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STRUCTURAL AND PETROGRAPHIC OBSERVATIONS ON LAYERED GRANITES FROM SOUTHERN GREENLAND[1]

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ABSTRACT

Mineral layering is developed in the upper and marginal parts of two granite stocks intruding Precambrian gneisses north of Tigssaluk Fjord, southern Greenland. The layering consists of unusual concentrations of biotite, sphene, opaque minerals, allanite, zircon and apatite. Their modal proportions are commonly over 30% (by volume), rising to more than 80% in some instances. The layered structures include well-developed, rhythmically repeated mafic bands, layers with gravity-stratification, indications of trough banding, and distorted layering resembling slump structures in sediments.

The more mafic layers have distinctive cumulate textures. Euhedral biotite, sphene, allanite, zircon and apatite are poikilitically enclosed by quartz, microcline perthite, plagioclase and in places fluorite. Large euhedral crystals of microcline perthite and plagioclase are also present, the latter generally showing albitic overgrowths (An5 about) on andesine cores (An25+).

Textural and structural features of the layering are comparable with those developed in many basic, ultrabasic and syenitic intrusions. It is suggested that in the granites the layering formed during the later stages of crystallization of unusually fluid magmas, with bottom accumulation of early-formed dense minerals concentrated by the action of intermittent magmatic currents.

INTRODUCTION

The Tigssaluk Complex consists of two stocks of biotite granite emplaced in Ketilidian basement gneisses (Wegmann, 1938, and Bethelsen, 1961, for chronological terminology). The granites are cut by thick dikes of olivine dolerite and other rock types, by sills of carbonate mica peridotite, and are faulted (Fig. 2). In the chronology of the Ivigtut area the Tigssaluk Complex is pre-Gardar and belongs to the group of granite intrusions of post-Ketilidian age which have been collectively termed Sanerutian (Fig. 1; Berthelsen, 1961).

The stock forming the conspicuous mountain group of Pyramidefjeld about 5 km north of Tigssaluk Fjord (Fig. 1) was discovered in 1955 by J. Bondam, of the Geological Survey of Greenland,[2] during a reconnaissance survey of the country north of Ivigtut. In 1957 and 1958 the writer completed the survey of this intrusion and the smaller granite southeast of Pyramidefjeld.

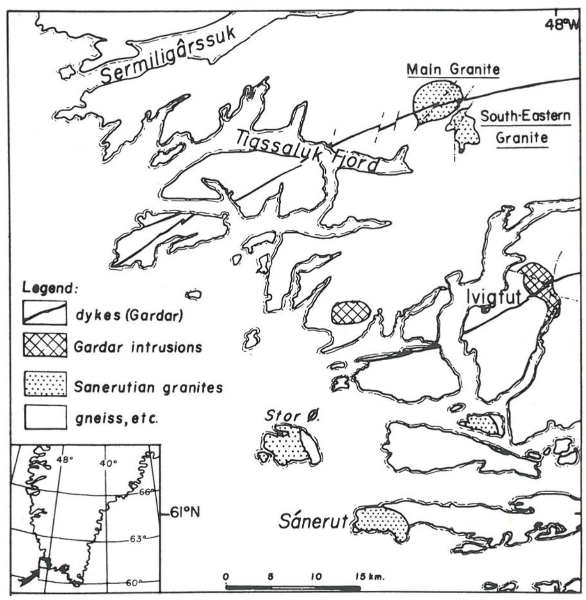


FIG. 1. Sketch map showing the positions of the principal Sanerutian and Gardar intrusions near Ivigtut. Inset map gives the location of the area in Southern Greenland.

GENERAL DESCRIPTION OF THE GRANITES

The Main Granite of Pyramidefjeld. The granite is exposed through a vertical distance of over 1000 meters. Above about 300 meters elevation the proportion of exposed rock is high (Bondam, 1956, Fig. 6), there is little vegetation and only scattered glaciers, moraines and lakes obscure the rocks (Fig. 2). Contacts with the country rocks are steep, sharply defined and cut across structures in the gneisses, and an early generation of basic dikes.

The intrusion consists of medium-grained granite with abundant microcline perthite phenocrysts, to 3 cm in length, in a medium-grained groundmass (5 mm +) of microcline perthite, plagioclase, quartz and biotite, with accessory amounts of sphene,

[1] Publication with permission of the Director, Geological Survey of Greenland.

