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New pieces to the Archaean terrane jigsaw puzzle in the Nuuk region, Southern West Greeland: steps in transforming a simple insight into a complex regional tectonothermal model

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Abstract

In the south of the Nuuk region of West Greenland our 1980s mapping recognized four Archaean gneiss terranes (Færingehavn, Tre Brødre, Tasiusarsuaq and Akia terranes) with different protolith ages and separate early tectonothermal histories. Later in the Archaean these were juxtaposed and then experienced the same 2700-2500 Ma tectonothermal events. Here we abandon extrapolation of only these four terranes across the whole region, and distinguish two new terranes in the NE. The northernmost Isukasia terrane (previously regarded as the northernmost exposure of the Færingehavn terrane) consists of Palaeoarchaean rocks (>3600 Ma) tectonically bounded on its south by the 3075-2960 Ma Kapisilik terrane; these were juxtaposed and metamorphosed together by 2950 Ma. The previously recognized Fæ ringehavn terrane to the SW is another, separate entity of Palaeoarchaean rocks that was juxtaposed with adjacent terranes only after c. 2800 Ma. Hence in an increasingly complex regional model, there were several mid- to Neoarchaean terrane assembly events, with superimposed 'orogenies' from c. 2950 Ma until after 2700 Ma. Although the Færingehavn and Isukasia terranes were incorporated into the later Archaean terrane collage at different times, they might be fragments from a larger Palaeoarchaean complex rifted apart from c. 3500 Ma onwards.

Keywords

tectonothermal, greeland, west, southern, region, nuuk, puzzle, jigsaw, terrane, archaean, pieces, regional, complex, into, insight, simple, transforming, model, steps, GeoQUEST

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New pieces to the Archaean terrane jigsaw puzzle in the Nuuk region, southern West Greenland: Steps in transforming a simple insight into a complex regional tectonothermal model

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Abstract: In the south of the Nuuk region of West Greenland our 1980s mapping recognised four Archaean gneiss terranes (*Færingehavn, Tre Brødre, Tasiusarsuaq and Akia terranes*) with different protolith ages and separate early tectono-thermal histories. Later in the Archaean these were juxtaposed and then experienced the same 2700-2500 Ma tectono-thermal events. Here we abandon extrapolation of only these four terranes across the whole region, and distinguish two new terranes in the northeast. The northernmost *Isukasia terrane* (previously regarded as the northernmost exposure of the Færingehavn terrane) consists of Palaeoarchaean rocks (>3600 Ma) tectonically bounded on its south by the 3075-2960 Ma *Kapisilik terrane* – these were juxtaposed and metamorphosed together by 2950 Ma. The previously recognised Færingehavn terrane to the southwest is another, separate entity of Palaeoarchaean rocks that was juxtaposed with adjacent terranes only after *c.* 2800 Ma. Hence in an increasingly complex regional model, there were several mid- to Neoarchaean terrane assembly events, with superimposed "orogenies" from *c.* 2950 Ma until after 2700 Ma. Although the Færingehavn and Isukasia terranes were incorporated into the later Archaean terrane collage at different times, they might be disporia from a larger Palaeoarchaean complex rifted apart from *c.* 3500 Ma onwards.

Keywords: terrane assembly, Archaean gneiss complexes, U-Pb zircon geochronology, West Greenland

Much of the Archaean (>2500 Ma) geological record is dominated by polyphase banded granulite-amphibolite facies orthogneisses displaying complex tectonothermal histories (e.g., McGregor 1973). As barometry on these complexes always yields pressures of 5 to 10 Kbar (starting from Wells 1976) these gneisses must represent deep levels of ancient orogens. However, the general lithological uniformity of these ancient basement rocks has hampered understanding the orogenies that moulded them. In contrast, Phanerozoic orogens contain distinctive arrays of both basement rocks and cover sequences (not deformed prior to the orogeny) that have eased interpretation of their tectonothermal evolution that, nowadays, is understood via plate tectonics involving lithospheric motions. This causes juxtaposition of tectono-stratigraphic terranes of unrelated rocks as described by Coney *et al*. (1980).

In the Nuuk region of southern West Greenland, Friend *et al.* (1987, 1988) recognised that the Archaean orthogneiss complex is divided into tectono-stratigraphic terranes bounded by (commonly folded) amphibolite facies Archaean mylonites (Fig. 1). These terranes have different early histories prior to tectonic juxtaposition along the mylonites later in the Archaean (Friend *et al*. 1987, 1988; Nutman *et al*. 1989). This simple insight enabled understanding of the gneiss complexes to be viewed in a more modern perspective (Table 1). Thus McGregor *et al*. (1991) proposed that the region presented a deeply eroded (only basement rocks present) Archaean continent-continent collision zone, and produced the first tentative sketches of how the proposed collision zone might have evolved from *c.* 2800 to 2550 Ma. This understanding of Archaean gneiss complexes has been paralleled by a new understanding of Archaean (lower metamorphic grade) granite-greenstone terranes via plate tectonic principals. Several granite greenstone terrains have now provided well-documented evidence of tectonic assembly of different portions, for example in Barberton (e.g. Lowe *et al*. 1999), and the Superior Province (e.g. Calvert & Ludden 1998; Percival 2001). Greenstone-granite terranes have been proposed as representing higher crustal levels than the gneiss complexes (e.g. Tarney *et al*. 1976; Percival *et al*. 2001 and refs. therein). Thus granite-greenstone terranes and gneiss complexes probably represent nothing else but different exposure levels through Archaean crust, rather than having formed by entirely different mechanisms.

Using the simple observation that Nuuk region Archaean gneiss complex is divided into mylonite-bounded terranes of unrelated rocks (Fig. 1, Table 1), we have up to now, tried to accommodate the tectonothermal evolution of the region using only the four terranes first identified in the south and west, the

Færingehavn, Tasiusarsuaq, Tre Brødre and Akia terranes of Friend *et al*. (1987, 1988). This basic interpretation has been independently verified in the south by a detailed integrated structural and U-Pb mineral dating study (Fig. 1; Crowley, 2002). In this paper we abandon the approach of using only four terranes for the region, and recognise that additional terranes are present, starting here with the introduction of the *Isukasia* and *Kapisilik* terranes in the north and east (Fig. 1). This is a further application of the simple insight of recognition of assembly of unrelated terranes to create increasingly accurate regional geological syntheses. A parallel would be at the advent of plate tectonics regarding the European Alps as containing a single simple collision, rather than as now realised that it contains several collisional events, that were also superimposed on older tectonothermal events within the involved blocks of basement rocks.

Other Precambrian high-grade gneiss complexes are now also recognised to consist of individual tectono-stratigraphic terranes that were sequentially assembled during ancient orogenies throughout the Archaean and Proterozoic. For example, a similar scenario of terrane assembly is proposed for the Narryer Gneiss Complex in Western Australia (Nutman *et al*. 1993), and in NW Scotland the Lewisian Gneiss Complex has been shown to have been assembled between *c*. 2400 and 1670 Ma (Friend & Kinny 2001; Love *et al*. 2004). Additionally, the southern part of the West Greenland craton would also appear to be made up of terranes that were assembled in the Neoarchaean (Friend & Nutman 2001) and a similar model has recently been proposed for southern India (e.g. Radhakrishna *et al*. 2003).

Interpretations of crustal evolution in the Nuuk region

McGregor (1973, 1979) demonstrated that the "grey gneisses" of the Archaean high-grade gneiss complex of southern West Greenland were derived from plutonic rocks of predominantly tonalitic composition, rather than being granitised quartzo-feldspathic sediments as previously thought (Table 1). Based on regional Pb-Pb and Rb/Sr isochron suites (Black *et al*. 1971; Moorbath *et al*. 1972; Taylor *et al*. 1980) recognised two main pulses of juvenile crust (tonalite) formation, the Palaeoarchaean Amîtsoq gneisses (the dominant component of what we now term the Itsaq Gneiss Complex – Nutman et al., 1996) and the mid to Neoarchaean Nûk gneisses (Table 1). These were considered to be followed by a single Meso-Neoarchaean peak granulite-amphibolite facies metamorphic event (Wells 1976, 1979) and finally by a pulse of crustal melting at *c.* 2550 Ma represented by the Qôrqut granite (Brown *et al*. 1981). These findings permitted the first modern tectonic interpretations of Archaean gneiss complexes, with consideration of processes operating in the Phanerozoic such as horizontal lithospheric motions (e.g. Talbot 1973; Bridgwater *et al.* 1974). Greater complexity in the Nuuk region geology was revealed by further geological studies (e.g., McGregor *et al*. 1983) combined with more zircon dating (e.g. Baadsgaard & McGregor 1981). Increasingly, the model of two pulses of juvenile crust formation followed by a single regional granulite-amphibolite facies metamorphism and finally intrusion of the Qôrqut granite could no longer accommodate the accumulating data.

