Earth's oldest well-preserved mafic dyke swarms in the vicinity of the Isua greenstone belt, southern West Greenland

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The Isukasia region of southern West Greenland contains the Earth's oldest known supracrustal rocks (the *c*. 3.8–3.7 Ga Isua greenstone belt: Appel *et al.* 1998) and well-preserved mafic dyke swarms (Inaluk and Tarssartôq dykes: Nutman *et al.* 1983). This report describes field investigations of the dykes carried out in 1999 as part of the *Isua Multidisciplinary Research Project*, and summarises current knowledge of the dykes. The project was initiated in 1997 with the aim of coordinating a detailed reinvestigation of this geologically important region. Fifteen members of the group were involved in field work in 1999 and this article represents only one aspect of the work.

The occurrence, state of deformation and geochemical composition of the dykes provide important information on the evolution of the continental crust into which the dykes were intruded. Cross-cutting relationships between dykes and host rocks, and between different generations of dykes, yield valuable relative time constraints, and dykes provide significant time markers between structural and metamorphic events. The compositions of the least altered and least metamorphosed dykes help to define the properties of their mantle source region, as well as the nature of the crust through which the magmas travelled.

Regional geology

The Isua greenstone belt – hereafter referred to as the *Isua belt* – is located 150 km north-east of Nuuk, within the Archaean craton of southern West Greenland (Fig. 1; Bridgwater *et al.* 1976). It comprises heterogeneously deformed, metamorphosed and metasomatised volcanic and volcaniclastic rocks, and minor sedimentary rocks (Bridgwater & McGregor 1974; Nutman 1986; Rosing *et al.* 1996; Myers in press). The Isua belt has an intensely deformed contact with 3.8–3.7 Ga tonalitic gneisses (Nutman *et al.* 1996, 1999) that are broadly contemporaneous with the 3.8–3.6 Ga tonalitic Amîtsoq gneisses in outer Godthåbsfjord and outer Ameralik fjord (Black *et al.* 1971; Moorbath *et al.* 1972).

Major dyke swarms, the subject of this paper, post-date the juxtaposition of the Isua belt and the tonalitic gneisses. Some of these dykes are generally assumed to be correlative with the Ameralik dykes found in outer Godthåbsfjord and outer Ameralik fjord (e.g. Bridgwater *et al.* 1976). The majority of the rocks in the vicinity of the Isua belt are early Archaean, but they were involved in complex, still poorly understood, late Archaean and Proterozoic events. These events included late Archaean amphibolite facies metamorphism (Boak & Dymek 1982; Nutman 1986; Gruau *et al.* 1996), metamorphism and metasomatism associated with Proterozoic faulting (Boak *et al.* 1983) and a 1600 Ma thermal event (Baadsgaard *et al.* 1986).

Episodes of dyke intrusion

During July and August 1999, three locations were studied (Fig. 1a). These demonstrated the relationships of three episodes of dykes with different host lithologies that have different structural and metamorphic histories (Table 1).

The oldest dykes (Episode 1, Table 1) were observed close to areas A and B in the northern gneisses (Fig. 1a). These sparse dykes, termed the *Inaluk dykes* by Nutman *et al.* (1983), cut previously deformed tonalitic gneiss (*grey gneisses* of Nutman *et al.* 1983) and were themselves intruded by sheets of pegmatite and granite (*white gneisses* of Nutman *et al.* 1983) during the deformation that formed the regional gneissosity (Fig. 2). The Inaluk dykes (defined as dioritic by Nutman *et al.* 1983) are generally 20 cm to 4 m wide and range from meladioritic to tonalitic (up to 65% SiO_2: this study). Most dykes are melanocratic, containing hornblende and biotite with plagioclase feldspar and some quartz; the