[2] Grønlands Geologiske Undersøgelse; subsequently referred to as G.G.U.

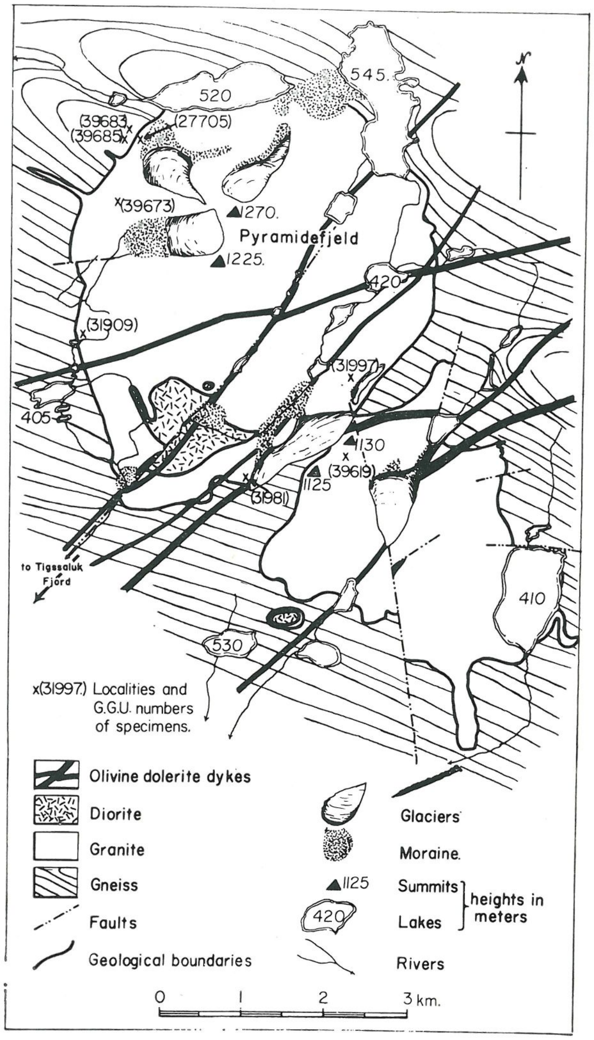


FIG. 2. Geological sketch map of the Tigssaluk Complex.

allanite, opaque minerals (magnetite and pyrite), apatite and zircon. Minor amounts of colorless to deep purple fluorite are usually present, where colored the mineral is conspicuous in hand specimens. Preferred orientation of feldspar phenocrysts or other minerals is uncommon. An average mode for the granite has been calculated (Table I, A).

Lobate, rounded basic inclusions are present throughout all but the layered parts of the intrusion. Those sampled by the writer consist of biotite, sphene, opaque minerals, intermediate plagioclase, apatite and chlorite, with rare allanite and irregular patches of microcline. Amphibole has been recorded (Bondam, 1956, pp. 13, 15). Mineralogically the inclusions resemble the rock of a small intrusion of biotite-diorite cutting the southern extremity of the granite (Fig. 2).

The Southeastern Granite. Irregular contacts dipping outwards at low to moderate angles, and numerous gneiss xenoliths in granite near the highest summits (1130, 1125, Fig. 2) indicate that the Southeastern Granite has only been slightly unroofed by erosion.

The intrusion comprises a single mass of medium-

TABLE I. MODAL ANALYSES OF MAFIC LAYERED GRANITES

	A.	27705	31909	31981	31997	39673	39683	39685	39619
Alkali Feldspar	34.3	17.6	x	9.7	4.5	14.3	4.0	1.4	23.4
Plagioclase	30.7	32.3	23.9	22.6	7.5	25.0	37.7	6.4	24.3
Quartz	28.4	29.5	25.2	28.9	13.0	26.3	34.4	12.9	26.6
Biotite	4.9	15.4	34.8	28.6	36.3	22.7	10.3	46.0	16.3
Sphene	0.6	1.5	6.4	4.8	12.2	5.1	2.0	2.7	4.2
Opaques	0.5	2.0	5.2	3.7	13.4	4.0	5.6	21.1	2.1
Allanite	x	0.4	4.1	1.1	12.2	1.2	0.1	4.4	1.3
Apatite	x	0.2	0.1	0.4	0.5	0.5	0.1	0.8	0.3
Zircon	x	0.3	0.2	0.2	0.3	0.4	0.4	0.9	x
Muscovite	0.5	0.8	0.1	x	0.1	0.5	5.4	3.0	1.5
Fluorite	0.1	x	x	x	x	x	x	0.4	x

(Vol. %. All analyses mean of two or more determinations.)
x = present but <0.1%.
A = mean of 10 specimens of normal Main Granite.
27705–39685 all from the Main Granite.
39619 from the Southeastern Granite.
See Fig. 2 for localities.

