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BULLETIN No. 84

PRECAMBRIAN ALKALINE-ULTRAMAFIC/CARBONATITE VOLCANISM AT QAGSSIARSSUK, SOUTH GREENLAND

BY

J. W. STEWART

WITH 20 FIGURES AND 9 TABLES IN THE TEXT,
AND 6 PLATES

DANISH GEOLOGICAL CONTRIBUTION
TO THE INTERNATIONAL UPPER MANTLE PROJECT

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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Abstract

An outburst of alkaline-ultramafic/carbonatitic volcanic activity took place at Qagssiarssuk in the early Gardar period (about 1300 m.y.). High level volcanic structures which have been preserved include the remnants of pyroclastic cones and the uppermost parts of diatremes, some of which did not penetrate to the surface. There are many features which recall the carbonatite volcanoes of East Africa and Zambia, including the presence of flows of carbonatitic material.

As a consequence of faulting and subsequent erosion, crystalline basement rocks are exposed nearby. They are penetrated by tuffisite diatremes and other minor intrusions, comagmatic with the effusive rocks, but corresponding to a depth of at least half a kilometre.

The igneous rock types belong to three main groups: (i) monchiquite – alnöite – mica-peridotite, (ii) melilite-rock (a high-level equivalent of uncompahgrite) and (iii) mica-pyroxenite. In addition, a concealed body of carbonatite is directly indicated by blocks of sövite, and other material, in the pyroclastics.

An episode of calcitic carbonatization was followed by ankeritic carbonatization. Carbonatization of the melilite-rock was particularly intense. Barytes and fluorite were also introduced.

The volcanism was characterized by an abundance of volatiles and it is probable that fluidized systems were developed.

Granitic basement rocks adjacent to the intrusions underwent progressive potash feldspathization with the ultimate production of almost pure potash feldspar rock, locally intrusive ($Na_2O = 0.50\,\%$; $K_2O = 13.50\,\%$).

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INTRODUCTION

The settlement of Qagssiarssuk (104 inhabitants, 1960) is situated about 5 km west of Narssarssuaq airport, in the upper reaches of Tunugdliarfik fjord (Eriksfjord), Julianehåb District, South Greenland (Plate 5). Most of the rocks with which this paper is concerned outcrop within a 10 km radius of Qagssiarssuk.

The field work for this investigation was done during a three-week period in the summer of 1962 as part of the geological mapping programme being carried out by the Geological Survey of Greenland. Aerial photographs on a 1:40 000 scale were available and geological observations were recorded on the 1:20 000 topographic map.

The laboratory work was performed at the geology department of the University of Durham during the latter part of 1962 and the whole of 1963. The field and laboratory results constituted part of a thesis submitted for the degree of Doctor of Philosophy at the University of Durham in 1964.

Until now, little has been published about the geology of the area. WEGMANN (1938) notes the presence of diatremes and pyroclastics near Qagssiarssuk, and WALTON (1965), in an account of geological investigations in the basement country north of Narssarssuaq, describes occurrences of Gardar ultramafic minor intrusions east of Tunugdliarfik.

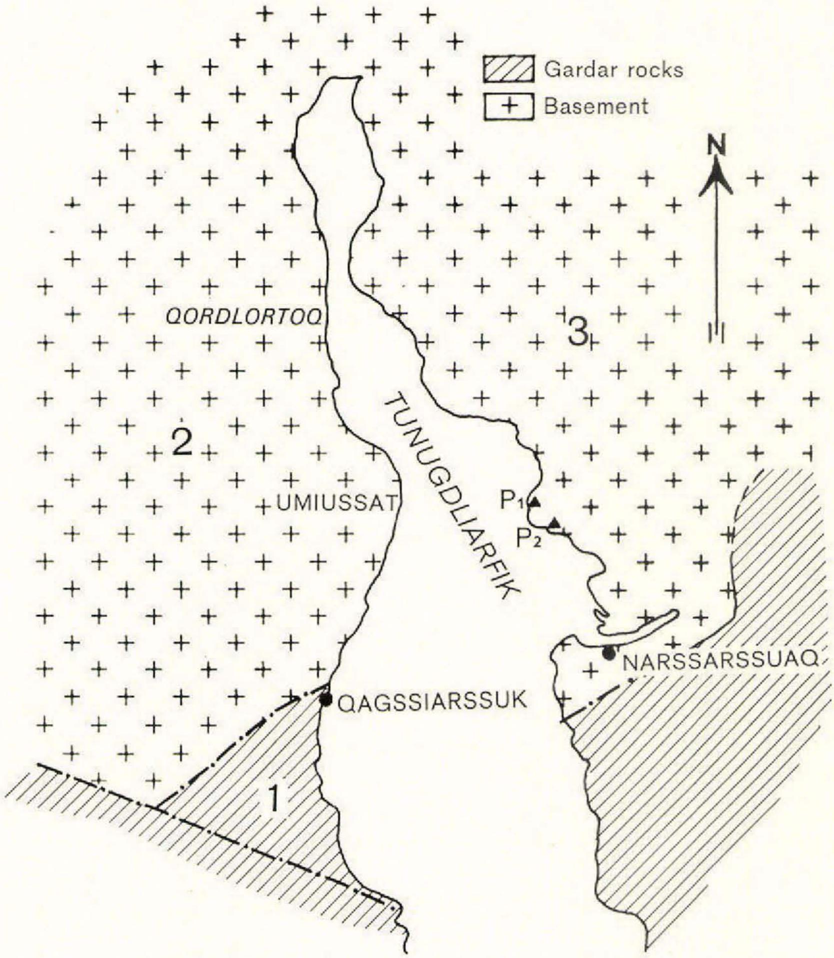

Fig. 1. Sub-areas referred to in the text. Sub-area 1 is the Qagssiarssuk Triangle.

Part I. GEOLOGY

1. Regional setting

The crystalline basement of the Qagssiarssuk region consists mainly of granites and gneisses formed during pre-Ketilidian, Ketilidian (1800–1650 m.y.) and Sanerutian (1650–1500 m.y.) metamorphic episodes (Walton, 1965). Between about 1500 m.y. and 1300 m.y. ago, the crust in this region became consolidated as a cratonic block and underwent late to post-orogenic uplift and erosion.

The ensuing Gardar period, which began 1300 m.y. ago, was one of crustal tension. Basic and alkaline magmas penetrated to high levels and block faulting was common (Wegmann, 1938; Walton, 1965). Continental sandstones were laid down on the eroded pre-Gardar basement, and lavas of the initial basaltic Gardar volcanism of the region became interstratified with the sediments (Poulsen, 1964). After a stratified sequence with a thickness of about 500 m had accumulated, a completely distinct, alkaline ultramafic magma rose in the crust near Qagssiarssuk. This magma was highly charged with volatiles, and numerous diatremes drilled their way upward through the basement and the overlying strata. Where the diatremes reached the surface, pyroclastic cones developed.

Subsequently, the ultramafic volcanism waned. The pyroclastic deposits were partly eroded and were covered by the products of renewed arenitic sedimentation. Meanwhile, effusion of basaltic magma was resumed. Later still, the Ilímaussaq, Igaliko and some lesser alkaline centered intrusive complexes were emplaced in the region.

At this time or later a NE–SW fault with a minimum downthrow of 500 m to the south-east developed close to the present day settlement of Qagssiarssuk. Erosion has since removed all the Gardar strata from the country north-west of the fault, exposing sections of diatremes corresponding to a depth of at least half a kilometre, emplaced in crystalline basement rocks.

By contrast, on the south-east side of the fault Gardar strata are preserved in a 2 km^2 area of roughly triangular shape, hereafter referred to as The Qagssiarssuk Triangle (fig. 1). Here the uppermost parts of a number of diatremes are exposed and the associated effusive products occur interstratified with sandstone.

2. The Qagssiarssuk Triangle (sub-area 1)

In the Triangle, exposure on flatter ground is much restricted by soil and vegetation. The basalt which outcrops on the shore at Qagssiarssuk is isolated from the rest of the area by raised-beach deposits.

The stratigraphic succession within the Triangle has been subdivided into three units:

(i) a *lower sandstone unit* whose base is not exposed,
(ii) a *volcanic unit* composed of predominantly pyroclastic material,
(iii) an *upper sandstone unit* which outcrops on the scarp of Angmagssiviup qáqâ, the southern limit of the Triangle.

The overall strike of the succession in the Triangle is roughly NE–SW and the average dip 20° south-east. Local divergences from these values are common, due to distortion of the stratification by intrusions, and tilting related to fault movements. Local repetition of parts of the sequence has been caused by faults which strike 50° and 80°, with downthrow to the north-west and north respectively. On account of the poor exposure only a very generalized and qualitative account of the stratigraphy can be provided.

The lower sandstone unit

The exposed thickness of this unit is about 100 m. The principal rock type is a white, medium-grained sandstone, extensively cross-bedded. A 10–20 m sill of compact, aphyric, olivine-free basalt occurs about 60 m below the top of the unit.

Basalt of Qagssiarssuk shore. This outcrop, which covers an area of ca 250 m², is built up of flows 0.5–1.5 m thick. The basalt of the shore contrasts in appearance with that of the sill described above, being of unfresh aspect, vesicular, and in places finely feldsparphyric. Oxidised flow-tops and corded surfaces occur. Thin section study revealed the presence of olivine.

Since the outcrop is isolated from the other rocks of the area, its location within the Gardar stratigraphical succession is uncertain.

The volcanic unit

The rocks of this unit, which cover rather more than half of the Triangle, appear to be exclusively volcanic and predominantly pyroclastic. Fossil mud-cracks in fine-grained pyroclastic beds indicate that locally, volcanic ash fell in shallow water.

The volcanic strata tend to be impersistent laterally and vertical sequences change rapidly from place to place; the unit thins swiftly towards the west. The nature of the rock types, and their distribution, indicate accumulation close to an eruptive centre, and the volcanic strata undoubtedly represent the base of a partly eroded cone or group of adjacent cones.

Based on an outcrop width of 1100 m and a dip of 20° to the south-east, the maximum thickness of the unit would be 375 m, near the coast – a figure probably inflated by repetition caused by concealed faults. Three small outcrops of sandstone overlie volcanic strata close to the south-east end of the stock of melilite-rock. Assuming that these are outliers of the upper sandstone unit, the volcanic unit is approximately 40 m thick at this point.

Farther west, where the unit outcrops south-east of Lake B, the thickness is reduced to 1 m; southwards from there, the thickness increases again to 10 m over a distance of less than 1 km.

While the wedge-like form of the volcanic unit may be partly a consequence of erosion which preceded the deposition of the upper sandstone unit, it certainly reflects a thinning of the pyroclastic pile away from the eruptive centres which are concentrated in the eastern part of the Triangle. This inference is supported by the fact that the distinctive pyroclastic beds at the base of the volcanic unit thin out westwards.

The lowest horizons of the volcanic unit outcrop along an east-west scarp 500 m south of Qagssiarssuk. The sequence is as follows:

Top

(v)	Amygdaloid	at least 2.0 m
(iv)	Coarse, reddish tuff with graded bedding, containing small, angular fragments of red, crystalline rock derived from the basement	4.3 m
(iii)	red-brown tuff	0.5 m
(ii)	fine, grey carbonate tuff	0.5 m
(i)	red-brown tuff	5.5 m

Base

The *amygdaloid* is an intensely carbonatized, highly vesicular lava, which develops a weathered surface characteristic of limestone (fig. 2). In several places it has been possible to demonstrate that sheets of amygdaloid were extruded at the surface: rubbly scoriae from flow tops are incorporated in overlying stratified clastic deposits (fig. 3). Few of the flows are more than 2 m thick.

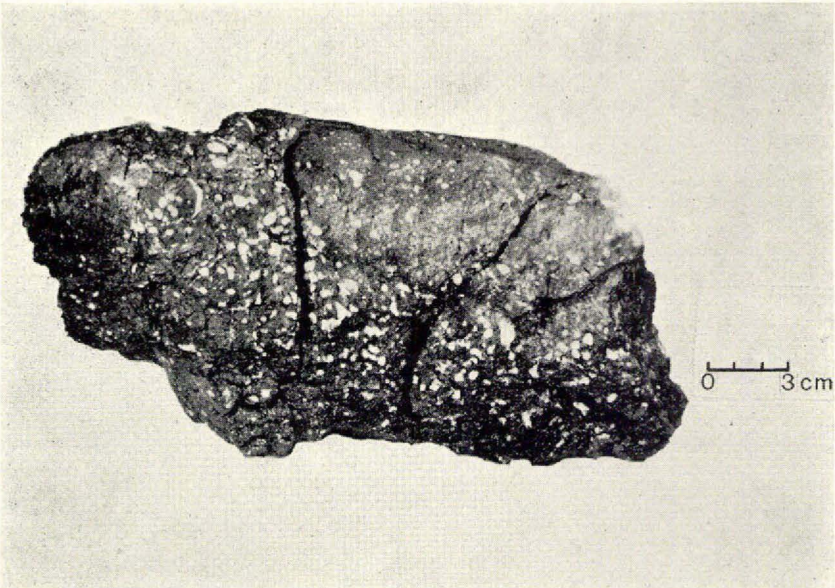

Fig. 2. Amygdaloid—extrusive carbonatized melilite-rock.

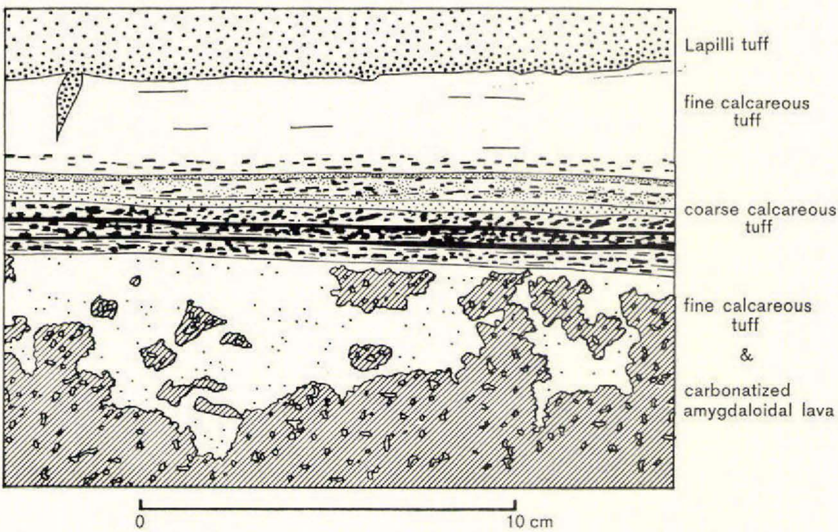

Fig. 3 Scoriaceous upper surface of an amygdaloid flow overlain by pyroclastics.

The *red-brown tuff* is a fine-grained, very compact rock in which bedding is seldom prominent. The freshly broken surface resembles terracotta. Large quartz grains can be distinguished in the groundmass.

Followed west along the scarp, the basal beds are progressively overlapped by higher, less well stratified volcanic rocks. Near where the basal beds wedge out, rounded bodies of amygdaloid about 1 m in diameter, resembling pillow structures, are set close together in a matrix of brown, carbonate-rich tuff.

A section through the main part of the volcanic unit is moderately well exposed along the shore. The section is interrupted by volcanic vents which cut the stratified succession at localities marked V_1 and V_2 on Plate 6. Sheets of amygdaloid are interstratified with alternate beds of coarse and fine carbonate-rich tuff, and there are occasional partings a few millimetres thick, caused by layers of particularly fine-grained carbonate tuff. In general, these beds have a mauve colour.

Throughout the section, there are numerous layers of inclusions, identified as ejected blocks and volcanic bombs. In addition, sporadic inclusions occur at all levels. The distribution of the inclusions in the tuff beds indicates a succession of showers of ash containing a variable amount of coarser ejectamenta. The inclusions are of five principal kinds:

(i) red, coarse-grained orthoclasite (transformed basement granite),
(ii) fine-grained, pale grey, massive carbonate rock,
(iii) amygdaloid,
(iv) coarse carbonate tuff,
(v) coarse white carbonate rock (sövite).

Inclusions of type (i) are usually angular; the rest are generally spheroidal. The diameter of the inclusions normally ranges up to 10 cm, but inclusions of type (ii) can be up to 25 cm in diameter, or greater.

South of the vent V_1 a very distinctive *martite tuff* outcrops. Euhedral octahedra of martite up to 1 cm long occur in thin impersistent layers parallel to the bedding planes. The matrix of the tuff is fine-grained carbonate of a deep wine-red colour. Irregular patches of barytes and fluorite are visible.

As the second volcanic vent V_2 is approached from the north, the pyroclastic beds show bright red and yellow colours, while the amygdaloid becomes purple. A strong cleavage is developed parallel to the stratification, and shattering is widespread.

Carbonate is the predominant constituent of the effusive rocks exposed north of V_2.

In the higher part of the succession south of V_2 the volcanic strata are almost entirely of pyroclastic origin. They contain substantially less carbonate than the beds lower in the succession and fine-grained varieties of tuff are generally absent. The tuffs contain abundant lamprophyric material, and *alnöite tuff* is an important rock type. Red, brown and bluish colours are usual, and large-scale cross-bedding is common. There are some agglomerate layers containing inclusions of sandstone, granite

Fig. 4. Section of agglomerate and bedded pyroclastics. Note alnöite bombs with radial carbonate veins.

and dark-brown bombs of lamprophyre, penetrated by radial veins of white carbonate (fig. 4).

Near the top of the volcanic unit vertical fissure fillings of red sandstone penetrate agglomeratic tuff. These structures measure up to 10 cm in thickness and 2 m in height. The sandstone shows cavernous weathering and resembles the sandstone at the base of the upper sandstone unit.

The topmost beds of the volcanic unit contain thin layers of soft, red, shaly material which may be very fine-grained carbonate tuff.

The lapilli beds. Beds of lapilli tuff, with a maximum thickness approaching 40 m, outcrop on the southern face of Angmagssiviup qáqâ, and form a number of small hills on the flat ground below the cliffs.

The lapilli are dark red, well-rounded, highly oxidized pellets of alnöite, mostly 2–3 mm in diameter, isolated from each other by a con-

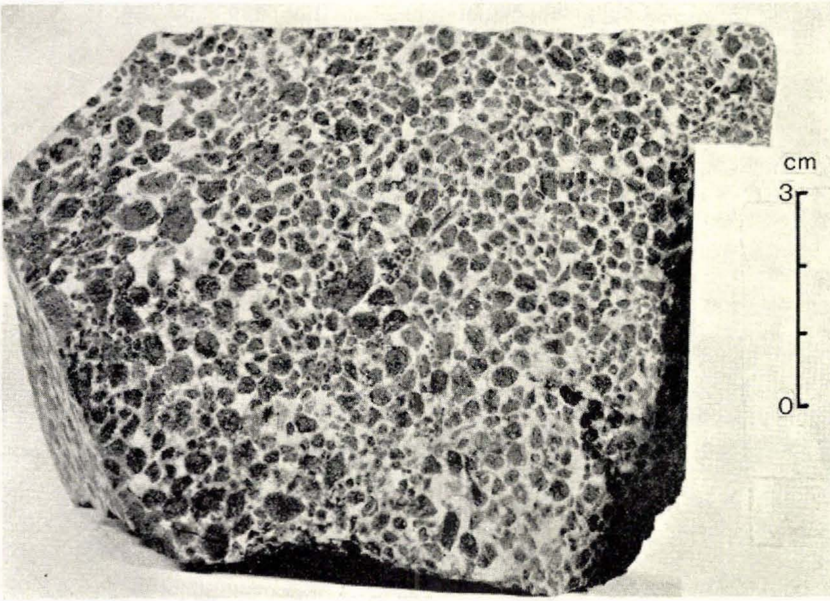

Fig. 5. Lapilli tuff.

tinuum of white carbonate (fig. 5). In places the tuff shows excellent stratification and occasionally, graded bedding can be observed. Coarser ejectamenta with a diameter exceeding 1 cm are rare.

