directions of ice movement have been deduced from striated floors, till fabric and palaeo-current directions. Flow directions from the vicinity of the present-day continental margins can give some indication, whether and where ice sheets may have moved from one of the now widely separated continents onto another. This may have happened between Africa and South America, between Antarctica and Africa and Antarctica and Australia (Fig. 4).

The Kaokoveld ice lobe of northwestern Namibia may have entered the northern part of the Paraná Basin which was fed by ice from an offshore source (Maack, 1969; Martin, 1961). The directions of ice movement would support such an assumption. But it is also possible that a marine basin of limited width existed already at that time in the southern part of the South Atlantic (Frakes & Crowell, 1968; Martin, 1975). This possibility is supported by the conclusion of Theron & Blignaut (1975) that, in the westernmost part of the Great Karoo Basin, the ice movement was directed westwards, and not eastwards, as hitherto assumed (Stratten, 1970).

Ice sheets have probably also entered the Great Karoo Basin from the south and the east. The existence of a "southern highland centre" has been made probable by till fabric studies (Stratten, 1970). The Falkland Plateau which, before the breakup, seems to have been joined to southern Africa (Labrecque & Hayes, 1979), may be a deeply subsided part of this source area (see p. 483). The Natal ice sheet entered the Great Karoo Basin from the east, from an "extra-African" source (Du Toit, 1922). This ice sheet seems to have been voluminous enough to deflect the large Transvaal ice sheet (see p. 493). There is one piece of very good evidence indicating Antarctica as its source area. This is the finding of Archaeocyathide bearing limestones as erratics in Dwyka diamictite. Such limestones occur in Antarctica, but have never been found anywhere in Southern Africa (Cooper & Oosthuizen, 1974).

In southeastern Australia and Tasmania numerous striated floors show that ice moved over a hilly terrain north- and northeastwards. An ice centre must therefore have existed somewhere to the south, off the present coast, presumeably on Antarctica.

The fact that glacial and glacially influenced sediments occur right across Australia in all the basins containing Permo-Carboniferous deposits indicates the severity of the climate and the possibility that ice sheets could have entered Australia from Antarctica along the entire present south coast, at one time or another during the Sakmarian, when the pole was situated on Antarctica.

The conclusion seems justified that Antarctica, on which the pole was situated from the Westphalian to the Sakmarian, was the main ice centre of Gondwana from which ice sheets flowed into the Great Karoo Basin and far into Australia. From Africa ice may have reached the Paraná Basin.

The question, whether a systematic shift of the ice centres can be discerned, will be discussed together with the problem of the number of glacial advances and retreats (see p. 493).

Facies types

The thicknesses of the glacial deposits range from thin patches on the uplands to sequences of more than 1,500 m in some basins, and the facies types range from basal moraine, glaciofluvial and glaciolacustrine to glaciomarine deposits.

The following facies types have been identified:

- Basal moraines with a high matrix to clast content overlying striated floors. Boulder pavements have been observed in this type at many places.
- Remnants of terminal moraines in glacially shaped palaeovalleys.
- Small subglacial or supraglacial eskers (FRAKES, 1968).
- Tills, re-sedimented by mass-flow, probably triggered by thixotropic change, interbedded in outwash sands or lacustrine varved siltstones containing dropstones. Soft sediment deformation and slump structures are frequently observed in this facies (FRAKES & CROWELL, 1969, p. 1028; BRUNN, v., in press). Cyclic repetitions of such features indicate repeated advances and retreats of the ice.
- Periglacial lacustrine deposits in the form of varved sediments with dropstones are frequently interbedded in diamictites, but are not developped in fully marine glacial sequences, e.g. the South Kalahari Basin (Fig. 4).
- A small field of periglacial dunes occurs in the Paraná Basin (MARTIN et al., 1960), but no loess blanket has been reported from any part of Gondwana.
- A tundra-type vegetation seems to have covered the ice-free areas. This is indicated by the presence of spores and pollen in all the investigated diamictites (KEMP, 1975).

