The Archaean Atâ intrusive complex (Atâ tonalite), north-east Disko Bugt, West Greenland

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The 2800 Ma Atâ intrusive complex (elsewhere referred to as 'Atâ granite' or 'Atâ tonalite'), which occupies an area of *c.* 400 km² in the area north-east of Disko Bugt, was emplaced into grey migmatitic gneisses and supracrustal rocks. At its southern border the Atâ complex is cut by younger granites. The complex is divided by a belt of supracrustal rocks into a western, mainly tonalitic part, and an eastern part consisting mainly of granodiorite and trondhjemite. The 'eastern complex' is a classical pluton. It is little deformed in its central part, displaying well-preserved igneous layering and local orbicular textures. Near its intrusive contact with the overlying supracrustal rocks the rocks become foliated, with foliation parallel to the contact. The Atâ intrusive complex has escaped much of the later Archaean and early Proterozoic deformation and metamorphism that characterises the gneisses to the north and to the south; it belongs to the best-preserved Archaean tonalite-trondhjemite-granodiorite intrusions in Greenland.

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The area north-east of Disko Bugt consists mainly of polyphase Archaean grey gneisses and sequences of Archaean and Proterozoic supracrustal rocks (Garde & Steenfelt 1999, this volume). An approximately 400 km² large area is occupied by relatively homogeneous granitoid rocks, tonalitic to granodioritic in composition: the 'Atâ granite' of Escher & Burri (1967; Fig. 1). On the geological maps of Garde (1994) and Escher (1995) these rocks are shown as 'Atâ Tonalite' and the 'Atâ pluton', respectively. In this report we present a general description of the rocks and a regional survey of their composition and fabric. Because most of the rocks are not granitic, and have variable compositions, we refer to them here as the 'Atâ intrusive complex', or the 'Atâ complex'. The complex consists of two main outcrop areas, separated by a north–south-running belt of mafic metavolcanic rocks (Fig. 1). We will refer to these areas as the 'western' and 'eastern' Atâ complex where appropriate, and to the metavolcanics as the 'central supracrustal belt'.

Apart from the study of the complex on foot, a collection of 100 grid samples was prepared with a 2 km grid point distance in order to obtain a statistically reliable impression of the regional variation in composition and rock fabric.

Rocks similar to Atâ granitoids occur throughout the area north-east of Disko Bugt. Some of these (see, for example, Higgins & Soper 1999, this volume) may be similar in age and origin to the Atâ intrusive complex. Because of the uncertainty of lithological correlations, however, the present study is restricted to the rocks originally mapped as Atâ granite by Escher & Burri (1967).

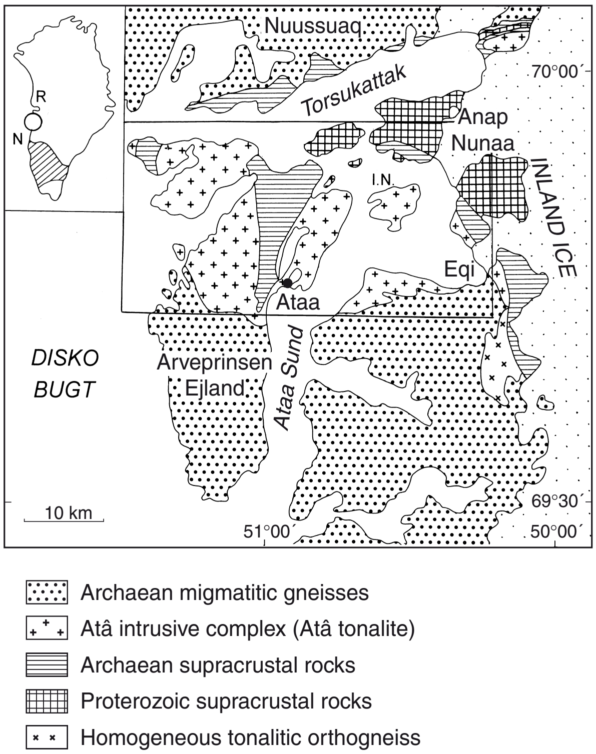

Fig. 1. Geological sketch map of the area north-east of Disko Bugt with the Atâ intrusive complex. Area covered by Figs 3 and 6 outlined. Inset shows the location of the Ataa region in Greenland (circle) between the early Proterozoic Nagssugtoqidian and Rinkian orogenic belts (N and R, respectively). I.N.: Illuluarsuit Nunataat.

