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Stratigraphy and sedimentology of the Ahlmannryggen Group in the Borgmassivet, western Dronning Maud Land

J J P Swanepoel*

Department of Geology, University of Stellenbosch, Stellenbosch 7600, Republic of South Africa

*Present address: Coal Exploration, Iscor, P O Box 450, Pretoria, Republic of South Africa

The Ahlmannryggen Group is the lower, predominantly sedimentary part of the Ritscherflya Supergroup, a Precambrian platform deposit occurring in the Ahlmannryggen and Borgmassivet areas of western Dronning Maud Land, Antarctica. A new stratigraphic subdivision is proposed on the basis of 21 measured stratigraphic sections (at 20 localities in the Borgmassivet and one in the Ahlmannryggen) and on the application of the lithofacies concept. From the base upwards the Ahlmannryggen Group is composed of the coarsening-upward Friis-Baastadnuten Formation, the fining-upward Veten Formation and the coarse grained Grunehogna Formation. Lithologically the three formations comprise cobble to pebble conglomerates, intraformational conglomerates, gritstones, sandstones and shales. The following sedimentary structures are displayed: massive to poor bedding, planar bedding (upper flow regime), tabular and trough cross-bedding, ripple cross-lamination, wavy bedding and parallel bedding (lower flow regime). The composition of the sandstone is predominantly arkosic and the conglomeratic zones are lithic. Deposition took place in a tectonically controlled fluvial environment. Uplift of the source area, or subsidence of the depositional basin, alternating with tectonically stable periods, caused prograde and retrograde migration of the fluvial system. Depositional conditions fluctuated between the middle, sandy braided stream environment and the lower, meandering stream environment. In a Gondwana reconstruction the closest stratigraphic analogue is the Umkondo Group of Zimbabwe, but the possibility that the latter is a proximal facies of the Ahlmannryggen Group is considered unlikely.

Die Ahlmannryggen Groep is die onderste, oorwegend sedimentêre gedeelte van die Ritscherflya Supergroep, 'n Prekambriese platform-afsetting wat in die Ahlmannryggen- en Borgmassivetareas van westelike Dronning Maudland, Antarktika voorkom. 'n Nuwe stratigrafiese indeling word voorgestel op grond van 21 gemete stratigrafiese profiele (by 20 lokaliteite in die Borgmassivet en een in die Ahlmannryggen) en die toepassing van die litofasies-konsep. Van onder na bo bestaan die Ahlmannryggen Groep uit die opwaartsgrowwerwordende Friis-Baastadnuten Formasie, die opwaarts-fynerwordende Veten Formasie en die grofkorrelrige Grunehogna Formasie. Litologies is die drie formasies saamgestel uit keisteen- en rolsteenkonglomerate, intraformasionele konglomerate, grintstene, sandstene en skalies. Die volgende sedimentêre strukture word vertoon: massiewe tot swak gelaagdheid, plat gelaagdheid (hoë vloei-omgewing), tafelvormige en trogvormige kruisgelaagdheid, riffelkruisgelaagdheid, golwende gelaagdheid en horisontale gelaagdheid (lae vloei-omgewing). Die samestelling van die sandstene is grotendeels arkosies en die konglomeratiese sones is lities. Afsetting het in 'n tektonies-gekontroleerde fluviale omgewing plaasgevind. Opheffing van die brongebied of daling van die afsettingskom het met tydperke van tektoniese stabiliteit afgewissel en het komwaartse en bronwaartse migrasie van die fluviale sisteem veroorsaak. Afsettingstoestande het gewissel tussen die middelste, sanderige vlegstroomoorheersde omgewing en die laere, kronkelstroomoorheersde vloedvlakte-omgewing. In 'n rekonstruksie van Gondwana is die naaste stratigrafiese analoog die Umkondo Groep van Zimbabwe, maar die moontlikheid dat laasgenoemde 'n proksimale fasies van die Ahlmannryggen Groep verteenwoordig word as onwaarskynlik beskou.

Introduction

The Borgmassivet is a highland situated approximately 130 km south of SANAE in western Dronning Maud Land, Antarctica (Fig 1). It covers an area of some 1500 km^2 of which roughly one-tenth is exposed in the form of block-like mountains and nunataks protruding through the permanent ice cap. The elevation of the undulating snow surface is between 1600 m and 2000 m above sea level and the highest peak, Högsaetet, reaches an altitude of 2 717 m.

The Borgmassivet consists of a sub-horizontal Precambrian sedimentary succession intruded by thick sills and younger mafic dykes of a continental tholeiite suite. The sills tend to build resistant units that often form sheer cliffs protecting the underlying strata against erosion. The geomorphological development of the area was largely controlled by post-depositional faulting, as exemplified by the linear trends of the Raudbergdalen and Frostlendet valleys that transect the Borgmassivet

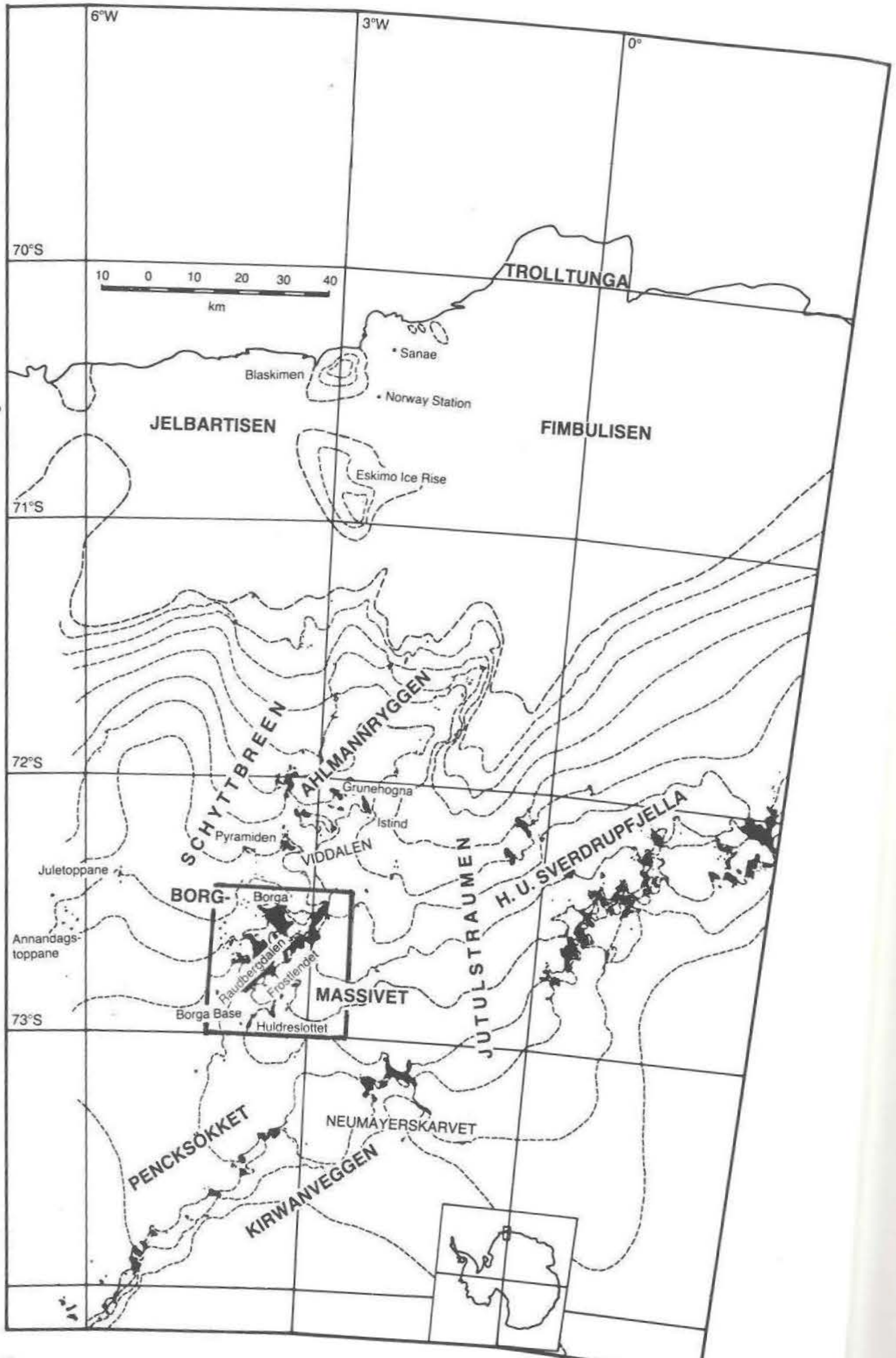

Fig 1. Locality map, after Wolmarans and Kent (1982)

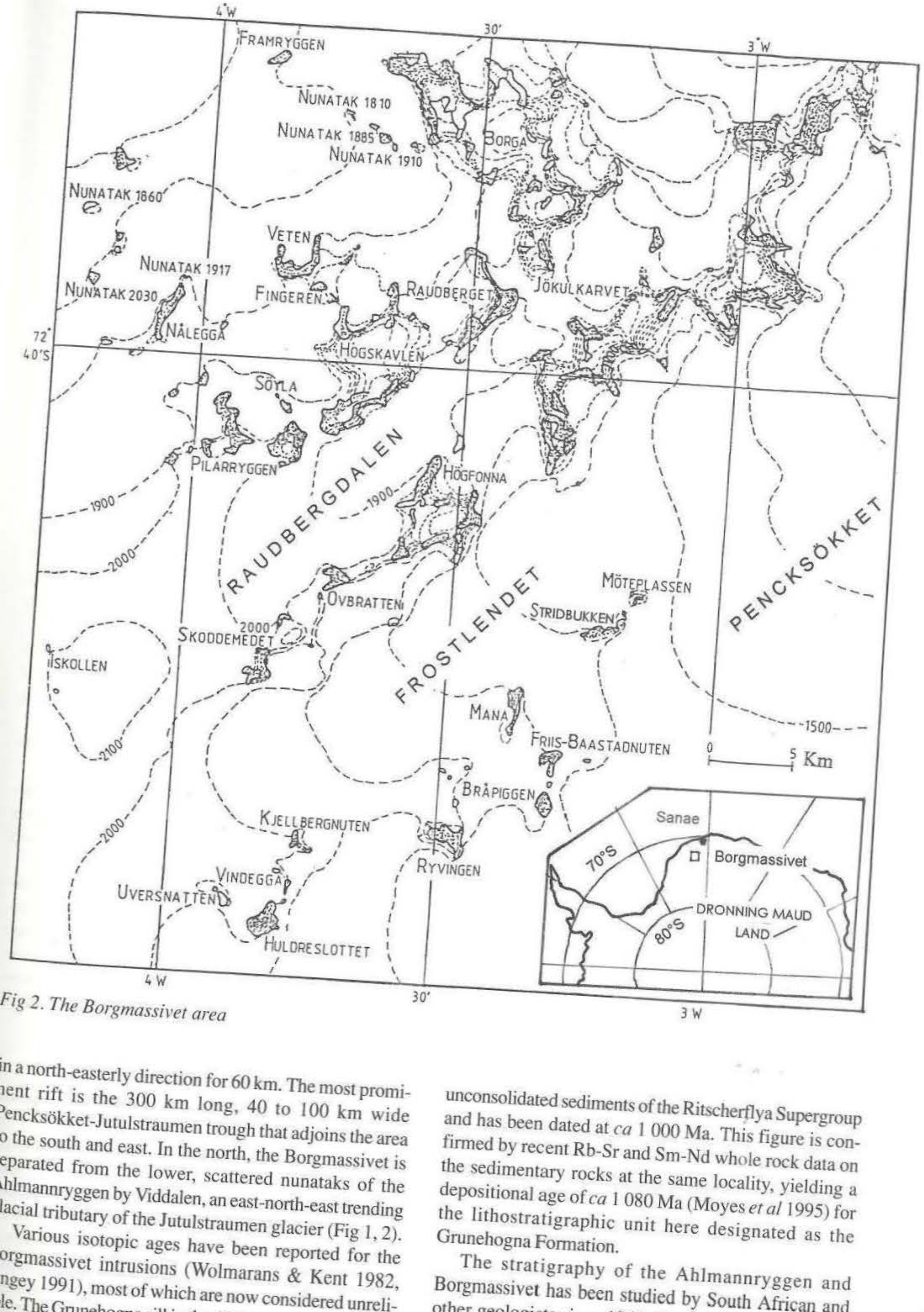

Fig 2. The Borgmassivet area

in a north-easterly direction for 60 km. The most prominent rift is the 300 km long, 40 to 100 km wide Pencksökket-Jutulstraumen trough that adjoins the area to the south and east. In the north, the Borgmassivet is separated from the lower, scattered nunataks of the Ahlmannryggen by Viddalen, an east-north-east trending glacial tributary of the Jutulstraumen glacier (Fig 1, 2).

Various isotopic ages have been reported for the Borgmassivet intrusions (Wolmarans & Kent 1982, Tingey 1991), most of which are now considered unreliable. The Grunehogna sill in the Ahlmannryggen intruded unconsolidated sediments of the Ritscherflya Supergroup and has been dated at *ca* 1 000 Ma. This figure is confirmed by recent Rb-Sr and Sm-Nd whole rock data on the sedimentary rocks at the same locality, yielding a depositional age of *ca* 1 080 Ma (Moyes *et al* 1995) for the lithostratigraphic unit here designated as the Grunehogna Formation.

The stratigraphy of the Ahlmannryggen and Borgmassivet has been studied by South African and other geologists since 1964. The results of this earlier work was summarised by Wolmarans and Kent (1982).

Owing to the discontinuous nature of the outcrops, the absence of marker horizons, vertical displacement by faults, logistic difficulties and other reasons that will be discussed below, no finality about the subdivision of the stratigraphic column could be reached. Helicopter support for geological fieldwork first became available in the 1980/81 summer season and a new base camp was constructed at Grunehogna in 1983/84. This enabled a second phase of more intensive geological investigations to be initiated under the South African Antarctic Programme. The author was among the first participants and was given the task to study the sedimentary rocks of the Borgmassivet by detailed measuring of stratigraphic sections using modern sedimentological techniques. This was done during several weeks between December and February 1981/82, 1982/83 and 1983/84. A similar investigation was carried out in the Ahlmannryggen the following field season (Ferreira 1986a and b).

Nomenclature and methods

Lithology

The concept of lithofacies types (Miall 1977, 1978) was used to describe and eventually to interpret the strata encountered in the field. Sixteen lithofacies types were recognised and grouped into three main categories based on grain size:

A. Coarse grained lithofacies group: grain size range from cobble to grit size.

- A.1 Extraformational conglomerate: massive to poorly bedded, matrix supported
- A.2 Intraformational conglomerate (clay pebble conglomerate)
- A.3 Tabular cross-bedded gritstone

B. Medium grained lithofacies group: grain size range from very coarse sand to fine sand.

- B.1 Conglomeratic (extraformational), tabular cross-bedded sandstone
- B.2 Conglomeratic (intraformational), tabular cross-bedded sandstone
- B.3 Planar bedded sandstone
- B.4 Large scale tabular cross-bedded sandstone
- B.5 Tabular cross-bedded sandstone
- B.6 Trough cross-bedded sandstone
- B.7 Low angle cross-bedded sandstone
- B.8 Small scale cross-bedded sandstone
- B.9 Massive bedded sandstone

C. Fine grained lithofacies group: grain size range from fine sand to clay.

- C.1 Ripple cross-laminated sandstone
- C.2 Wavy bedded sandstone
- C.3 Parallel bedded sandstone
- C.4 Shale

The distinction between B3 and C3 (called planar and parallel respectively purely for identification in subsequent descriptions) is based to a lesser extent on grain size than on association with other lithofacies: B3 is interpreted to represent the upper flow regime and C3 the lower flow regime (Simons *et al* 1965; Southard & Boguchwal 1990). Low angle cross-bedded sandstone is very characteristic of the former and ripple cross-lamination of the latter. Other diagnostic features of the upper flow regime (B3) is the discontinuous nature of the sandstone laminae and the presence of current (parting step or streaking) lineation (Picard & High 1973).

Lithostratigraphic columns were compiled at a scale of approximately 1:400, for each measured section, using the above classification (Fig 3). Due to the appreciable difference in thickness between lithofacies units, ranging from 0.01 up to 17.0 m, all units with a thickness of less than 0.40 m had, for practical purposes, to be left out during the compilation of the columns. They were, however, taken into account in the description of the sedimentary successions as well as in the interpretation of the environment of deposition.

The lithostratigraphic information was applied in the definition of primary (meso-) (Allen 1965), and secondary (mega-) cycles. Megacycles stem from recognisable, mega-scale lithological changes that characterise the sedimentary succession, and are as follows:

Coarsening-upward: if there is an upward increase in the ratio of the lithofacies units belonging to the coarse and medium grained lithofacies groups, relative to those belonging to the fine grained lithofacies group.

Fining-upward: if there is a corresponding upward decrease.

Coarse grained: if the ratio of the lithofacies units belonging to the coarse and medium grained lithofacies groups, relative to those belonging to the fine grained lithofacies group, is consistently high.

Correlation of the lithological successions at different nunataks is hampered by the absence of marker horizons. Recognition of the mega-cycles, and the nature of the lithofacies units constituting them made it possible to effect correlations successfully. These megacycles were used as basis for a new stratigraphic subdivision of the Ahlmannryggen Group.

Petrography

The petrographic classification system of Dott, as modified by Pettijohn *et al* (1972) was used. Owing to the mixed petrological composition of most samples, the name of the most representative rock type was placed closest to the word arenite, for example sublithic-arkosic arenite. Sedimentary rock clasts were classified by using the photomicrograph representation of Pettijohn *et al* (1972). Wentworth's particle size classification (Pettijohn *et al* 1972) was used for grain size descriptions; Folk's comparison chart as modified by Pettijohn

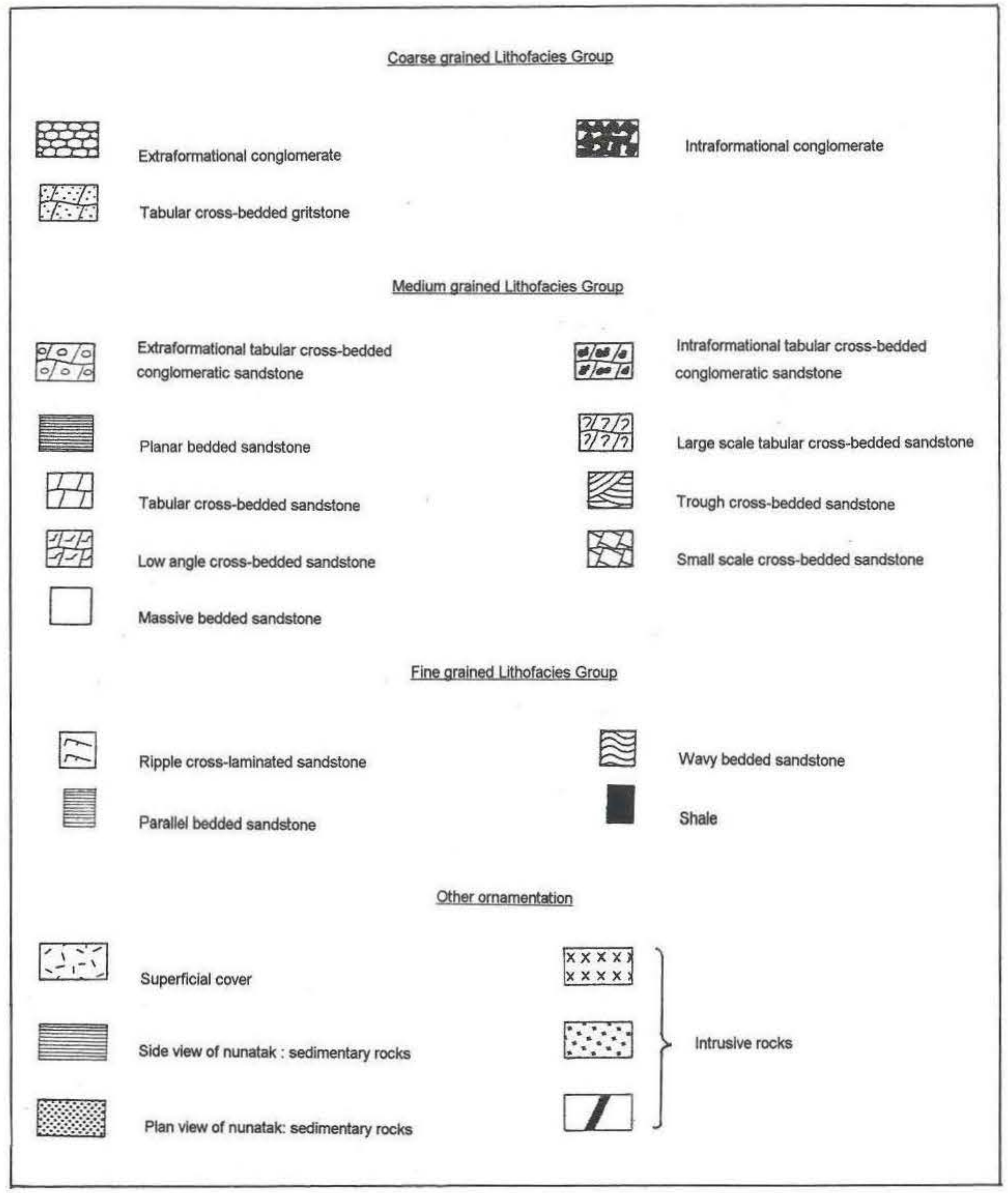

Fig 3. Legend for maps and stratigraphic sections showing classification of lithofacies

et al (1972) to describe sorting; and Powers' roundness images and classes, as redrawn by Pettijohn *et al* (1972), to describe roundness. The petrography of the sandstone is summarised below under Provenance .

Colour

The upper part of the Ahlmannryggen Group has been described as a red-bed succession (Wolmarans & Kent 1982) and a few brick-red volcaniclastic beds are also present in the Borgmassivet. However, a distinction must be made between the original colour of the sediments and secondary colouration. The sandstones generally have a greenish tinge on fresh surfaces. This can be ascribed to widespread epidotisation as a result of hydrothermal alteration during emplacement of the mafic intrusions, and to low-grade (greenschist facies) metamorphism. Clay minerals have been recrystallised to chlorite and sericite. In the poorly sorted sandstone and siltstone iron was liberated from ferromagnesian constituents in the matrix to form hematite during diagenesis, giving a red-brown colour, but it would be misleading to describe these rocks in the Borgmassivet as red beds.

In the conglomeratic base of the Veten Formation (at Veten, Fingeren, Nålegga and Friis-Baastadnuten) hematite is present as spheroidal aggregates and lath-like specularite crystals over a thickness of about 15 m. In the upper part of the Friis-Baastadnuten Formation detrital iron minerals are sometimes present as lamellae, and reach a higher concentration than elsewhere in the Ahlmannryggen Group. Sporadic copper mineralisation (green spots consisting of atacamite) is present on many outcrops and is especially striking on the eastern side of Framryggen. Such secondary colouration is obviously not of sedimentological significance.

