1-1-2009

The whole rock Sm-Nd 'age' for the 2825 Ma Ikkattoq gneisses (Greenland) is 800 Ma too young: Insights into Archaean TTG petrogenesis

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Recommended Citation
Friend, Clark R L; Nutman, Allen Phillip; Baadsgaard, Halfdan; and Duke, M John M: The whole rock Sm-Nd 'age' for the 2825 Ma Ikkattoq gneisses (Greenland) is 800 Ma too young: Insights into Archaean TTG petrogenesis 2009, 62-76.
https://ro.uow.edu.au/scipapers/906

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Keywords

800, greenland, gneisses, ikkattoq, ma, 2825, age, nd, sm, rock, petrogenesis, whole, ttg, archaean, into, insights, young, too, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

Friend, C. R L., Nutman, A. Phillip., Baadsgaard, H. & Duke, M. (2009). The whole rock Sm-Nd 'age' for the 2825 Ma Ikkattoq gneisses (Greenland) is 800 Ma too young: Insights into Archaean TTG petrogenesis. Chemical Geology, 261 (1-2), 62-76.

The whole rock Sm-Nd 'age' for the 2825 Ma Ikkattoq gneisses (Greenland) is 800 Ma too young: insights into Archaean TTG petrogenesis

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Abstract

The Ikkattoq gneisses of the Archaean gneiss complex in the Nuuk region, southern West Greenland, are the orthogneiss component within the amphibolite facies Tre Brødre terrane. They have mostly granodioritic compositions, with a small amount of quartz-diorite. Sm-Nd isotopic data for a quartz-diorite and five granodiorite Ikkattoq gneiss samples from within 5 km of the Ikkattoq (fjord) type locality yielded a regression with a slope equivalent to 2005 ± 52 Ma (MSWD=0.72). Regardless of the low MSWD, this cannot be the true age of the Ikkattoq gneisses, because all Ikkattoq gneisses yield U-Pb zircon dates of c. 2825 Ma and they are cut by the undeformed 2560 Ma Qôrqut granite complex. This anomalously young regression 'age' resulted instead from mixing of different Nd components, indicating that the Ikkattoq gneisses are derived from mixed source materials. Taking the true age of the Ikkattoq gneisses as 2825 Ma from U-Pb zircon dating, the range of initial ε_{Nd} in the Ikkattoq gneisses is -7.1 to -1.8. The negative initial ε_{Nd} values mean that older, light rare earth enriched, sialic crust contributed to the igneous precursors of the Ikkattoq gneisses. This Nd evidence for contribution of older sialic crust is supported by positive ε_{Sr} values for the Ikkattoq gneisses.

With ε_{Nd} values as low as -7.1 this older crustal component has to be Eoarchaean. The presence of scarce quartz-diorites (low SiO_2, high MgO) suggests that ultramafic rocks (upper mantle?), metasomatised by the passage of fluids or silicic melts, was another contributing source. The Ikkattoq gneisses are proposed as a complex suite incorporating material derived from melting of much older sialic crust and probably upper mantle. The intercalation of tectonostratigraphic terranes during collisional orogeny at c. 2720 Ma destroyed the architecture of this 2825 Ma magmatic system, and the Ikkattoq gneisses now form a slice tectonically isolated from their source region. In terms of trace element parameters, the Ikkattoq gneisses resemble Phanerozoic volcanic arc granites. Thus an Andean-style arc setting for the generation of the Ikkattoq gneiss precursors is possible.

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Key words: *Archaean TTG, Ikkattoq gneisses, Nd isotopes, spurious isochrons, Nuuk region, W. Greenland*

1. Introduction

A less publicised aspect of the work of Bob Pidgeon, whom this issue honours, was his early zircon geochronology of orthogneiss complexes in southern West Greenland. This comprised several attempts to date a series of geological events to constrain the regional evolution in the Fiskenæsset area (south of the Nuuk region discussed here). Although his attempts to date different components of the orthogneisses by bulk zircon methods was frustrated by discordant age determinations (Pidgeon et al., 1976; Pidgeon & Kalsbeek 1978), a robust result was to obtain the age of granulite facies metamorphism in the Fiskenæsset area, by dating a single large metamorphic zircon (Pidgeon et al. 1976). The age of 2795 $^{+11}_{-7}$ Ma obtained for this metamorphism has been replicated (Crowley 2002) and this result still stands today as pinning an important event in the regional geology of southern West Greenland. This present paper explores some complexities of these West Greenland orthogneiss suites, through an integrated field, whole rock geochemistry, radiogenic isotope and U-Pb zircon dating study of the Ikkattoq gneisses. The Ikkattoq gneisses are a distinct suite that occupies an Archaean thrust slice in the Nuuk region (Fig. 1). The problems discussed here surrounding the Ikkattoq gneisses are relevant to Archaean orthogneiss complexes throughout the world.

Most high-grade gneiss complexes consist mostly of polyphase quartzo-feldspathic rocks, which are interpreted to be dominated by protoliths of tonalite-trondhjemite-granodioritic (TTG) affinity (e.g. McGregor 1973, 1979; Barker, 1979; Martin, 1986, 1987, 1995; Martin et al. 1995; Martin & Moyen 2002). These TTG rocks are usually dominated by tonalitic compositions with subordinate dioritic and granodioritic phases (e.g. McGregor 1979; Garde et al. 2000). Such rocks are usually interpreted as being produced by partial melting at high pressure of some form of basaltic crust that was either subducted or underplated (for modern summaries see Martin et al. 2005; Rapp 1997; Wyllie et al. 1997; Smithies 2000, Smithies et al. 2003). Residues of the melting are dominated by garnet because of the high pressure, which imparts distinctive trace element signatures on the rocks. For the Nuuk region TTG suites discussed here, it was proposed that Sr and Nd radiogenic isotopic data indicate that there was little or no involvement of much earlier continental crustal material, and that the TTG were derived from mafic material that had had a short crustal residence time (e.g. Moorbath 1975, 1977; Moorbath & Taylor 1985).

More recently, the studies of both ancient and modern TTG suites have been directed towards looking at the chemical distinction of magmas produced in particular environments, with variants of convergent plate boundaries as the favoured setting (e.g. Rapp 1997; Smithies 2000; Martin & Moyen 2002; Champion & Smithies 2007). Additionally, the evolutionary path of the melts is also important because those components derived at depth (e.g. a subducted slab) will interact with overlying mantle and crustal rocks during their ascent. Obviously the nature of the crust transited by the melts (mafic or felsic) has a strong influence on their final composition. Thus in modern systems, complex interaction between several components is noted to occur in giving rise to silica-saturated arc magmas (e.g., Hildreth and Moorbath, 1988). This style of work can now be applied to better-delineated units within the Archaean. In this paper, the 2825 Ma Ikkattoq gneisses of southern West Greenland are used to illustrate the involvement of older crust in the generation of some Archaean TTG suite rocks.

2. Ikkattoq gneisses in the context of the regional geology

2.1. History

The well-exposed high-grade gneiss complex of the Nuuk region of southern West Greenland (Fig. 1) is a classic area for the study of Archaean crustal development. McGregor (1968, 1973) first demonstrated that the quartzo-feldspathic 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 partially melted and ‘granitised’ quartzo-feldspathic sediments according to generally accepted interpretations of such rocks at that time. McGregor (1968, 1973) also established a first-order division of the regional gneisses, recognising an older, Eoarchaean component, the >3600 Ma Amîtsoq gneisses cut by the Ameralik dykes and a younger Archaean component, the Nûk gneisses (e.g. Black et al. 1971; Moorbath et al. 1972; Baadsgaard 1973, 1976; Moorbath & Pankhurst, 1976). In the vicinity of Nuuk and in south-western Godthåbsfjord, rocks defined as the type Nûk gneisses were shown to be 3070 to 2940 Ma old (Taylor et al 1980; Baadsgaard & McGregor, 1981). Elsewhere in the region quartzo-feldspathic gneisses not containing

Ameralik dykes (and therefore, not mapped as Amîtsoq gneisses) were believed to be of similar age as the type Nûk gneisses and were correlated with them (e.g. Compton 1978; Chadwick and Nutman 1979; McGregor 1979; Wells 1979; Coe 1980; Taylor et al. 1980; Chadwick & Coe 1983; Hall & Friend 1983; Robertson 1986).

The assembly of the complex was initially interpreted as the product of interleaving of early Archaean rocks with a group of mixed origin, middle Archaean supracrustal rocks penecontemporaneous to the generation of the younger TTG suite (McGregor 1973; Bridgwater et al. 1974). These ideas fed through into the concept that there were broadly two continuous sequences, as isotopically defined continental accretion-differentiation suites (Moorbath 1975, 1977; Moorbath & Taylor 1985; Moorbath et al. 1986). However, it became increasingly apparent from structural, metamorphic and geochronological studies that the Nûk gneisses (*sensu* McGregor, 1973) were polygenetic, and were emplaced as several suites between 3070 and 2660 Ma (e.g. Roberts, 1979; McGregor et al., 1983, 1986; Kinny 1987; Robertson, 1987; Schiøtte 1987).

2.2. Recognition of tectonostratigraphic terranes assembled late in the Archaean

The first interpretation of the geological evolution of the Nuuk region has now been radically revised through a long programme of fieldwork supported by a large programme of single grain U-Pb zircon dating (e.g. Friend et al., 1987, 1988, 1996; Nutman et al. 1989, 1996, 2001; McGregor et al. 1991; Garde et al., 2000; Crowley, 2002; Friend & Nutman 2005; Nutman and Friend, 2007). The Archaean gneiss complex is now recognised to contain a series of unrelated, but similar looking, gneiss blocks separated by thin, folded metamylonites. These blocks are interpreted as tectonostratigraphic terranes (*sensu* Coney 1980) that each contain the products of one or more accretionary events (accretionary is used here in the Archaean sense, meaning growth of crust by emplacement of juvenile magmas, probably at convergent plate boundaries). The accretionary products that dominate these terranes are the TTG orthogneiss suites, that were intruded into assemblages of amphibolites derived from both volcanic (e.g. pillow lavas) and plutonic (gabbroic) protoliths, with lesser amounts of ultramafic and metasedimentary rocks. Thus juxtaposed distinct terranes presently recognised in the Nuuk region (Fig. 1) are the Eoarchaean Isukasia and Færingehavn terranes, the Mesoarchaean Akia and Kapisilik terranes and the Neoarchaean Tre Brødre and Tasiusarsuaq terranes (see Friend and Nutman 2005).

More recently recognised is a thin package of Neoarchaean supracrustal amphibolites and metasedimentary gneisses intruded by layered gabbroic anorthosite (with no associated TTG assemblage) that occurs between the Færingehavn and Tre Brødre terrane (Nutman and Friend 2007). All terranes have their own internal early tectonothermal histories that were overprinted by tectonothermal events common to groups of terranes, following their assembly.

2.3. Ikkattoq area, Tre Brødre terrane and the Ikkattoq gneisses

The Archaean geology of the Ikkattoq area consists of the intercalated and then folded Færingehavn, Tre Brødre and Tasiusarsuaq terranes (Fig. 2). The lithological components of the Eoarchaean Færingehavn terrane are not discussed here (for a recent summary see Nutman et al. 2007). The Tre Brødre terrane comprises three main components, the oldest of which is mixed mafic meta-volcanic and meta-sedimentary supracrustal rocks. These were intruded by a stratiform, layered gabbroic-anorthosite complex (Chadwick et al. 1982; Dymek and Owens 2001). All of these rocks were subsequently intruded by the igneous precursors of the Ikkattoq gneisses. The Tre Brødre terrane has been subjected to polyphase metamorphism under amphibolite facies conditions only, which distinguishes it from the two adjacent terranes, both of which underwent granulite facies metamorphism as part of their own development (the Færingehavn terrane at 3650 to 3600 Ma and the Tasiusarsuaq terrane at c. 2790 Ma; Pidgeon and Kalsbeek 1978; Crowley, 2002; Friend and Nutman, 2005). Terrane assembly must have occurred in the Neoarchaean because terrane boundaries cut the Ikkattoq gneisses, but are cut by sheets of granite and pegmatite correlated with the c. 2560 Ma Qôrqut granite complex (e.g. Friend et al. 1988, 1996; Crowley 2002; Nutman and Friend 2007). Tectonic assembly was associated with, and succeeded by deformation and recrystallisation under amphibolite facies conditions (see Friend et al., 1987; Nutman et al., 1989; Nutman and Friend 2007 and references therein). Following assembly, the terranes were cut by late kinematic granitic sheets ranging in age between 2720 and 2610 Ma (Roberts 1979; McGregor et al., 1983; Friend et al. 1996). The Archaean tectono-thermal evolution of the region was completed by the emplacement of the post-kinematic c. 2560 Ma Qôrqut granite complex (Moorbath et al. 1981; Friend et al. 1985).