Fragments of bedded and unbedded lapilli tuff figure prominently in the vent breccia of V_2. The lateral limits of the lapilli beds are not sufficiently well exposed to permit a decision on whether they constitute a horizon of the main volcanic unit or whether they are contained within the circumference of V_2.

The upper sandstone unit

In some places a thin lens of conglomerate is developed at the base of the unit. More usually, the unit is separated from the preceding one by a red shaly horizon (fine calcareous tuff). The lowest few metres are of a reddish sandstone with a notably cavernous weathering pattern which may reflect a high content of carbonate derived from the underlying volcanic unit.

3. Minor intrusions in the basement north of Qagssiarssuk (sub-area 2)

General

The granites and gneisses of the pre-Gardar basement which outcrop north of Qagssiarssuk are penetrated by numerous minor intrusions of alkaline-ultramafic rock types. All of these intrusive rocks have been carbonatized to a greater or less extent and they weather readily, commonly producing abundant soil of a distinctive ochre colour, which facilitates their recognition.

The intrusions belong to two structural groups, *viz.*

(i) thin, intrusive sheets, usually dipping at low angles,
(ii) steep, pipe-like bodies.

Both non-clastic ultramafic intrusive rock and intrusive volcanic breccia are encountered in the sheets and pipes; in some of the intrusive bodies non-clastic intrusive rock and breccia coexist.

The same igneous rock types are common to both the sheet-like and pipe-like intrusions, *viz.*

(a) lamprophyre,
(b) melilite-rock.

In this investigation, the term 'lamprophyre' is used as a collective term, embracing a range of ultramafic, chrysophyric rock types (see p. 31); monchiquite, mica-monchiquite, alnöite and mica-peridotite have been identified in thin section. Both the lamprophyres and the melilite-

Table 1. *Appearance of carbonatized intrusive rock types.*

Specimen Number	Appearance on weathered surface	Appearance on fresh fracture	Identification from thin section
61607	Warm-brown coloured rock of homogeneous appearance, cut by 5 cm thick nodular band of same colour.	Both units are white, marble-like. The host rock contains numerous black specks, the nodules are dark grey.	Mica-peridotite cut by nodular melilite-rock. (The black specks are dark mica.)
61682	Warm-brown, very rough knobbly surface with protruding, large black ore grains.	Dark grey, compact, fresh-looking rock, resembling pale dolerite.	Biotite-monchiquite. The ore grains are corroded magnetite phenocrysts.
61685	Pale brown, fine-grained rock. Flow structure is indicated by parallel alignment of tiny, rectangular pits and dark elongated vesicles.	Very pale grey with white rectangular phenocrysts and dark green vesicle fillings.	Monchiquite; the rectangular pits are weathered-out carbonate, pseudomorphing olivine phenocrysts.
61630	Small black nodules, closely packed in a dark grey matrix.	Black, tough, flinty rock. The nodules are scarcely distinguishable from the matrix.	Nodular melilite-rock. The nodules, which are of lamprophyric material, are partially disintegrated, merging into the groundmass.

Fig. 6. Composite sheet intrusion with melilite-rock cutting mica-peridotite. (Open compass is 20 cm long).

rock are invariably heavily carbonatized, and distinction of the various types in the field is usually difficult or impossible.

Macroscopic descriptions of typical specimens of the principal varieties are listed in Table 1.

At a number of localities there is evidence of more than one intrusive episode. Where the intersecting rock types have been identified, the earlier has proved to belong to the lamprophyric group, and the later to be of melilite-rock (fig. 6). Characteristics of the appearance in outcrop of the two groups are compared in Table 2.

Table 2. *Comparison of lamprophyre and melilite-rock in outcrop.*

Nature of characteristic seen in outcrop	Incidence of characteristic in lamprophyre	Incidence of characteristic in melilite-rock
Large grains of iron ore; dark mica; indications of pseudomorphs after olivine.	May be present	Absent
"Ultrabasic" weathering pattern.	May be present (See fig. 6)	Absent
Small, well-rounded, nodular inclusions.	Absent	May be present
Pronounced "flow" structure.	Rare	May be present

Fig. 7. Anastomosing sheets of carbonatized melilite-rock cutting basement granite.

The sheet intrusions

The majority of these are sill-like bodies about 1 m thick, and dip south at an angle of 25°–30°. Steeply inclined sheets also occur, but these are thinner, and relatively rare. Away from the shore section, exposure is very limited and there are not sufficient data available to determine whether there is a systematic regional pattern in the distribution and attitude of the sills.

The sheets are impersistent along the strike, thinning and pinching out, transgressing, splitting and generally tending to form an anastomosing complex more or less confined to a particular plane (fig. 7). A few sills present an uninterrupted linear outcrop of about half a kilometre and locally thicknesses of more than 10 m have been observed; however, such dimensions are unusual.

Some 40 sills, half a metre or more thick, are exposed on the shore between Qagssiarssuk and Umiussat, and it is likely that a similar number is concealed by superficial deposits.

Many exposures of the sills show tabular screens of granite wholly or partly detached from the wall rock. Sharp, angular granite fragments of different shapes and sizes occur locally in the sills.

Apparently there was a tendency for sheets of melilite-rock to intrude lamprophyre sheets in preference to the country rock; such multiple intrusions are quite common.

Fig. 8. Nodular melilite-rock (× $^{2}/_{3}$).

Nodular melilite-rock

Sills of this distinctive variety of melilite-rock are widely distributed throughout the area. Smooth, oblate spheroidal or ellipsoidal bodies stand out prominently on the weathered surface (fig. 8). The maximum diameter of these nodules rarely exceeds 1 cm. Where the nodules are closely packed, they are orientated with their maximum diameter parallel to the sill contacts. The excellent rounding of the nodules contrasts markedly with the angular nature of coexisting granite fragments. Generally the nodules are concentrated in bands parallel to the contacts.

Nodular lamprophyric breccia

This rock type occurs as a 1 m thick intrusive sheet, choked with well-rounded fragments of lamprophyre, ranging in diameter from a fraction of a centimetre up to more than 5 cm and accompanied by angular fragments of gneiss up to 10 cm across (fig. 9). Many of the nodules show traces of pseudomorphed olivine phenocrysts, and dark mica can be seen in some. The nodules are tightly packed right to the margins of the intrusion and even the smallest interstices are filled with tiny nodules.

Fig. 9. Intrusive sheet of nodular lamprophyric breccia.

Volcanic pipes

Volcanic pipes outcrop sporadically in the basement country of sub-area 2, north of Qagssiarssuk (fig. 1, fig. 10). All the pipes have steep sides with contacts seldom inclined at more than 20° from the vertical. The horizontal cross-section of most of the pipes is elongate, ranging from broadly elliptical to dike-like. Outcrop width ranges from a few metres to approximately 500 m. Certain of the more attenuated, dike-like outcrops of intrusive volcanic breccia are not well exposed; some of these may consist of a row of small, roughly circular diatremes. Evidently the emplacement of many of the pipes was controlled by linear fissures, apparently of random orientation in this particular sub-area.

Most of the pipes contain intrusive volcanic breccia (fig. 11), the matrix of which is a carbonate-impregnated tuffisite (intrusive volcanic microbreccia). The colour is deep brown or red.

In unusually fresh breccia material from one pipe the tuffisitic groundmass contains the following constituents, closely packed in a base of yellow ankerite:

(i) dark, well-rounded pellets of lamprophyre, 1–3 mm in diameter,
(ii) rare, anhedral grains of iron oxide up to 5 mm across,
(iii) occasional angular grains of feldspar or, less commonly, of quartz, derived from the country rocks.

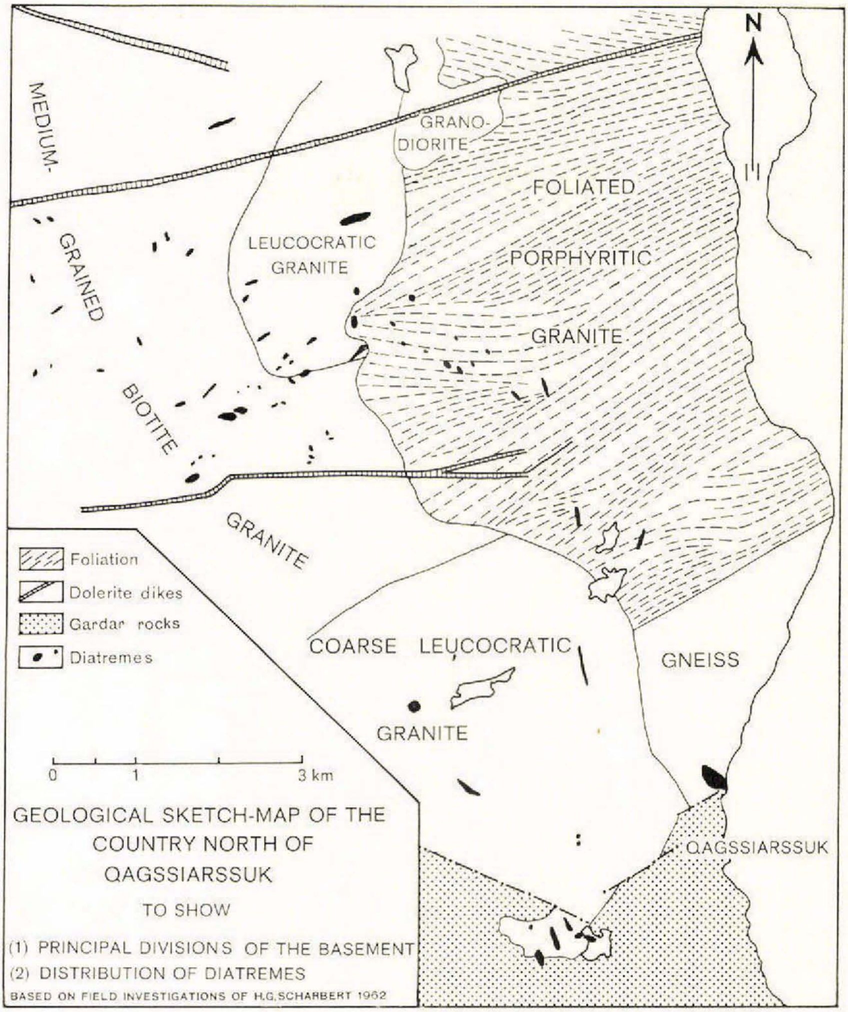

Fig. 10.

A few breccia pipes contain a matrix of lamprophyre. Toward the margin of one such pipe, the inclusions (mainly of gneiss) become progressively smaller, down to 1.0–0.5 cm in diameter, while remaining sharp and angular. This zone is followed by an inclusion-free, vesicular band ca 15 cm thick, chilled against the country gneiss.

Country granites and gneisses are by far the most abundantly represented rock types occurring as fragments in the pipes. Inclusions of lamprophyre, though comparatively much less abundant, are very widely distributed, and some can be found in nearly every outcrop of breccia. These inclusions are nearly always well-rounded, and range in size from tiny pellets up to blocks 30 cm across; a diameter of 5–10 cm

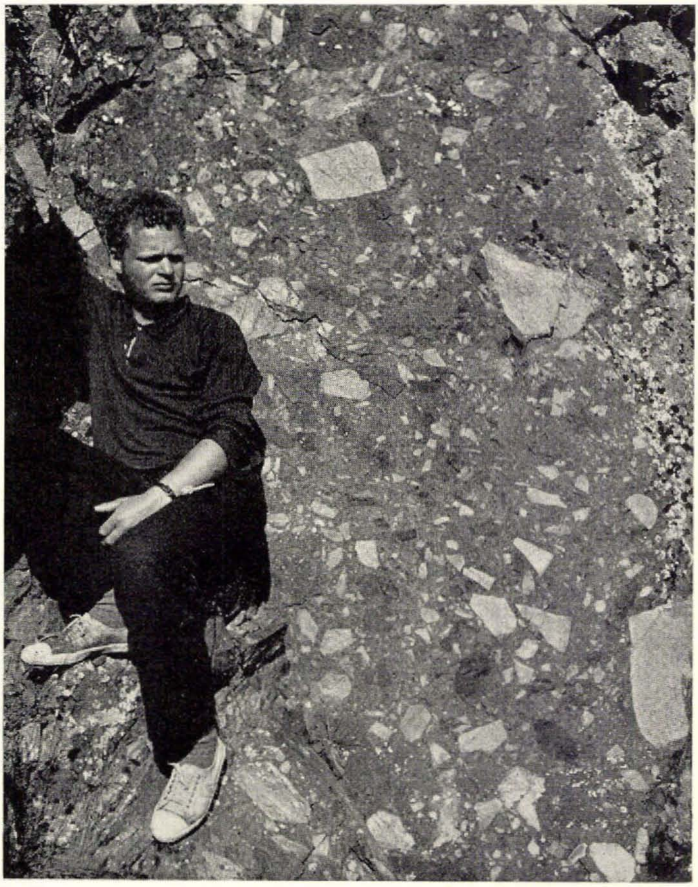

Fig. 11. Typical pipe breccia with pale angular fragments of granite and dark rounded bodies of lamprophyre.

is particularly common. The rock type is rather fine-grained, speckled with small black pseudomorphs after olivine phenocrysts. Usual colours range from pale grey to dark brown, red and black.

The granitic inclusions are most often angular in form. In general, their size range resembles that of the lamprophyric inclusions, although individual blocks may be considerably larger. A few composite inclusions have been found in which an angular fragment of gneiss is mantled by lamprophyre.

Other fragmental material (in particular, sedimentary or basaltic rock types obtained from the supracrustal Gardar strata) has not been recorded in the diatremes of this area.

In some of the diatremes, fragments of similar size are evenly distributed throughout the outcrop, while in others, inclusions of contrasting sizes occur together. The relative abundance of fragments in the matrix

Fig. 12. Vertical flow-lineation in pipe-breccia.

likewise varies from one pipe to another. A complete range from inclusion-free tuffisite to fragment-packed, coarse volcanic breccia has been found.

Vertical flow-lineation has been observed in breccia adjacent to the margin in a few pipes; fig. 12 shows one of the best examples. Low-angle stratification has not been recorded anywhere in the pipe-breccias of the basement country.

Very few contacts of pipe-breccia against country rock are exposed. An exception occurs at the edge of a large diatreme where a block of gneiss about 7 m across is wholly or almost wholly surrounded by volcanic breccia. Towards the block, the concentration of inclusions in the breccia diminishes markedly and a few centimetres from the block, the tuffisite grades into nearly pure, yellow ankerite by a gradual decrease in the amount of lamprophyre pellets and attrited granitic material.

Fig. 13. Ellipsoidal fractures developed in basement granite adjacent to an ultramafic intrusion.

Ankerite veins penetrate the gneiss intimately in a zone some decimetres broad, forming a mosaic in which the gneiss fragments have suffered little displacement. Hereabouts, the gneiss (which is usually red) has a leached appearance, and in places is white, particularly in the centres of detached fragments. Some of the fragments of gneiss are very fine-grained and have a streaked appearance, so that they closely resemble rhyolite. In general, however, contact alteration effects related to the pipes are not evident in the field.

Isolated areas of gneiss breccia

About 3.5 km west of Qagssiarssuk there are a few outcrops of deep red, fine-grained gneiss. The rock is intensely brecciated into fragments up to 10 cm across, with random orientation. The interstices between the blocks are occupied by ankerite. Neither lamprophyre nor tuffisite is exposed in the vicinity, and it is suggested that the breccia represents the roof zone above a concealed diatreme or other related intrusion.

Exfoliation ellipsoids in the country rock

An unusual effect associated with some of the sheet and pipe intrusions is the development of ellipsoidal fractures in the country granite or gneiss within some tens of metres of the contact. Most of these structures are of very regular form, consisting of near-perfect ellipsoids of granite enclosed in concentric shells of even thickness. The size of the cores ranges from about 10 cm on the major axis, up to 50 cm. Farther from the contact, the development of concentric shells becomes less pronounced, and at several metres distance from the contact single ellipsoidal fractures occur.

Approaching the contact, yellow ankerite becomes visible in the fractures, and there is a gradual transition into an ankeritic breccia in which ellipsoids of granite are set in a matrix of small angular granitic fragments and granitic rubble (fig. 13).

4. Minor intrusions in the basement north of Narssarssuaq (Sub-area 3)

General

Ultramafic pipes and sheets intrude the basement rocks in the country east of Tunugdliarfik, north of Narssarssuaq. While some pipes and sills on the shore are of pyroxenite, and have not been carbonatized, most have affinities with the lamprophyric suite. The inland diatremes resemble those of the country north of Qagssiarssuk, with the difference that they show some tendency to be elongated in an ENE–WSW or NE–SW directions, parallel to the foliation of the country granitic rocks (Walton, 1965).

Lamprophyric intrusions

These are closely similar to the minor ultramafic intrusions north of Qagssiarssuk and, like the latter, are highly carbonatized.

Intrusions of mica-pyroxenite

Intrusions of this material have only been recognized on the coast. Two possible necks of the rock are marked P_1 and P_2 on fig. 1. The remainder of the intrusions, which outcrop sporadically along the shore north of P_1, are sheet-like and 10 cm–2 m thick. The rock is coarse, greenish-black and micaceous, with a characteristic weathering pattern of deep parallel grooves.

Fig. 14. Pipe of mica-pyroxenite with partly rounded inclusions of granite.

At P_1 there is an outcrop of pyroxenite with a maximum width of 8 m. The rock, although similar in type to that of the sills, is finer grained and has a porous weathered surface. In parts of the outcrop inclusions are abundant, while in adjacent parts there are none. Most of the inclusions are angular fragments of pyritic granite, ca 10 cm across, with rounded edges and corners (fig. 14). There are also some smaller well-rounded inclusions of a very fine-grained black, heavy, magnetic rock.

Three smaller, poorly-exposed outcrops on the shore at P_2 have steep contacts. They are of dark pyroxenite, contain granitic inclusions and are crossed by veins or narrow pods of a coarse, micaceous rock.

5. Minor intrusions in the Qagssiarssuk Triangle

The contrast in the geology north and south of Qagssiarssuk settlement is a consequence of the substantial downthrow on the NE–SW fault. The effusive rocks, the volcanic vents and other minor intrusions described in the succeeding paragraphs, are evidently the surficial or near-surface manifestations of diatremes such as those described in the preceding section.