Lithostratigraphy

The sedimentary rocks of the Borgmassivet belong to the Ahlmannryggen Group, which is the lower portion of the Ritscherflya Supergroup (Wolmarans & Kent 1982). The historical development of the lithostratigraphic classification of the Ahlmannryggen Group culminated in Wolmarans and Kent's (1982) sixfold subdivision (Fig 4). Although the present investigation did not include the Ahlmannryggen area where the type localities for three of these formations are situated, the sixfold subdivision was found to contain important overlaps and omissions. It was therefore necessary to propose a new classification and to rename the constituent formations to avoid confusion with the old ones. In accordance with the large-scale lithofacies changes (megacycles) in the succession, the Ahlmannryggen Group is subdivided into:

1. A basal, coarsening - upward Friis-Baastadnuten Formation (at least 300 m thick),
2. A fining-upward Veten Formation (*ca* 300 m thick),
3. A coarse grained Grunehogna Formation (at least 270 m thick)

The contacts between the formations are concordant and there is no lateral facies change between them. Formal descriptions will be followed by a discussion of the relationship between the old and new lithostratigraphic units.

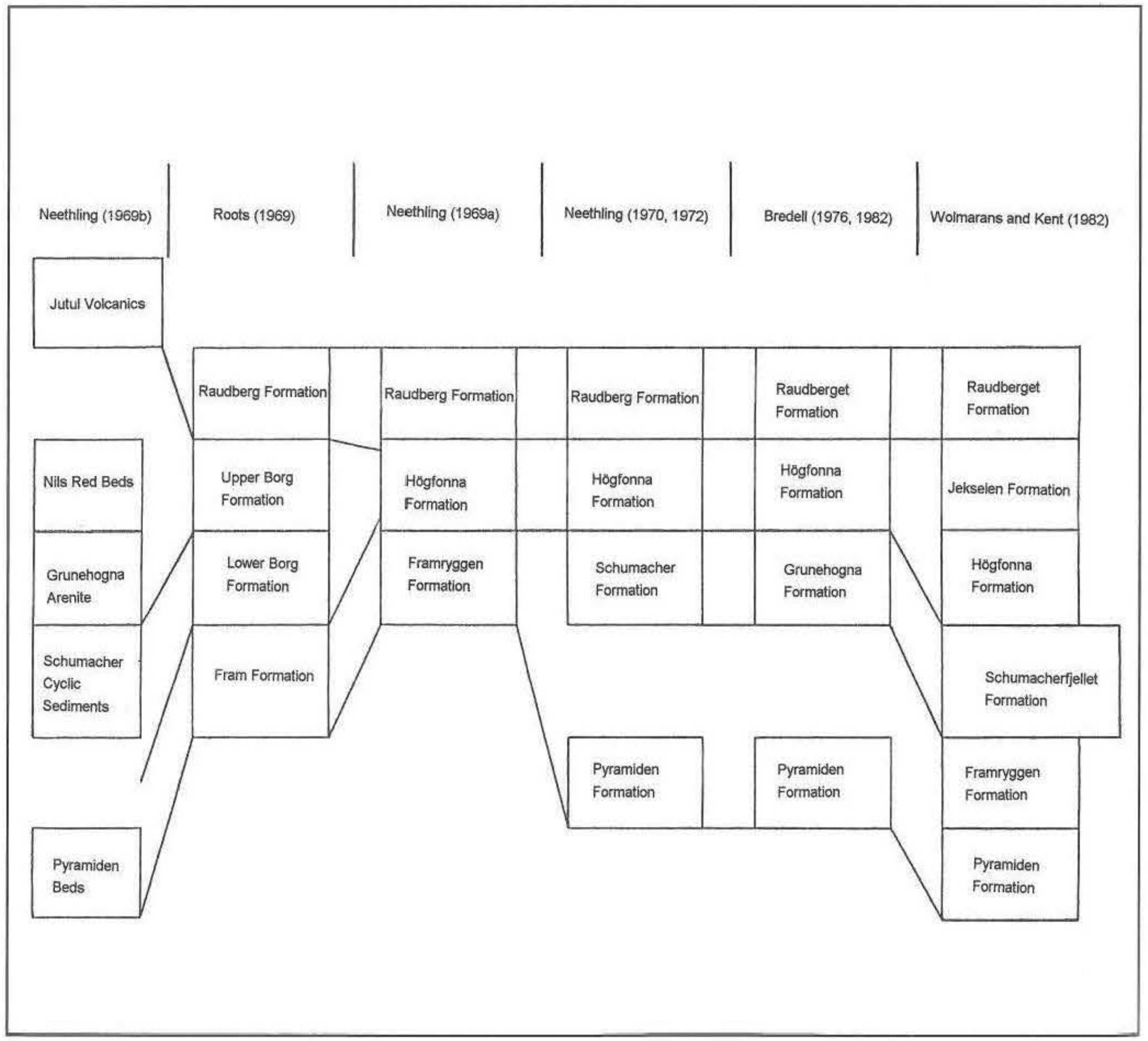

Fig 4. Previous stratigraphic subdivisions of the Ahlmannryggen Group

Friis-Baastadnuten Formation

Definition: The Friis-Baastadnuten Formation, with its type locality at Friis-Baastadnuten (Fig 5, 6), is characterised by a progressive coarsening-upward lithofacies change. The petrological composition changes from sublithic-arkosic in the lower part, to tuffaceous, sublithic-arkosic in the middle to tuffaceous, lithic-arkosic at the top. The lower contact of the Friis-Baastadnuten Formation is not exposed, while the top is conformably overlain by the Veten Formation. A stratigraphic thickness of at least 300 m is estimated from the succession at the stratotype.

Historical review: Wolmarans and Kent (1982) described the succession at Friis-Baastadnuten, *viz* the Friis-Baastadnuten Formation and the conglomeratic base of the Veten Formation, as a correlate of the Högfonnaksla Member (Högfonna Formation).

Distribution and thickness: The Friis-Baastadnuten Formation is exposed at Stridbukken (334 m), Mana, Kjellbergnuten (402 m), Vindegga (210 m), Uversnatten, Friis-Baastadnuten (262 m), nunatak 2030 (269 m), nunatak 1860 (155 m), Nålegga (66 m), Veten (56 m), Fingeren (7 m) and Pilarryggen (26 m), and its contact with the overlying Veten Formation at Friis-Baastadnuten, nunatak 1860, Nålegga, Veten, Fingeren, Pilarryggen, and Uversnatten (Fig 2).

Lithology: The lower part of the formation, which comprises the first 130 m of the succession at the type local-

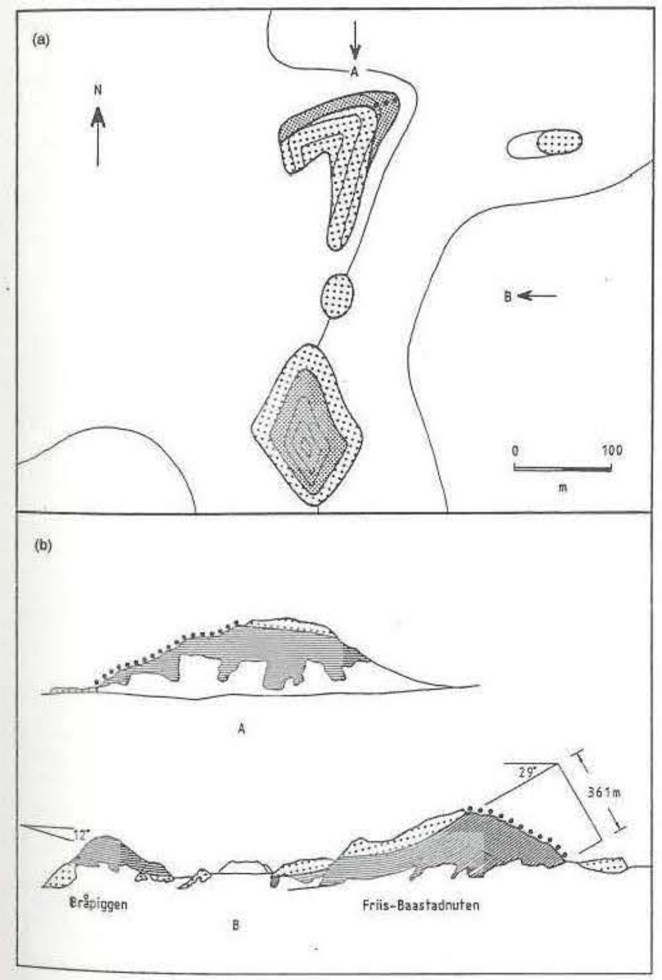

Fig 5. Plan and side views (A, northern and B, eastern) of Friis-Baastadnuten, type locality of the Friis-Baastadnuten Formation, as well as of Bråpiggen

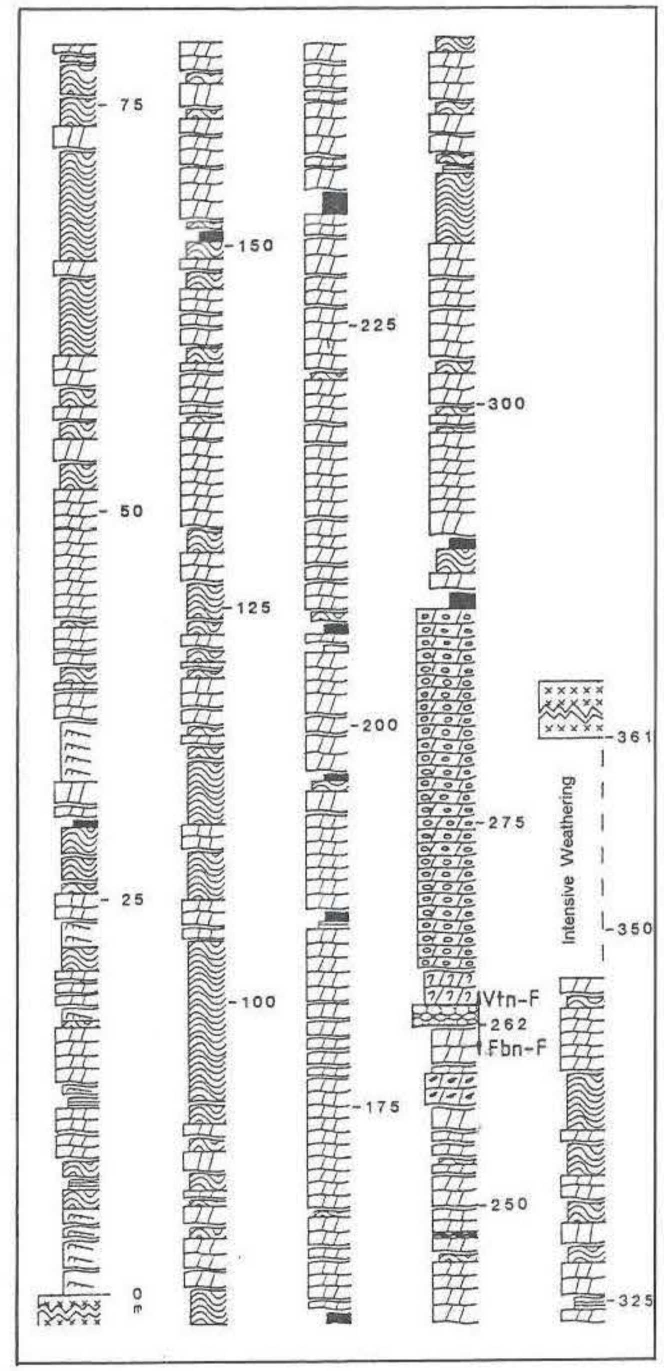

Fig 6. Stratigraphic section at Friis-Baastadnuten viz *the stratotype of the Friis-Baastadnuten Formation and the base of the Veten Formation*

ity, consists of interbedded tabular cross-bedded, ripple cross-laminated, wavy bedded and parallel bedded sandstones, with isolated shale beds, whereas the upper part between 130 m and 262 m, constitutes stacked, multi-lateral, multi-storied, tabular and trough cross-bedded sandstones with subordinate interbedded ripple cross-laminated, wavy bedded and parallel bedded sandstones. The progressive lithofacies change, therefore, consists of an upward increase of the tabular and trough cross-bedded sandstones in the formation, as opposed to an upward decrease of the ripple cross-laminated, wavy bedded and parallel bedded sandstones. This change is evident at the type locality as well as the reference stratotypes at Stridbukken and Kjellbergnuten.

The thickness of the cross-bedded units, which comprise multiple foreset beds, increases from between 0.18 and 2.05 m in the lower part of the formation to between 0.20 and 4.20 m in the upper part. The lower contacts of the beds are erosive, especially in the upper part of the formation, where they are often characterised by intraformational conglomerates, which are interpreted as channel lag deposits.

At Kjellbergnuten there are isolated pebbles and gritstone lenses in the upper part of the formation. The pebbles are rounded, with a diameter of between 2 and 2.5 cm, and consist of quartz, quartzite, chert and jasper, while the gritstone lenses are characterised by the presence of jasper grains.

The ripple cross-laminated, wavy bedded and parallel bedded sandstones are from 0.20 to 4.00 m thick in the lower part of the formation and commonly display ripple marks and desiccation cracks. In the upper part, however, they seldom exceed 0.40 m in thickness.

Fining-upward facies cycles, comprising a basal, tabular cross-bedded sandstone, which is gradational into ripple cross-laminated, wavy bedded and parallel bedded sandstones, and occasionally shale beds, are isolated in the lower part of the formation. In the upper part, however, they succeed each other with basal contacts that are often characterised by intraformational conglomerates. The grain size of the cross-bedded sandstones increases from fine grained in the lower part of the formation, to coarse to medium grained in the upper part. The lithofacies units form sheet-like deposits and individual beds can be followed visually through the length and width of outcrops.

Veten Formation

Definition: The Veten Formation is a fining-upward sequence (Fig 7, 8) with a stratigraphic thickness of approximately 300 m at the type locality (Veten) where both top and bottom are exposed as conformable contacts. The petrological composition at the base of the formation is lithic to tuffaceous, lithic-arkosic, changing to sublithic-arkosic to subarkosic in the upper part.
Historical review: De Ridder (1970), Bredell (1976, 1982) and Wolmarans and Kent (1982) respectively described the lithological sequence at Veten, *viz* the upper part of the Friis-Baastadnuten Formation, the Veten Formation and the base of the Grunehogna Formation, as follows: De Ridder as the Lower Member (Högfonna Formation), Bredell as the Borgmassivet Member (Högfonna Formation) and Wolmarans and Kent (1982) as the Veten Member (Högfonna Formation).
Distribution and thickness: The Veten Formation is exposed at Veten (312 m), nunatak 1860 (63 m), Friis-Baastadnuten (98 m), nunatak 1917 (8 m), Fingeren (51 m), Nålegga (70 m), Pilarryggen, Framryggen (220 m), nunatak 1885 (104 m), nunatak 1810 (59 m), Ovbratten (42 m), Huldreslottet and Ryvingen (105 m). The conformable contact with the overlying Grunehogna Formation is exposed at Veten, Pilarryggen, Raudberget, Framryggen, nunatak 1885, Högfonna, Ovbratten and Ryvingen.
Lithology: The lithofacies units throughout the Veten Formation are sheet-like and individual beds can be followed visually over large distances. The base of the Veten Formation is conglomeratic, comprising extraformational conglomerates and pebbly, tabular and trough cross-bedded sandstones, which are interbedded with large to medium scale, tabular and trough cross-bedded sandstones. Isolated intraformational conglomerate and

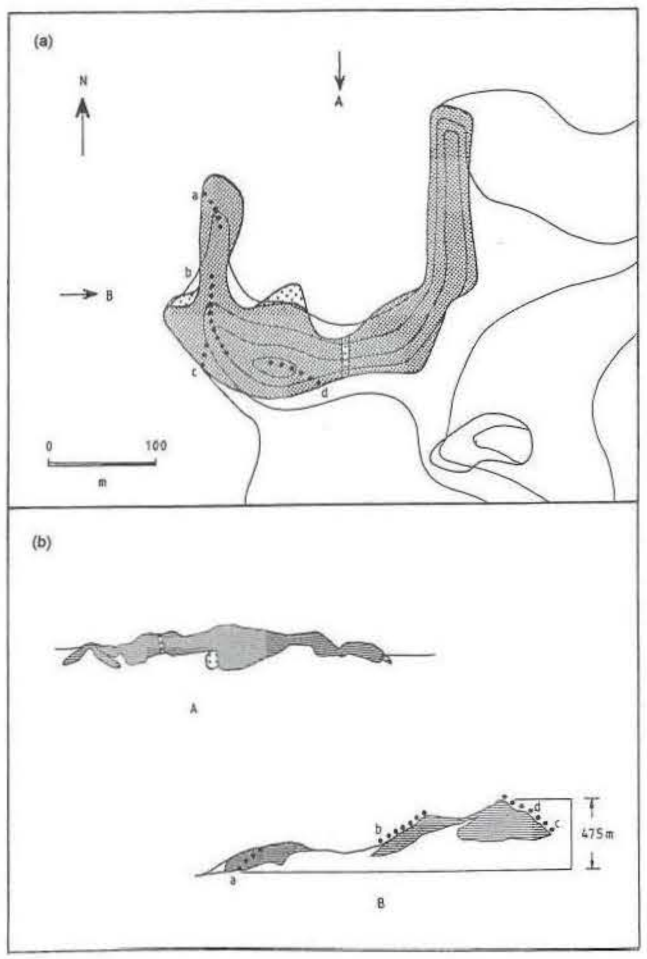

Fig 7. Plan and side view (A, northern and B, western) of Veten, type locality of the Veten Formation

gritstone beds are also present. At the type locality, the conglomeratic basal unit reaches a thickness of 11.12 m but it varies as follows at the reference stratotypes: Friis-Baastadnuten (26,05 m), nunatak 1860 (20,25 m), Nålegga (11,43 m), Fingeren (8,24 m) and Pilarryggen (8,55 m).

The extraformational conglomerate beds that are present in the basal unit are similar in structure and composition throughout the area. Structurally, they are massive to poorly bedded, while the clasts are matrix-supported, with the matrix comprising coarse to fine sand. Texturally, the clasts are rounded, and comprise pebbles with a diameter of 2 to 2.5 cm, although cobbles, with a diameter of up to 12 cm, have been found at the reference stratotype at Pilarryggen (Fig 9). The clasts consist of quartz, quartzite, chert and jasper. Bed thickness for the area ranges between 0.02 m and 2.70 m. The beds are exceptionally thin at the stratotype, where they are from 0.02 to 0.25 m in thickness, but they are much better developed at the reference stratotypes, where the maximum thickness varies as follows: 1.70 m at nunatak 1860, 0.85 m at Nålegga, 0.38 m at Fingeren, 2.70 m at Pilarryggen, and 1.50 m at Friis-Baastadnuten. The pebbles in the pebbly, cross-bedded sandstones are similar in texture and composition to those that constitute the extraformational conglomerates, which indicates that the latter had been reworked after deposition.

Fig 9. The base of the Veten Formation at Pilarryggen. Massive to poorly bedded matrix-supported cobble and pebble conglomerate on an eroded floor of tabular cross-bedded sandstone belonging to the Friis-Baastadnuten Formation

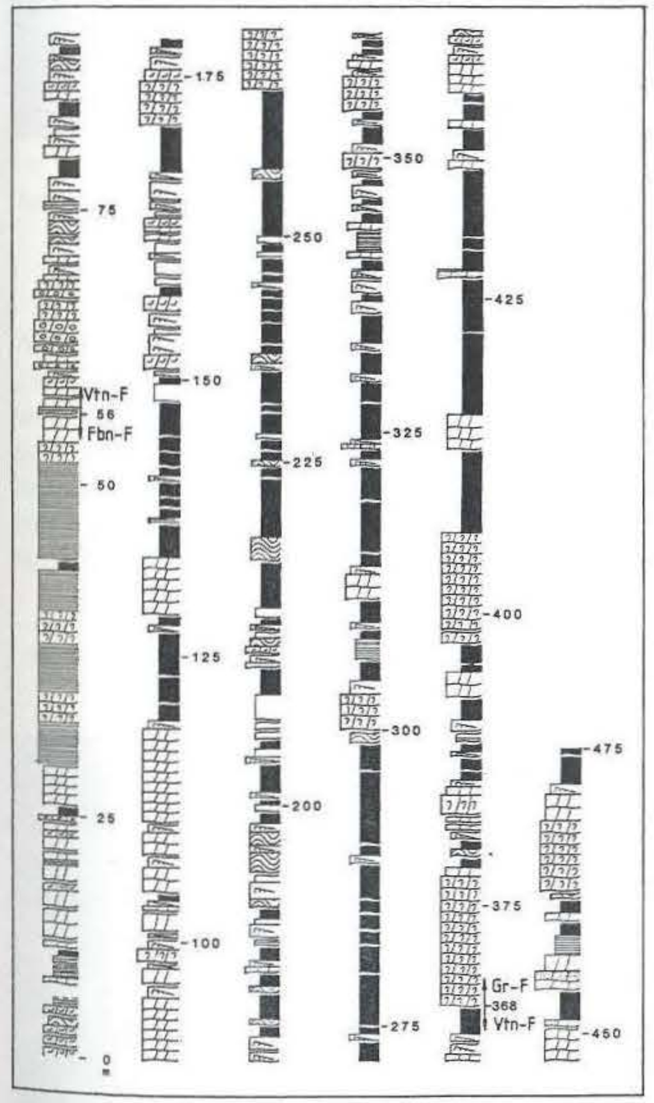

Fig 8. Stratigraphic section at Veten viz *the upper part of the Friis-Baastadnuten Formation, the stratotype of the Veten Formation and the base of the Grunehogna Formation*

Subordinate intraformational conglomerate and gritstone beds are also interbedded in the conglomeratic basal unit of the formation, whereas some of the sandstone beds are characterised by mudclasts and gritstone lenses and grains. Characteristic of the gritstones are the presence of scattered jasper grains. The grain size of the sandstones that are interbedded in the conglomeratic zone, ranges from very coarse to fine grained.

There is a strong similarity between the conglomeratic zones exposed at the reference stratotypes at Fingeren and Friis-Baastadnuten. Both successions are characterised by heavy epidotisation, which gives a greenish colour to the sandstones and intensive specularite mineralisation.

The conglomeratic unit at the base of the Veten Formation is overlain by fining-upward facies cycles, beginning with a tabular cross-bedded sandstone bed which grades into ripple cross-laminated, wavy bedded and parallel bedded sandstones, and shales higher up. The lower contacts of the cycles are erosional, and are often characterised by intraformational conglomerates (channel lag deposits).