The Tasiusarsuaq terrane also contains Neoarchaean rocks, and structurally overlies the Tre Brødre terrane. It underwent granulite facies (e.g. Wells 1976, 1979) and subsequent partial retrogression (Friend et al. 1988; Nutman and Friend 1989). It comprises amphibolites of several origins, an anorthosite complex, a number of TTG phases and a major later granitoid (e.g. Chadwick and Coe 1983). These rocks have ages from 2920 to 2810 Ma (e.g. Kinny 1987; Schiøtte et al. 1989; Friend and Nutman 2001; Crowley 2002). Granulite facies metamorphism in this terrane has been dated at c. 2790 Ma (Pidgeon and Kalsbeek 1978; Crowley 2002). At the structural base of the terrane, the Qarlliit Nunaat fault, metamorphism is retrogressive and only in amphibolite facies (Friend et al. 1987, 1996; Nutman et al. 1989).

3. Field relationships of the Ikkattoq gneisses

In early work, carried out when the geochronology was dominated by whole-rock isotopic studies, the gneisses now distinguished as the Ikkattoq gneisses were regarded as components of the Nûk gneisses *sensu* McGregor (1973), and were variably given local names, for example in the Ameralik - Færingehavn area they were known as the 'grey gneiss complex' (e.g. Compton 1978). Subsequently, with the understanding of the separation of the gneisses into different blocks, the Nûk gneisses were confined to the Akia terrane northwest of the Ivinnguit Fault (Friend et al. 1988). All of those gneisses southeast of the Ivinnguit Fault and northwest of the Qarlliit Nunaat Fault that had previously been termed ‘Nûk gneisses,’ by default became Ikkattoq gneisses (e.g. Friend et al. 1996). As the unravelling of the tectonics of the region has progressed supported by U-Pb zircon geochronology, more recent works have revised this view with the recognition of the Mesoarchaean Kapisilik terrane (Friend and Nutman 2005) and other components (Nutman and Friend 2007).

The gneisses defined here as the Ikkattoq gneisses are confined to the Tre Brødre terrane (Fig. 1) and are named after the fjord in which they were first recognised as a distinct unit (Fig. 2). Most of the Ikkattoq gneisses are grey, biotite ± rare garnet-bearing granodioritic rocks with a widely spaced pegmatite banding (Fig. 3a). In places volumetrically minor amounts of hornblende + biotite ± garnet quartz-dioritic phases are present (e.g. G85/370 – Fig. 2). A striking feature of the Ikkattoq gneisses at most outcrops is their homogeneity (Fig 3a) which is in marked contrast to the polyphase character of both the TTG gneisses in the Itsaq Gneiss Complex and the type Nûk gneisses in the Akia terrane (see McGregor 1973, figs 2-16; Garde et al. 2000). However, close to enclaves and rafts of supracrustal rocks the Ikkattoq gneisses may become schlieric, markedly garnetiferous and locally even contain sillimanite as a measure of contamination.

Generally the rocks are strongly deformed, but only under amphibolite facies conditions, having never attained granulite facies conditions (e.g., Nutman et al. 1989; Nutman and Friend 2007). Strain usually increases markedly towards the tectonic contacts, e.g. with the Tasiusarsuaq terrane in Ikkattoq (Fig. 2) and with a particularly obvious strain gradient against the Akia terrane on the southern end of Sadelø (Fig.1, 3b,c).

4. Ikkattoq gneiss geochemistry

4.1. Sample suite description

There is a core set of six samples from the Ikkattoq area (G85/356, -357, -370, -489, -490 and -491, Fig. 2) for which there is U-Pb zircon, Sm-Nd, Rb-Sr and Pb whole rock isotopic data, plus whole rock chemical analyses (Tables 1 to 5). These are all granodioritic, apart from G85/370 which is quartz-dioritic. In addition, from Ikkattoq there is granodioritic sample G85/369 for which there is only whole rock chemical data. The samples G87/45, -188, -261, G88/15, G00/37, G03/23, -14, -16, -69 and VM97/01 from the Ameralik and Godthåbsfjord areas to the north (Fig. 1) all have structural settings, U-Pb zircon dates of c. 2825 Ma (Nutman and Friend, 2007 and this paper) plus some whole rock chemistry showing they are mostly granodioritic, and are certainly the lateral equivalents of the type Ikkattoq gneisses. Samples G87/188, -242, G91/69 and G03/14, -16, -37 and 292407 all have zircon ages of 2825 to 2810 Ma, but it is less certain if they are in packages of rocks structurally continuous with the Tre Brødre terrane and the type Ikkattoq gneisses. These are regarded as possible, but yet to be confirmed Ikkattoq gneisses. Samples 437641 and 437636 from near Kapisillit are c. 2800 Ma granites affected by c. 2630 Ma metamorphism (Hollis et al., 2005; Nutman and Friend, 2007). These are from units regarded in our 1980s reconnaissance mapping to be Ikkattoq gneisses. However on the basis of the subsequent zircon dating and more detailed fieldwork, they are no longer regarded by us as being so. Data from some of the samples away from Ikkattoq is used in the following sections.

4.2. Isotopic data

Integrated U-Pb zircon, whole rock Pb-Pb, Sm-Nd and Rb-Sr data are presented on the six samples from the type area around Ikkattoq. Details of analytical methods are given in the supplementary data document xxxxxx and data are presented in Tables 1 to 4. Plotting and regressions were undertaken using Isoplot3 (Ludwig, 2003). The decay constants used in age computations are those presented by Steiger and Jaeger (1977).

4.2.1. U-Pb zircon

SHRIMP (Sensitive High Resolution Ion MicroProbe) U-Pb isotopic data for Ikkattoq gneiss zircons were presented in Nutman and Friend (2007). This extensive data set of 120 zircon analyses on twelve samples revealed only one inherited (pre-magmatic) zircon core (age of c. 3000 Ma - grain 5, sample G88/45; Table 1 of Nutman and Friend, 2007). The amount of metamorphic overgrowth zircon is also small, thus most grains are dominated by igneous zircon that is variably recrystallised. Most SHRIMP U-Pb analyses of well-preserved igneous domains yielded close to concordant ages, with calculated weighted mean ^{207}Pb/^{206}Pb zircon ages for the twelve samples being in the narrow range from 2829 ± 11 Ma to 2817 ± 9 Ma (Nutman and Friend, 2007).

In this paper, thermal ionisation mass spectrometry U-Pb zircon data are presented for six Ikkattoq gneiss samples from the type area south of Færingehavn, plus sample G88/15 from Sadelø in Godthåbsfjord (Figs. 1, 2, 4). Most measurements are on ‘bulk’ zircon aliquots (16.8 to 23.9 mg), but on samples G85/370 and G88/15 there are ^{205}Pb-^{235}U mixed spike measurements on a few selected crystals (0.1034 and 0.0476 mg). For the type area Ikkattoq gneiss sample G85/370, there are zircon U-Pb measurements by SHRIMP, and IDTIMS bulk zircon and a few selected crystals methods (Fig. 4). This sample yielded a SHRIMP zircon ^{207}Pb/^{206}Pb weighted mean age of 2829 ± 11 Ma (n=6 with no rejects; 95% confidence, Nutman and Friend, 2007), the measurement on a selected few crystals gave apparently concordant ages with a lower ^{207}Pb/^{206}Pb age of 2791 Ma, and the bulk zircon sample gave discordant ages with an apparent ^{207}Pb/^{206}Pb age of 2759 Ma (Fig. 4). For sample G88/15 from Sadelø in Godthåbsfjord, the measurement on a selected few crystals aliquot gave almost concordant ages with a ^{207}Pb/^{206}Pb age of 2815 Ma, compared with the SHRIMP ^{207}Pb/^{206}Pb weighted mean age of 2825 ± 8 Ma (n=10 with no rejects; 95% confidence). The bulk zircon aliquots of the remaining Ikkattoq gneisses from the type area all yielded discordant ages, with apparent ^{207}Pb/^{206}Pb ages between 2781 and 2750 Ma (Table 1, Fig. 4). Given the lack of inheritance detected in the Ikkattoq gneisses in the cathodoluminescence imaging-SHRIMP study, these discordant results give the minimum ages for the igneous crystallisation of the Ikkattoq gneisses. Thus the Ikkattoq gneisses are c. 2825 Ma (Nutman and Friend, 2007). This Archaean age agrees with the observation that Ikkattoq gneisses had been deformed and tectonically intercalated with other rocks, prior to intrusion of the mostly undeformed c. 2560 Ma Qôrqut granite complex (Baadsgaard, 1975 Moorbath et al., 1981).

4.2.2. Sm-Nd whole rock

The six samples from the Ikkattoq area (Table 2) yielded a well-fitted Sm-Nd regression (MSWD=0.72) with an apparent age of 2005 ± 52 Ma with initial ^{143}Nd/^{144}Nd = 0.50865 ± 0.00004 (Fig. 5a). From the Ikkattoq zircon U-Pb results presented above, plus the field evidence that the Ikkattoq gneisses predate the 2560 Ma Qôrqut granite complex, a Palaeoproterozoic age for the Ikkattoq gneisses is impossible, because they must be Archaean in age. Therefore, the apparent Sm-Nd isochron of 2005 ± 52 Ma is a mixing line giving an apparent age c. 800 Ma younger than the true age, brought about by the Ikkattoq gneisses containing more than one initial Nd component. This is also indicated by ε_{Nd}(2825 Ma) for the Ikkattoq gneisses ranging from -0.6 to -6.5, well beyond expected errors of ± 0.5 epsilon units on each datum (Table 2, Fig. 5b). The nature of the different Nd components is discussed below, and is important in understanding the petrogenesis of the Ikkattoq gneisses.

4.2.3. Rb-Sr whole rock

The Rb-Sr isotopic measurements (Fig. 6) have scatter beyond what would be expected for a genuine isochron, and have an apparent age of 2839 ± 79 Ma (MSWD=13; initial ^{87}Rb/^{86}Sr=0.7024±0.0032) (Fig. 6a). The high MSWD indicates a probability of <0.01% that 2839 Ma is the true age of these rocks obtained using these data.

4.2.4. Pb whole rock

The whole rock Pb isotopic data form a scatter in a ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb plot (Fig. 7). A best fit reference line with a slope equivalent to an apparent age of 2984 ± 210 Ma can be constructed from these data. The large scatter (MSWD = 533) indicates that this reference line has no significance for the age of the rocks. Noteworthy however is that the Ikkattoq lead compositions lie well below a chord drawn through 2825 Ma and the present on the Stacey and Kramers (1975) model mantle evolution curve (line A-B on Fig. 7; note that other common models to mimic Archaean mantle Pb isotopic evolution could be used, with equal effect). Because the Pb data lie well below this chord, it indicates that the Ikkattoq gneisses contain unradiogenic Pb derived from older U-depleted crustal rocks.

4.3. Whole Rock Chemistry

The whole rock data are divided into 3 categories, (a) Ikkattoq gneisses from the type area south of Færingehavn, (b) definite Ikkattoq gneisses to the north around Ameralik and in the southern reaches of Godthåbsfjord, and (c) 2820 to 2800 Ma orthogneisses further to the north and east, some of which might correlate with the Ikkattoq gneisses (Fig. 1). It is important to note that for the key category of type Ikkattoq gneisses, there is U-Pb zircon dating indicating that all the samples belong to the same suite.

The whole rock analyses of previously unpublished data come from diverse laboratories, and are explained in the Table 5 footnotes. The major element and some trace element data were obtained by XRF analyses on Li-borate fused glass discs and on pressed powder pellets. Fuller suites of major and trace elements, including the rare earth element (REE) were obtained by ICPAES. In addition we re-present analyses from Compton (1978) that are Ikkattoq gneisses from the south side of Ameralik (Fig. 1). These samples occur in a fold core that is the northern continuation of the Tre Brødre terrane from the type area of the Ikkattoq gneisses. The SHRIMP zircon age of 2817 ± 9 Ma on sample G03/69 supports this correlation (Nutman and Friend, 2007).

Overall, the whole rock data set is small, and by modern analytical protocols, the suite of trace element data that is presented is limited. Thus, we are fully aware that with this data set a detailed petrogenetic scheme for the Ikkattoq gneisses cannot be presented. Instead, the available whole rock chemical data are integrated with the isotopic data, to provide a broad understanding of the Ikkattoq gneisses, in terms of the environment in which they formed, and why the whole rock Sm-Nd isotopic data produce an ‘isochron’ that is 800 Ma younger than the true age of the rocks.