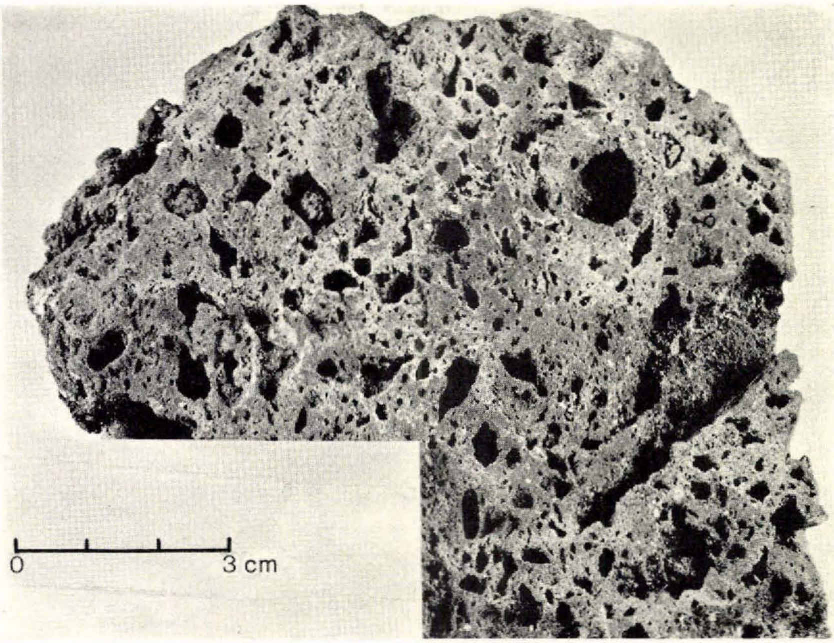

Fig. 15. Weathered surface of "sandy tuffisite".

Tuffisite Intrusions of Irregular Shape

Intrusive tuffisite outcrops over an area of ca 1300 m² south of Lake A, and forms an elongate outcrop of ca 700 m² on the hillside south of Lake B. Generally, the tuffisitic rocks are poorly exposed.

The most usual type of tuffisite, termed "*sandy tuffisite*", is fine-grained, reddish-brown, with a glassy lustre on the freshly broken surface due to the abundance of quartz grains present. The weathered surface is deeply pitted, a consequence of the high carbonate content of the rock (fig. 15). Coarser varieties, with a smaller content of quartz grains, are identical with the tuffisite of the three diatremes south and west of Qagssiarssuk (see p. 27). A kind of stratification somewhat resembling cross-bedding has been seen at a few localities, involving this coarser variety of tuffisite, and may represent a flow structure rather than a phenomenon related to sedimentation. The scarcity of dip and strike measurements prevents any structural deductions.

Near the western edge of the northern tuffisite body, a greenish rock is exposed which contains carbonate inclusions several centimetres across. There are also cavities of similar size, containing large, euhedral calcite crystals. The greenish rock has been identified in the laboratory as a highly carbonatized and chloritized alnöite or alnöitic tuffisite.

Fig. 16. Breccia of sandstone blocks near roof of irregular intrusion of tuffisite.

The bulk of the tuffisite is of medium to coarse sand grade, and inclusions more than a few centimetres in diameter are relatively uncommon and widely scattered. Most of the rock types known to underlie the intrusion are represented in the tuffisite, and inclusions of basement granite, lamprophyre, sandstone and olivine-basalt have been found. Lamprophyre inclusions up to 10 cm in diameter are most common, but study of the tuffisite in thin section has indicated the local abundance of micro-inclusions of basaltic types.

On the eastern side of the northern tuffisite body, about 100 m south of Lake A, a contact against sandstone is well exposed, striking 25° and dipping eastward at 45°. The contact is concordant with the bedding of the sandstone, which has been somewhat arched by the intrusion. Towards the contact, the tuffisite grades into an ankeritic breccia which contains numerous small, angular fragments of deep red, basement granite (more or less transformed to orthoclasite), and larger blocks of sandstone.

Followed south-west, the contact transgresses gradually upward into the volcanic unit. Where the roof rock is sandstone, a breccia of great blocks of the sediment is formed (fig. 16). Some of these blocks, which measure up to 1 m across, are wholly detached and isolated within the tuffisite, while others remain close together, more or less *in situ*.

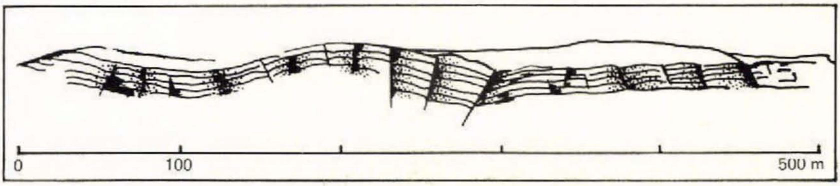

Fig. 17. Folded and faulted sandstone overlying the tuffisite intrusion on the south side of Lake B.

A small isolated area of coarse, sandstone breccia rests on tuffisite ca 100 m south of Lake A and is an outlier of the sedimentary roof.

Where the roof is formed by carbonate-rich rocks of the volcanic unit, a contrasting type of eruptive contact is developed in which rather rounded blocks of carbonate rock are set in a tuffisite matrix.

An isolated, pear-shaped area of tuffisite outcrops at a small lake ca 100 m south of the main body, from which it is separated by a strip of sandstone ca 100 m wide, which forms a low ridge. It is very probable that the two tuffisite bodies are in continuity underneath the sandstone.

It seems certain that the present level of erosion coincides closely with the roof of the intrusion, which must have been nearly flat or slightly domed. Where exposed, the contacts dip outward at comparatively low angles. The available observations do not however indicate whether the tuffisite body becomes steep-sided and pipe-like at depth, or whether it is a flat-lying, laccolithic sheet.

A very poorly exposed body of tuffisite, roofed by sandstone, outcrops on the hillside south of Lake B. It may originally have been in continuity with the main intrusion and have suffered sinistral translation along the east-west fault on the north side of Lake B. The well-bedded sandstone which overlies the elongate tuffisite outcrop is buckled and faulted (fig. 17).

Tuffisite diatremes

Three bodies of tuffisite and volcanic breccia, with very steep, arcuate, intrusive contacts, outcrop on the face and top of the cliff south of Qagssiarssuk. In each of them the northern contact is concealed. The largest, easternmost body is better exposed than the others; it is roughly circular in plan and about 200 m in diameter. The adjacent country sandstone has been considerably disturbed, with minor faulting and tilting of the strata. The middle and eastern diatremes, which have diameters of 100 m and ca 10 m respectively, are seen to cut through the lower sandstone unit and the well-bedded, basal beds of the volcanic unit, while in the westernmost diatreme the vent filling is seen to be overlain by a coarse-grained red tuff, presumably belonging to a horizon slightly higher than the basal beds of the volcanic unit.

All three diatremes are filled with similar brownish tuffisite, locally stratified and/or fragment bearing. The characteristics of the pipe fillings change rapidly both horizontally and vertically. Sandstone is the dominant rock type forming inclusions in the pipe fillings, followed by fragments of granite (rounded or angular), rounded blocks of carbonatized lamprophyre, coarse-grained saccharoidal carbonate rock (sövite) and rounded inclusions of a fine-grained pale grey carbonate rock.

600 m south of Lake B there is a fourth intrusion of tuffisite, which appears to have the form of a vertical cylinder 80 m in diameter, partly roofed by carbonate tuff. The upper contact relations are similar to those described at the eastern margin of the large, irregularly shaped tuffisite body where it is roofed by the volcanic unit.

Three other pipes of brown tuffisite, none exceeding 25 m in diameter, outcrop in the western part of the Triangle.

Volcanic vents

Two volcanic vents, corresponding to levels in volcanic conduits, higher than those exposed in the diatremes described above, outcrop on the shore at V_1 and V_2 (Plate 6).

Vent V_1. Ca 1 km south of Qagssiarssuk a 15 m-long section through a volcanic vent is exposed along the shore. The northern wall of the structure is very steep at the water's edge, but upwards it inclines out at an increasingly shallow angle.

Rocks of the volcanic unit (carbonate tuff etc.) are cut transgressively by a deep red, coarse, even-grained *orthoclasite.* Southwards, this rock is intensely brecciated by ankeritic veins, and a mosaic is produced consisting of small angular fragments of orthoclasite set in a matrix of brown carbonate. The orthoclasite contains numerous large irregular blocks of fine-grained, pale grey carbonate rock, up to 0.5 m in diameter. The latter rock rather resembles non-amygdaloidal, carbonatized melilite-rock. Some of the blocks, in turn, contain small inclusions of altered granite, or orthoclasite. Farther south, the vent material grades into a breccia consisting of fragments of bedded and unbedded lapilli tuff set in a fine-grained dark red matrix.

Vent V_2. This vent contains a variety of volcanic rock types including bedded tuffs, amygdaloid and volcanic breccia. Beds of lapilli tuff are steeply inclined against the northern edge of the vent. Thin beds of fine-grained red carbonate tuff occur interbedded with the lapilli tuff. Some layers of the fine tuff contain mud-cracks, indicating that the sediment was wet at one stage. A flow of amygdaloid occurs interstratified with the pyroclastic beds.

Southwards, the bedded sequence within the vent is overlain by a volcanic breccia consisting of fragments of bedded and unbedded lapilli tuff (up to 0.5 m in diameter) and rounded blocks of fine-grained carbonate rock (maximum diameter 2 m), set in a deep red, fine-grained matrix. Examination of thin sections of the matrix has shown it to be a micro-breccia formed by the comminution of consolidated lapilli tuff. Over the greater part of the 300 m-long exposed section the volcanic breccia alternates with coarse, cross-bedded tuffs. Locally the tuffs are agglomeratic and contain bombs of carbonatized lamprophyre.

Diatremes of basaltic tuffisite

The larger of two pipes of basaltic tuffisite outcrops at the western end of Lake A. The tuffisite has a greenish colour due to the presence of abundant chlorite and is composed of tiny fragments of olivine-basalt, with a variable admixture of quartz grains and small pieces of sandstone. Angular inclusions of olivine-basalt about 1 cm in diameter are quite abundant and evenly distributed; there are also rarer ellipsoidal inclusions about 10 cm long.

In a few places stratification is seen; near the centre of the body a strike of 110° and a dip of 40° to the north were recorded in poorly stratified tuffisite containing basalt blocks of notable angularity.

A smaller intrusion of similar composition outcrops at the southwest end of Lake B and shows a sharp intrusive contact against sandy tuffisite.

Intrusions of carbonatized melilite-rock

Half a kilometre south of Lake A, a stock of carbonatized rock with a maximum diameter of ca 300 m cuts the lower sandstone unit, the volcanic unit and the large, irregularly shaped body of tuffisite. The rock is fine-grained, dark purple-brown in colour and has a peculiar weathering pattern which is probably related to vertically elongated vesicular structures. There are sparse small inclusions, most of them of severely altered basement granite. Affinities of the intrusive carbonatized melilite-rock with the extrusive amygdaloid are not obvious in the field, but in thin section the two rocks are closely similar.

Approximately 400 m to the south of this stock, there is a small oval outcrop of purple amygdaloid which seems to represent another steep-sided intrusion.

100 m south-west of Lake C, a 5 m-thick sill of fine-grained carbonatized melilite-rock is intruded conformably into sandstone, close to the NE–SW fault. It closely resembles the sheet intrusions of the basement country.

Sandstone dome

On the north slope of Angmagssiviup qáqâ, about 100 m above sea level, beds of the upper sandstone unit are arched into a very regularly-shaped dome about 50 m across. The strata maintain their thickness across the dome and there is no sign of rupture. The structure recalls the disposition of sediments above salt domes and strongly indicates the presence of an underlying pipe-like volcanic intrusion.

Barytes mineralization

Barytes is common throughout the volcanic unit, occurring partly as local pods of coarse crystals and partly in a disseminated form throughout the intergranular interstices of the pyroclastic rocks. It also occurs on a microscopic scale in the intrusive breccias and tuffisites.

Part II. PETROGRAPHY

1. Preliminary observations

Subsequent alteration

All of the rocks discussed in the present chapter are believed to have been subjected to low grade thermal metamorphism imposed by younger intrusive centres of the region, in particular the Igaliko intrusive complex (Ussing, 1912). The emplacement of this complex occurred distinctly later in the Gardar period than the volcanic events of the Qagssiarssuk area.

Nomenclature

The term "lamprophyre" is used here in the sense of Knopf, *i.e.* "mesotype (= mesocratic) or melanocratic rocks carrying solely ferromagnesian phenocrysts in an aphanitic groundmass, and in which the ferromagnesian minerals in the groundmass show notable idiomorphism" (Knopf, 1936, pp. 1748–1749). Monchiquite, alnöite and mica-peridotite (*cf.* Watson, 1955, p. 567) all fall within the scope of Knopf's definition.

Traditionally, the term lamprophyre is restricted to intrusive rocks, since equivalent extrusive magmas are rare or unknown. The term is maintained in the present work regardless of mode of occurrence.

2. Systematic petrography of the ultramafic rocks

General

The following ultramafic rock types have been identified in thin section:

(i) monchiquite
(ii) mica-monchiquite
(iii) alnöite
(iv) mica-peridotite
} lamprophyres
(v) melilite-rock
(vi) mica-pyroxenite

Carbonatization

Without exception, specimens of types (i)–(v) show evidence of having been subjected to intense, mainly syngenetic, alteration processes (see p. 60). The chief manifestation of these processes is the widespread replacement of original silicate minerals by carbonate. The degree of carbonatization of the lamprophyres varies considerably, both from one intrusive body to another and also within a single intrusion. The melilite-rock invariably shows evidence of extreme carbonatization.

Olivine and melilite, two of the principal original silicate minerals, are never preserved in unaltered form, although they usually leave pseudomorphs which are sufficiently distinctive to permit identification. Only rare traces of pyroxene still remain, although this mineral was an important primary constituent of many of the rocks. Perovskite has generally been almost completely destroyed.

The high carbonate content of most of the rocks has made them particularly susceptible to plastic deformation and/or recrystallization, leading to widespread destruction of pseudomorphic textural features. In favoured localities, however, the greater part of the original texture is preserved, permitting a fairly complete assessment of the original mineral assemblage. In general, pseudomorphs after olivine phenocrysts have proved particularly resistant to destruction (Pl. 1 a).

Monchiquite

Of all the ultramafic rock types of the region, this variety has the widest spatial distribution. It is intruded into some of the volcanic pipes, constitutes the most common kind of igneous inclusion in the pipe-breccias and forms many intrusive sheets in the granites of the basement.

Specimens of monchiquite which have not suffered carbonatization have been obtained from minor intrusions at Igaliko and Sitdlisit and from a flow 5 km north-east of Ilua. These rocks are identical to the monchiquites of the Qagssiarssuk area, differing only in their superior state of preservation. These comparatively unaltered rocks served as a valuable reference when identifying pseudomorphed minerals in the carbonatized suite.

The monchiquites are vesicular and porphyritic, with pilotaxic texture in the groundmass. The vesicles are 2–3 mm in diameter and contain chlorite and/or carbonate.

The phenocrysts (0.5–2.00 mm in length) are of pseudomorphed olivine, accompanied by a smaller amount of pyroxene (the latter mineral unaltered in some instances). The pseudomorphed olivine occurs as phenocrysts only, while pyroxene occurs both as phenocrysts and as a constituent of the groundmass. Yellow or pinkish-brown clinopyroxene occurs as phenocrysts of elongated prismatic form and as acicular groundmass grains.

Small amounts of titanomagnetite, apatite and an altered mineral tentatively identified as perovskite, also occur.

Feldspar and biotite-phlogopite are absent from the monchiquites.

The principal secondary minerals are carbonate (ankeritic where determined), chlorite, chalcedony and haematite.

It is estimated that in the average monchiquite, the volumetric proportions of the primary minerals before carbonatization would have been approximately as follows:

olivine	15 %
pyroxene	30 %
titanomagnetite and perovskite ..	5 %
apatite	1–3 %

Almost half of the volume of the rock, now occupied by carbonate, chlorite and silica, consisted of glass or of some mineral or minerals no longer identifiable.

Mica-monchiquite and alnöite

It is probable that most of the intrusive sheets on both sides of Tunugdliarfik belong to these categories; on the other hand, such material rarely occurs as inclusions in the tuffisite diatremes.

Mica-monchiquite and alnöite cannot be distinguished from each other in the field, however their rather coarser grain size and the presence of visible biotite help to distinguish them from monchiquite.

The essential petrographic difference between mica-monchiquite and alnöite is the presence of pseudomorphed melilite in the latter; since alteration has precluded recognition of this definitive mineral in many specimens, it is convenient to describe the two rock types together.

Two generations of olivine phenocrysts are tentatively distinguished, from pseudomorphs. The earlier generation, forming less than 5 % of the rock, occurs as compound euhedra (*i.e.* several crystals grown together) 2 mm or more in length; the second generation is represented by simple idiomorphic grains ca 0.8 mm in length which constitute 20 % of the rock. The nature and disposition of the alteration products (Table 3) indicate an original difference in composition between the olivine crystals of the two generations. The coexistence of two kinds of olivine (*e.g.* crysolite and monticellite) is a rather common feature of alnöites and kimberlites (*cf.* Wagner, 1914, pp. 54 and 82: Bowen, 1922, p. 2).

The pseudomorphs after melilite show a lath-like habit characteristic of the mineral (Pl. 1 b), have an average length of ca 0.4 mm and a length: breadth ration of 6:1. Squarish cross-sections are seen and the typical median parting is commonly preserved within the replacive chlorite.

Table 3. *Location and percentage of replacive minerals in pseudomorphed olivine grains of an alnöite.*

		Carbonate	Quartz	Serpentine	Chlorite
1st generation	Percentage	55 %	35 %	—	10 %
	Location	peripheral	internal	—	central
2nd generation	Percentage	15 %	15 %	70 %	—
	Location	peripheral	peripheral	overall	—

The chlorite fibres are arranged normal to the elongation of the grains, as is usual with fibrous alteration products of melilite.

Other volumetrically important groundmass minerals of these rocks are pyroxene and dark mica. The pyroxene is acicular and similar to the pyroxene of the monchiquites; the mica occurs as euhedral grains.

Phenocrysts of magnetite occur sporadically and occasionally conspicuously (some measure 1 cm across), but they do not constitute an

Table 4. *Analyses of carbonatized rock types from minor intrusions.*

	1	2	3	4	5	6
SiO_2	39.3	22.5	13.0	45.6	29.0	17.4
TiO_2	2.7	3.4	3.8	3.1	4.4	5.1
Al_2O_3	7.9	4.2	6.3	9.2	5.4	8.4
Fe_2O_3	2.7	7.5	3.9	3.1	9.6	5.2
FeO	10.2	9.7	18.7	11.8	12.5	25.0
MnO	0.2	0.2	0.5	0.2	0.3	0.7
MgO	7.1	12.7	11.9	8.2	16.3	15.9
CaO	9.8	13.1	10.4	11.4	16.8	13.9
Na_2O	trace	trace	trace			
K_2O	0.9	1.1	0.7	1.1	1.4	0.9
P_2O_5	1.3	0.5	0.5	1.5	0.6	0.7
CO_2	13.8	20.8	24.5			
H_2O	3.3	2.1	2.8	3.8	2.7	3.7
BaO	0.5	0.4	1.3	0.6	0.5	1.7
SrO	0.2	0.5	0.9	0.2	0.6	1.2
ZrO	trace	trace	trace			
Total...	99.9	98.7	99.2			

1. 61685, carbonatized monchiquite; 400 m altitude, 7 km north of Narssarssuaq Harbour.
2. 61682, mica-monchiquite with magnetite phenocrysts; 550 m altitude, 8 km from Narssarssuaq harbour, 350° bearing.
3. 61606, carbonatized nodular melilite-rock; 40 m altitude in river at Qordlortoq.