At the reference stratotype at Pilarryggen, the lower part of the Veten Formation differs slightly in lithofacies from the rest of the area. The following differences were observed: the maximum thickness for an extraformational conglomerate bed in the Borgmassivet, namely 2.70 m, is reached at this locality. It is also the only place where the conglomerate beds are characterised by cobble size clasts. Finally, the conglomeratic base is not directly overlain by fining-upward facies cycles, as at the stratotype at Veten, but by a multi-lateral, multi-storied trough cross-bedded sandstone sequence (Fig 10),

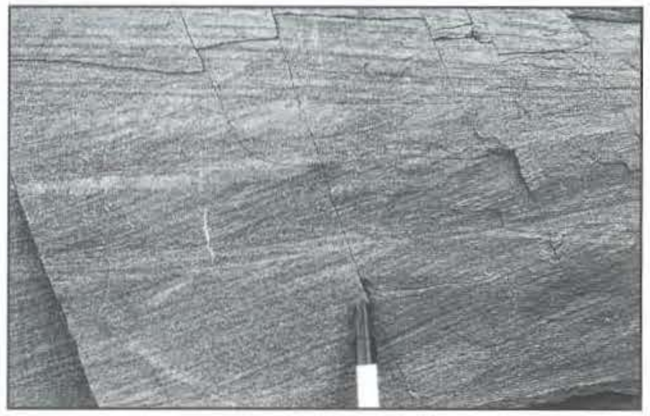

Fig 10. Multi-storied tabular cross-bedded sandstone near the base of the Veten Formation, Pilarryggen

with a cumulative thickness of at least 46 m. This minor difference in lithofacies composition probably resulted from lateral changes in depositional conditions within the depositional basin, but will be discussed in more detail below. Channels that are exposed at the eastern face of Pilarryggen within the above-mentioned multi-lateral, multi-storied, trough cross-bedded sequence, have a high width-to-depth ratio. Channel widths have been measured from 10 to 25 m and depths from 0.50 to 1.20 m.

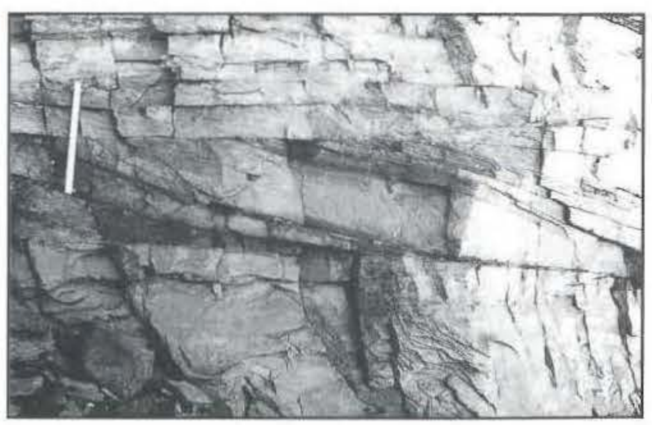

Fig 11. Large scale tabular cross-bedded sandstone in the upper part of the Veten Formation, Veten

The middle and upper parts of the formation consist predominantly of shale beds. The thicknesses of the more prominent ones vary between 2.00 m and 6.60 m. Subordinate tabular cross-bedded, ripple cross-laminated, wavy bedded and parallel bedded (lower flow regime) sandstones are also present. Characteristic of this part of the succession are the isolated, very thick-bedded sandstone units which comprise multiple, large scale, cross-bedded sets (Fig 11). Bed thicknesses of these sandstones, which are erosive and cut deeply into the underlying deposits, vary between 2.50 m and 5.30 m.

Current structures (scour marks) and parting lineation are present in the sandstones at the base of the formation, and ripple marks (straight, sinuous and lunate), raindrop imprints and mudcracks occur in the fine grained sandstones and shales in the middle and upper parts of the formation (Fig 12, 13). Load structures (ball and pillow) sometimes with a diameter of up to one meter, characterise the shale beds that constitute the upper part of the formation.

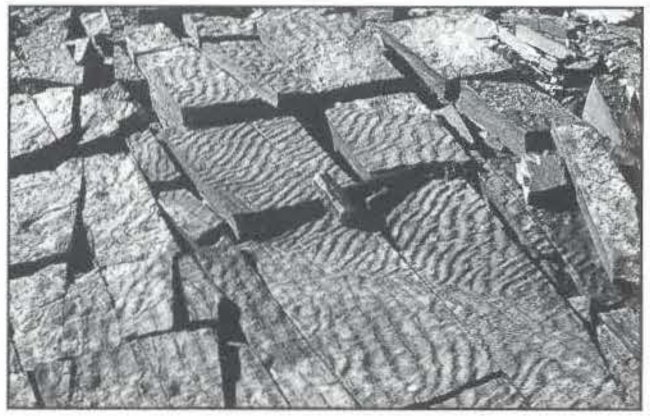

Fig 12. Asymmetric ripple marks in fine grained sandstone of the Veten Formation, Veten

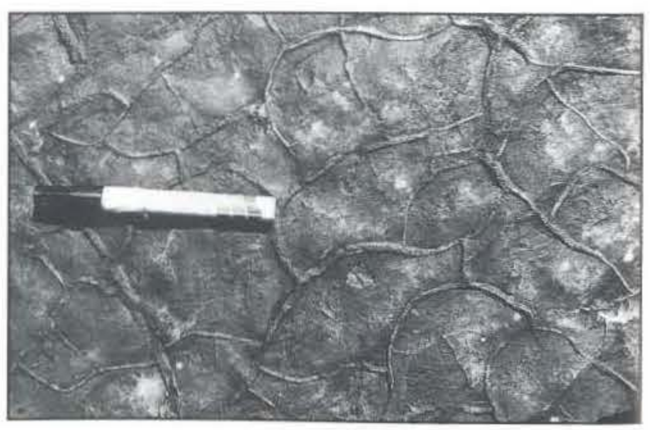

Fig 13. Desiccation cracks in shale in the upper part of the Veten Formation, Veten

Grunehogna Formation

Definition: The Grunehogna Formation with its type locality at Grunehogna (peak 1285) in the Ahlmannryggen is a relatively coarse grained succession (Fig 14, 15), consisting predominantly of sandstones with subordinate extra- and intraformational conglomerates and shale beds. It changes petrologically from tuffaceous, sublithic-arkosic at the base, to tuffaceous, lithic-arkosic, interbedded with some lithic layers in the upper part.

The formation overlies the Veten Formation conformably. The contact is exposed at the stratotype as well as the small, unnamed nunatak immediately to the south-west of Grunehogna and the localities already mentioned under Veten Formation. The top of the formation is not exposed but it has a stratigraphic thickness of at least 200 m at the type locality and 270 m at the reference stratotype at Högfonna. Although a thicker sequence of the Grunehogna Formation is exposed at Högfonna in the Borgmassivet, Grunehogna (peak 1285) is chosen as type locality, because the succession at Högfonna is largely weathered and therefore not suitable as a stratotype.

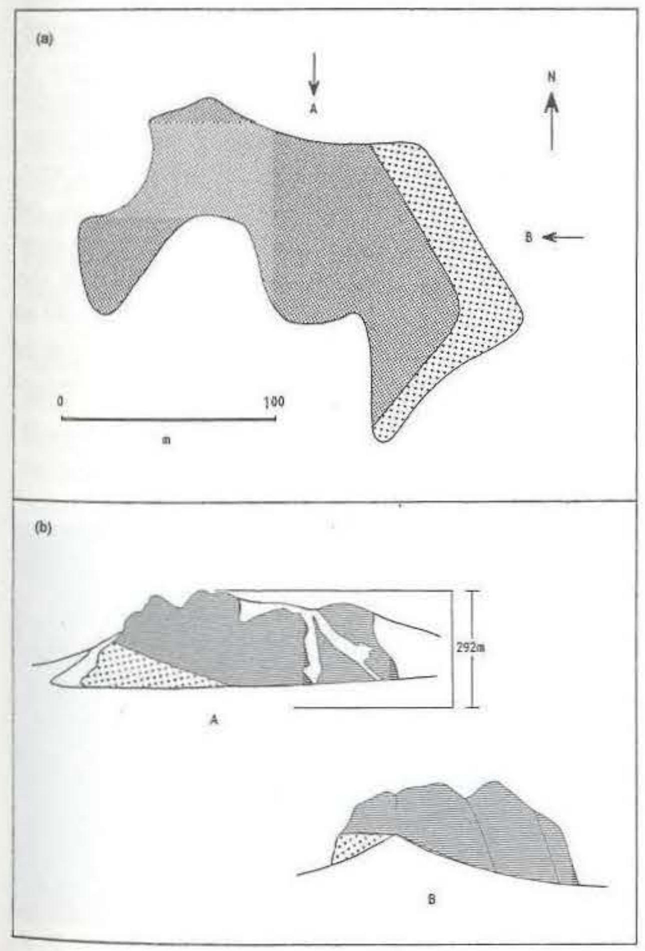

Fig 14. Plan and side views (A, northern and B, eastern) of Grunehogna, type locality of the Grunehogna Formation

Historical review: Aucamp (1972), Bredell (1976, 1982) and Wolmarans and Kent (1982) respectively described the Grunehogna Formation as follows: Aucamp as the Högfonna Formation, Bredell as the Borgmassivet Member and Wolmarans and Kent as the Grunehogna Member (Högfonna Formation).

Distribution and thickness: The Grunehogna Formation is exposed at Grunehogna (peak 1285) (192 m), Högfonna (272 m), Ovbratten (114 m), Ryvingen (210 m), Pilarryggen (12 m), Raudberget, Veten (107 m), Framryggen (68 m) and nunatak 1885 (75 m).

Lithology: The Grunehogna Formation, which comprises the part of the stratotype between 100 m and the top (292 m), predominantly consists of stacked, multi-lateral, multi-storied, tabular and trough cross-bedded sandstones, with scattered intraformational conglomerates, and subordinate ripple cross-laminated, wavy bedded and parallel bedded sandstones, and shale beds.

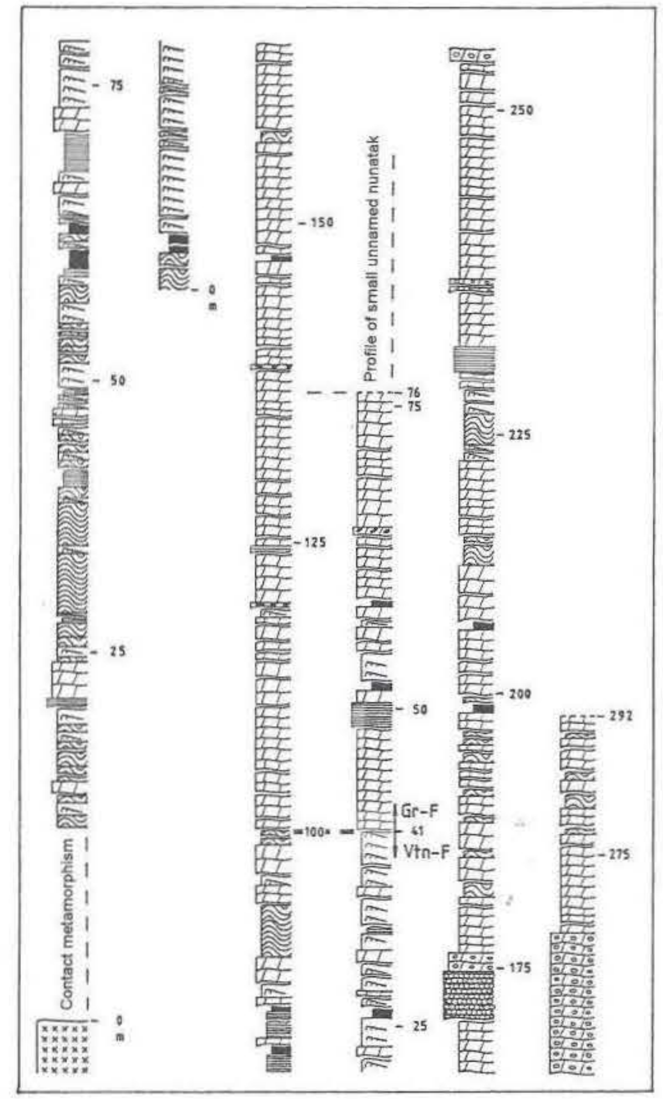

Fig 15. Stratigraphic section at Grunehogna (Peak 1 285) as well as the small unnamed nunatak immediately south-west of Grunehogna, viz the top of the Veten Formation and the stratotype of the Grunehogna Formation

The upper part of the formation, 170 m to 292 m of the stratotype, is characterised by two extraformational conglomeratic zones which will be described in more detail below. Isolated, tabular cross-bedded gritstone beds are present in the uppermost part of the succession overlying the upper conglomeratic zone (235 m plus), while some of the sandstones are characterised by scattered pebbles, as well as gritstone lenses and grains.

The thickness of the tabular and trough cross-bedded sandstones, which internally comprise multiple foreset beds, ranges between 0.40 m and 7.00 m. Beds are erosional at the base, and grade into ripple cross-laminated, wavy bedded and parallel bedded sandstones at the top, to form fining-upward facies cycles.

The ripple cross-laminated, wavy bedded and parallel bedded sandstones, which are scattered throughout the formation, are predominantly thin-bedded, ranging between 0.10 m and 0.40 m in thickness. Only in isolated cases have beds with a thickness of up to 1.0 m been found.

Intraformational conglomerates, with thicknesses of between 0.02 m and 0.45 m are widely scattered throughout the formation. They are present as channel lag deposits at the erosional base of the cross-bedded sandstones. The thicker beds are matrix-supported, with the matrix comprising sandy material. Clay clasts are also commonly present on the foreset beds of the cross-bedded sandstones.

The extraformational conglomerate beds in the upper part of the formation are mainly concentrated in two separate zones. The lower zone is about 70 m from the base of the formation (170 m from the base of the succession) at the stratotype at Grunehogna, and the upper zone at about 135 m (235 m from the base of the succession). The total thickness of the lower zone is 5.32 m and it consists of a single, matrix-supported, extraformational conglomerate bed, with a thickness of 3.85 m, which is overlain by pebbly, trough cross-bedded sandstones, while the upper zone comprises interbedded, thinly-bedded, extraformational conglomerate and pebbly, trough cross-bedded sandstone beds, with a total thickness of 6.40 m. The thickness of the extraformational conglomerate beds in this upper zone ranges between 0.05 m and 0.40 m. The extraformational clasts constituting both conglomerates comprise pebbles of sedimentary origin, which include quartz, quartzite, chert and jasper. Clasts are rounded, with diameters between 2 and 2.5 cm. Typical of both zones is the presence of gritstone lenses which are characterised by scattered jasper grains. The grain size of the cross-bedded sandstones increases from medium grained in the lower part of the formation, to medium to coarse grained in the upper, conglomeratic part.

The Grunehogna Formation is also exposed at the reference stratotype at Högfonna in the Borgmassivet, where it comprises the part of the succession between 47 m and the top (310 m). The succession correlates lithologically very well with the stratotype, although a much thicker sequence is exposed: 270 m against the stratotype's 192 m. Both conglomeratic zones are also present: the lower one, with a total thickness of 6.30 m, is situated about 200 m from the base of the formation, and the upper one, with a total thickness of 5.28 m, at about 270 m. These zones also consist of interbedded, extraformational conglomerates and pebbly, trough cross-bedded sandstones. The trough cross-bedded sandstones that overlie the upper conglomeratic zone are also characterised by isolated pebbles, as well as gritstone beds, lenses and grains, corresponding with the succession at the stratotype.

The lithofacies units at the stratotype and at the different reference stratotypes are present as sheet-like deposits, arranged to form fining-upward facies cycles. These cycles comprise erosive, tabular cross-bedded sandstones at the base, grading into wavy bedded and, to a lesser extent, ripple cross-laminated and parallel bedded sandstones. Channels that have been measured at frequent intervals at Högfonna exhibit a high width-to-depth ratio, with widths of up to 18 m, and depths of up to 1,2 m. Parting lineation, ripple marks and desiccation cracks are scattered throughout the formation, characterising the fine grained and shaly deposits.

Notable of the lower part of the formation at the reference stratotypes at Högfonna and Ryvingen, is the presence of a few closely-spaced, brick-red, fine grained beds, which are interbedded with the other deposits. At Högfonna they are approximately 162 m from the base of the formation (that is 209 m from the base of the succession), with a bed thickness of between 0.30 m and 0.70 m. These beds are of volcaniclastic origin as evidenced by numerous glass shards that can be recognised in thin section (Fig 16).

Fig 16. Photomicrograph of brick-red sandstone in the Grunehogna Formation at Högfonna, showing evidence of a pyroclastic origin in the shape of glass shards (X40)

Discussion of stratigraphic relationships

Previous uncertainties regarding the stratigraphic subdivision of the sedimentary succession west of the Pencksökket-Jutulstraumen tectonic boundary can be ascribed to several reasons:

1. The lack of marker horizons and disruption by faulting hampered correlation between isolated nunataks. Conglomeratic beds proved to be of some help in correlation, in spite of their repeated occurrence in the succession.
2. The limited stratigraphic thickness exposed at most localities, to such an extent that vertical lithofacies changes cannot be easily detected, prevent meaningful extrapolation from one locality to the next.
3. The Ahlmannryggen was more easily accessible to the earlier expeditions and most stratigraphic units were first studied there. However, an overall view of the stratigraphic relationships could only be obtained after studying the Borgmassivet as well.
4. Before the advent of helicopter transport, a large number of geologists participated in mapping the area. This inevitable fragmentary approach led to the definition of formations based on particular outcrops with which each geologist happened to be familiar, thus causing unavoidable duplication.
5. The lithofacies concept has an important bearing on correlation problems in non-fossiliferous sedimentary rocks. Procedures for conducting sedimentological studies and paleoenvironmental models based on this concept have only been developed in the last three decades. Earlier geologists did not have the full benefit of these methods.

The threefold lithostratigraphic subdivision of the Ahlmannryggen Group proposed here is based on measured sections of 21 localities representing the whole Borgmassivet area (cf Fig 6, 8, 15 and addenda), and reflects the lithofacies changes that have been recognised. A quantitative representation of the lithofacies changes is shown in Fig 17 and a correlation diagram based on these data is given in Fig 18.

The new proposal differs from earlier stratigraphic columns not only in recognising lithofacies change as a proper basis for subdivision, but by eliminating overlaps in the sixfold scheme of Wolmarans and Kent (1982) given below, thus necessitating new names for the three formations. The relations between the old and new nomenclature are briefly as follows (Fig 19):

Pyramiden Formation

The type area of the Pyramiden Formation, which is exposed at nunataks Pyramiden, Sphinksen and Knallen, is in the Ahlmannryggen, outside the study area. However, a short visit was paid to Pyramiden, the type locality of the Pyramiden Formation. It was found to consist of a coarsening-upward sequence, which may be correlated with the coarsening-upward Friis-Baastadnuten Formation. This opinion is supported by the fact that correlates of the overlying Veten Formation are found in the same vicinity. For instance, the conglomeratic base of the Veten Formation is exposed at Trioen, while the succession at Framryggen, some distance to the southeast, belongs to the upper and lower parts of the Veten and Grunehogna Formations respectively (cf Wolmarans & Kent 1982, Fig 15, 17).

The Pyramiden Formation is therefore most probably a duplication of the Friis-Baastadnuten Formation in the newly proposed subdivision. Friis-Baastadnuten is preferred as type locality because a thicker succession, as well as the upper contact with the Veten Formation, is exposed here.

Framryggen Formation

The sedimentary succession at Framryggen, type locality of the Framryggen Formation, is a fining-upward sequence (220 m), overlain by a coarse grained (74 m) unit. It correlates lithologically and petrographically with the upper part of the succession at Veten. The same conclusion is valid for the succession at nunatak 1885, which was proposed as a reference stratotype for the Framryggen Formation.

The Framryggen Formation is therefore a duplication of the Veten Member (Högfonna Formation) in the stratigraphic column of Wolmarans and Kent (1982), and of the upper part of the Veten Formation and base of the Grunehogna Formation in the new proposal. This locality is used as a reference stratotype for the Veten Formation.

Schumacherfjellet Formation

The strata at the base of Grunehogna (peak 1 285) in the Ahlmannryggen, *viz* the Schumacherfjellet Formation, is a fine grained sequence (100 m), which correlates well with the rocks exposed at the base of Högfonna and Ovbratten in the Borgmassivet, *viz* Wolmarans and Kent's (1982) Högfonnaksla Member. It is therefore a duplication of an existing formation. In the proposed subdivision, it is used as a reference stratotype for the upper part of the Veten Formation.

Högfonna Formation

Veten Member

The sedimentary rocks exposed at Veten (475 m), type locality of the existing Veten Member (Högfonna Formation), comprise the upper part of the newly proposed Friis-Baastadnuten Formation (56 m, reference stratotype), the Veten Formation (312 m, stratotype) and the lower part of the Grunehogna Formation (107 m, reference stratotype).

The upper part of the formation, 170 m to 292 m of the stratotype, is characterised by two extraformational conglomeratic zones which will be described in more detail below. Isolated, tabular cross-bedded gritstone beds are present in the uppermost part of the succession overlying the upper conglomeratic zone (235 m plus), while some of the sandstones are characterised by scattered pebbles, as well as gritstone lenses and grains.

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The Pyramiden Formation is therefore most probably a duplication of the Friis-Baastadnuten Formation in the newly proposed subdivision. Friis-Baastadnuten is preferred as type locality because a thicker succession, as well as the upper contact with the Veten Formation, is exposed here.

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The Framryggen Formation is therefore a duplication of the Veten Member (Högfonna Formation) in the stratigraphic column of Wolmarans and Kent (1982), and of the upper part of the Veten Formation and base of the Grunehogna Formation in the new proposal. This locality is used as a reference stratotype for the Veten Formation.

Schumacherfjellet Formation

The strata at the base of Grunehogna (peak 1 285) in the Ahlmannryggen, *viz* the Schumacherfjellet Formation, is a fine grained sequence (100 m), which correlates well with the rocks exposed at the base of Högfonna and Ovbratten in the Borgmassivet, *viz* Wolmarans and Kent's (1982) Högfonnaksla Member. It is therefore a duplication of an existing formation. In the proposed subdivision, it is used as a reference stratotype for the upper part of the Veten Formation.

Högfonna Formation

Veten Member

The sedimentary rocks exposed at Veten (475 m), type locality of the existing Veten Member (Högfonna Formation), comprise the upper part of the newly proposed Friis-Baastadnuten Formation (56 m, reference stratotype), the Veten Formation (312 m, stratotype) and the lower part of the Grunehogna Formation (107 m, reference stratotype).