4.3.1. Major and trace element chemistry

The samples of the type Ikkattoq gneisses and those correlated with them have SiO_2 > 69 wt% apart from one quartz-dioritic sample (Fig. 8). They have TiO_2 <0.9 wt%, Al_2O_3 13.8-17.91 wt.% and most have >15 wt.% Al_2O_3 at 70 wt.% SiO_2. Mg# is between 0.15 and 0.38 and K_2O/Na_2O is low, ranging from 0.3 to 1.0. TTG were divided by Barker & Arth (1976) into high- and low-Al types that was extended to include Sr and Eu contents (Martin et al. 2005). The high-Al types have high Sr and Eu and highly fractionated patterns whereas the low-Al type has lower Sr and Eu and less fractionated patterns. The Ikkattoq gneisses do not show high Sr, but otherwise appear to correspond best with the high-Al group of TTG lithologies. Cast as CIPW norms, the compositions of the Ikkattoq gneisses contain plagioclase + quartz + K-feldspar and mostly correspond to granodiorites. Relative to the projected positions of the phase boundaries within the salic tetrahedron the granodioritic compositions are close to the 5 kbar plagioclase – K-feldspar cotectic, giving the possibility of crystallising either feldspar first (Fig. 8a). The quartz-diorite plots well into the plagioclase primary phase volume. The indications are that these are not simple melts derived from a mafic source. The SiO_2 vs. MgO plot (Fig. 8b) is used to explore the interaction between liquid and other sources, e.g. mantle (e.g. Rapp et al. 1999; Martin & Moyen 2002). The granodioritic Ikkattoq gneisses have normal low MgO contents (and Mg#) for granodiorites, and it would thus seem that the liquids have not encountered a more magnesian material during emplacement. On a granite discriminant plot of Rb vs. Y+Nb (Pearce et al. 1984) the Ikkattoq gneisses fall within the field of volcanic arc granites (Fig. 8c). Plotting La_N/Yb_N against Yb_N (Fig. 8d) places the Ikkattoq gneisses largely in the field of Archaean TTG (Martin 1986). Using melting curves for different plausible sources suggests that they are better explained by the melting of a garnet amphibolite composition rather than eclogite or amphibolite. Thus few (if any) of the Ikkattoq gneisses have bulk compositions that can be interpreted as straightforward slab melts in the pressure-temperature regime of eclogite or high pressure granulite, as has been widely proposed as an important source for TTG magmas (e.g. Arth and Hansen 1975; Rapp 1997; Martin et al. 2005). This is also indicated by the REE patterns (Fig. 9) see below. Sample G87/370 is a quartz-diorite, which is too magnesian to have been produced solely by melting of mafic eclogite, and, as argued by Martin et al (2005), must involve some melting of mantle, refertilised by fluids or melt. On the other hand, the predominant granodiorites are too evolved and potassic to be melts derived from melting of solely garnet amphibolite and instead, their compositions suggest some involvement of pre-existing felsic crust in their genesis.

4.3.2. REE element chemistry

The type Ikkattoq gneisses show enrichment of the light rare earth elements (LREE) over the heavy rare earth elements (HREE), with La/Yb(N) of 4 to 58 (Fig. 9a, Table 5). The patterns are not as highly fractionated as some TTG rocks (e.g. summary in Martin et al. 2005) but show steeply inclined LREE with flatter, little fractionated HREE resulting in overall concave patterns. This concave character of the Ikkattoq REE patterns is more pronounced than in the steeper patterns with dished HREE displayed by TTG compositions thought to be dominated by residual garnet during partial melting of eclogite, responsible for the steep pattern of the HREE (e.g. Arth and Hanson 1975). Eu anomalies are small to negligible, indicating that major plagioclase fractionation has not been important at any stage in their petrogenesis. This observation is important, because the Ikkattoq granodiorites cannot then be regarded as primary tonalitic melts which have undergone marked plagioclase fractionation during their ascent (Fig. 8a). Instead, the Ikkattoq gneiss precursors would appear to be primary granodioritic liquids. Experimental petrology indicates that such granodioritic compositions are liquid at temperatures of 900-1000ºC (Moyen and Stevens, 2006). The data obtained by Compton (1978) are represented in Fig. 9b show similar patterns for the LREE as the type rocks. However, with fewer HREE analysed using the neutron activation technique, the HREE part of the pattern is difficult to assess properly and, because the concentration of the HREE are close to their respective detection limits applicable to the methods at the time, the reported HREE concentration may be too low, thus giving the pattern a steeper trend than it should have.

Primitive mantle discriminant spidergrams for the type rocks are presented in Fig. 8e. The negative Sr anomaly of the type rocks distinguishes them from other TTG suites that usually show little evidence of this. The low Sr is not considered to be due to metamorphic effects because the rocks have only been subjected to amphibolite facies conditions. Like most crustal granitoids, they show negative Ti and Nb anomalies, reflecting the influence of rutile as a residual phase in high pressure melting during the event that formed juvenile sialic crust (Gill, 1981). This signature is inherited by second generation granitoids, and does not dictate that rutile fractionation was involved in their immediate petrogenesis. Another prominent feature is the marked positive Pb abundance anomalies. Concentration of Pb via fluids could be due to either syn-magmatic processes or during subsequent metamorphism (see Pb isotope section below).

4.3.3. Zircon saturation thermometry

Using zircon saturation thermometry of Watson and Harrison (1983), the Ikkattoq granodiorites should have become saturated between 813 and 769ºC (Table 5), i.e. below the likely temperature at which these melts probably formed (900-1000ºC). The quartz-diorite sample G85/370 indicates a zircon saturation temperature of 726ºC, which is well below the temperatures of >1000ºC at which such melts are thought to form (e.g. Rapp 1997). This is in accord with the general lack (apart from 1 grain) of inherited, pre-magmatic zircon in the Ikkattoq gneisses, a trait shared with other hot granitoids of the Nuuk region (Nutman et al., 2000; Mojzsis and Harrison, 2002).

5. Origin of the Ikkattoq gneisses

The following points can be made concerning the Ikkattoq gneisses that are of significance in understanding their origin:

(a) More than one magma type/source is present within them. Thus the rare quartz-diorites would have involved melting of (metasomatised) mantle, whereas the predominant granodiorites originated as granodioritic magmas and not by plagioclase fractionation from tonalites.

(b) Zircon saturation thermometry and the lack of inherited zircons indicates that the granodiorites formed at >800ºC, and thus are hot granites (*sensu* Miller et al., 2003).

(c) In trace element discriminant diagrams, the Ikkattoq gneisses plot well within the field of volcanic arc granites (VAG), intimating a crustal accretionary – plate boundary origin, rather than originating as granites formed in collisional orogenic or within-plate settings.

(d) Zircon geochronology indicates the Ikkattoq gneisses are c. 2825 Ma old.

(e) Whole rock isotopic data, particularly Sm-Nd, with negative ε_{Nd}(2825 Ma) values as low as -7 (Fig. 5b), indicates some older low Sm/Nd (0.11 to 0.12) sialic crust is involved in their petrogenesis.

(f) The Sm-Nd 2005 Ma spurious 'isochron age' (Fig. 5a) indicates mixing of more than one initial Nd component during formation of the Ikkattoq gneisses.

5.1. The 2005 Ma Sm-Nd 'isochron' - interpretation and significance

From the zircon geochronology and the regional geological constraints, the Ikkattoq gneisses are Neoarchaean in age, c. 2825 Ma. Thus the well-fitted (MSWD=0.72) 'isochron' of 2005 Ma for the Ikkattoq gneisses (Fig. 5a) is 800 Ma too young and cannot be the age of the rocks. Instead, it is a mixing line between two (or more) source components. There is a marked negative correlation between ^{147}Sm/^{144}Nd and Nd abundance (Table 2; inset in Fig. 5c). We contend that at c. 2825 Ma, one source had a higher Sm/Nd, higher LREE abundance and lower ^{143}Nd/^{144}Nd at 2825 Ma than the other (Fig. 5c). The higher Sm/Nd and lower ^{143}Nd/^{144}Nd at 2825 Ma source is likely to be an Eoarchaean sialic crustal component, in order to account for ε_{Nd}(2825 Ma) values as low as -7 (Fig. 5b). The only suitable Eoarchaean sources in the region are rocks in the Færingehavn and Isukasia terranes (Fig. 1, Fig 5b). The next oldest-known crustal component in the Nuuk region are c. 3230 Ma quartz diorites in the Akia terrane. However, these display too high ε_{Nd}(2825 Ma) values to be the sole old crustal component (Fig. 5b). The nature of the one or more other components (less negative to positive ε_{Nd}(2825 Ma) values and lower Sm/Nd) are less certain. The magnesian quartz-diorite G85/370 suggests a melt contribution from metasomatised upper mantle sources which was subsequently contaminated by crustal material (giving ε_{Nd}(2825 Ma) = -4.0 in G85/370). Sample G85/356 with the least negative ε_{Nd}(2825 Ma) value of -0.6 and lowest Sm/Nd (Fig. 5b), clearly still has to involve older, low Sm/Nd crust in its genesis, rather than being an entirely juvenile component with a positive ε_{Nd}(2825 Ma). Thus at present only two sources are proposed. These are the remelting of Eoarchaean sialic crust, and melt extracted from metasomatised mantle. The possible environment for this to occur would be at a plate boundary, where mantle-derived melts interacted at high temperature with older Eoarchaean sialic crust.

5.2. Interpretation of Ikkattoq gneiss whole rock Pb isotopic data

The Ikkattoq gneiss Pb isotopic data (Fig. 7) plot well below tie line A-B passing through present and 2825 Ma Pb compositions on the uranogenic Stacey and Kramers growth curve (which is used here as one approximation of mantle evolution in the Archaean). This shows that the Pb in the Ikkattoq gneisses was derived wholly or in part from older crust. The least radiogenic Pb of the Ikkattoq gneisses plot close to the field for plagioclase feldspars from Eoarchaean Itsaq Gneiss Complex rocks of the Færingehavn terrane (Fig. 7; data from Kamber and Moorbath, 1998). The feldspars of these Eoarchaean rocks were thoroughly recrystallised during the Neoarchaean tectonothermal events associated with terrane assembly. Because they are feldspars, they are very low U, and represent a proxy for the Eoarchaean whole rock lead isotopic compositions in the Neoarchaean when the Ikkattoq gneisses formed. From these feldspar data, much of the Pb in the Ikkattoq gneisses can be argued to be derived from an ancient, unradiogenic Pb crustal source. However, given the much greater mobility of Pb versus Nd during high temperature events in the deep crust (e.g. McCulloch et al., 1992), this does not automatically imply that the present Pb abundances and isotopic characteristics of the Ikkattoq gneisses reflects igneous processes at 2825 Ma. It is also possible that the present Ikkattoq gneiss Pb compositions reflect metasomatic movement of Pb during subsequent terrane assembly, metamorphism and folding. This has already been demonstrated for the Tasiusarsuaq terrane. The Pb in Tasiusarsuaq terrane unretrogressed granulites is more radiogenic than that in amphibolite facies rocks which were derived by ductile deformation of the granulites (Friend et al., 1987; Nutman and Friend 1989). Those authors proposed that the unradiogenic Pb present in the retrogressed granulites was metasomatically introduced from Eoarchaean rocks in the structurally underlying Færingehavn terrane. To get to the structurally higher Tasiusarsuaq terrane fluids would have passed through the Tre Brødre terrane (e.g. Fig. 2). It is therefore possible that the Pb systematics of the Ikkattoq gneisses were modified during, or subsequent to, the Neoarchaean interleaving and deformation of the assembled terranes (Fig. 1).

5.3. Interpretation of the Rb-Sr 'isochron'

Superficially, the age of 2839 ± 79 Ma given by the Rb-Sr 'isochron' would seem to agree within error with the zircon age of 2825 Ma. However, with an MSWD

= 13, there is only a very low probability that this represents a true age for this suite of rocks (Fig. 6a), which is confirmed by the field relations as described above. Plotting ε_{Sr} against ε_{Nd} (Fig. 6b) also shows that the Ikkattoq gneisses do not fall into the field expected for juvenile material, but lie in the field requiring a variable input from a more ancient crustal source.

6. Discussion

6.1. Mixed sources for magmas in the Ikkattoq gneisses

In their integrated petrologic and isotopic study of the Andean arc, Hildreth and Moorbath (1988, page 455) noted that ‘*Base-level isotopic and chemical values for each volcano are established by blending of subcrustal and deep-crustal magmas in zones of melting, assimilation, storage and homogenization (MASH) at the mantle-crust transition. Scavenging of mid to upper-crustal silicic-alkalic melts and intracrustal AFC (prominent at the largest center) can subsequently modify ascending magmas, but the base-level geochemical signature at each center reflects the depth of its MASH zone and the age, composition, and proportional contribution of the lowermost crust.*’ We regard this statement, summarising their interpretation of igneous processes deep with Andean margins, as a template for understanding the geochemistry and isotope systematics of the Ikkattoq gneisses. In this particular instance, the mixing of Nd from different sources has resulted in an apparently perfect isochron that is 800 Ma too young for the rocks. We regard this perfect isochron as entirely fortuitous, and predict that the addition of Sm-Nd data from Ikkattoq gneisses away from the type locality would lead to increased scatter. An environment likened to modern day Andean arc environments would be in accord with the trace element variation of the Ikkattoq gneisses, as represented via Pearce discrimination diagrams (Fig. 8). However, we stress strongly that we are in no way proposing that the Ikkattoq gneisses within the Tre Brødre terrane represent a tectonic slice of an *exact* c. 2825 Ma equivalent of a modern Andean arc. We only propose that similar source materials, i.e., metasomatised mantle and older continental crust, contributed to their genesis.