Regional setting and earlier investigations

Escher & Burri (1967) were the first to map and describe the Atâ intrusive complex in some detail. The granitoid rocks of the complex separate regional gneisses (to the south) from sequences of supracrustal rocks (Fig. 1), and Escher & Burri (1967) believed that they were formed by granitisation of the gneisses and overlying supracrustals. Kalsbeek *et al.* (1988) dated samples from the eastern Atâ complex at *c.* 2800 Ma (whole-rock Rb-Sr, Pb-Pb, Sm-Nd and zircon U-Pb data), and this age has recently been confirmed by a SHRIMP U-Pb zircon date of 2803 ± 4 Ma (Nutman & Kalsbeek 1999, this volume). Gneisses to the south, believed to represent deformed Atâ granitoids, yielded a Rb-Sr whole-rock isochron age of *c.* 2670 Ma, which Kalsbeek *et al.* (1988) interpreted as dating an event of deformation and migmatisation during which Atâ granitoids were transformed into grey gneisses.

Escher & Burri (1967) described the plutonic rocks as sheared granodiorites and quartz diorites in the marginal parts of the body, grading into well-preserved granite in the central part. Samples studied by Kalsbeek *et al.* (1988) varied between tonalite-trondhjemite and granodiorite. One of the aims of the present investigation was to study the distribution of granites, granodiorites and tonalitic varieties within the Atâ complex in more detail.

At many localities, for example near the abandoned village Ataa, the rocks of the Atâ complex contain a multitude of felsic dykes, a few tens of centimetres wide, cutting each other, and running in many different directions (Kalsbeek *et al.* 1988). Often these dykes are hardly or not deformed and display well-preserved magmatic structures, even where the host rock shows a distinct planar fabric. Isotope data from these dykes fall near the *c.* 2800 Ma Rb-Sr and Pb-Pb isochrons defined by the surrounding rocks. The dykes were therefore interpreted to be of Archaean origin, and Kalsbeek *et al.* (1988) believed that the pattern of veins and dykelets was related to a system of cooling joints in the main granitoid body. Based on the state of preservation of the dykes, Kalsbeek *et al.* (1988) concluded that later Archaean and Proterozoic deformation of these rocks was insignificant.

Field investigations

The Atâ complex is well exposed, but at most inland localities the bed rock is heavily covered with lichen, and geological details can often only be studied in coastal outcrops.

The rocks are medium grained and have light- to dark-grey colours. Locally igneous layering is well preserved (Fig. 2A). At several localities felsic granitoid phases intrude darker, foliated rocks, and in coastal outcrops east of Ataa large inclusions of foliated, darker rock were observed within more felsic granitoids. Apparently the Atâ complex is polyphase, but boundaries between different phases are difficult to map inland.

Border relationships

Atâ granitoids commonly have sharp intrusive borders towards the surrounding supracrustal rocks. West of Ataa, for example, sheets of Atâ granodiorite cut into supracrustal amphibolites. Intrusive breccias have been observed at the border between the western Atâ com-