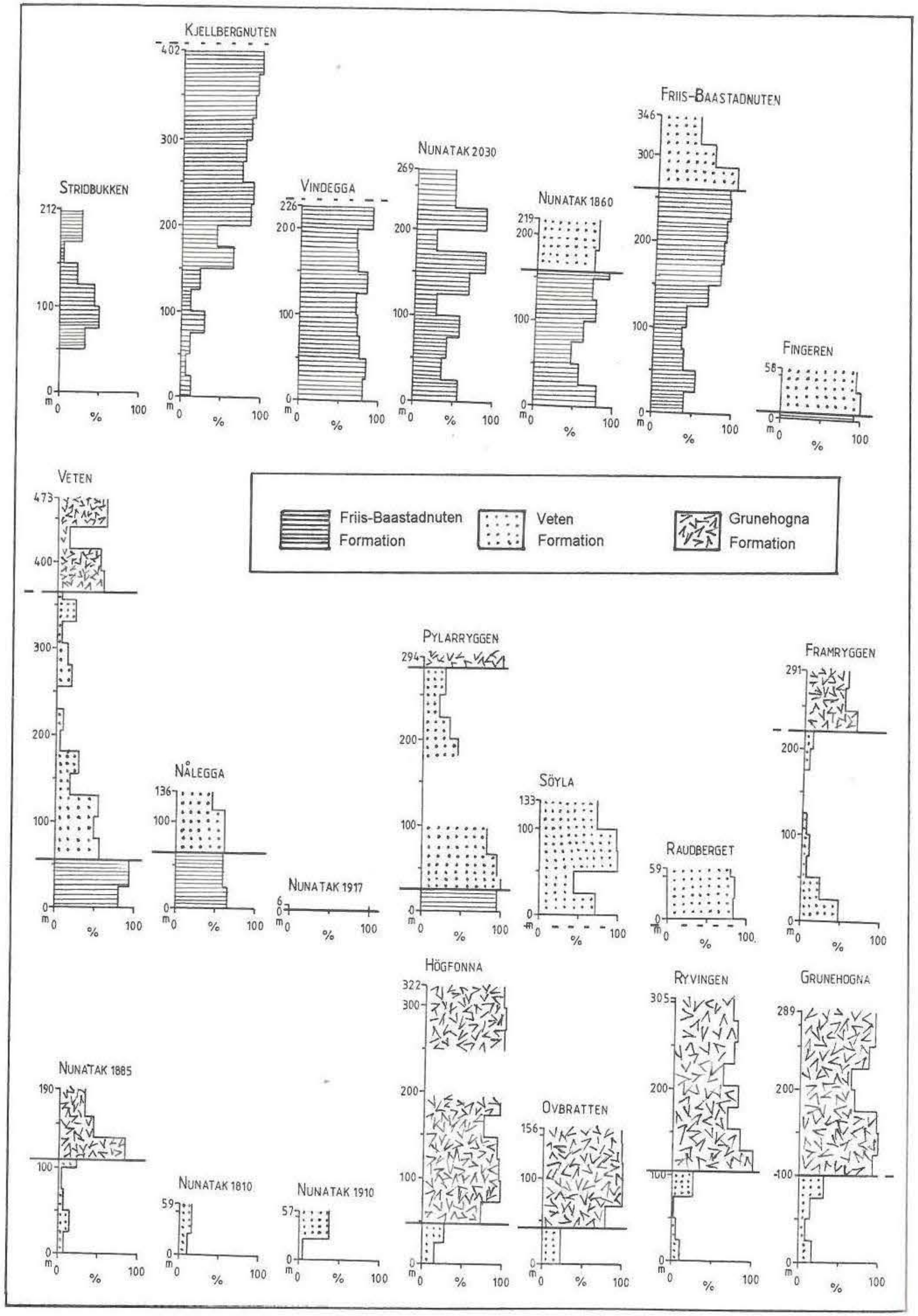

Fig 17. Percentages of coarse and medium grained lithotypes versus height in the measured stratigraphic sections (cf Fig 6, 8 15 and the addenda)

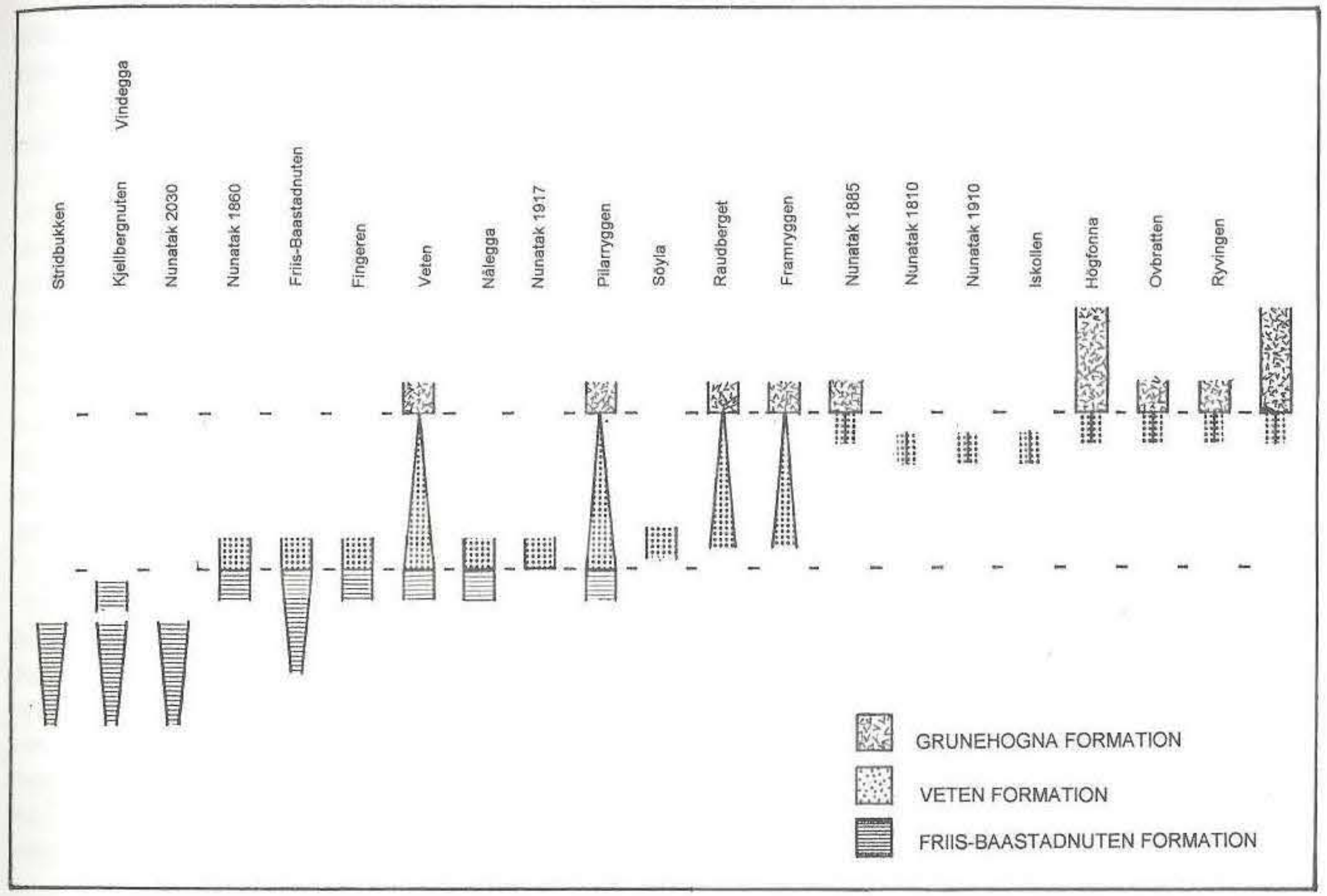

Fig 18. A summary of the correlation between the measured stratigraphic sections (stratotypes and reference stratotypes) in the Borgmassivet

Grunehogna and Högfonnaksla Members
The succession at Grunehogna (peak 1 285) in the Ahlmannryggen, namely the Grunehogna Member, is a correlate of the succession at Högfonna in the Borgmassivet, *viz* the Högfonnaksla Member. These two members therefore duplicate each other in the existing stratigraphic column.

The lower part of the succession at both Grunehogna and Högfonna consists of fine grained sequences, and therefore correlates with the upper part of the Veten Formation. The upper part of the succession at Grunehogna is defined in this paper as the Grunehogna Formation, while the upper part of the Högfonna succession is used as a reference stratotype for the Grunehogna Formation.

Jekselen Formation

The Jekselen Formation, with type locality at Jekselen outside the study area, crops out only in the Ahlmannryggen, and comprises a sedimentary unit of approximately 80 m occurring as a massive inclusion in an intrusion. Visual inspection of the succession during a short visit by the author, revealed the presence of two conglomeratic horizons; on this rather limited information, the most likely correlation appears to be with the Grunehogna Formation.

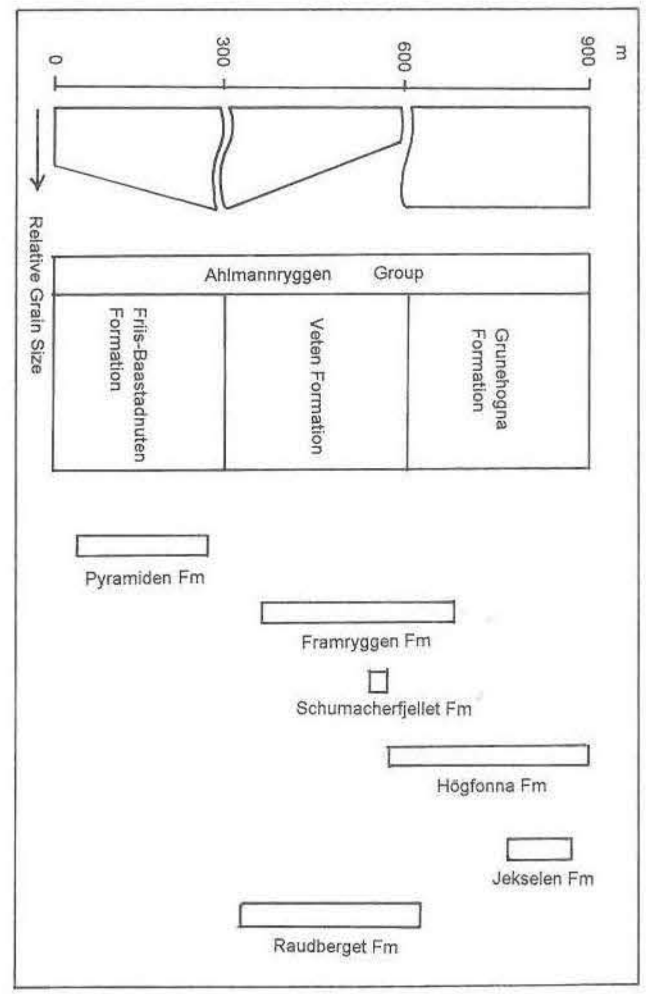

Fig 19. Relation between the proposed stratigraphic subdivision and the six previous formations of Wolmarans and Kent (1982)

Raudberget Formation

The sedimentary rocks exposed at Raudberget, type locality of the Raudberget Formation, are so weathered that it cannot be used as a type locality. It is, however, clear that the succession consists of a fining-upward sequence, which is overlain by a coarse grained unit. It therefore may comprise the upper part of the Veten Formation and the base of the Grunehogna Formation. Mapping of the lower part of the succession showed the presence of pebbly, tabular cross-bedded sandstones at the base, which the author believes to be part of the conglomeratic base of the Veten Formation. This strengthens the argument for the succession to be a correlate of the Veten Formation.

Structure

Correlation between isolated nunataks in the Borgmassivet would have been difficult without taking into account the effects of block-faulting. The two prominent north-east-trending valleys, the Raudbergdalen and Frostlendet, are parallel and structurally related to the Pencksökket-Jutulstraumen rift which, in a Gondwana context, has been interpreted as a continuation of structures associated with the western limb of the East African rift (Grantham & Hunter 1991). The vertical displacement of the sedimentary succession on either side of these valleys indicates that they are major fault lines (Fig 20).

Less prominent is a series of faults in the northern part of the Borgmassivet, north-west of the Raudbergdalen, where the stratigraphic successions exposed at different outcrops, namely Framryggen, nunatak 1 885, Veten, Fingeren, Nålegga and Raudberget can be correlated successfully with one another as a result of the constant dip of less than 10° to the south-east. A fault, or series of faults, is also present in the southern part of the Borgmassivet, between the Frostlendet and the Pencksökket, where the strata at Kjellbergnuten and Stridbukken can be correlated with the succession at Friis-Baastadnuten, in spite of the southerly dip of more than 25° at both localities.

The bedding of the sedimentary succession is, in general, subhorizontal with a dip of less than 10° over most of the area. Between the Raudbergdalen and the Frostlendet, however, an open synclinal structure is present. In the southern part of the Borgmassivet, between the Frostlendet and Pencksökket, the dip increases: at Möteplassen, Vindegga and Huldresslottet it is 35° to 40° to the south-east, while another open synclinal structure occurs at Friis-Baastadnuten and Ryvingen.

From the above it is clear that the main structural development of the Borgmassivet is dominated by north-easterly, block-like displacements parallel to the Pencksökket, while numerous faults with small scale displacements, many of which remain undetected as a consequence of the snow cover, are present within each block. The question whether there is a temporal relationship between the major and minor faults has been discussed by Krynauw *et al* (1991). Tectonic activity probably reached its highest level closest to the Pencksökket-Jutulstraumen rift, resulting in greater distortion of the bedding closer to it.

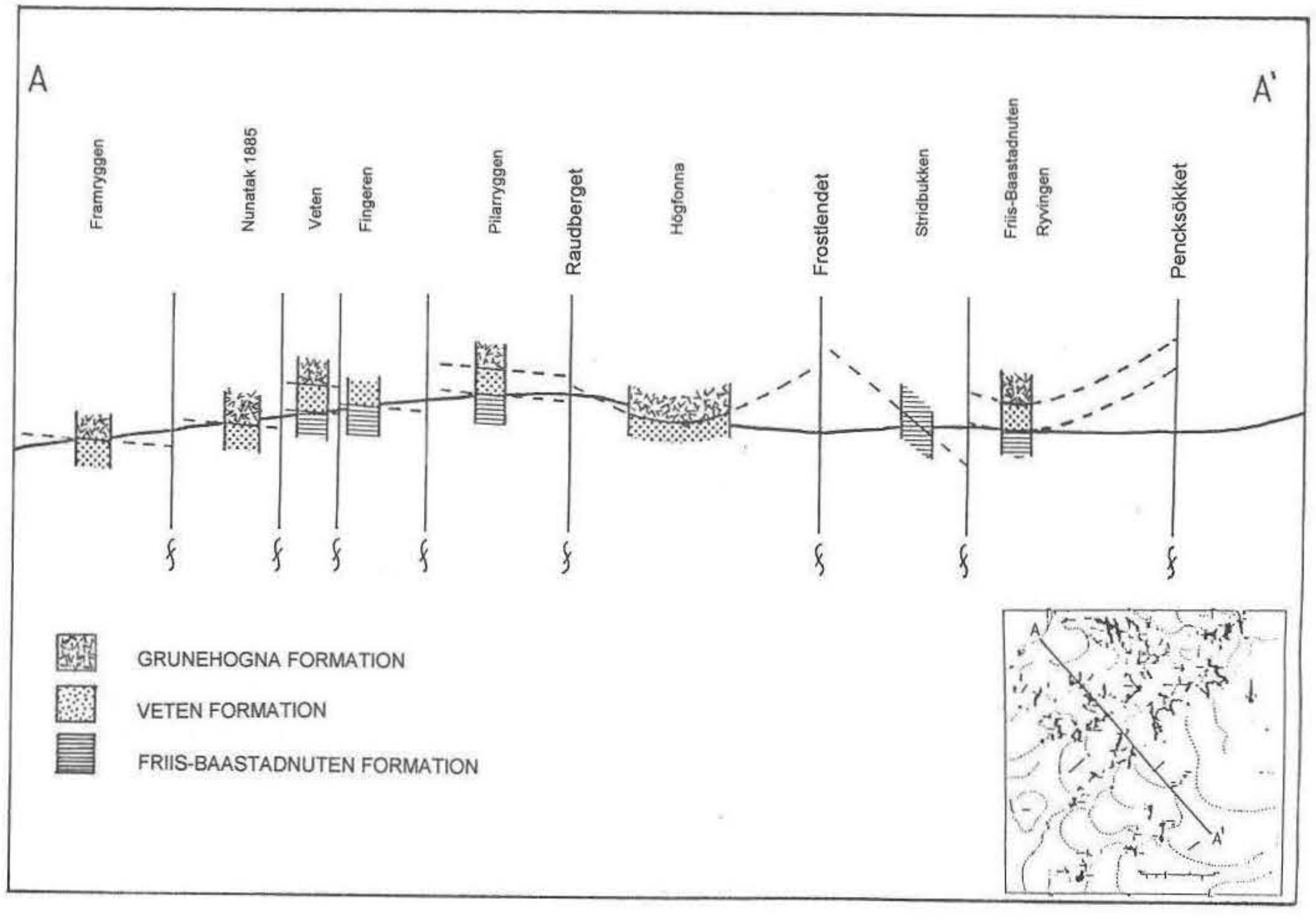

Fig 20. Schematic northwest-southeast section through the Borgmassivet to show flexuring and faulting of the Ahlmannryggen Group

Palaeographic reconstruction

The 21 vertical sections that were measured primarily in order to sort out the stratigraphy of the Ahlmannryggen Group, can be interpreted to reconstruct the depositional conditions and environments of the strata in the form of a facies model. Miall (1985) criticised this approach and proposed a new method of analysis for fluvial deposits *viz* architectural element analysis which emphasizes the three-dimensional geometry of facies assemblages. He admitted, however, that the vertical profile method will probably continue to be used and will continue to have the same kind of predictive value, particularly where only exploration bore-holes (Fielding 1993) or widely spaced cross-sections (as in the Borgmassivet) are available. Caution has also been expressed against the uncritical application of a preconceived facies model that could lead to selective observations in the field (Collinson 1986). In the Borgmassivet it was seldom possible to observe the shape of palaeochannels, bars, flood basins or other sand bodies in all three dimensions and a simple model will therefore have to suffice.

Depositional model

The lithological composition, primary sedimentary structures, lithofacies types (Fig 3) and their arrangement into fining-upward facies cycles leave little doubt that the sediments of the Ahlmannryggen Group were deposited in a fluvial environment. Many lithofacies correspond closely to the types that have been identified in modern braided river deposits (Miall 1977, 1978).

In general a fluvial environment (Fig 21) comprises four gradational subenvironments, each of which is characterised by its own distinctive facies model. Depending on tectonic and/or climatological conditions, all four subenvironments, or only some, could be present in a specific fluvial system. The lithological compositions associated with the subenvironments is a function of progressive sorting which, in turn, is a function of slope. The subenvironments comprise the following:

1. Source area-associated, alluvial fan subenvironment: stacked, massive to poorly bedded, extraformational conglomerates;
2. Upper pebbly, braided stream subenvironment: interbedded, poorly to well bedded, extraformational conglomerates, gritstones and coarse grained sandstones;
3. Middle sandy, braided stream subenvironment: bedded sandstones, with subordinate interbedded extraformational conglomerates, siltstones, shales and mudstones; and
4. Lower meandering stream subenvironment: siltstones, shales and mudstones, with subordinate interbedded sandstone beds.

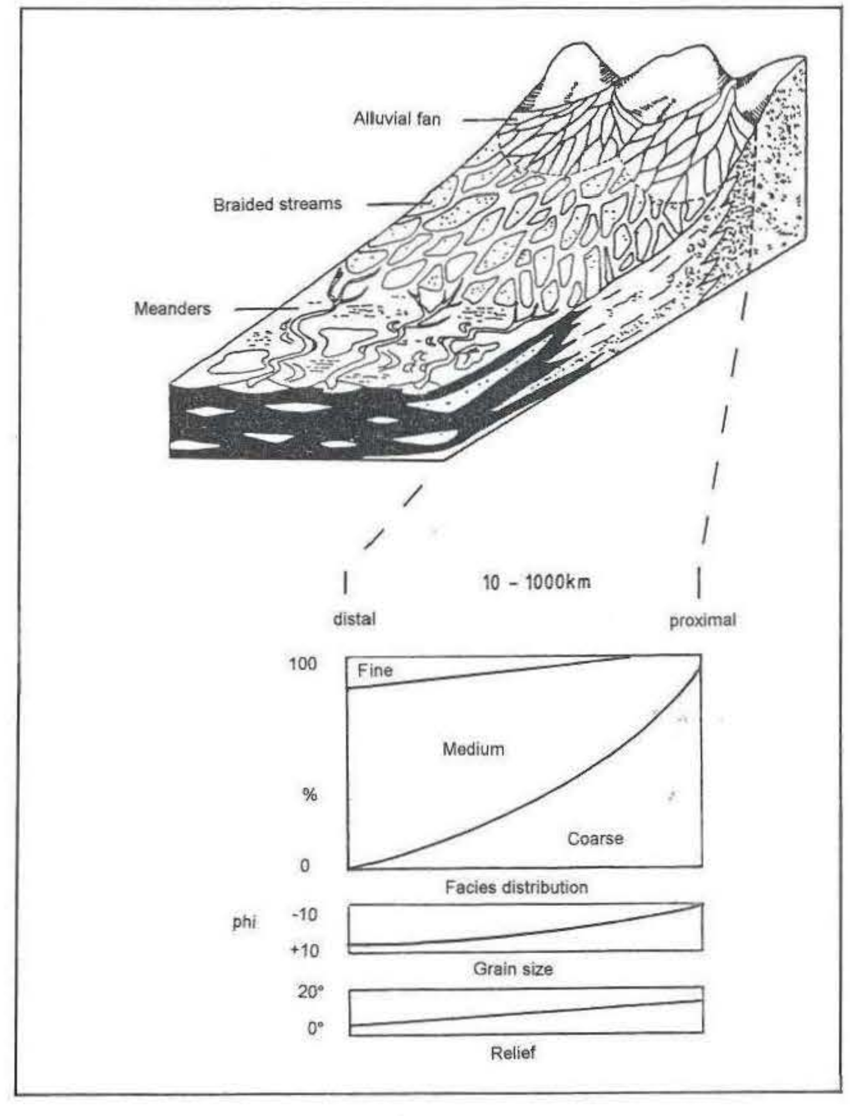

Fig 21. Fluvial depositional model for the Ahlmannryggen Group (cf Selley 1976, Hobday & von Brunn 1979)

The lateral distribution of the subenvironments is also a function of slope; a steep gradient will be characterised by a wide distribution and a low gradient by a limited one. Changes in slope will result in the forward (basinward), or backward (sourceward) migration of the complete fluvial depositional system, coupled with a lateral lithofacies change. These changes could be sudden or gradual, resulting in a sudden or gradual, secondary lithofacies change. Tectonism, that could either be associated with the source area or the depositional basin, is the most important control mechanism of slope. Therefore, unless intense variations of climate are postulated, major vertical lithofacies changes (like those on which the new stratigraphic subdivision of the Ahlmannryggen Group was based) can be ascribed to syn-depositional tectonic activity.