6.2. Extent of the Ikkattoq gneisses

The Ikkattoq gneisses were first recognised and defined south of Færingehavn by mapping in 1985 (Friend et al., 1987, 1988) combined with bulk zircon U-Pb dating that is finally published here. In 1987 and 1988, reconnaissance geological studies further north into the Godthåbsfjord and the Ameralik areas (Fig. 1), lead to the proposal that large amounts of post Eoarchaean orthogneisses in the eastern part of that vast area were Ikkattoq gneisses (Friend et al. 1988; Nutman et al., 1989; McGregor et al., 1991). This interpretation propagated through our accounts of the regional geology published throughout the 1990s (e.g. Friend et al. 1996). However, renewed mapping combined with a zircon dating programme (Friend et al., 2005; Hollis et al., 2005; Nutman and Friend, 2007) discovered that in the northeastern and eastern parts of the region large areas of rocks assigned in the 1980s to the Ikkattoq gneisses and the Tre Brødre terrane on the basis of their appearance during reconnaissance field studies, are in fact rocks of different age. They include c. 2960 Ma granitic gneisses and also a suite of granitic gneisses dated at 2800 Ma, which makes them marginally younger than the type Ikkattoq gneisses. Some of these granitic gneisses are indicated in Fig. 1, with whole rock geochemistry in Table 5 and are plotted on geochemical variation diagrams (Fig. 8). Removing such samples from the Ikkattoq data set leaves a suite of samples with greater geochronological and compositional coherency, and more limited geographic extent.

The northernmost Ikkattoq gneisses that can be traced southwards as belonging to the Tre Brødre terrane in type area are represented by G88/15 on eastern Sadelø in the west and G03/23 in inner Ameralik in the east (Fig. 1). This reduces the definite extent of the Ikkattoq gneisses and the Tre Brødre terrane to a thin (<5 km thick) thrust slice in the southern and western part of the region. In the south, where the sequence of terranes is presently known in most detail, this thrust slice structurally overlies the Eoarchaean Færingehavn terrane and is overthrust by the Tasiusarsuaq terrane (see Fig. 2). To the northwest, in Godthåbsfjord, the Ikkattoq gneisses are truncated by the Ivinnguit Fault (Fig. 1) and there is a more complicated sequence of thrust packages. The northeastern parts of the region into which we had proposed that the Ikkattoq gneisses continued, generally have a 2650 to 2630 Ma metamorphic signature. This metamorphic signature is unknown in genuine Ikkattoq gneisses (Nutman and Friend, 2007). Thus these northeastern rocks of similar age are probably unrelated to the Ikkattoq gneisses, and belong to a different series of tectonostratigraphic terranes. However, a fuller programme of geochemistry and dating on these rocks is needed to explore this issue.

6.3. Is the non-juvenile nature of the Ikkattoq gneisses unique amongst the TTG suites of the Nuuk region?

In the landmark 1970s Rb-Sr isotope geochemistry papers on the TTG suites of the Nuuk region, Moorbath and co-workers (e.g., Moorbath et al. 1972; Moorbath and Pankhurst 1976) noted the low initial $^{87}Sr/^{86}Sr$ values for their regressions, indicating the studied rocks were dominated by juvenile additions to the crust. This was a revolutionary observation for study of the earliest geological record, because it demonstrated that ancient gneiss complexes contained new crustal additions, and did not represent much older crust that had been subsequently reworked. This interpretation from the strontium data was subsequently supported by positive initial ε_{Nd} values for the gneiss suites (e.g., Taylor et al., 1986; Bennett et al., 1993).

Clearly, the c. 2825 Ma Ikkattoq gneisses do not fit into this juvenile crustal mould, because they contain large contributions from >3600 Ma sialic crust. However, with more isotopic data now available, it is appropriate to question how juvenile are the other TTG suites of the Nuuk region? This is addressed by reviewing the Nd data for the Nûk gneisses in their type area in the southern part of the Akia terrane around Nuuk town, and for Eoarchaean orthogneisses of the Færingehavn and Isukasia terranes (Fig. 1). An ε_{Nd} versus age plot (Fig. 10) summarises these data. Excluded from these data sets are those samples known to represent post-TTG crustal melts, for example, the 3640 Ma augen granite suite of the Færingehavn terrane, and 2970 Ma granodiorites and granites of the Akia terrane, polyphase banded orthogneisses, and those samples without an independent zircon age determination on the exact same sample from which the Nd data was obtained. The data are from Duke (1993), Bennett et al. (1993, 2007), Vervoort et al. (1996), Nutman et al. (2007), Bennett (unpublished data). In addition, samples 283672 (3220 Ma quartz-diorite) and 289246 (3020 Ma tonalitic gneiss) from further north in the Akia terrane (Garde et al., 2000) are included.

All the simple single intrusive phase Eoarchaean gneisses are of tonalitic and quartz-dioritic composition, and yield positive initial ε_{Nd} values of mostly between +1.5 and +4.0. Despite much debate over the past decade (e.g., Bennett et al., 1993 versus Vervoort et al., 1996), these elevated initial values have become broadly accepted (e.g. Caro et al., 2003) and mean that these rocks were derived largely from material with a short crustal pre-history, originating from a mantle reservoir which was strongly depleted very early in Earth's history (e.g. Bennett et al., 1993; Caro et al., 2003).

For the type Nûk gneisses of the Akia terrane, three orthogneiss components are present, older c. 3230 Ma quartz-diorites, younger tonalitic-granodioritic rocks with zircon ages of 3050 to 3000 Ma, and a yet younger suite of c. 2970 Ma granite-granodioritic bodies (McGregor et al., 1991; Duke et al., 1990; Duke, 1993; Garde et al., 2000). In our appraisal here, rocks belonging to the youngest of these suites, where an inherited crustal component is already accepted, are not considered. Three of the presented samples are c. 3230 Ma quartz-diorites which occur as inclusions in younger orthogneisses, whereas the others are 3050 to 3000 Ma old, and are mostly of tonalitic-granodioritic composition. The quartz-diorites have ε_{Nd} values of +3.0 to +5.0. These straddle on or just above the linear depleted mantle evolution line (ε_{Nd} = 0 at planetary formation to +10 at the present day), in accord with them representing juvenile crustal additions when they formed (Fig. 10). The 3050 to 3000 Ma suite, comprising only non-banded, single phase meta-igneous rocks, in which (deformed) igneous textures are preserved in some samples, display initial ε_{Nd} values from almost -2 to over +4. Given the sluggish diffusion of Nd and Sm in solid crustal systems (Baxter and DePaulo, 2004), this variation of initial ε_{Nd} values is interpreted to reflect mixed sources for these Nûk gneisses – a juvenile 3000 Ma crustal addition and reworking of older material (this finding was also noted by Garde et al. 2000 for the northern part of the Akia terrane). However, this detailed finding does not detract from the fundamental observation by Moorbath et al. (1972) and Moorbath and Pankhurst (1976), that suites of Archaean grey gneisses such as those in the Nuuk region are dominated by juvenile additions to the crust from the mantle. It should also be noted that Moorbath and Pankhurst (1976, page 126) remarked in the context of Sr isotopic results that '*The small but statistically significant range of age and initial* $^{87}Sr/^{86}Sr$ *ratios of the Nûk gneisses in West Greenland may genuinely reflect small differences in the age of emplacement and pre-history of the parent magmas.*' Therefore at that early juncture, complications in the Rb-Sr isotopic data had been recognised, which indicated the rocks were the products of complex geological systems.

Thus the other TTG suites of the Nuuk region are also highly variable in their nature. The Eoarchaean suites and the Akia terrane 3230 to 3220 Ma quartz-diorite suite with narrow ranges of positive initial ε_{Nd} values can be construed as juvenile crustal additions with only minor, or no, components of older sialic crust incorporated into the magmas (Fig. 10). On the other hand, the Ikkattoq gneisses and at least some of the c. 3000 Ma Nûk gneisses display a ≥4 epsilon unit variation in their initial Nd isotopic compositions, which lie below depleted mantle evolution reference curves. Such suites clearly indicate the involvement of older sialic crust during their petrogenesis.

This interpretation of the Nd isotopic data (Fig. 6) superficially replicates the conclusions of the whole rock Pb-Pb isotopic study of the Nûk gneisses by Taylor et al. (1980), whose work was undertaken in the days when the orthogneisses of the Nuuk region were divided into only the Amîtsoq gneisses and the younger Nûk gneisses. Subsequently, the Nûk gneisses as then defined, have been shown to incorporate several suites of unrelated rocks of different age (3230 to 2700 Ma) in different tectonostratigraphic terranes (Friend et al., 1988; Nutman et al., 1989). Many of the Nûk gneiss samples presented by Taylor et al. (1981) contained unradiogenic Pb derived from older sialic crust, and were interpreted to indicate variable degrees of contamination of juvenile Nûk magmas passing through the border of an older continental fragment of Eoarchaean Amîtsoq gneisses. We have reviewed the data of Taylor et al. and find that rocks with the highest component of unradiogenic Pb are candidates for Ikkattoq gneisses, plus definite sheets of c. 2700 Ma granite cutting Eoarchaean gneisses. Samples with high unradiogenic Pb contamination also occur at the margins of the Akia and Tasiusarsuaq terranes, where they are in closest proximity to Eoarchaean rocks. Regardless of age and lithology, a correlation is observed between the magnitude of the unradiogenic Pb component and distance from the terrane boundary (Nutman et al., 1988; Nutman and Friend, 1989). This suggests secondary metasomatic effects during and after tectonic terrane assembly have been significant in imparting these rocks their Pb isotopic signatures. Thus at this stage, it is unresolved if some of this whole rock Pb data also reflects earlier, syn-magmatic contamination from Eoarchaean sialic crust.

7. Conclusions

- The Ikkattoq gneisses contain mostly granodiorites and lesser amounts of quartz diorite – both shown by zircon dating to have the same age of c. 2825 Ma. This lithological diversity suggests that the Ikkattoq gneiss magmas incorporate more than one source material.
- Ikkattoq gneiss initial (i.e. 2825 Ma) ε_{Nd} values range from -0.6 to -6.5 and ε_{Sr} ranges from -2 to +66. This indicates a significant contribution of older (low Sm/Nd, high Rb/Sr) crust into the Ikkattoq gneisses. A suitable candidate would be Eoarchaean rocks represented by those of the Isukasia and Færingehavn terranes.
- Using field evidence and the zircon age of the type Ikkattoq gneisses the apparently perfect 2005 Ma Sm-Nd ‘isochron’ (MSWD=0.72), is shown to be too young. The ‘isochron’ is interpreted as a fortuitous blending of source materials of different age and origin. We suspect that the MSWD would rise if an extra geographically broader suite of Ikkattoq gneisses was added to this regression.
- In both their isotopic systematics and trace element chemistry, the Ikkattoq gneisses show broad parallels with granitoids from modern Andean settings, where melts derived from metasomatised mantle interact with an older continental crust margin. However, we would stop short at championing the Tre Brødre terrane with its Ikkattoq gneisses as a tectonic slice through an exact analogue of the mid-crustal levels of a modern Andean margin.
- The contamination of the Ikkattoq gneisses by older continental crust is not unique within the Archaean TTG suites of the Nuuk region, because Nd data from 3000 to 3050 Ma type Nûk gneisses shows a similar variability in initial $^{143}Nd/^{144}Nd$ ratio (this paper and Garde et al. 2000).

Acknowledgements

The key fieldwork on the Ikkattoq area undertaken in 1985 was supported partly by C.R.L. Friend and A.P. Nutman from their own pockets and partly by the Geological Survey of Greenland. Laboratory work by H. Baadsgaard and M.J.M. Duke was supported by NSERC funding.

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Figure Captions

Figure 1. Location map showing the distribution of terranes in the Nuuk region and the location of the Ikkattoq area. Inset shows the study area in relation to the Greenland Archaean craton.

Figure 2. Geological map of the Ikkattoq area.

Figure 3. (A) Typical homogeneous biotite-granodiorite facies of the Ikkattoq gneisses, with widely-spaced subconcordant pegmatite layers. (B and C) Strain gradient towards the Neoarchaean Ivinnguit Fault on the south-east corner of Sadelø (see Fig. 1; Ik=Ikkattoq gneisses, g=later Archaean granitic sheets). In (B) east away from the terrane boundary, the Ikkattoq gneisses are cut by discordant late Archaean granite sheets. In (C) to the west near the terrane boundary, the late Archaean granite sheets have been further deformed and rotated into parallelism with the layering of the Ikkattoq gneisses and the terrane boundary, <100 m to the west.