4, 5 and 6 are 1, 2 and 3 respectively, calculated to total 100 % without CO_2.

Analyst B. I. Borgen.

important modal element of the average rock. The mineral was idiomorphic, with octahedral habit, at an earlier stage in its history, but subsequently has been greatly modified by vigorous corrosion. Groundmass grains of magnetite 0.02–0.05 mm across are nearly all octahedral and have not suffered corrosion. Despite the high normative ilmenite content (6.5 % Il) indicated by the analysis of a typical specimen (61682, Table 4) magnetite is the only opaque mineral which appears in polished section; investigation of the crystals by X-ray diffraction failed to reveal the presence of any phase other than magnetite.

Sheaves of small apatite prisms occur in the rocks; they crystallize later than the main mafic minerals and may be of secondary development, related to carbonatization. Tiny, octahedral grains of leucoxene may be pseudomorphs after perovskite.

The alteration of these rocks resembles the alteration of the monchiquites.

A hypothetical average alnöite of the area, before carbonatization, would have had approximately the following mineralogical constitution:

magnetite phenocrysts + olivine of the first generation	5 %
olivine of the second generation	20 %
dark mica	25 %
groundmass magnetite	10 %
melilite	20 %
groundmass pyroxene, accessories (apatite, perovskite), other minerals	20 %

There is a moderate direction of the rock fabric, manifested by the pseudomorphs after olivine and melilite, which tend to be orientated parallel to one another. In alnöite specimens where substantial amounts of pseudomorphed melilite crystals are preserved, the rock bears a very close resemblance to katungite, a volcanic rock akin to kimberlite, found in Uganda (Holmes, 1936).

Mica-peridotite

This rock type is represented by a single specimen (61607). A description of the appearance in outcrop can be found in Table 1; see also fig. 6. In thin section (Pl. 2 a) the rock proved to be highly carbonatized.

Recognizable pseudomorphs after olivine constitute approximately half of the volume of the rock; there are also indications that a considerable quantity of altered olivine grains have been broken down to a stage where certain identification is no longer possible. The pseudomorphed olivine grains are mostly from 0.5–1.0 mm in length, but some exceed 2 mm; the larger grains tend to be rounded, while idiomorphic habit is common in the smaller individuals. (Olivine grains of two contrasting forms occur in some kimberlites, *cf.* VERHOOGEN, 1940).

The mica resembles that of the alnöites, and flakes of mica are closely packed between the pseudomorphed grains of olivine.

Small grains of opaque minerals are scattered throughout the fine-grained carbonate groundmass. The majority are octahedra of iron oxide; a few may be pseudomorphs after perovskite.

There are a few carbonate-filled interstitial vug-like structures less than 1 mm across.

Melilite-rock (intrusive and extrusive)

Melilite has been highly susceptible to carbonatization in all of the rocks under review, and the melilite-rock, on account of its high original melilite content, is now the most highly carbonatized rock type of the ultramafic suite. Many specimens contain 80 $^0/_0$ or more of modal carbonate.

The melilite-rock which forms the flows of the volcanic unit is essentially the same rock type which occurs as intrusive sheets in the basement granite, and as stocks cutting the strata of the Qagssiarssuk Triangle.

The mineralogy is simple, consisting of melilite (without exception pseudomorphed by carbonate), a few flakes of chlorite; apatite and iron oxide. The replacive carbonate is ankerite in the minor intrusions, and predominantly calcite in the flows. Many of the intrusive bodies are contaminated to a greater or less extent by the breakdown products of inclusions of lamprophyric material and of fragments of granitic country rock; the lavas, on the other hand, contain extremely little extraneous material.

As a rule textural detail is much better preserved in the flows than in the intrusive rocks. In thin section the lava is seen to consist almost entirely of carbonate, most of it in the form of lath-shaped grains which pseudomorph melilite (Pl. 2 b). The laths are typically 0.3–0.4 mm long, with a length:breadth ratio of 6:1. Some specimens contain a second size group with an average length of about 1 mm. The large laths usually consist of a single crystal of carbonate with its c-axis parallel to the direction of elongation, while the smaller laths are made up of a mosaic of anhedral granules of carbonate.

In specimens of melilite-rock from the minor intrusions the laths belong to the smaller size group only, but are usually replaced by a single crystal of carbonate.

In both flows and intrusions the elongate grains (*viz.* pseudomorphed melilite and mica, apatite) are closely packed and show strong fluxional alignment. Vesicles are very abundant in the extrusive melilite-rock;

Table 5. *Analyses of carbonatitic rocks.*

	1	2	3	4	5
SiO_2	4.4	5.62	1.01	7.29	3.99
TiO_2	2.4	0.53	0.06	0.86	0.06
Al_2O_3	0.7	1.29	0.23	1.04	0.57
Fe_2O_3	4.1	2.84	0.64	2.23	3.36
FeO	0.5	1.94	3.19	1.58	trace
MnO	0.5	0.46	1.12	0.35	1.40
MgO	7.2	1.46	0.88	3.74	1.35
CaO	40.1	46.88	49.02	45.71	48.54
Na_2O	0.2	0.40	0.14		0.21
K_2O	0.1	0.64	0.13		0.13
P_2O_5	2.7	1.96	0.69	0.67	0.07
CO_2	36.4	33.02	41.66	34.88	40.22
H_2O	0.1	1.57	0.40	1.78	0.09
BaO	0.1	0.75	0.60		
SrO	0.4	0.39	0.01		
SO_2		0.48			
F			0.18		
S			0.49	0.20	
SO_3		0.48			
Total...	99.9	99.91	100.44	100.33	99.99

1. Melilite-rock flow (amygdaloid) 61740, Qagssiarssuk.
Analyst: B. I. Borgen.
2. Carbonated lava, C. 5509, bomb from Kalyango Volcano, Fort Portal volcanic field, Uganda.
Analyst: W. H. Herdsman, (Holmes, 1956).
3. Alvikite dike, analysis No. 120, Alnö.
Analyst: R. Blix, (von Eckermann, 1948).
4. Carbonate dike, Premier Mine, (No. 3125).
Analyst: Miss H. E. Vassar (Daly, 1925).
5. Sövite, Tundulu, Malawi.
Analyst: Miss J. R. Baldwin (Garson, 1962).

they are 1–2 cm long, elongate, occasionally dumb-bell shaped and are filled with coarsely crystalline carbonate and a little barytes. Elongate vesicles occur in the stock, but vesicles are rare in the sheet intrusions.

The finer details of the original texture of the melilite-rock are now lost owing to alteration processes, and the exact limits of the original melilite grains are no longer clear; thus a reliable volumetric estimate of the original melilite content of the rock cannot be made and the volume of the associated intergranular areas is likewise uncertain. Undoubtedly the volumetric percentage of melilite was originally very high, certainly over 60 % and possibly over 90 %.

The remaining recognizable minerals do not rise above accessory status. The chlorite unmistakably pseudomorphs flakes of dark mica less than 1 mm long. The iron oxide is haematite, with octahedral habit in some instances, presumably replacing magnetite and/or perovskite. Apatite occurs as sparsely distributed prisms up to 0.5 mm long, usually showing signs of corrosion, or partial replacement by carbonate.

The alkalis, alumina, and part of the silica recorded in the analysis of a specimen of the lava (Table 5) are possibly accommodated in alkali feldspar (present as fine-grained xenolithic material derived from basement granite). Some of the silica is present as secondary interstitial quartz. The high titania of the analysis would be referred to ilmenite and sphene in the norm (0.43 % and 0.94 % respectively). It is probable that these minerals are actually present in the rock in a very fine-grained form, although they have not been observed.

Nodular melilite-rock

The groundmass of this subordinate rock type corresponds to melilite-rock, while the mineralogy of the nodules is similar to that of monchiquite or mica-monchiquite (alteration of the nodules precludes the possible recognition of melilite). Some of the smallest nodules consist of a single pseudomorphed olivine phenocryst with a small amount of fine-grained lamprophyric matrix adhering to it (Pl. 2 a). In a few of the specimens, dark mica forms an important or dominant part of the mineralogy of the nodules. Towards the peripheries of such nodules, the elongated mica flakes have a very strong tangential orientation and the outermost part of many nodules is a nearly monomineralic mica shell.

Mica-pyroxenite

In the more usual medium-grained variety of mica-pyroxenite, dark mica makes up 50 % to 80 % of the rock, occurring as untidy assemblages of ragged broad flakes up to ca 1.5 mm long. Subhedral grains of iron oxide (0.1 mm or less in diameter) are unevenly scattered through the rock, in places accompanied by clusters of sphene granules; isolated idiomorphic sphene grains up to 0.5 mm across also occur.

Most of the groundmass between the mica flakes consists of an aggregate of elongated grains ca 0.04 mm long, of a mineral which is probably pyroxene, with a very pale, greenish-yellow tinge. Within the mesostasis there are some small areas of a water-clear mineral, thought to be relics of earlier-formed large grains of pyroxene.

In the coarse pegmatitic mica-pyroxenite, relics of euhedral pyroxene prisms several millimetres in length are found. Most of these have been extensively broken down to a felt of undirected tiny grains of secondary

Table 6. *Analyses of mica-pyroxenites and ugandite.*

	1	2	3	4
SiO_2	37.5	39.8	36.9	42.14
TiO_2	6.2	3.7	3.7	3.38
Al_2O_3	6.2	5.6	9.0	8.73
Fe_2O_3	5.9	6.5	5.8	4.72
FeO	12.0	12.0	8.5	5.63
MnO	0.2	0.3	0.2	0.18
MgO	13.1	16.9	19.1	16.59
CaO	7.2	10.4	7.3	8.98
Na_2O	0.2	0.9	0.9	2.00
K_2O	4.9	2.9	5.8	3.98
P_2O_5	1.0	0.3	<0.1	0.48
CO_2	2.7	—	—	0.31
H_2O	1.6	1.6	2.7	1.99
BaO	0.6	—	—	0.22
SrO	0.2	—	—	0.14
Total...	99.5	100.9	100.0	100.07

1. Mica-pyroxenite (61634) Qagssiarssuk.
   Analyst: B. I. Borgen.
2. Mica-pyroxenite D 2644, B. H. 11 (145 ft.), Nakupa, W. Bukusu.
   Analyst: J. W. Baldock (Baldock, 1967).
3. Mica-pyroxenite B.H.S. (190 ft.), Surumbusa, N. Bukusu.
   Analyst: J. W. Baldock (Baldock, 1967).
4. Ugandite (with xenocrysts of biotite) G.44. Katwe Crater, Uganda.
   Analyst: H. F. Harwood (Holmes, 1956).

pyroxene. Indications are strong that large euhedral pyroxene grains constituted the main mineral of this rock at an earlier stage.

The latest stage of crystallization of the pegmatitoid appears to be represented by small vugs and tiny interstitial areas where carbonate and quartz are developed together or independently. Adjacent to these areas the groundmass pyroxene adopts a greenish tinge and right at the margins of the areas there is a zone of needles of aegirine which pierce both carbonate and quartz.

Tuffs

The following varieties of tuff are distinguished:

1. fine calcareous tuff
2. coarse calcareous tuff
3. martite tuff
4. red-brown tuff
5. lapilli tuff
6. alnöite tuff

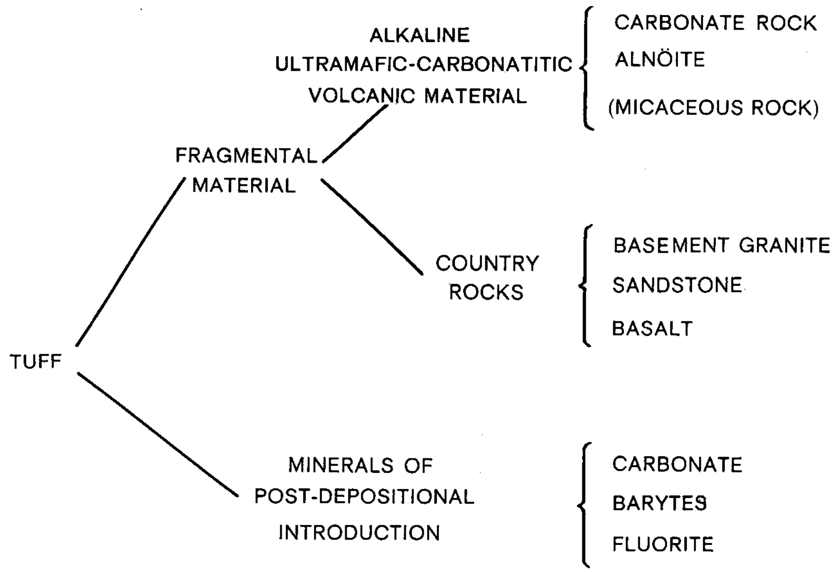

Fig. 18. Constituents of the tuffs.

Fig. 18 shows the rocks and minerals which constitute the tuffs, and outlines their sources.

The term "carbonate rock" includes carbonatized silicate rock types, in particular carbonatized melilite-rock, and also includes primary carbonate material possibly derived from carbonatite magma.

Of the volcanic rock types which contribute to the pyroclastic beds, carbonate rock is dominant and alnöite considerably less important. "Micaceous rock"—in parentheses in fig. 18—is barely represented.

Fine calcareous tuff. The very small grain size and lack of any but the tiniest fragments of cognate or accidental material suggest that this variety of tuff represents the finest ash fraction which was dispersed in the atmosphere by a volcanic explosion.

The *coarse calcareous tuff* is largely composed of pyroclasts of carbonatized melilite-rock. The larger fragments are vesicular and texturally identical with the lava, whereas most of the groundmass consists of anhedral grains of various sizes, among which a few entire or fragmentary lath-shaped carbonate pseudomorphs after melilite can be recognised. Grains of magnetite or haematite, and apatite, similar to those of the lavas, are quite common. Grains of quartz and alkali feldspar, principally derived from the country sandstone and granite respectively, occur in varying quantity. There are also grains and small angular fragments of a syenitic rock resembling the feldspathized basement granite (see p. 46).

The *martite tuff* consists of euhedral crystals of martite up to 1 cm in length and apatite euhedra up to 1 mm long set in a matrix of dolomite, with subsidiary fluorite and barytes.

The dolomite has a low iron content and occurs mainly as clear euhedral grains up to 0.5 mm across. Fluorite and barytes constitute a considerable proportion of the matrix locally. The barytes occurs as crystals of all sizes up to several centimetres in length; the fluorite, which shows neither cleavage nor crystal outlines, encloses grains of barytes and tiny turbid euhedra of dolomite.

The deep red colour of the matrix is due to a dissemination of minute scales of haematite. Correlation of this observation with the low iron content of the magnesian carbonate (unusual in the area) indicates that the carbonate was originally an ankeritic variety, which suffered oxidation.

The martite megacrysts show the "stepped" faces commonly found in magnetite crystals from carbonatite. In section these grains prove to be highly corroded, and many are dendritic skeletons (fig. 19). Apatite is relatively abundant in this variety of tuff; some grains are broken and some show rounding, but the majority are sharply euhedral. Some apatite grains penetrate crystals of martite.

Fig. 19. Skeletal martite grain from martite tuff, × 10.

Probably the solutions which were responsable for the introduction of the barytes and fluorite into the tuff caused the oxidation of the carbonate and brought about the transformation of the original magnetite to martite.

Red-brown tuff. Essentially this rock is a haematite-stained fine-grained carbonate tuff with a varying admixture of accidental material derived from the country rocks. The carbonate groundmass consists of anhedral granules of dolomite less than 0.1 mm in diameter; the combination of low-iron dolomitic carbonate and fine-grained disseminated haematite again suggests oxidation of a formerly ankeritic carbonate.

The non-carbonate grains are predominantly of quartz; there are also some grains of microcline and a few of albite and probable orthoclase. These accidental grains occur in two rather distinctive size fractions, the larger ca 0.4 mm in diameter, well rounded, and the smaller 0.1 mm in diameter and noticeably angular. Many of the large quartz grains are unmistakably sand grains derived from the country sandstone.

Lapilli tuff. This variety of tuff consists of altered lapilli of alnöite set in a matrix of clear, anhedral carbonate grains (Pl. 3 a). The lapilli are highly vesicular and porphyritic; the phenocrysts are pseudomorphs after olivine and melilite. The alteration is either to haematite and sphene or to carbonate. Examples of both types of alteration are distributed randomly.

The groundmass of the lapilli consists of pseudomorphed laths of melilite, accompanied by magnetite, ?perovskite and (occasionally) biotite. Melilite has commonly formed at least 50 $^{0}/_{0}$ of the groundmass; the laths tend to be arranged tangentially around the pseudomorphed olivine phenocrysts but usually bear no such relationship to the peripheries of the lapilli. (This is clear evidence that the present spherical shape of the lapilli has resulted at least partly from the attrition of solid material and not solely from the action of surface tension on liquid droplets).

The *alnöite tuff* resembles the more homogeneous parts of the coarse carbonate tuff, with the important addition of approximately 10 $^{0}/_{0}$ of pseudomorphed euhedral olivine grains about 1 mm long, which correspond to the phenocrysts of the alnöites. In the rather obscure haematite-stained groundmass, carbonatized melilite laths up to ca 0.2 mm in length can be distinguished, together with oxidised magnetite, pseudomorphed ?perovskite and the abundant sphene which invariably accompanies these. A few grains of apatite occur. The mineral components of this tuff agree closely with those of the associated alnöite bombs and with the lapilli described above.

Lamprophyric tuffisite

(i) *In pipes north of Qagssiarssuk.* This material, which is found in many of the diatremes, consists of highly carbonatized comminuted lamprophyre. Generally, alteration processes have obliterated the original minerals and textures very thoroughly. Pseudomorphs after olivine are commonly recognizable and carbonatized laths are occasionally present; phenocrysts of iron oxide occur sporadically.

The rock has undergone a kind of auto-brecciation leading to the development of rounded fragments a few millimetres in diameter set in a fine-grained matrix of similar mineralogical composition. This carbonatized, alnöitic micro-breccia can be classified as an "autoclastic explosion-breccia", which by the definition of WRIGHT and BOWES (1963) "forms by the disruption of a semi-solid mass of igneous material by the explosion of cognate gases".

(ii) *In pipes south of Qagssiarssuk.* The tuffisite of these intrusions has suffered extreme alteration; secondary barytes and haematite occur in the interstices. Irregularly-shaped grains of dolomitic carbonate 0.5–1.0 mm in diameter are particularly abundant and a number of them contain poorly preserved pseudomorphic structures suggestive of alnöite. The carbonate is full of tiny red scales, probably haematite derived from the oxidation of ankerite. Grains of microcline, quartz and heavily altered olivine-basalt are present in widely varying proportions.

Tuffisite of the irregular intrusions

The most common type of microbreccia in these intrusions is the variety given the field name of "*sandy tuffisite*". This rock consists essentially of grains of quartz with moderate sphericity, rounding and size-sorting, mostly less than 0.5 mm in diameter, in a calcareous matrix. These quartz grains represent the distintegration of the country sandstone. The groundmass is of fine-grained turbid carbonate, and finely divided haematite which is responsible for the characteristic brown or purplish colour of the rock.