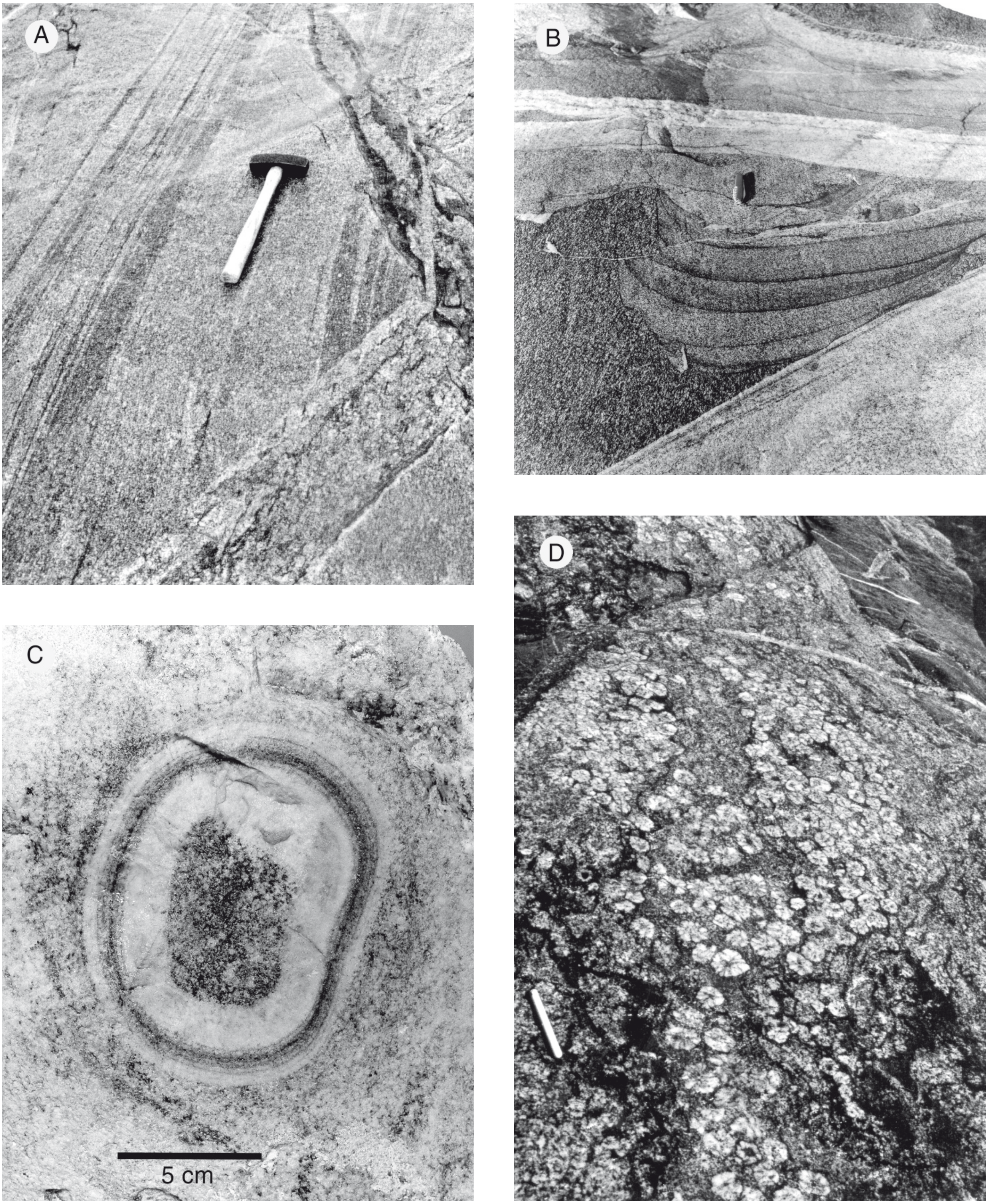

Fig. 2. **A**: Igneous layering in Atâ granitoids cut by various dykes, south-east coast of Illuluarsuit Nunataat. **B**: Trough layering in late granitoid dyke at Ataa; pocket knife for scale. **C**: Orbicule in Atâ granodiorite, south-east coast of Illuluarsuit Nunataat; largest diameter of orbicule 13 cm. **D**: Flower-like orbicular fabric in dyke within Atâ granodiorite, south-east coast of Illuluarsuit Nunataat; orbicules are up to *c*. 5 cm in diameter (pencil for scale).

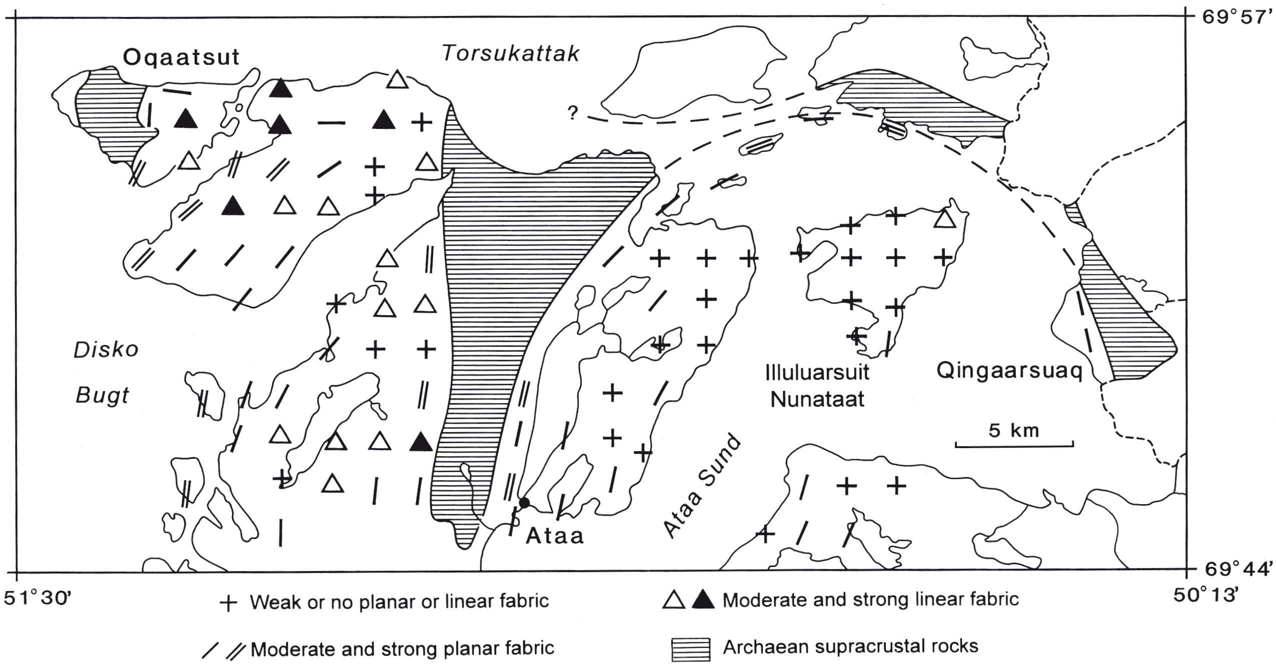

Fig. 3. Variation in intensity of rock fabrics within the Atâ intrusive complex based on the study of 100 grid samples (see text). Orientation of foliation from field observations; orientation of linear structures is not well known.

plex and the central supracrustal belt on the north coast of Arveprinsen Ejland. Over large distances, however, such features are not observed, and there is just a sharp, commonly strongly sheared border between homogeneous Atâ granitoids and homogeneous amphibolite. Rafts and inclusions of amphibolite and metagabbroic rocks in the Atâ complex occur locally, but are not common.