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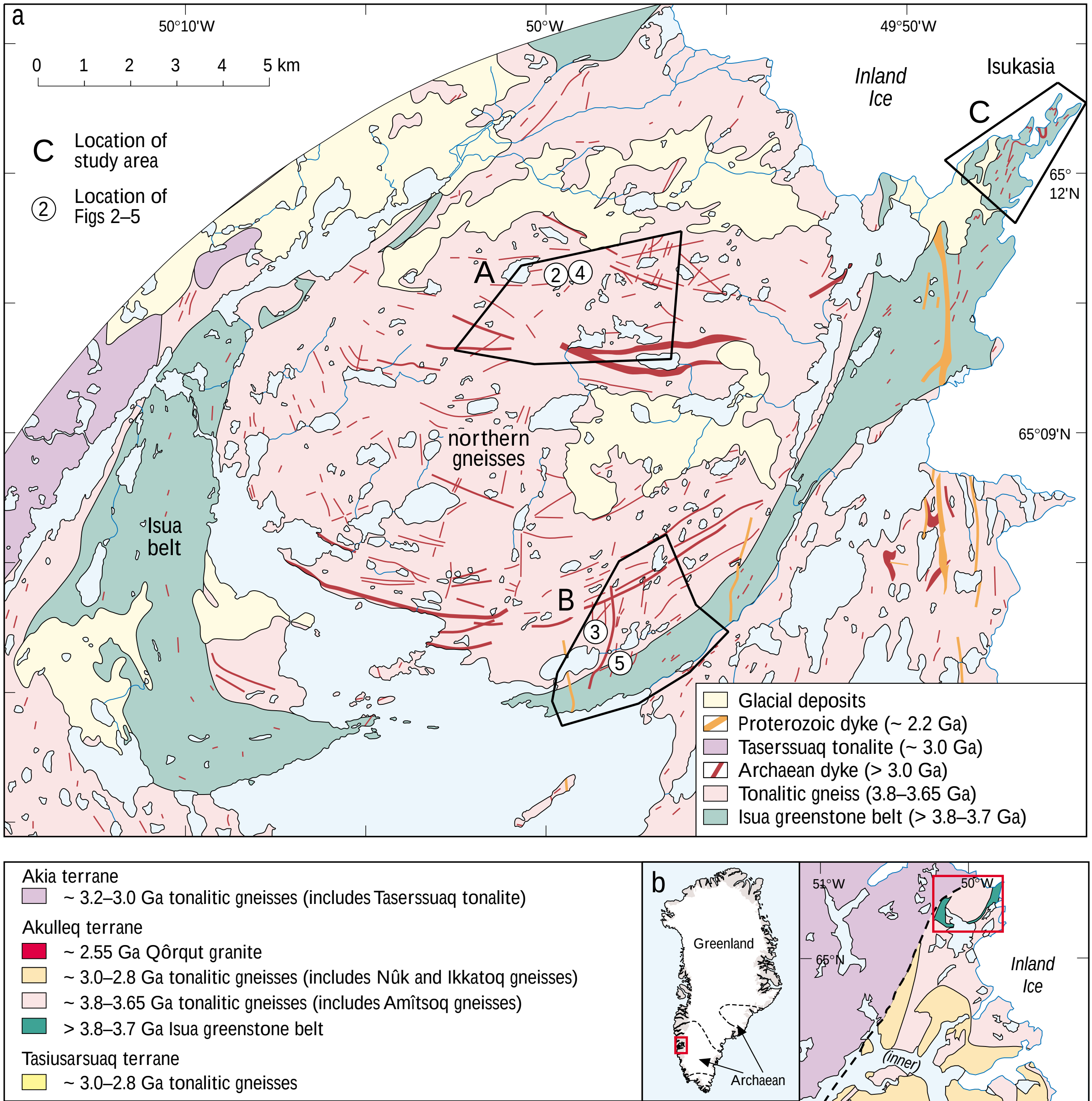

