South African Antarctic Earth Science Programme 1959–1969: Solid Earth Geophysics, Oceanography and Glaciology

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Director:
Antarctic Earth Science Research
Programme (1965–1970)

Introduction

South Africa commenced research in the earth sciences some two years after the close of the International Geophysical Year. Since then, a continuing programme of exploration in the fields of geology, glaciology, solid earth geophysics, and oceanography, and a station observatory programme in seismology have been maintained in the sector longitude 1°W to 6°30′W, latitude 69°S to 74°12′S (Fig. 1). The area investigated constitutes part of the Queen Maud Land region of East Antarctica and includes the King Haakon VII Sea, the Fimbul Ice Shelf, the ice-covered mountains of the Ahlmannryggen and Borgmassivet occurring inland from the Princess Martha Coast, and the Kirwanveggen, an escarpment along the edge of the Polar Plateau.

This review of the first decade summarizes the results of the earth science research activities that were complementary to the main geological mapping programme (a review of which may be published later). The results achieved are a tribute not only to the geologists themselves but to all the members of the 1st to the 10th South African Expeditions who assisted in the Earth Science Research Programme.

The expedition geologists were: Victor von Brunn (1960); Barry Butt (1961); Dirk Neethling (1962, 1968); Otto Langenegger (1963); André du Plessis (1964): Wolfgang Pollak (1965); Eddie de Ridder and Horst Bastin (1966); Kobus Retief and Charles Kingsley (1967); Brian Watters (1968); Anton Aucamp (1968, 1969) and Leon Wolmarans (1969). The Programme Director also participated in the U.S. Deep Freeze Expedition to Victoria Land during 1964, and in expeditions to Bouvet Island during 1964 and 1966. In 1968 he was joint leader of a combined South African-Belgian Expedition to western Queen Maud Land.

(*a*) *Programme organization*

The Earth Science Programme, as an integral part of the South African National Antarctic Research Programme, is administered by the Geological Survey of the Department of Mines on the advice of the South African Scientific Committee for Antarctic Research (SASCAR). Its long-term objectives have been formulated, within the limitations of available logistic support which is provided by the Department of Transport, in accordance with the recommendations of SCAR, the Scientific Committee for Antarctic Research set up during the IGY by the International Council of Scientific Unions (ICSU).

Following an initial period of largely unco-ordinated research, in which various organizations were involved, the Earth Science Programme was re-organized on a permanent basis when an Antarctic Section was established within the Geological Survey. The Chief Geologist of this Section was designated Programme Director and was responsible for the formulation of long-term objectives, direction of field programmes and supervision of data processing. Expedition geologists are attached to the Antarctic Section for contract periods, of approximately $1\frac{1}{2}$ years, comprising 3 to 4 months of pre-expedition training at the Geological Survey in Pretoria, and 13 to 14 months wintering in Antarctica followed by a post-expedition data-processing period of 3 to 12 months. A total of 195 Earth Science Programme reports have been completed during the period under review; most of the data have been published, or are in the press.

(*b*) *Logistics*

During the first two years, oversnow expeditions were staged from the Norwegian IGY base, Norway Station, and thereafter from the main South African base, Sanae (70°18,5′S, 2°21,5′W), which is about 21 km to the north-east (Fig. 1). Both these bases are more than 120 km from the nearest rock outcrop and as exploration proceeded further inland, increased support missions over severely crevassed regions were required to establish and maintain supply depots at stategic points in and *en route* to the mountain areas. It soon became evident that, in spite of the provision of additional tractor support, the method of pre and post-winter field seasons using Sanae as wintering base greatly reduced the time available for field work during the short summer season. During 1966 the establishment of a subsidiary 4-6 man inland wintering base was therefore proposed in order to extend the scope of exploration activities. This led to the establishment in 1969 of Borga Base (72°58′S, 3°48′W) some 350 km south of Sanae (Fig. 1). Implicit in its

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original conception is that Borga Base should be regarded as a temporary station and that it should be moved to keep pace with advances in exploration activities.

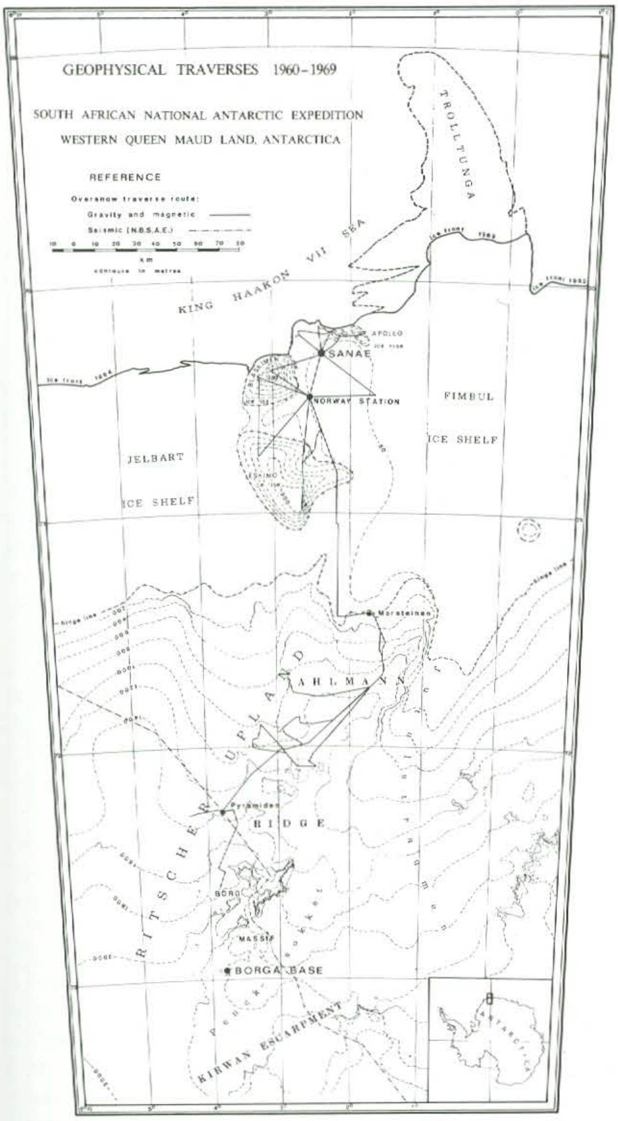

Fig. 1. Map showing routes of oversnow traverse parties and site of Borga Base, Ahlmann Ridge (reproduced from TSO Misc. 4554, Trigonometrical Survey, Pretoria)

Submarine and Subglacial Morphology of the Princess Martha Coast

A geophysical-glaciological observation programme, supplemented by late-winter/autumn ice-shelf traverses, was programmed for both the geological and the support field parties in order to explore the submarine and subglacial features below the ice-shelf and ice-sheet. Although the routes of inland oversnow traverses from Sanae were largely determined by the location of the areas selected for geological mapping, these fortunately involved repeated journeys along the larger part of a more than 300-km north-south line which traversed contrasting morphological regions of the ice-covered continental margin and its hinterland. Extensions of the main traverse across the inland border of the ice-shelf included several detours to obtain additional subsurface detail of inter-nunatak and transglacier bedrock configuration of the continent. In addition, reconnaissance marine surveys were made in the offshore waters of the King Haakon VII Sea to investigate the morphology of the continental slope and rise.

Oversnow Geophysical Surveys

The interdependence of logistics and traverse operations necessitated planning of the oversnow geophysical programme in several distinct stages in order to maximize the use of the logistic support available at Sanae.