The marine environment has also produced several facies types which are, of course, connected with one another by transitions. From the off-shore region basinwards the following types have been recognized:

- Melt-out till under a grounded ice-shelf, represented by massive diamictite overlying sediments which are in some places hydroplastically deformed or deeply furrowed, e.g. southwestern Great Karroo Basin (THERON & BLIGNAUT, 1975).
- Massively stratified diamictites interpreted as till-flows down a foreset slope under a floating ice-shelf. Occasional boulder beds were produced by the winnowing action of currents. Advances and retreats of the ice-shelf are

represented by cycles of the above sediment types (Theron & Blignaut, op.cit.).

- Subfacial eskers and turbidites in the Falkland Islands (Frakes, 1967).
- Indistinctly stratified mudstones enclosing widely dispersed pebbles, boulders and giant erratics dropped from floating ice. This facies may contain graded boulder beds and turbidites, outwash arenites in the form of thin sheets or shallow channels, and also beds of cone-in-cone marlstones, thin limestone layers and calcareous concretions. A sparse endemic marine cold-water fauna characterizes this facies which is very well exposed in the South Kalahari Basin (Heath, 1972; Martin & Wilczewski, 1970).
- Iceberg drift with deposition of dropstones in highly fossiliferous beds continued in Tasmania and the Sydney Basin into middle Permian (Artinskian-Kungurian) time. The icebergs were propably derived from glaciers which persisted on some part of Antarctica after the ice had disappeared from the rest of Gondwana (Crowell & Frakes, 1971).

Retreats and advances, and the migration of ice centres

Disregarding the scanty evidence for lower Carboniferous glacial activity in western Argentina, the Permo-Carboniferous glacial period may have lasted about 40 Ma (Westphalian, or uppermost Namurian to Sakmarian). The bulk of the deposits seems to date from the Stephanian-Sakmarian (Kemp, 1975). During this long time-span many fluctuations, certainly not always synchronous for the whole of Gondwana, would be expected. The evidence for the number of ice advances and retreats is very incompletely documented in the rock record, partly because of the limitations of the discontinuous exposures, partly because younger advances may have destroyed older deposits. The number of fluctuations which have been recognized can, therefore, only be regarded as a minimum. The greatest number of advances and retreats is represented in the Paraná Basin, where up to twelve diamictites have been recognized in the subsurface. Some of these retreats lasted long enough for the establishement of a tundra-type vegetation, as proved by the presence of thin coaly interbeds at several stratigraphic levels (Rocha-Campos, 1967, p. 55).

In the Congo Basin five cycles have been found. The climatic fluctuations which accompanied the advances and retreats, were pronounced enough to have affected the microfloral assemblages contained in the respective sediments (Cahen & Lepersonne, 1978).

From none of the glacial sequences has a soil profile indicating a warm interglacial period been reported. It is therefore likely that the climatic cycles were more of an interstadial than an interglacial nature. Such fluctuations should have had their greatest influence in relatively low latitudes. With the pole on Antarctica the northern Paraná Basin and the Congo Basin would have occupied such positions. This may be the reason, why in these areas more cycles seem to be present than in the other glaciated regions.

In the western part of the Great Karoo Basin four advances and retreats of a partly grounded, partly floating ice shelf have been recognized (see p. 491—492), whereas only two can be discerned at the northern basin margin closer to the Transvaal source area (Visser et al., 1978).

In Africa and South America the well-documented retreats and readvances seem to be of lower Permian age (KEMP, 1975, MCLACHLAN & ANDERSON, 1975). There is one good example showing that the final retreat of a major ice sheet, the Namaland ice of the South Kalahari Basin, was followed, after a phase of deglaciation, by the waxing of another ice centre, the Transvaal ice, more than 1,000 km to the east, and by a concomittant change in the direction of ice flow (DU TOIT, 1922; MARTIN & WILCZEWSKI, 1970).

Similar shifts have probably occurred in other parts of Gondwana, too. A tentative case can be made out for two such shifts. One concerns the Paraná Basin, the other the eastern Great Karoo Basin. For the Paraná Basin the evidence is highly conjectural. Glaciomarine beds in the southern part of the basin contain an invertebrate fauna suggesting a Carboniferous, rather than a Permian age for diamictites which were probably derived from the small Rio Grande do Sul ice centre (ROCHA-CAMPOS, 1967, p. 94), whereas farther north the bulk of the glacigenic sediments seems to have a lower Permian age, and to have been derived from an extra-South American source, perhaps the Kaokoveld ice lobe of northwest Namibia (see p. 490). This interpretation could imply a west-east shift of ice accumulation in the lowermost Permian.