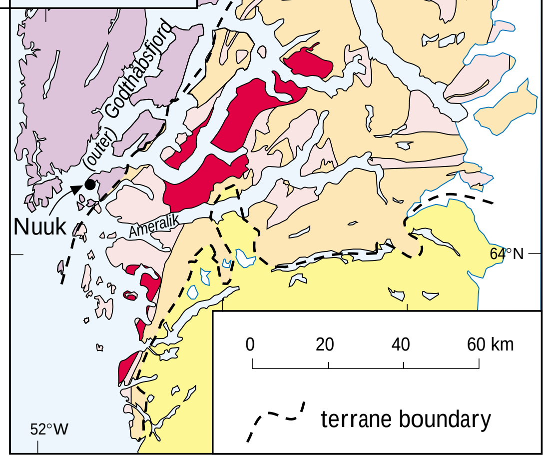

Fig. 1. **a**: Simplified geological map of the Isua belt and surrounding gneisses, modified from Nutman (1986). **Frames A**, **B** and **C** outline the areas where detailed studies of mafic dykes were carried out in 1999; locations of photographs in Figs 2–5 are indicated. **b**: Location of the Isua belt in the Godthåbsfjord region of southern West Greenland. Positions of the early Archaean rocks and terrane boundaries are after Allaart (1982) and McGregor *et al.* (1991), respectively. For clarity, the only supracrustal rocks indicated are those of the Isua belt. Main regions of Archaean gneiss that escaped pervasive ductile Proterozoic deformation are shown on the inset map.

more leucocratic members have significant modal quartz (> 20%). In Area A (Fig. 1a), Inaluk dykes and the cross-cutting granite and pegmatite sheets are locally weakly deformed (Fig. 2). Because they are metamorphosed, further detailed geochemical studies of the Inaluk dykes are not planned, although U–Pb zircon dating to obtain igneous crystallisation ages will be attempted.

The second episode of dyke intrusion (Table 1) forms the focus of this study (Fig. 3). These dykes have been correlated with the Ameralik dykes in outer Godthåbsfjord and outer Ameralik fjord (Bridgwater & McGregor 1974). However, this correlation is unproven, and we follow the recommendation of Nutman *et al.* (1983) and refer to the dykes in the vicinity of the Isua belt as *Tarssartôq dykes*. These volumetrically important swarms are predominantly basaltic in composition, are a few centimetres to about 100 m thick, and some can be traced for several kilometres. They post-date the cessation of early Archaean plutonism, metamorphism and deformation, but are locally affected by late Archaean amphibolite facies events. The Tarssartôq dykes are subdivided into four distinct swarms (Table 1): early NNE–SSW-trending ultramafic dykes, noted by Nutman (1986) but not seen in our study areas; thick E–W-trending norite dykes (T1); E–W-trending dolerite dykes (T2), the 'tangential' dykes of Allaart (1975); and N–S-trending dolerite dykes (T3), 'radial' dykes of Allaart (1975).

The youngest episode of dyke intrusion post-dates the late Archaean metamorphism, and resulted in norite dykes, mainly N–S-trending, in which igneous mineralogy is widely preserved (Table 1). One of these dykes has yielded a SHRIMP U–Pb zircon age of *c.* 2.2 Ga (Nutman *et al.* 1995). These Proterozoic dykes are volumetrically minor compared to the Tarssartôq dykes and are not considered further here.

Table 1. Episodes of dyke intrusion in the vicinity of the Isua belt

Episode	Swarm	Rock type*	Trend†	Abundance
3. Proterozoic		Norite	Mainly N–S	Sparse
2. Tarssartôq (Archaean)	T3	Dolerite	N–S	Abundant
	T2	Dolerite	E–W	Abundant
	T1	Norite	E–W	Sparse
	–	Ultramafic‡	NNE–SSW	–
1. Inaluk (Archaean)		Meladiorite –tonalite	Folded	Sparse

* Prefix 'meta' is omitted although dykes are variably metamorphosed.
† Approximate trend given for dykes that are not folded.
‡ Not seen in this study; characteristics from Nutman (1986).

Fig. 2. A dioritic Inaluk dyke cutting the oldest gneissosity in tonalitic gneiss, and cut by folded pegmatite sheets in Area A. The card at the lower margin of the dyke is 8 cm long. For location, see Fig. 1a.

Fig. 3. Earth's oldest well-preserved mafic dyke swarms emplaced into tonalitic gneisses close to the northern margin of the Isua belt in Area B. Note the podded nature of the E–W-trending (T2) dykes (running left to right). Relief of hillside is about 250 m. For location, see Fig. 1a.