There is clear evidence of both partial and complete replacement of quartz grains by carbonate. The granitic rocks of the basement are represented by occasional grains of microcline, usually well rounded. Tiny fragments of basalt-like material occur locally; these are of two kinds, (i) angular, containing feldspar laths up to 1 mm long, derived from holocrystalline olivine-basalt, (ii) rounded, fine-grained lapilli-like and probably from a separate, alnöitic magma. Carbonatized melilite-rock occurs as a minor clastic constituent.

The even-grained, rather fine-grained quartz-rich "sandy tuffisite" variety passes gradationally into coarser, more calcareous, more heavily altered tuffisites similar to those encountered in the diatremes.

Feldspathized tuffisite. A single specimen of tuffisite taken from the main outcrop close to Lake A has unusual characteristics. In section it appears at first glance to be a sandstone with moderately rounded quartz grains, a few small fragments of altered olivine-basalt, a little epidote and a few zircons; however the matrix in which the grains are rather loosely packed is fine-grained alkali feldspar. Investigation of the powdered rock by X-ray diffraction revealed the presence of a monoclinic potash feldspar phase, and albite. The interstitial feldspar is probably an orthoclase microperthite.

Basaltic tuffisite

This rock type differs from the "sandy tuffisite" in having olivine-basalt as a major constituent. The matrix is of fine-grained, rather turbid carbonate and in it are set grains of quartz up to 0.5 mm in diameter, and angular to rounded fragments of strongly chloritized olivine-basalt up to 2–3 mm across.

In addition to irregularly-shaped fragments of olivine-basalt there are numerous spherical lapilli-like bodies of altered alnöite, generally less than 1 mm in diameter (Pl. 3 b). Within these, chloritic pseudomorphs after lath-shaped grains of melilite, and chloritized euhedral olivine phenocrysts, are set in an opaque matrix. In a number of these small pellets there appears to be a systematic arrangement of the elongated pseudomorphs tangential to the margin (*cf.* the pellets of the lapilli tuff). A fragment of carbonatized, highly vesicular melilite-rock ca 2 mm in diameter was observed enclosed in a thin envelope of altered alnöite in which the elongate grains were arranged tangentially about the core. This contrasts with the sequence of intrusion observed in the sheet intrusions, where melilite-rock cuts lamprophyre.

Inclusions in tuff

Block of red orthoclasite (Pl. 4 a). The principal component of the orthoclasite is alkali feldspar, occurring in two forms: (i) rather cloudy rectangular grains up to ca 4.0 mm long, consisting of microcline and another feldspar phase, and (ii) small clear microcline grains of equant shape, ca 0.5 mm long. The interstices between the feldspar grains are occupied by ragged masses of haematite which show a structure somewhat reminiscent of the cleavage of mica. It is probable that this material pseudomorphs mafic minerals. Small clear grains of carbonate, occasional grains of apatite and a few euhedral zircons are also present.

Investigation of the powdered rock by X-ray diffraction revealed the presence of triclinic and monoclinic potash feldspar phases (*viz.* microcline and orthoclase), occurring in similar amounts. Chemical analysis of the feldspar for alkalis gave the following results.

	wt. %
Na_2O	0.30
K_2O	11.08

Many of the large grains consist of two components: (i) clear microcline with distinct "tartan" twinning, (ii) cloudy feldspar free from microcline twinning—presumably orthoclase—but occasionally showing a rather faint repetitive twinning like albite twinning. The relative distribution of microcline and orthoclase is quite irregular in some grains but more commonly the microcline occurs marginally, enclosing and apparently replacing orthoclase.

Apatite-sövite inclusion from diatreme. This coarse crystalline calcitic rock type contains apatite and haematite (?martite) as accessories. The anhedral calcite grains, which have a typical diameter of 2.5 mm, are very clear and show well-developed polysynthetic twinning. The intergranular boundaries are intricate and interlocking. Rather rounded grains of apatite not exceeding 0.2 mm in diameter, many of them showing moderate signs of corrosion, occur as localized clusters; it is unlikely that they constitute more than 1–2 $^0/_0$ of the rock. Anhedral grains of haematite up to 1 mm in diameter probably represent original magnetite which has suffered oxidation; some of these grains are pierced by apatite. A number of tiny pale yellow granules are probably sphene.

Intrusive orthoclasite (from edge of V_1)

This rock is closely similar in essentials to the orthoclasite which occurs as an inclusion in tuff. The X-ray diffraction patterns of the two rocks are almost identical and chemical analysis for alkalis gave similar results, but with the alkali content of the intrusive variety even higher.

	wt. $^0/_0$
Na_2O	0.50
K_2O	13.50

Texturally, the feldspar grains are less idiomorphic, and boundaries are commonly rather intricate.

3. Investigation of the carbonates of the carbonatized ultramafic rocks

Nature of the carbonates

Samples of the principal carbonatized rock types of the Qagssiarssuk area were investigated by X-ray diffraction to determine the nature of the carbonate phase or phases present. In the majority of the rocks investigated the most abundant or only carbonate mineral detected was a ferromagnesian variety within the range dolomite - moderately ferroan ankerite. A composition corresponding to $Ca_4 Mg_3 Fe (CO_3)_8$ is particularly common.

Calcite is the next most important carbonate mineral, occurring in most of the rocks studied. Siderite was tentatively identified in two specimens only, both from minor intrusions in the basement. The X-ray reflections corresponding to siderite were weak, indicating a very small amount of the mineral.

Areal distribution of the carbonate Minerals

Many of the carbonatized rocks of the Qagssiarssuk area contain both calcite and dolomite-ankerite. In an attempt to determine whether the calcite: ankerite ratio in these rocks is subject to some systematic spatial distribution pattern, the ratio was determined in 25 specimens. A rapid semi-quantitative X-ray procedure was employed, adapted from a method described by TENNANT and BERGER (1957).

In all the investigated specimens from intrusions of lamprophyre and melilite-rock in the basement, and in specimens from the melilite-rock intrusions (*viz.* stock, dike and sill) and the vents of the Qagssiarssuk Triangle, ankerite was the dominant carbonate phase. In most of the carbonatized effusive rocks, on the other hand, calcite was more abundant than ferro-magnesian carbonate; in specimens of effusive rocks collected from the vicinity of the various volcanic conduits, however, dolomite-ankerite was dominant.

The distribution of the two types of carbonate would be consistent with the hypothesis that there were two episodes of carbonatization: (i) an earlier calcitic carbonatization which resulted in the extensive calcification of the effusive rocks, particularly the amygdaloidal lava; followed by (ii) an episode of ankeritic carbonatization which affected all the intrusions of lamprophyre and melilite-rock at lower levels (*i.e.* in the basement). At a high level, within the stratified sequence, the ankeritic fluids were channelled in the various volcanic conduits, from which centres they penetrated outwards into the effusive rocks of the volcanic unit. Here the transformation was less complete than in the basement, and locally the calcium carbonate introduced earlier is partly or wholly preserved.

4. Potash feldspathization of the basement granites

Progressive transformation

Potash feldspathization of the country rock adjacent to carbonatite bodies is a comparatively common phenomenon and has been recorded at a number of localities in Africa and elsewhere (BAILEY, 1960; GARSON, 1962). Comparable effects have been observed in the basement granite and gneiss north of Qagssiarssuk, where these rocks are penetrated by ultramafic minor intrusions which have been carbonatized.

Stages in the progressive transformation of the granitic rocks were studied in a small suite of specimens collected from within and adjacent to intrusive sheets and volcanic pipes.

Where the degree of alteration has permitted, the parent rock has been identified as mesocratic adamellite; in its ultimate development the metasomatic process has led to the transformation of the parent adamellite to a rock consisting principally of highly potassic monoclinic feldspar, and microcline. Whereas the transformation is considered to be an essentially gradational process, it is convenient to discuss it in terms of stages.

Stage 1. Mechanical effects are very prominent at this stage. Mortar structure is developed, with a notable size contrast between the remaining large grains (microcline, plagioclase and quartz) and the small plagioclase and microcline granules of the comminuted groundmass.

Quartz is generally absent from the groundmass, and mafic minerals if present are dispersed as small shreds. The plagioclase shows well-developed polysynthetic twinning which occassionally manifests strain effects; composition is in the range of 5–10 % An.

Analysis of a specimen for alkalis gave the following results:

	wt. %
Na_2O	5.00
K_2O	5.00

Stage 2. The strongly directed fabric found in Stage 1 persists and the size contrast between megacrysts and groundmass is still pronounced, but there has been considerable recrystallization in parts of the groundmass, leading to a rather coarse allotriomorphic granular mixture of microcline and plagioclase.

The composition of the plagioclase is near albite. Many of the grains have a peculiar uneven extinction suggestive of gradational zoning, occasionally developed around several centres in a single crystal. Albite twinning is preserved to a varying degree; commonly it is very faint or absent.

Small replacement patches of microcline occur sporadically within some of the albite grains. These patches are irregular in shape and their orientation is unsystematic. They occur marginally and along internal fractures in the crystals, or isolated in the interior of the host grain. Small blobs of myrmekite occur where grains of microcline and plagioclase are in juxtaposition.

X-ray diffraction investigation indicated the presence of monoclinic potash feldspar in significant amount (fig. 20). The location of this material is unknown.

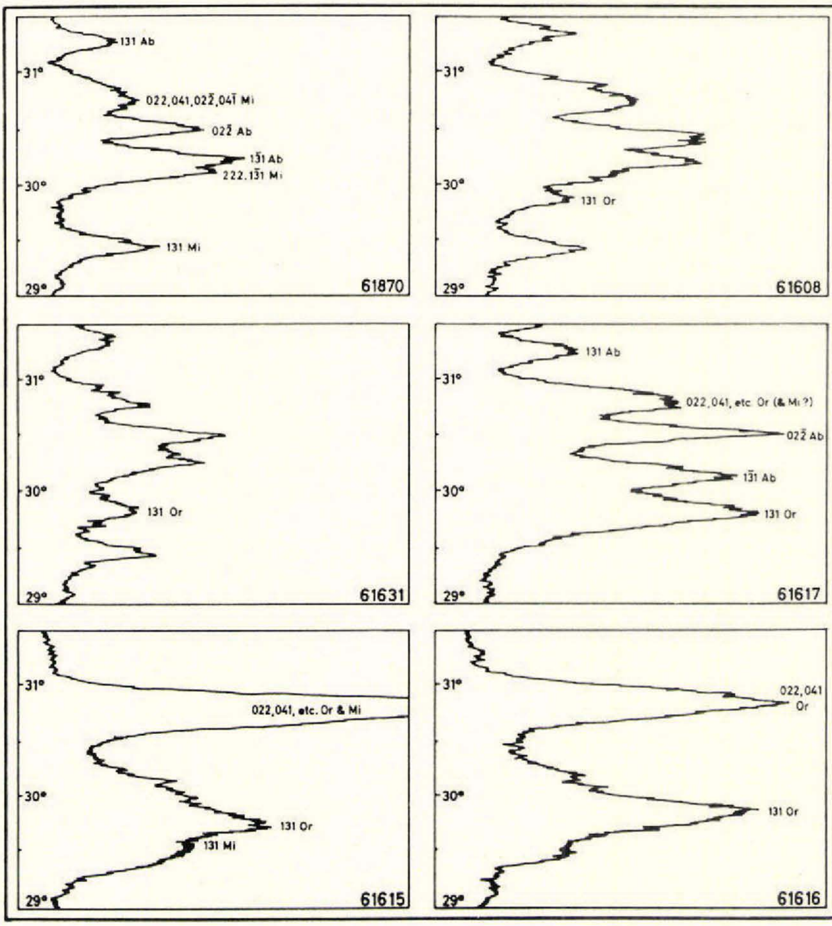

Fig. 20. X-ray diffraction traces of feldspathized rocks. 61870 typifies stage 1, 61608 and 61631 stage 2 and 61615 and 61616 stage 3. 61617 is perthosite.

Stage 3. Foliation is still prominent on a macroscopic scale and appears as thin parallel streaks of colourless feldspar in the red rock. In thin section the structure is discernible as alternating elongate areas of clear and cloudy feldspar in roughly equal proportions. Investigation by X-ray diffraction of rocks representative of this stage showed microcline and orthoclase to be present in important amounts, but reflections from an albitic phase were not detected. The clear feldspar is microcline in which characteristic twinning is poorly developed or invisible. The cloudy feldspar is orthoclase. Quartz is typically absent at this stage.

Chemical analysis of a specimen for alkalis gave the following results:

	wt. %
Na_2O	0.05
K_2O	11.57

Perthosite. A contrasting type of transformation of the country granite is represented by a single specimen. The rock is composed of perthite with very narrow parallel exsolution lamellae, accompanied by a subordinate amount of acid plagioclase. The feldspar grains are anhedral and interlocking. The only evidence of a directed fabric is the presence of parallel strings of carbonate grains. The X-ray diffraction trace of the rock (fig. 20) indicates that whereas monoclinic potassic feldspar and albite are both abundant, microcline is effectively absent; thus the principal mineral of the rock is orthoclase microperthite. Partial chemical analysis yielded these results:

	wt. %
Na_2O	6.40
K_2O	7.60

Summary

Summing up, the process of potash feldspathization when fully developed to stage 3 converts a granitic rock composed of microcline, plagioclase, quartz and mafic minerals to a syenite consisting of potash feldspar and very little else. The intermediate stages are not well documented; however, on the basis of the rather limited results obtained it is suggested that the transformation process takes place as follows:

First the country rock is subjected to cataclasis. Next the plagioclase becomes cloudy and sericite develops, lime is expelled and the plagioclase becomes albitic. Small patches of replacement microcline appear in the albite, and cryptic orthoclase develops in the rock. The mafic minerals and quartz are eliminated soon after. (If the rock were heated above the alkali feldspar solvus at this stage and then cooled, with exsolution of perthite, a rock such as the perthosite might result). The principal constituents are now presumably albite, monoclinic potash feldspar, and microcline.

Potash is now introduced on a large scale, soda is mostly removed and there is a general recrystallization. The resulting rock consists almost entirely of orthoclase and microcline.

It is interesting to note that the mineralogy and chemical composition of this end product are closely similar to those of two rock types from the Qagssiarssuk Triangle. The rocks in question are the block of red orthoclasite which occurs in tuff, and the intrusive orthoclasite. It is reasonable to suppose that these rocks were formed from a basement granite parent by the processes outlined above, with the addition of a further rheomorphic stage wherein the potash feldspar rock became mobile and intrusive.

In the suite of feldspathized rocks described, there does not appear to be any sympathetic relation between the stage of feldspathization and the quantity of carbonate present.

Table 7. *Alkali content of feldspathized rocks and their rheomorphic products.*

	1	2	3	4	5	6	7
Na_2O	0.30	0.05	0.50	0.22	0.38	0.28	0.49
K_2O	11.08	11.57	13.50	15.55	14.97	13.54	13.71

1. Block of red orthoclasite in tuff, Qagssiarssuk. Analyst: R. Lambert.
2. Feldspathized gneiss adjacent to tuffisite diatreme, Qagssiarssuk. Analyst: R. Lambert.
3. Intrusive orthoclasite, Qagssiarssuk. Analyst: R. Lambert.
4. Feldspathic breccia, G1344, Nathace, Tundulu. Analyst: Miss J. Baldwin (Garson, 1962).
5. "Feldspathic Fenite". SUT 242, E. Toror. Analyst: A. Mayer (Sutherland, 1965).
6. Trachyte. G1449, Kalicelo, Tundulu. Analyst: Miss J. Baldwin (Garson, 1962).
7. Potash-trachyte. SUTo 512, East Road. Tororo. Analyst: D. S. Sutherland (Sutherland, 1965).

5. Trace element studies

General

It is well established that carbonatites and associated ultramafic silicate rocks are characterized by enrichment in certain minor elements, in particular Ti, P, Ba, Sr, Zr, Nb, Y, Ce, La and the rare earths (*cf.* HIZAGY, 1954; PECORA, 1956; CAMPBELL SMITH, 1956).

A selection of the principal ultramafic silicate rocks and carbonate rocks from the Qagssiarssuk area were analysed for Rb, Sr, Zr, Nb and Ba by X-ray fluorescence (Table 8).

The values obtained resemble those found in associations of ultramafic silicate rocks and carbonatite in other areas (Table 9).

The mica-pyroxenite, which has not suffered carbonatization, has a chemical composition resembling that of ugandite (Table 6) and the distribution of the minor elements is closely similar to that found in the potassic ultramafic rocks of Western Uganda (HIZAGY, 1954).

In suites of alkaline ultramafic rocks diversity of rock type is a very common feature; however, many rocks of contrasting mineralogy have closely similar chemical composition and the amounts of minor

Table 8. *Concentrations of trace elements in rocks from Qagssiarssuk.*

	1	2	3	4	5	6	7	8
Rb......	55	85	30	90	115	x	x	330
Sr.......	5000	1600	9500	1850	3120	4300	> 4000	2050
Zr.......	500	600	560	200	780	320	< 200	1100
Nb......	40	60	50	5	85	475	ca 500	85
Ba......	4000	5000	13000	x	1000	1000	< 1000	6000

Amounts are in parts per million. Analytical method: X-ray fluorescence.
Ba determined by B. I. Borgen, other elements by J.W. Stewart.
x ...... not detected.

1. 61682, mica-monchiquite.
2. 61685, mica-monchiquite.
3. 61606, nodular melilite-rock.
4. 61614, vein ankerite with some granite fragments.
5. 61710, lapilli tuff.
6. 61740, flow of carbonatized melilite-rock.
7. 61696, apatite-sövite.
8. 61634, mica-pyroxenite.

elements such as Sr, Zr, and Nb varies little from one rock type to another (*cf.* Hizagy, 1954). It is reasonable therefore to postulate that before carbonatization the lamprophyres and melilite-rock of Qagssiarssuk had trace element assemblages similar to that of the uncarbonatized mica-pyroxenite. The present trace element distribution in the carbonatized rocks thus reflects modification of the original trace element pattern by the carbonatizing processes.

The accidental inclusion of apatite-sövite found in a diatreme has a mineral content and texture typical of massive intrusive carbonatite. The Sr and Nb values are likewise typical of carbonatite (61696, Table 8).

Some of the flows of melilite-rock have been so intensely carbonatized that their present chemical composition reflects the nature of the carbonatizing fluids rather than the composition of the original silicate rock (*e.g.* specimen 61640, Table 8 and Table 9). The trace element concentrations in this specimen are closely similar to those of the sövite block and since both rocks are highly calcareous, the major element concentrations must likewise be nearly the same. We are therefore presented with the intriguing occurrence of two rocks of almost identical chemical and mineralogical composition, one certainly formed by low-temperature metasomatic (hydrothermal) replacement of a silicate rock, the other probably representing an intrusion of primary carbonatite.

The extreme case of ankeritic carbonatization is exemplified by veins of nearly pure ankerite which penetrate basement granite at the edge of a carbonatized tuffisite diatreme (p. 22). This ankerite contains

Table 9. *Trace elements of mica-pyroxenite, carbonatized melilite-rock aud comparable rocks.*

	Rb	Sr	Zr	Nb	Ba
1. 61634, mica-pyroxenite, Qagssiarssuk .	330	2050	1100	85	6000
2. Sphene-rich biotite-pyroxenite, Uganda	170	1000	1200	xx	1200
3. Average katungite, Uganda..........	220	6685	1000	xx	3370
4. Average ankaratrite, Uganda	170	6900	550	xx	2900
5. Kimberlite, Basutoland	100	1000	450	200	2600
6. Average ultrabasic rock	0.2	1	45	16	0.4
7. Average basic igneous rock	30	465	140	19	330
8. 61640, carbonatized melilite-rock, Qagssiarssuk	x	4300	320	475	1000
9. 61696, apatite-sövite, Qagssiarssuk ...	x	4000	200	500	1000
10. Average carbonatite	xx	2900	83	1600	2500
11. Carbonatite dike, Premier Mine, S. Africa	x	1000	90	xx	290
12. Carbonatite, Oldoinyo Dili, Tanzania..	x	2500	200	800	3500
13. Average carbonate sediment	3	610	19	0.3	10

x ...... below level of detection. Amounts in parts per million
xx ...... not recorded.