(*a*) *Stage I* (*Sanae Base — Fimbul Ice Shelf — Ahlmannryggen — Borgmassivet*)

This initial reconnaissance, with Sanae as the starting point, embraced more than 800 traverse-kilometres in the period 1962 – 1968 (Fig. 1). Observations of relative gravity, and of vertical and total magnetic field variations were made at more than 360 field stations spaced approximately 3 km apart. Elevations were determined by barometric observations using either the fixed point or trailing method (*Neethling et al.*[1,2] 1968; *De Ridder*[3] 1970; *Retief*[4] 1968). No absolute gravity base existed in western Queen Maud Land before 1971 and the relative gravity data were used mainly to calculate subglacial rock elevations from regionally corrected free-air anomalies. All traverses were linked to localities of zero ice thickness at rock outcrops and a conversion factor of 20 m per milligal free-air anomaly was used in the computation of the rock floor elevations. This factor was determined by comparison of the free-air anomalies with seismic refraction soundings by *Robin*[5] (1958) and a good fit was obtained for values of ice thickness less than 1 000 m. At ice depths exceeding 1 000 m the gravimetric method was apt to give values that are lower by about 20 per cent.

Some indication of the nature of the bedrock and of its structure was also obtained from the magnetic data. In general it was observed that the pattern of both gravity and magnetic anomalies existing on the continental shelf approximates the east-north-easterly trend of the edge of the continental slope and other prominent lineaments in the Ahlmannryggen. Within the area of Blåskimen and Eskimo Ice Rises, vertical magnetic and free-air anomalies are mainly positive and of short wave length (*c.* 20 km), and range in amplitude from 300 to 6 000 gamma and 30 to 60 milligal respectively.

(*b*) *Stage II* (*Borga Base — Kirwanveggen — Polar Plateau*)

After the establishment of Borga Base in 1969, the potential range of the traverse operations was greatly extended. The main project planned for this stage is a 2 000-km return traverse to the northernmost turning point of the United States South Pole — Queen Maud Land Traverse (*Neethling*[6] 1969; *Wolmarans & Neethling*[7] 1970). This traverse, which should have commenced during 1971, has now, due to logistic considerations, been rescheduled for the summer of 1973/74. The return route has been planned to intersect a Soviet plateau traverse made during 1968 (Fig. 2). Traverse observations will include radio echo sounding, gravity, magnetics (all elements), astronomical observations for position fixing, glaciological observations, ice flow studies, and collection of snow samples for stable isotope determinations. Major traverse stations will be spaced 80 km apart, with minor ones every 8 km.

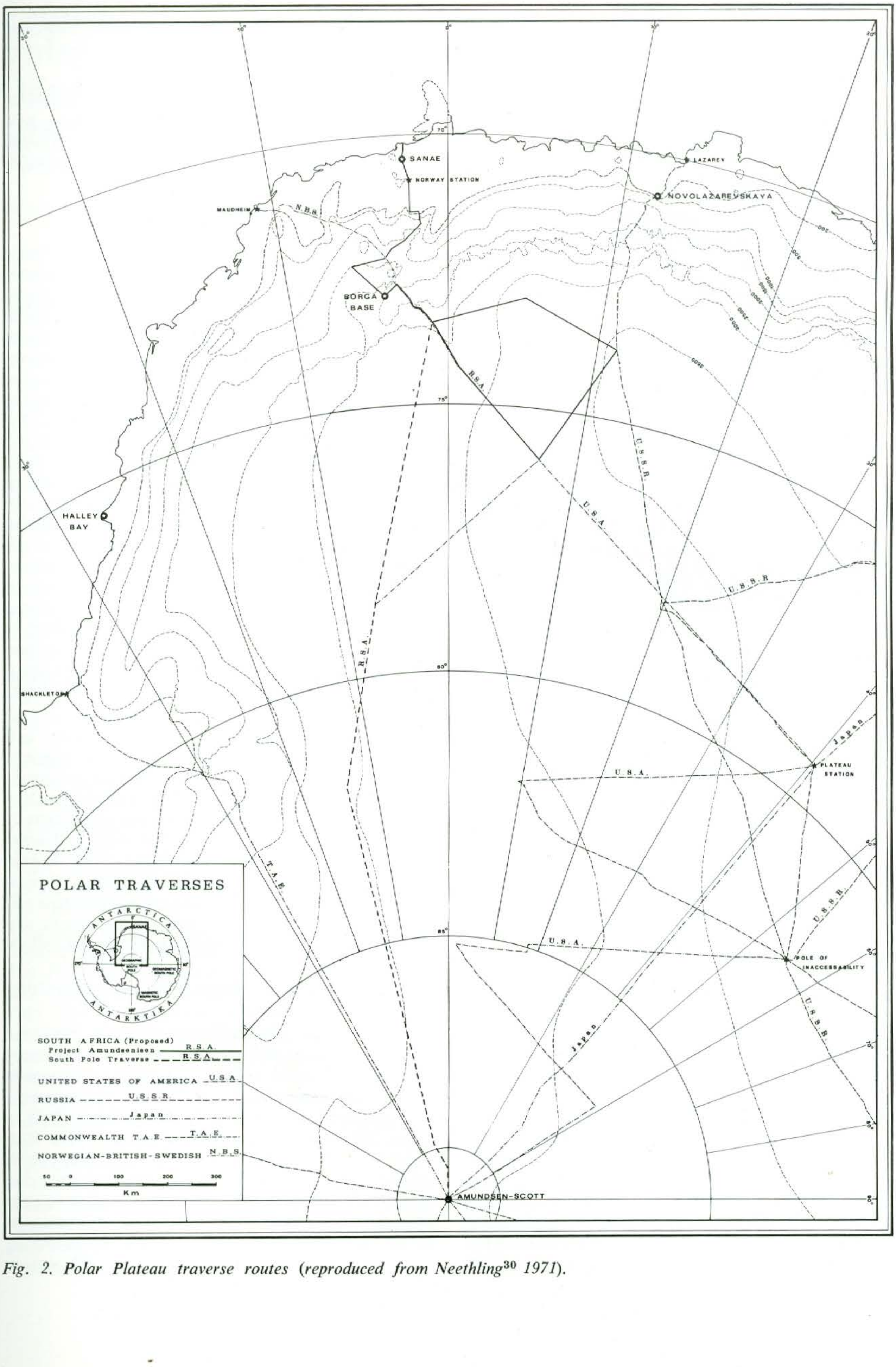

Fig. 2. Polar Plateau traverse routes (reproduced from Neethling[30] 1971).

The establishment of an absolute gravity tie-in and the addition of radio echo sounding facilities during this stage would allow for more detailed study of crustal structure and glacier flow dynamics, hitherto not possible.

At some later stage, possibly during the Third Five Year Programme (1973/78), an oversnow traverse to the Geographic South Pole might well be undertaken if logistics permit.

Marine Surveys

No oceanographic programme was formulated by SASCAR during the period under review and the location of observations was therefore determined by ice conditions, available equipment, and opportunity during the annual relief voyages of the South African polar vessel *RSA*. Results of these initially uncoordinated observations, particularly those made in the offshore waters of the King Haakon VII Sea to the north of Sanae, proved to be of such significance that the oversnow geophysical observations on the ice-shelf-covered continental terrace were programmed to provide additional subsurface detail of the continental shelf to supplement the information obtained from the marine surveys. The offshore shipboard investigations were made under the supervision and with the enthusiastic co-operation of Captain K. T. McNish, master of the M.V. *R S A* . In addition to her programmes of continuous deepsea soundings and observation of sea surface temperature, which have been directed by the Institute of Oceanography, University of Cape Town, since 1969, the *R S A* also made several total magnetic traverses between Cape Town and Sanae across the mid-Indian Ocean Ridge to the east of Bouvet Island. The oceanographic surveys and routine observations in the King Haakon VII Sea comprised:

(*a*) *Radar coastal mapping*, 0° — 5° *W longitude*

The Southern Ocean seaboard of western Queen Maud Land is an ice-bound, ever-changing shoreline of floating shelf-ice separating the Antarctic Mainland from the King Haakon VII Sea, one of several marginal seas of the Atlantic — Indian — Antarctic Basin (*Goodell*[10] 1966). During 1964, the *R S A* conducted a radar survey of 370 km of ice front from 0° to 5°W (*Langenegger & Neethling*[11] 1964). This survey was repeated during February 1969, and recorded significant changes in the configuration and position of the ice front during the intervening 5 years, the most important being the calving of nearly two-thirds or 1 800 km^2, of the Trolltunga, the ice tongue located along the Greenwich Meridian (McNish, personal communication, 1968; and Fig. 1). This event, which apparently took place during the winter of 1968, according to a study of United States *ESSA* satellite photographs, is of cartographic and glaciological significance and constitutes a major change in the configuration of the Antarctic ice coastline in these latitudes.