Tarssartôq dykes: field results

Area A: northern gneisses

Area A is located in the middle of the gneisses that lie north of the Isua belt (Fig. 1a). Exposure is generally good and extensive, although some areas are covered by small boulder fields and snowfields. Three generations of Tarssartôq dykes were observed (T1–T3: Tables 1, 2). There is no evidence for any significant geological event between the emplacement of the three generations of dykes and it is possible that they are similar in age.

The oldest dykes (T1) are two ≤ 100 m thick brown-weathering norite dykes forming prominent E–W-trending ridges that can be traced for several kilometres. A poikilitic texture is observed in some hand specimens, with plagioclase crystals up to 3 cm in size enclosing the mafic minerals (predominantly orthopyroxene with some olivine). No internal structures or significant lithological variations were observed within the dykes.

Fig. 4. Abundant euhedral relict plagioclase megacrysts in an E–W-trending (T2) dyke in the gneisses of Area A. For location, see Fig. 1a.

Dykes of the next generation (T2) are abundant, and form a prominent E–W-trending swarm. They are rectilinear bodies, commonly up to 20 m wide, that are vertical or dip steeply to the south. One of these dykes is seen to cross-cut one of the norite dykes (T1) described above. Nutman *et al.* (1983) considered the T2 dykes to be a single conjugate set with a 30° intersection angle. Some of the dykes contain abundant 2–5 cm euhedral plagioclase megacrysts. Locally the megacrysts range up to 15 cm in length (Fig. 4). Widely dispersed megacrysts occur in many dykes, often concentrated in bands and close to a dyke margin. The dykes have fine-grained margins, and are undeformed except for brittle faulting and localised shearing along some margins. Ophitic and sub-ophitic textures generally contain igneous pyroxene (especially in the larger, coarser-grained dykes) and secondary amphibole.

Cross-cutting relationships at several localities consistently demonstrate that both sets of E–W-trending dykes (T1 norites and T2 dolerites) are cut by a swarm of subvertical N–S-trending dolerites (T3). These dykes, some of which contain plagioclase megacrysts, were chilled against the gneisses and earlier dykes. The N–S dykes are similar to the T2 dykes, although they tend to be narrower (usually < 10 m), finer grained and with igneous mineralogy less well preserved.

Area B: contact between Isua belt and tonalitic gneiss

Area B was specifically selected to examine dyke behaviour near the contact between the Isua belt and the tonalitic gneiss (Fig. 1a). The generally good exposure allowed determination of the relationships between the dykes and a range of different rock types. Field observations are summarised in Table 2.

Two dyke swarms cut the tonalitic gneiss: E–W-trending dykes are consistently older than N–S-trending dykes. These dykes are correlated with the T2 and T3 swarms of Area A, respectively. Some dykes of both swarms contain megacrysts; they have chilled margins and in the northern part of Area B are rectilinear and undeformed.

Many of the T2 dykes are podded, a feature particularly conspicuous in the larger dykes (Fig. 3). The origin of this 'podding' has been debated. Bridgwater & McGregor (1974, p. 50) proposed that the E–W dykes were "intruded as a series of elongate pods …… under conditions of regional stress". James (1975) broadly agreed, suggesting that they were intruded during deformation. Bridgwater *et al.* (1976) considered that the podded form indicated emplacement into plastic country rocks during deformation. Gill & Bridgwater (1976) reiterated that the podding was a primary intrusive phenomenon and they considered that it reflected intrusion into ‘warm’ (or ‘hot’: Gill & Bridgwater 1979) country rock. In contrast, Nutman (1986) interpreted the podding as tectonic.

Our interpretation of the origin of the podding is based on the following structural observations pertaining to the rocks located > 400 m from the Isua belt; a different structural regime exists within 400 m of the Isua belt (see below). The pods typically terminate against the host gneiss at sharp points in two-dimensional outcrop surfaces. In three dimensions, the ends of the pods are wedge-shaped. The dykes and pods are oriented at a high angle to the gneissosity, apart from a < 3 m wide zone at the terminations of the pods and along the dyke margins, in which the gneissosity in the host rock is typically warped. The gneissosity strikes NE–SW and dips 30–50° to the SE, whereas the dykes and pods are subvertical and trend between E–W and NE–SW. Throughout the dykes and pods there are no ductile deformation fabrics and any plagioclase megacrysts are undeformed.