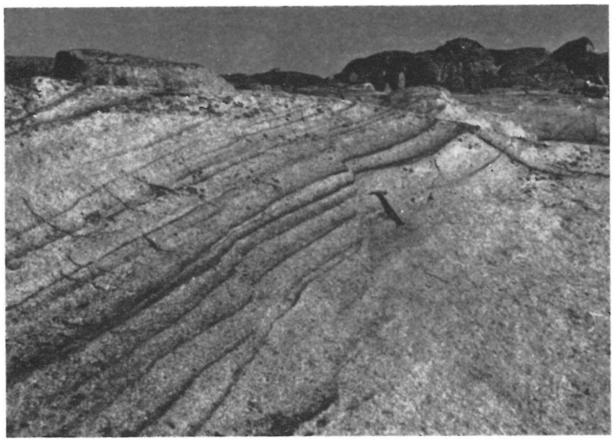


FIG. 3. Mineral layering in the north-west of the Main Granite (locality of 39673). Scale: hammer shaft about 0.5 m long.

grained rock resembling the Main Granite except that there are relatively few alkali feldspar phenocrysts. Basic inclusions similar to those found in the Main Granite occur through much of the granite and are mineralogically comparable to the central member of the small composite plug of granite and biotite-diorite close to the southwestern margin of the intrusion (Fig. 2).

THE LAYERED STRUCTURES

Field relations. The field appearance of the layering will be described briefly as details have been published elsewhere (Harry and Emeleus, 1960). In both intrusions the layering results from high concentrations of biotite and the normal accessory minerals of the granites. It includes rhythmically-repeated bands of mafic rock a few centimeters thick separated by normal granite (Fig. 3); impersistent cross-cutting structures resembling current bedding in sediments; mafic layers contorted and brecciated in a manner suggesting slumping in a mass of poorly consolidated crystals (Harry and Emeleus, 1960, Fig. 4), and local structures resembling trough-banding (Harry and Emeleus, 1960, Fig. 6). The mafic layers are frequently gravity stratified (Fig. 4; Harry and Emeleus, 1960, Figs. 2, 6) and consistently "young" upwards. In a number of examples of banding involving extreme concentrations of biotite and accessories, large crystals of alkali feldspar within the mafic layers lie parallel to the plane of the layering (Harry and Emeleus, 1960, Fig. 6). These feldspars, which are presumably of early crystallization, are microcline perthites similar to the phenocrysts of the normal granites.

In both intrusions the principal areas of layering are found at high levels (Fig. 2); in the Southeastern Granite layering appears to be confined to the ground immediately south of the 1130 meter summit. In both, the structures dip at low angles (under 30°) although it should be borne in mind that the recorded dips may not be original since there appears to have been contemporaneous disturbance of some of the layered rocks and, furthermore, the granites may have been tilted after consolidation. In the Main Granite localized areas of intense mafic layering a few meters in extent occur in granite sheets and apophyses cutting gneisses on the northwestern edge of the intrusion (39683, 39685,[1] see Fig. 2) and in a number of localities at or close to the margins (Harry and Emeleus, 1960, Fig. 7).

Mineralogy. With the possible exception of ilmenite among the opaque minerals no new mineral phase occurs in the layering which is not found in the normal granites. The grain size of the layered rocks is generally less than in the normal granites.

The light minerals include alkali feldspar, quartz and plagioclase. The alkali feldspar is a perthitic microcline whether as phenocrysts or in the groundmass, although the groundmass material is noticeably less perthitic than the phenocrysts. Quartz is usually anhedral and crowded with minute inclusions which in some cases are rutile. The plagioclase has three contrasted modes of occurrence: as well formed crystals (An15–25) to 3 mm or more in length; as relatively albitic overgrowths on these euhedral crystals extending into the spaces between biotite and the accessory minerals; and as inter-

[1] 39685, etc., refer to G.G.U. specimen numbers.