(*b*) *Bathymetry, King Haakon VII Sea*

The approaches to the Fimbul Ice Shelf westwards of the Greenwich Meridian were charted during several summer voyages. Most of the traverses were of reconnaissance standard and limited to the outer regions of the continental terrace. Navigational control was by shipboard radar, the only fixed portion of the ice shelf being the seaward front off Blåskimen Ice Rise (Fig. 1). Survey lines were not spaced at regular intervals and micro relief was therefore not delineated. Additional offshore, sub-surface detail was inferred from the distribution of grounded icebergs. Bathymetric maps prepared from the available information outline the significant geomorphological submarine and subglacial features of the continental terrace of this part of Antarctica (*McNish & Neethling*[12] 1970).

(*c*) *Gravimetric determination of ocean tides*

There is no suitable exposure of solid rock or grounded ice along the shelf-ice shore of the King Haakon VII Sea from where ocean tidal variation can be recorded. It was therefore decided to measure the vertical motion caused by ocean tides on a floating ice-shelf, by using a gravimeter and methods previously described by *Pratt*[13] (1960) and *Thiel et al.*[14] (1960). The gravity measurements made at Substation (*Pollak & Sharwood*[15] 1970), close to the ice front, indicate an average peak-to-peak movement corresponding to a tidal range of 0,70 to 1,65 m, which confirms the theoretical range of 1,2 m predicted for this region by the *Oceanographic Atlas of the Polar Seas*[16] (1957). A tidal range of 0,1 to 1,3 m was obtained near the inland margin of the Fimbul Ice Shelf. This determination was made by repeated theodolite observations at a site 4 km from the nearest rock outcrop and 130 km from the ice front (*Butt & Von Brunn*[17] 1963).

(*d*) *Bottom sediments of the continental shelf*

A dredging cruise programmed for the 7th Expedition yielded 12 bottom-sediment samples from localities immediately inshore from the ice front (*De Ridder & Bastin*[18] 1967). A 30,5 cm Petersen grab on loan from the Department of Sea Fisheries was used, and the region traversed extended from near the breakaway of the continental shelf to as much as 20 km inshore from the breakaway; water depths ranged from 120 to 300 m (values uncorrected for current effects). The dredged deposits comprised mainly poorly-sorted, angular to rounded, sand-sized to pebble-sized, mafic and sedimentary rocks. Lithology, size-distribution, and the abundance of striated pebble-surfaces indicate that the bottom sediments represent ice-rafted material transported by floating ice from a source terrain quite similar in composition to the sedimentary and mafic intrusive rocks exposed in the Ahlmannryggen some 150 km to the south. The importance of associated organic components, mainly Foraminifera, Bryozoa, echinoid spines, sponge spicules and shell fragments, has yet to be evaluated.

(*e*) *Pack ice and icebergs*

The northern limit of pack ice in the South Atlantic between Africa and Queen Maud Land oscillates from latitudes south of Bouvet Island (*c.* 56°S) during winter, to the King Haakon VII Sea (*c.* 69°S) during summer. Observations of ice conditions and distribution entered in the log of the *RSA* indicate that the most severe ice conditions were encountered during the return journey of her maiden voyage in late summer of 1962. During this time, the *RSA* was beset for more than 5 weeks in close pack only 180 km from Sanae. On the 39th day, while on a steady drift towards the Weddell Sea, she broke loose at approximately 5°W, 68°S, and completed the 2 400-km journey to Cape Town in only 12 days.

In the King Haakon VII Sea pack ice usually forms during autumn and breaks up in early spring when dense clouds of frost smoke and ever-widening leads appear as south-easterly winds break the hold of the pack on the ice shelf. The westerly coastal current disperses the floes and ice fragments, and on occasions the region to the west of Trolltunga becomes a polynya with a lead of open water extending from the ice front to the southern limit of close pack beyond the northern horizon. Narrow bands of shore and bay ice usually remain in the more sheltered bukten (bays) in the ice front, to be removed later in summer or, in exceptional cases, to remain intact for several seasons. Large tabular icebergs on their westerly drift towards the Weddell Sea often crash spectacular ice-strewn paths through the pack to collide with the front of the Fimbul Ice Shelf. Icebergs also run aground in shallow water to the north of Blåskimen and Apollo Ice Rises, where they remain for several seasons. During 1968 more than a hundred tabulars, many of them no doubt resulting from the fragmentation of the Trolltunga ice tongue, were reported offshore from Otterbukta.

The more significant features of the submarine and subglacial morphology of the continental margin of western Queen Maud Land between 0° and 3,5°W, as determined from these marine and oversnow geophysical investigations, have been interpreted by *Neethling*[19] (1970). These are:

The Continental Terrace

(a) Continental rise

A stepped continental rise, some 140 km wide, forms the line of junction between a relatively featureless abyssal plain and the steep outer edge of the continental terrace. The rise, which laps onto the foot of the continental slope at a depth of 2 000 m, appears to comprise two distinct surfaces tilted oceanwards, the upper being steeper than the lower (Fig. 3). In some profiles a narrow ridge at the foot of the continental slope may represent a more recent sedimentary train caused by gravity slides.

(b) Continental slope

The continental slope, which forms the main transition between continental and oceanic depths and which also defines the edge of the continent has at break-away point a depth of 400 to 600 m. The slope plunges 2 000 m to the upper part of the continental rise within a horizontal distance of a mere 6 to 12 km; the average gradient is 7,5° to 14,0° (Fig. 3). It trends fairly straight on the whole, but is markedly sinuous wherever canyon-like features are present. Its surface is quite smooth, with little apparent exogenic modification. A well-defined canyon, which may mark the prolongation of the Jutulstraumen, occurs at 2°E longitude (*Soviet Atlas*[20] 1966).

(c) Continental shelf

As is typical of shelves off glaciated regions, there is a great diversity of relief on the continental shelf of Queen Maud Land. A line of prominent shoals, some rising above sea level, and valleys more than 1 000 m deep present contrasting submarine features of the same magnitude as the subglacial topography of the mainland (Fig. 4). Three, possibly four, morphological zones seem to be indicated by the available evidence:

1. An inner coastal zone with very steep submarine topography and marked by offshore islands hidden beneath the ice.
2. An intermediate zone defined by a 1 200 m deep trench, which is approximately 20 km wide at the 1 000 m isobath.
3. An outer marginal shelf zone characterized by a more even submarine surface probably of accumulative origin. The apparent landward slope of this zone may be due to increased deposition towards the ice front, or in part to marginal uplift. Inland-sloping, outer shelf surfaces were also reported from the Ross Sea area by *Lepley*[21] (1964).
4. Transverse and longitudinal ridges, on which the Fimbul Ice Shelf is grounded to form Eskimo, Blåskimen and Apollo Ice Rises, may represent a fourth morphological zone. The apparently flat upper surfaces of some of the shoals, which average from 150 to 200 m below sea level, may represent a bevelled submarine surface. Little is known about the composition of these ridges but the longitudinal one below Blåskimen and Eskimo