These observations suggest that the pods did not form during regional deformation: (1) the pods do not have the shape typical of boudinaged Ameralik dykes that are widespread in outer Godthåbsfjord; (2) there is no evidence in the host gneisses for strain that is compatible with the pods being boudins of dykes; and (3) there are no ductile deformation fabrics in the dykes or pods that suggest they underwent solid-state deformation. We therefore interpret the podding of T2 dykes, within the northern gneisses > 400 m from the Isua belt, as being a primary intrusive feature.

The T3 dykes are parallel-sided > 400 m from the Isua belt. James (1975) considered that they were emplaced during a tensile phase.

Less than 400 m from the Isua belt, a dramatic increase in strain is seen in the northern gneisses. Initially, the gneissosity is deformed into steeply plunging folds with steeply dipping axial surfaces (60–70°) parallel to the contact with the Isua belt. These folds become progressively tighter towards the contact and about 100 m from the contact the gneissosity is transposed into a younger fabric parallel to the contact. This fabric is mylonitic within ~ 50 m of the contact; kinematic analysis of the mylonitic fabric in thin section is currently being undertaken.

The E–W and N–S dykes (T2 and T3) within this zone of increasing strain are generally undeformed, and the N–S dykes transect the contact between the Isua belt and the tonalitic gneiss at a high angle. Although they post-date the main high-strain event, the dykes do show evidence of an increasing amount of ductile strain towards the Isua belt, and across it. At about 300 m from the contact, a pinch-and-swell structure at the margin of an E–W dyke is the first indication of strain, and such structures are abundant in E–W dykes within a few tens of metres of the contact. At these locations, the dykes are foliated and the plagioclase megacrysts are stretched into a steep lineation (Fig. 5). The N–S-trending dykes also show evidence for deformation at a similar distance from the Isua belt, and as they approach and cross the Isua belt they are deflected westwards. These deflections are more abundant within the Isua belt than in

Table 2. Summary of characteristics of Tarssartôq dyke swarms in the different study areas

Area (see Fig. 1a)	Tarssartôq dyke phase* T1	T2	T3
A, northern gneisses	Two large E–W norites	Undeformed E–W dolerites	Undeformed N–S dolerites
B, > 400 m north of Isua belt	not observed	E–W dolerites, locally podded	Undeformed N–S dolerites
B, < 400 m north of Isua belt	not observed	Pinch-and-swell in E–W dykes; sheared megacrysts	N–S dykes deflected to W; dykes are deformed where deflected
B, within Isua belt	not observed	Foliated and lineated amphibolites concordant with the host rocks	Foliated and lineated amphibolites discordant to structures in Isua belt
B, south of Isua belt	not observed	NE–SW concordant dykes	~ N–S discordant dykes
C, Isukasia	not observed	Folded, or rotated into parallelism with axial planes of folds	

* Prefix ‘meta’ is omitted although dykes are variably metamorphosed.

Fig. 5. Stretched relict plagioclase megacrysts in an E–W-trending (T2) dyke at the contact between the Isua belt and the northern gneisses in Area B. The lens-cap is 6 cm across. For location, see Fig. 1a.

the gneiss, and the deflected parts of the dykes are foliated and contain a steeply plunging lineation.

Within the Isua belt, E–W and N–S dykes are abundant, and correlate with T2 and T3 dykes. They exhibit a significant southwards increase in deformation and degree of metamorphic recrystallisation, and occur as strongly foliated and lineated amphibolites towards the southern margin of the Isua belt. Many E–W dykes cannot be traced over significant distances due to their discontinuous nature, and because, where foliated, they appear similar to the metavolcanic components of the Isua belt. Although the N–S dykes penetrate southwards into the Isua belt, poor exposure makes it impossible to determine whether they cut the southern contact.