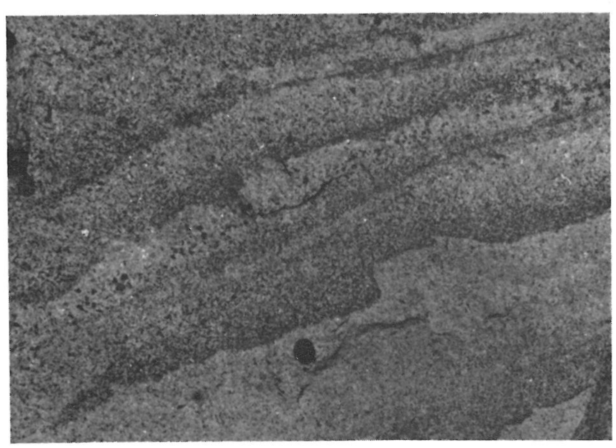


FIG. 4. Gravity-stratified layering in the South-eastern Granite (locality of 39619). Scale: coin about 3 cm in diameter.

stitial and poikilitic crystals (An 5–10) enclosing biotite, sphene and other accessories.

Biotite is in approximately equidimensional crystals 1–2 mm across, rather more elongate in the *c* direction than usual. The mineral appears to be only moderately iron-rich with β from 1.615–1.625, $2V_x = 10°$ and less, and pleochroic with X=pale yellow-green and Y=Z=olive-green. Brown or red-brown sphene is usually in characteristic lozenge-shaped crystals although locally almost skeletal, allanite too is almost invariably euhedral except in a few instances where crystals were found with embayed outlines reminiscent of the quartz phenocrysts from some acid rocks. Allanites may be as much as 3 mm across, the crystals commonly show simple twinning and are strongly colored, pleochroic from greenish brown to olive green. $2V_x$ is high (near 90°). In some specimens (*e.g.* 31909) the central parts of the allanites are completely isotropic, in others examples were found where partial change to the metamict state gave crystals with uneven, patchy extinction.

The opaque minerals have a distinctive porous structure due to the inclusion of small prisms of apatite (Fig. 11). Magnetite is the principle constituent, with minor amounts of ilmenite, hematite and pyrite. In some examples they are rimmed by granular sphene (31997).

Other components include short prismatic crystals of apatite, generally larger than those included in the opaques, and zircon with prominent concentric growth zones. Fluorite is almost always present although not in especially high proportions (Table I); it may be colorless or pale purple and shows a marked deepening in color where against allanite. Colorless mica occurs along with epidote as an alteration product of the more calcic plagioclase; muscovite of apparently primary origin was noted in several sections (*e.g.* 39683, 39685).

Modal analyses. Modal analyses of sections cut from the mafic specimens and from normal granites are summarized in Table I. A limited number of specimens was available, consequently any conclusions based on the modal data can only be regarded as tentative. Despite this, several interesting features have emerged, the must striking being the high concentrations of biotite and accessory minerals attained, exceeding 70% and even 85% in a few specimens. Secondly the proportions of quartz and total feldspar remain fairly constant when the concentration of biotite, etc., exceeds about 40% (Fig. 5), and if the modes are recalculated on an alkali-feldspar—free basis, quartz and plagioclase are found to be present in almost equal proportions regardless of the concentration of biotite, etc. (Fig. 6). Finally, the proportion of alkali-feldspar to plagioclase and quartz appears to be less in the mafic rocks than in the normal granite (Table I) and to decrease in amount with increase in the proportions of biotite and accessories (Figs. 5, 6: compare values plotted below 40% biotite, etc.).

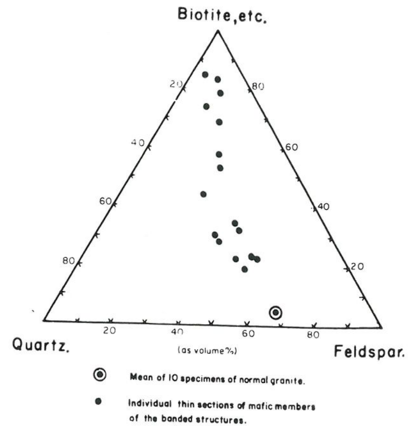


FIG. 5. Modal analyses of mafic specimens from the layered structures.