Figure 4. U-Pb Concordia plot showing the data for the bulk and ^{205}Pb-spiked Ikkattoq gneiss zircon samples. Analytical errors are depicted at the 2σ level. * marks the SHRIMP ^{207}Pb/^{206}Pb age determinations for samples G85/350 and G88/15 from Nutman and Friend (2007).

Figure 5. Sm-Nd isotopic systematics for the Ikkattoq gneisses. (A) ^{147}Sm/^{144}Nd vs. ^{143}Nd/^{144}Nd isochron plot. (B) ε_{Nd} vs. age plot indicating the Ikkattoq gneiss compositions at 2825 Ma and the evolution of components of the Itsaq Gneiss Complex and the oldest components of the Nûk gneisses. DM=depleted mantle and CHUR=chondritic uniform reservoir. (C) Prerequisites for the age and relative initial ^{143}Nd/^{144}Nd ratios of mixed source components in the Ikkattoq gneisses. Inset shows the correlation between Sm/Nd and Nd (in ppm).

Figure 6. (A) ^{87}Rb/^{86}Sr vs. ^{87}Sr/^{86}Sr isochron diagram for the type Ikkattoq gneisses (B) ε_{Nd} vs. ε_{Sr} plot for the type Ikkattoq gneisses. CHUR=chondritic uniform reservoir.

Figure 7. ^{206}Pb/^{204}Pb vs. ^{207}Pb/^{204}Pb plot for the Ikkattoq gneisses. The model mantle evolution curve is Stacey and Kramers (1975). Field for Pb isotopic compositions for typical Eoarchaean orthogneisses of the Færingehavn terrane

in the Neoarchaean is constructed using the compositions of (recrystallised) plagioclases (Kamber and Moorbath, 1998). Line A-B shows the expected Pb isotopic compositions for the Ikkattoq gneisses if they were a juvenile 2825 Ma suite derived from a model Stacey and Kramers mantle source.

Figure 8. Geochemistry of the Ikkattoq gneisses. (A) SiO_2 vs. MgO (wt%) plot. Fields for different-aged TTG are from Martin (2005). (B) Q-Ab-Or Normative proportions of Ikkattoq gneisses. 1, 5 and 10 kbar phase boundaries are from Johannes and Holtz (1996). (C) Nb+Y vs. Rb discrimination diagram. Note – use of Rb is considered justified (despite the metamorphosed state of these rocks), because the Ikkattoq gneisses have only ever experienced maximum middle amphibolite facies metamorphism, with Rb being retained in biotite. (D) Yb vs. La/Yb(N) plot. Fields for modern arc rocks and TTG are from Martin (1986). E) Primitive mantle normalised trace element spider diagram. Calculations and plotting were undertaken using Geoplot (Zhou and Li, 2006).

Figure 9. REE patterns for (A, B) the Ikkattoq gneisses and (C) rocks of a similar age further northeast in the Nuuk region. Calculations and plotting were undertaken using Geoplot (Zhou and Li, 2006).

Figure 10. Initial $^{143}Nd/^{144}Nd$ values (in ε format) for type Nûk gneisses near Nuuk, where their age is known independently via zircon U-Pb dating (Duke et al., 1990; Duke, 1993; Bennett, unpublished data), together with two samples from further north in the Akia terrane (Garde et al., 2000). The early suite of 3230-3220 Ma quartz diorites appear to be a juvenile addition to the crust, whereas the 3050-3000 Ma suites are not entirely juvenile additions, but contain some contributions from older crust.

Figure-1(ed)

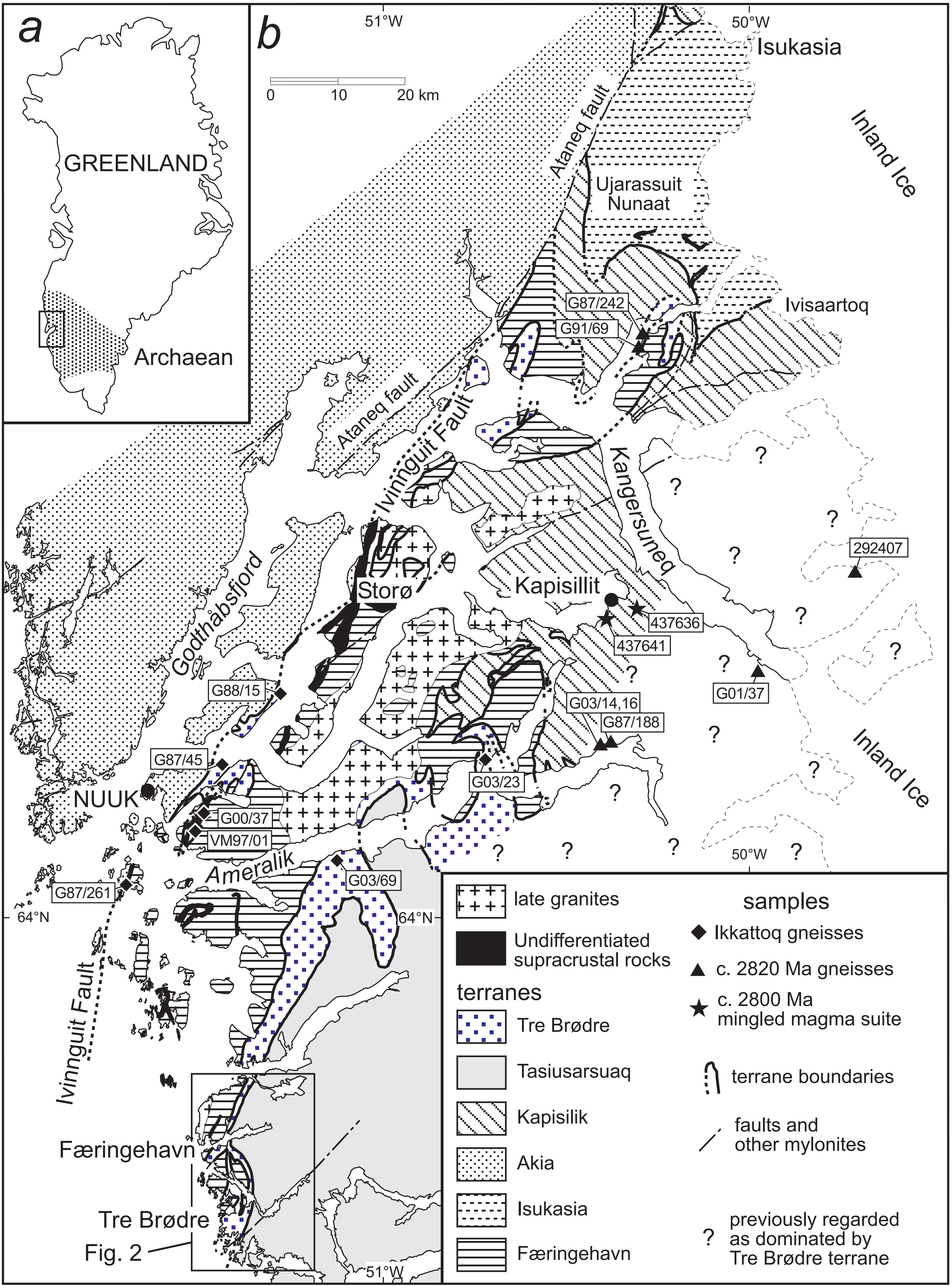

a
GREENLAND
Archaean
b
51°W
50°W
Isukasia
0
10
20 km
Inland Ice
Ataneq fault
Ujarassuit Nunaat
Ivisaartoq
G87/242
G91/69
Ataneq fault
Ivinnguit Fault
Kangersuneq
?
292407
Storø
Kapisillit
437636
437641
Godthåbsfjord
G01/37
G03/14,16
G87/188
G88/15
G87/45
G03/23
NUUK
G00/37
VM97/01
Inland Ice
Ameralik
50°W
G87/261
G03/69
64°N
64°N
Ivinnguit Fault
Færingehavn
Tre Brødre
Fig. 2
51°W
late granites
Undifferentiated supracrustal rocks
terranes
Tre Brødre
Tasiusarsuaq
Kapisilik
Akia
Isukasia
Færingehavn
samples
Ikkattoq gneisses
c. 2820 Ma gneisses
c. 2800 Ma mingled magma suite
terrane boundaries
faults and other mylonites
previously regarded as dominated by Tre Brødre terrane

Figure-2(ed)

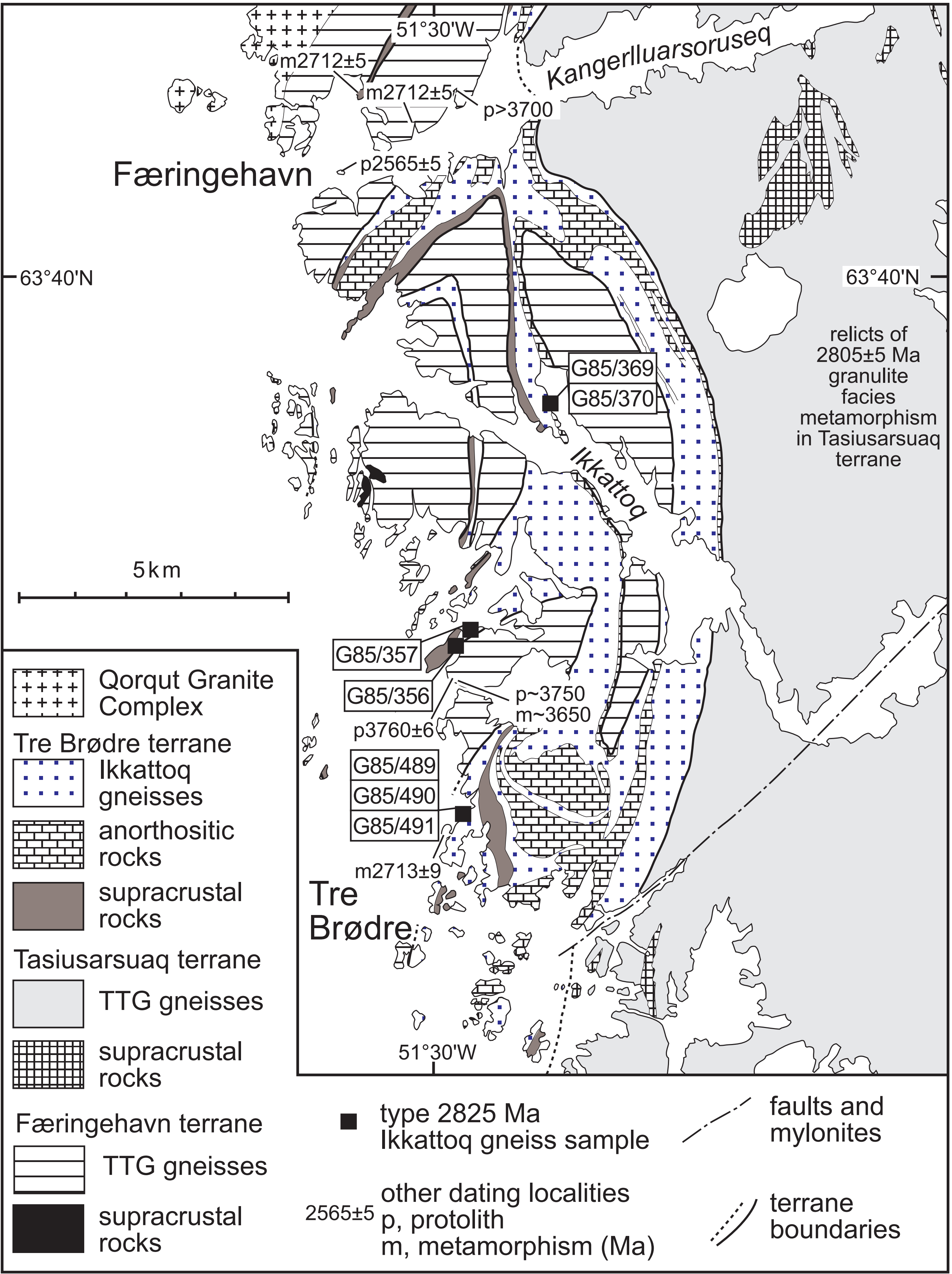

51°30'W
Kangerlluarsoruseq
m2712±5
m2712±5
p>3700
Færingehavn
p2565±5
63°40'N
63°40'N
relicts of 2805±5 Ma granulite facies metamorphism in Tasiusarsuaq terrane
G85/369
G85/370
Ikkattoq
5 km
G85/357
G85/356
p~3750
m~3650
p3760±6
G85/489
G85/490
G85/491
m2713±9
Tre Brødre
51°30'W
Qorqut Granite Complex
Tre Brødre terrane
Ikkattoq gneisses
anorthositic rocks
supracrustal rocks
Tasiusarsuaq terrane
TTG gneisses
supracrustal rocks
Færingehavn terrane
TTG gneisses
supracrustal rocks
type 2825 Ma Ikkattoq gneiss sample
2565±5
other dating localities
p, protolith
m, metamorphism (Ma)
faults and mylonites
terrane boundaries