These relationships suggest that two superimposed strain gradients are present in Area B: an older gradient resulting from deformation that affected the gneisses prior to the Tarssartôq dykes, and a younger gradient resulting from post-dyke deformation. The older gradient, which is first detectable about 400 m north of the contact, is strongest within the gneiss located about 100 m from the Isua belt; the younger gradient is strongest at the contact and within the Isua belt. These strain gradients probably developed in response to competency contrasts between the northern gneisses and the supracrustal units of the Isua belt.

A reconnaissance survey to the south of the Isua belt revealed two swarms of mafic dykes cutting the well-banded gneisses. One swarm of NE–SW-trending dykes is broadly concordant with the gneiss fabric and a younger swarm of broadly N–S-trending dykes is discordant. These dykes were heterogeneously deformed at amphibolite facies. It is likely that they correlate with the E–W and N–S swarms of the north, i.e. T2 and T3.

Area C: Isukasia

The dykes at Isukasia (Fig. 1a) are generally grey-green, altered and discordant to the dominant layering and foliation of their host rocks, which comprise metamorphosed cherts and banded iron formation. These dykes are abundant and some contain relict plagioclase megacrysts. They probably correlate with the T2 and T3 Tarssartôq dykes in Areas A and B.

There are two sets of dykes, but all the dykes are deformed and cross-cutting relationships were rarely seen. The dykes intersect each other at a low angle, and are generally subparallel with the axial planes of folds that deform the dominant foliation and layering (transposed bedding) of the host rocks. These folds plunge steeply to the south-east and are Z-shaped when viewed down-plunge.

Correlation between Ameralik and Tarssartôq dykes?

The suggested correlation between the Tarssartôq dykes in our study region and the Ameralik dykes *sensu stricto* in the outer Godthåbsfjord region is based on field appearance and occurrence, both cutting 3.8–3.6 Ga tonalitic gneisses (Bridgwater & McGregor 1974). This hypothesis needs to be tested and proved before unequivocal regional correlations can be made.

According to Nutman (1986), the Tarssartôq dykes post-date 3.4 Ga pegmatites and are cut by 2.55 Ga pegmatites. A more precise age constraint is given by the late Archaean amphibolite facies metamorphism that affected the Isua belt and the Tarssartôq dykes: a Sm–Nd amphibole-plagioclase isochron age of 2849 ± 116 Ma was obtained from mafic schists of the Isua belt (Gruau *et al.* 1996). Furthermore, Wagner (1982) suggested that the Tarssartôq dykes are older than 3.1 Ga, based on Pb–Pb and Rb–Sr isotopic evidence. A firm correlation between the Ameralik and Tarssartôq dykes can only be achieved by obtaining the crystallisation ages of both sets of dykes. This may be difficult for the strongly tectonised Ameralik dykes in outer Godthåbsfjord.

In the northern gneisses (Area A), the well-preserved Tarssartôq dykes bear little resemblance to the Ameralik dykes of the type area, apart from both suites being basaltic and having relict igneous plagioclase megacrysts in some dykes. Several authors, however, have observed that the Tarssartôq dykes can be traced southwards into and beyond the Isua belt, where they become more deformed and increasingly concordant with the compositional banding in the host gneisses, e.g. Bridgwater & McGregor (1974), Bridgwater *et al.* (1976), Gill & Bridgwater (1976) and Nutman *et al.* (1983). As the degree of deformation increases, the Tarssartôq dykes appear to be "identical with the least deformed Ameralik dykes in the area south-east of Godthåb [Nuuk]" (Bridgwater & McGregor 1974, p. 50). It was, however, noted by Gill & Bridgwater (1976) that the Tarssartôq dykes in the vicinity of the Isua belt are generally thicker and more widely spaced than the type Ameralik dykes, and that a greater proportion of Ameralik dykes contain relict plagioclase megacrysts.