Towards the south the Atâ complex borders migmatitic grey gneisses, and boundary relations are here more difficult to establish. Local observations show three different relationships: (1) granitoid rocks of the eastern Atâ complex intrude into older gneisses on the mainland south of Illuluarsuit Nunataat; (2) southward on Arveprinsen Ejland and on the mainland, Atâ granitoids become increasingly folded and migmatised and lose their identity as Atâ rocks; (3) on Arveprinsen Ejland the western Atâ complex is locally intruded in the south by younger granitoid rocks, and deformed together with these. A sample of such a younger granite has yielded a SHRIMP U-Pb zircon age of 2758 ± 2 Ma (Nutman & Kalsbeek 1999, this volume). The younger granites may contain large rafts and inclusions of folded and migmatised Atâ granitoids. Because of imperfect exposure and similarity of the different rock types it is not possible to map the southern border of the Atâ complex in any detail.

Fabric

The granitoid rocks of the Atâ complex commonly exhibit a foliation or lineation of variable intensity. Mapping variations in fabric intensities was not possible in the field, partly because of heavy lichen cover. Therefore, an attempt was made to quantify fabric intensity throughout the Atâ intrusive complex with the help of the grid sample collection. Fabric intensities were graded for individual samples on a scale from 0 to 5 (0 = no visible foliation or lineation; 5 = strong planar or linear fabric). Grading was carried out independently by both authors with very similar results. Figure 3 shows the results of this approach: within the eastern Atâ complex there is a large area within which tectonic fabrics are poorly developed. Towards the supracrustal rocks this area is surrounded by increasingly gneissified granitoids. The foliation is here everywhere parallel with the border of the complex, turning from NE on Arveprinsen Ejland through E–W in the north to SE on Qingaarsuaq in the east (Fig. 3). Along the north coast of Illuluarsuit Nunataat, where only a very weak planar fabric is visible, this follows the same pattern, from ENE in the west over E–W to SE in the north-eastern corner of the island. Where igneous layering is visible, the foliation is normally parallel to it. All these features suggest that this weak