In the south and west of the region, Friend *et al.* (1987, 1988) recognised the Færingehavn, Tre Brødre, Tasiusarsuaq and Akia tectono-stratigraphic terranes (Fig. 1b) separated from each other by deformed, amphibolite facies Archaean mylonites (mostly <5 m wide). Each of these terranes is dominated by their own suite of juvenile crust tonalitic rocks and they display early structures and metamorphism unique to that terrane (Friend *et al*. 1988; Nutman *et al*. 1989). Later in the Archaean these terranes were tectonically juxtaposed with each other (Table 1). Afterwards, the terranes and their mylonitic boundaries experienced the same superimposed later metamorphic and structural history, and were cut by late granites. This simple insight accommodated all accumulated data from the region. The region was then viewed as containing a continent-continent collision (McGregor *et al*. 1991), probably coinciding with major regional metamorphism at *c*. 2700 Ma (Friend *et al*. 1996). The terrane model was tested in the south of the region by Crowley (2002). He also found evidence for terranes with different protolith ages and early metamorphic histories that were later tectonically juxtaposed and deformed together.

The mylonites bounding the different terranes in high-grade gneiss complexes are hard to recognise because (a) they are typically narrow (<5 m), commonly folded in later events and metamorphosed, and (b) the gneisses on either side can appear similar in the field even though they can be very different in age and early histories (see data in Friend *et al*. 1987, 1988; Nutman *et al*. 1989; McGregor *et al*. 1991). Additionally, because of subsequent polyphase deformation and metamorphism mylonites have recrystallised and mostly do not preserve kinematic indicators relating to movements during terrane assembly (*e.g.* Friend *et al*. 1987; Crowley 2002). Locally, granitoid sheets cut the Neoarchaean mylonites or were incorporated into them as lithons during some of the latest movements. Dating these sheets and lithons provides some constraints on the timing of mylonite development, for example as used to constrain Palaeoarchaean mylonites (Nutman *et al*. 2002). However, because granitoid lithons do not occur in all mylonites, recording early crustal evolution and growth via terrane assembly largely depends on accurate dating of the protolith components and the metamorphic events on either side of the mylonites bounding terranes.

The Nuuk region (almost the area of Switzerland) is mostly covered by GEUS (Geological Survey of Denmark and Greenland) 1:100,000 scale maps, produced before tectono-stratigraphic terrane assembly was recognised in the region. Although our *interpretations* can diverge considerably from these maps, they still represent an indispensable resource for work in the region. Consequently, our terrane assembly models for the whole region which grew out of detailed work in the south and west (Table 1; Friend *et al*. 1987, 1988 and onwards), have largely been based on combining interpretations of this regional mapping with an expanding coverage of our own key locality remapping and our U-Pb zircon dating (e.g. Friend *et al*. 1996; Nutman *et al*. 2002). Inevitably, therefore, there is more U-Pb zircon dating and remapping in some parts of the region than others.

Our regional syntheses from the late 1980s until now have tried to extrapolate the four first recognised terranes across the whole region, including the least known eastern part (Friend *et al*. 1988, 1996; Nutman *et al*. 1989; McGregor *et al*. 1991). However, with new zircon data from the north and east of the region we now abandon trying to account for the region's evolution with the assembly of just four tectono-stratigraphic terranes, and instead recognise that more terranes are present, creating a more complex geological evolution. As our first improvement to the terrane model, in this paper we introduce the *Isukasia* and the *Kapisilik* terranes as two new tectonic entities in the north and east of the region.

Nuuk region terrane geology – new jigsaw pieces in the north and east

The first mapping of the inner Godthåbsfjord to Isukasia area (Fig. 1) identified tracts of Palaeoarchaean gneisses and assigned the rest of the gneisses to the Meso-Neoarchaean Nûk gneisses, conforming to the geology throughout the region (Allaart et al. 1976; Chadwick 1985; McGregor *et al.* 1986). Robertson (1986) and Brewer (1985) reported whole rock Rb-Sr and Pb-Pb geochronology from the inner Godthåbsfjord and concluded that Mesoarchaean gneisses and numerous generations of Neoarchaean granites were present. However due to open system behaviour (plus probably difficulty in grouping similar looking rocks of several ages for making isochron suites) definitive ages (with low MSWD and small uncertainties) could not be obtained, particularly for the older generations of rocks. However, in their general conclusions, our zircon work reported here indicates that these workers were correct in surmising that Mesoarchaean gneisses and abundant later Archaean granites are present in inner Godthåbsfjord.

Following erection of the terrane model in the south and west of the region, we undertook reconnaissance studies in inner Godthåbsfjord, but still without zircon dating coverage. This work involved extrapolation of terranes from the coastal areas to the southwest (e.g. Friend *et al*. 1987, 1988). From this, all of the Palaeoarchaean rocks were assigned to the Færingehavn terrane (≥3600 Ma) whilst later Archaean gneisses and associated supracrustal rocks in tectonic contact with Palaeoarchaean rocks were simply assigned (erroneously) to the Tre Brødre terrane (2835-2825 Ma) – based on zircon dating of sample G87/242 (Fig. 1c) and another east of the head of Kangersuneq. In the absence of zircon dating, rocks of intermediate age of *c*. 3000 Ma were regarded as being confined to the Akia terrane, *west* of the Ivinnguit and Ataneq Faults (e.g. Nutman *et al*. 1989; McGregor *et al*. 1991). This paper describes the *Kapisilik terrane*, an entity of *c*. 3000 Ma rocks *east* of the Ivinnguit fault (including the Ivisârtoq supracrustal belt), plus distinguishes the region's northernmost Palaeoarchaean rocks (including the Isua supracrustal belt) as the *Isukasia terrane*, distinct from the Færingehavn terrane to the southwest.

Kapisilik terrane

The name Kapisilik terrane is used for tectonically-bounded units of *c*. 3000 Ma rocks *east* of the Ivinnguit fault (Fig. 1b, c). The Kapisilik terrane contains tonalitic to granitic orthogneisses plus supracrustal units dominated by amphibolites, the largest of which is the *Ivisârtoq supracrustal belt*, and associated anorthositic rocks (Fig. 1c). Presently, only amphibolite facies metamorphism has been found in the rocks assigned to the Kapisilik terrane. The Kapisilik terrane is named after the locality of that name (near the village Kapisillit) where the first *c*. 3000 Ma zircon date was obtained east of the Ivinnguit fault, from inner Godthåbsfjord (Fig. 1b). However, we do not regard this as a "type locality" displaying the full diversity of rocks and events within all parts of Kapisilik terrane.

Between Kapisillit and Kangersuneq there is a dome of gneisses, the *Nivko antiform* (NA, Fig. 1c), containing granitoid rocks and diatexites bounded by units of supracrustal rocks containing quartz-cordierite gneisses. Strain is concentrated at the boundaries with some silicification, suggesting a tectonic boundary. Therefore, in the absence of any geochronological data we interpret these supracrustal rocks as belonging to a different terrane, structurally above the Kapisilik terrane. Within this dome the orthogneisses have been widely subjected to *in situ* anatexis and the emplacement associated granite sheets. Sample G87/223 is from an area of diatexite granite from at the head of Kapisillit fjord (Fig. 1c) with small, irregular clots of biotite set in leucosome. It provided a complex population of zircons that have cores mantled by distinct high-U overgrowths. These latter are characterised by low Th/U (≥0.12; Table 2). A weighted mean $^{207}Pb/^{206}Pb$ date for the four most concordant analyses (seen in CL images to lie in single domains) yields a poorly defined date of 2598 ±29 Ma (MSWD = 5.5 - dates are quoted at 95% confidence limits; Fig. 2). It is concluded that these high-U zircon domains crystallised from a granitic liquid generated during a high-grade metamorphic event, but were then isotopically disturbed in younger events. We interpret these overgrowths as denoting the *in situ* melting event occurred at *c*. 2600 Ma. Nine analyses of the abundant cores of lower U zircon gave $^{207}Pb/^{206}Pb$ dates ranging between 3070 and 2920 Ma (Table 2, Fig. 2). Five analyses gave a well-constrained weighted mean $^{207}Pb/^{206}Pb$ date of 2973 ±9 Ma (MSWD = 0.24) suggesting a 2970-2980 Ma component was important in the gneiss. The dates up to *c.* 3070 Ma suggest somewhat older components might have been present in the gneiss as well.

The *Ivisârtoq supracrustal belt* (Fig. 1c) is one of the region's largest bodies of mixed mafic-ultramafic and metasedimentary rocks and retains remnants of pillow- and agglomeratic-structured rocks showing it was derived from ultramafic and tholeiitic flows (e.g. Hall *et al*. 1987). Early isoclinal folds in the belt, folded tectonic contacts with Palaeoarchaean rocks to the north, and superimposed large sheath folds indicate a complex structural evolution (Hall & Friend 1983; Chadwick 1985, 1990) – although these authors begged to differ in their interpretations. With the new data presented below some of these differences may be understood and resolved.