Application of the model

The lithofacies types at the base of the coarsening-upward Friis-Baastadnuten Formation, namely alternating tabular cross-bedded, ripple cross-laminated, wavy bedded and parallel bedded (lower flow regime) sandstones, with isolated shale beds, indicate that deposition took place between the middle, sandy braided stream and lower, meandering stream subenvironments. From the subordinate occurrence of tabular cross-bedded sandstones it is deduced that braiding had already ceased, although meandering had not yet started, in view of the absence of any prominent shale beds. The sandy character of the deposits, however, indicates that deposition most probably took place at the lower end of the middle, sandy, braided stream subenvironment.

The bulk of the deposits, namely ripple cross-laminated, wavy bedded and parallel bedded (lower flow regime) sandstones, are floodplain deposits. This indicates that the floodplain had been continuously supplied with fine grained material, which was reworked by weak currents. Isolated shallow, stagnant water bodies were also present on the floodplain, as indicated by the local presence of shale beds, which resulted from suspension fall-out. The presence of mudcracks indicates that the surface of the floodplain was frequently subjected to subaerial exposure, during which the cohesive materials underwent shrinkage upon loss of water.

The scattered, tabular cross-bedded sandstones show that isolated streams periodically flowed across the floodplain. Bed thickness, which varies between 0.18 and 1.20 m, proves that they were shallow, and probably represent the downstream extensions of large rivers. Some of the cross-bedded sets could also have originated during flooding of the floodplain. However, the absence of prominent channel deposits at the base of the Friis-Baastadnuten Formation calls the existence of a meandering stream environment downstream from the base of the formation into question. Thickly bedded tabular cross-bedded sandstones, representing large channel fills would be expected to be present to allow a sufficient volume of water through to such an environment, if it existed. It is concluded that the base of the Friis-Baastadnuten Formation could have been deposited within a depositional basin of limited extent, probably a local depression on a larger, undulating floor.

The upper part of the Friis-Baastadnuten Formation, which comprises stacked, multi-lateral, multi-storied, large to medium scale, tabular and trough cross-bedded sandstones, with subordinate interbedded, wavy bedded beds, suggests that the succession underwent a major lithofacies change between the base of the formation and its upper part. According to the fluvial model adopted here, the upper part would have been deposited in the middle sandy, braided stream subenvironment, which suggests that the lithofacies change resulted from a change in depositional environment. The multi-lateral, multi-storied tabular and trough cross-bedded sandstones, which are characterised by multiple internal scoured surfaces, show that the flood basin was characterised by multi-channel (braided), bedload rivers, which comprised an extensive network of fast-flowing, erosive streams, continuously sweeping across it. The subordinate, interbedded wavy bedded sandstones are floodplain deposits, which were deposited in the interchannel areas as overbank deposits. The high sediment load, which is characteristic of braided streams, resulted in a high depositional rate. Deposition took place within the channels as side and mid-channel bars, and choking resulted in the generation of new channels around existing bars. This repeated bar formation and channel branching were the mechanisms that caused the braid-pattern. Erosion of the floodplain which, as already mentioned, was severe as a result of high stream velocity, was further intensified by the absence of plant-cover during the Precambrian.

The above-mentioned lithofacies change that characterises the Friis-Baastadnuten Formation, can best be ascribed to tectonism and it can be assumed that gradual uplift of the source area, or subsidence of the depositional basin occurred, which resulted in progressive increase in the gradient of the palaeoslope throughout the depositional phase with the consequent gradual basinward progradation of the fluvial system. The depositional environment therefore changed from the lower end of the middle sandy braided stream subenvironment at the base, to the middle of the same environment in the upper part of the formation. In view of the progressive upward increase in the presence and prominence of the cross-bedded sandstones this change was gradual.

On the floodplain the upward increase in the gradient of the palaeoslope resulted in an increase of stream velocity and, consequently, of erosion. The nature of the streams therefore gradually changed to braiding, which explains the progressive increase in the presence and prominence of channel deposits, of which the tabular cross-bedded sandstones are the product, higher up in the formation. At the same time, there was a decrease in interchannel deposits, of which the ripple cross-laminated, wavy bedded and paralled bedded (lower flow regime) sandstones and shale beds are the products.

The build-up of tectonic activity that presumably occurred throughout the deposition of the Friis-Baastadnuten Formation reached a climax with the deposition of the conglomeratic base of the Veten Formation. Cobble to pebble size extraformational conglomerates, intraformational conglomerates, tabular cross-bedded gritstones and tabular and trough cross-bedded sandstones were deposited, with the latter often characterised by scattered pebbles, gritstone lenses and grit-size grains. According to the fluvial model, deposition took place in the upper part of the middle sandy, braided stream subenvironment. Extraformational conglomerates accumulated within the channels as sheet-like gravel bars, due to streams losing their transport capacity as a result of a decrease in stream velocity. Both channel widening and an uneven floor could have been reasons for this decrease. The intraformational conglomerates that are present, were most probably generated by the washing out and eventual collapse of channel sides, or by the erosion of the muddy channel floor. Dune migration within wide, shallow channels resulted in the deposition of the large to medium scale, tabular to trough cross-bedded sandstones. The pebbly nature of some of the beds indicates that recycling of the underlying extraformational conglomerates took place.

Multiple fining-upward facies cycles, which in general comprise a basal tabular cross-bedded sandstone, grading into ripple cross-laminated, wavy bedded and parallel bedded (lower flow regime) sandstones, and shale beds, overlie the conglomeratic base of the Veten Formation. This indicates that migrating rivers continued to comb the floodplain after the deposition of the conglomeratic beds. The sandstones above the basal unit and the shale beds suggest that the erosional capability of the rivers had already started to diminish.

The noticeable differences between the lower part of the Veten Formation at Veten (stratotype) and Pilarryggen (reference stratotype) was mentioned during the description of the lithology of the Veten Formation. These differences include the following: the maximum thickness for an extraformational conglomerate bed in the Borgmassivet, namely 2.70 m, is reached at Pilarryggen. It is also the only place where the conglomerate beds are characterised by cobble-size clasts. Furthermore, the conglomeratic base is not directly overlain by fining-upward facies cycles as at Veten, but by a multi-lateral, multi-storied trough cross-bedded sandstone sequence, with a cumulative thickness of at least 46 m. It is inferred that the succession at Pilarryggen was deposited close to the lowest point of the floodplain, which would explain the evidence of slightly higher energy conditions. The high width (18.0 m) to depth (1.20 m) ratio of the multi-lateral, multi-storied channels that were measured at Pilarryggen, confirms the braided stream origin of the deposits in the lower part of the formation.

According to the fluvial model, the upper part of the Veten Formation, which comprises prominent shale beds with subordinate tabular cross-bedded, ripple cross-laminated, wavy bedded and parallel bedded sandstones is typical of the lower, meandering stream subenvironment. Large, stagnant water bodies must have been present on the floodplain, resulting in the prominent shale beds formed by suspended sediment fall-out. Shallow drainage channels further characterised the floodplain, leading to the deposition of the subordinate tabular cross-bedded sandstone beds, while the thin, interbedded ripple cross-laminated, wavy bedded and parallel bedded sandstones, which are fine-grained, can be interpreted as crevasse splay deposits. The prominent, large to medium scale, tabular cross-bedded sandstones, which are also present in the upper part of the formation, grading into ripple cross-laminated, wavy bedded and parallel bedded sandstones, are typical point bar deposits, originating from the slow migration of meanders across the floodplain. The thickness of these beds, which varies between 2.50 m and 5.30 m, is an indication of the magnitude of the meanders. Stream velocity within these channels was slow, as a result of the characteristic low gradient of a meandering stream environment. This reduced the rate of erosion, which was further reduced by the cohesiveness of the shaly bank material. Ripple marks in the fine grained deposits in the upper part of the formation point towards shallow water movement on the floodplain, while the mudcracks and raindrop imprints are evidence of subaerial exposure.

The progressive lithofacies change from the base of the Veten Formation (which is conglomeratic) to the lower part (which mainly comprises fining-upward facies cycles) to the upper part (which is predominantly shaly) can be ascribed to the waning of tectonic activity. However, denudational processes in the source area and infilling of the depositional basin continued, with the former resulting in the progressive lowering of the source area. Continuation of this process resulted in a decrease in the gradient of the palaeoslope, with the result that the fluvial environment slowly became more distal higher up in the formation. Depositional conditions therefore changed during deposition of the formation from the upper part of the middle sandy, braided stream subenvironment at the base, to the lower, meandering stream subenvironment in the upper part of the formation.

The lithological composition of the Grunehogna Formation, which comprises multi-lateral, multi-storied tabular to trough cross-bedded sandstones, with subordinate ripple cross-laminated, wavy bedded and parallel bedded (lower flow regime) sandstones and shale beds, indicates a complete lithofacies change, since the underlying beds are predominantly shaly. The flúvial model suggests that the Grunehogna Formation was deposited in the middle sandy, braided stream subenvironment, which is a radical departure from the inferred meandering stream subenvironment of the upper part of the Veten Formation. The erosive base of the formation and the lithofacies change both indicate that renewed, vigorous tectonic uplift of the source area or subsidence of the depositional basin had occurred, which resulted in basinward migration (progradation) of the fluvial system.

The multi-lateral, multi-storied nature of the tabular and trough cross-bedded sandstones, which make up the bulk of the Formation, indicates that the floodplain was characterised by multi-channel (braided) bedload rivers, which comprised an extensive network of fast-flowing, erosive streams, that continuously swept across the plain. The cross-bedded sandstone beds could have originated as a result of dune migration within wide, shallow channels. The subordinate ripple cross-laminated, wavy bedded and parallel bedded sandstones and shale beds were deposited within the channels during low water stages, or in the inter-channel areas as overbank deposits.

The two conglomeratic horizons in the upper part of the formation suggest temporary revivals of tectonic activity, or they could be due to stormflood events. The beds were deposited as sheet-like gravel bars in the upper part of the middle sandy, braided stream environment. The pebbly nature of the overlying cross-bedded sandstones shows that the conglomerate beds were reworked by the migrating rivers. The high width (20.0 m) to depth (1.20 m) ratio of the channels measured at Högfonna and Ovbratten further supports the idea of a braided stream origin of the deposits.

The relatively uniform composition of the deposits throughout the Grunehogna Formation can be ascribed to predominant tectonic stability or very slow uplift with the result that the gradient of the palaeoslope was maintained, in spite of the denudation of the source area and the infilling of the depositional basin.

The depositional environments of the whole Ahlmannryggen Group is summarised in Fig 22.

Provenance

The sandstones of the Ahlmannryggen Group can be defined as arenitic, with a strong tendency towards wacke, due to a significant matrix content (Pettijohn *et al* 1972). The three formations have variable lithological compositions that can be summarised as follows:

Friis-Baastadnuten Formation: sublithic-arkosic in the lower part, changing to tuffaceous, sublithic-arkosic to tuffaceous lithic-arkosic at the top.

Veten Formation: lithic to tuffaceous lithic-arkosic at the base, changing to sublithic-arkosic to subarkosic in the upper part.

Grunehogna Formation: tuffaceous sublithic-arkosic at the base, changing to lithic to tuffaceous lithic-arkosic in the upper part.

Arkosic sandstones therefore predominate, but with a subordinate lithic component, mainly within the conglomeratic units *viz* the base of the Veten Formation and the upper part of the Grunehogna Formation. These lithic components are partly tuffaceous, as evidenced by the presence of volcanic clasts.

The same source areas were operative throughout the deposition of the Group. They appear to have included plutonic, sedimentary, metamorphic and volcanic

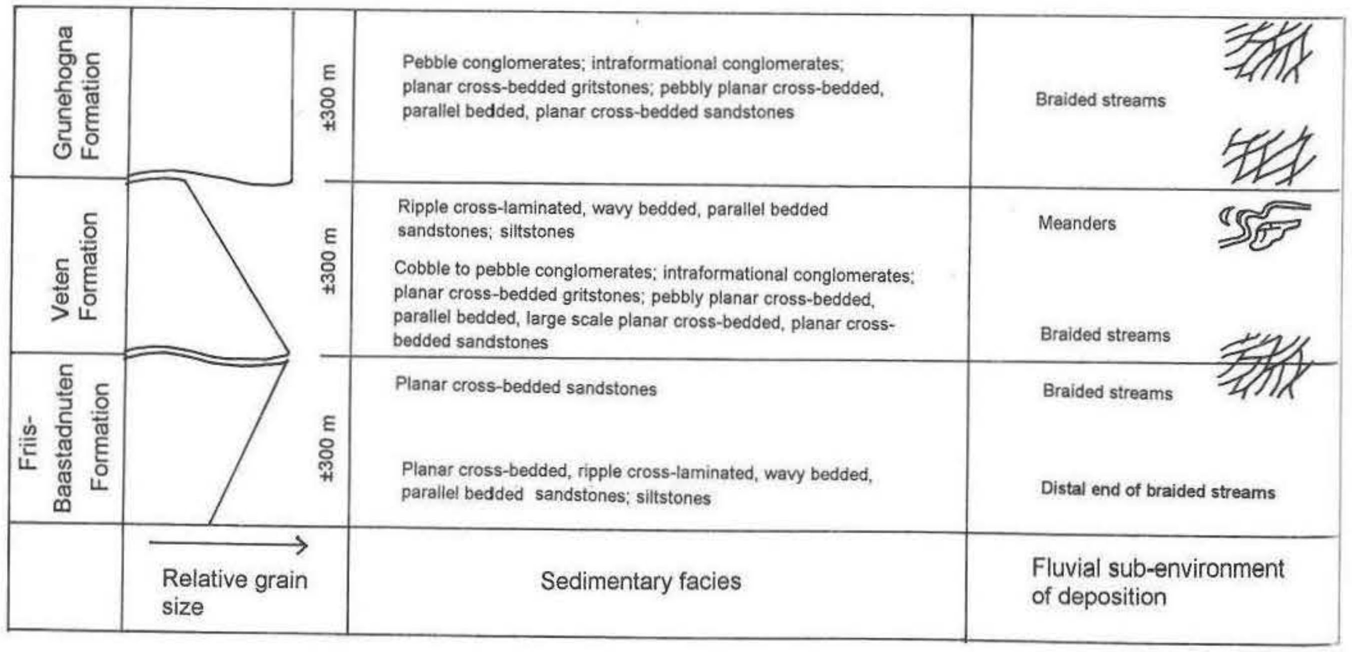

Fig 22. Summary of the lithofacies associations and depositional environments of the Ahlmannryggen Group

(including volcanically active) areas:

1. The quartz-arkosic composition of the sandstones indicates that a granitic source was the most important. It is, however, necessary to consider that the products of a plutonic source, namely quartz and feldspar, are far more competent to survive the rigorous conditions of a long transport distance in a fluvial environment, than the less prominent lithic fragments. Additional petrographic evidence in favour of a granitic source (Pittman 1970) are the following: many quartz grains have inclusions such as needle-like rutile; Na-rich feldspar (oligoclase) is present; microcline and quartz grains exhibit a micrographic texture, and pinkish detrital zircon is abundant.
2. The sedimentary provenance consisted in part of a carbonate-banded ironstone formation as evidenced by the vein quartz, chert and jasper pebbles and grains.
3. Detrital clasts of quartz-sericite and, to a lesser extent, quartz-chlorite and quartz-biotite schist, are an indication of the presence of a regionally metamorphosed source.
4. Clasts of volcanic origin exhibit feldspar microlites with a trachytic texture embedded in a black, glassy groundmass and are undoubtedly derived from lavas.
5. The brick-red, fine grained sedimentary beds that are present in the Grunehogna Formation contain glassy shards, indicating that they are of pyroclastic or volcaniclastic origin.

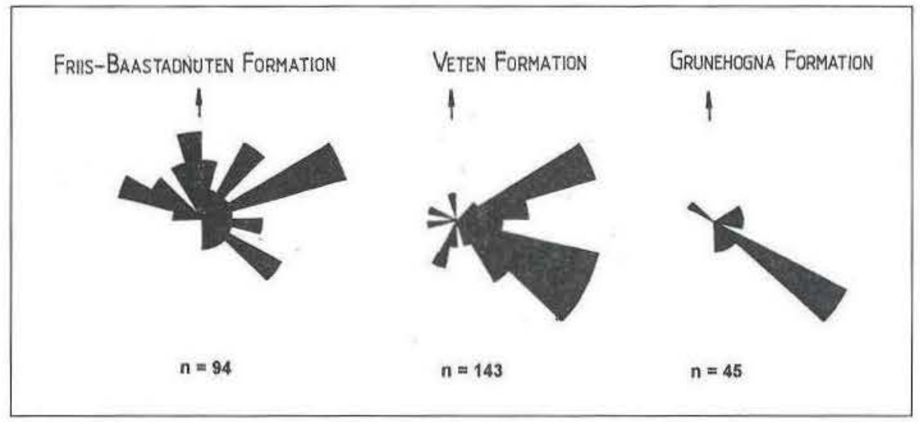

Fig 23. Rose diagrams of tabular and trough cross-bedding directions, showing a clockwise migration of the palaeostreams from bottom to top in the Ahlmannryggen Group

The degree of mineralogical maturity of the deposits, as reflected by the relative proportions of these products, fluctuated in context with the environment of deposition which, in turn, was tectonically controlled. Due to limited reworking the braided stream sandstones are relatively less mature, i e they comprise more unstable clasts such as feldspar and lithic fragments than the sandstones of the meandering streams. The lithic fragments are the least resistant against abrasion.

The red pigmentation of the deposits was microscopically found to be related to the sandstone matrix and the shale beds, where authigenic hematite is present as finely dispersed opaque specks. The hematite probably originated through diagenetic alteration of iron-bearing detrital silicate and oxide minerals (Walker 1967). Microscopic study also showed that some of the detrital clasts have a ferruginous coating, indicating that an oxidising atmosphere existed at the time of deposition of the Ahlmannryggen Group.

Palaeocurrent data normally provide the best information about direction of transport and possible location of provenance terrain. Unfortunately, nunataks typically exhibit vertical faces so that three-dimensional observations on cross-bedded sandstones were limited and in many cases only apparent palaeostream directions could be obtained. Nevertheless, the measurement of numerous tabular and trough cross-bedding dip directions lead to the conclusion that the general palaeostream direction of the Ahlmannryggen Group shifted progressively clockwise from the base of the succession to the top, *viz* from east- northeast for the Friis-Baastadnuten Formation, to east for the Veten Formation and, finally, east-southeast for the Grunehogna Formation (Fig 23). This directional shift can be ascribed to laterally uneven uplift of the source area or tilting (angular subsidence) of the depositional basin, which resulted in a progressive, lateral change in gradient and, consequently a shift in the stream direction.

The palaeostream information shows that the source area for the Ahlmannryggen Group was probably situated west of the Borgmassivet. The only outcrops in that direction are in Coats Land and consist of much younger rock formations than those of the Ahlmannryggen Group. Therefore, and from the advanced stage of rounding of the extraformational conglomerate clasts, it may be inferred that the source area was most probably situated further away than the present-day coastline of Coats Land. Possible source areas must be sought outside the Antarctic continent.

Gondwana perspective

Modern predrift Gondwana reconstructions, whether primarily based on oceanographic or continental data, all agree in placing Dronning Maud Land adjacent to the Mozambique coast (Martin & Hartnady 1986, Lawver & Scotese 1987, De Wit *et al* 1988, Groenewald *et al* 1991, Dalziel 1992), the various reassemblies differing mainly in tightness of fit. Correlates as well as source areas of the Ahlmannryggen Group could therefore be situated in present-day South Africa, Botswana, Zimbabwe, Zambia and Mozambique. Suitable plutonic, sedimentary, metamorphic and volcanic formations of Precambrian age are known in these countries. The source of contemporaneous volcanism to explain the volcaniclastic beds in the Grunehogna Formation is more problematic, but pyroclastic fragments could have been wind-borne from another direction. The volcanic activity may have been a precursor of the extensive lava flows that characterise the uppermost unit of the Ritscherflya Supergroup *viz* the Straumsnutane Formation occurring 50 km NNE of the Borgmassivet (Wolmarans & Kent 1982).

Mid-Proterozoic rocks in southern Africa that have been considered to be approximate chronostratigraphic equivalents of the Ritscherflya Supergroup are the Umkondo, Waterberg, Soutpansberg Koras and Volop Groups and the Ntingwe Formation (Groenewald *et al* 1991, Moyes *et al* 1995), all of which contain fluvial to shallow marine sediments with a red colour. The Soutpansberg and Umkondo Groups have tholeiitic volcanic rocks as well. Tankard *et al* (1982) describe all of them as continental successions deposited in structurally controlled basins or troughs.

The Umkondo Group (total thickness ± 1 730 m) is the one that was probably deposited in closest proximity to the Ahlmannryggen Group (± 900 m) and a correlation between the two has been suggested by Ferreira (1986a, 1986b) and Swanepoel (1988) on lithostratigraphic and sedimentological grounds. This correlation is strengthened by recent geochronological results. Allsopp *et al* (1989) provided a well-constrained Rb-Sr age of 1 080 + 140 - 25 Ma for the Umkondo Group. A similar age of 1 080 Ma was obtained by Moyes *et al* (1995) for the deposition of the Högfonna (i e Grunehogna) Formation. According to the best isotopic evidence the Waterberg, Soutpansberg and Matsap Groups are 670 to 945 m y and the Koras Group 100 m y older (Moyes *et al* 1995).

The question remains whether the Ahlmannryggen and Umkondo Groups, separated by a distance of roughly 1 000 km according to Martin and Hartnady's (1986) reconstruction, could have been deposited in the same basin. The generalised lithostratigraphic profiles of the two groups are therefore compared in Fig 24.

It is clear from these profiles that the two groups are characterised by somewhat similar facies changes. Both contain a basal coarsening-upward sequence, followed by one that is fining-upward and topped by one that is coarse grained. In more detail (Button 1977) the Umkondo Group comprises, from bottom to top, the following units:

1. *Calcareous Unit*: dolomites, limestones, calcareous hornfels and red siltstone, deposited in a tidal flat-lacustrine environment.
2. *Lower Argillaceous Unit*: horizontally laminated shale with thin arenite lenses in the upper part, which is the product of shallow shelf processes.
3. *Quartzitic Unit*: multi-lateral, multi-storied channel arkoses, interpreted as the product of a prograding fan delta.
4. *Upper Argillaceous Unit*: fining-upward point bar cycles imbedded in a mudstone matrix, deposited in a meandering stream environment.
5. *Arkosic Unit*: arkosic sandstones, deposited in a braided stream environment.

The upper parts of the Umkondo and Ahlmannryggen Groups correlate fairly well as far as lithological composition and depositional environment is concerned: the Quartzitic Unit of the Umkondo Group is similar to the upper part of the Friis-Baastadnuten Formation plus the lower part of the Veten Formation, the Upper Argillaceous Unit to the upper part of the Veten Formation, and the Arkosic Unit to the Grunehogna Formation.