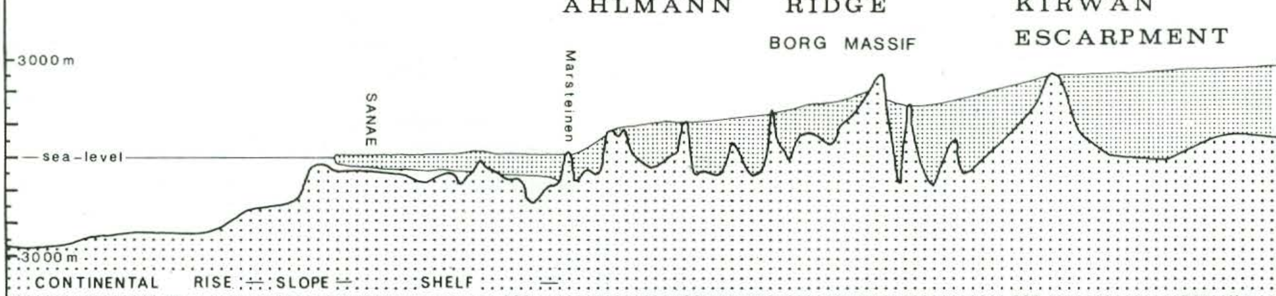

Fig. 3. Composite section along 2°W longitude across the outer edge of the Antarctic Continent and its continental terrace off Princess Martha Coast, Queen Maud Land (reproduced from Neethling[19] 1970)

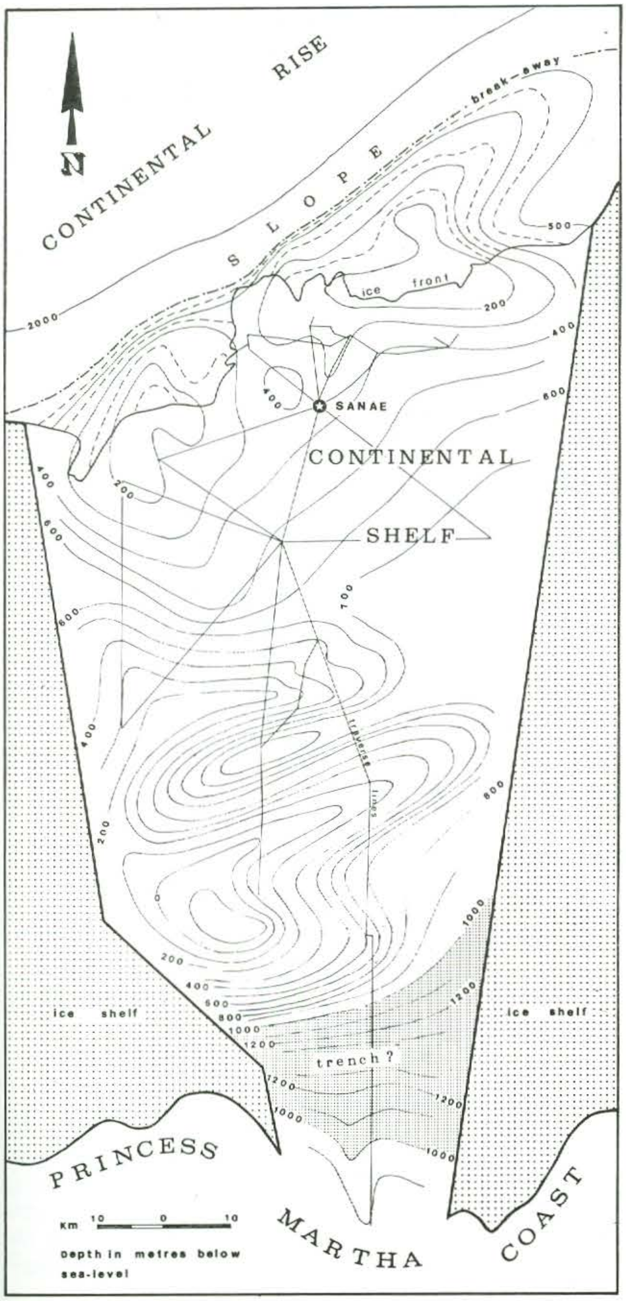

Fig. 4. The morphology of the continental terrace off Princess Martha Coast as determined by oversnow gravity traverses on the Fimbul Ice Shelf (reproduced from Neethling[19] 1970)

Ice Rises could represent lateral moraine of the Jutulstraumen and Schyttbreen formed during a previous glacial maximum, whereas the transverse shoals parallel to the edge of the continental shelf (Fig. 4) may represent terminal moraine deposits like the Pennell Bank in the Ross Sea (*Goodell*[22] 1966). The island below Eskimo Ice Rise lies some 100 m above sea level and most probably consists of mafic bedrock, as there are pronounced magnetic anomalies in this region (*Neethling et al.*[23] 1968; *Retief*[24] 1968).

(d) Origin of the continental terrace

The continental shelf off Princess Martha Coast appears to be of the fissured type (*Guilcher*[25] 1963), *i.e.* of tectonic origin, formed mainly by block movements as has also been suggested, *inter alia*, by *Znachko-Yavorsky & Ravich*[26] (1968). Possible marginal flexuring may, however, be indicated by tilted surfaces of the stepped continental slope, and by the elevated shelf edge and the inland slope of the terrace itself (Fig. 3) *Guilcher* (*op. cit.*) suggests that these features may denote marginal flexuring along an axis parallel to the coast. Similar tilted slope surfaces have also been recognised in the Antarctic by *Znachko-Yavorsky & Ravich* (*op. cit.*) who, however, attribute them to parallel faults.

The Mainland

Subglacial rock elevations indicate a dissected land surface below the ice sheet, with deep, ice-filled fjord-like valleys extending for some considerable distances inland. The steep subglacial terrain accentuates to an even greater extent the predominant north-north-easterly lineaments displayed by the surface topography. It delineates Ahlmannryggen as one of the most prominent geographical divides of Queen Maud Land, and Kirwanveggen as a prominent mountain range transecting the divide to the south, and it emphasizes the deep valley of the Pencksokket-Jutulstraumen as a significant negative feature separating regions of contrasting geomorphology and geology.

The main features of the subglacial land surface of these contrasting geomorphic regions of western Queen Maud Land are, according to *Neethling*[27] (1970):

(a) Northern Ahlmannryggen

This region of the Princess Martha Coast is marked by great irregularity, extreme glaciation and deep submergence. It is a fjord coast determined partly by geological structure and glacial erosion. The coastal zone and northern part of the Ahlmannryggen are characterized by advanced glacial erosion and mature alpine relief. At the surface they present a nunatak-studded ice sheet with rock surface elevations indicating a seaward slope of about 1° which may well be the result of late Tertiary to recent tilting (King, personal communication, 1971). Glacial sculpture has pared back the divide along prominent structural lineaments, producing finger-like separate ridges extending for considerable distances subglacially, with offshore islands marking their submarine extensions. The floors of the inter-ridge valleys are below sea-level, and longitudinal valley-profiles appear to display signs of basining, with shallower threshold elevations typical of fjords.

(b) Borgmassivet

This, which may be regarded as the southern part of Ahlmannryggen, contrasts with the coastal nunatak zone in that it comprises blocky massifs characterized by spectacular glacial scenery with elevations varying from 2 700 m above to 800 m below sea level. The predominant north-easterly structural grain of the divide is emphasized by parallel inter-nunatak troughs and corridors. Inter-trough divides, partly wasted to sharp-crested ridges on the surface, continue below the ice sheet for some distance below sea level. The prominent marginal drainage valleys, the Schyttbreen and the Jutulstraumen, have developed along major lineaments and are no doubt inherited from preglacial times.