The two diagrams (Figs. 5, 6) were compiled from all the available analyses regardless of the localities of the specimens. From these, and Table I, it is seen that the most intense concentrations of biotite and accessories are associated with the Main Granite, in the sheets just outside the intrusion, and in the areas of restricted layering near and at the margins. Comparing analyses of specimens taken from different parts of the same layered units, it seems that the trend brought out in Figs. 5 and 6 is paralleled within individual units of layering (Table II).

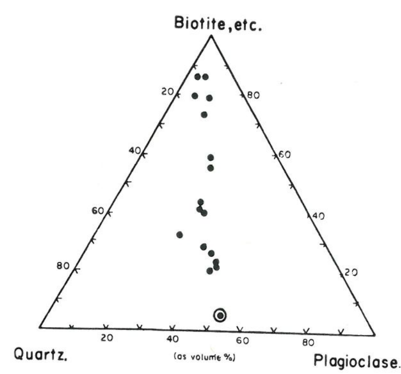


FIG. 6. Modal data used in Fig. 5 recalculated on an alkali feldspar-free basis. Symbols as in Fig. 5.

TABLE II. MODAL ANALYSES OF SPECIMENS FROM DIFFERENT LEVELS IN THE SAME UNIT OF LAYERING

	31981A	31981B	39683A	39683B
Alkali feldspar	1.8	17.6	0.7	7.4
Plagioclase	23.2	21.9	37.1	38.1
Quartz	22.5	35.4	35.2	33.4
Biotite	40.5	16.7	11.4	9.3
Sphene	5.4	4.2	3.0	1.0
Opaques	4.4	3.1	6.3	4.8
Apatite	0.5	0.3	0.1	0.2
Zircon	0.1	0.3	0.7	0.1
Muscovite	x	x	5.4	5.5
Fluorite	x	x	x	x
Allanite	1.6	0.5	0.1	0.2

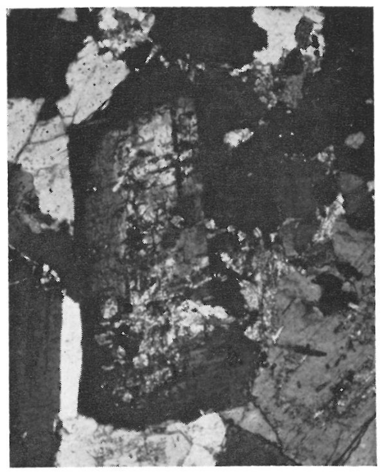
All as volume %.
x=present but >0.1%.
See Fig. 2 for localities.
31981. Specimen B taken about 10 cm. above A.
39683. Specimen B taken about 4 cm. above A.

Textural relationships. The minerals in the mafic parts of the layered structures are grouped in three categories on the basis of shapes and textural relationships. One group comprises the euhedral crystals, in a second are euhedral crystals with outlines modified by overgrowths, and in a third are placed those minerals of interstitial and poikilitic habit.

Biotite is the most conspicuous member of the first. The crystals are generally well-formed and lack evidence of overgrowths. Sphene may show slight signs of zoning with a lessening of color towards the edges, although this is not common. Allanite is included in the first group, although there are some indications of compositional zoning and overgrowths of euhedral rims on euhedral cores of slightly different optic orientation (39685). Both apatite and zircon are considered as members of this group; although characteristically zoned, the euhedral outline of zircon persists through the different layers.

Plagioclase is the most important member of the second group. Original cores of calcic oligoclase with well-developed crystal outline are surrounded by rims of more albitic composition (Fig. 7), which may show oscillatory zoning. In most instances the cores are 2–3 mm in length, the effects of the overgrowths being to increase the length to as much as 6 mm. The large crystals of alkali feldspar locally present in the mafic rocks (31997, 27705) have microcline mantles that are normally less perthitic than the central parts of the crystals. With both feldspars the textural effect of the overgrowth has been to convert originally euhedral crystals into forms which are anhedral and in extreme instances poikilitic towards their surroundings.

The third group includes examples of all the leucocratic minerals. Quartz is typically interstitial or poikilitic (Fig. 8), areas as much as 1 cm across enclosing numerous well-formed crystals of biotite, allanite, opaques, etc. With the exception of the uncommon phenocrysts, the microcline perthite in the mafic layered rocks is poikilitic in habit (Fig. 9). Poikilitic or interstitial plagioclase (Fig. 10) is particularly conspicuous as twinned crystals to 5 mm across. Fluorite is always interstitial in habit, and



A

B

FIG. 7. Plagioclase crystals with albitic overgrowths.