The mafic to ultramafic rocks that dominate the Ivisartoq supracrustal belt are unsuitable for zircon geochronology. However, a laterally continuous unit of sulphide-rich felsic schist from the southern arm of the belt (sample GGU200892) interpreted as having a volcano-sedimentary origin was chosen for analysis, on the basis that primary igneous (volcanic) zircons might be found. This yielded fine-scale, oscillatory-zoned prisms and fragments (Fig. 3) that closely resemble igneous grains, with no rounded detrital zircons observed. They are interpreted as representing a juvenile volcanic component that is locally derived. These grains gave a unimodal age distribution, with all twenty-three analyses undertaken giving a weighted mean $^{207}Pb/^{206}Pb$ date of 3075 ±15 Ma (MSWD = 0.58; Fig. 2c). This age is interpreted as a volcanic component in the Ivisârtoq belt and so provides a minimum time of deposition of at least part of the belt. The unusually high Th/U ratios of these zircons is a feature that has been noted in some other felsic volcanic units in association with komatiitic sequences (R.A. Armstrong, pers. comm. 2003).

The Ivisârtoq supracrustal belt partly surrounds a "dome" (CID; Chadwick 1990) of granitic rocks and migmatites (Fig. 1c, d) that are invasive into it (e.g. Hall & Friend 1983). A weakly deformed granite (sample GGU200499) within this dome yielded rather high-U, oscillatory-zoned, igneous zircons, with some grains displaying non-zoned low Th/U tips or shells. Multiple age determinations on individual oscillatory-zoned prisms (4 analyses on grain 10 and 2 analyses on grain 11) indicate that the spread of ages between 2800 and 3000 Ma (Table 2; Fig. 2d) can be interpreted to be due to ancient loss of radiogenic Pb. Applying this lead-loss model, 7 analyses interpreted as dating the least disturbed domains of igneous zircon yield a weighted mean $^{207}Pb/^{206}Pb$ date of 2961 ±11 Ma (MSWD =0.33), which is interpreted as the age of intrusion of the granite. Because granites of the dome intrude the supracrustal belt, *c*. 2961 Ma is a further (minimum) age constraint on this portion of the belt. Two analyses of high U, low Th/U grain tips yielded $^{207}Pb/^{206}Pb$ dates of *c.* 2700 Ma, probably reflecting tectono-thermal activity at that time.

Mafic-ultramafic metavolcanic rocks of the southern limb of the Ivisârtoq supracrustal belt are truncated on their south by an amphibolite facies mylonite up to 2m thick. South of this mylonite there are layered leucogabbroic to anorthositic rocks that are heavily broken up by tonalitic to granodioritic gneisses, only metamorphosed to amphibolite facies (Fig. 1c). Sample G03/71 of granodiorite intruded into anorthosites yielded prismatic, oscillatory-zoned zircons. In CL images many of the zircons display bright (low-U) oscillatory zoned middles mantled by dark (high U) oscillatory zoned edges, with apparently no break or discordance between them. This is confirmed by obtaining identical dates from both types of zircon, which is interpreted to be of igneous origin. Very few possible inherited cores of older zircon are apparent in the CL images. Particularly the high U zircon domains show patchy discordant recrystallisation domains. Fourteen SHRIMP dates were obtained on thirteen zircons. Both high and low U oscillatory zircon gave $^{207}Pb/^{206}Pb$ dates of ca. 2960 Ma, with a spread to younger dates (minimum 2880 Ma), with younger dates more prevalent from the higher U domains, suggesting some ancient loss of radiogenic Pb (Table 2, Fig. 2e). Accepting this interpretation, sites with the older dates are least disturbed and give a weighted mean $^{207}Pb/^{206}Pb$ date of

2963±8 Ma (MSWD = 0.92, n = 9). This is interpreted as the intrusion of gneiss G03/71. This gives the minimum age for the gabbro-anorthosite complex it intrudes. The age of G03/71 of 2963±8 Ma agrees well with the date of 2963±12 Ma for granite 200499 from the Central Ivisârtoq Dome (CID) to the north (Fig. 1c). Thus the mylonite along the southern side of the Ivisârtoq supracrustal belt is a post 2960 Ma structure dissecting the Kapisilik terrane.

Regional 1:100,000 scale GEUS mapping (Chadwick and Coe 1988) shows that the Ivisârtoq belt continues northwestwards in an attenuated form across Ujarassuit Nunaat (Fig. 1c). On Ujarassuit Nunaat (Fig. 1c) these supracrustal rocks are intruded on their southern side by deformed granitoids, represented here by homogeneous granodiorite G91/92 and migmatite G93/88. G91/92 yielded simple, oscillatory-zoned prismatic zircons (Fig. 3b), with nine out of ten analyses giving a weighted mean $^{207}Pb/^{206}Pb$ date of 3070±9 Ma (MSWD=0.94) (Fig. 2f). This date is interpreted as the age of intrusion into the adjacent supracrustal belt. G93/88 is a banded gneiss that has been examined only by reconnaissance dating. The zircons yielded a bimodal age distribution, with lower U, oscillatory-zoned zircon giving older $^{207}Pb/^{206}Pb$ dates (3075-3040 Ma) and higher U overgrowths and discrete sub-equant grains giving younger dates (2700-2600 Ma). The rock is interpreted as a *c.* 3070 Ma granitoid that was veined by new material and metamorphosed between 2700-2600 Ma (Fig. 2g). These mid-/Neoarchaean rocks continue further north and westwards across Ujarassuit Nunaat (Fig. 1c), as shown by granodiorite G91/83 with a zircon date of 2972±12 Ma, a rock that was previously assigned to the eastern fringe of the Akia terrane (e.g. Garde *et al*. 2000).

There is presently a gap in our new field and U-Pb zircon dating programmes between the head of Kapisillit fjord and Kangersuneq and the Ivisaartoq and Ujarassuit Nunaat areas, but we include the c. 3000 Ma rocks from both these areas within the Kapisilik terrane. The Kapisilik terrane is in tectonic contact with early Archaaean rocks (Isukasia terrane) to the north (Fig. 1b-d). On Ujarassuit Nunaat, in the vicinity of sample locality G93/88 (Fig. 1c), we have undertaken a transect over this boundary. Northerly Palaeoarchaean gneisses are juxtaposed against Kapisilik terrane supracrustal rocks that are interpreted as a westerly continuation of the Ivisârtoq supracrustal belt, as concluded by Chadwick (1990). At this locality the supracrustal rocks are <100 m wide. Approaching this boundary from the north, strain rapidly increases in the Palaeoarchaean rocks over a distance of about 50 metres with increasing intensity of the fabric. The last 5-10 metres are blasto-mylonites with varying degrees of recrystallisation forming a sharp contact with the supracrustal rocks that also are highly strained. The supracrustal rocks are intruded on their south side by gneisses with ages of c. 3070 Ma, represented by G91/92 and G93/88 (above). Strain decreases southwards in these gneisses. Similar relationships are seen on northwestern Ujarassuit Nunaat, in the vicinity of sample G91/73 (dated by Gaarde *et al*. 2001), except that the tectonic boundary between the Isukasia and Kapisilik terranes has swung around to a north-south orientation. Likewise, on northeastern Ivisaartoq, the contact of the Ivisârtoq supracrustal belt rocks and Palaeoarchaean gneisses to the north is a mylonite and hence tectonic (e.g. Hall & Friend 1979; Chadwick 1990). There is a strain gradient in the gneisses approaching this mylonite and the last *c.* 1 m of the gneisses and nearest supracrustal rocks are highly silicified.

Tre Brødre terrane rocks on western Ivisaartoq

To the west of the Ivisârtoq supracrustal belt, on Ujarassuit Pavaat, amphibolite facies banded granodioritic gneisses are in tectonic contact with supracrustal rocks. Samples G87/242 and G91/69 of these granodioritic gneisses from the same unit have been dated (Fig. 1c). Sample G87/242 consisted of only granodiorite, whereas sample G91/69 is a (concordant) pegmatite layer, with some of the host granodiorite adhering to it. G91/69 was divided into granodiorite and pegmatite prior to undertaking mineral separations. Dating of prismatic igneous zircon from G87/242 and a zircon from the small amount of G91/69 granodiorite yielded $^{207}Pb/^{206}Pb$ dates of 2781-2847 Ma (Table 2; Fig. 2h). Seven zircon sites from G97/242 gave a weighted mean $^{207}Pb/^{206}Pb$ date of 2801±7 Ma (MSWD=0.96), interpreted as giving the age of intrusion of the granodiorite. The pegmatite portion of G91/69 yielded metamict very high Th+U zircons, plus monazites. These metamict zircons yielded $^{207}Pb/^{206}Pb$ dates between 2700 and 2600 Ma, with few agreeing within error. Monazites also were obtained from the small amount of granodiorite adhering to the pegmatite (monazite is rare in the gneisses of the Nuuk region) and from the pegmatite itself (Table 2; Fig. 2h). An older generation of monazites from the granodiorite gave a date of 2712 ±5 Ma, whereas some monazites from the granodiorite plus all those encountered in the pegmatite gave a date of 2626 ±3 Ma. The monazite dating indicates a minimum of two thermal events that were superimposed onto the *c.* 2800 Ma granodiorite.