Figure-3

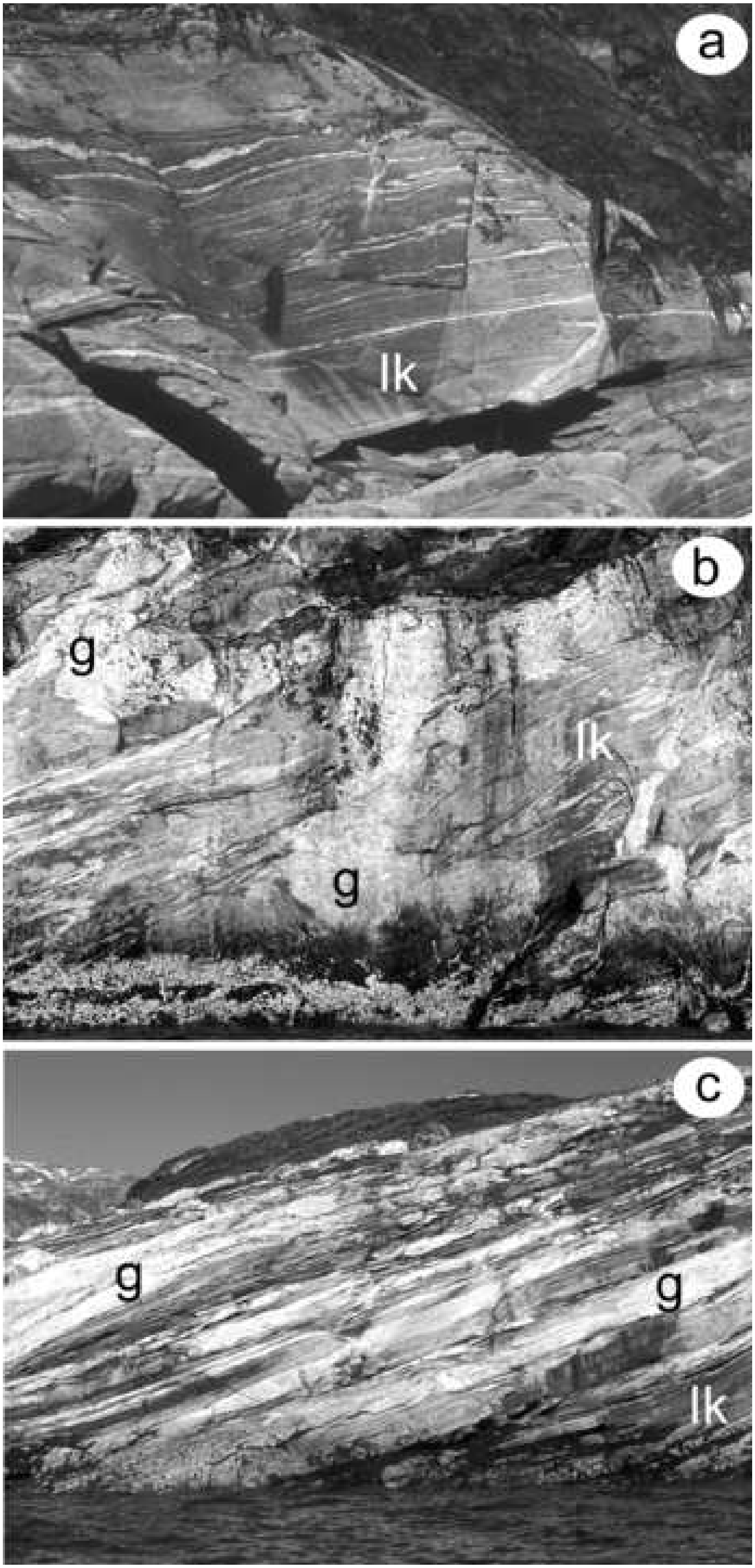


Figure 4

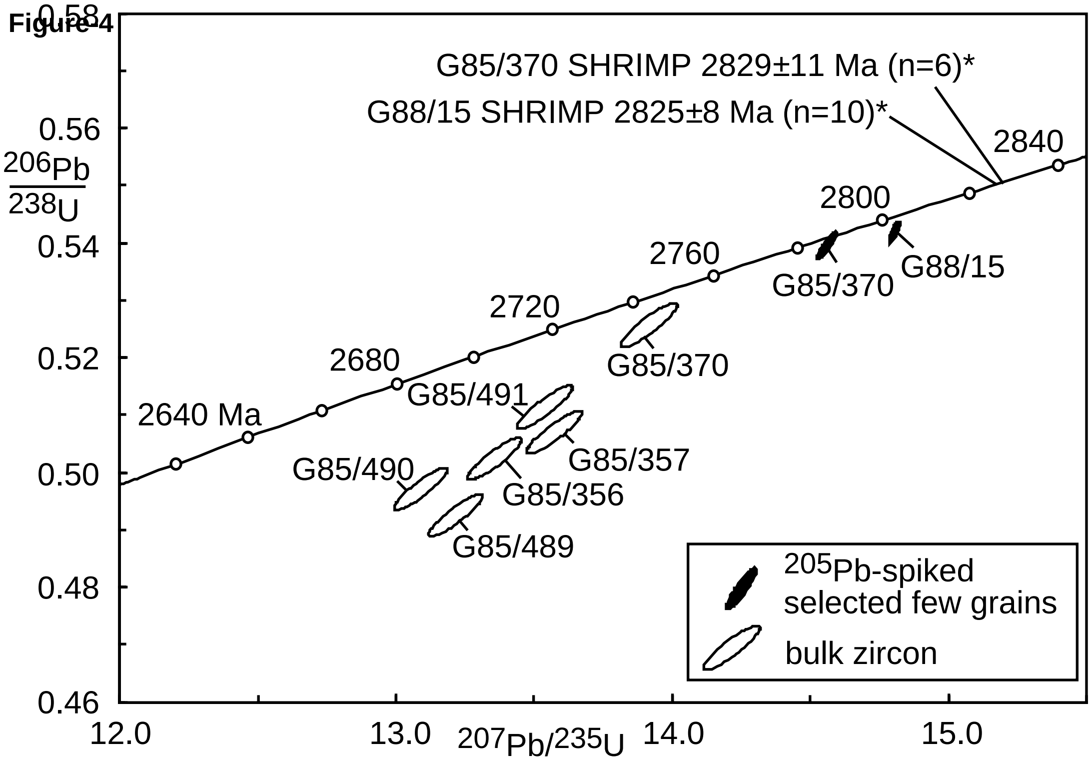

G85/370 SHRIMP 2829±11 Ma (n=6)*
G88/15 SHRIMP 2825±8 Ma (n=10)*
2840
2800
2760
2720
2680
2640 Ma
G85/370
G88/15
G85/370
G85/491
G85/357
G85/490
G85/356
G85/489
^{205}Pb-spiked selected few grains
bulk zircon
^{206}Pb/^{238}U
0.58
0.56
0.54
0.52
0.50
0.48
0.46
^{207}Pb/^{235}U
12.0
13.0
14.0
15.0

Figure-5(ed)

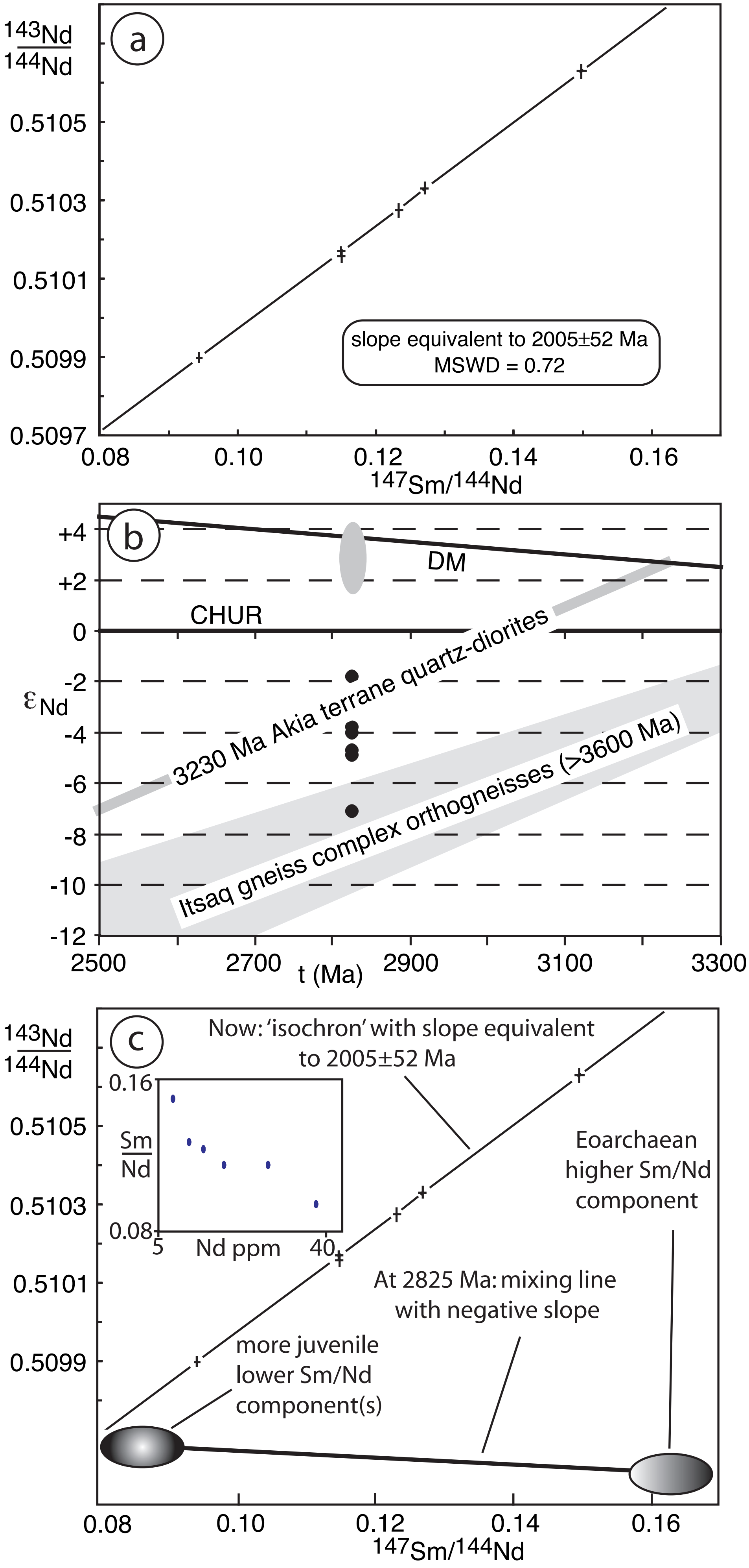
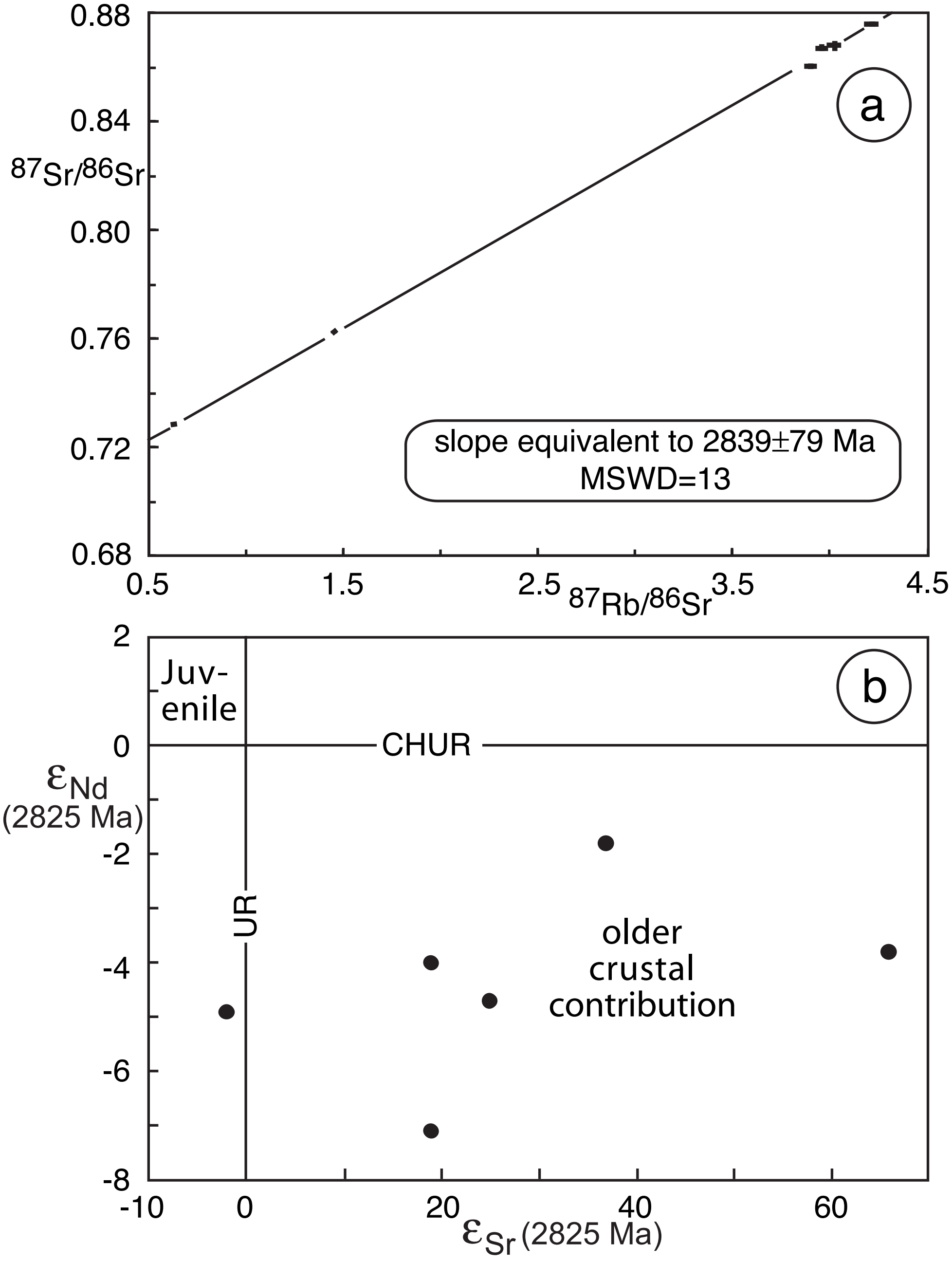
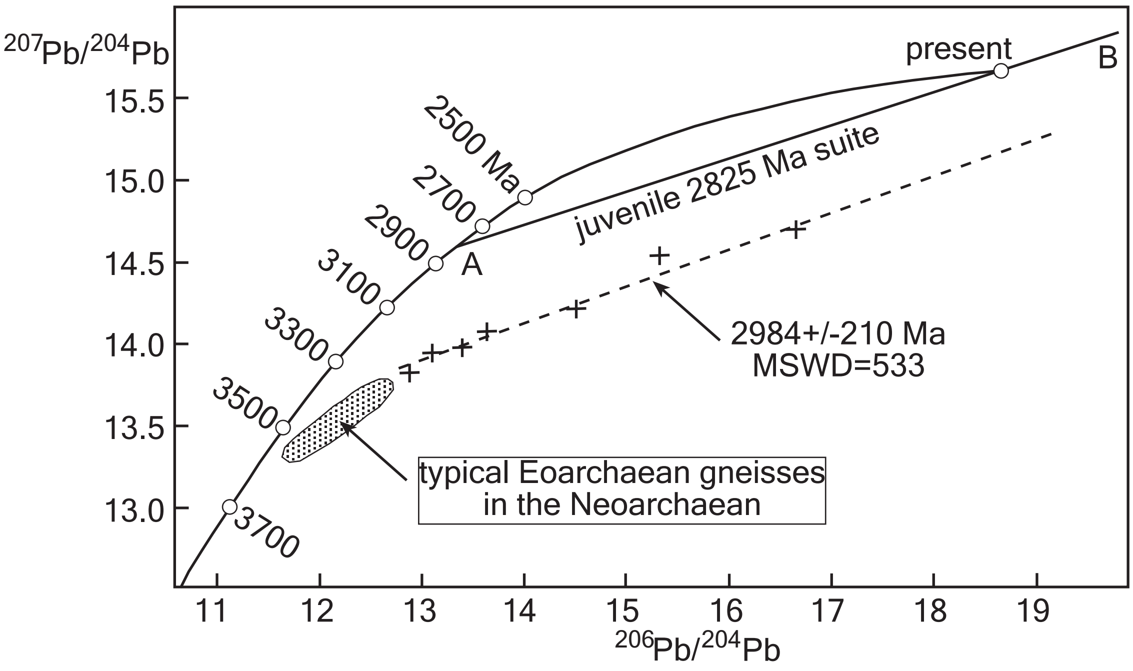