A. Original rounded crystal extended by albitic overgrowth. The albitic rim is anhedral towards biotite and opaques (upper right), euhedral towards quartz (upper left and left side of plagioclase) and does not develop where two plagioclase crystals come into contact (lower right). (39685), 22×, crossed polars.

B. Rimmed crystal with faint oscillatory zoning (upper and lower edges). (39619), 16×, crossed polars.

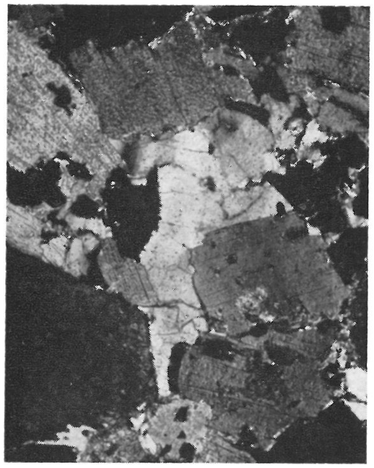


FIG. 8. Interstitial quartz (center) molded on biotite and on allanite (lower left). (39685), 18×, crossed polars.

usually is present in amounts that are too small to develop poikilitic crystals, although these were observed in a few places (Fig. 11).

The opaque minerals and quartz present difficulties in classification. The opaque minerals are poikilitic in that they contain apatite, yet they commonly are well-formed and in some instances their crystallization appears to have preceded that of biotite, sphene, or allanite. On balance they are thought to have crystallized early; quite apart from textural considerations an early crystallization would follow from their concentration in the mafic bands (Table I). There is also some textural evidence which suggests that quartz may have originally been present as discrete crystals since biotite,

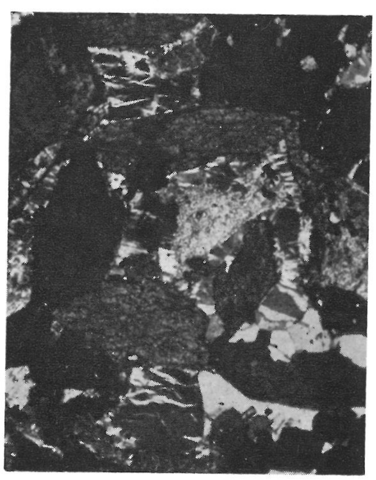
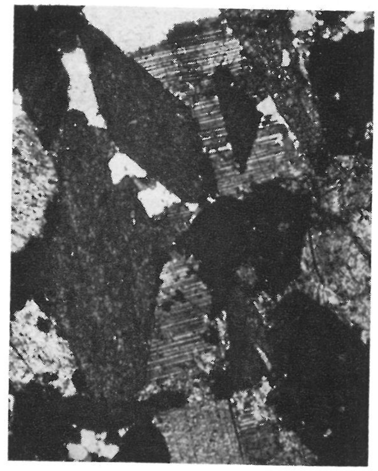
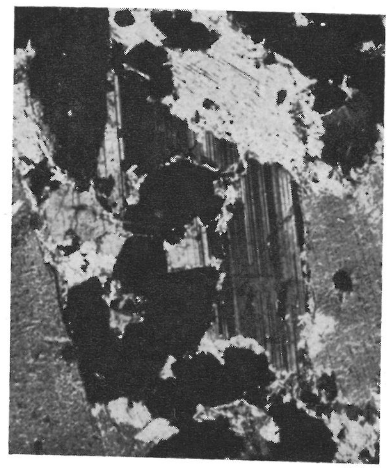


FIG. 9. Poikilitic perthitic alkali feldspar enclosing sphene, opaques and biotite. Also molded on the edge of allanite (upper left). (31997), 22×, crossed polars.



A



B

FIG. 10. Poikilitic plagioclase crystals.