This age of *c*. 2800 Ma is closest to *c*. 2825 Ma ages that have been obtained for 8 SHRIMP-dated amphibolite facies Ikkattoq gneisses of the Tre Brødre terrane from the southwest of Nuuk region where tectonostratigraphic terrane assembly was first recognised (e.g. Friend *et al.* 1996; Crowley 2002 and our unpublished data). The results from G87/242 and G91/69 suggest that in places the Kapisilik terrane appears to be in tectonic contact with northerly parts of the Tre Brødre terrane. We consider it most likely that the Tre Brødre terrane (and associated Færingehavn terrane) are now structurally above the Kapisilik terrane (Fig. 1d). In turn, on Ujarassuit Nunaat and northern Ivisaartoq, the northern limit of the Kapisilik terrane is structurally above the Palaeoarchaean rocks to the north, now termed the *Isukasia terrane* (Fig. 1c, d).

The Palaeoarchaean Isukasia terrane: c. 2960 Ma tectonothermal events and distinction from the Færingehavn terrane

Upon completion of reconnaissance geological mapping across the whole region (GGU 1983), all of the Palaeoarchaean rocks were considered to form essentially a single unit, continuous for *c.* 200 km from south of Nuuk to the Isua supracrustal belt area by the Inland Ice in the northeast. With the advent of the terrane model these Palaeoarchaean rocks were assigned to a single Neoarchaean (mylonite-bounded) tectonic entity – the Færingehavn terrane (Friend *et al*. 1988; McGregor *et al.* 1991; Nutman *et al.* 1996). The continuity of the Færingehavn terrane was tentatively questioned by Friend *et al*. (1996), who depicted that a tectonic slice of younger rocks on Ujarassuit Nunaat divided the Palaeoarchaean rocks into two portions (Friend *et al*. 1996). Because there was then no supporting zircon geochronology for this, we reverted to the general interpretation of continuity in Nutman *et al*. (1999, 2000). However, with our new field observations and zircon geochronology, we consider that the Palaeoarchaean rocks do reside in two Neoarchaean tectonic entities – the *Isukasia terrane* from Ujarassuit Nunaat north to the Isukasia area (were the Isua supracrustal belt is) and the Færingehavn terrane for southerly Palaeoarchaean rocks (Fig. 1b). From zircon dating, the Isukasia terrane is dominated by *c.* 3800 and 3700 Ma tonalites, *c.* 3650 Ma granite (*sensu stricto*) intrusive sheets and *c.* 3700 and 3800 Ma supracrustal, ultramafic and gabbroic rocks (Michard Vitrac *et al.* 1977; Baadsgaard *et al.* 1984; Compston *et al.* 1986; Nutman *et al.* 1996, 1997, 1999, 2000, 2002; Friend *et al*. 2002; Crowley *et al*. 2002; Crowley 2003). Thus there is ample information on the age of the Isukasia terrane's rocks and in this paper we concentrate on its later Archaean history.

In the northern end of the Isukasia terrane *c*. 3500 Ma (White *et al*. 2000; Nutman *et al*. 2004) Ameralik dykes are preserved as strongly discordant bodies, cross-cutting structures and lithological boundaries in their country rocks. In this area of lower late strain, cross cutting relations between successive generations of Palaeoarchaean granitic rocks is widely preserved (e.g. Bridgwater & McGregor 1974; Nutman & Bridgwater 1986; Crowely *et al*. 2002) and volcanic and sedimentary structures are locally well preserved in the Isua supracrustal belt (e.g. Nutman *et al*. 1984; Komiya *et al.* 1999). Southwards, later Archaean strain increases, bringing the mid Archaean Ameralik dykes into concordance with banding of the Palaeoarchaean rocks to make complex banded gneisses (Bridgwater & McGregor 1974; Nutman *et al.* 1996). This later Archaean strain continues to increase to the mylonite that marks the boundary between the Isukasia and Kapisilik terrane on Ujarassuit Nunaat (Fig. 1). In this southern more strongly deformed part of the Isukasia terrane the Palaeoarchaean rocks show some growth of metamorphic zircon between 3000-2940 Ma (Fig. 2a and Table 2). Thus nine analyses on high U, low Th/U overgrowths on c. 3800 Ma zircon from gneiss G91/80 gave $^{207}Pb/^{206}Pb$ dates between 3010±14 Ma and 2931±14 Ma (2σ) giving a pooled age of 2977±16 Ma (MSWD=18). Although statistically a disappointing result, these data still indicate zircon overgrowth development between 3000-2900 Ma. Also Palaeoarchaean paragneiss G93/54 (Nutman *et al*. 2002) shows high U, low Th/U rims with dates of <3000 Ma. Of these two main groups are apparent, with weighted mean $^{207}Pb/^{206}Pb$ dates of 2961±11 Ma (n=4, MSWD=1.07) and 2682±4 Ma (n=6, MSWD=0.81). Some other rocks also show growth of zircon at *c.* 2680 Ma – with the northern most example occurring in the Isua supracrustal belt (Nutman & Collerson 1991 – relevant data for the sample 81-0318 is reproduced in Table 2). Monazites in some Palaeoarchaean granite sheets also record an event at *c.* 2680 Ma (Fig. 2a and Table 2). Therefore U-Pb geochronology records two important thermal events. The first by 2950 Ma provides some link with the Kapisilik terrane, where there is clear evidence for tectono-thermal activity at that time – the dates of 2961 ±11 Ma from granite GGU200499 and 2963 ±8 Ma from granodiorite G03/71 in the east (Table 2) and 2972 ±12 Ma granodiorite G91/83 in the west Garde *et al*. (2001). This data is interpreted to indicate that these rocks might have been already in proximity by 2950 Ma and were undergoing contemporaneous metamorphism.

The name Færingehavn terrane is now limited to the Palaeoarchaean rocks to the *south* of and *structurally above* the Kapisilik terrane. We consider this division is justified because from over a thousand SHRIMP zircon U-Pb analyses on approximately fifty rocks, the Færingehavn terrane appears to be devoid of *c.* 2960 Ma metamorphic overprints (data in Nutman *et al*. 2002 and references therein). This *c.* 2960 Ma metamorphism distinguishes the Isukasia and Færingehavn terranes as separate mid- to Neoarchaean tectono-metamorphic entities.

Discussion

A c. 2960 Ma terrane assembly event in the northern part of the Nuuk region

The Isukasia and Kapisilik terranes already appear to have been in proximity by *c*. 2960 Ma because they share a common thermal event – reflected by metamorphism and granite emplacement respectively (Fig. 2). Therefore, it seems probable that a composite crustal block was developed prior to the generation of the *c*. 2825 Ma Ikkattoq gneisses of the Tre Brødre terrane and their *post* 2800 Ma juxtaposition with Kapisilik terrane. However, it is uncertain whether the mylonite zone now between the Kapisilik and Isukasia terranes is a *c*. 2960 Ma structure modified in later vents, or whether it is a younger (*c*. 2700 Ma?) structure, that has excised an earlier, original relationship between the two terranes. Using a Phanerozoic perspective, we would liken the early, *c*. 2960 Ma, assembly event in inner Godthåbsfjord to finding Caledonian or Hercynian tectonothermal activity hidden within the basement of the Alpine orogen. Subsequently the Tre Brødre terrane was juxtaposed along the southern part of this block in a younger assembly event by *c*. 2700 Ma (see Friend *et al*. 1996). Neither our account of this *c*. 2960 Ma event, nor work such as Hanmer *et al*. (2002 – see below), can justify questioning the validity of previously identified *c*. 2700 Ma terrane assembly events (e.g., Friend *et al*. 1996; Crowley 2002).

2800-2700 Ma terrane assembly superimposed on c. 2950 amalgamation of the Isukasia and Kapisilik terranes

The *c*. 2700 Ma events that juxtaposed the Tre Brødre terrane dominated by *c*. 2825 Ma rocks against a variety of other units with different ages (e.g. Friend *et al*. 1988, 1996; Crowley 2002), have always been regarded as *part* of a sequence of events – originally on the basis of field relations but increasingly being supported by zircon geochronology. The likely presence of tectonically truncated Ikkattoq gneisses of the Tre Brødre terrane on western Ivisaartoq is strong evidence that post-2825 Ma terrane assembly also occurred within the Ivisaartoq area. This is evidence for continuity with the *c*. 2700 Ma terrane assembly events known in the southern part of the region (McGregor *et al*. 1991; Friend *et al*. 1996; Crowley 2002). In Ivisaartoq and Ujarassuit Nunaat, these events must have been superimposed on the earlier amalgamation by *c*. 2960 Ma of the Isukasia and Kapisilik terranes (above). Neoarchaean (*c*. 2680 Ma) metamorphic zircon overgrowths and metamorphic monazites occur in the southern part of the Isukasia terrane and there are rare occurrences of *c*. 2680 Ma zircon growth as far north as the Isua supracrustal belt (Fig. 2a, Table 2, and in Nutman & Collerson 1991; Hanmer *et al*. 2002). Additionally, occurrences of *c*. 2700 Ma zircon growth occur in the Kapisilik terrane, for example, two reconnaissance analyses of rims in GGU200499 from Ivisaartoq (Table 2).