(c) Kirwanveggen

At the foot of this escarpment, which bounds the inland ice plateau, *Robin*[29] (1958) determined by seismic reflection sounding that the floor of the Pencksokket is 800 m below sea level. On the inland side of the escarpment he measured ice thicknesses exceeding 2 400 m. Kirwanveggen, even though largely covered by ice and projecting only a few hundred metres above the surface of the present-day ice sheet, therefore represents a 2 500-m high mountain range rather than an escarpment. It would appear that the range has been partially formed by headward erosion along an ancestral fault-line valley cut in a mature, inland dipping surface. The Borgmassivet to the north averages 200 to 500 m higher than the Kirwanveggen suggesting that some warping may have occurred, most probably during Cenozoic time. The Kirwanveggen is abruptly terminated in the east and separated from the Sverdrupfjella by the upper reaches of the Jutulstraumen ice stream which may also occupy a major transverse fault-line valley.

(d) Pencksokket — Jutulstraumen

This most striking subglacial feature of the Princess Martha Coast is a vast fjord which extends well below sea level into the interior of Antarctica and along which the largest outlet glacier in Queen Maud Land is channelled (Fig. 5). It comprises a meridional valley up to 100 km wide, the floor of which lies several hundred metres below sea level even at distances of up to 200 km inland from the shelf ice (*Robin, op. cit.*). Insufficient subsurface detail is at present available to resolve its complex topography but a bedrock floor of considerable relief is indicated. This relief comprises steep longitudinal ridges, shallower threshold elevation at *c.* 72°S latitude, and a probable extension of the valley up to the edge of the continental shelf. *Neethling*[30] (1971) considers that this valley has been formed along a major fracture which separates two crustal blocks of contrasting structural level and tectonic evolution.

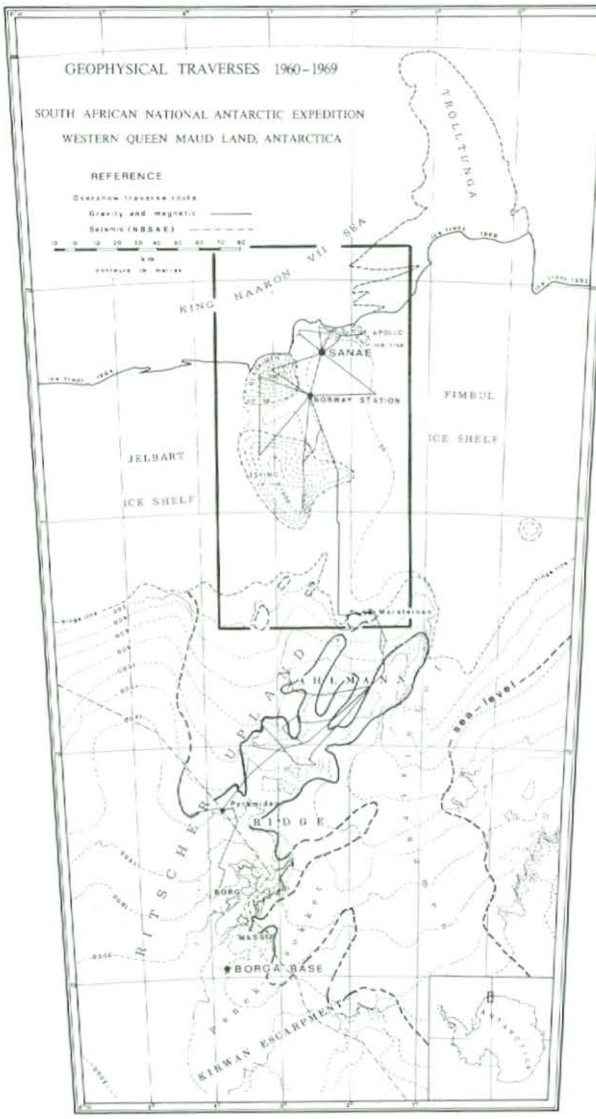

Fig. 5. Geophysical traverses by South African Antarctic Expeditions in the Ahlmannryggen. Approximate location of sea-level contour indicated a dissected land surface below the inland ice and a gigantic fjord extending along the Jutulstraumen outlet glacier (reproduced from Neethling[19] 1970)

Glaciology of The Western Part of The Fimbul Ice Shelf

Glaciological research by South African Antarctic Expeditions also constitutes a part-time project associated with the main geological and traverse geophysical investigations. It has, however, been programmed along the lines recommended by the SCAR Working Group on Glaciology within the limitations set by available logistic support and opportunity. Most of the observations were made during the Antarctic winter when the geologists were confined to base. Continuity of surface snow accumulation measurements was provided for by other members of the Expeditions during the absence of the geologists.

Base and traverse glaciological studies were made on the Fimbul Ice Shelf in the vicinity of past and present wintering bases, across nearby ice rises and along the main traverse routes onto the inland ice (Fig. 1). The mass balance studies commenced at Norway Station (70°30'S, 02°32'W) by the Norwegian IGY expedition (*Lunde*[31] 1961) were continued by the 1st and 2nd South African Expeditions until 1961 (*Butt & Von Brunn*[32] 1963). Observations were thereafter extended to Sanae, where they were incorporated in a long-term glaciological project initiated by the 3rd Expedition in 1962 (*Neethling*[33-35] 1962, 1967, 1970). Local projects included a 57-year stratigraphic profile (*Neethling*[36] 1963; *Langenegger*[37] 1964; *Bastin*[38] 1967), snow settling studies, density and grain-size profiles (*Du Plessis*[39,40] 1967), and a study of the variation of tidal movement on a floating ice shelf (*Pollak & Sharwood*[41] 1970). Expedition surveyors also observed the absolute movement and strain as well as the changes in elevation of the ice shelf. Additional observations along a 350-km oversnow traverse from Sanae to Borgmassivet (Fig. 1) have included the measurement of ice thickness (*Neethling et al.*[42] 1968; *De Ridder*[43] 1970); sampling of snow and ice for isotope $(0^{16}/0^{18})$ determinations (*Aucamp*[44] 1970); 10-m snow temperatures; and stratigraphic and density profiles utilizing rammsonde soundings, SIPRE-cores and pit observations. Traverse stations were spaced 3 to 9 km apart.

Snow Accumulation Studies: Temporal Variation and Spatial Distribution

The Fimbul Ice Shelf which has been described by *Swithinbank*[45] (1957) and *Lunde*[46] (1961) comprises three distinct physiographic regions: a western part, of typical flat-lying ice shelf with a prominent series of ice rises; a central part, demarcated by extensively crevassed zones delineating the northerly extension of the Jutulstraumen into the ice shelf — this part also included Trolltunga, a 90-km long ice tongue at the Greenwich Meridian; and an eastern part of flat-lying shelf ice with a few ill-defined low ice rises. The main features of the snow accumulation regime, and the relation thereof to the presently prevailing meteorological conditions in the western region of the Fimbul Ice Shelf, have been assessed by *Neethling*[47] (1970), and are summarized below:

STAKE MEASUREMENTS

(*a*) *Annual variation*

More than 4 000 measurements of surface snow accumulation were made at two stake networks located at Sanae. The mean annual rate of accumulation during the period 1963-1967, observed at a small-area (17 200 m^2) high-frequency network was determined as 43,9 g $cm^{-2} yr^{-1}$; (standard deviation 4,4 g $cm^{-2} yr^{-1}$; coefficient of variability 10,5 per cent). Annual accumulation values varied up to 65 per cent and deviated 38 per cent from the mean. A consistently lower average accumulation of 42,6 g $cm^{-2} yr^{-1}$ for a radial network of larger area (75 km^2) centred around Sanae was considered to be due to a decrease in accumulation recorded by those stake lines extending towards the ice front (Fig. 6). The average density used in calculating the water equivalent of the stake measurements at Sanae was 0,39 g cm^{-3} for the upper 1 to 1,2 m of firn, in contrast to a density of 0,45 g cm^{-3} used by *Lunde*[48] (1961) for observations at Norway Station.