A better documented case for a shift has been deduced by DU TOIT (1922) for the eastern part of the Great Karoo Basin. During a first stage ice moved from the Transvaal uplands (Fig. 4) southwards into the basin. During a second stage this flow was deflected into a southwesterly direction by a more voluminous ice sheet which entered Natal from the east, from an extra-African source region, presumably on Antarctica. Whilst this "Natal ice" continued its vigorous flow into the Great Karoo Basin, the Transvaal ice began to retreat. This interpretation is based on sedimentological features indicating that in northern Natal the meltwater of the Transvaal ice was ponded, in a fresh-water lake, against a southern barrier, presumably formed by the persisting Natal ice sheet. There was no re-advance of the Transvaal ice into this lake which was filled by lacustrine and fluvioglacial sediments. According to this interpretation the deglaciation began earlier on the Transvaal uplands than on Antarctica. The palaeomagnetic data can explain such a shift in a general way, because they indicate a pole shift from an upper Carboniferous position on the part of Antarctica facing Africa to a lower Permian position on the part facing Australia. The pole path, perhaps with some random shifts, may have led across the central part of Antarctica, if the NORTON & SCLATER fit is correct, instead of close to the Pacific margin, as tentatively indicated in CROWELL & FRAKES' (1975, Fig. 22.6) synthesis.

The following conclusions seem justified:

1. The recognizeable glacial advances and retreats seem to be of Stephanian-Sakmarian age. They were of an interstadial nature, and were more numerous in regions which occupied relatively low latitudes during this period. Conversely, the areas closer to the pole (i.e. Southern Africa and Antarctica) may have had a more or less permanent ice cover which, however, only left extensive diamictites during the deglaciation stages.
2. There is some evidence that the final deglaciation began (?) first in the Paraná Basin and progressed in stages across southern Africa and Antarctica until the pole had wandered into the Pacific Ocean. The changes of the directions

of ice flow may rather have been a result of the progressing deglaciation than of an actual migration of ice centres. Areas of maximum ice accumulation may nevertheless have migrated to some extent, because the retreating ice front was followed by a marine transgression which may have provided increased precipitation to neighbouring, still glaciated uplands.

3. It seems probable that all Antarctica was covered by ice from the upper perhaps even the middle Carboniferous to the early Permian, as long as the pole was situated on Antarctica. Antarctic ice sheets, not confined by surrounding oceans, moved far into southern Africa and Australia.
4. When the pole moved into the Pacific Ocean, the general ice cover of Antarctica disintegrated leaving a number of smaller ice caps, as indicated by the direction of ice and sediment transport.

Atmospheric and oceanic circulation and the glaciation of Gondwana

Frakes & Crowell (1970) have discussed the circulation pattern which can be expected for the southern hemisphere during the Gondwana glaciation, and have concluded that temperate and warm Pacific and Tethyan currents can have supplied sufficient moisture to different parts of Gondwana to have nourrished the ice sheets.

Conclusions

The main phase of the late Palaeozoic Gondwana glaciation lasted from the upper Carboniferous to the lower Permian. During this period large continental ice sheets existed from the Andean belt to eastern Australia. The question, whether these ice sheets existed contemporaneously, cannot yet be answered satisfactorily. The pole seems, during this time, to have been situated on Antarctica.

Major ice sheets were centred on uplands which stood 1,000 to 1,500 m above sealevel. In most of the major basins the ice sheets reached sealevel. All the glacial, glaciomarine and periglacial facies types, known from Pleistocene glaciation, have been recognized, with the exception of widespread loess blankets and interglacial soil profiles.

There were numerous advances and retreats. The latter seem to have been of an interstadial nature. There are indications that the final deglaciation, during the lower Permian, proceeded from South America over Africa to Antarctica, where glaciers persisted to the middle Permian.

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