New terrane jigsaw pieces and structural interpretations

The new elements to the terrane jigsaw puzzle – the Palaeoarchaean Isukasia terrane now separated from the Færingehavn terrane, and the Mesoarchaean Kapisilik terrane – have arisen from work in parts of the inner Godthåbsfjord area, where previously there was no published zircon geochronology and where the geological constraints coming from lithological mapping undertaken prior to recognition of terrane assembly in the Nuuk region. Previously, there was a divergence in structural interpretations (c.f. Hall & Friend 1979; Chadwick 1990). With the new zircon geochronology and recognition of more tectonic boundaries that mark the edges of terranes, it can be demonstrated that early folds *internal* to terranes are truncated at the mylonitic boundaries, and therefore much of the structural ambiguity disappears (Fig. 1d). The solution is that there are two main periods of deformation, one pre- the mylonitic boundaries and restricted to individual terranes and the other post-terrane assembly and occurring across all terranes.

In a pegmatite (sample S37) within Palaeoarchaean gneisses in the northwestern edge of the Isukasia terrane, near the Isua supracrustal belt, Hanmer et al. (2002) found a minority of 2948±8 Ma low Th/U zircons and overgrowths with abundant Palaeoarchaean higher Th/U zircons, and a further generation of zircon growth at *c.* 2682 Ma. They chose to interpret the low Th/U 2948 Ma zircon as giving the intrusive age of the pegmatite. We have also found the growth of zircon at this time in the southern edge of the Isukasia terrane – Fig. 2, Table 2. Hanmer et al. (2002) linked their few young dates (2948 Ma) from the pegmatite zircons with intrusion of the 2980–2990 Ma Tasersuaq tonalite (Garde *et al*. 1986, 2001) in the Akia terrane to the west. Hanmer et al. then concluded that the Isukasia terrane was stitched to the Akia terrane by the time the Tasersuaq tonalite was intruded, and used this interpretation to question our timing of *c.* 2700 Ma for major terrane assembly events throughout the region (≤2700 Ma assembly has been confirmed by Crowley 2002).

Hanmer et al's interpretation did not address important structural features well-established from regional mapping. In the north near the Isua supracrustal belt where they undertook their study, the Ataneq Fault forms a sharp boundary between the Palaeoarchaean rocks of the Isukasia terrane (hanging wall) to the east and the Mesoarchaean Akia terrane to the west (foot wall). The Ataneq Fault is a latest Archaean to Palaeoproterozoic uppermost greenschist facies mylonite (e.g. Park 1986; Chadwick & Coe 1988). However, for >150 km from the islands south of Nuuk to the head of Godthåbsfjord (e.g. Friend *et al*. 1988) the eastern edge of the Akia terrane (Fig. 1b) is delineated by the Ivinnguit Fault, a post-2825 Ma Ikkattoq gneiss mylonite (e.g. McGregor *et al*. 1991). The relationship between the Ivinnguit and Ataneq faults is presently unclear, with the possibility that parts of them are temporally related and so needs re-investigation. However, there is clearly a major post-2850 Ma Ikkattoq gneiss late tectonic break between the Akia terrane and all the other terranes to the east. In Hanmer *et al*.'s (2002) study area at the western edge of the Isua supracrustal belt, the importance of the Ataneq Fault was not accounted for, when they suggested that the Akia terrane's *c*. 2980 Ma Tasersuaq tonalite intruded Palaeoarchaean rocks near the Isua supracrustal belt.

We agree with Hamner *et al*. (2002) that the Isukasia terrane has seen a *c*. 2950 Ma event, but we would link this with assembly with the Kapisilik terrane to the south, rather than the Akia terrane to the west, with the relationship between the Akia and Kapisilik terranes being presently unkown. Further field and geochronological studies are required to establish whether the younger components of the 3220-2970 Ma Akia terrane and the Kapisilik terrane are parts of the same entity, dislocated from each other by latest Archaean (2700-2500 Ma) major displacements over the Ataneq/Ivinnguit faults or whether they are unrelated, but contain some rocks of similar ages.

Two terranes of Palaeoarchaean rocks

The discovery of the Kapisilik terrane implies that the Palaeoarchaean rocks of the region, previously entirely embraced within the Færingehavn terrane (Friend *et al*. 1988 onwards), are divided into two later Archaean tectonic entities – the Færingehavn and Isukasia terranes. The Færingehavn terrane is restricted to the southern part of the region and contains rocks that are between 3850-3600 Ma and underwent Palaeoarchaean granulite facies metamorphism in most parts by *c*. 3600 Ma. They were then subject to several Neoarchaean metamorphisms dating from *after* 2800 Ma, but with no apparent record of *c*. 2960 Ma metamorphism. The Isukasia terrane is north of the Kapisilik terrane on Ujarassuit Nunaat and consists of 3810-3600 Ma gneisses that have never experienced Palaeoarchaean granulite facies metamorphism and subsequently underwent both *c.* 2960 Ma and *c.* 2700 Ma metamorphisms.

The division of the Palaeoarchaean rocks of the Nuuk region into two Neoarchaean tectonic entities is compatible with some previously noted differences in their Palaeoarchaean histories, notably metamorphism (Griffin *et al*. 1980; Nutman *et al*. 1996). Despite these early differences, both the Isukasia and Færingehavn terrane are cut by the Ameralik dykes, the earliest of which in both terranes have yielded dates of 3450–3500 Ma (Nutman *et al*. 2004). We interpret the Færingehavn and Isukasia terranes as fragments derived from a more extensive complex of Palaeoarchaean crust, that were rifted apart from 3500 Ma onwards with intrusion of the Ameralik dykes. Later these were juxtaposed with younger terranes of the Nuuk region in several Neoarchaean events. Other disporia from this rifted Palaeoarchaean complex could be the Aasivik terrane (Rosing *et al.* 2001) and the Qarliit Tasersuat assemblage (Nutman *et al*. in press) both further north in Greenland and the Uivak gneiss complex of northern Labrador (e.g. Collerson & Bridgwater 1976; Schiøtte *et al*. 1989).

Present and abandoned terrane terminology

Deformed late, grey gneiss sheets cut the Palaeoarchaean rocks of the Færingehavn terrane (e.g., McGregor *et al*. 1983, 1991). In the early days of the terrane assembly interpretation, few of these sheets had been dated. Therefore, based on lithological similarities, McGregor *et al*. (1991) considered these sheets included not only *c.* 2700 Ma intrusions but also intrusions coeval with the *c.* 2825 Ma Ikkattoq gneisses from the neighbouring Tre Brødre terrane. If this were the case there would be some linkage to the Færingehavn and Tre Brødre terranes, prior to their present tectonic relationship. To reflect this interpretation, McGregor *et al.* (1991) introduced the term Akulleq terrane, with the Færingehavn and Tre Brødre terrane as sub-terranes within it. Further dating of the grey gneiss sheets has indicated that they were intruded at 2720 Ma or later, with *no* c. 2825 Ma sheets (equivalent in age to the Ikkattoq gneisses of the Tre Brødre terrane) having been found (Friend *et al*. 1996; Nutman and Friend unpublished zircon dating). This extra dating has failed to justify retention of the term Akulleq terrane, because no (early) linkage has been found between the Færingehavn and the Tre Brødre terranes. Therefore in recent papers we have dropped the term Akulleq terrane, and have reverted to solely using Færingehavn and Tre Brødre terranes.

Presently we have recognised and named six tectonothermal terranes, which are dominated by their own suites of quartzo-feldspathic gneisses and supracrustal and mafic rock inclusions. In addition, combined further mapping and zircon geochronology in the south of the region (Nutman & Friend 2002; Friend & Nutman 2004) has recognised an as yet unnamed thin, discontinuous panel of *c.* 2835 Ma supracrustal rocks which is located between the Færingehavn and Tre Brødre terranes. This includes the units of "Malene" supracrustal rocks against the Palaeoarchaean rocks of the Færingehavn terrane, first described by McGregor (1973), Bridgwater *et al.* (1974) and Chadwick & Nutman (1979).

The structure of southeastern part of the Nuuk region now remains the least known (Fig. 1). As remapping and zircon geochronology progresses there we expect:

(a) discover that the area comprises intercalations of Færingehavn, Kapisilik, Tasiusarssuaq and Tre Brødre terranes (Fig. 1), with the Tasiusarsuaq terrane forming klippes extending further north than portrayed in syntheses from our 1980s reconnaissance studies (e.g., Friend *et al*. 1988, 1996; Nutman *et al*. 1989; McGregor *et al*. 1991);

(b) find evidence for yet more terranes different from the first four originally recognised and defined in the region's coastal southwest part (Fig. 1b; Friend *et al*. 1988).