a
$^{143}Nd/^{144}Nd$
0.5105
0.5103
0.5101
0.5099
0.5097
slope equivalent to 2005±52 Ma
MSWD = 0.72
0.08
0.10
0.12
0.14
0.16
$^{147}Sm/^{144}Nd$
b
+4
+2
0
-2
-4
-6
-8
-10
-12
ε_{Nd}
DM
CHUR
3230 Ma Akia terrane quartz-diorites
Itsaq gneiss complex orthogneisses (>3600 Ma)
2500
2700
2900
3100
3300
t (Ma)
c
$^{143}Nd/^{144}Nd$
Now: 'isochron' with slope equivalent to 2005±52 Ma
0.16
Sm/Nd
0.08
5
Nd ppm
40
Eoarchaean higher Sm/Nd component
At 2825 Ma: mixing line with negative slope
more juvenile lower Sm/Nd component(s)
0.5105
0.5103
0.5101
0.5099
0.08
0.10
0.12
0.14
0.16
$^{147}Sm/^{144}Nd$

Figure-6(ed)



0.88
0.84
$^{87}Sr/^{86}Sr$
0.80
0.76
0.72
0.68
0.5
1.5
2.5
$^{87}Rb/^{86}Sr$
3.5
4.5
a
slope equivalent to 2839±79 Ma
MSWD=13
2
0
-2
-4
-6
-8
ε_{Nd}
(2825 Ma)
Juv-
enile
CHUR
UR
b
older
crustal
contribution
-10
0
20
40
60
ε_{Sr} (2825 Ma)

Figure-7



$^{207}Pb/^{204}Pb$
15.5
15.0
14.5
14.0
13.5
13.0
11
12
13
14
15
16
17
18
19
$^{206}Pb/^{204}Pb$
present
B
2500 Ma
2700
2900
3100
3300
3500
3700
A
juvenile 2825 Ma suite
2984+/-210 Ma
MSWD=533
typical Eoarchaean gneisses
in the Neoarchaean

Figure-8(ed)

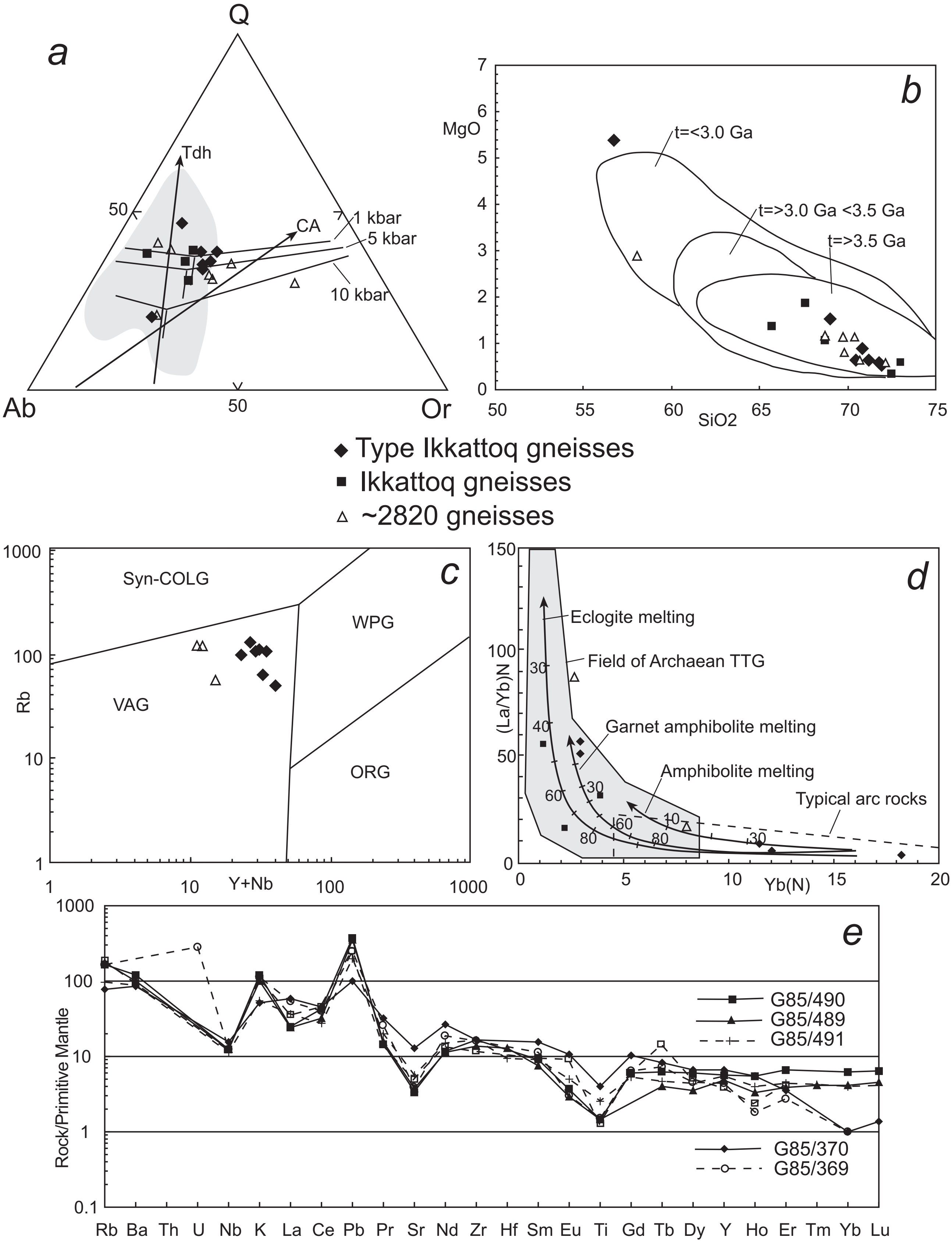
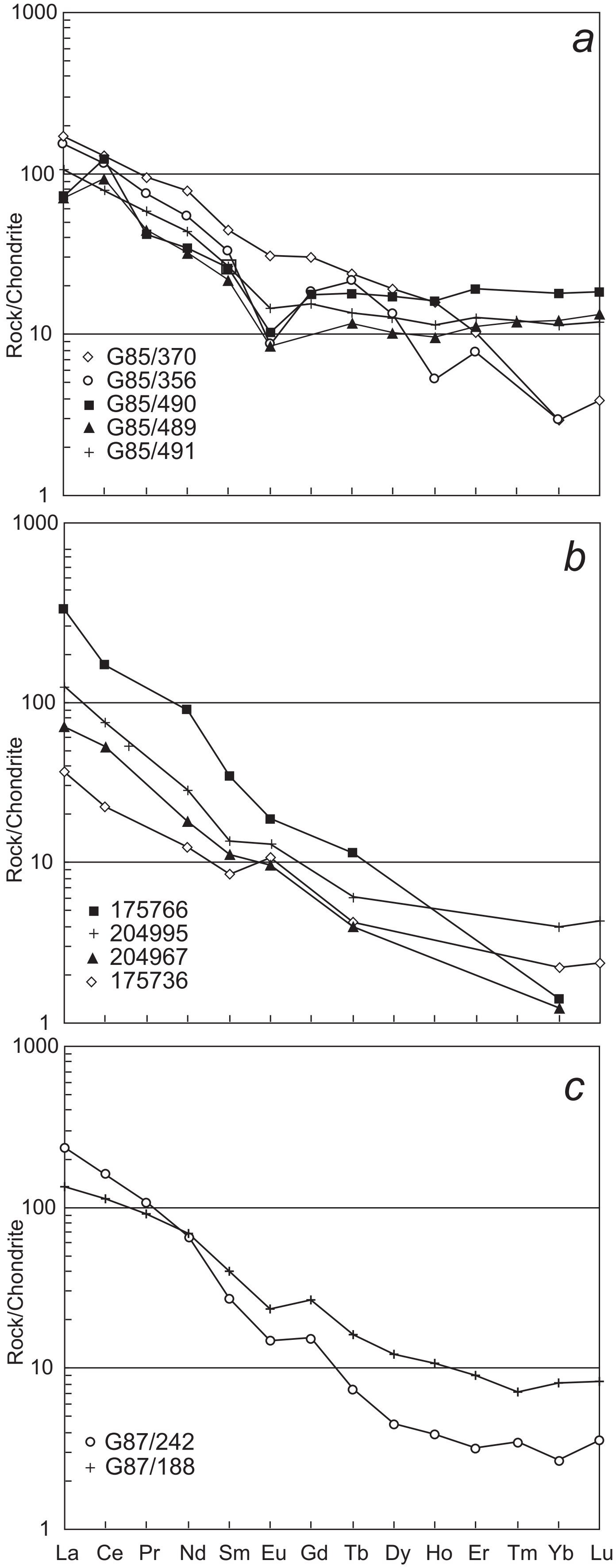
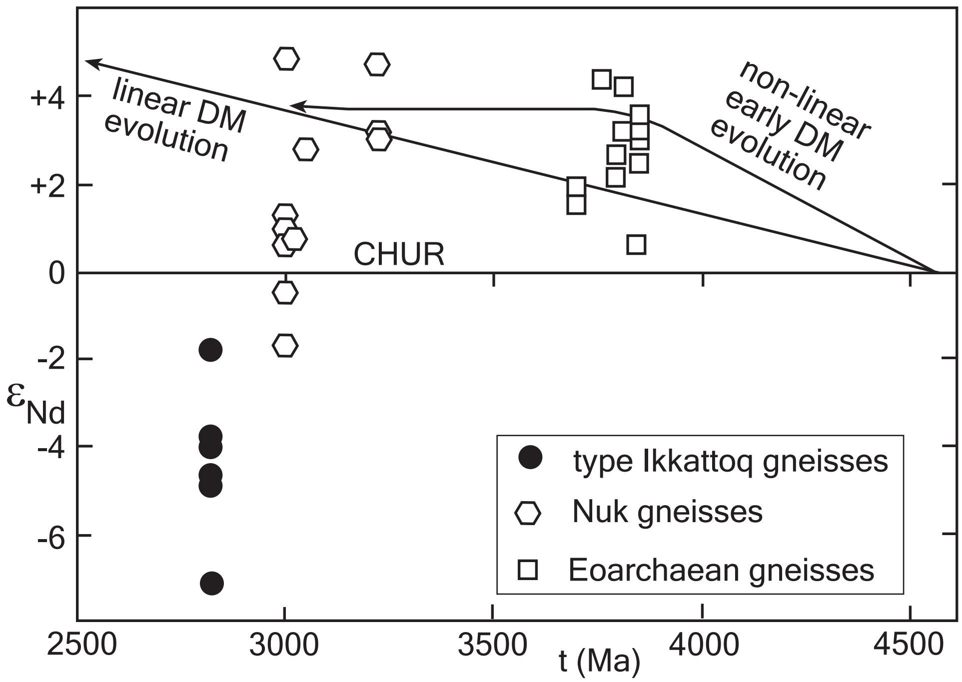