On the other hand, the basal parts of the two sequences, namely the Calcareous and Lower Argillaceous Units of the Umkondo Group and the lower part of the Friis-Baastadnuten Formation, differ markedly in lithological composition. Both are low energy deposits, with those of the Umkondo Group more calcareous and shaly than those of the Friis-Baastadnuten Formation. A possible explanation for this difference is that the basal parts of both Groups were deposited in separate depressions within the same basin, and that only after these initial depressions had been filled, were the upper parts subjected to similar depositional conditions.

The resemblance in lithofacies change between the two groups can be ascribed to related tectonic activity, and it is concluded that they were most probably deposited in the same basin, but laterally separated from each other. They probably had a common source area to the east. The possibility of defining the Ahlmannryggen Group as the distal facies of the Umkondo Group was therefore considered, but rejected because of the absence of extraformational conglomerates in the Umkondo Group, which was situated closer to the source area.

According to Tankard *et al* (1982) the Waterberg, Soutpansberg and Umkondo Groups were all deposited in east-northeast-trending fault-bounded troughs and are also extensively displaced by post-depositional faults. Unfortunately due to the extensive snow and ice cover in Dronning Maud Land, it is not possible to tell to what extent the deposition of the Ahlmannryggen Group had been structurally controlled, and whether the lineaments are of pre- or post-depositional age. But prominent structural lineaments like these can generally be related to linear weaknesses in the earth's crust and are likely to be long-lived. Their existence is in accordance with the syndepositional tectonic activity inferred from the changes in lithofacies.

In conclusion, it is clear that several intracratonic basins or aulacogens developed in this part of Gondwana during the mid-Proterozoic, probably just before the onset of the Kibaran orogenesis (Groenewald *et al* 1991). The palaeocontinent had an uneven topography, comprising a highland which was drained by multiple rivers, and a lowland, or series of depositional basins. Weathering of the highland, which acted as source, was severe due to the absence of vegetation. Faulting between source area and depositional basin ensured that the highland/lowland relation in the interior of Gondwana was maintained and that fluvial conditions prevailed over a very long time. Tectonically active periods alternated with more stable, or less active ones, leading to minor lithofacies changes that characterise all these mid-Proterozoic successions.

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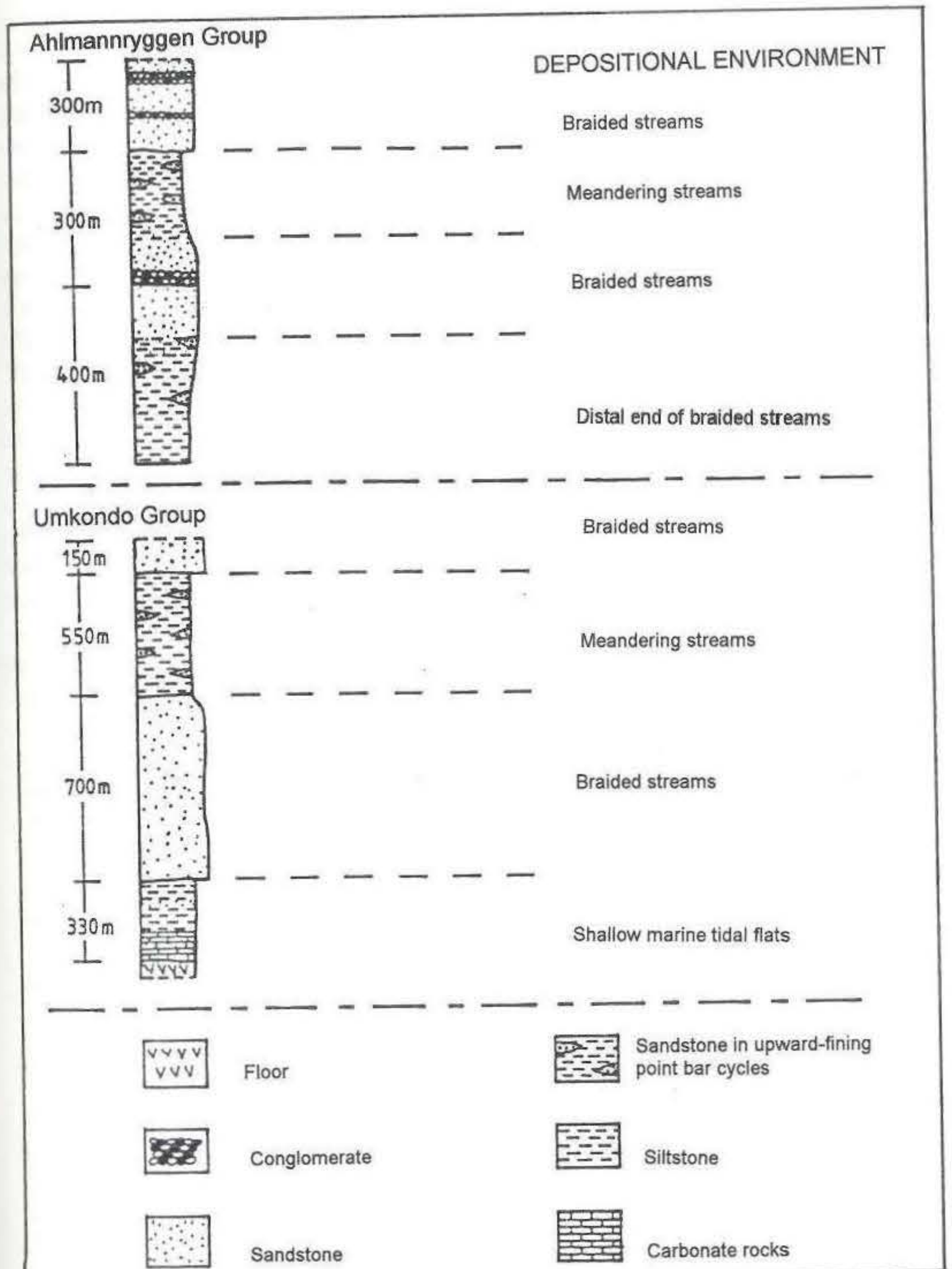

Fig 24. Lithological comparison of the Umkondo and Ahlmannryggen Groups

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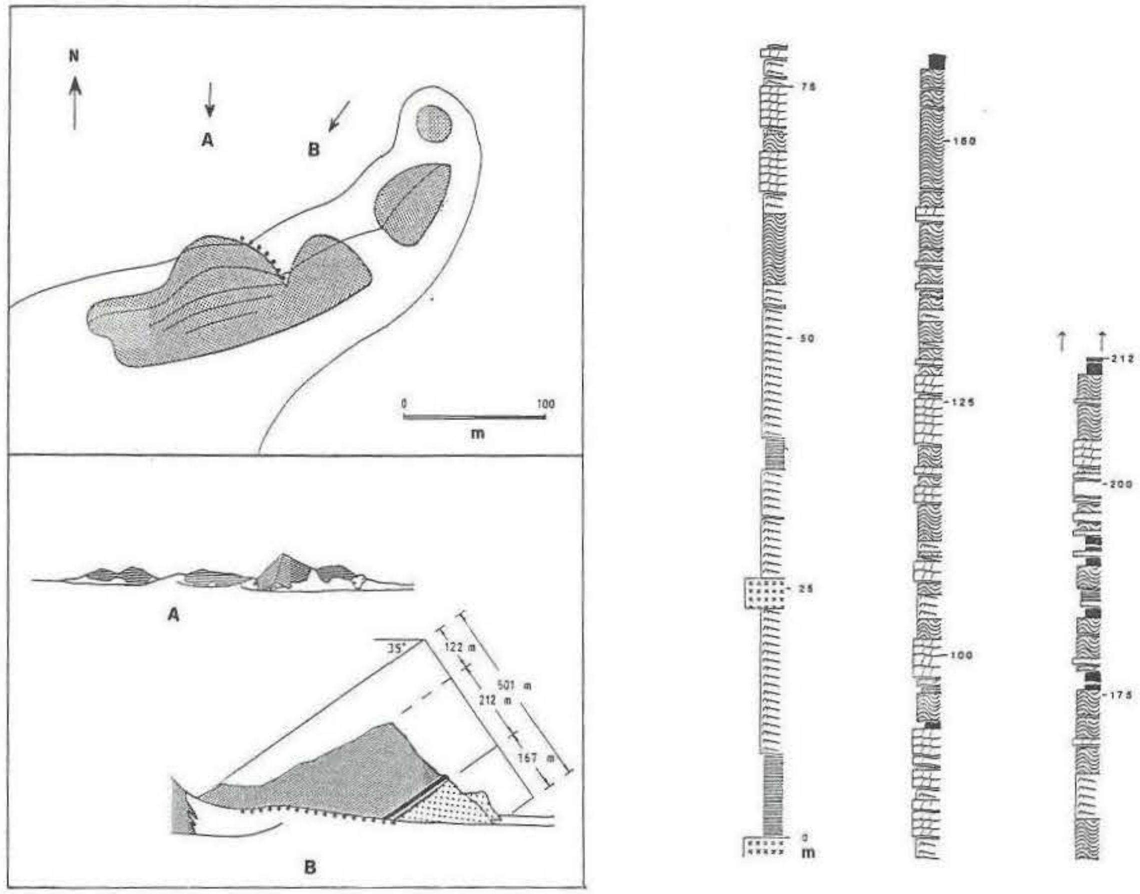
Addenda 1 - 18:

Plans, side views and stratigraphic sections of nunataks that are described as reference stratotypes in the Borgmassivet. Routes of measured profiles shown as dotted lines, contours at 100 m intervals.



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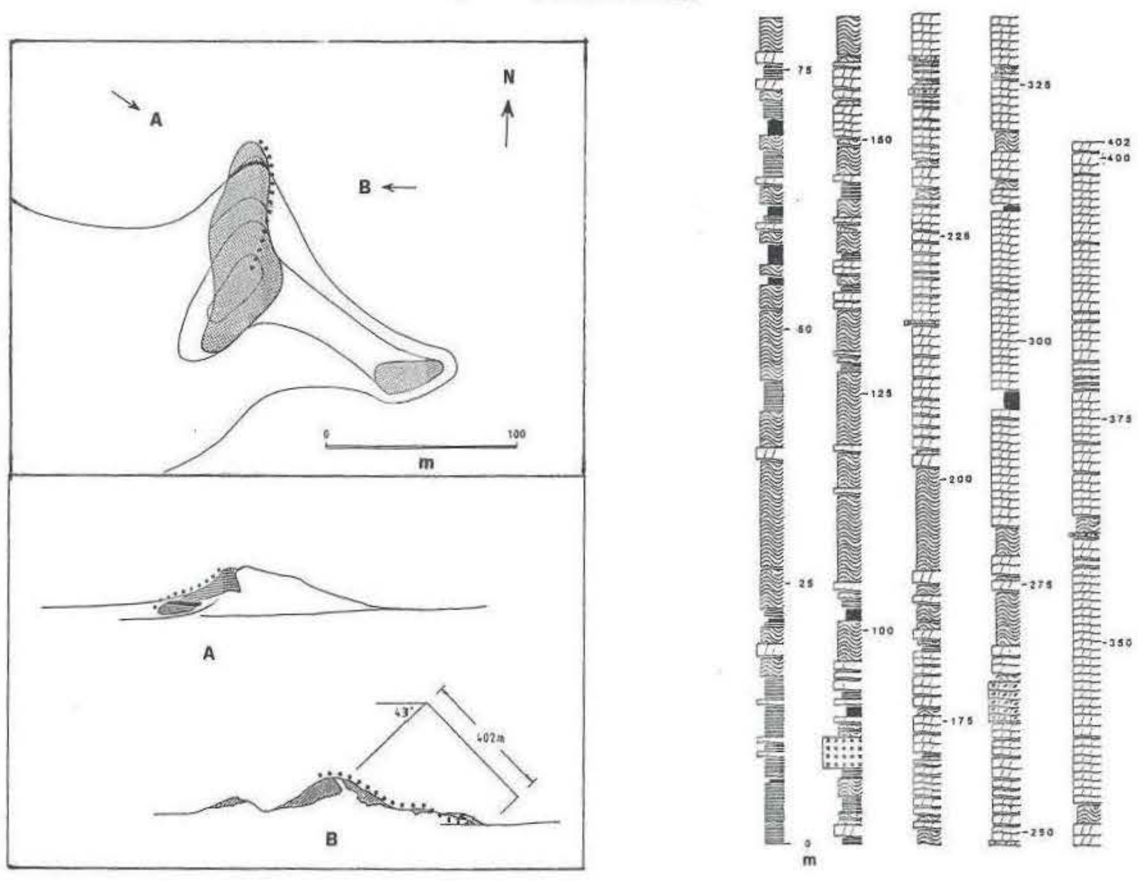

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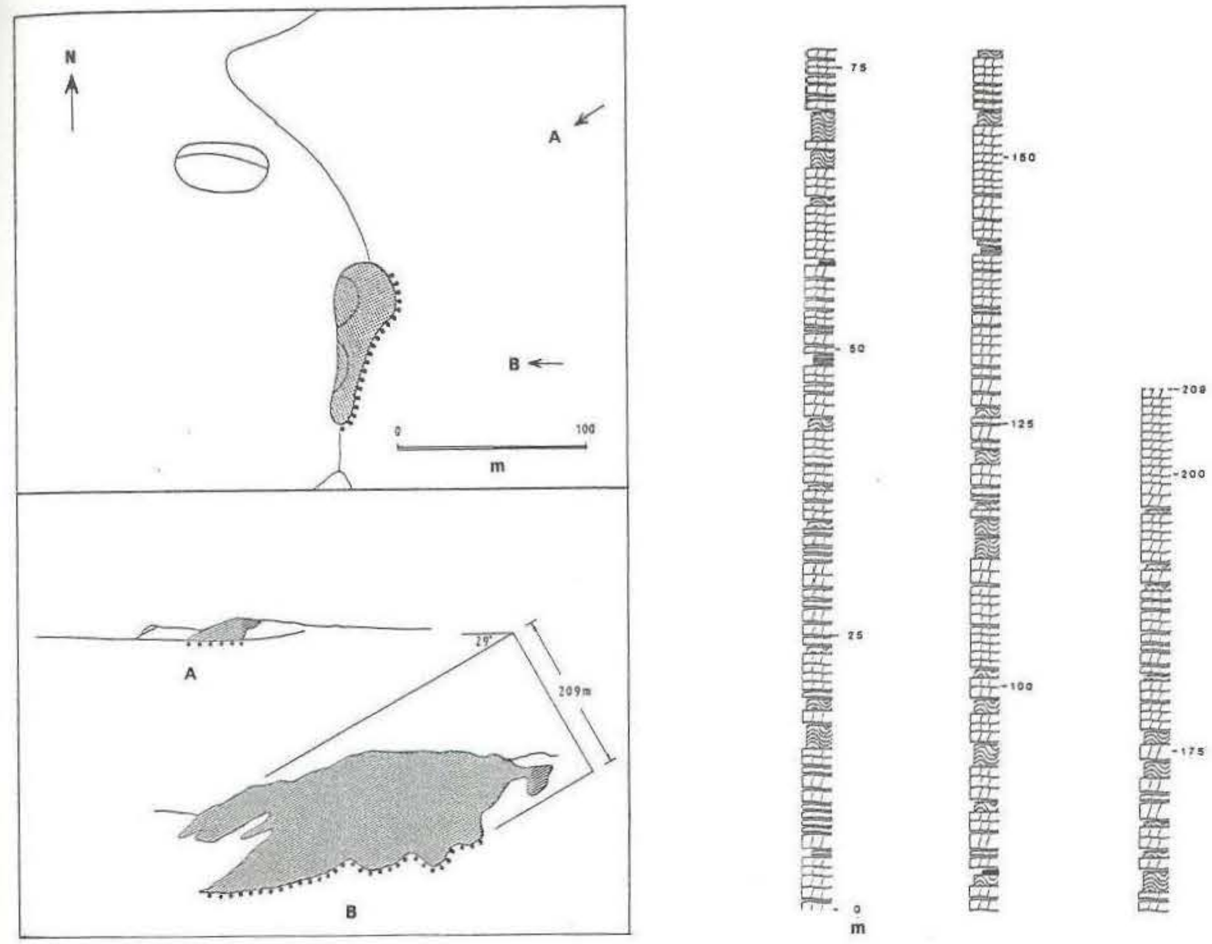

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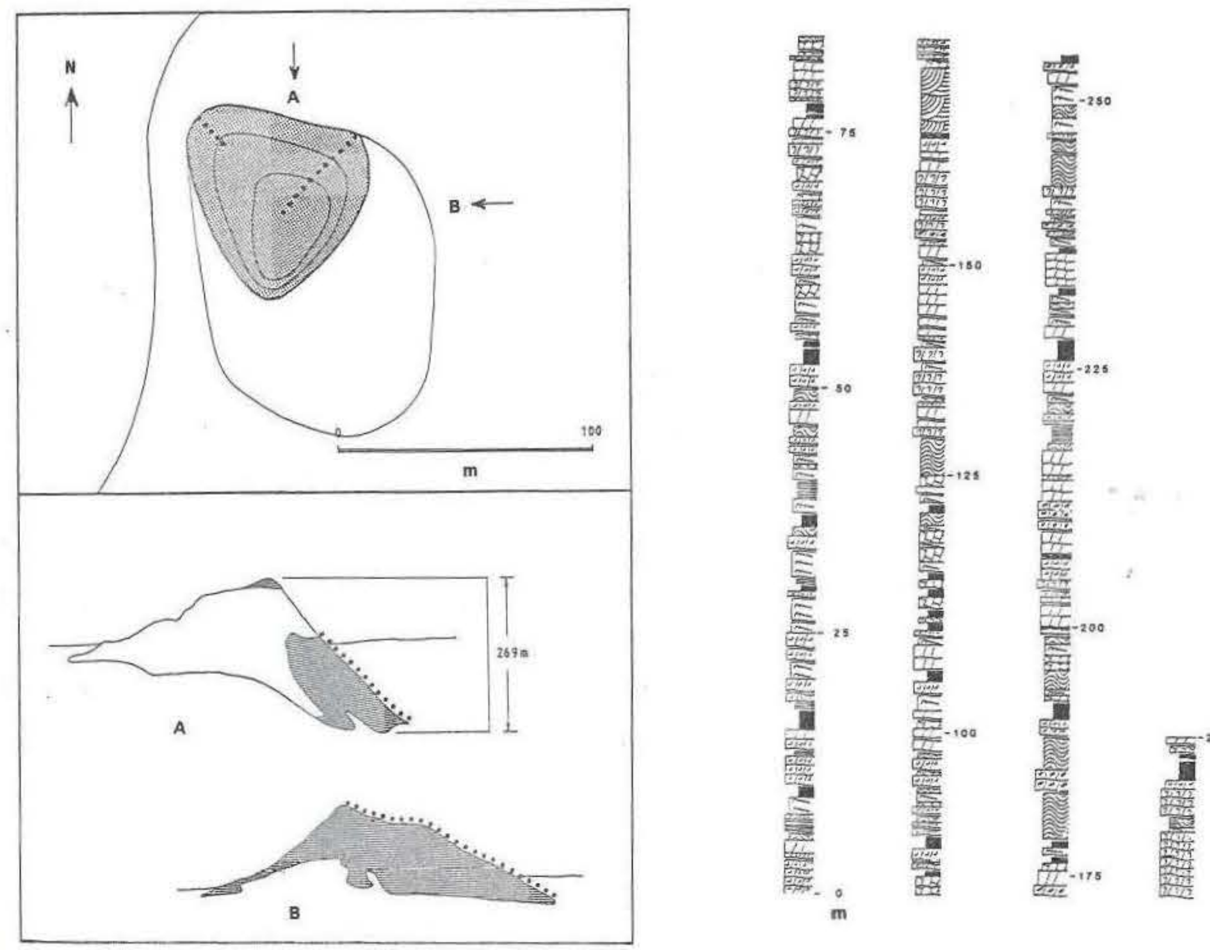

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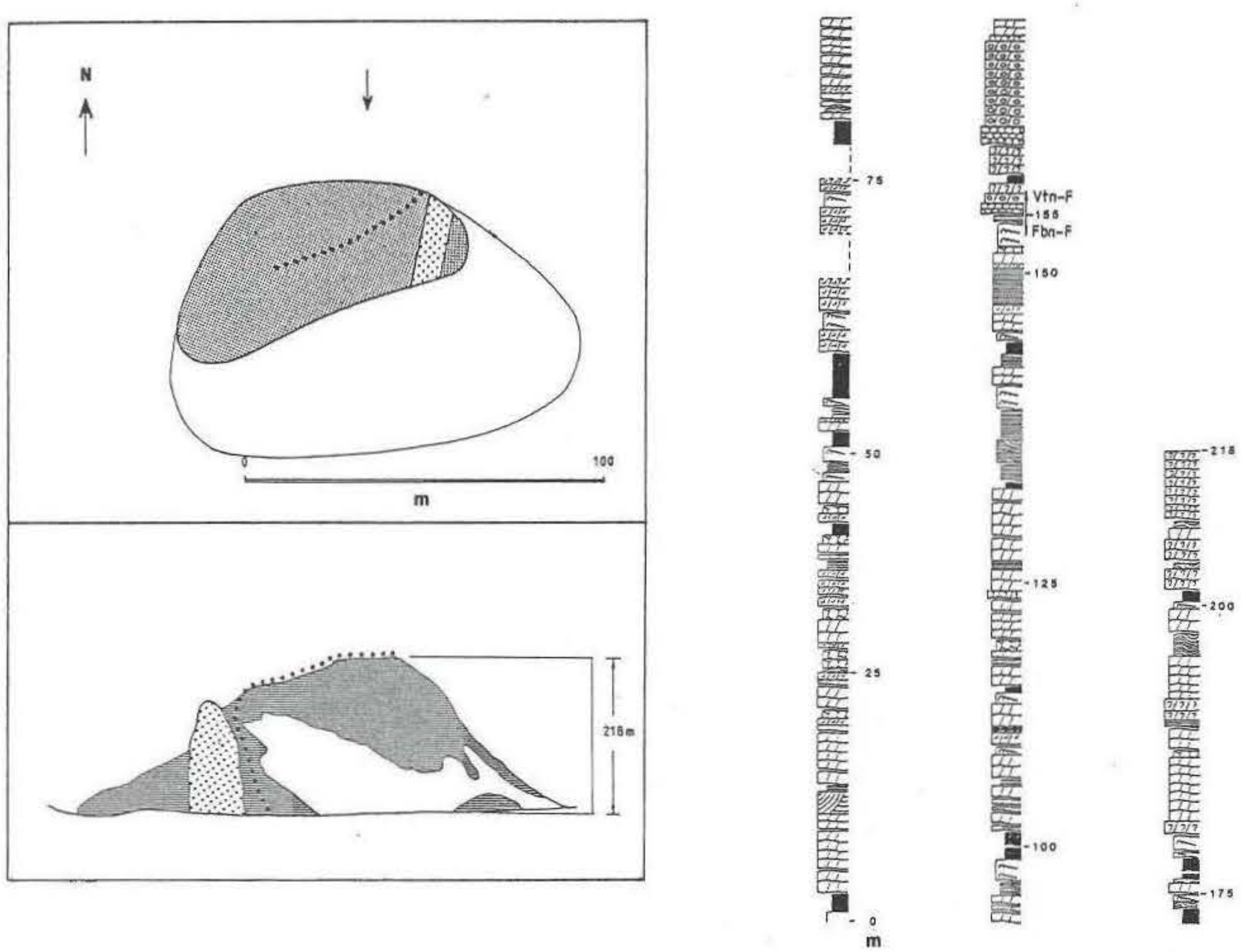