A correlation between the Ameralik and Tarssartôq dykes on geochemical grounds is less straightforward. Geochemical data for dykes from outer Godthåbsfjord and the vicinity of the Isua belt (Gill & Bridgwater 1976, 1979; Chadwick 1981) suggest that the dykes fall into three compositional groups: (A) primitive low-K tholeiites with flat REE patterns; (B) more evolved tholeiites with lower Mg#, lower Ni and slightly enriched REE; and (C) an orthopyroxene-bearing, high-MgO, high-SiO_2 'Ugpik' group that may represent pyroxene cumulates. According to Gill & Bridgwater (1976, 1979), all three groups are represented in Ameralik dykes from outer Godthåbsfjord, but the dykes in the vicinity of the Isua belt consist only of group A. They suggest, however, that groups A and B could be closely related by fractional crystallisation (Gill & Bridgwater 1979). More recently, large orthopyroxene-bearing norite dykes have been observed cutting the gneisses north of the Isua belt (Nutman 1986; this study); preliminary geochemical data (this study) indicate that these are compositionally similar to dykes of the 'Ugpik' group.

Future work

Nearly 150 dykes were sampled in 1999; these will be used for petrographic, geochemical and geochronological studies aimed at characterising the composition and age of the Tarssartôq dykes. Dating of the Tarssartôq dyke swarms would be an important contribution to a better understanding of the geochronology of the region close to the Isua belt, and correlation with the outer Godthåbsfjord region. The presence of baddeleyite (ZrO_2) and zircon should enable precise U–Pb isotopic ages to be obtained. Geochemical data will evaluate the compositional variability of the Tarssartôq dykes, and any genetic link with the Ameralik dykes. Evaluation of chemical changes due to alteration, metamorphism and possible crustal contamination will be a pre-requisite for this work.

The presence of plagioclase megacrysts within some Tarssartôq dykes raises the question of links to anorthosites. Petrogenetic information about the dykes may have a bearing on the generation of Archaean anorthosites.

As indicated by Gill & Bridgwater (1976), the Ameralik (and Tarssartôq) dykes are the oldest known basaltic rocks that intruded stable continental crust. Petrogenetic modelling of geochemical data from the best-preserved Tarssartôq dykes will, therefore, provide information about the character of the Archaean mantle from which they were derived. Determination of the temperature and depth of melting that generated the Tarssartôq dykes will have implications for the structure and thermal characteristics of the contemporaneous sub-continental lithosphere and asthenosphere.

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References

Allaart, J.H. 1975: Field mapping of the pre-3760 m.y. old supracrustal rocks of the Isua area, southern West Greenland. Rapport Grønlands Geologiske Undersøgelse **75**, 53–56.

Allaart, J.H. 1982: Geological map of Greenland, 1:500 000, Frederikshåb Isblink – Søndre Strømfjord, sheet 2. Copenhagen: Geological Survey of Greenland.

Appel, P.W.U., Fedo, C.M., Moorbath, S. & Myers, J.S. 1998: Recognizable primary volcanic and sedimentary features in a low-strain domain of the highly deformed, oldest known (~3.7–3.8 Gyr) Greenstone Belt, Isua, West Greenland. Terra Nova **10**, 57–62.

Baadsgaard, H., Nutman, A.P., Rosing, M., Bridgwater, D. & Longstaffe, F.J. 1986: Alteration and metamorphism of Amîtsoq gneisses from the Isukasia area, West Greenland: recommendations for isotope studies of the early crust. Geochimica et Cosmochimica Acta **50**, 2165–2172.

Black, L.P., Gale, N.H., Moorbath, S., Pankhurst, R.J. & McGregor, V.R. 1971: Isotopic dating of very early Precambrian amphibolite facies gneisses from the Godthaab district, West Greenland. Earth and Planetary Science Letters **12**, 245–259.

Boak, J.L. & Dymek, R.F. 1982: Metamorphism of the ca. 3800 Ma supracrustal rocks at Isua, West Greenland; implications for early Archaean crustal evolution. Earth and Planetary Science Letters **59**, 155–176.

Boak, J.L., Dymek, R.F. & Gromet, L.P. 1983: Petrology and rare earth element geochemistry of clastic metasedimentary rocks from the Isua supracrustal belt, West Greenland. Rapport Grønlands Geologiske Undersøgelse **112**, 23–33.