"Plate tectonics" and interpretation of Archaean gneiss complexes

In the Phanerozoic there are combinations of evidence that lead to the conclusion that plate tectonics operates. In Archaean high-grade complexes it is more difficult to find analogous parts for all of the modern system, largely because of the size of the areas involved (Archaean gneiss complexes are preserved fragments of once much more continuous orogens) and level of exposure (only deep crustal levels are preserved for study). However, by analogy with Phanerozoic orogens, the initial phases of TTG present in all terranes can be regarded as crustal accretion in the proximity of the Archaean equivalents of subduction zones, whilst the movement and assembly of individual terranes with different accretionary histories is the parallel of modern collisional orogeny, including some major strike slip movements partitioning the orogen, adding further complexity. These are interpreted as key evidence for the operation of some form of early Precambrian plate tectonics expressed in gneiss complexes.

Conclusions

The new geochronology plus our reconnaissance structural observations reveals that in the inner Godthåbsfjord area there is a mylonite-bounded panel containing major belts of supracrustal rocks some with a volcanic age of *c*. 3070 Ma, invaded by *c*. 3070-2960 Ma orthogneisses. These rocks are grouped together and are named the Kapisilik terrane. The recognition of the Kapisilik terrane implies that the Palaeoarchaean rocks of the region, previously entirely embraced within the Færingehavn terrane (e.g. Friend *et al*. 1988 onwards), is divided into two entities. Assembly of the terranes appears to have taken place in at least two episodes, the Isukasia terrane was first intercalated with the Kapisilik terrane and subsequently this composite block was juxtaposed with the composite Færingehavn and Tre Brødre terranes. These findings represent a revision to our terrane model, and is to be expected when more of the Nuuk region is re-examined in detail with U-Pb zircon geochronology and new mapping, reducing reliance on interpreting the original regional mapping undertaken two to three decades ago. These new findings are adding complexity to the terrane model, with evidence for more terranes beyond the first four we recognised in the 1980s, plus a more protracted history of terrane assembly, with events at c. 2950 and c. 2700 Ma being important ones.

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List of Figures:

Fig. 1. Sketch maps of the terranes of the Nuuk region and their disposition. (a) Location of the Nuuk region in the Archaean craton in West Greenland. (b) Representation of the terranes as presently recognised in the Nuuk region. The previous extrapolation of Tre Bødre terrane in inner Godthåbsfjord is now uncertain with further areas of Kapisilik terrane anticipated. (c) Sketch map of Inner Godthåbsfjord showing the position of the newly identified Kapisilik and the Isukasia terranes in relation to the other terranes presently recognised in the area. Locations of geochronological samples studied, identified by sample numbers, are indicated. (d) Sketch section at sea level (*SL*) along the line *AB* depicted in (b). Note that that only the Færingehavn and Tre Bødre terranes appear to be affected by migmatisation – dashes. Ages together with uncertainties are quoted at 95% confidence. Other ages quoted without sample numbers are not discussed here but are given in order to indicate the possible extent of certain units. Abbreviations: AF, Ataneq Fault; CID, Central Ivisaartoq dome; IF, Ivinnguit Fault, KA, Kangerssuaq antiform; NA, Nivko antiform. The structures CID and KA are adopted from Chadwick (1990).

Fig. 2. SHRIMP U-Pb zircon dating of diatexite G87/223 from the head of Kapisillit fjord (Fig.1). Because most analyses are concordant within error, $^{207}Pb/^{206}Pb$ ages for the individual analyses (after correction for generally very small amounts of common Pb) are shown. The $^{207}Pb/^{206}Pb$ ages are displayed as histograms (20 Myr bins) in the foreground with the cumulative relative probability shown in the background.

Fig. 3. Representative cathodoluminescence images of dated zircons from (a) GGU200892, a felsic schist within the Ivisârtoq supracrustal belt and (b) G91/92, meta-granodiorite from Ujarassuit Nunaat. Uncertainties on the ages are quoted at 2σ.

Fig. 4. Summary of SHRIMP U-Pb zircon and monazite dating from the Ivisaartoq and Ujarassuit Nunaat areas of inner Godthåbsfjord. See Table 2 and the appendix for complete data, discussion of analytical method and calculation method for the pooled ages (given at 95% confidence). Sample sites are shown, located by sample numbers, on Figure 1. Diagram constructed in the same way as Fig. 2. (**a**) Composite diagram of analyses of Neoarchaean metamorphic zircon overgrowths and metamorphic monazites from

the Isukasia terrane. (**b-g**) Results from the Kapisilik terrane, which is separated from the Isukasia terrane to the north by folded Neoarchaean mylonites (Fig. 1). (**b**) diatexite G87/223 from the head of Kapisillit Kangerllua. (**c**) Granite GGU200499, intruding the Ivisârtoq supracrustal belt. (**c**) Felsic volcano-sedimentary rock GGU200892 (**d**) Granite GGU200499, intruding the Ivisârtoq supracrustal belt. (**e**) Sample G03/71 is a deformed granodiorite intruding the gabbro-anorthosite complex on the southern side of the of the Ivisârtoq supracrustal belt. This gabbro-anorthosite complex is separated from the supracrustal belt by a Neoarchaean mylonite. (**f**) G91/92 Sample G91/92 is a homogeneous granitoid intruding the southern side of the northern continuation of the Ivisârtoq supracrustal unit on southern Ujarassuit Nunaat. This supracrustal unit is then separated from the Isukasia terrane to the north by folded, late Archaean mylonites. (**g**) G93/88 is a banded gneiss that also cuts the same supracrustal unit, but has only been examined in reconnaissance fashion. (**h**) An example of Ikkattoq gneiss. Samples G87/242 and G91/69, from the same unit form the most northerly dated occurrence of the Tre Brødre terrane, on the western the coast of Ivisaartoq. These rocks (and associated Palaeoarchaean rocks of the Færingehavn terrane in Godthåbsfjord) are separated from the Kapisilik terrane to the north by late Archaean mylonites (Fig. 1).

List of Tables

Appendix

SHRIMP U-Pb zircon analytical method

All new U-Pb zircon and monazite SHRIMP data relevant to the paper are given in Table 1. Some data for Isukasia terrane rocks have previously been published elsewhere, and this is indicated in the Table. Zircon and monazite concentrates were hand-picked using a binocular microscope, to produce a varied assortment of least metamict, least damaged grains for analysis. Together with chips of standard zircon and monazite, these were cast into epoxy resin discs and polished. Assessment of grains and choice of sites for analysis were based on transmitted/reflected light microscopy and (also for zircons) cathodoluminescence (CL) imaging.

U-Pb zircon isotopic data used in this study were obtained from the Australian National University (ANU) SHRIMP I, II and RG instruments. The zircon analytical procedures are given by Compston *et al*. (1984), Stern (1998) and Williams (1998). For zircon, the U concentration of unknowns was calibrated against fragments of the single crystal SL13 standard (572 Ma, 238 ppm U). Due to differential yield of metal versus oxide species and different efficiencies of ionisation between elements during sputtering, inter-element ratios are calibrated with a standard, where the ratios are known by isotope dilution thermal ionisation mass spectrometry (IDTIMS). Thus $^{206}Pb/^{238}U$ ratios have an error component (typically 1.5 to 2.0%) from calibration of the measurements using the standard zircons as explained fully by Compston *et al*. (1984), Claoué-Long *et al*. (1995), Stern (1998) and Williams (1998). For Pb/U, zircon unknowns were calibrated against the 417 Ma Temora standard (I.S. Williams, personal communication 2001), AS3 (Paces and Miller, 1993) or SL13 (for samples analysed in the early 1990s). Monazite unknowns were calibrated against monazites from Thompson mine, Canada. Several isotope dilution thermal ionisation analyses of these give an average U content of 2100 ppm and a mean $^{207}Pb/^{206}Pb$ age of 1767±0.3 Ma, but a slightly dispersion of $^{206}Pb/^{238}U$ ages, giving both slightly normal to reverse discordant points (C. Roddick, pers. comm., 1995).

Quoted errors on isotopic ratios also take into account non-linear fluctuations in ion count rates above that expected from counting statistics alone (Stern 1998; Williams 1998). This is particularly important for old, damaged, high U+Th zircons (e.g. samples in samples such as GGU200499), where damage has resulted in post-crystallisation heterogeneity of species on the sub-micron scale. Reliance on only counting statistics in measurements of such targets would result in considerable under-estimation of analytical error.

The decay constants and present-day $^{238}U/^{235}U$ value given by Steiger & Jäger (1977) were used to calculate dates. The reported dates are derived from $^{207}Pb/^{206}Pb$ ratios, following correction for common Pb using measured ^{204}Pb and use of Cumming & Richards (1975) model Pb compositions. For monazites (measured on SHRIMP 1) there is a small isobaric interference under the ^{204}Pb peak. In the Archaean monazites with large amounts of accumulated radiogenic Pb reported here, this has caused at the most a 2 Ma (*c.* 0.1%) systematic underestimate in the dates. Ages of intrusion presented in this paper are weighted mean $^{207}Pb/^{206}Pb$ dates (95% confidence, with analyses inverse variance weighted). Weighted means were calculated on subgroups of analyses of sites with the same morphology and microstructure (e.g., particularly those with micron-scale oscillatory zoning). The weighted mean dates were calculated in the program Isoplot/Ex of Ludwig (1997).