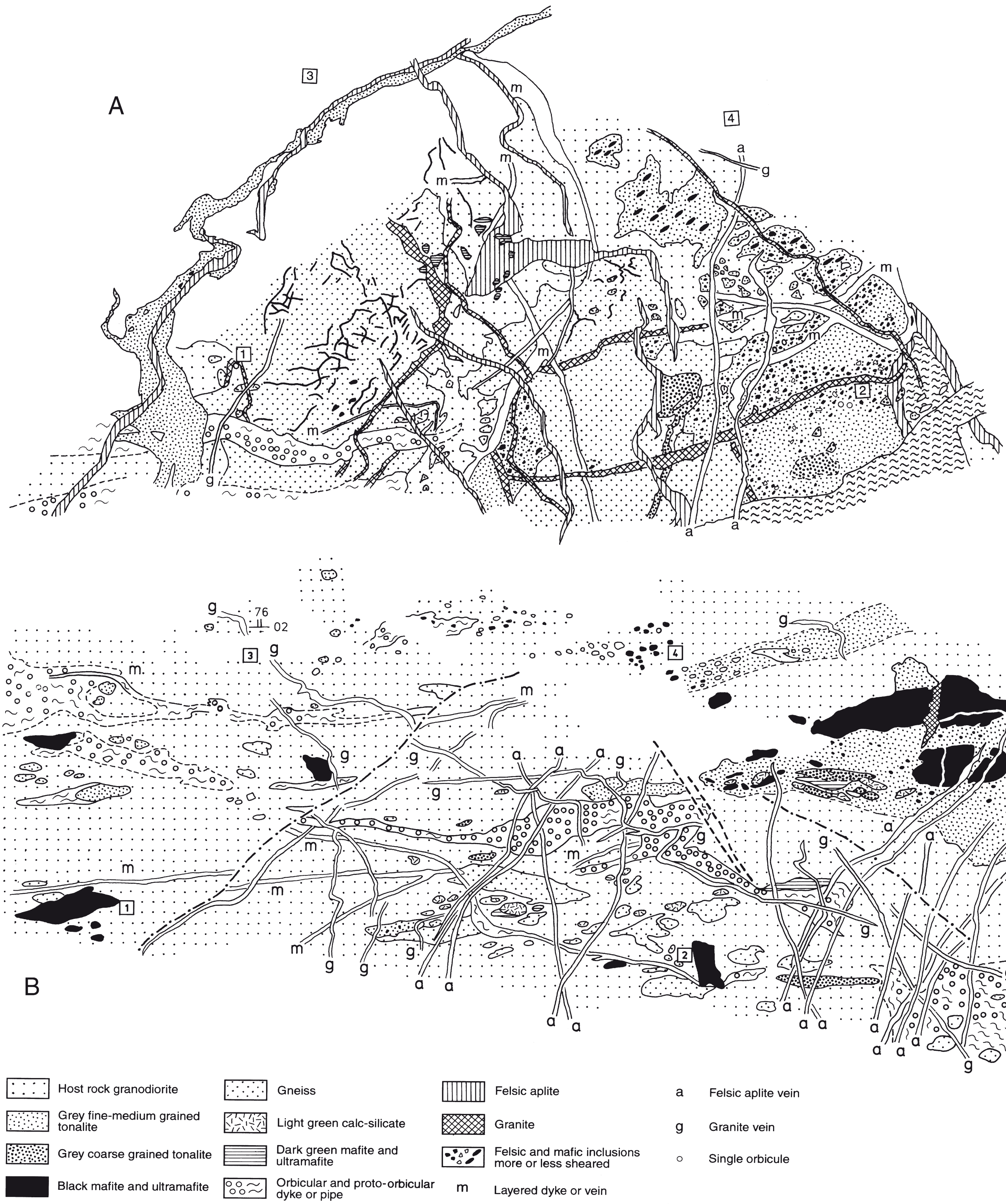

Fig. 4. **A**, **B**: Coastal outcrops on south-east Illuluarsuit Nunataat mapped in the field on photographs. Not to scale: points 1, 2, 3 and 4 mark the corners of squares with 20 m side length. Area covered by **A** is dominated by inclusions; that of **B** by Atâ granodiorite. Orbicules are rare outside the irregular dykes, but a few occur near point 2 in **A** and point 4 in **B**. Strike and dip symbol in **B** (near 3) shows the orientation of igneous layering.

fabric is due to magma flow rather than to later deformation. Petrographic observations (see p. 109) support this suggestion.

In the western complex, Atâ granitoids often exhibit a well-developed planar or linear fabric, but even in the most strongly sheared rock undeformed (Archaean) felsic dykes may be found, indicating that most of the deformation took place during or shortly after emplacement of the complex. In areas of weak deformation the rock commonly has a linear rather than a planar fabric. Due to lichen cover it is nearly impossible to measure the orientation of the lineation with any precision; in general it appears to plunge moderately to steeply east.

Felsic dykes and orbicular textures

In the southern parts of its outcrop area the rocks of the Atâ complex contain numerous felsic dykes (Fig. 4). They range up to *c.* 50 cm in width and consist of fine-grained granitoid rocks in different shades of grey, within which magmatic layering may locally be well preserved (Fig. 2B). Locally pink pegmatite dykes are also common. Some dykes exhibit beautifully preserved orbicular textures (Fig. 2D, see below).

The dykes show complex cross-cutting relationships; at some localities up to ten successive generations of veins and dykes can be distinguished. The dykes cut the foliation in the surrounding granitoid rocks, though some themselves have a planar fabric clearly discordant to that of the host rock, and often subparallel with the dyke margins. It is not uncommon to find foliated dykes cutting unfoliated ones. This suggests that the fabric is related to deformation during consolidation of the cross-cutting dyke, at a time when older dykes had already totally solidified and therefore were less susceptible to penetrative deformation. Near the southern margin of the Atâ complex the dykes are commonly folded, but folded dykes are locally cut by undeformed ones, confirming the polyphase origin of the dykes.

Felsic dykes are especially numerous around Ataa, in the southern part of Illuluarsuit Nunataat and on the mainland to the south. They become gradually less common in northward direction, and in the northern parts of the complex dykes are very rare. It is therefore possible that at least the later dykes are related to the granitoid rocks which intrude the Atâ complex at its southern margin. We do not have sufficient chronological information on the felsic dykes to substantiate this suggestion.

Granitoid rocks with spectacular orbicular textures (Fig. 2C) occur on the south-east coast of Illuluarsuit Nunataat. Orbicules and less well-developed proto-orbicules most commonly occur in irregular dykes and pipes but have also been locally observed in the granodioritic host rock (Fig. 4). The orbicules consist mainly of quartz and feldspar; commonly they show rhythmic zonation, and sometimes they have a core similar to the local Atâ granodiorite (Fig. 2C). Another kind of orbicular bodies, composed of quartz, feldspar and minor biotite, arranged into a radial pattern to form flower-like aggregates a few centimetres across (Fig. 2D), was found in a late flat-lying dyke in the same area.

The outcrops which contain orbicular dykes and pipes show extremely complex structures. Atâ granitoids here have a large variety of variably deformed supracrustal and granitoid inclusions, some of which contain second-order inclusions. A large number of veins of different compositions and generations cross-cut the Atâ granodiorite as well as the inclusions and the orbicular dykes. Only a few layered dykes or veins appear to be older than the orbicular granite.