A. Twinned plagioclase enclosing sphene and opaques. (31997), 35×, crossed polars.

B. Plagioclase enclosing opaques and molded on sphene and biotite. (39685), 25×, crossed polars.

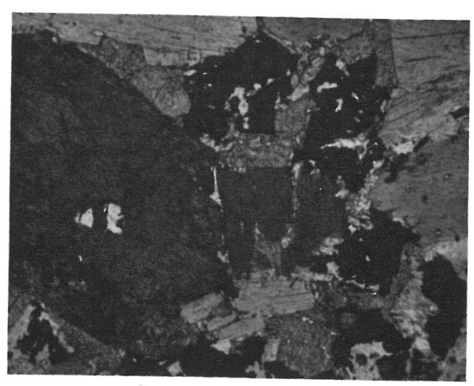


FIG. 11. Biotite, sieve-textured opaques and a large crystal of allanite (left) with interstitial areas of fluorite (high-relief mineral on the upper edge of allanite, between opaques in the upper right part of the illustration, and near the lower right-hand corner). (39685), 20×, plane polarized light.

allanite and sphene are here and there molded on, or enclose, rounded or subhedral quartz crystals. Consequently it is probably not correct to assign all the quartz to the third group.

From the textures of the layered rocks it appears that all minerals, with the exception of fluorite, were available from an early stage of crystallization, as would be expected in a melt of essentially granitic composition. The crystallization of zircon and apatite, and opaques, biotite, sphene and allanite was completed fairly rapidly; crystallization of the feldspars extended over a longer period, whereas most of the quartz and the fluorite completed crystallization relatively late in the sequence.

The textures described and illustrated are, for the most part, taken from specimens having the higher concentrations of biotite and accessories. With increased amounts of quartz and feldspars the poikilitic habit of the light minerals is less pronounced, the textures as a whole becoming those of a normal granite, although through all stages the characteristic rimmed and zoned plagioclases may be recognized, and the mafic minerals tend to remain euhedral.

Discussion

Close similarities exist between the layered structure in the granites and those present in basic, ultrabasic and other intrusions. Particularly noticeable is the repeated, rhythmic banding, the gravity stratification, the contorted structures attributed to slumping and the trough banding (*cf.* Wager and Deer, 1939; Brown, 1956; Upton, 1960). Compared with basic and ultrabasic intrusions the amount of layering in the granites is very restricted, suggesting that it may owe its origins to the existence of special conditions over a limited part of the history of cooling and consolidation of the magmas. The concentration of volatiles, principally water and fluorine, in the upper parts of the stocks is suggested as an important factor in promoting layering; their effects would be to lower the crystallization temperature, increase the time available for crystallization and lower the viscosity of the magmas. Although the mineralogy does indicate the former activity of fluorine and water, the modal amount of fluorite is small (Table I), considerably less than in other granites where layering does not appear to develop (Exley, 1959). This suggests that additional factors may have been in operation at Tigssaluk; for example, slow cooling of the magma may have been aided by elevated temperatures in the country rocks. In support of pre-heating it should be mentioned that the Sanerutian granites appear to be high-level representatives of a phase involving extensive metamorphism, granitization and emplacement of granite to the south of Ivigtut (Berthelsen, 1961), so it is likely that the Tigssaluk granites intruded country rocks already raised to moderate temperatures.

The development of gravity-stratified bands in the layered structures, rhythmic repetition of the layering, local trough banding, and igneous lamination involving the large tabular crystals of alkali feldspar enclosed in the more extreme mafic bands are considered to require the operation of magmatic currents during the accumulation of the layered rocks.

Interpreting the layered rocks as crystal accumulates, concentration of the different phases seems to have been governed largely by density contrast. Opaques, biotite and accessories settled first together with some plagioclase, a minor amount of alkali feldspar, and possibly quartz. Aggregation of biotite, accessories and opaques is suggested by the occurrence of mutually interfering boundaries, and may have assisted in their early accumulation by providing larger settling units. The interstitial and poikilitic minerals of the second and third groups represent the crystallization products of the trapped intercumulus liquid (Wager *et al.* 1960). The compositional contrast between the cumulus and intercumulus plagioclase (pp. 24–25) suggests that crystallization of the trapped liquid proceeded without completely free connection with the overlying magma, as in orthocumulates (Wager *et al.* 1960, p. 74). However, the layered rocks are clearly not simple orthocumulates; if this were so, the proportions of poikilitic and interstitial quartz, alkali feldspar and plagioclase would be expected to approximate to those in normal granite. The modal analyses demonstrate that this is not the case, the proportion of quartz in particular being high (Table I; Fig. 6), although until a means is found of distinguishing between cumulus and intercumulus quartz, the significance of the high proportion cannot be fully assessed. From the almost complete absence of alkali feldspar in some of the mafic rocks it is suggested that this component may have been able to diffuse from the trapped liquid into the overlying magma.

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