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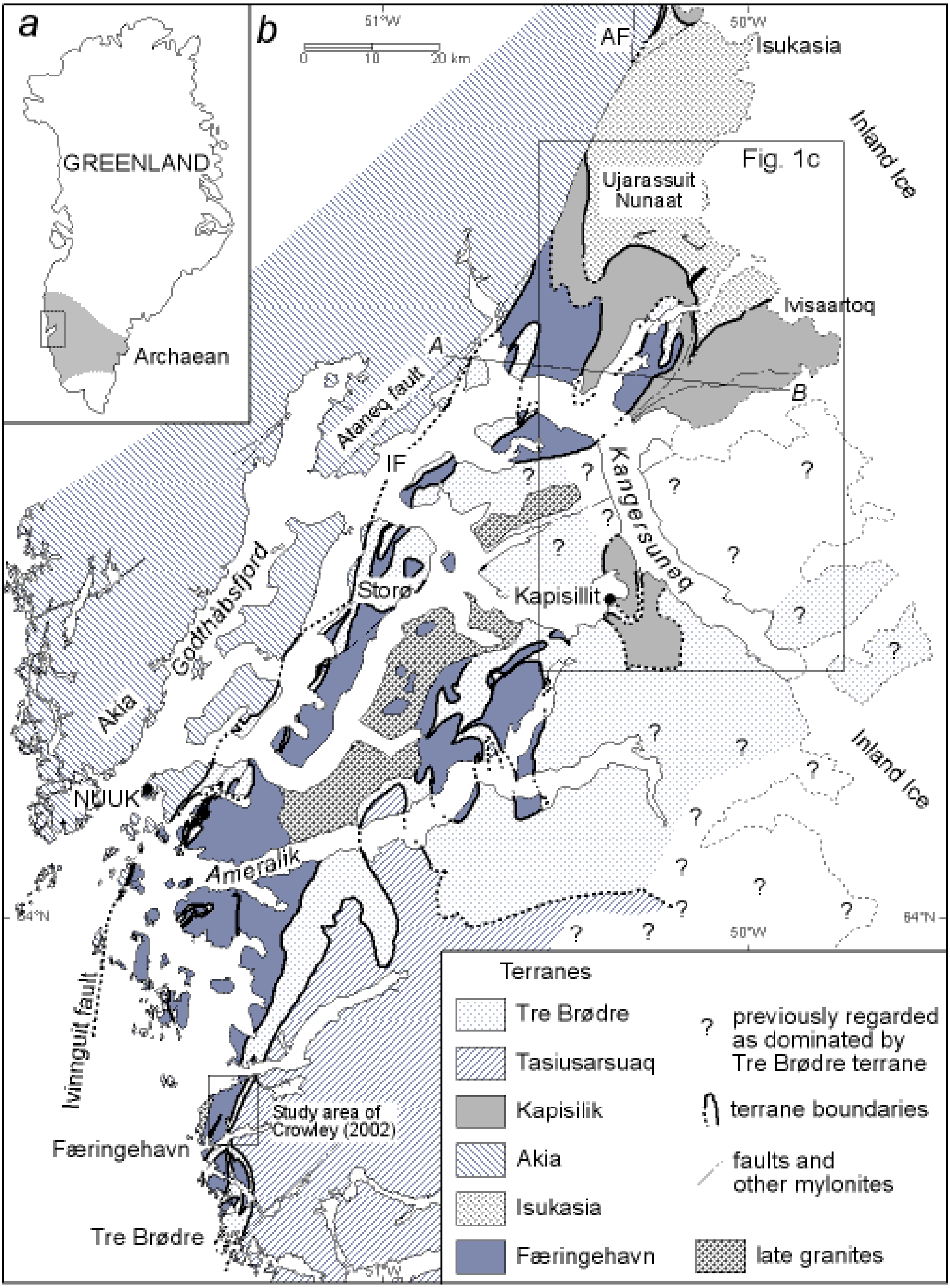
Fig. 1a,b