Elliston (1984) has given convincing evidence that formation of orbicules takes place in a hydrous silica gel during alternating static and dynamic conditions, and that the occurrence of orbicules indicates crystallisation of hydrosilicates. The orbicular textures thus may suggest this locality lies near the roof of the eastern Atâ complex, where water was available to react with the granitoid magma. The presence of abundant inclusions would be consistent with this suggestion, but igneous layering here dips steeply to the east.

Petrography

Mineralogical composition

Samples of the Atâ complex consist mainly of plagioclase (oligoclase to andesine) and quartz, with variable proportions of K-feldspar, biotite and hornblende. K-feldspar in any significant proportion and hornblende do not occur together in the same sample; this is a common feature in basement gneisses in Greenland, biotite taking the place of hornblende + K-feldspar. Apatite, zircon, titanite and allanite are common accessories, and opaque minerals occur in minor proportions. In many samples the plagioclase is partly replaced by epidote and fine-grained white mica; chlorite commonly replaces biotite.

Modal compositions of samples from the complex

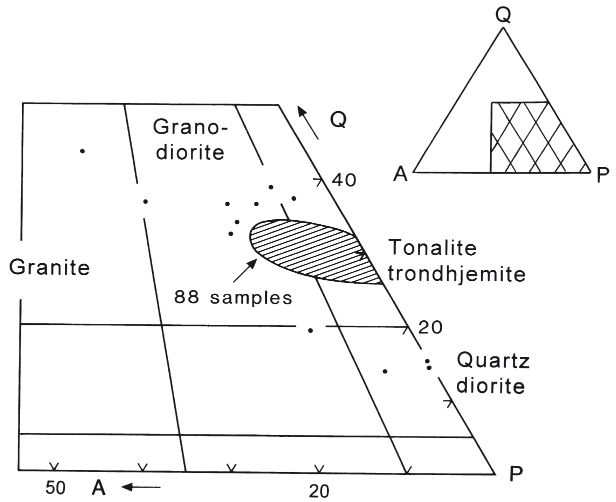

Fig. 5. Streckeisen QAP (Quartz – Alkali feldspar – Plagioclase) diagram showing the modal composition of 100 grid samples from the Atâ intrusive complex. The mode was calculated from the chemical composition of the rocks, see text.

were estimated with help of chemical analyses (see p. 110). Plotted in the Streckeisen (1976) Quartz (Q) – Alkali feldspar (A) – Plagioclase (P) diagram (Fig. 5), most samples fall in the fields of tonalite-trondhjemite and granodiorite.

Fabric

In most samples the rock is medium grained. Plagioclase commonly forms subhedral crystals a few millimetres long, with length to width ratios of the order of 1.5. Some samples have K-feldspar megacrysts up to *c.* 1 cm, with inclusions of euhedral plagioclase up to a few millimetres. Quartz is recrystallised to more fine-grained mosaics with irregular crystal boundaries.

In many samples with weak to moderately well-developed foliation, plagioclase crystals have a preferred orientation, parallel to the foliation. This fabric is often not very pronounced because of the moderate elongation of the plagioclase crystals. Biotite shows a preferred orientation parallel to that of plagioclase, but also this is not always very distinct. In many samples there is no evidence of deformation of the rock-forming minerals to explain the alignment of plagioclase and biotite crystals. This suggests that the foliation in these rocks is due to magmatic flow rather than later deformation (Paterson *et al.* 1989).

Samples with a more pronounced foliation probably underwent additional subsolidus deformation. In some cases trains of biotite crystals wrap around plagioclase, and sometimes quartz has recrystallised into ribbons parallel with the foliation. Because of sub-