Particulars of analytical data in Table 9

1. 61634, altered mica-pyroxenite, Qagssiarssuk.
2. Sphene-rich biotite pyroxenite. Ejected block, K4, Katwe Crater, SW Uganda (Hizagy, 1954).
3. Average katungite, SW Uganda (Hizagy, 1954).
4. Average ankaratrite, SW Uganda (Hizagy, 1954).
5. Micaceous hardebank, analysis No. 343, Robert Dike, Basutoland (Dawson, 1962).
6. Average ultrabasic rocks (Turkenian and Wedepohl, 1961).
7. Average basaltic rocks (Turkenian and Wedepohl, 1961).
8. 61740, flow of carbonatized melilite-rock, Qagssiarssuk.
9. 61696, apatite-sövite, Qagssiarssuk.
10. Average carbonatite (D. P. Gold, 1963).
11. Carbonatite dike, Premier Mine, South Africa (Hizagy, 1954).
12. Carbonatite, analysis J. G. 2349, Oldoinyo Dili, Tanzania (Bowden, 1962).
13. Average carbonate sediment (Turkenian and Wedepohl, 1961).

1, 8 and 9 ...... analysts J. W. Stewart, B. I. Borgen and H. W. Wiik.
2, 3, 4 and 11 ... analyst R. A. Hizagy.
5 .... analysts Miss J. M. Rooke and Mrs. P. E. Fisher.
12............. analyst P. Bowden.

significantly lower amounts of Zr and Nb than the mica-pyroxenite and the calcitic rock referred to above. Ankeritic carbonatization of the silicate rocks appears to have caused little change in the concentrations of the trace elements with the exception of Zr, whose concentration may have been diluted by Zr-poor secondary ankerite.

Distribution of the trace elements

Rb. The amount of rubidium present in rocks of the suite is very closely related to the presence of the potash-bearing minerals mica (*e.g.* 61634, Table 8) and potash feldspar (*e.g.* 61614). 61640, which is virtually free from both these minerals, has a very low Rb value.

Sr. Strontium is abundant in all the specimens. There is no sign of important depletion or concentration of the element in any particular rock type and it is likely that the percentage of strontium in the silicate rocks and the percentage carried by secondary carbonate were similar.

Zr. Zircon has not been identified in any of the rocks analysed, and this element is probably located in sphene (*cf.* HIZAGY, 1954, p. 51). Sphene is most readily identifiable in 61634 and 61710, which show higher Zr values than any of the rocks analysed (Table 8). Original contents of ca 1000 p.p.m. in the silicate rocks may have been diluted to a moderate extent by Zr-poor replacive carbonate.

Nb. This element appears to have a close genetic link with calcitic carbonatite. While sphene is probably capable of accomodating the element in the quantities occurring here (WINCHELL and WINCHELL 1951, p. 525), there is poor correlation between the amounts of sphene and Nb coexisting in the various specimens.

Ba. Barium has been relatively abundant in the original ultramafic magmas but in very low concentration in the carbonatizing fluids. Ba is much more abundant than Sr in the pyroxenite while the ratio is greatly reduced or reversed in the other rocks. It appears logical to ascribe this change to carbonatization processes. Barium is present in carbonate and/or sulphate.

Part III. DISCUSSION

General

An important characteristic of the alkaline-ultramafic and associated magmas responsible for the volcanic events of the Qagssiarssuk area was their high content of volatiles. The numerous breccia pipes and the predominantly pyroclastic nature of the related effusive rocks are the most obvious indications of this characteristic; it is probable that many of the unusual lithological and structural features recorded in the area are a consequence of fluidization (Reynolds, 1954).

Diatremes

Early in the Gardar period, after a succession of sandstones some hundreds of metres thick, with intercalations of basalt, had been laid down on the pre-Gardar basement, a new and distinctive alkaline-ultramafic magma, highly charged with H_2O and CO_2, rose in the crust. Vanguards of this magma in the form of diatremes began to drill their way toward the surface. The isolated areas of gneiss breccia in the basement may represent brecciation ahead of diatremes (*cf.* Gates 1959, p. 812).

The excellent vertical linear arrangement of inclusions in a tuffisite diatreme, illustrated in fig. 12, is local evidence of gas flow with energy sufficient to induce alignment, but inadequate to cause entrainment, which inevitably would have been followed by sudden collapse and disorientation. It is thought that a fluidized system could have subsided gradually, preserving the attitude of the aligned inclusions.

With the continued passage of fragment-laden gases, the diatremes became enlarged. Most of the diatremes in the basement are small in cross-section and the location of some of them on steep planar fissures can hardly be disputed; on the other hand the vents of the Triangle mostly show a subcircular cross-section of considerably greater area. The sides of a few of these vents are visibly inclined outwards. This effect of widening with decreasing depth is a common feature of volcanic pipes (*cf.* Wagner, 1914, pp. 5–15) and is further evidence that the exposures of the basement country and those of the Triangle are at substantially different erosion levels.

It is probable that the large instrusive body of "sandy tuffisite" had very limited access to the surface. Its marginal contacts, in contrast to the near-vertical or outward flaring sides of the diatremes and vents, are clearly overhanging in places, and portions of roof are preserved.

Wilshire (1961) describes a group of tuffisite diatremes which occur near Sydney, Australia and presents a list of observations which show convincingly that these structures were not open to the surface. The intrusive body of "sandy tuffisite" near Qagssiarssuk shares the following characteristics with the Australian examples:

(i) variability in composition and grain size of the tuffisite,
(ii) local stratification in the tuffisite,
(iii) local carbonatization of the tuffisite,
(iv) extensive roofing by country rocks,
(v) local folding and faulting of the overlying strata.

Wilshire postulates that emplacement of the diatremes near Sydney was largely effected by wedging and lifting of the country strata; the effects of lifting of the cover can be clearly seen in the intrusion near Qagssiarssuk, but there is also ample evidence that the country rock was attacked by the tuffisite and incorporated in it.

The buckling and faulting of the strata south of Lake B (fig. 17) may indicate subsidence of the rocks which roofed the intrusion; possibly this occurred as the result of a volume decrease following the deactivation of a fluidized system.

The body of tuffisite undoubtedly represents the uppermost part of a diatreme; however, the area exposed is much greater than that shown by any of the diatremes of the area and it is possible that this intrusion has the form of a laccolith and was fed by an underlying pipe of considerably smaller diameter (see Plate 6).

As is usual in volcanic districts, the diatremes were not all active concurrently. The westernmost of the diatremes just south of Qagssiarssuk appears to have become inactive before the main sequence of the volcanic unit was laid down. The tuffisite body of irregular shape and the diatreme 600 m south of Lake B were emplaced later than the initiation of deposition of beds of the volcanic unit, for both penetrate the tuffs at the base of the unit. The main neck of melilite-rock cuts the tuffisite body of irregular shape.

A smaller tuffisite diatreme cuts the upper sandstone unit and must have penetrated a minimum of 50 m of this unit. This intrusion and the domical structure in the sandstone nearby indicate that volcanic activity continued—albeit with greatly reduced intensity—after the main episode of volcanism responsible for the tuffs and flows of the volcanic unit.

It is unlikely that the pipes of basaltic tuffisite are cogenetic with the other diatremes of the area; it is improbable that such a preponderance of olivine-basalt material could have been achieved by derivation from basalt layers in the lower sandstone unit. Instead, the pipes are probably related to effusive olivine-basalts which occur much higher in the Gardar succession than the strata exposed near Qagssiarssuk. The location of the pipes may have been influenced by pre-existing diatremes drilled during the lamprophyric volcanic episode.

In general, evidence of breccia pipes is rare in strata above the top of the volcanic unit.

Sheet intrusions

The numerous low-angle sub-parallel fissures occupied by the ultramafic sheet intrusions are apparently unrelated to any pre-existing laminar features of the host granites, such as compositional banding or foliation; (where foliation occurs it is invariably vertical). The fissures are most likely related to cryptic jointing of tectonic origin. They have little in common with the systems of tension and shear cracks induced by magmatic pressure at some carbonatite localities (*cf.* GARSON and CAMPBELL SMITH, 1958).

It is probable that many of the fissures were blind and did not communicate with the surface. Flows corresponding to the "lamprophyric" magmas (*viz.* alnöitic, monchiquitic *etc.*) have not been recorded in the vicinity. The fissures show few signs of corrosion by the magma—commonly the topographic details of hanging wall and foot wall agree closely. Once the magma had filled the fissure it cooled rapidly under the influence of a steep thermal gradient toward the wall rock, assisted by the escape of the cognate gases through minute channels.

The occurrence, in some of the lamprophyric sheets, of screens and blocks of country rock almost but not wholly detached from the fissure wall, appears to testify to the rapidity with which the magma cooled; however, DAWSON (1962c) invokes fluidization to explain the survival of similar fragile wall appendages in some kimberlite intrusions.

The existence of fluidization in some of the minor intrusions at Qagssiarssuk is supported by the nodular rock types. Nodular lamprophyric breccia was observed entirely filling a planar fissure. The nodules, which are extremely well rounded, range from a diameter of 5 cm down to tiny pellets. It is thought that the fissure opened suddenly and that the gaseous magma expanded into it violently with simultaneous solidification and disruption of the lamprophyric material. The nodules do not have a chilled skin and their excellent rounding points to mutual attrition such as would have been achieved in a fluidized system.

The alnöitic nodules found in the intruded sheets of nodular melilite-rock may also have formed by the expansion of alnöitic magma into fissures; at a later stage a magma corresponding to melilite-rock was injected into these fissures, sweeping the nodules into suspension.

The lamprophyric tuffisite of the diatremes has the characteristics of autoclastic explosion breccia (WRIGHT and BOWES, 1963). It too is believed to have formed by disruption of the magma by gases expanding explosively, followed by attrition in a fluidized system. Since many of the diatremes had outlets to the atmosphere (unlike the low-angle fissures) there was continuous upward passage of gases for some time, and fluidization was maintained long enough to reduce most of the nodules to pellets a few millimetres in diameter.

Flows of carbonatized melilite-rock

The carbonatized melilite-rock which occurs as amygdaloidal flows and high-level minor intrusions is extremely unusual and presents special problems of genesis. The transformation from melilite-rock to almost pure carbonate has been so complete that the disposal of the expelled material (principally SiO_2 and Al_2O_3) is a problem which must not be overlooked, particularly if it is assumed that the carbonatization took place *in situ*.

There are no signs of silicification in the area; silicification is a common feature of volcanic centres where carbonatite is present, *e.g.* Chilwa Island (GARSON and CAMPBELL SMITH, 1958) and the Rufunsu province (BAILEY, 1966). In terms of traditional geological interpretation a considerable thickness of rock cover would be necessary to accommodate the expelled material presumed to be driven ahead of the carbonatizing fluids (at such a high level a limited system volume-for-volume metasomatic exchange would not be expected). However, it is improbable that any such thick cover existed at the time of carbonatization; rather, the regional picture indicates that the ultramafic volcanism waned in the area before the upper sandstone unit was deposited and it is most likely that the ultramafic volcanism and the carbonatization were penecontemporaneous.

An alternative approach to the explanation of the genesis of the carbonatized melilite-rock is proposed. MCCALL (1963) states that the highly carbonatized dikes of North Ruri, which contain abundant pseudomorphs after melilite, "must surely have been intruded as carbonatite (alvikite), not as alnöite". He believes that certain of these dikes "represent an alnöitic magma which has been at least partly crystallized and then metasomatically transformed by a pulsation of carbonate on its upward passage, and solidified as alvikite".

It is tentatively postulated that the carbonatization of the flows and minor intrusions at Qagssiarssuk took place at depth. The transformation involved the conversion of a mobile silicate magma—consisting of abundant crystals of melilite in a proportionately rather limited amount of silicate liquid—to a mobile carbonatitic magma consisting of carbonate crystals in a continuum of carbonatitic fluid. Throughout the transformation two physically distinct phases—*viz.* crystals and fluid matrix—were maintained.

The readiness with which melilite can be replaced by carbonate is well known and is exemplified by numerous observations in the volcanic fields of East Africa. Recent investigation of some East African volcanoes, *e.g.* Homa Mt. and Hanang, indicate that such replacement is even more common than was formerly realized (T. C. JAMES, T. DEANS, pers.comms.). It is visualized that the melilite crystals underwent wholesale replacement by carbonate, but that the replacement was systematic so that each melilite crystal was replaced by a single crystal of carbonate with its c-axis parallel to the elongation of the original mineral.

Since the interstitial silicate material was in a liquid state there was no crystalline structure to encourage the development of crystalline carbonate, hence the exchange of silica and alumina radicles for carbonate was a wholesale but unsystematic process and the matrix remained liquid.

At this stage, the composition of the carbonatized magma was probably essentially that of the analysed amygdaloid sample (Table 5), *i.e.* typically alvikitic with regard to both major and trace elements (see Table 9); in addition it must have contained considerable quantities of CO_2, H_2O, F, etc. in solution.

The textures of the intrusive and extrusive melilite-rock leave no doubt that these rocks were formed by the intrusion and extrusion of a magma. The flow alignment of the pseudomorphed melilite laths and their tangential disposition around the vesicles can only be explained in terms of fluid mechanics. The highly vesicular nature of the flows testifies to the abundance of cognate gases.

Following experimental studies on the system CaO-CO_2-H_2O, WYLLIE and TUTTLE (1960) concluded that a carbonatite magma might exist in nature at a comparatively low temperature and might even be extruded at the surface as a lava. Investigations by EITEL (1954) showed that the presence of alkalis in a carbonate melt would depress the freezing point considerably.

Subsequently, the actual eruption of carbonatite lava was observed at the volcano Oldoinyo Lengai in Tanzania (DAWSON, 1962 a, 1962 b). This lava is composed dominantly of sodium carbonate and consists of crystals of the carbonate in a fine-grained groundmass of the same composition. Through the courtesy of Mr T. DEANS of the Institute of Geological Sciences, London, the writer had the opportunity to examine thin sections of this lava, and is of the opinion that the carbonate crystals may be pseudomorphs after at least two silicate mineral species—one tentatively identified as melilite, the other(s) with less certainty as olivine and/or biotite.

The sodium carbonate lava of Oldoinyo Lengai is generally acknowledged to be a manifestation of the extrusion of carbonatite magma (see TUTTLE and GITTINS, 1966, p. xviii); it is now suggested that the Qagssiarssuk amygdaloid also represents effusive carbonatite magma. The chief petrographic differences between the two rocks are (i) the nature of the carbonate (*i.e.* sodium carbonate in the one, calcite in the other) and (ii) the volumetric proportion of material representing primary carbonatite fluid as against the volume of carbonatized silicate crystals. In the African lava primary carbonatite material is dominant while in the Greenland example pseudomorphed melilite crystals are the principal constituent.

The "lapilli tuff" of Qagssiarssuk may present a closer parallel to the lava of Oldoinyo Lengai. The lapilli rarely touch each other and are isolated by the crystalline carbonate matrix. This feature is anomalous in terms of normal sedimentary mechanisms which govern the deposition of pyroclastic material such as ash showers. Dr G. J. H. McCALL (pers. comm.) has observed similar rocks in East Africa and has suggested that they may represent the outpouring, at the surface, of a highly mobile (fluidized?) suspension of alnöite pellets in carbonatitic fluid. The carbonate is volumetrically more important than are the pellets of alnöite.

It is possible that the magmatic and replacive carbonate of the Qagssiarssuk effusives contained a significant (or even dominant) proportion of alkali radicles at the time of eruption. (The alkali need not have been soda; in fact the potash feldspathization in the area, considered in conjunction with the absence of fenitization and nepheline, would suggest rather that it would have been potash). Such alkaline carbonate could have been replaced by calcite after extrusion, by hydrothermal or even low temperature calcareous solutions.

The pyroclastics

The various sources of the constituent materials of the tuffs are outlined in fig. 18. Quartz and feldspar grains have been derived from the country rocks, while the particles of alnöite and melilite-rock have clearly been derived from two of the silicate magma types most abundantly represented in the intrusions of the area. (The affinities of the "micaceous rock" are uncertain). The bulk of the pyroclastic deposits, however, is composed of carbonate material lacking in original or pseudomorphic structures which would define its source. The following alternative (and not mutually exclusive) origins may be postulated for grains of carbonate in the pyroclastic beds:

(i) silicate rock carbonatized before effusion,
(ii) silicate rock carbonatized after effusion and deposition,
(iii) primary carbonatite magma.

The martite tuff provides evidence of the existence of a plutonic body of carbonatite; abundant phenocrysts of magnetite or martite, and apatite crystals up to 1 mm long have not been recorded in any of the intrusive rocks of the area (the occurrence of broken and rounded individuals among the apatite crystals precludes their having grown in the tuff after its deposition). The martite megacrysts closely resemble the magnetite octahedra found in abundance in many African carbonatites.

The inclusions of apatite-sövite which occur sporadically in the pyroclastic beds may—like the martite tuff—be considered as samples of a carbonatitic rock type which does not otherwise occur at the present level of erosion. The rather coarse, even-grained texture contrasts strongly with that of the carbonatized silicate rocks and with the texture of the vein ankerite, suggesting direct crystallization from carbonate magma at moderate depth. Certain trace elements in the sövite show concentrations typical of carbonatite (Table 8 and Table 9).

Carbonatization

The distribution of the carbonate minerals in the Qagssiarssuk igneous rocks indicates the possibility that an episode of calcite carbonatization was succeeded by an episode of ankeritic carbonatization (see p. 46).

Reasons have been advanced for supposing that calcitic carbonatization of the melilitic lavas took place prior to their extrusion. It is probable however that the calcite of the pyroclastics originated in several different ways, *viz*:

(i) from a parent sövitic magma,
(ii) by calcitic carbonatization of silicate magma prior to effusion,
(iii) by hydrothermal carbonatization of mainly silicate clastic material after deposition.

The nature and relative importance of the mechanisms which brought about the calcitic carbonatization of the volcanic rocks are imperfectly known. In the case of the subsequent ankeritic carbonatization, however, evidence points clearly to hydrothermal fluids as the transforming agency. Where conditions were particularly favourable for the passage of such fluids—*e.g.* in brecciated granite—veins of ankerite, together with subordinate amounts of silica and barytes, were formed. The structure of these veins indicates that they were built up by fissure filling.

While it is possible that certain of the intrusive rocks initially contained some primary carbonate (most probably calcite) in equilibrium with the silicate minerals, this was subsequently replaced by the ferro-magnesian carbonate.

Consideration of analyses of carbonatized lamprophyres recalculated to 100 % on a carbonate-free basis (Table 4; *cf.* HOLMES, 1936) reveals the secondary nature of the ankeritic alteration. Particularly to be noted are:

(i) that the carbonate-free compositions do not correspond to those of any naturally occurring igneous rocks.