a
Q
Ab
Or
50
50
Tdh
CA
1 kbar
5 kbar
10 kbar
b
MgO
SiO2
t=<3.0 Ga
t=>3.0 Ga <3.5 Ga
t=>3.5 Ga
7
6
5
4
3
2
1
0
50
55
60
65
70
75
◆ Type Ikkattoq gneisses
■ Ikkattoq gneisses
△ ~2820 gneisses
c
Rb
Y+Nb
Syn-COLG
WPG
VAG
ORG
1000
100
10
1
1
10
100
1000
d
(La/Yb)N
Yb(N)
Eclogite melting
Field of Archaean TTG
Garnet amphibolite melting
Amphibolite melting
Typical arc rocks
150
100
50
0
0
5
10
15
20
30
40
60
80
30
60
80
10
30
e
Rock/Primitive Mantle
1000
100
10
1
0.1
G85/490
G85/489
G85/491
G85/370
G85/369
Rb Ba Th U Nb K La Ce Pb Pr Sr Nd Zr Hf Sm Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu

Figure-9(ed)



a
b
c
1000
100
10
1
Rock/Chondrite
◇ G85/370
○ G85/356
■ G85/490
▲ G85/489
+ G85/491
■ 175766
+ 204995
▲ 204967
◇ 175736
○ G87/242
+ G87/188
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu

Figure-10



+4
+2
0
-2
-4
-6
ε_{Nd}
2500
3000
3500
4000
4500
t (Ma)
linear DM evolution
non-linear early DM evolution
CHUR
● type Ikkattoq gneisses
⬡ Nuk gneisses
☐ Eoarchaean gneisses

Table-1

sample	weight (mg)	206Pb/204Pb	±	238U ppm	206Pb ppm(rad)	f206%	206Pb/238U	±%	207Pb/235U	±%	207Pb/206Pb	±%	7/6age
bulk 208Pb-235U spiked													
G85/356	16.8	17360	120	723	314	0.49	0.5024	0.30	13.36	0.30	0.19281		2766
G85/357	19.4	18450	850	646	283	0.45	0.5070	0.30	13.57	0.30	0.19414		2778
G85/491	23.9	16393	800	589	261	0.49	0.5114	0.30	13.54	0.30	0.19199		2759
G85/370	22.4	5650	60	173	78.8	0.42	0.5257	0.30	13.92	0.30	0.19193		2759
G85/489	20.6	6849	140	512	218	0.92	0.4925	0.30	13.22	0.30	0.19458		2781
G85/490	21.4	10753	450	758	326	1.01	0.4971	0.30	13.09	0.30	0.19093		2750
small sample 205Pb-235U spiked													
G85/370	0.048	1689	17	108.9	50.2	1.31	0.5396	0.18	14.56	0.10	0.19565	0.07	2791
G88/15	0.103	10309	134	424	197.5	0.9	0.5420	0.11	14.81	0.04	0.19811	0.03	2811

Table-2

sample	Sm	Nd	147Sm/144Nd	err	143Nd/144Nd	err	εNd(2825)
G85/356	5.94	38.0	0.09440	0.00019	0.509898	0.000005	-1.8
G85/357	3.90	20.5	0.11497	0.00023	0.510170	0.000005	-3.8
G85/370	5.50	28.9	0.11500	0.00023	0.510157	0.000007	-4.0
G85/489	2.91	13.8	0.12705	0.00025	0.510331	0.000007	-4.9
G85/490	2.67	10.8	0.14977	0.00030	0.510629	0.000008	-7
G85/491	3.38	16.6	0.12334	0.00025	0.510274	0.000008	-4.7

sample	87Rb/86Sr	err	87Sr/86Sr	err	εSr(2825)
G85/356	4.021	0.010	0.86808	0.0003	37
G85/357	3.955	0.010	0.86740	0.0003	66
G85/370	0.631	0.002	0.72829	0.0004	19
G85/489	3.900	0.010	0.86038	0.0002	-2
G85/490	4.212	0.011	0.87601	0.0004	39
G85/491	1.454	0.004	0.76231	0.0002	25

Table-4

sample	206Pb/204Pb	err	207Pb/204Pb	err	208Pb/204Pb	err
G85/356	13.678	0.001	14.062	0.002	36.049	0.004
G85/357	13.411	0.001	13.958	0.001	35.317	0.003
G85/370	12.895	0.001	13.816	0.002	33.957	0.003
G85/489	13.129	0.003	13.932	0.003	35.297	0.011
G85/490	14.515	0.001	14.199	0.001	37.04	0.005
G85/491	16.693	0.002	14.672	0.002	41.954	0.006
G88/15	15.341	0.002	14.527	0.004	36.339	0.012

Table-5(ed)

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Table 5. Ikkattoq gneiss geochemistry

	2825 Ma Ikkattoq gneisses from type area												Ikkattoq gneisses outside of type area			
Sample	G85/370	G85/370	G85/491	G85/491	G85/356	G85/356	G85/369	G85/489	G85/489	G85/357	G85/357	G85/490	G03/69	175736	175766	204967
wt%	MUN	OBU	MUN	OBU	MUN	OBU	OBU	MUN	OBU	MUN	OBU	OBU	ANU	C 1978	C 1978	C 1978
SiO2	56.70			69.00	71.20	70.47	70.80		71.20		71.76	71.90	68.75	65.68	67.59	72.5
TiO2	0.88			0.56	0.28	0.33	0.28		0.32		0.32	0.32	0.34	0.49	0.41	0.17
Al2O3	15.80			14.90	14.40	14.53	15.50		14.40		14.40	13.80	16.25	15.97	15.33	14.86
Fe2O3	8.20			5.52	2.58	2.45	2.44		2.60		2.42	2.49	3.39			
FeO													0.04	3.45	2.33	1.23
MnO	0.11			0.03	0.04	0.05	0.05		0.04		0.05	0.04	1.14			
MgO	5.80			1.53	0.73	0.64	0.88		0.63		0.59	0.52	4.45	1.36	1.87	0.32
CaO	7.22			2.34	2.52	2.56	2.86		2.42		2.42	2.10	4.00	5.56	3.60	3.01
Na2O	3.40			3.53	3.38	4.01	3.64		3.76		4.01	3.49	1.22	3.86	3.95	4.27
K2O	1.56			1.68	3.69	3.46	3.45		3.03		3.39	3.60	0.08	0.98	2.76	2.7
P2O5	0.17			0.11	0.05	0.09	0.05		0.05		0.08	0.06				
SO3																
Sum	99.84			99.20	98.87	98.59	99.95		98.45		99.44	98.32	99.66	97.35	97.84	99.06
LOI							0.28		0.18							
ppm																
Li				3								2				
Sc				9		5					4	11				
V						22	18				23	12				
Cr						19					34					
Ni						11	2				18					
Co						79					59					
Cu						2	4	3				3				
Zn						34					38					
Pb	7.00		14.00			18.00	19	25.00		16.00	21.00	27.00				
Rb	49		62			106	128.00	111		95	97	105		36	73	51
Sr	269		118	175		81	106	79		73	77	72		244	277	233
Ba	603		618				698	710		763		838		921	2886	1660
Y	30.0		25.0			20.0	18	22.0		22.0	23.0	26.0				
Zr	183		186			182	137.0	152		161	182	183				
Nb	11		8			9	9	9		11		9				
Hf			3					4						4.4		
Cs																
La	32.30	40.40		25.00		36.30	25.20	16.68				17.00		8.7	89	16.6
Ce	63.60	79.50		48.00		70.00	84.30	57.42				76.00		13.6	104.3	32.2
Pr	7.20	9.00		5.50		7.10	4.20	4.24				4.00				
Nd	28.90	36.50		20.30		25.50	19.00	15.17				16.00		5.8	41.6	8.35

Sm		6.80		4.10		5.00	4.30	3.32				4.00		1.3	5.3	1.7
Eu	5.50	1.80		0.84		0.50	1.60	0.49				0.60		0.62	1.1	0.56
Gd	1.44	6.20		3.16		3.80	3.70					3.60				
Tb	4.96	0.90		0.51		0.80	1.60	0.44				0.68		0.16	0.43	0.15
Dy	0.72	4.90		3.23		3.40	3.80	2.64				4.40				
Ho	3.92	0.90		0.65		0.30	0.40	0.55				0.91				
Er	0.72	1.70		2.13		1.30	2.00	1.85				3.20				
Tm	1.36			0.31				0.31								
Yb				1.96		0.50	nd	2.06				3.10		0.38	0.24	0.21
Lu				0.31			nd	0.34				0.47		0.06		
Th	0.40	0.50				6	2				10			32.5	32.5	11.00
U	0.08	0.10														

Analyses: Samples with the same numbers analysed at MUN and OBU were carried out on different portions of the same material separated at the time of collection.
MUN: Memorial University, Newfoundland.
OBU: Oxford Brookes University, UK. Majors by a AA spectroscopy, trace and RE elements by ICPAES.
ANU: Australian National University. Majors by XRF and traces by ICPMS
C 1978: Data from Compton (1978)

	North and eastern 2820 to 2800 Ma gneisses						
204995	G87/242	G87/188	G03/14	G03/16	292407	437636	437641
C 1978	OBU	OBU	ANU	ANU	ANU	ANU	ANU
73.01	70.71	58.02	69.83	69.75	68.74	70.42	72.12
0.21	0.21	0.58	0.35	0.41	0.44	0.43	0.21
14.01	14.07	16.37	15.39	15.17	14.92	14.16	15.76
	1.76	5.82	3.17	3.69	2.97	5.83	2.06
1.91							
	0.02	0.08	0.04	0.05	0.03	0.07	0.02
0.57	0.64	2.90	0.81	1.15	1.16	1.13	0.58
2.92	2.10	5.89	3.92	3.51	2.27	0.64	2.13
3.91	3.33	4.02	4.27	4.14	3.87	2.27	4.15
2.7	4.30	1.97	1.31	1.82	3.65	7.33	4.12
	0.05	0.17	0.12	0.10	0.16	0.20	0.1
			0.01	0.01		0.02	0.08
99.24	97.19	95.82	99.22	99.80	98.21	102.50	101.32
						-2.74	-1.44
		91			29		
					29		
					13		
					89		
		28			32		
					28.00		
91	119	56			119		
163	420	351			420		
1701	1810	1024			1810		
	6.0	15.5			6.1		
	271	64			271		
	6				5		
3.15							
29.9	56.30	31.79					
46.1	97.40	69.00					
	10.20	8.60					
13.3	30.90	31.93					

2.1	4.20	6.10
0.75	0.86	1.36
	3.18	5.43
0.23	0.28	0.60
	1.14	3.09
	0.22	0.61
	0.53	1.49
0.1	0.09	0.18
0.67	0.46	1.37
0.11	0.09	0.21
7.7		

.