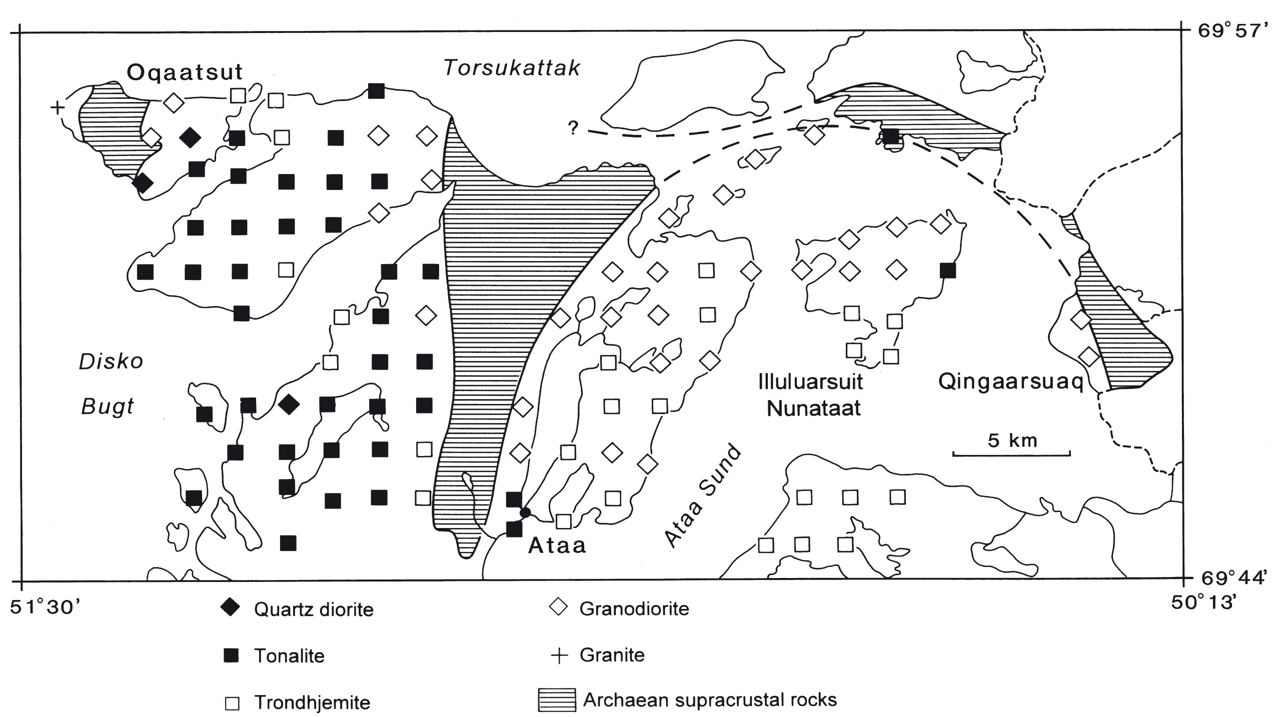

Fig. 6. Distribution of rock types within the Atâ intrusive complex. Rock classification according to Streckeisen (1976) with modal compositions calculated from the chemical compositions (see text).

Table 1. Chemical composition of selected samples from the Atâ intrusive complex

GGU no.	348655 Qd (W)	348621 To (W)	349650 To (E)	348625 Tr (E)	348697 Gd (E)
SiO_2	61.41	66.68	69.84	70.45	72.36
TiO_2	0.54	0.44	0.39	0.33	0.23
Al_2O_3	18.62	15.76	15.25	14.85	14.84
Fe_2O_3*	4.70	3.82	2.96	2.51	1.96
MnO	0.05	0.05	0.03	0.03	0.02
MgO	1.83	1.57	1.02	0.75	0.55
CaO	5.78	4.07	3.29	2.81	2.33
Na_2O	5.29	4.32	4.62	4.62	4.61
K_2O	0.66	1.38	1.36	1.86	2.36
P_2O_5	0.17	0.13	0.12	0.08	0.06
l.o.i.	0.20	0.60	0.80	0.50	0.60
Sum	99.25	98.82	99.68	98.79	99.92
Rb	16	37	38	56	57
Ba	266	402	510	562	866
Pb	7	8	9	13	9
Sr	603	460	478	407	370
La	14	21	21	20	19
Ce	36	40	42	36	33
Nd	19	17	15	16	15
Y	10	9	8	10	6
Th	3	7	7	8	6
Zr	79	121	155	133	120
Nb	2.1	3.9	3.4	4.8	3.1
Zn	62	68	65	63	54
Cu	55	10	9	14	5
Ni	16	14	5	5	4
Sc	10	6	3	3	2
V	77	54	35	28	20
Cr	26	15	8	7	8
Ga	21	19	19	19	18
Cation norm					
cor	–	0.08	0.54	0.36	0.67
qz	10.67	22.29	26.34	26.71	27.91
or	3.92	8.35	8.17	11.23	14.09
ab	47.70	39.72	42.17	42.40	41.83
an	25.22	19.81	15.80	13.72	11.29
di	1.97	–	–	–	–
hy	8.82	8.37	5.81	4.63	3.51
mt	0.59	0.49	0.37	0.32	0.25
il	0.76	0.63	0.55	0.47	0.32
ap	0.36	0.28	0.26	0.17	0.13

Major elements analysed at Activation Laboratories Ltd, Canada, by XRF on glass discs.
Fe_2O_3*: all iron reported as Fe_2O_3.
Trace elements were determined by XRF on powder tablets at the Institute of Geology, University of Copenhagen, Denmark.
Qd: quartzdiorite.
To: tonalite.
Tr: trondhjemite.
Gd: granodiorite.
The letters W and E indicate whether the samples are from the western or eastern Atâ complex.

solidus recrystallisation and alteration of the igneous minerals it is not always easy to differentiate the effects of magmatic flow and later subsolidus deformation in individual samples.