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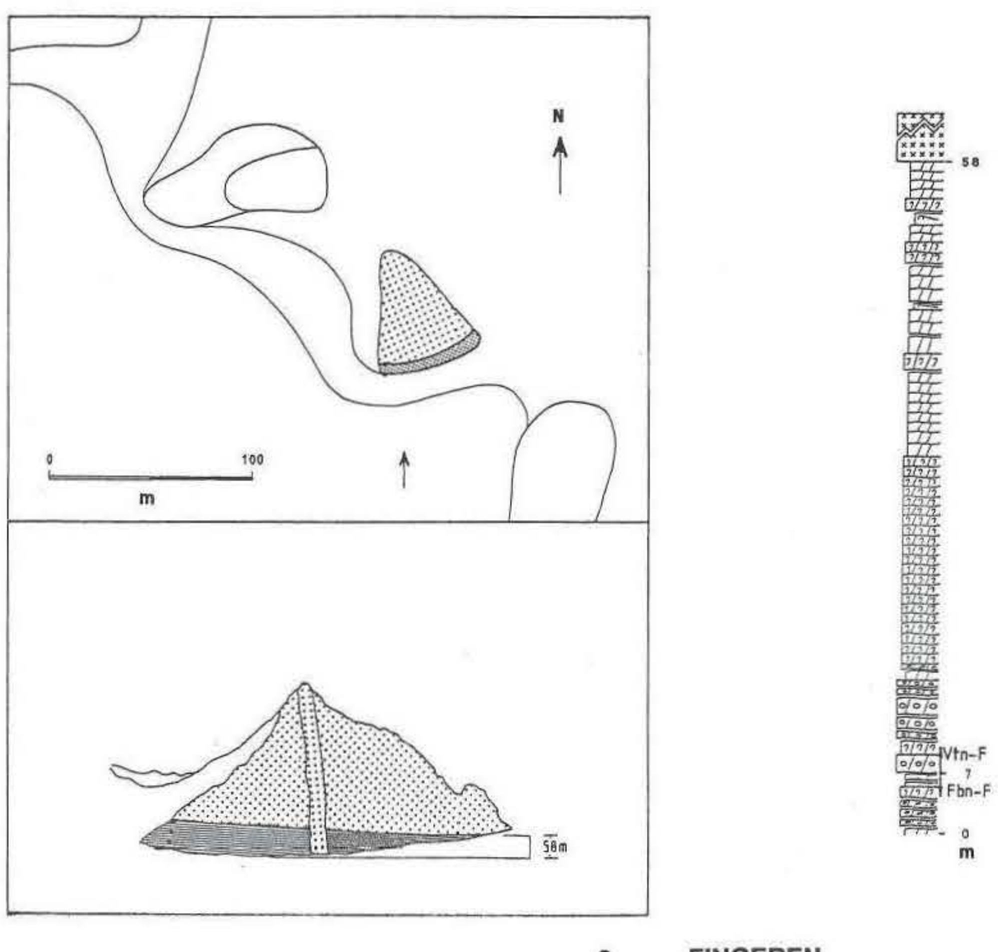

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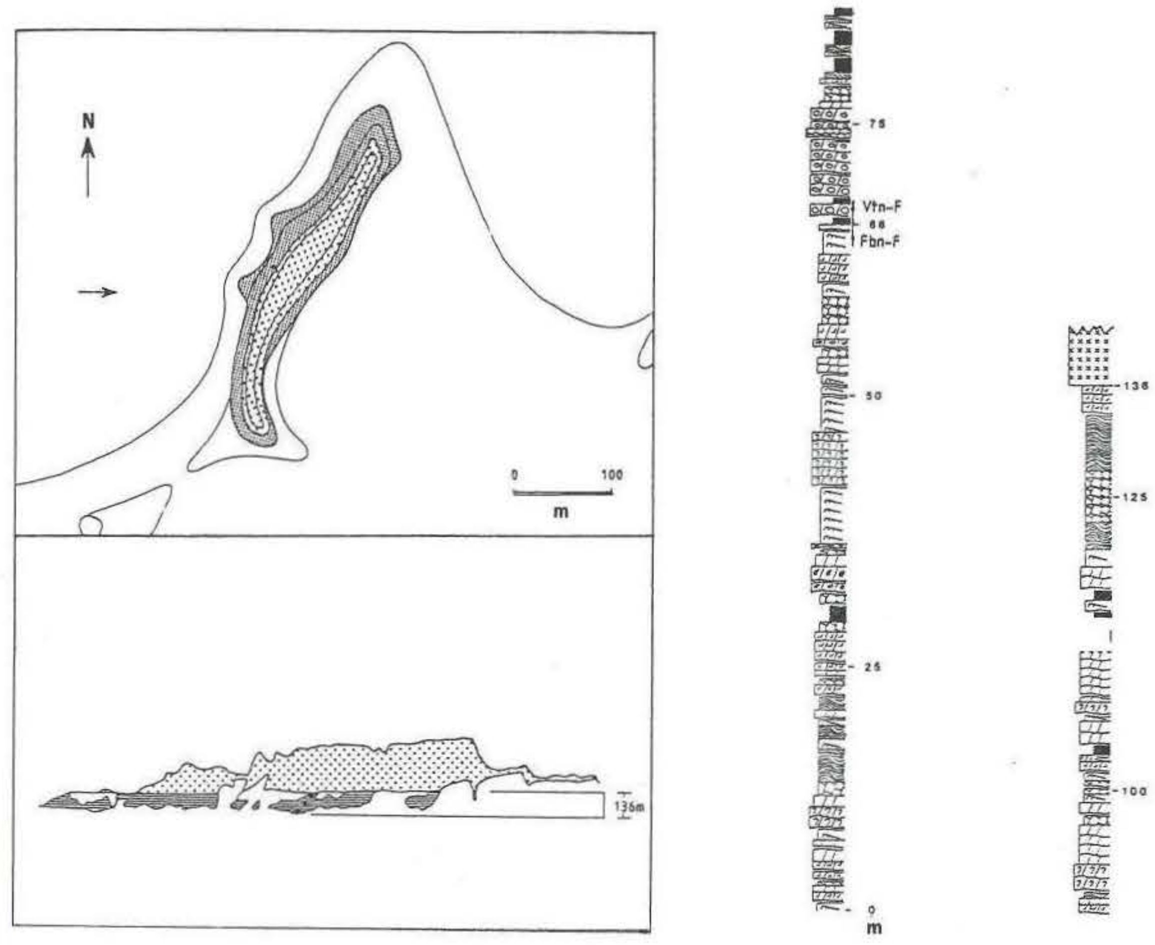

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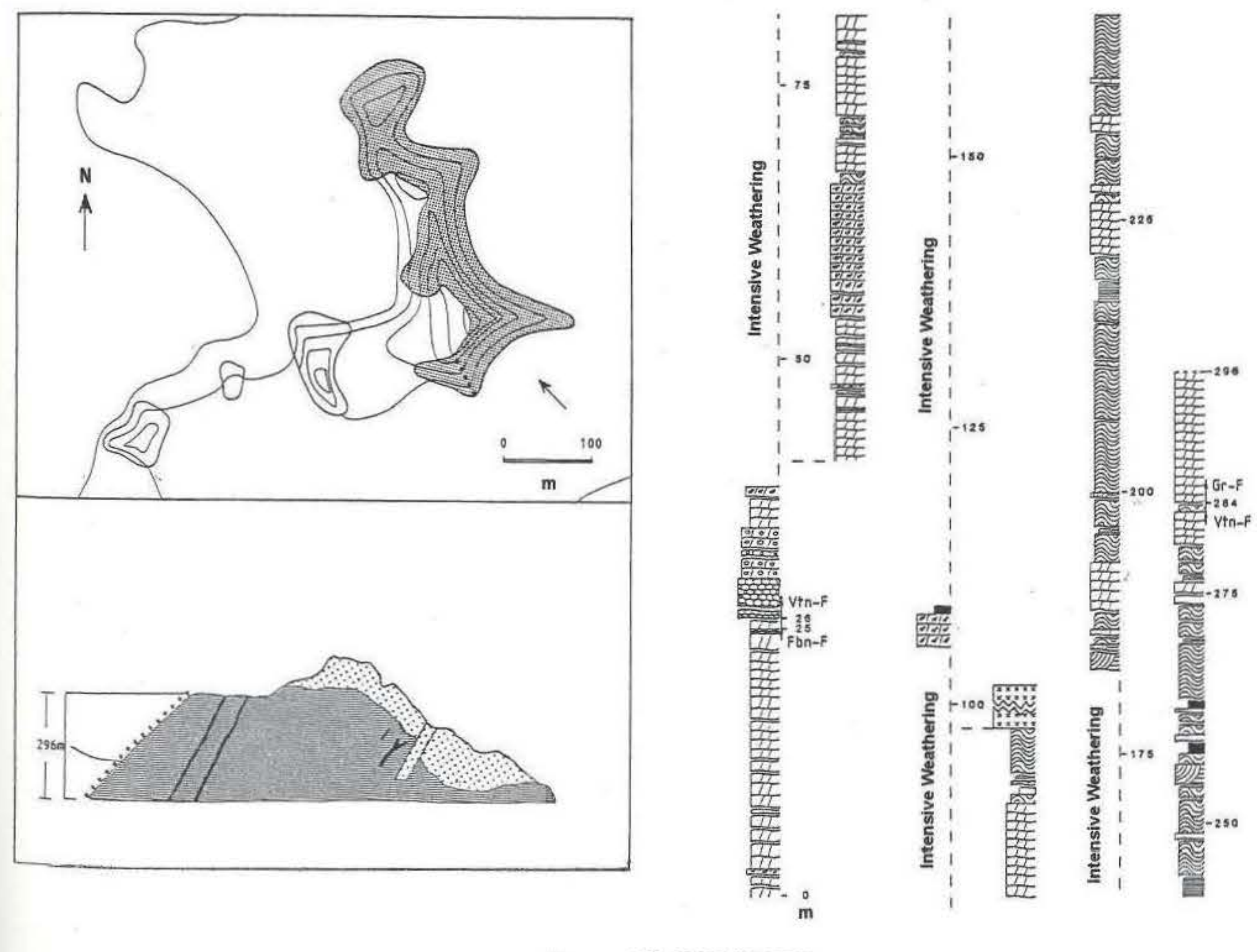

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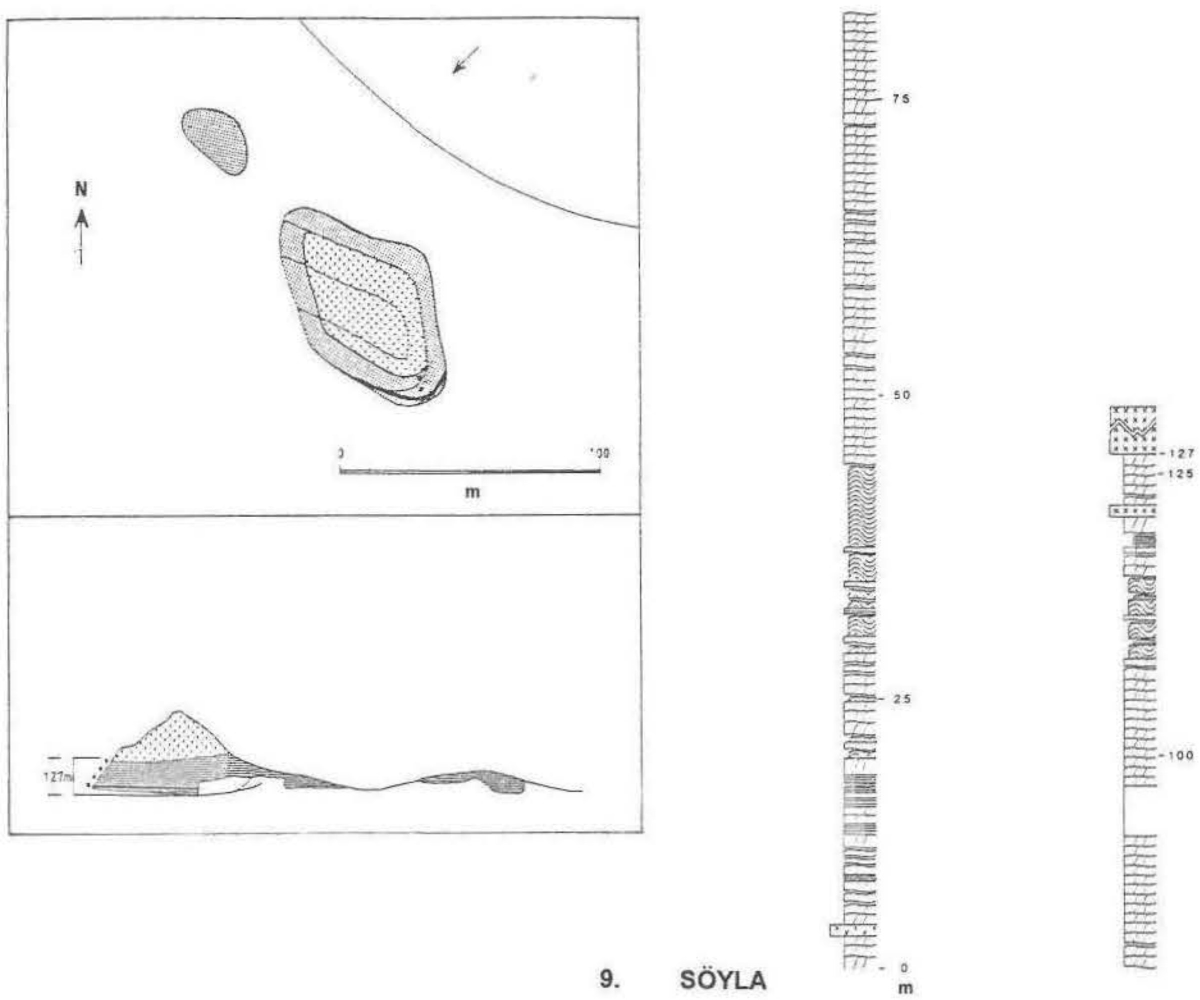

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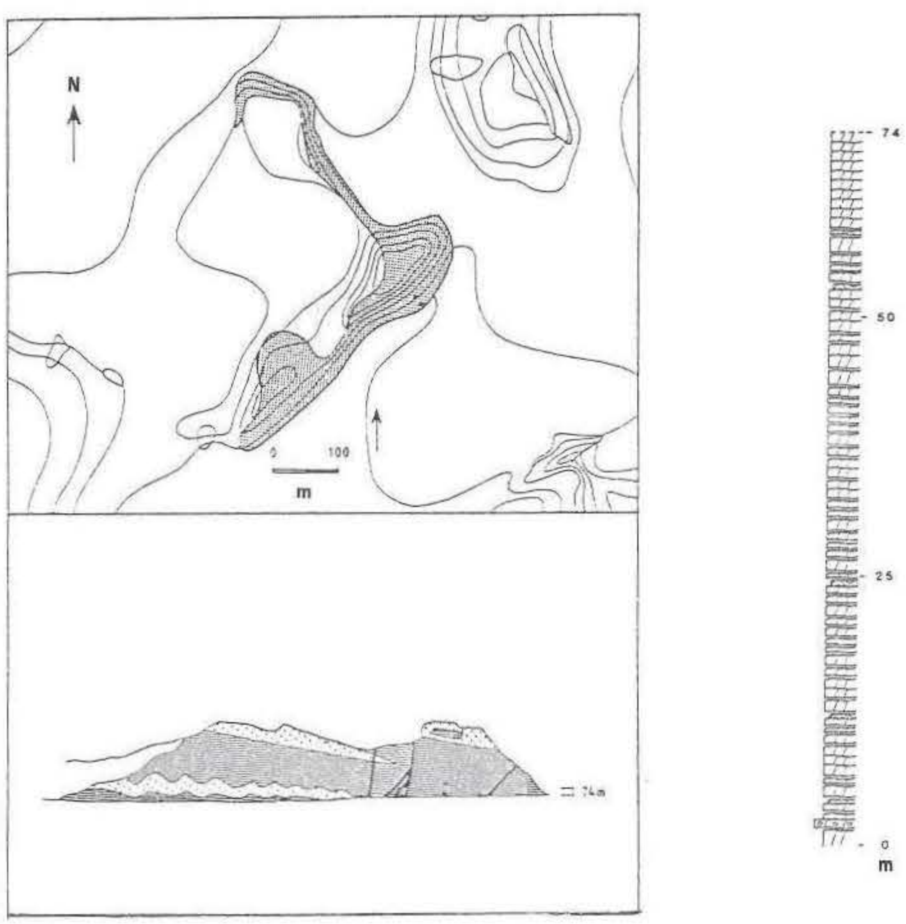

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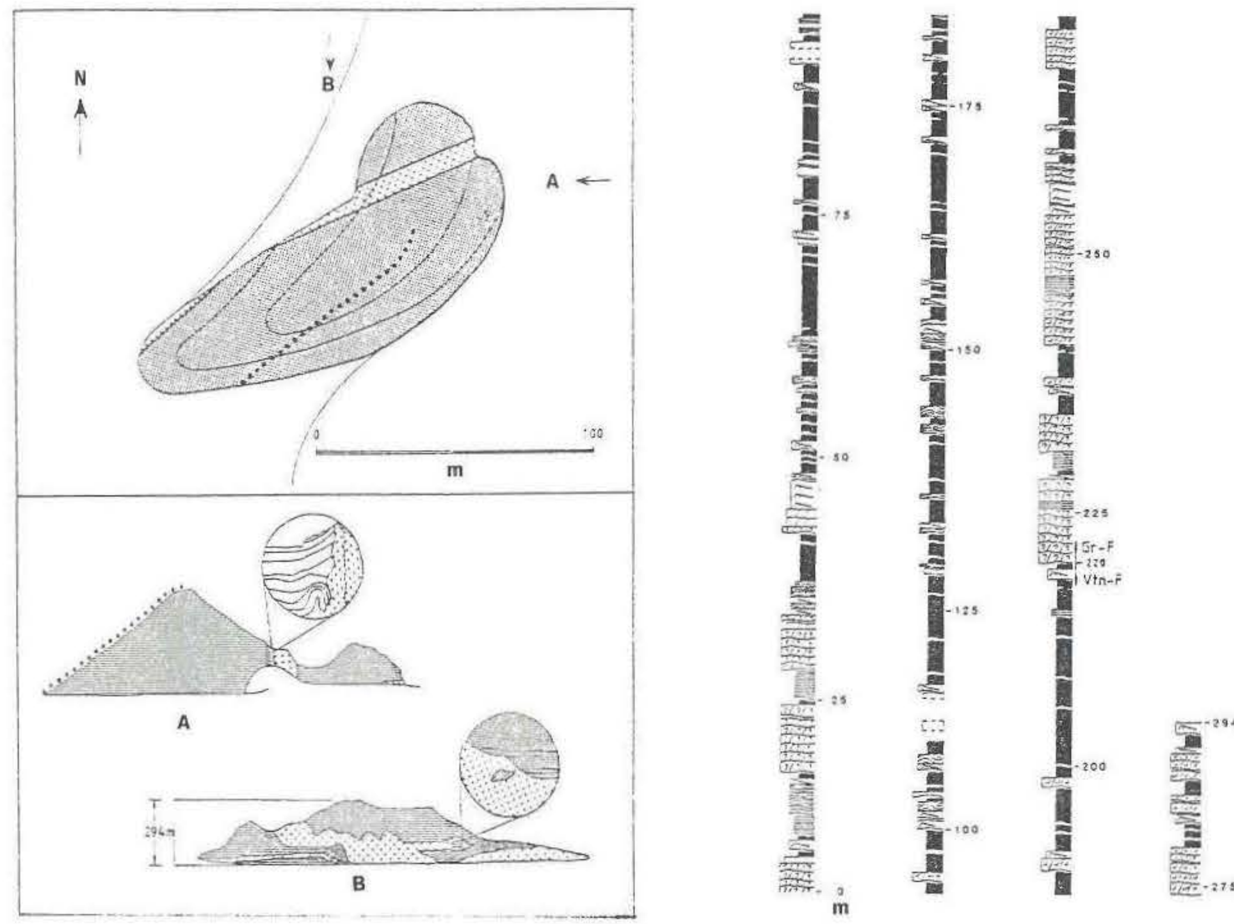

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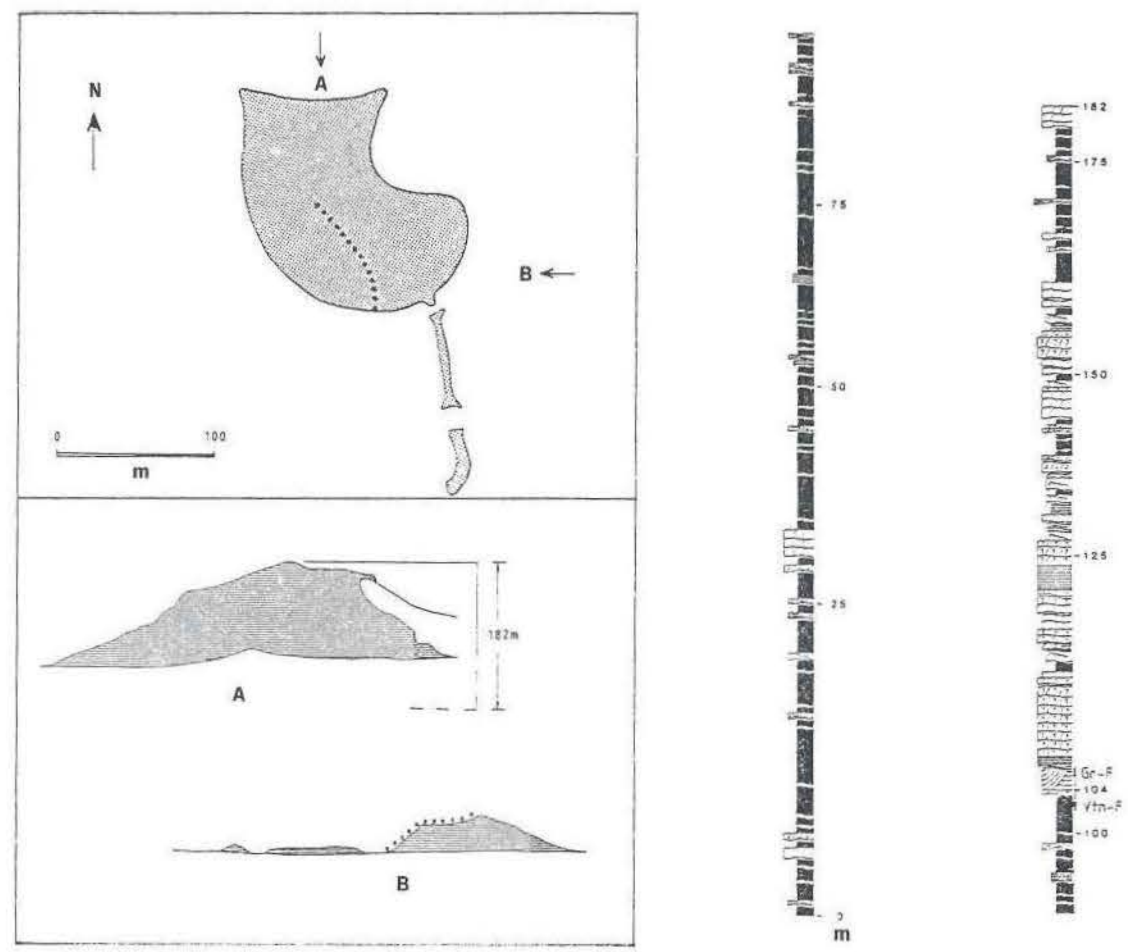