(*b*) *Seasonal variation*

The mean variation in monthly snow accumulation indicates that there is a period of ablation during December, a distinct accumulation low during January, and periods of peak accumulation during March, June and July. Although the snowfall during all other months appears to be evenly distributed, there are individual months, from one year to another, when there are large variations in precipitation (Fig. 7).

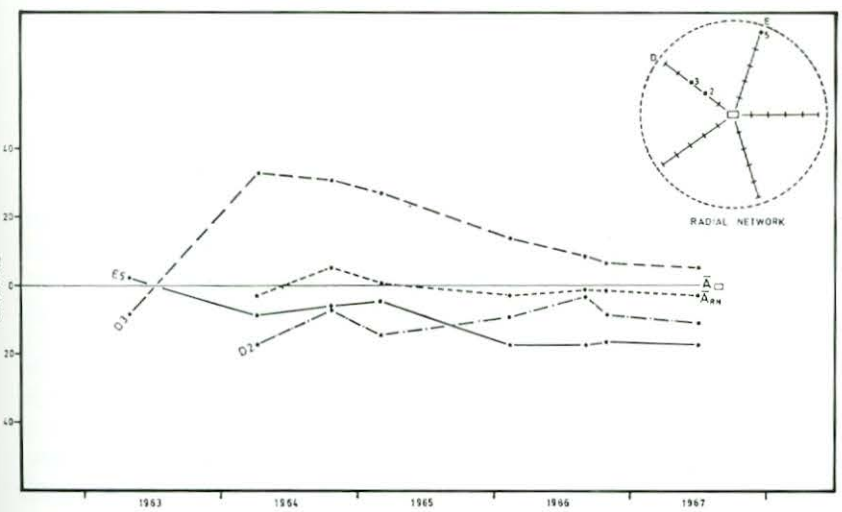

Fig. 6. Deviation of snow accumulation, small-area network ($\bar{A}$) v. radial network (RN), Sanae (reproduced from Neethling[35] *1970)*

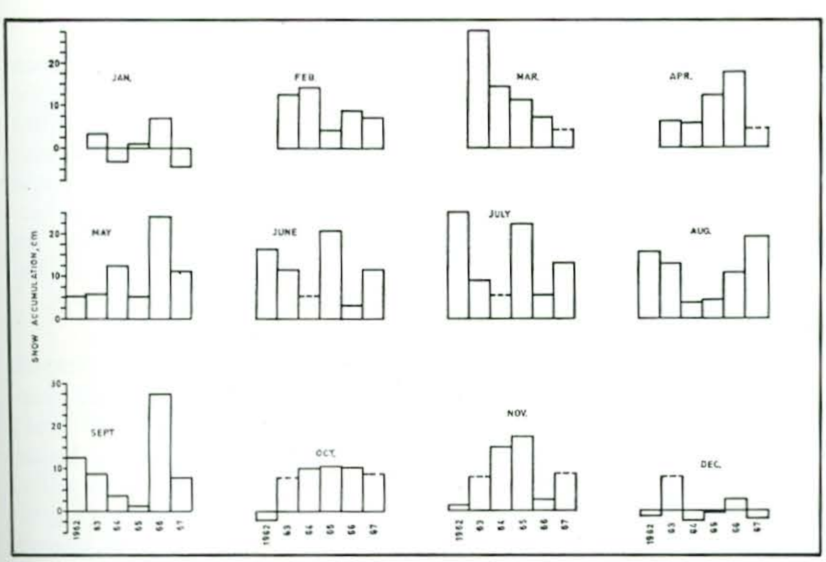

Fig. 7. Variation of monthly snow accumulation determined from small-area, high-frequency network, Sanae, 1962-1967 (reproduced from Neethling[35] *1970)*

Table 1

Mean annual accumulation and density measurements for the period 1930 — 1960 as determined from a composite pit and SIPRE core profile at Sanae (reprinted from Neethling[48] 1970)

Year	Density g cm^{-3}	Accumulation g cm^{-2}	Year	Density g cm^{-3}	Accumulation g cm^{-2}
1960	0,425	41,1	1936	0,622	42,7
1959	0,452	48,2	1935	0,607	32,2
1958	0,459	49,0	1934	0,628	39,9
1957	0,484	41,8	1933	0,639	32,5
1956	0,499	27,9	1932	0,629	39,3
1955	0,520	54,2	1931	0,641	44,0
1954	0,502	44,6	1930	0,647	41,2
1953	0,598	38,0	1929	0,642	35,3
1952	0,570	39,1	1928	0,643	45,8
1951	0,553	33,7	1927	0,638	37,2
1950	0,565	25,6	1926	0,654	29,9
1949	0,618	44,0	1925	0,654	30,5
1948	0,571	36,2	1924	0,658	33,5
1947	0,557	38,2	1923	0,648	39,6
1946	0,567	40,9	1922	0,657	29,2
1945	0,573	48,2	1921	0,652	33,5
1944	0,575	27,2	1920	0,655	32,8
1943	0,579	55,1	1919	0,653	39,8
1942	0,586	29,3	1918	0,669	34,0
1941	0,588	45,9	1917	0,673	34,2
1940	0,605	52,1	1916	0,657	30,0
1939	0,618	45,2	1915	0,681	44,4
1938	0,647	24,7	1914	0,673	25,6
1937	0,633	37,0	1913	0,687	39,8

(c) Annual local areal variability

The annual local areal variability in this region of the Fimbul Ice Shelf is 3,6 g cm^{-2}yr^{-1} (mean deviation ± 0,5). An increase in the magnitude of areal variability in the monthly accumulation values during 1963 and 1965 was probably due to periods of above-average frequency and velocity of southerly wind, which resulted in greater variation in the surface micro-topography owing to the formation of a cross-drift pattern on the prevailing east-west orientated sastrugi.

STRATIGRAPHIC OBSERVATIONS

(a) Annual and temporal variation

The variation in snow accumulation during the period 1913-1960 was established from the interpretation of firn stratigraphy and density measurements made in a 32 m-deep composite pit and SIPRE-core profile at Sanae (*Neethling*[48] 1970 and Table 1).

This 48-year stratigraphic profile indicates a local temporal variability of 7,4 g cm^{-2}yr^{-1} for a mean annual accumulation of 37,4 g cm^{-2}yr^{-1}. The estimated errors, determined by comparison of the number of definite and doubtful summer surfaces, are 11 and 15 per cent for the pit and core measurements respectively. Determination of mean annual accumulation by stratigraphic methods is on the average 11 and 17 per cent lower than that obtained by stake measurements made at Sanae and at Norway Station respectively.

(b) Long-term variation

Five-year snow-accumulation averages show that there has been a slight increase in precipitation over the past 50 years; three-year averages indicate that there was a gradual increase from 1913-40, followed by an apparent 11-year cycle with an accumulation low in 1951 and a high in the early 1960's. Melt phenomena in the firn profile indicate that the Fimbul Ice Shelf lies predominantly within the percolation facies of *Benson*[49] (1962) and Fig. 8; complete soaking, however, occurred during the summers of 1937, 1949 and 1955.

(c) Areal variation in western Queen Maud Land

It has been determined that sympathetic variations in precipation, long-term trends, and diagenetic facies changes exist between the Fimbul, the Brunt (26°W) (*Ardus*[50] 1965) and the Maudheim Ice Shelves (11°W) (*Schytt*[51] 1958). *Neethling*[52] (1970) also noted a remarkably close agreement in mean annual accumulation between the Fimbul and Maudheim Ice Shelves *viz* 37 g cm^{-2}yr^{-1} (mean deviation 0,5) for the period 1924-1951.