Bridgwater, D. & McGregor, V.R. 1974: Field work on the very early Precambrian rocks of the Isua area, southern West Greenland. Rapport Grønlands Geologiske Undersøgelse **65**, 49–54.

Bridgwater, D., Keto, L., McGregor, V.R. & Myers, J.S. 1976: Archaean gneiss complex of Greenland. In: Escher, A. & Watt, W.S. (eds): Geology of Greenland, 18–75. Copenhagen: Geological Survey of Greenland.

Chadwick, B. 1981: Field relations, petrography and geochemistry of Archaean amphibolite dykes and Malene supracrustal amphibolites, northwest Buksefjorden, southern West Greenland. Precambrian Research **14**, 221–259.

Gill, R.C.O. & Bridgwater, D. 1976: The Ameralik dykes of West Greenland, the earliest known basaltic rocks intruding stable continental crust. Earth and Planetary Science Letters **29**, 276–282.

Gill, R.C.O. & Bridgwater, D. 1979: Early Archaean basic magmatism in West Greenland; the geochemistry of the Ameralik dykes. Journal of Petrology **20**, 695–726.

Gruau, G., Rosing, M., Bridgwater, D. & Gill, R.C.O. 1996: Resetting of Sm-Nd systematics during metamorphism of > 3.7-Ga rocks: Implications for isotopic models of early Earth differentiation. Chemical Geology **133,** 225–240.

James, P.R. 1975: Deformation of the Isua supracrustal belt, southern West Greenland. Rapport Grønlands Geologiske Undersøgelse **75**, 56–58.

McGregor, V.R., Friend, C.R.L. & Nutman, A.P. 1991: The late Archaean mobile belt through Godthåbsfjord, southern West Greenland: a continent-continent collision zone? Bulletin of the Geological Society of Denmark **39**, 179–197.

Moorbath, S., O'Nions, R.K., Pankhurst, R.J., Gale, N.H. & McGregor, V.R. 1972: Further rubidium-strontium age determinations on the very early Precambrian rocks of the Godthaab District, West Greenland. Nature **240**, 78–82.

Myers, J.S. in press: Protoliths of the 3.8–3.7 Ga Isua Greenstone Belt, West Greenland. Precambrian Research (Bridgwater volume).

Nutman, A.P. 1986: The early Archaean to Proterozoic history of the Isukasia area, southern West Greenland. Bulletin Grønlands Geologiske Undersøgelse **154**, 80 pp.

Nutman, A.P., Bridgwater, D., Dimroth, E., Gill, R.C.O. & Rosing, M. 1983: Early (3700 Ma) Archaean rocks of the Isua supracrustal belt and adjacent gneisses. Rapport Grønlands Geologiske Undersøgelse **112**, 5–22.

Nutman, A.P., Hagiya, H. & Maruyama, S. 1995: SHRIMP U-Pb single zircon geochronology of a Proterozoic mafic dyke, Isukasia, southern West Greenland. Bulletin of the Geological Society of Denmark **42**, 17–22.

Nutman, A.P., McGregor, V.R., Friend, C.R.L., Bennett, V.C. & Kinny, P.D. 1996: The Itsaq Gneiss Complex of southern West Greenland; the world's most extensive record of early crustal evolution (3900–3600 Ma). Precambrian Research **78**, 1–39.

Nutman, A.P., Bennett, V.C., Friend, C.R.L. & Norman, M.D. 1999: Meta-igneous (non-gneissic) tonalites and quartz-diorites from an extensive ca. 3800 Ma terrain south of the Isua supracrustal belt, southern West Greenland: constraints on early crust formation. Contributions to Mineralogy and Petrology **137**, 364–388.

Rosing, M.T., Rose, N.M., Bridgwater, D. & Thomsen, H.S. 1996: Earliest part of Earth's stratigraphic record: a reappraisal of the >3.7 Ga Isua (Greenland) supracrustal sequence. Geology **24**, 43–46.

Wagner, P.A. 1982: Geochronology of the Ameralik dykes at Isua, West Greenland, 92 pp. Unpublished M.Sc. thesis, University of Alberta, Canada.

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