Chemical composition

To obtain statistically reliable information on the composition of the Atâ complex, aliquots of all samples from the grid collection were chemically analysed. Chemical data were acquired from Activation Laboratories Ltd., Canada; a few representative analyses are shown in Table 1.

Cation norms, with orthoclase + hypersthene recalculated into equivalent proportions of biotite + quartz (5 or + 6 hy = 8 bi + 3 qz), were used as an estimate of the modal composition of the rock. Because most samples contain only moderate amounts of mafic minerals (< 15%), this probably yields a fair approximation of the true modal composition. According to the calculations most samples classify as tonalites or trondhjemites (leuco-tonalite with < 10% mafic minerals), about one third are granodiorites, a few are quartz diorites and one is a granite (Fig. 5). There is a clear distinction between the areas west and east of the central supracrustal belt of Arveprinsen Ejland. Nearly all samples to the west are tonalites, whereas to the east trondhjemites and granodiorites are predominant (Fig. 6). This difference suggests that the eastern and western outcrop areas of Atâ granitoids may represent independent intrusions.

The only true granite in the collection is from the western tip of the island Oqaatsut north-west of Arveprinsen Ejland (Fig. 6); it is also the only muscovite-rich sample. Two other samples from Oqaatsut also have high proportions of K-feldspar relative to other Atâ granitoids. It is not clear how far these rocks relate to the Atâ complex.

Discussion, summary and conclusions

Atâ granitoids outcrop in two main areas, west and east of a belt of basic metavolcanic rocks in the northern part of Arveprinsen Ejland. The western and eastern outcrops differ in composition and may represent two independent intrusions.

The western area is dominated by tonalitic rocks, variably transformed into (hornblende-) biotite gneisses.

This body may represent a several kilometres wide sheet intruded into supracrustal rocks.

The eastern body consists mainly of trondhjemites and granodiorites, and forms a classic pluton. In its central part the rocks are often almost devoid of planar or linear fabric, and where preferred mineral orientations are visible these are probably the result of magmatic flow, parallel with the border of the pluton. Towards the margin the foliation becomes more intense. This is the result of subsolidus deformation, which probably followed soon after solidification, because many of the late granitoid veins are totally undeformed. Deformation in the marginal parts of plutons is commonly ascribed to 'ballooning' of the magmatic interior of a pluton, related to buoyancy forces or to the intrusion of new magmatic pulses (e.g. Paterson *et al.* 1989). Magmatic features such as mineral layering and orbicular fabrics are locally beautifully preserved within the eastern pluton. Altogether, this is probably one of the best preserved Archaean trondhjemite-granodiorite intrusions in Greenland, having escaped both later Archaean and early Proterozoic deformation and metamorphism. Even the Archaean K-Ar isotope systems in hornblende from metagabbroic inclusions in the Atâ complex are preserved in this area (Rasmussen & Holm 1999, this volume).

Towards the south the Atâ granitoids grade into the regional grey migmatitic gneisses. Atâ granitoids become deformed and migmatised and intruded by younger granitoid phases. Elsewhere, rocks of the Atâ complex intrude somewhat older gneisses (see Nutman & Kalsbeek 1999, this volume). Gneisses in the area south of the Atâ complex have undergone a complex history of Archaean and Proterozoic deformation (Escher *et al.* 1999; Grocott & Davies 1999, both in this volume). If rocks once belonging to the Atâ complex occur there, they cannot be recognised as such.

Archaean regions can be divided into two types: (1) granulite–gneiss terrains, consisting mainly of grey migmatitic gneisses, and (2) granite–greenstone belt terrains (e.g. Windley 1984). The area within which the Atâ complex is exposed has the characteristics of a granite–greenstone terrain: relatively low-grade basic supracrustal rocks being intruded by tonalite–granodiorite plutons. Such terrains cover large parts of Canada, South Africa and Australia (see e.g. Windley 1984) but are rare in Greenland. In north-eastern Disko Bugt there is a rapid transition between the 'granite-greenstone' terrain of northern Arveprinsen Ejland and Illuluarsuit Nunataat, and the 'grey gneiss' terrain of southern Arveprinsen Ejland and the mainland east of Ataa Sund. There is no doubt that this change in character of the rocks is due to later deformation and metamorphism in the south.

Kalsbeek *et al.* (1988) speculated that, since the Ataa region had largely escaped the early Proterozoic deformation and high-grade metamorphism that characterise the Nagssugtoqidian and Rinkian belts, to the south and to the north respectively, it did not belong to either of these belts. However, structural investigations (Escher *et al.* 1999; Garde & Steenfelt 1999; Grocott & Davies 1999, all in this volume) have shown that the area north-east of Disko Bugt, like the Rinkian belt, is characterised by large west- and north-west-directed thrust sheets. These studies suggest that the Atâ intrusive complex may lie within one of these thrust sheets, with early Proterozoic deformation concentrated along the thrust boundaries, without affecting the Atâ com plex itself.

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