(d) Accumulation maximum at Norway Station

The mean annual accumulation at Norway Station was determined from stake and stratigraphic measurements over a period of 10 years (*Lunde*[53] 1961; *Neethling op. cit.*). It indicates a consistently higher accumulation rate, of the order of 5 to 8 cm water, for Norway Station in comparison with Sanae (Fig. 9). Although no simultaneous meteorological records are available, a marked difference in wind distribution and velocity appear to exist between these two stations which are a mere 21 km apart (Fig. 10). Southerly winds, which are usually associated with low accumulation and high sublimation, have a higher mean velocity and are twice as frequent at Sanae as at Norway Station; whereas westerly winds, in particular west-south-westerlies, which according to Lunde may contribute up to 2 per cent of the annual accumulation, are six times as frequent at Norway Station. These differences in wind regime, and the close proximity of Blåskimen Ice Rise, could well be the cause of the higher precipitation observed at Norway Station.

Climatology as Related to Accumulation

A preliminary analysis of the salient features of the meteorological environment at Sanae and its possible relationship to seasonal trends of accumulation was made by *Neethling*[54] in 1970, who used the surface weather observations obtained during the 1st to 7th South African National Antarctic Expeditions (*SA Weather Bureau*[55] 1965 and 1966). *Burdecki*[56,57] (1969 and 1970) has published a detailed analysis of the climate at Sanae. The seasonal division used was: summer (November to February), autumn (March to April), winter (May to August) and spring (September and October) after *Swithinbank*[45] (1957).

(*a*) *Surface Winds*

The surface wind regime on the Fimbul Ice Shelf in the vicinity of Sanae appears to be complicated by the local influence of ice rises, the effect of drainage winds funnelled northwards down the Jutulstraumen onto the ice-shelf, and the existence of Trolltunga, the large ice-tongue formerly extending beyond the general northern limit of the ice-front. The rare occurrence of katabatic winds on an ice-shelf, some 120 km distant from the edge of the continent, seems to be indicated by a high frequency of wind in the south-east quadrant at Sanae, a more unidirectional wind-rose than at Norway Station and a relationship between a decrease in surface temperature and southerly wind direction. The wind-direction frequency curve also displays a prominent skewness biased to the east-south-east or offshore wind quadrant. Peak frequencies in descending order of magnitude occur in the easterly, south-easterly, southerly and, during some years, in westerly directions. Sanae with a mean

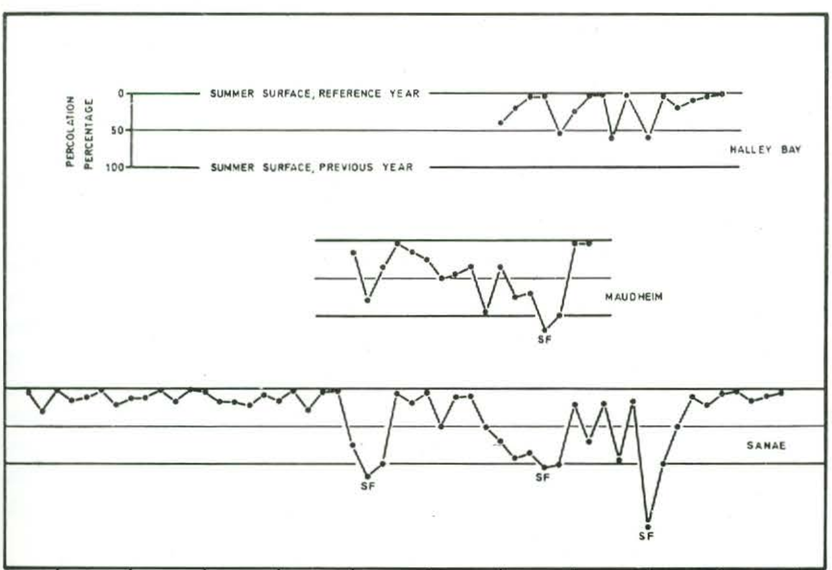

Fig. 8. Diagenetic snow facies, Fimbul Ice Shelf, western Queen Maud Land (reproduced from Neethling[35] 1970)

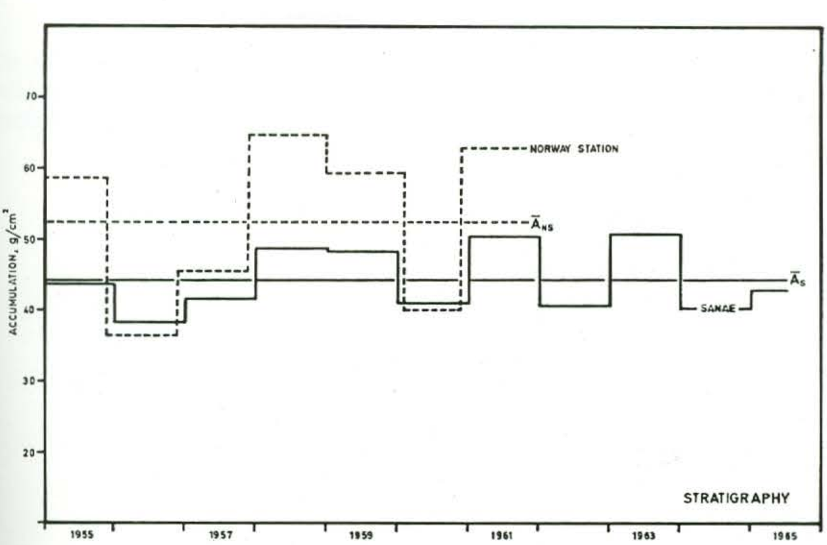

Fig. 9. Stratigraphic interpretation of the variation in mean annual accumulation at Sanae ($\bar{A}_s$) and Norway Station ($\bar{A}_{ns}$), 1955-1965 (reproduced from Neethling[35] 1970)

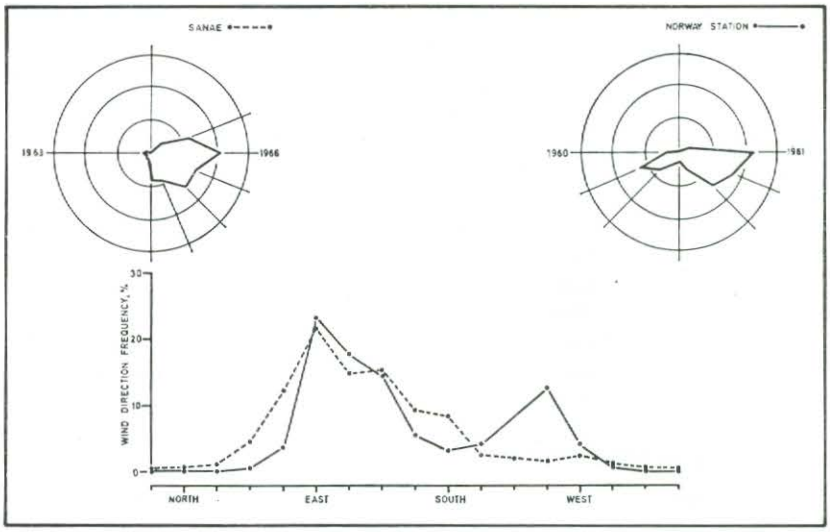

Fig 10. Variation of mean annual wind direction at Sanae (1963-1966) and Norway Station (1960-1961) (reproduced from Neethling[35] 1970)

annual overall windspeed of 7 m sec^{-1} (mean deviation ± 0,4) falls between the low-speed (4-6 m sec^{-1}) and high-speed (10-12 m sec^{-1}) wind groups proposed by *Streten*[58] (1968) for the East Antarctic coastal zone. At Sanae the essential part of the accumulation took place at wind speeds higher than 5-8 m sec^{-1}, particularly during periods of east-north-easterly, and to a lesser extent, easterly winds. In the same way as described by *Lunde* (1961) for Norway Station, low wind velocities (0,4 m sec^{-1}) produced precipitation from all points of the compass. An all-year, mid-summer low in mean windspeed corresponds to an annual low in accumulation, maximum temperature, and diversity of wind direction. Peak velocities and accumulation maxima concurred during autumn and winter but not necessarily during spring.