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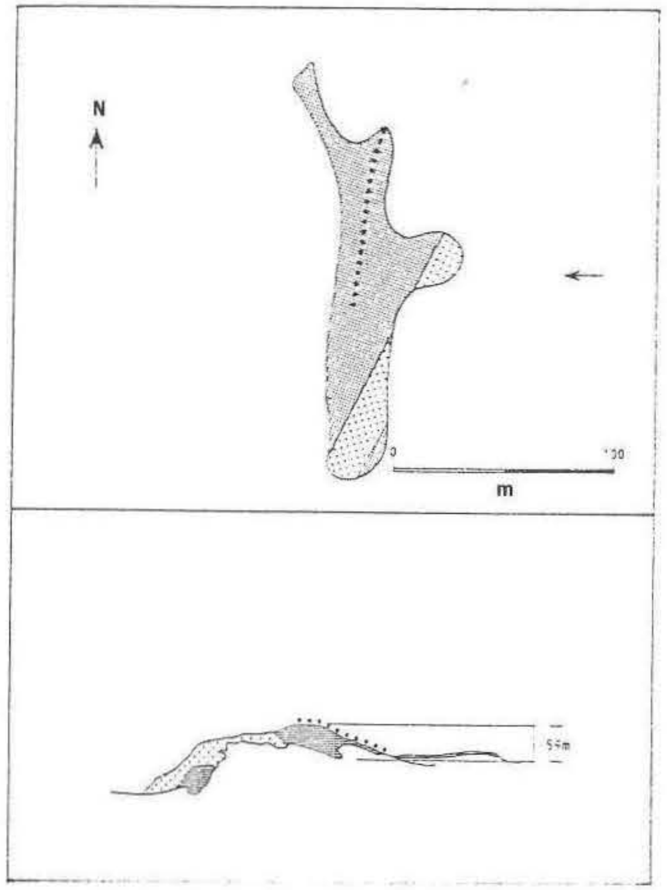

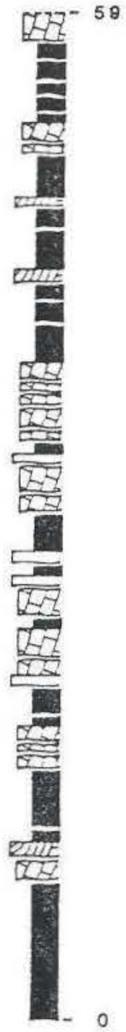

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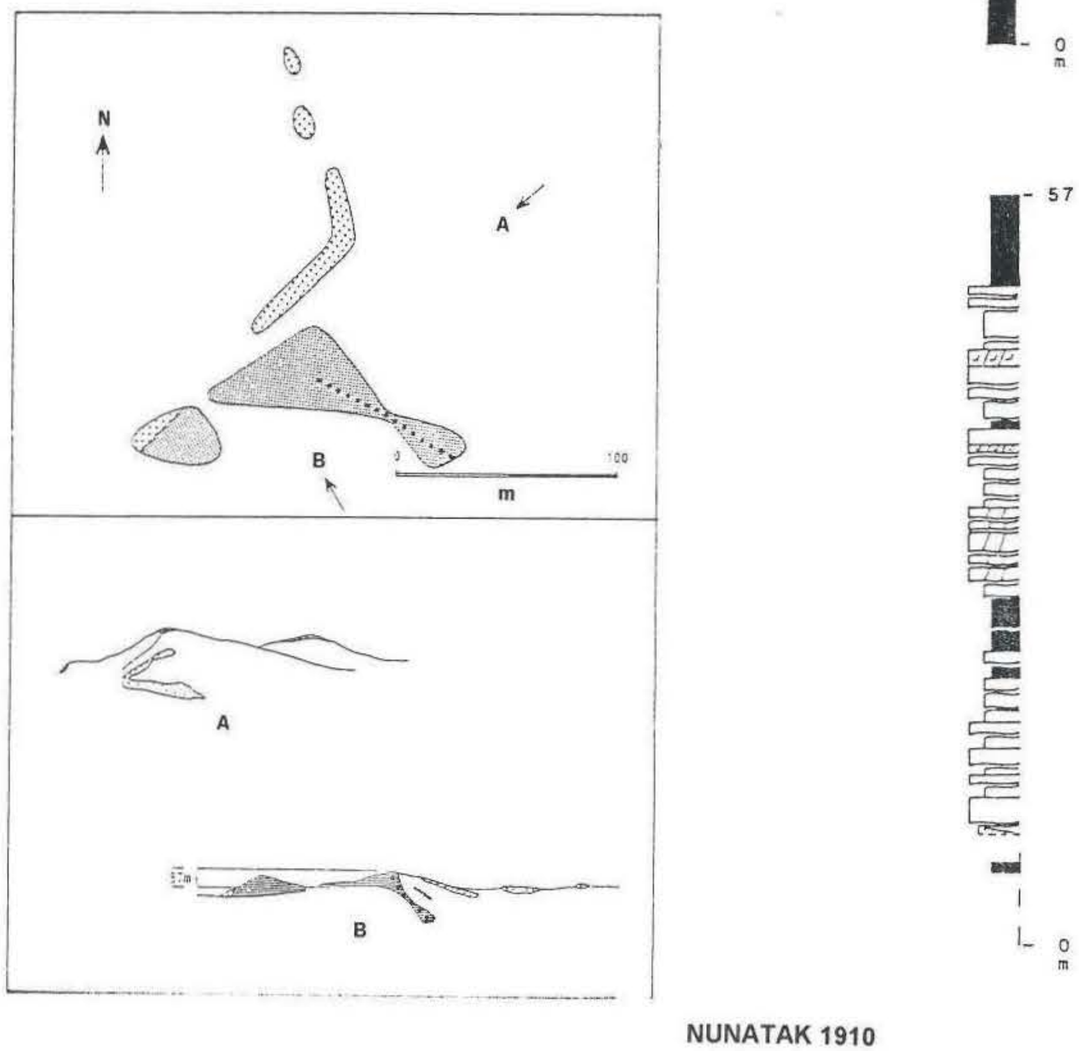

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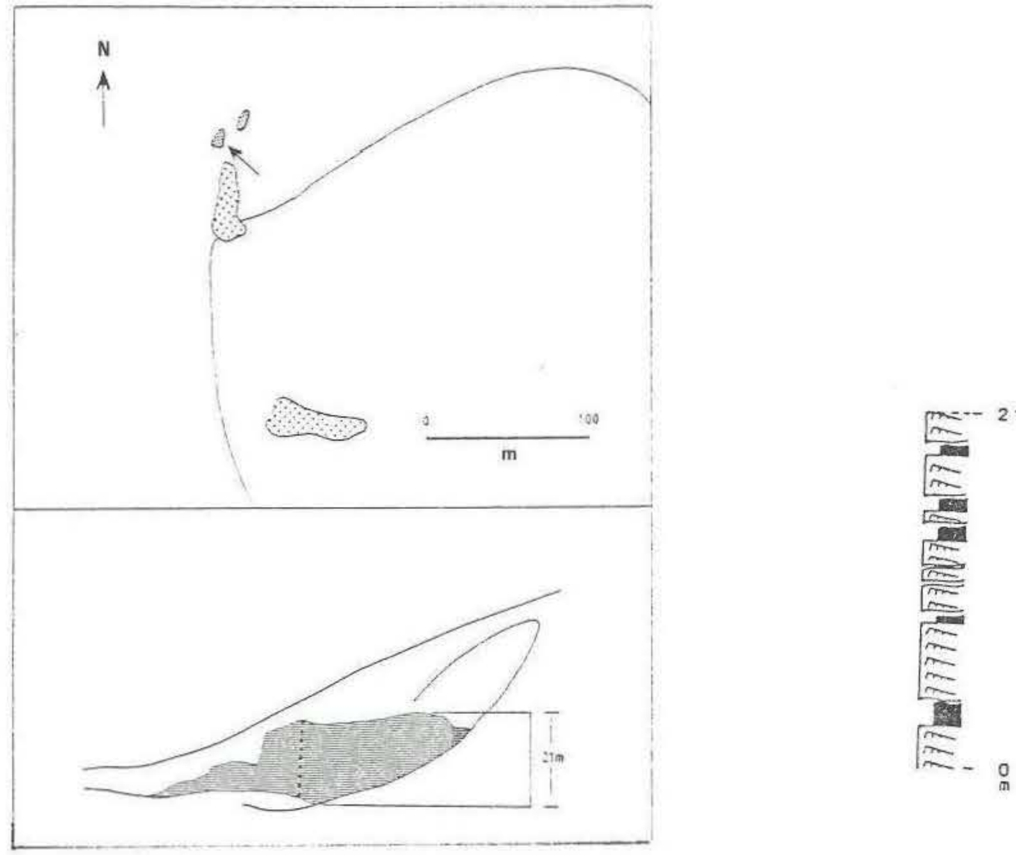

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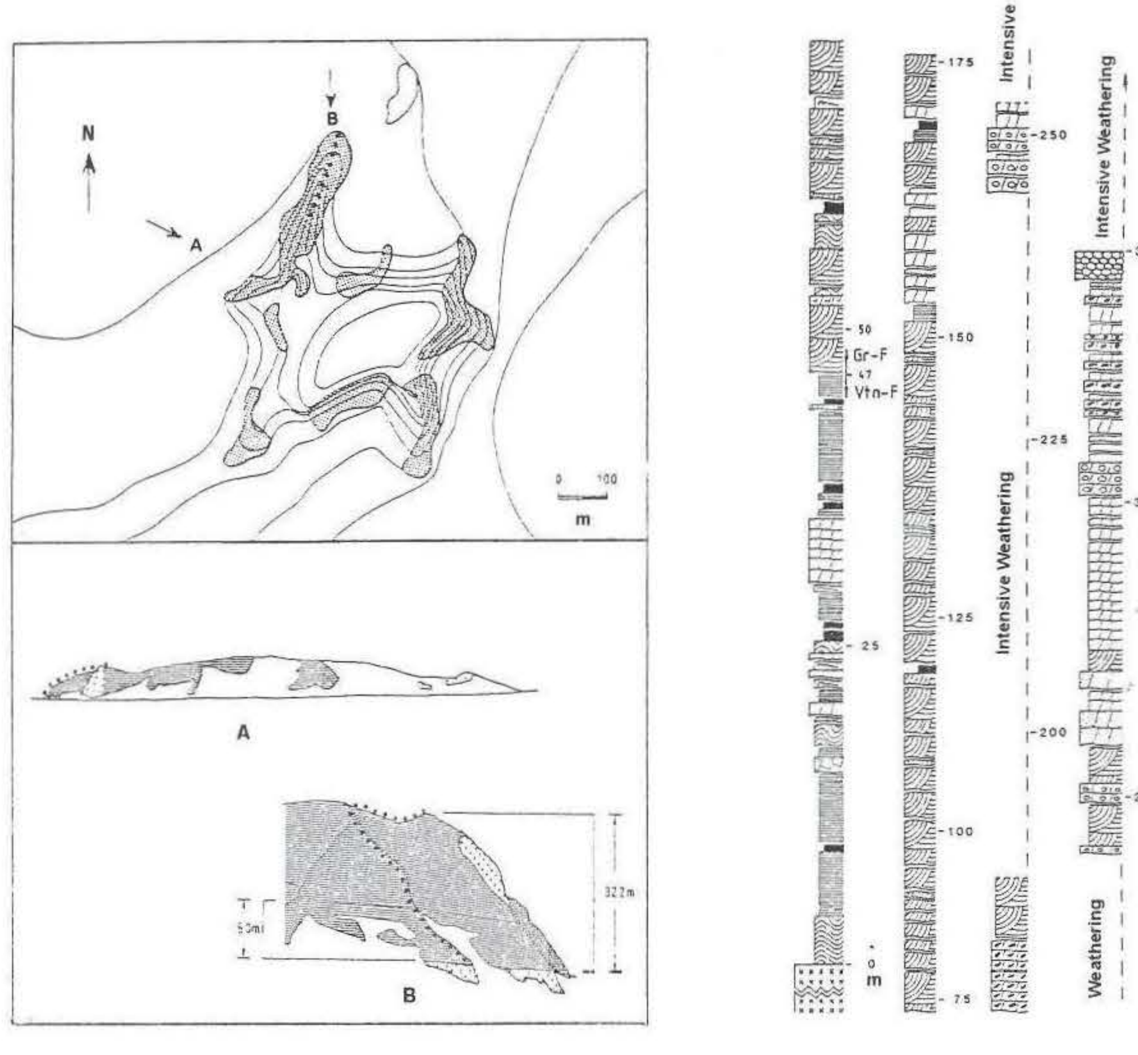

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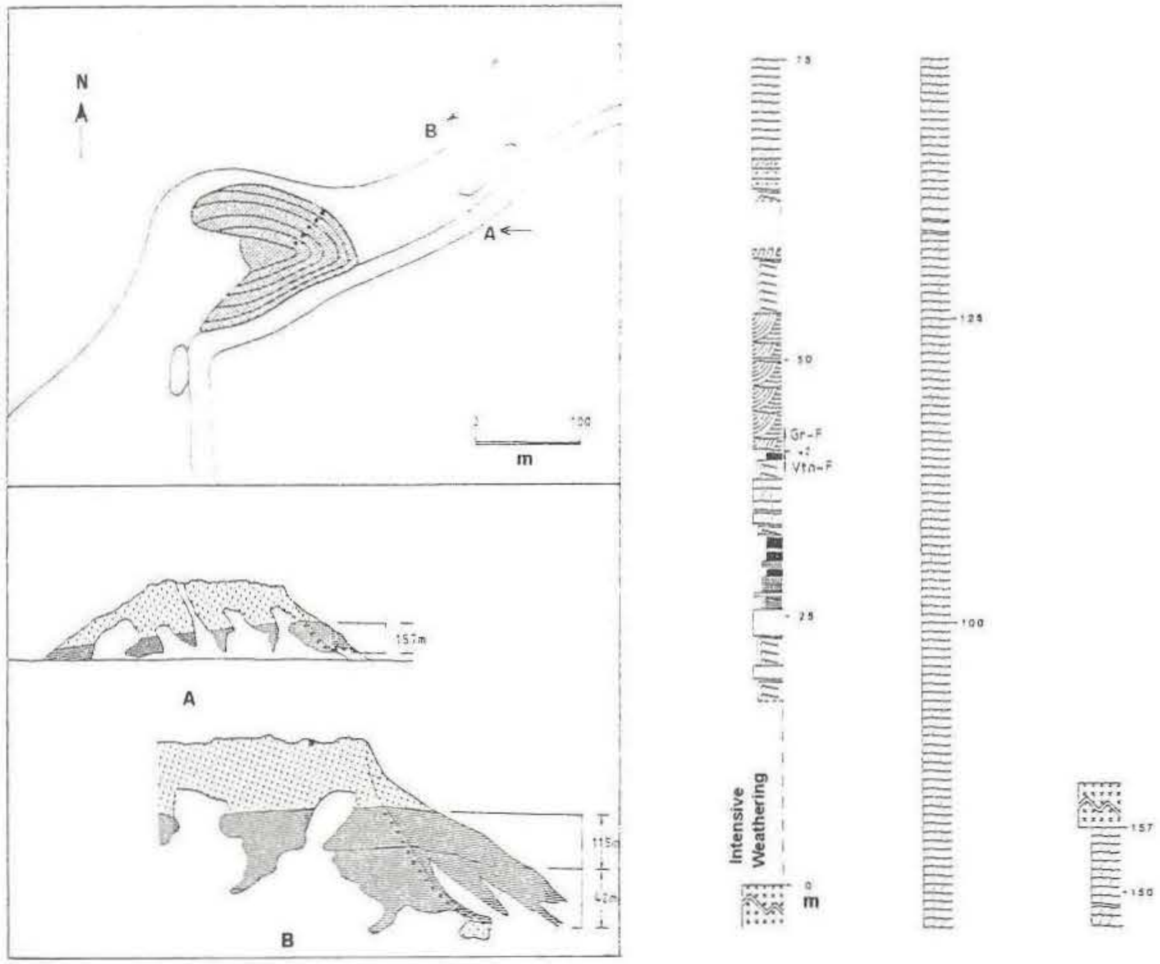

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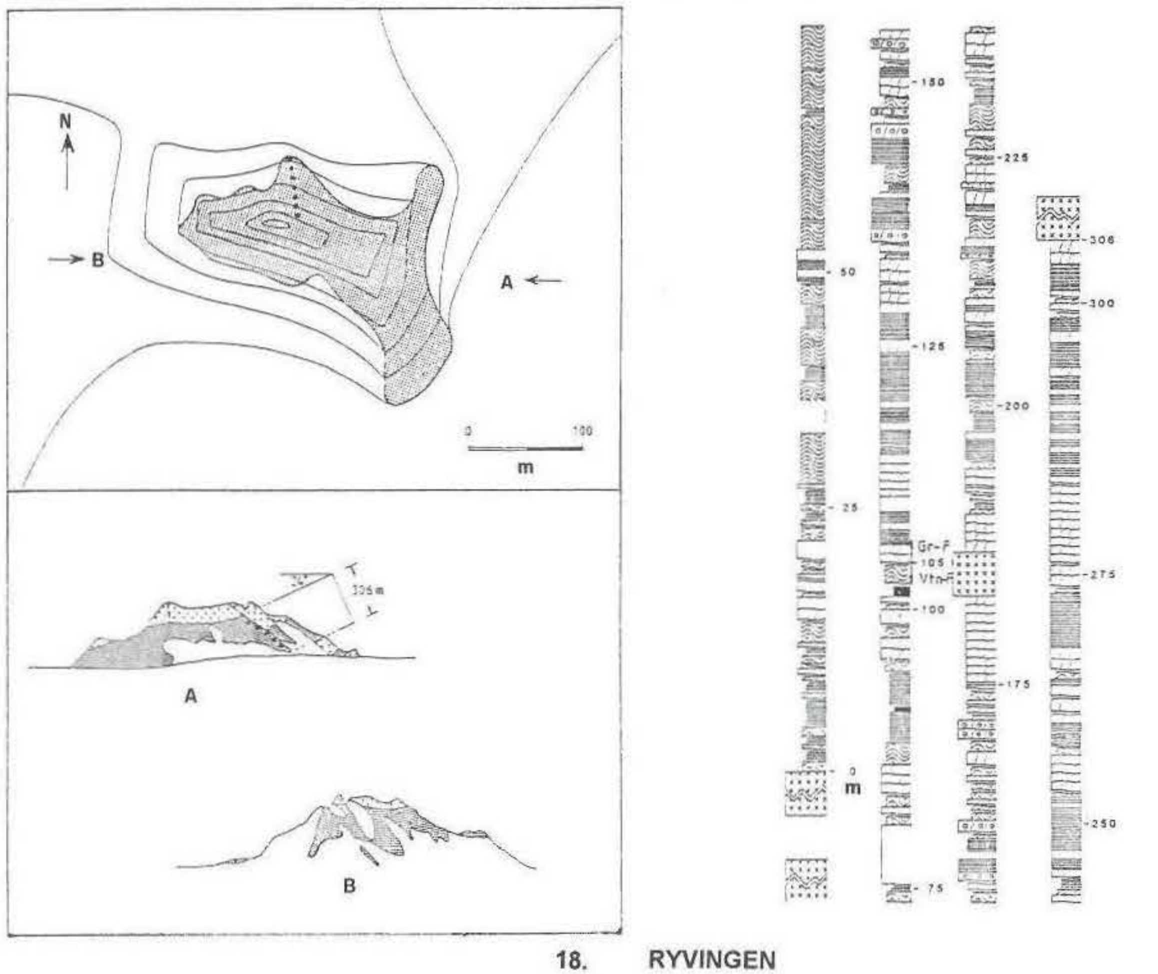

18. RYVINGEN

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J R E Lutjeharms

Department of Oceanography, University of Cape Town, 7700 Rondebosch, South Africa
Department of Zoology and Entomology, Rhodes University, P O Box 94, 6140 Grahamstown, South Africa and
Department of Geography and Environmental Management, Rand Afrikaans University, P O Box 524, 2000 Johannesburg, South Africa

Introduction

This is the last edition of the South African Journal of Antarctic Research.

This journal was first published in 1971 and during the subsequent period of 26 years it has contained a wide range of articles and reports. Articles reporting results stemming from basic research, historical articles on Antarctic research endeavours, as well as notes and news on South African participation in Antarctic work have been included in the pages of this journal. The latter are a rich archival source of information on the participants in South Africa's Antarctic Programme over the years. Climatological data from the South African weather stations in the subantarctic have regularly been published, making a valuable set of environmental data available to the international scientific community. Research articles and notes have covered a wide spectrum of disciplines including geology, meteorology, physical oceanography, marine biology, ornithology, ichthyology and others.

The journal has been distributed widely to libraries and to individuals who have an interest in Antarctic and Southern Ocean matters. During the last few years the scope of the journal and the number as well as quality of the scientific contributions have increased, thus attracting increasing numbers of manuscripts from abroad. Decreasing funds have however forced the South African Committee for Antarctic Research to make a decision to terminate the journal.

The purpose of the bibliography that follows is to make the full set of research articles and notes published in the South African Journal of Antarctic Research over the past 26 years available to the scientific community in an easily accessible way. Only scientific and historical articles with identified authors have been included. The bibliography is arranged in an alphabetical order, by the names of authors, and also in a chronological sequence, in order to give easy access to the information. The last editorial staff of the journal hope that this bibliography will be useful for current and future users.

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