(ii) that the carbonate-free compositions of the various rocks are markedly different, although the chemical differences between comagmatic members of such lamprophyric suites are typically very small.

Feldspathization

The emplacement of carbonatite is characteristically accompanied by metasomatic transformation of the country rocks. A common type of alteration, found at the classic carbonatite localities of Fen and Alnö, and elsewhere, is fenitization, in which desilication, and introduction of alkalis are prominent. Typically, sodic pyroxene and sodic amphibole are developed in fenitic rocks. There is no evidence of fenitization at Qagssiarssuk; sodic pyroxene and amphibole are absent.

Feldspathization is a less common type of transformation and is found at Qagssiarssuk and associated with a number of carbonatite occurrences in Africa, in some instances associated with fenitization (*e.g.* at Chilwa Island; GARSON and CAMPBELL SMITH, 1958) and in other cases unaccompanied by fenitization (*e.g.* at Rufunsu, Zambia; BAILEY 1960).

Chemically, the outstanding feature of feldspathization is the development of the molecule $KAlSi_3O_8$ at the expense of other material. This is accompanied by the introduction of large amounts of K_2O, accompanied by Al_2O_3 in some instances. The end product is a nearly monomineralic potash-feldspar rock—orthoclasite (see Table 7).

At most of the African localities where feldspathization occurs, the country rock is basement granite, and feldspathization of other rock types has seldom been observed; BAILEY (1960) records feldspathized sandstone and conglomerate. In the Qagssiarssuk region feldspathization is mainly confined to the basement granites, but feldspathization of sandstone and olivine basalt has been recorded by the writer near Igaliko (Plate 5).

Rheomorphic orthoclasite

At some carbonatite localities in Africa the feldspathized country rocks are believed to have been locally mobilized and intruded as dikes (*e.g.* GARSON, 1962, p. 198). In the Qagssiarssuk area the red orthoclasite which occurs in the volcanic vent V_1 is considered to have originated in this manner.

A sill of orthoclasite interstratified with Gardar sediments at Mussartût (Plate 5) is sufficiently similar to suggest a like origin. The higher soda content of the latter rock (Na_2O, 2.3 %; K_2O, 9.4 %) suggests that mobilization took place before the potash-feldspathization process had been carried to completion (see p. 49).

Brecciation

Many carbonatite bodies are surrounded by an aureole of strongly crushed or shattered country rock, *e.g.* the "thermal shock-zone" of VON ECKERMANN (1948) or the contact breccia described by GARSON and CAMPBELL SMITH (1958). The exfoliation ellipsoids and accompanying breccia developed adjacent to the carbonatized minor intrusions north of Qagssiarssuk are regarded as comparable phenomena.

VON ECKERMANN (op. cit.) considers this brecciation to be due mainly to dynamic strain set up by heat flowing out from the intrusion. Other causes of dynamic strain could be volume changes related to the carbonatization of the ultramafic intrusions and/or the feldspathization of the country rock.

Plastic flow

A limited amount of plastic flow, possibly related to the hypothetical volume changes just referred to, is indicated in some of the carbonatized minor intrusions. Structures which indicate this phenomenon are (i) fractured apatite prisms (Pl. 4 b), (ii) the flattened form of the alnöite nodules in the nodular melilite-rock (fig. 8). (Both the matrix and the nodules of this rock type contain substantial amounts of carbonate).

Evidence of the existence of carbonatite

Direct evidence that a carbonatite body exists in the Qagssiarssuk area below the present level of erosion or beneath the waters of the fjord, is provided by:

(1) the ejected block of apatite-sövite in tuff,
(2) the martite-apatite tuff.

Both of these rocks closely resemble material from known carbonatite occurrences.

Supporting evidence is provided by some features which typically occur in the vicinity of carbonatite:

(3) rocks very rich in secondary carbonate (replacing silicate material), with trace-element concentrations characteristic of carbonatite,
(4) potash feldspathization and rheomorphic orthoclasite,
(5) melilite-rock; the best known examples of rocks with exceedingly high content of melilite occur in complexes where carbonatite is represented (see p. 64),
(6) barytes and fluorite mineralization—a characteristic late-stage manifestation of carbonatitic igneous activity (*cf.* Garson and Campbell Smith, 1958, p. 82; King and Sutherland, 1960, 0. 513).

Petrogenesis

Nature of the magmas

The igneous rocks of the Qagssiarssuk area belong to two distinct kindreds, one basaltic, the other alkaline-ultramafic/carbonatitic. No rock type intermediate between the two kindreds has been recorded in the vicinity and it seems probable that magmas of the two associations developed separately (*cf.* King and Sutherland, 1960, p. 717).

The Qagssiarssuk basalts, whether olivine-free or olivine-bearing, do not differ significantly from those of the 3 km thick Gardar basalt and sandstone sequence of the Tunugdliarfik region. In general the Gardar basalts resemble the Permian basalts of the Midland Valley of Scotland (Tomkeieff, 1937).

The alkaline-ultramafic rocks of Qagssiarssuk belong to three main groups:

(i) the lamprophyres, *i.e.* monchiquite, mica-monchiquite, alnöite and mica-peridotite,
(ii) melilite-rock,
(iii) mica-pyroxenite.

The origin of the magmas

The lamprophyres. While there is a considerable range in the mineralogical composition of this group, gradation between the several varieties appears to be rather complete; moreover in the Qagssiarssuk area the different varieties show the closest association in time and space. These observations indicate that the lamprophyre group represents the differentiation products of a single magma. Probably the differentiation took place at a relatively high level where the variability of physical conditions inherent in a subvolcanic environment influenced the course of crystallization.

The melilite-rock. In its various occurrences as flows and minor intrusions the melilite-rock has a rather constant mineralogical composition; rock types transitional between melilite-rock and lamprophyre were not recorded. Thus it seems unlikely that the melilite-rock and the lamprophyre group evolved one from the other, or both from a common parent, solely by progressive magmatic processes of differentiation and assimilation. Instead it is considered probable that some other petrogenetic process was involved in the formation of the melilite-rock magma —possibly metasomatic transformation of material of the lamprophyre group by carbonatitic solutions, or hybridization involving a carbonatite melt.

At Turja in the U.S.S.R. (KRANCK, 1928), Rangwa in Kenya (MCCALL, 1958), Iron Hill in the U.S.A. (TEMPLE and GROGAN, 1965) and Bukusu in Uganda (BALDOCK, 1967), rocks very rich in melilite, such as turjaite and uncompahgrite, occur in alkaline subvolcanic complexes. In each occurrence carbonatite is also present. Directly, or by implication, the authors advocate a metasomatic origin for the melilite rocks of these areas; ijolite, pyroxenite and lamprophyre are variously considered as the country rock which suffered transformation.

KRANCK (1928, p. 90) outlines the transformation process as follows: ... the melilite ... originated under the influence of residual solutions (or melts) rich in lime which had penetrated into a partly consolidated pyroxene-bearing rock belonging to ... the lamprophyres." KRANCK's ideas might apply equally to the genesis of the melilite-rock of Qagssiarssuk. The "residual solutions (or melts) rich in lime" are visualized as having the closest identity with carbonatite—either in the form of a melt or as more tenuous carbonatitic emanations. The concept of incomplete consolidation of the country rock is endorsed: if the lamprophyric parental material were in a more or less molten state, this would facilitate rapid and complete transformation, besides helping to maintain the high environmental temperature necessary for the existence of a magma corresponding to melilite-rock.

The mica-pyroxenite. The outcrops of this rock type are isolated from those of the lamprophyres and the melilite-rock; no rocks transitional between mica-pyroxenite and the other groups have been recorded. Petrographic observations indicate that much of the mica is replacive toward pyroxene and it is probable that an original pyroxenite underwent a metasomatic or autometasomatic transformation which caused the development of mica at the expense of pyroxene. The most important chemical changes involved in such a process would have been loss of CaO and gain in K_2O. The presence of calcite in the pegmatitic facies of the mica-pyroxenite suggests that CO_2 was an active agent in the process, indicating a genetic link with carbonatite.

The carbonatite. No sedimentary carbonate rock occurs near Qagssiarssuk or in the surrounding region. Moreover the trace element content of carbonatite samples (Table 8) is quite unlike that of sedimentary limestone (Table 9). These observations, considered in conjunction with the nature of the associated rock types (especially the orthoclasite) leave no doubt that we are dealing with an igneous carbonatite (*cf.* King and Sutherland, 1960, p. 709). Nepheline-bearing rocks do not occur at Qagssiarssuk, so there is little liklihood of the carbonatite being an extreme fractionate of an ijolitic magma (*cf.* King and Sutherland, 1960, 1966).

The parental magma

The volcanic rocks exposed at Qagssiarssuk correspond to surficial and high subvolcanic environments remote from the levels where the several magma types developed and far removed from the ultimate parental material. The following comments are largely speculative.

The melilite-rock is undoubtedly a derived rock type and does not merit consideration as a possible parent.

The lamprophyre group shows a considerable range in composition. Alnöite and the poorly represented mica-peridotite are akin to kimberlite and alkali-peroditite, both of which are widely favoured as primary magmas capable of producing carbonatite and alkaline-ultramafic rock types (Tuttle and Gittins, 1966). Nevertheless the monchiquite, on account of its wide spatial development (see p. 32) and persistence in time, has a claim to consideration as the parental rock type.

There is petrographic evidence which indicates that the biotite-pyroxenite may represent metasomatically modified pyroxenite. It is generally considered that pyroxenite does not possess the characteristics expected of a magma which could occupy a parental relationship to a varied alkaline-ultramafic/carbonatite suite (*e.g.* King and Sutherland, 1960, p. 718).

Of the various igneous rock types which outcrop at Qagssiarssuk, most show signs of having been affected by processes of differentiation, and none combines the characteristics which would mark it out as an obvious representative of a parental magma from which all the other rock types could have been derived.

It is believed that the carbonatite, the lamprophyres and the mica-pyroxenite (or its hypothetical precursor, pyroxenite) are all ultimately "differentiates of a magma not likely to be found at the surface of the earth" (JAMES, 1958, p. 8).

Regional considerations

Epeirogenic conditions prevailed in South Greenland throughout the Gardar period. The pre-Gardar cratonic block was broken up by numerous faults and penetrated by a number of alkaline and peralkaline intrusive complexes (SØRENSEN, 1966).

The Grønnedal-Ika intrusive complex (EMELEUS, 1964), located 150 km west of Qagssiarssuk, consists of nepheline syenites cut by a central plug of carbonatite. Alkaline-ultramafic rock types similar to those of Qagssiarssuk are absent. The other alkaline complexes lack both alkaline-ultramafic rocks and carbonatite, with the exception of a few thin carbonate dikes which cut the Igaliko complex (EMELEUS, 1966).

On the basis of present knowledge there is little to suggest that the centred alkaline intrusive complexes originated as ultrafenitic by-products of parental carbonatite. The carbonatite plug of Grønnedal-Ika and the carbonate dikes of the Igaliko complex may well be the residual fractions of ijolitic crystallization (KING and SUTHERLAND, 1966). SØRENSEN (1966) presents a plausible case for derivation of the alkaline magmas from basalt.

In addition to the associated alkaline-ultramafic and carbonatitic rocks which outcrop at Qagssiarssuk, similar material occurs as minor intrusions in the Ivigtut region and in the country to the west and north of Ivigtut (EMELEUS, 1966). Similar rocks have also been recorded at Aillik Point in Labrador (KRANCK, 1939)—the Gardar igneous province probably extended across the Davis Strait.

It is possible that the manifestations of alkaline-ultramafic/carbonatite rocks in the Gardar province, and the centred alkaline and peralkaline complexes, have no genetic connection and simply represent two contrasting types of igneous phenomenon which can develop independently in an epeirogenic tectonic setting. Nonetheless, the alkaline-ultramafic and carbonatitic rocks of Qagssiarssuk occur in such close proximity to the great alkaline intrusive complex of Igaliko that the possibility of a genetic relationship cannot be disregarded. As a logical consequence the origin of the other alkaline intrusive complexes of South Greenland must remain open to question.

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Færdig fra trykkeriet den 11. marts 1970.

PLATES

Plate 1

Plate 1 (a) Photomicrograph of monchiquite, × 6, ordinary light. Note pseudomorphs after euhedral olivine phenocrysts.

Plate 1 (b) Photomicrograph of carbonatized alnöite, × 50, ordinary light, to show carbonate pseudomorphs after olivine (phenocrysts) and melilite (lath-shaped grains).

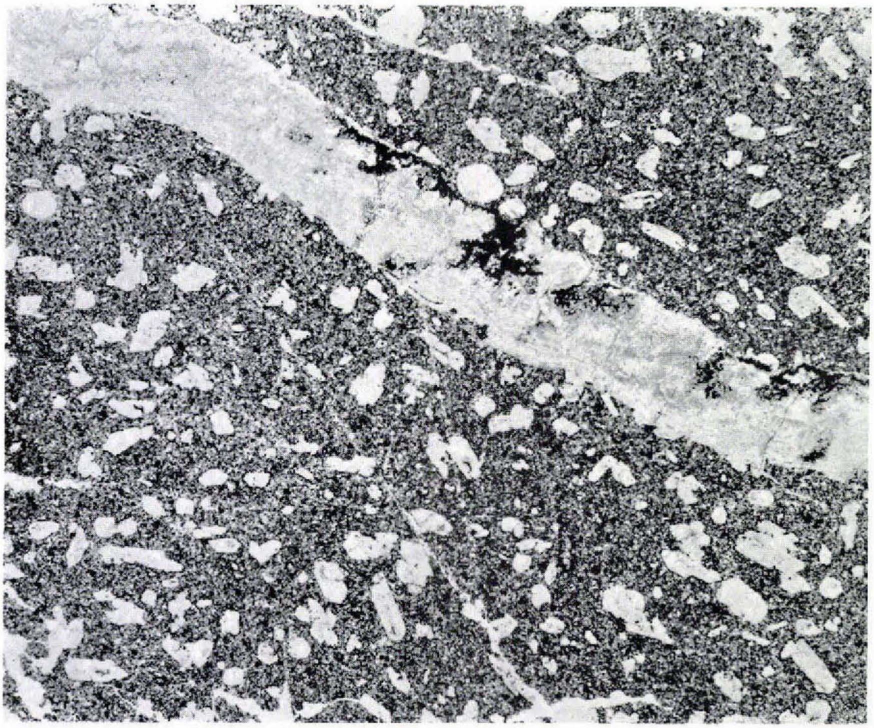


Plate 1 a.

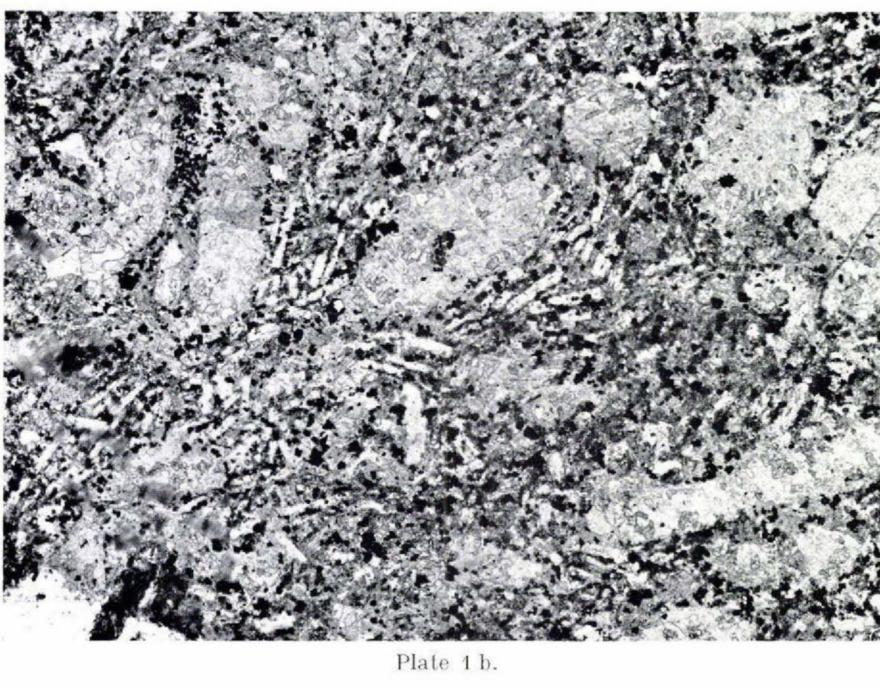
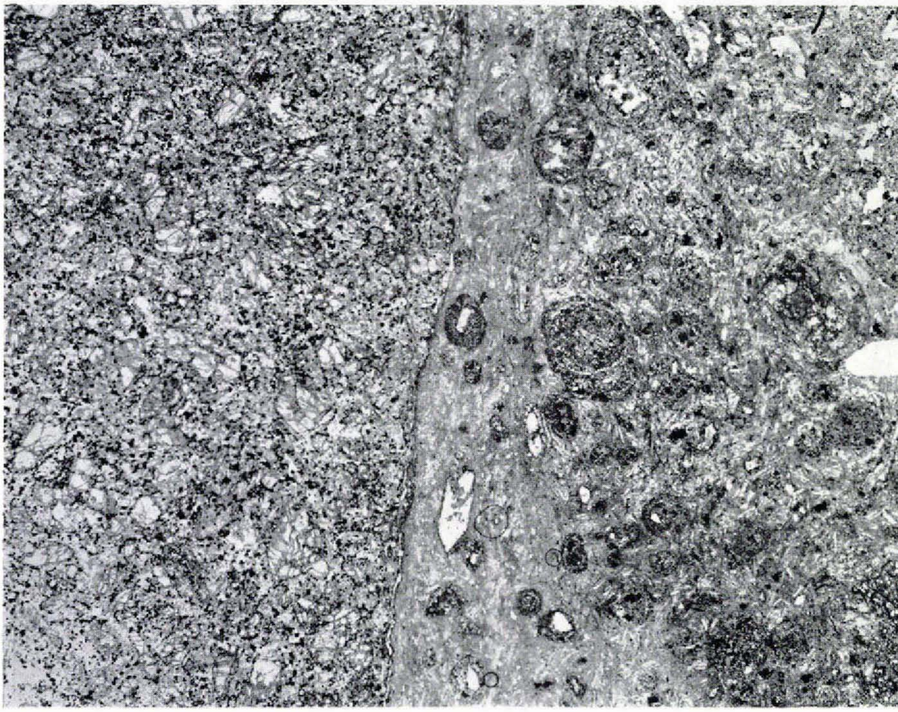


Plate 1 b.

Plate 2

Plate 2 (a) Photomicrograph of mica-peridotite (left) cut by nodular melilite-rock, × 7, ordinary light. Flow structure in the melilite-rock is emphasized by laths of carbonatized melilite.

Plate 2 (b) Photomicrograph of extrusive carbonatized melilite-rock (amygdaloid), × 8, ordinary light.