(b) Surface temperature

The annual march of temperature at Sanae is very much the same from year to year. The annual temperature cycle is typically asymmetric and displays the usual gradual autumn fall and rapid spring rise. The relatively sharp summer peak is symmetrically disposed to the month of January, while minimum temperatures occur invariably in August or September. The annual mean surface air temperature for the period 1963-1966 is —17,7°C (mean deviation ±0,4); temperatures ranged from a maximum of +7,3°C, (mean + 5,7°C, deviation ± 1,0) to a minimum of —51,0°C (mean —48,9°C, deviation ± 1,8). In the summer of 1962, the temperature at Sanae on windless days showed an average diurnal range of 7°; positive summer temperatures occur for an average of 32 days. All winters from 1960 onwards, with the exception of 1966, were coreless and display typical "kernlose" temperature reversals (*Rubin*[59] 1964).

Ice Flow Measurements

The results of repeated measurements of absolute movement of the Fimbul Ice Shelf by expedition surveyors and geologists were limited by the absence of a suitable fixed point of reference, and by an initial high-percentage loss of observation stakes during periods of high snow fall in areas critical to the main objective of the study. The results of these studies and their significance in relation to the regime of the Fimbul Ice Shelf, in particular to the variation in the rate of bottom melting with increasing distance from the ice front, are yet to be evaluated. Flow rates obtained by *Bosman*[60] (1970), indicated the absolute movement of the Fimbul Ice Shelf to be as low as 30 m yr^{-1}, the rate of movement varying from 30 to 60 m yr^{-1} at distances of 28 to 5 km from the ice front. The predominant direction of movement of the ice shelf in the Sanae region is north-north-west. *Butt & Von Brunn*[61] (1962) reported an absolute movement of the ice shelf at its inland hinge area of 62 m yr^{-1}.

Seismology: USCGS Station SNA

The unique position of Antarctica, in the centre of an oceanic hemisphere open to most of the world's belts of seismic activity, means that the seismological

Table 2

Seismological Programme

Component	Magnification	Seismograph and Galvanometer Periods ts	tg
N — S	50 000 and 25 000	1	0,75
E — W	50 000 and 25 000	1	0,75
Vertical	50 000 and 25 000	1	0,75

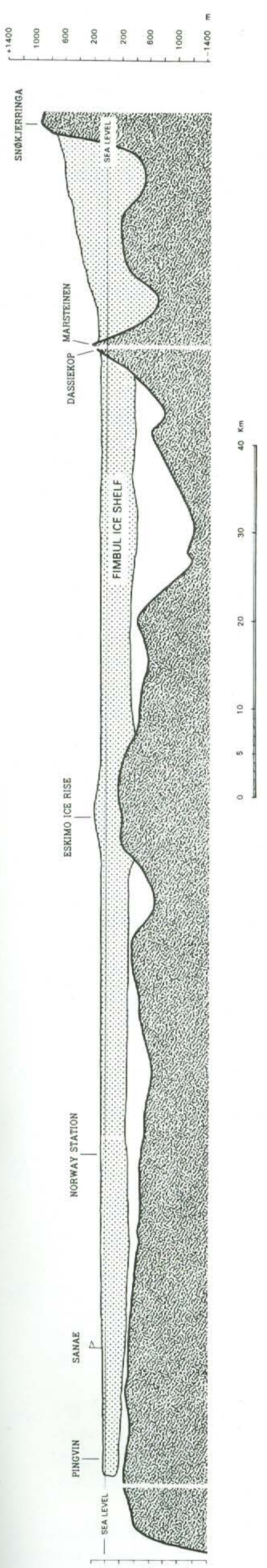

Fig. 11. Location of USCGS/WWSS Seismograph Station SNA (Sanae) on a floating ice shelf (reproduced from TSO Misc. 4389, Trigonometrical Survey, Pretoria)

stations there can receive earthquake surface and body waves from all directions and distances, as there are no intervening continents to affect either travel times or signal amplitudes. The Antarctic continent itself, mainly as a result of the weighting-down effect of the more than 30-million-km^3 ice cap, is essentially an aseismic region with only weak shocks occurring in the coastal zone. In contrast, the circum-Antarctic oceanic region is one of the most active seismic zones on earth.

Sanae Observatory

(a) Instrumentation

A standardized seismograph was installed at Sanae during mid-summer of 1963/64 by personnel of the US Coast and Geodetic Survey (USCGS), and code-named Station SNA in their world-wide seismograph network. The seismograph is a short-period Benioff variable reluctance model, equipped with a 3-drum recorder which allows continuous and simultaneous recording of the vertical, N-S and E-W components of ground displacement. Table 2 provides details of the magnification of components and instrument wave-period times. Preliminary times and phases of shocks are measured at Sanae and then forwarded by telex to USCGS, Washington D.C., *via* the Geological Survey, Pretoria, which is in technical control of the observatory. Epicentral loci, origin times, focal depths and magnitude determinations are then published in USCGS bulletins and data sheets.

(b) Location

The location of the Sanae observatory is significant in that it is situated a mere 25 km inshore from the break-away point of the continental shelf. The vault itself is located approximately 450 m above the surface of the continental shelf and in the upper 10 metres of a 350 m-thick floating section of the Fimbul Ice Shelf (Fig. 11). This siting of the observatory on a floating ice shelf was determined more by logistic than by seismological considerations, the nearest rock outcrop for a more suitable site being more than 120 km distant from Sanae. Although a variety of foreseeable operational problems arose from this unstable foundation, successful recording of short period waves at a magnification of 50 000 has been feasible. Experimental recording of long-period waves at a magnification of 10 was also achieved but this has since been discontinued and the system dismantled. Microseismic activity is intense during summer, particularly during periods of bad weather when open coastal leads prevail a mere 15 km distant from the observatory. In addition, continuous tilting of the seismometers, which are placed directly on individual base plates on a low-density snow floor, has also made frequent and time-consuming re-levelling adjustments necessary. Arching of the snow floor has also contributed to this rapid drift in level.

(c) Seismicity

Although the station was inactive for the larger part of 1969, due to technical difficulties, it recorded more than 1 180 shocks during the period 1965-68. Among the major earthquakes recorded at Sanae was the disastrous Alaskan earthquake of 1966. Operation Long Shot, the nuclear explosion during October 1965, was also recorded. However, most of the other earthquakes originated in the mid-ocean ridge system in the South Atlantic, particularly in the region of Bouvet Island (54°26′S, 3°24′E). This ice-capped island at the southernmost end of the Mid-Atlantic Ridge comprises the uppermost 800 m of an immense volcano rising more than 5 000 m above the ocean floor. From the distribution of earthquake epicentres in its vicinity, Bouvet Island appears to be located in a particularly active region which, according to USCGS data, shows a number of shocks varying in magnitude from 4,7 to 6 (Richter Scale) per year. The region is considered to represent a juncture of major tectonic features in the earth's crust, and is therefore of considerable interest in problems of sea-floor spreading, plate tectonics and continental drift.

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In this review, one was of necessity time and again reminded of the constraints imposed on field exploration by logistic, mechanical and human problems, and by the severe Antarctic environment. The geologists who have participated in the Earth Science programme during these first years of SA Antarctic research, are most grateful for the financial, logistic and moral support provided by the CSIR and the Departments of Transport and Mines, and in particular to each and every one of the members of those expeditions who voluntarily and enthusiastically contributed to the results achieved and reviewed here.

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