14/05/04 Friend & Nutman Fig. 1c,d

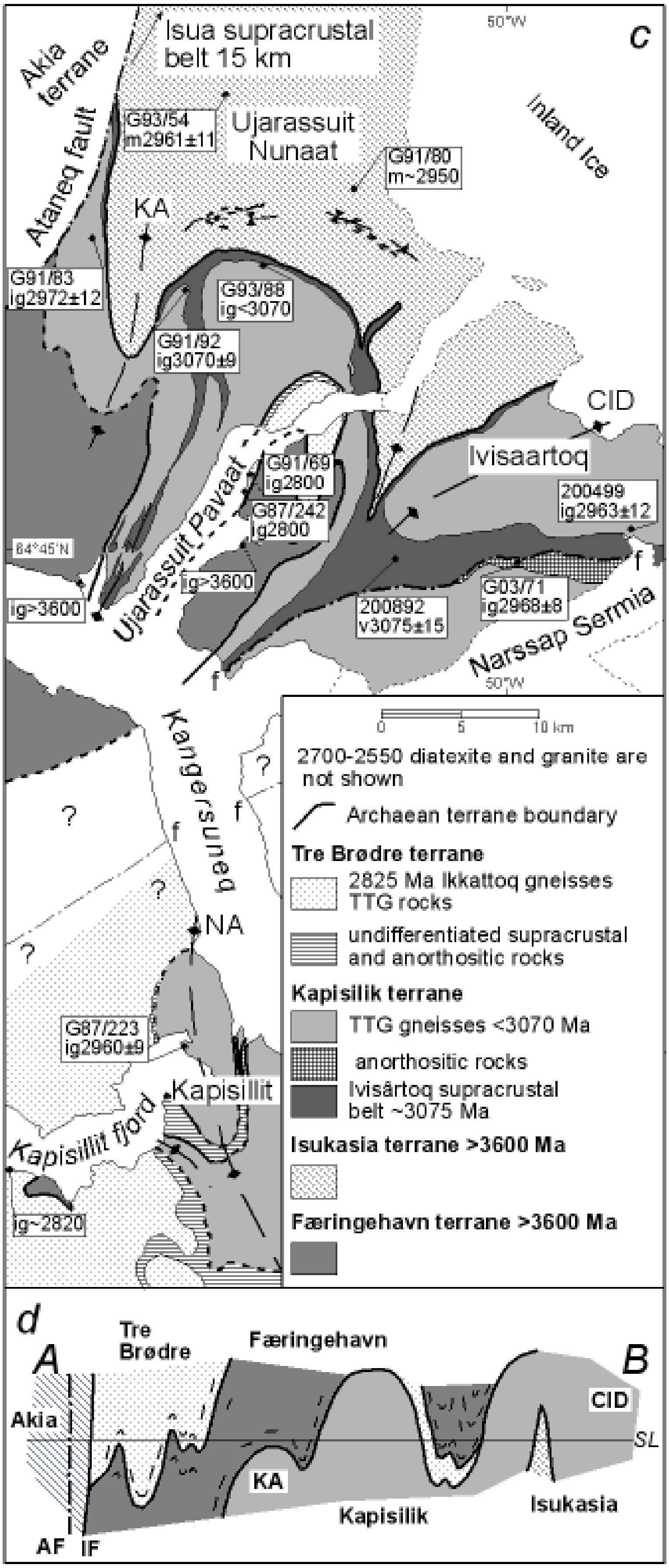


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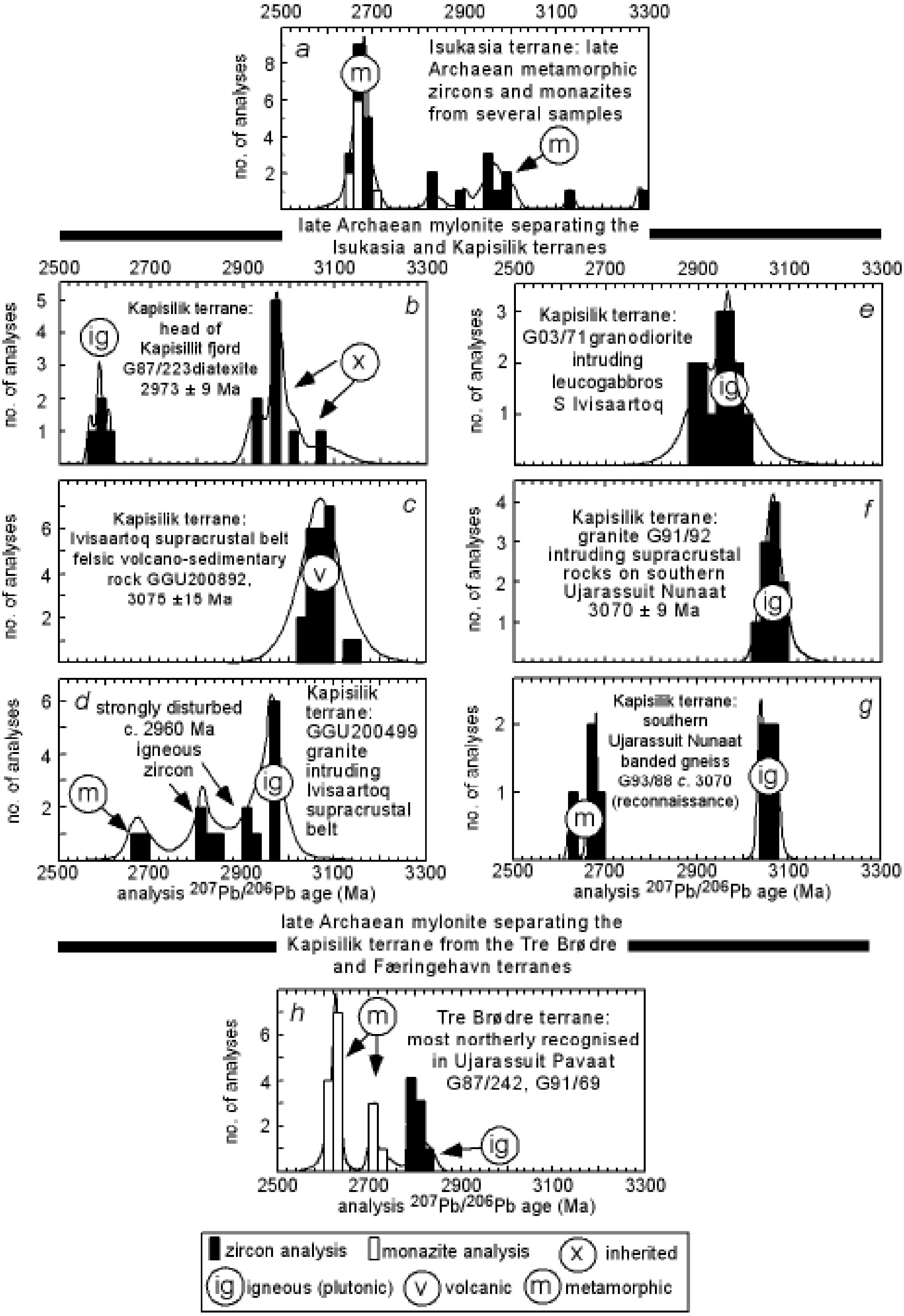
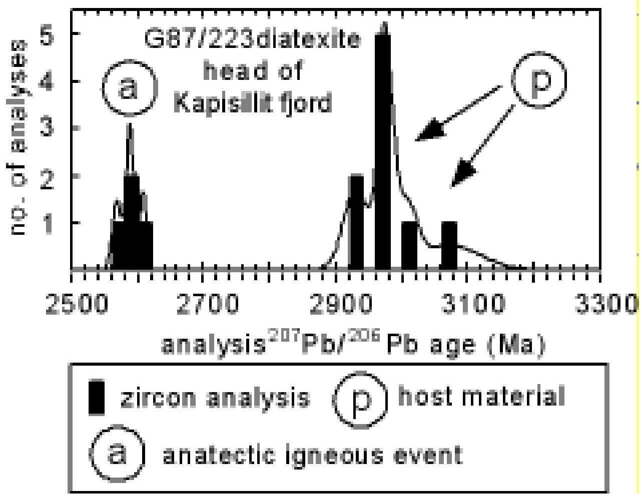
Fig. 4 - page width



14/05/04 Friend & Nutman
Fig. 2 - single column



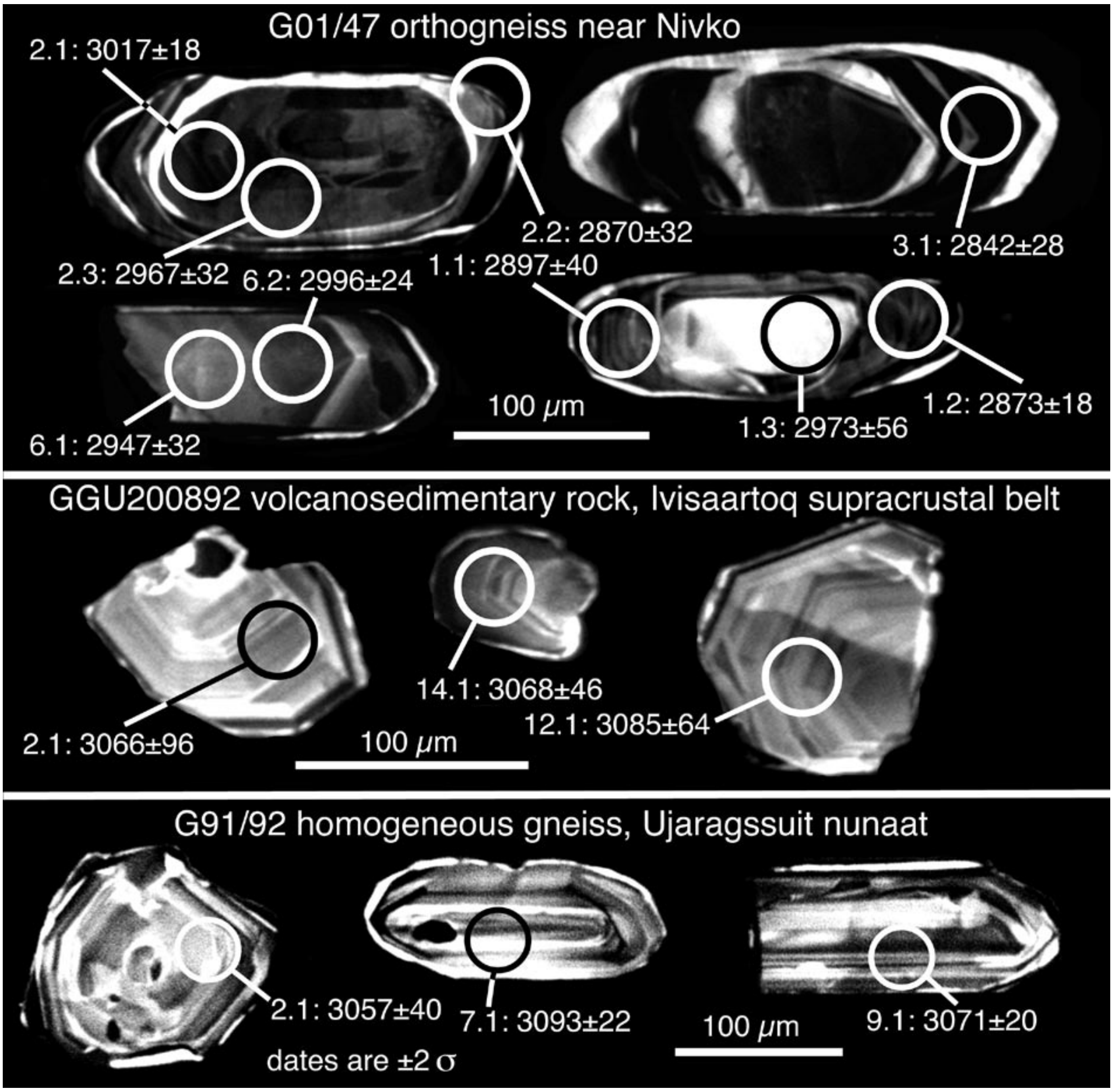

G01/47 orthogneiss near Nivko
2.1: 3017±18
2.2: 2870±32
3.1: 2842±28
2.3: 2967±32
6.2: 2996±24
1.1: 2897±40
100 μm
1.2: 2873±18
1.3: 2973±56
6.1: 2947±32
GGU200892 volcanosedimentary rock, Ivisaartoq supracrustal belt
14.1: 3068±46
12.1: 3085±64
2.1: 3066±96
100 μm
G91/92 homogeneous gneiss, Ujaragssuit nunaat
2.1: 3057±40
7.1: 3093±22
100 μm
9.1: 3071±20
dates are ±2 σ

Fig. 3.

Table 1. Summary of the development of the main hypotheses explaining the development of the Nuuk region.

	McGregor (1968, 1973); numerous papers by Moorbath and co-workers; Wells (1976)	Friend et al. (1987, 1988)	Crowley (2002)	this paper
1960s	1970s to mid-1980s	from mid-1980s	post-2002	2004
Granitised meta-greywackes intruded by Qôrqut granite	Two, TTG-dominated, juvenile crust formaing superevents: early Archaean (Amitsoq); late Archaean (Nûk) followed by one regional high-grade regional meta,morphism in thick crust. Finally intrusion of post-tectonic Qôrqut granite	Region divided into four tectono-stratigraphic terranes (Færingehavn, Akia, Tasiusarsuaq and Tre Brødre) with their own early evolution prior to assembly in the late Archaean. Qôrqut granite post-dates terrane assembly events, but is locally deformed	Independent mapping confirming the terrane interpretation and IDTMS zircon dating confirming SHRIMP zircon dating	Recognition of more than four terranes and a more protracted sequence of terrane assembly