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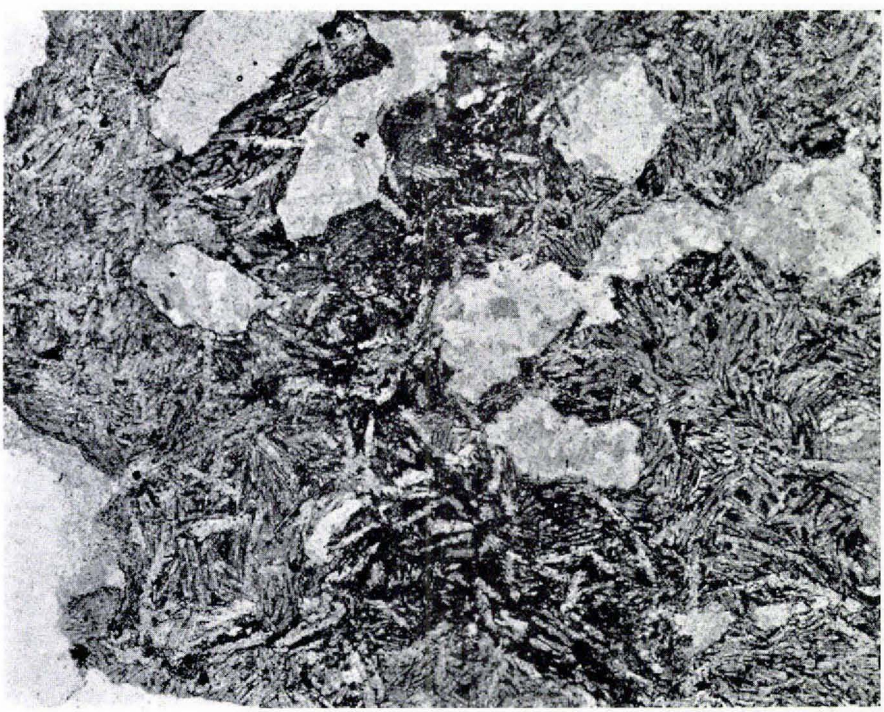
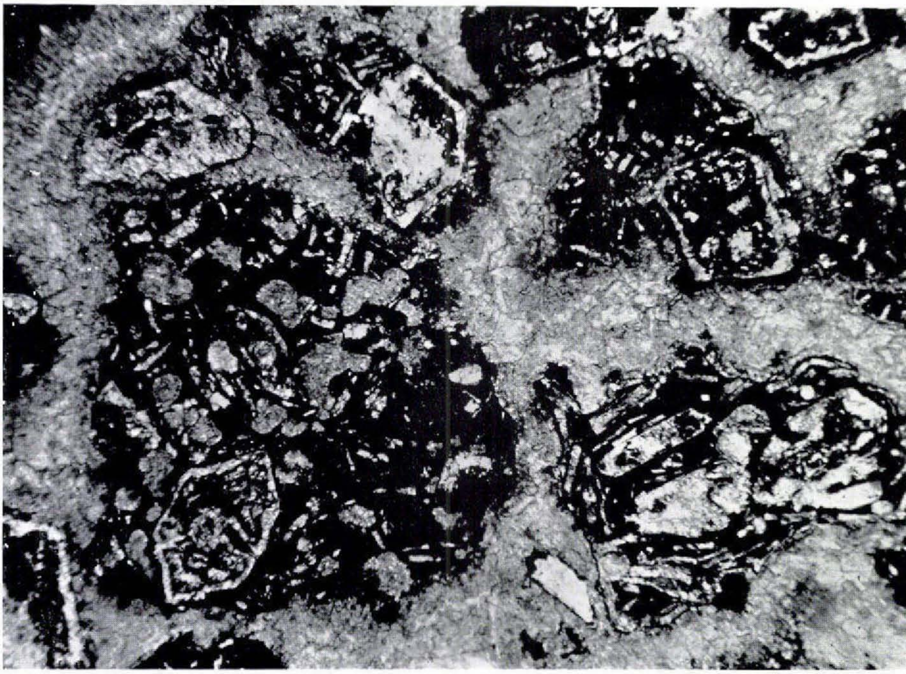


Plate 2 b.

Plate 3

Plate 3 (a) Photomicrograph of lapilli tuff, × 40, ordinary light. Pseudomorphed euhedral olivine phenocrysts, pseudomorphed melilite laths and vesicles can be distinguished within the lapilli.

Plate 3 (b) Photomicrograph of basaltic tuffisite, × 40, ordinary light, showing alnöite lapilli (left), sand grains and fragments of olivine basalt.



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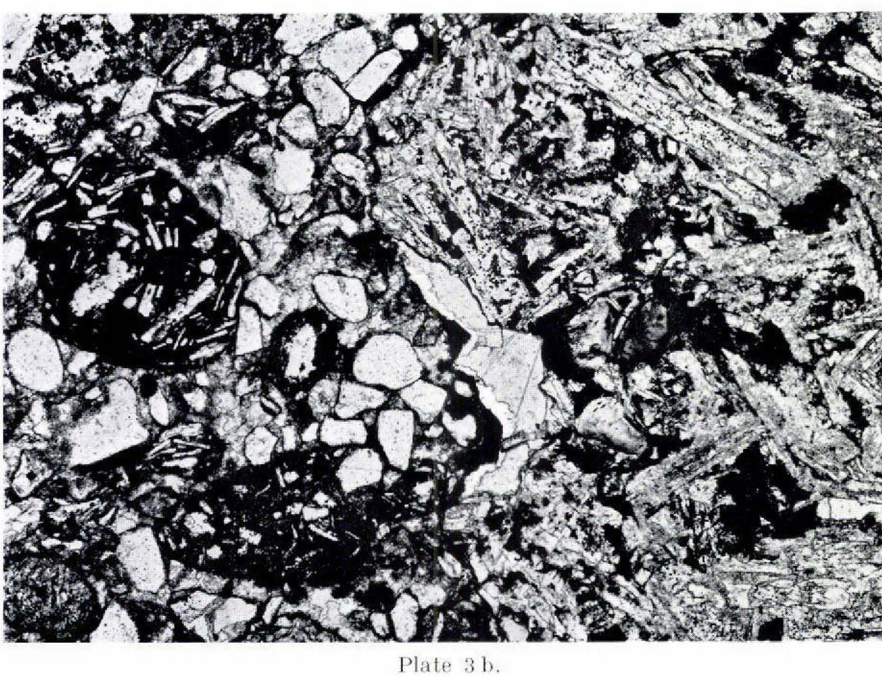


Plate 3 b.

Plate 4

Plate 4 (a) Photomicrograph of red orthoclasite block from tuff, × 10, crossed polars.

Plate 4 (b) Photomicrograph of carbonatized melilite rock, × 120, ordinary light, to show fractured apatite prism.

Plate 4 a.

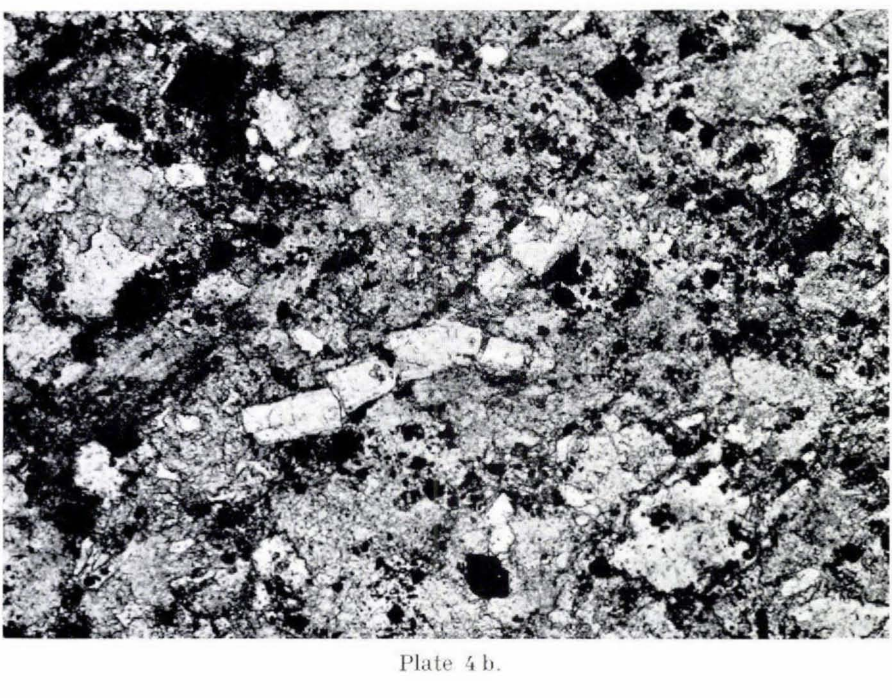
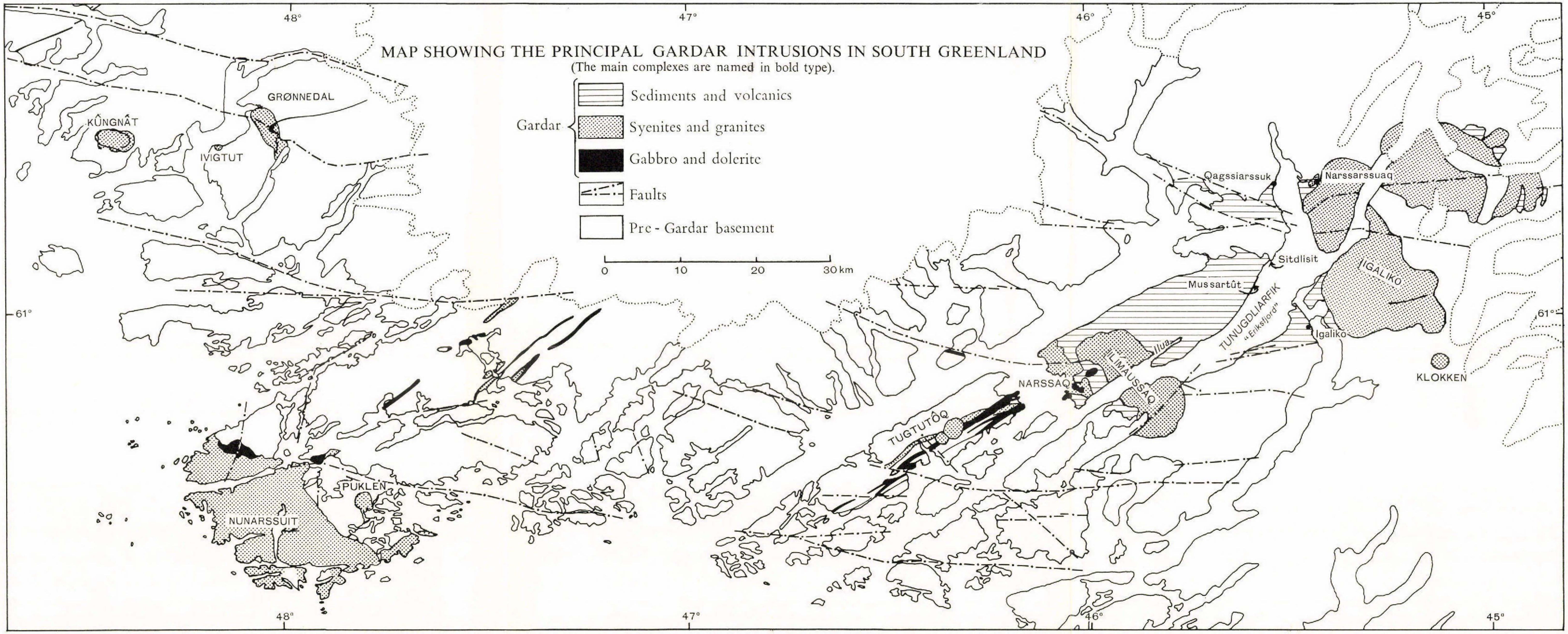


Plate 4 b.

GRØNLANDS GEOLOGISKE UNDERSØGELSE

THE GEOLOGICAL SURVEY OF GREENLAND



GRØNLANDS GEOLOGISKE UNDERSØGELSE
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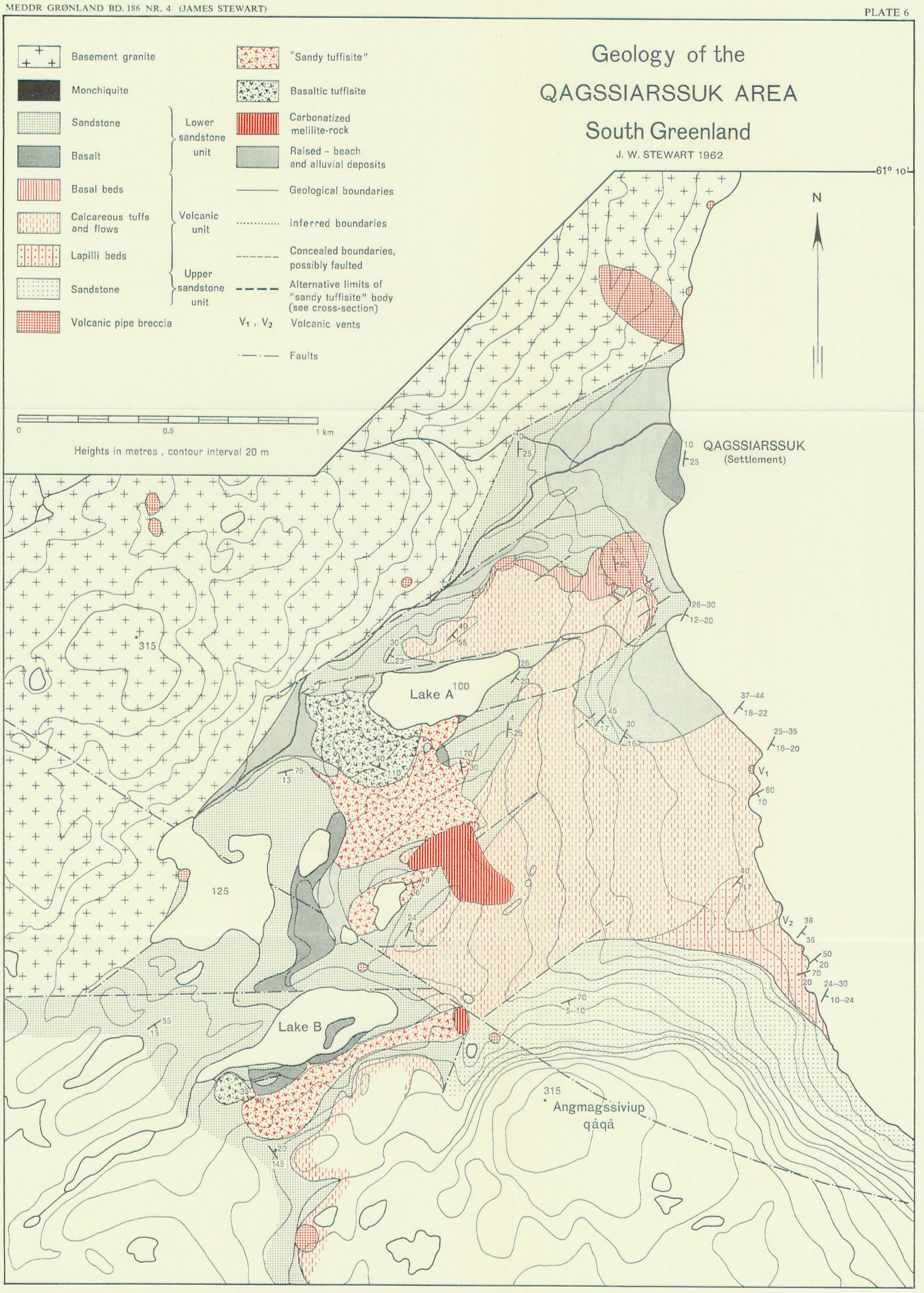

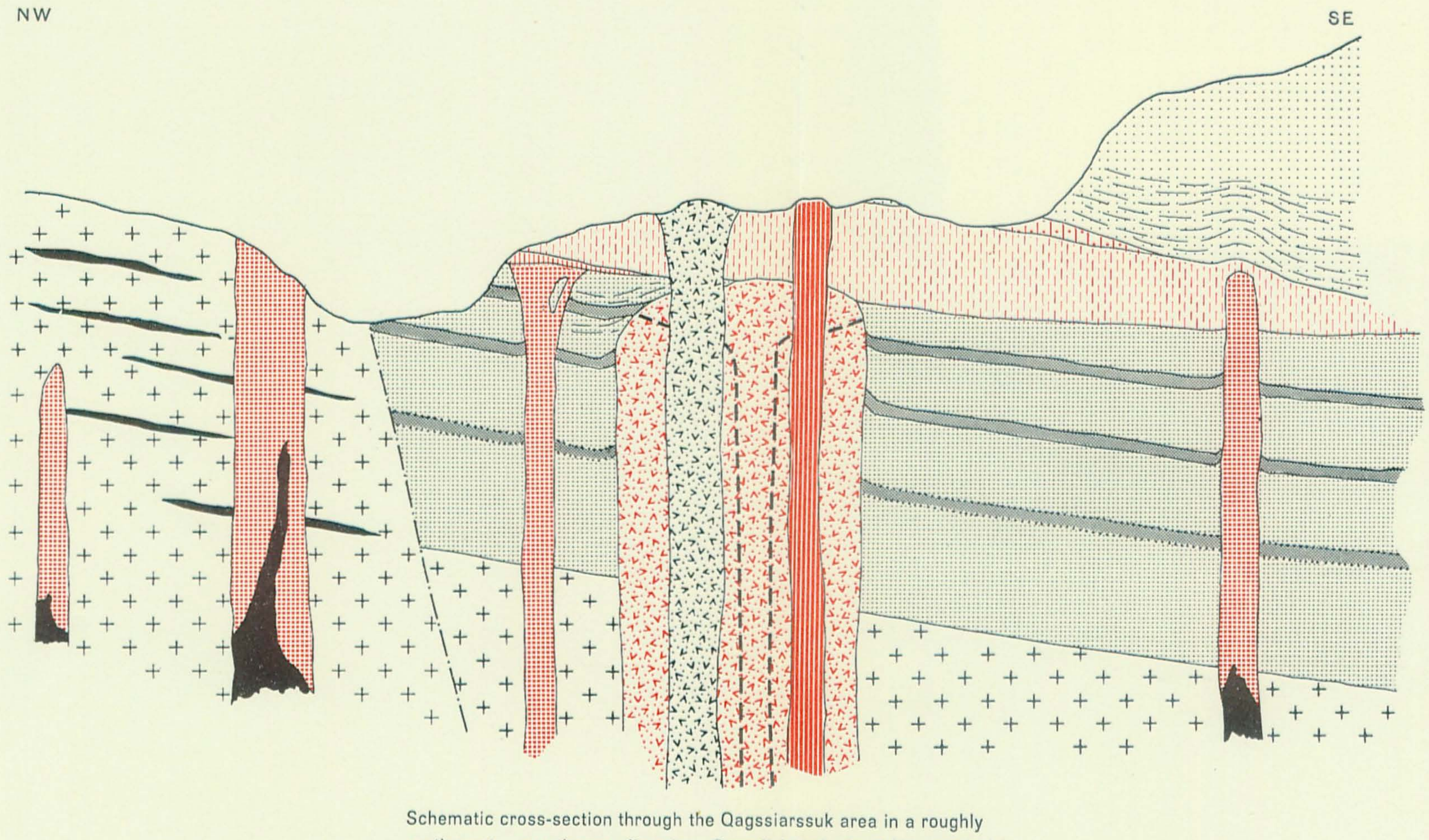

Schematic cross-section through the Qagssiarssuk area in a roughly north-west — south-east direction. Overall length ca. 3 km; vertical component of relief exaggerated ca. $2^1/_2$ times.

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